



**SRC/SEMATECH Engineering Research Center  
for Environmentally Benign Semiconductor Manufacturing**

**2011 ANNUAL REPORT**

**February 2011**

# **Cytotoxicity of Nanoscale CeO<sub>2</sub>: Summary of Round Robin Findings**



# Cytotoxicity of Nanoscale CeO<sub>2</sub> Summary of Round Robin Findings

## PIs:

- JA Field, S. Boitano, R. Sierra-Alvarez, Univ. of Arizona
- J. Posner & TJ Thornton, Arizona State University
- Y. Chen, Georgia Institute of Technology
- R. Mumper, A. Tropsha, Univ. of North Carolina/Chapel Hill
- R. Draper, S. Nielsen, P. Pantano, Univ. of Texas/Dallas

# Objectives

**Instructions Round Robin: Compare physical chemical properties and cytotoxicity of the same CeO<sub>2</sub> sample in different laboratories**

- 1) Measure particle size distribution (PSD) and zeta potential (ZP) of 200 to 300 mg/L suspension with DLS around pH 3.5 to 4.5.
- 2) Measure PSD and ZP of 200 to 300 mg/L suspension with pH 7 water, phosphate buffer and/or biological medium
- 3) Measure change in PSD, ZP and CeO<sub>2</sub> concentration after 24 h
- 4) Measure cytotoxicity (Inhibition) up to a maximum concentration of 1,500 mg/L of CeO<sub>2</sub>.

# Methodology

## Cerium(IV) oxide, dispersion

### Supplier

**Sigma-Aldrich, P/N 643009**

### Form

**Dispersion (pH 4.5), nanoparticles  
No dispersant added**

### Concentration

**10 wt. % in H<sub>2</sub>O**

### Particle size

**<25 nm**

# Methodology: Cytotoxicity

Participants	Bioassay <sup>†</sup>	Target	Exposure time
Univ. of Arizona	Microtox	Bacterium ( <i>Vibrio fischeri</i> )	30 min
	Oxygen uptake rate	Yeast ( <i>S. cerevesiae</i> )	10 h
	Impedance-based RTCA*	Human lung epithelial cells 16HBE14o-	60 h
	Live/Dead assay	Human skin cells (Hacat)	2 h
Arizona State Univ.	---	---	---
Georgia Tech.	---	---	--
Univ. of North Carolina/Chapel Hill	MTT	A549 lung cancer cells	24 h
	Membrane integrity assay	A549 lung cancer cells	24 h
Univ. of Texas/Dallas	Cell proliferation assay	Normal rat kidney (NRK) cells	4 days

<sup>†</sup> ASU = lipid layer partitioning, and membrane leakage; GT = plant uptake (see individual reports)

\* RTCA= Real time cell analysis with xCELLingence instrument (Roche)

# Methodology: Ce Analysis

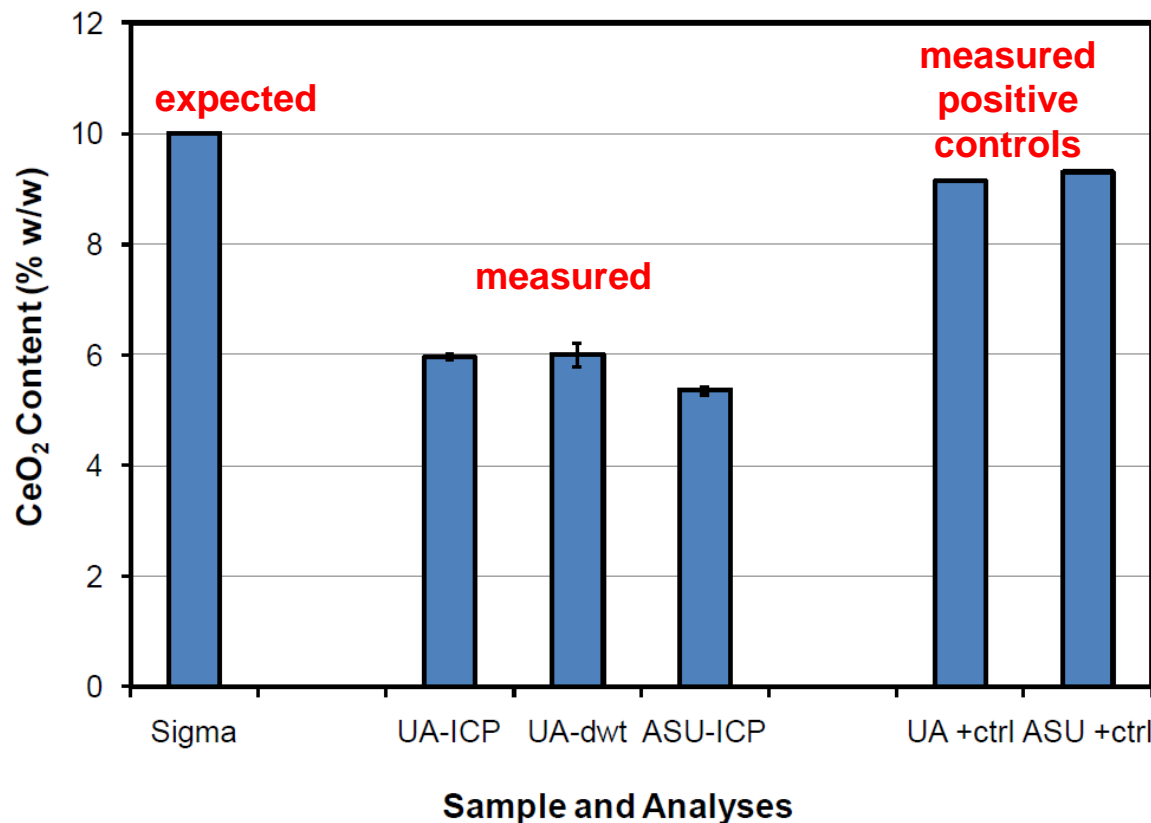
Participants	Ce Analysis	Particle Size Analysis	Zeta Potential
Univ. of Arizona	Microwave digestion/ ICP-OES	DLS*	Doppler velocimetry/PALS**
Arizona State Univ.	Acid digestion/ICP	DLS	??
Georgia Tech.	-----	DLS	Doppler velocimetry/PALS
Univ. of North Carolina/Chapel Hill	-----	DLS	Doppler velocimetry/PALS
Univ. of Texas/Dallas	-----	DLS	ELS*** /PALS

\* DLS= Dynamic Light Scattering, ++ PALS = Phase analysis light scattering

\*\* Electrophoretic light scattering (ELS)

# Results

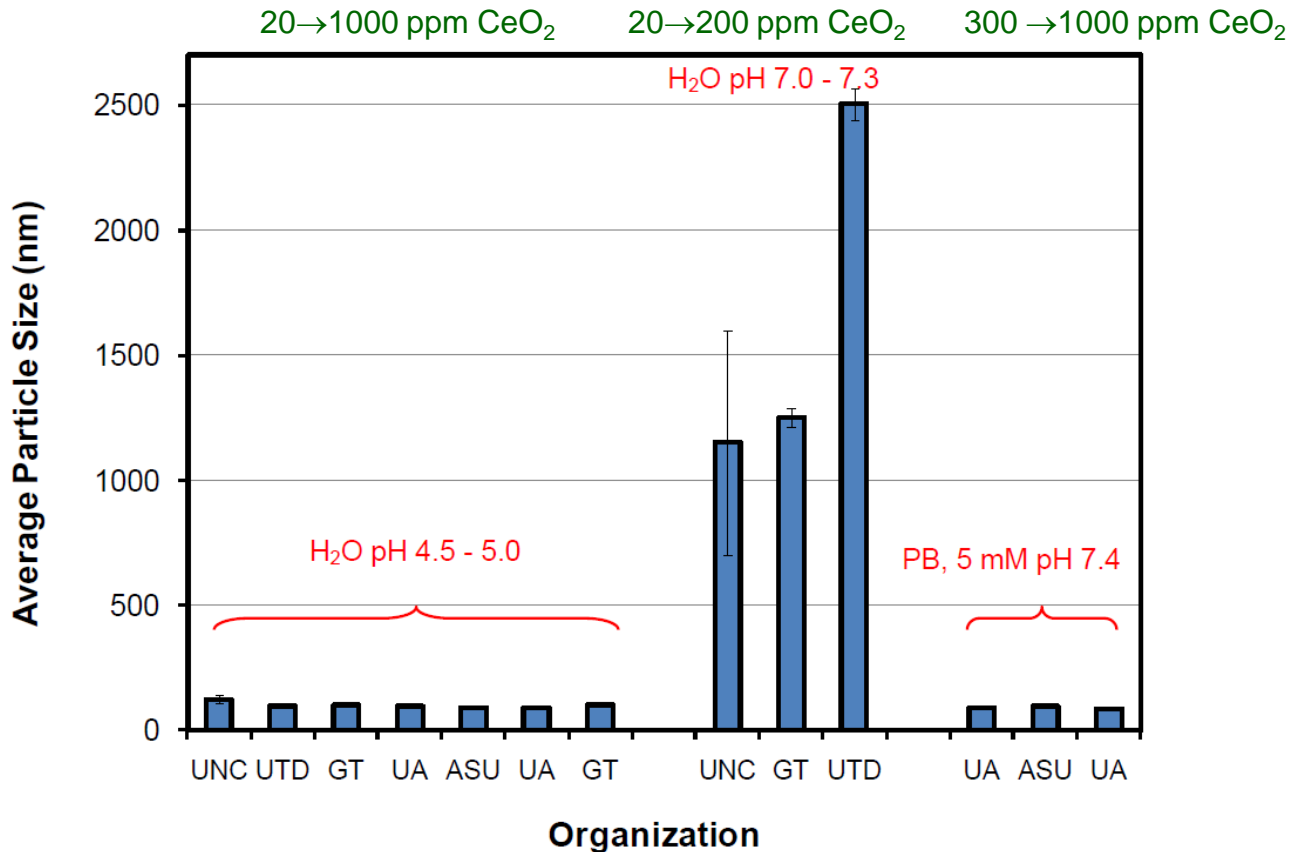
How Much  $\text{CeO}_2$  was in Sigma 10% w/w Sample?



**Conclusion:** Based on ICP, the sample contained approx. 57% of the expected  $\text{CeO}_2$  concentration. Purity could also be rapidly estimated with a simple dry weight measurement. Real Conc. =  $0.57 \times \text{Reported Conc.}$

# Results

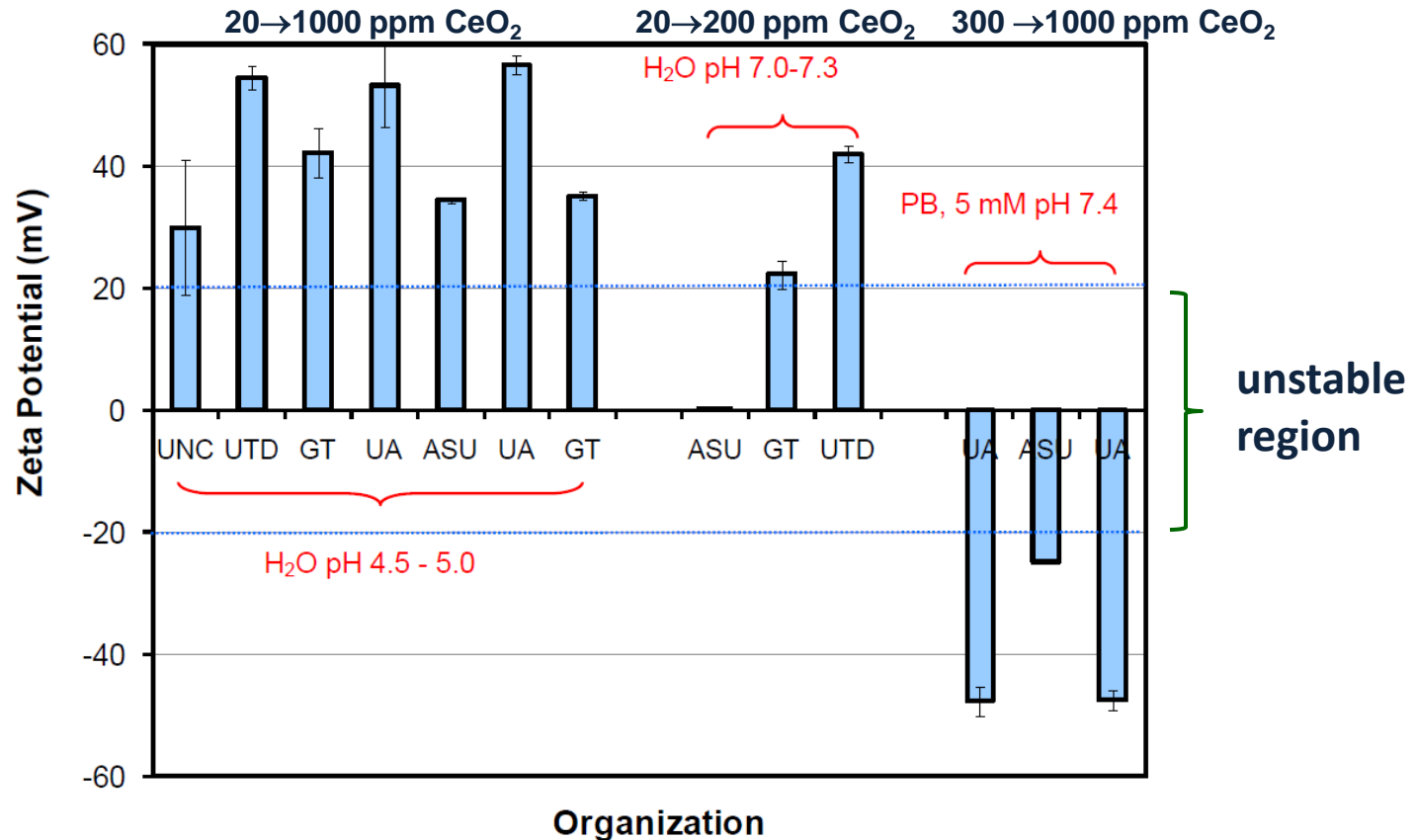
## Intensity Averaged Particle Size in Water and Phosphate Buffer (PB)



**Conclusion:** Excellent dispersion of CeO<sub>2</sub> NP in water at pH 4.5 and PB pH 7.4. Dispersion could be repeated from lab to lab. Unstable dispersion of CeO<sub>2</sub> NP in neutral water, variability within and between labs.

# Results

## Zeta Potential in Water and Phosphate Buffer (PB)

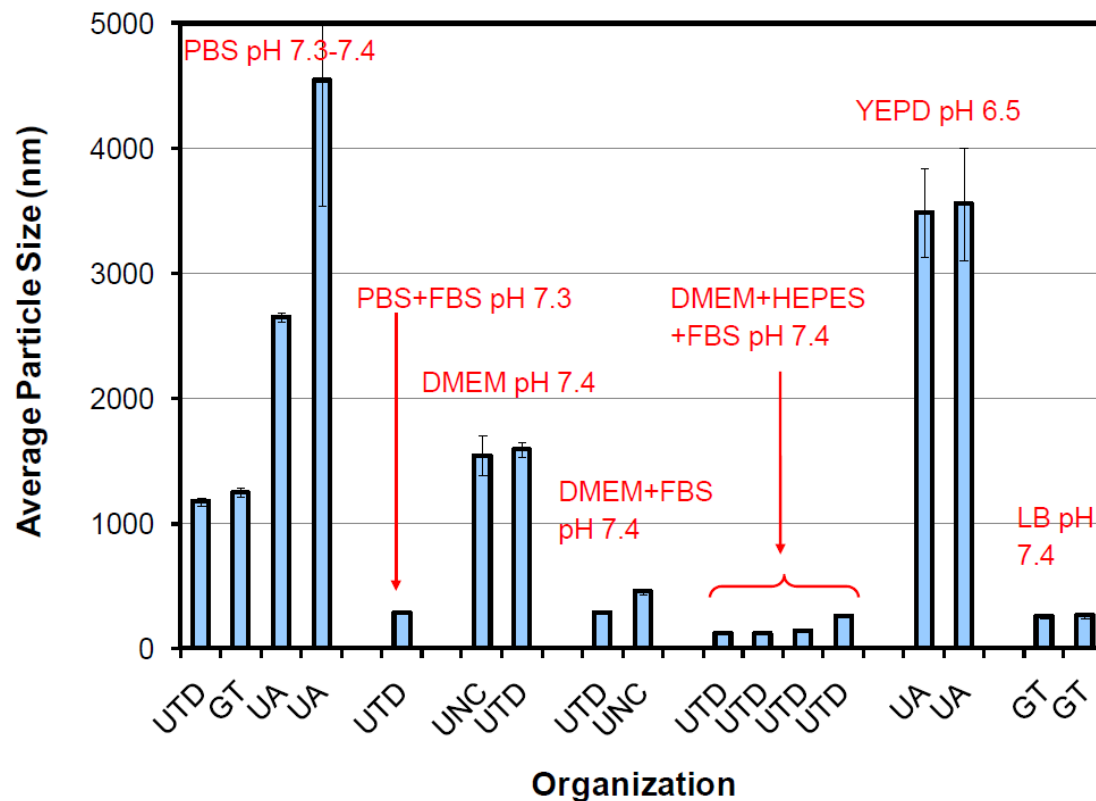


**Conclusion:** High absolute values of ZP in water at pH 4.5 and PB pH 7.4 to keep NP dispersion stable. ZP values could be repeated from lab to lab. Unstable and highly variable values of ZP in neutral water.



# Results

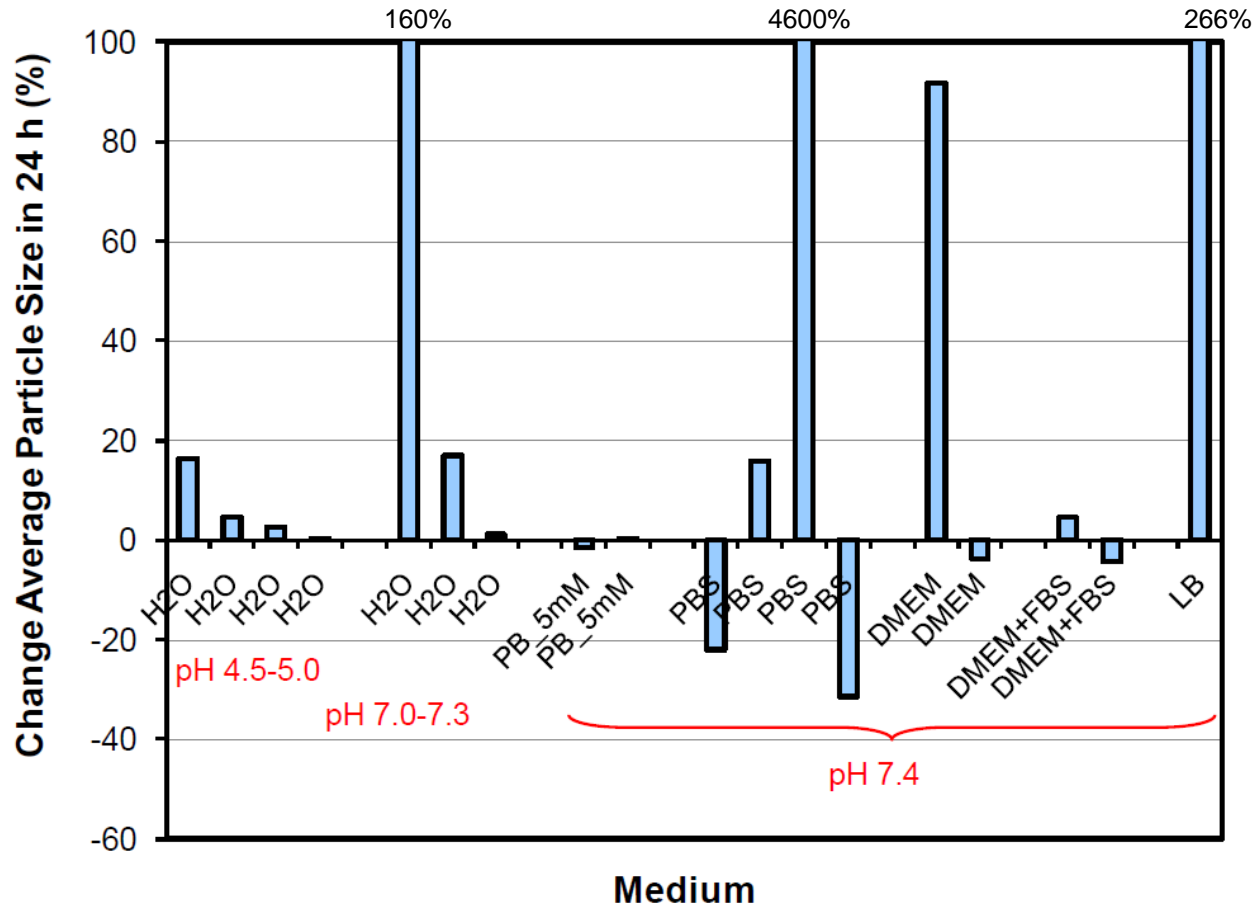
## Light Intensity Averaged Particle Size in Media



**Conclusion:** Many of the media types cause moderate to severe agglomeration of  $\text{CeO}_2$  NPs. FBS 10% and HEPES decrease agglomeration, both together are very effective in dispersing  $\text{CeO}_2$ . But result needs to be confirmed by more than one lab.

# Results

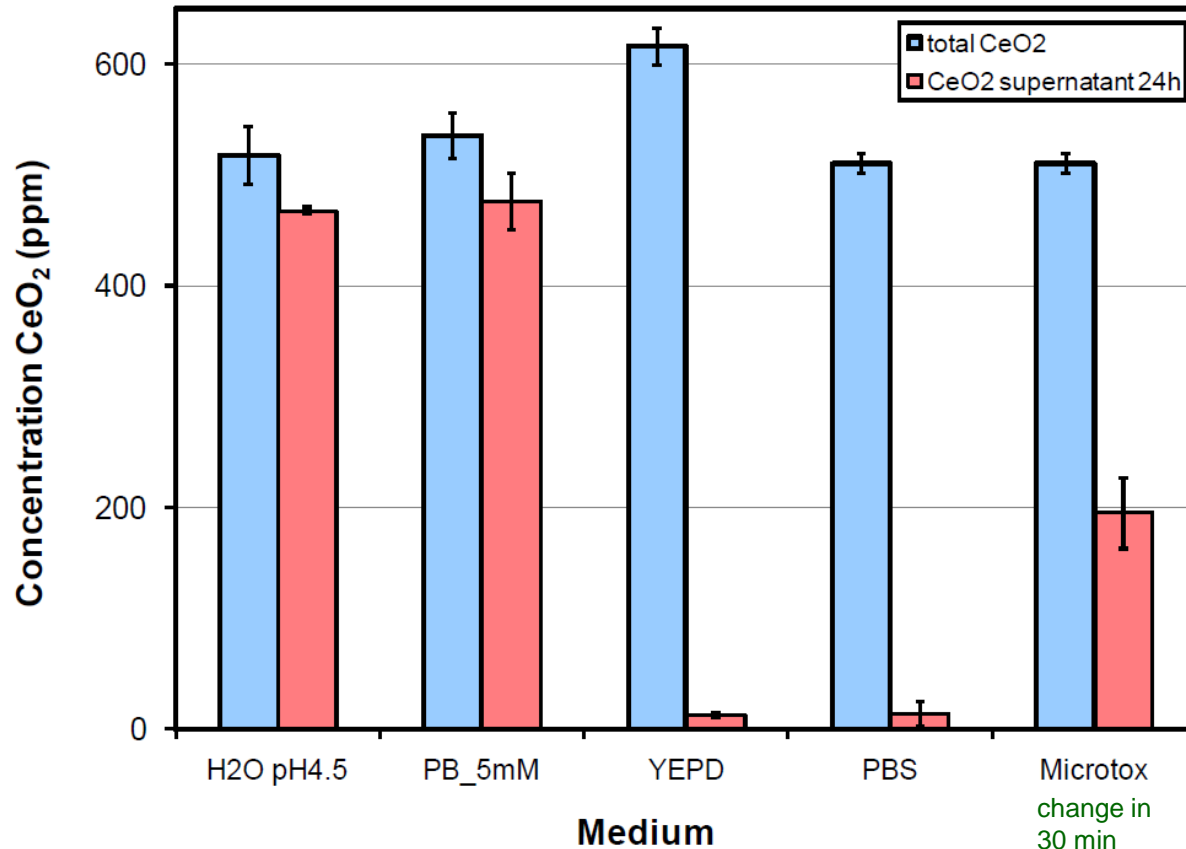
## Change in Particle Size in 24 h



**Conclusion:** Particle size stable in acid water, PB and DMEM+FBS. In all other media changes were highly variable depending on laboratory.

# Results

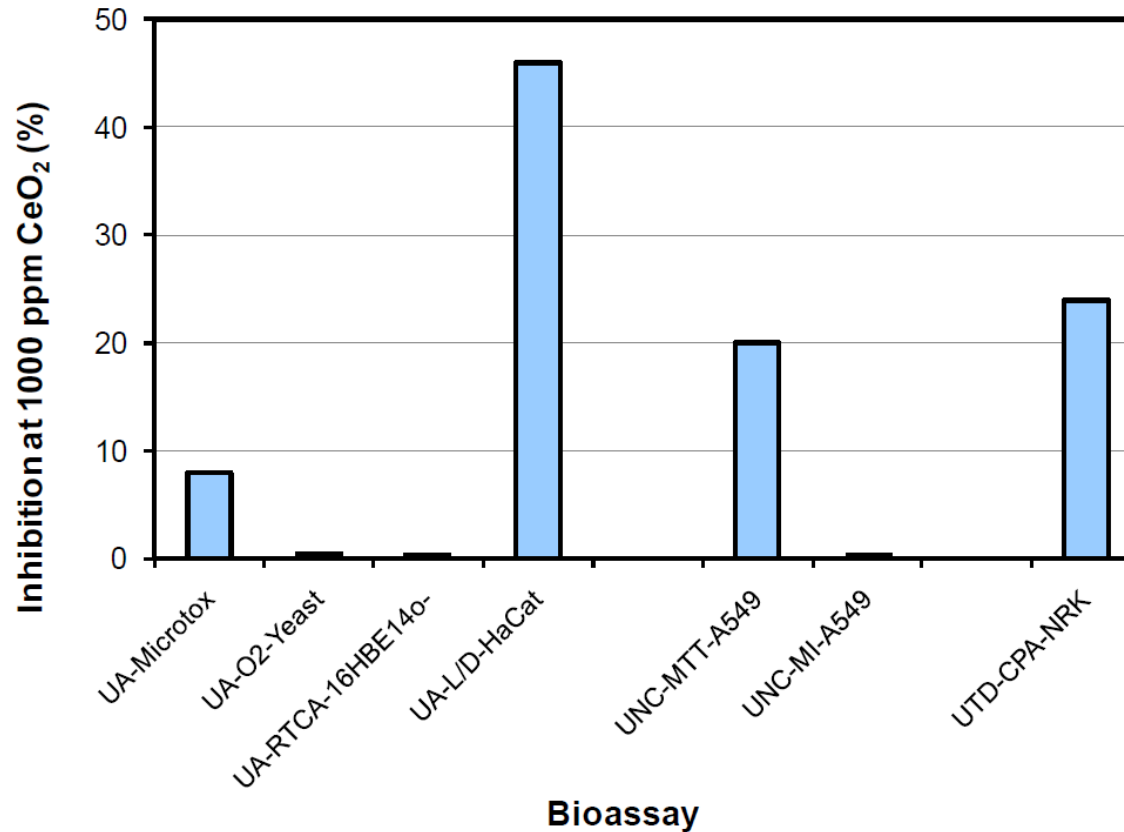
## Change in CeO<sub>2</sub> Concentration in 24 h (only tested by UA)



**Conclusion:** CeO<sub>2</sub> concentration stable in acid water and PB. In bioassay media, CeO<sub>2</sub> NP agglomerated and settled such that the concentration in suspension decreased by more than 90% in 24 h.

# Results

## Cytotoxicity of CeO<sub>2</sub>



**Conclusion:** In most assays CeO<sub>2</sub> is either non-toxic or displays low toxicity. A moderate toxicity was observed with HaCat cells tested with the Live/Dead assay using PBS. (Note real conc. was approx. 600 mg/L)

# Conclusions

- Manufacturer reported concentration of  $\text{CeO}_2$  was off by more than 40% (a simple gravimetric analysis is sufficient as a preliminary quality control measure).
- Acid water and 5 mM phosphate buffer (pH 7.4) provide stable  $\text{CeO}_2$  NP dispersions which can be repeated from lab to lab.
- Most assay media cause instability and agglomeration of  $\text{CeO}_2$  NP, causing them to settle out of suspension.
- A few media types (e.g. those including FBS, HEPES & Dispex) provide stability of  $\text{CeO}_2$  NP dispersions in biological media. But this still needs to be confirmed by research across multiple laboratories.
- $\text{CeO}_2$  caused no to low inhibition in most of the assays. Moderate inhibition was only observed with HaCat cells assayed in PBS.

# Future Work

- Study media with dispersing ingredients across multiple laboratories.
- Determine if HaCaT cells (human skin cell line) are truly more sensitive to CeO<sub>2</sub> compared to other biological targets.
- Round robin needs to focus on NP stability test based on measuring NP in supernatant.
- Common cytotoxicity test for all labs in round robin.
- Choose next NP type to work with.

**Environmental Safety and Health (ESH) Impacts of  
Emerging Nanoparticles and Byproducts from Semiconductor Manufacturing  
Preparation and Characterization of Nanoparticles:- Subtask 1  
(Task # 425.023)**

**PIs:**

- Reyes Sierra, Dept. Chemical and Environmental Engineering (ChEE), UA
- Farhang Shadman, Dept. Chemical and Environmental Engineering, UA

**Graduate Students:**

- Isabel Barbero: PhD candidate, Chemical and Environmental Engineering, UA
- Monica Rodriguez: MS candidate, Chemical and Environmental Engineering, UA
- Jeff Rottman: PhD candidate, Chemical and Environmental Engineering, UA
- Hao Wang: PhD candidate, Chemical and Environmental Engineering, UA

**Other Researchers:**

- Antonia Luna, Postdoctoral Fellow, Chemical and Environmental Engineering, UA
- Jim A Field, Dept. Chemical and Environmental Engineering, UA

**Cost Share (other than core ERC funding):**

- \$80k from UA Water Sustainability Program
- \$43k for instrumentation purchase from UA Water Sustainability Program , UA College of Engineering, and ChEE
- Fellowship to J Rottman from SRC/GRC graduate fellowship program
- Fellowship to A Luna (partial support), Mexican Science Foundation
- UofA GIGA fellowship (1 year) to I Barbero

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# Overall Objectives

- **Characterize toxicity of current and emerging nanoparticles (NP) & NP byproducts**
- **Develop new rapid methodologies for assessing and predicting toxicity**



# **ESH Metrics and Impact**

1. *Reduction in the use or replacement of ESH-problematic materials*

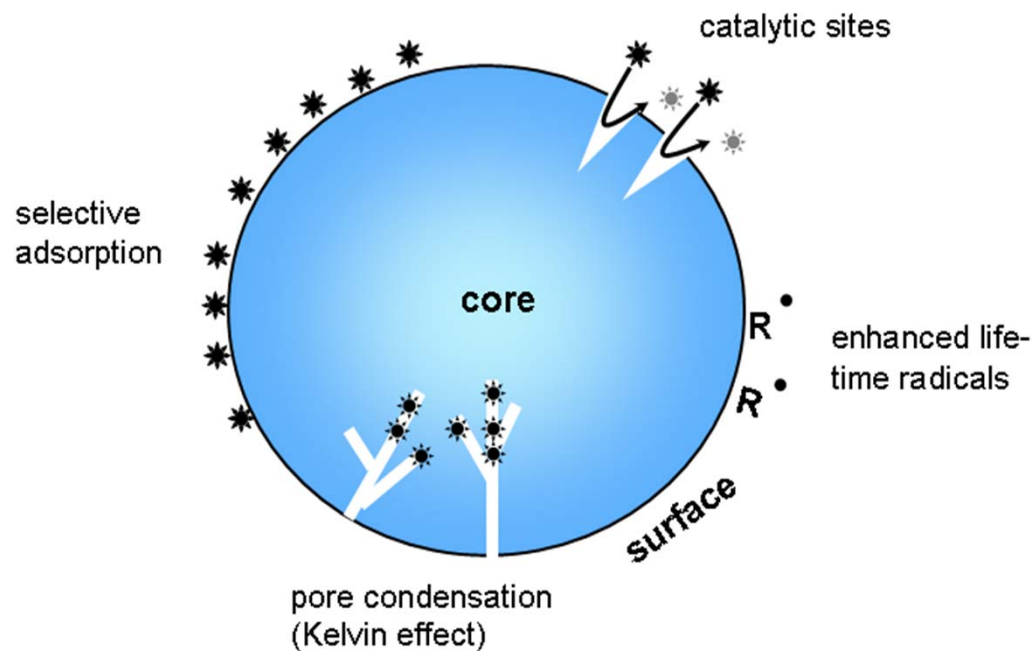
**This project will evaluate the toxicity of various types of nanoparticles utilized or considered for application in semiconductor manufacturing, and the impact of manufacturing steps on their toxicity. This information can assist in selecting materials which are candidates for replacement or use reduction.**

2. *Reduction in emission of ESH-problematic material to environment*

**The knowledge gained can be utilized to modify the manufacture of nanoparticles so that they have a lowered toxicity and thus a lowered environmental impact.**

# Hypotheses

- Surface chemistry plays an important role in NP toxicity
- The size of NPs intrinsically makes them more adsorptive to external chemicals, and these surface molecules contribute to the observed toxic effects of NPs on cells.



# **Overview Tasks**

- **Task 1. Preparation and Characterization of NPs**

- 1.1. Preparation of NPs**

- 1.2 Physicochemical Characterization**

- 1.3 Adsorption of Contaminants on NPs**

- Assessment**

- Modeling**

- 1.4 Characterizing and Improving NP Dispersion in Biological Medium**

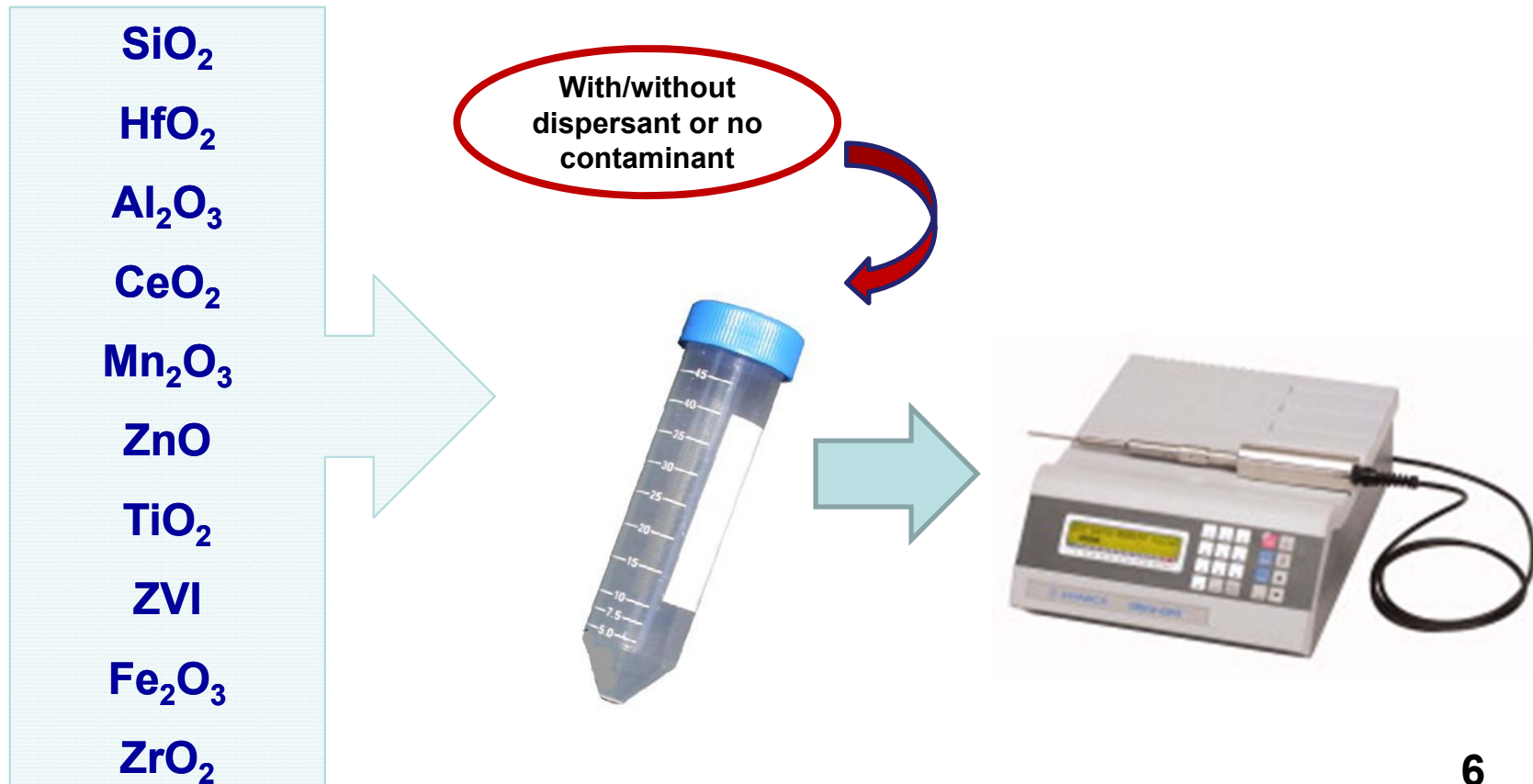
- **Task 2. Removal of NP in porous media**

- 2.1. Assessment**

- 2.2. Modeling**

# Materials & Methods

- Preparation of NPs suspensions



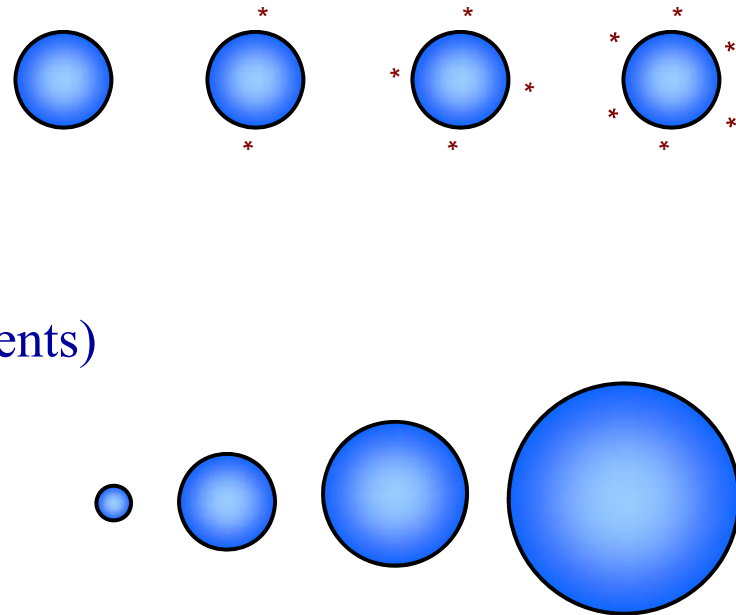
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# Preparation and Characterization NP

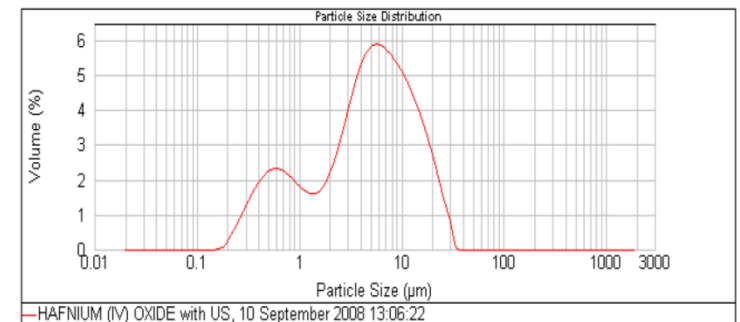
## • Preparation

- Gradients of surface contamination
  - adsorption of defined contaminants
  - surface modification
  - removal of contaminants (chelators, solvents)
- Gradients of particle size
- Fluorescently-labeled NPs



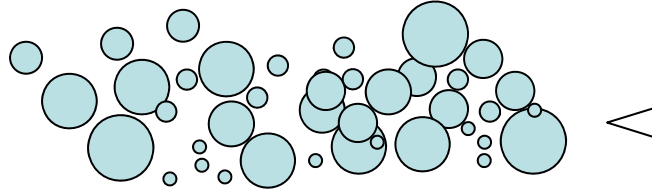
## • Characterization

- Particle size distribution
- Zeta potential
- Chemical analysis of dispersed NP fraction
- Adsorptive surfaces
- Adsorption isotherms

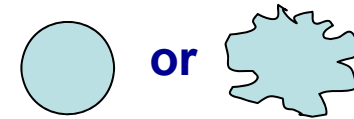


# Surface Physical Characterization

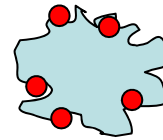
- Particle size distribution (dynamic light scattering)



- Specific area (area/volume or area/mass of NP)

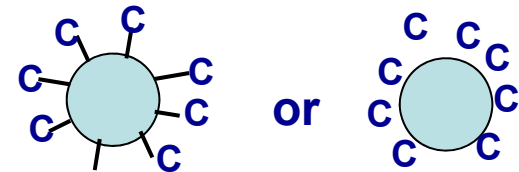


- Active site density; site energetics

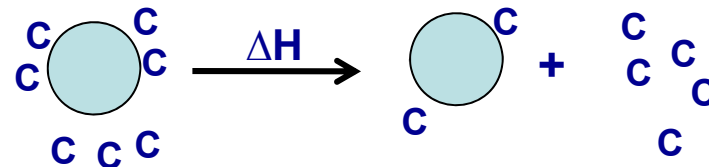


What is at the particle surface and how is bound?

- Physical adsorption vs chemical adsorption



- Retention of contaminants



# **Characterization of the Surface Properties of Oxide Nanoparticles Used in SC Manufacturing**

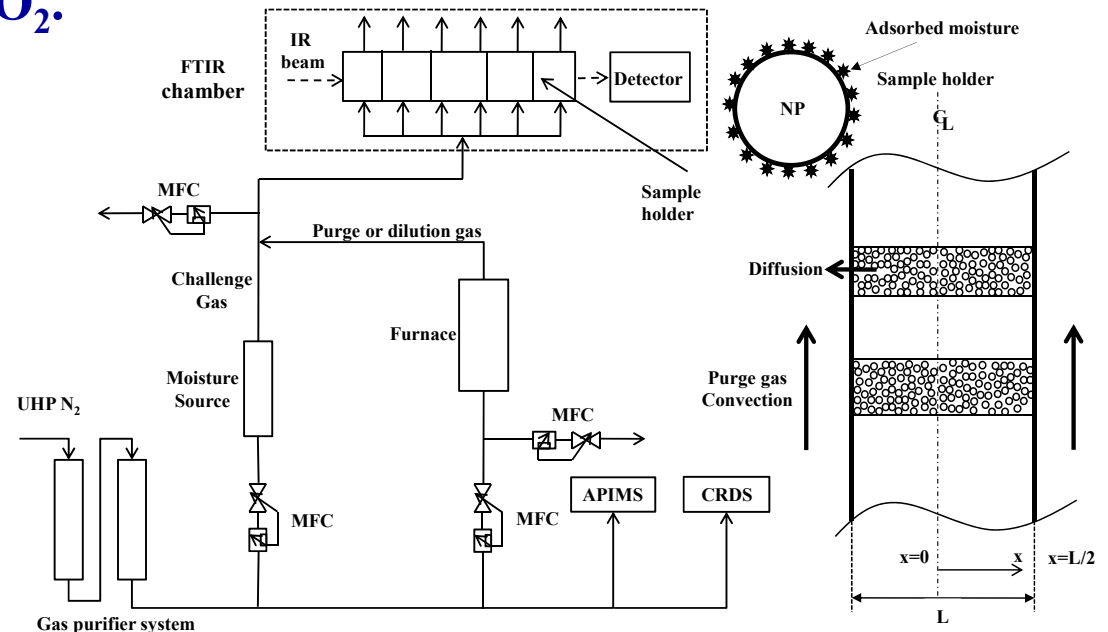
**PhD students: Hao Wang**

**Chemical and Environmental Engineering**

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

## Objectives and Method Approach

- **Objective:** Characterization of the surface sites on nanoparticles that contribute to concentration, retention, and enhanced transport of toxic chemicals.
  - **Method approach:** Surface hydroxylation (adsorption and desorption of contaminants).
  - **Materials:**  $\text{SiO}_2$ ,  $\text{HfO}_2$ ,  $\text{CeO}_2$ .
  - **Parameters:** Oxide type, particle size, temperature.
  - **Results:** Capacity and energetics of capture and retention of contaminants on active sites.
- 
- The diagram illustrates the experimental setup for nanoparticle characterization. It includes a UHP N<sub>2</sub> gas source, a moisture source, a furnace, a sample holder, an FTIR chamber, and detectors (APIMS and CRDS). The sample holder contains a layer of nanoparticles (NP) with adsorbed moisture. The FTIR chamber is positioned above the sample holder, and the detectors are positioned below it. The flow of gas is controlled by MFCs (Mass Flow Controllers). The diagram also shows a cross-section of the sample holder with a diffusion barrier and a coordinate system (x=0).





# Process Simulation for Data Analysis

**Adsorbent concentration in the gas phase:**

$$\frac{\partial C_g}{\partial t} = D_e \frac{\partial^2 C_g}{\partial x^2} + (1 - \varepsilon) \frac{3}{r} [k_d C_s - k_a C_g (S_0 - C_s)]$$

**Adsorbent concentration on the surface:**

$$\frac{\partial C_s}{\partial t} = k_a C_g (S_0 - C_s) - k_d C_s$$

$C_g$  concentration in the gas phase,  $\text{gmol} \cdot \text{m}^{-3}$

$C_s$  concentration on the surface,  $\text{gmol} \cdot \text{m}^{-2}$

$k_a$  adsorption rate coefficient,  $\text{m}^3 \cdot \text{gmol}^{-1} \cdot \text{s}^{-1}$

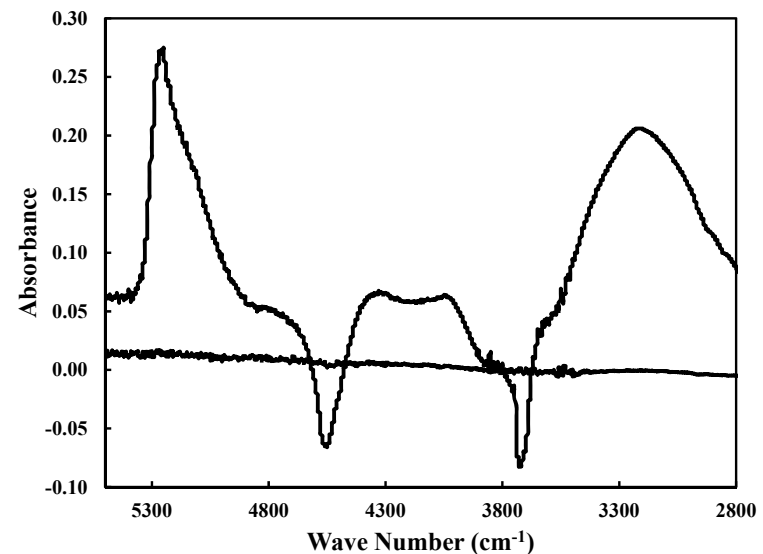
$k_d$  desorption rate coefficient,  $\text{s}^{-1}$

$S_0$  maximum capacity of the surface,  $\text{gmol} \cdot \text{m}^{-2}$

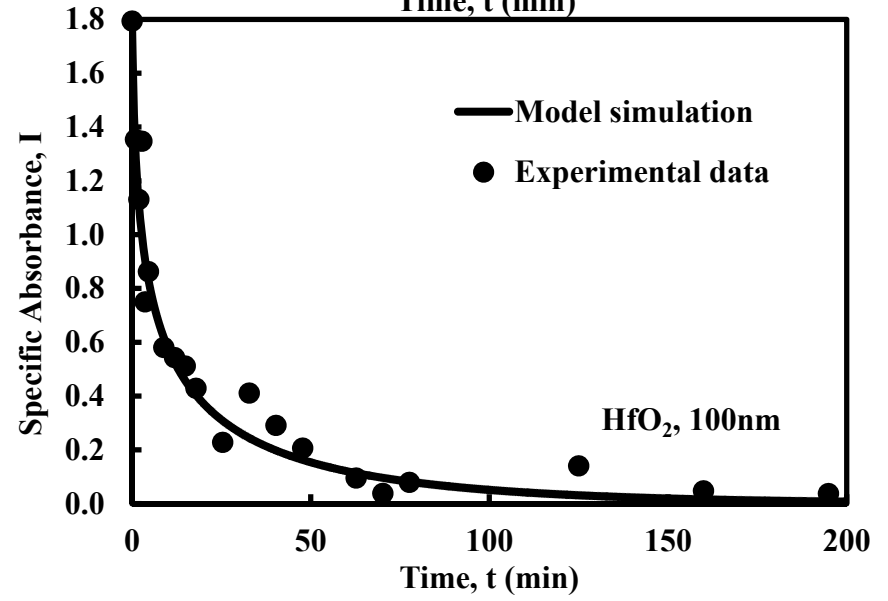
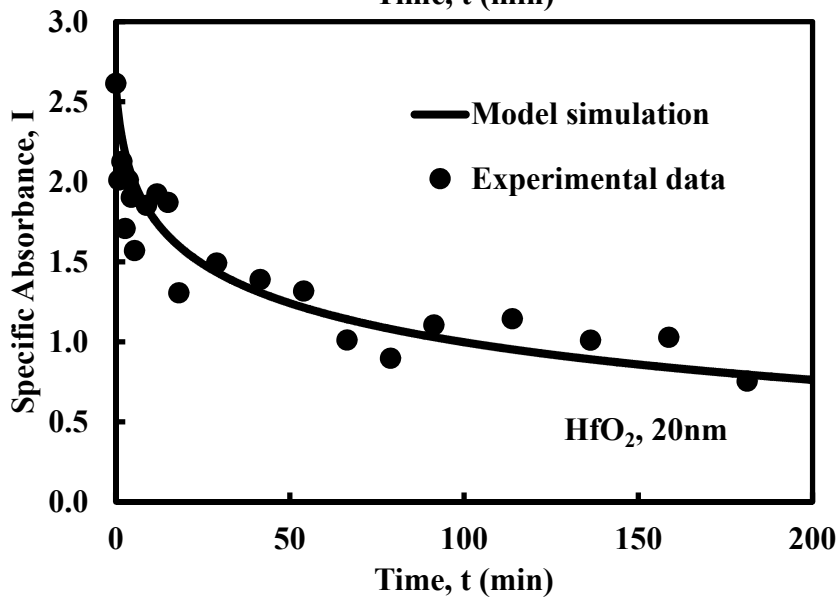
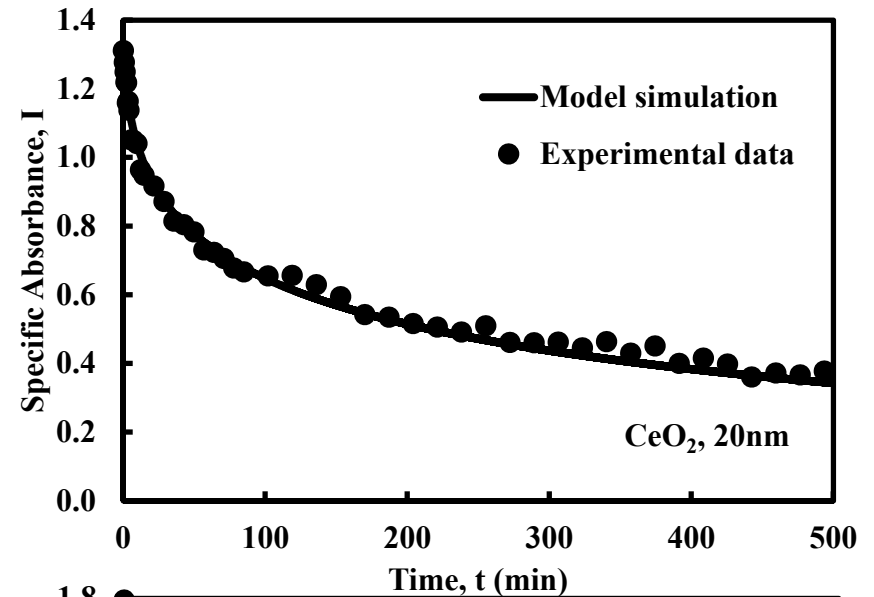
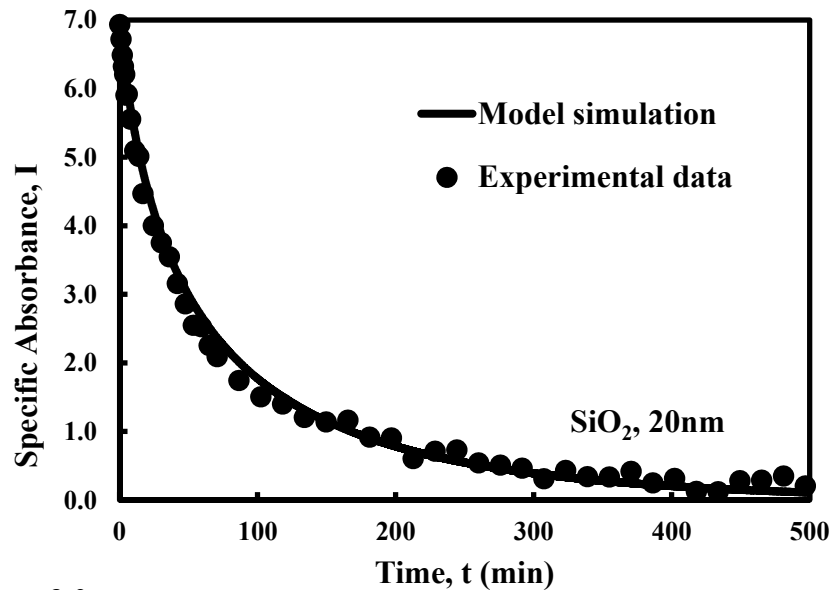
$\varepsilon$  packing porosity

$r$  radius of nanoparticle, m

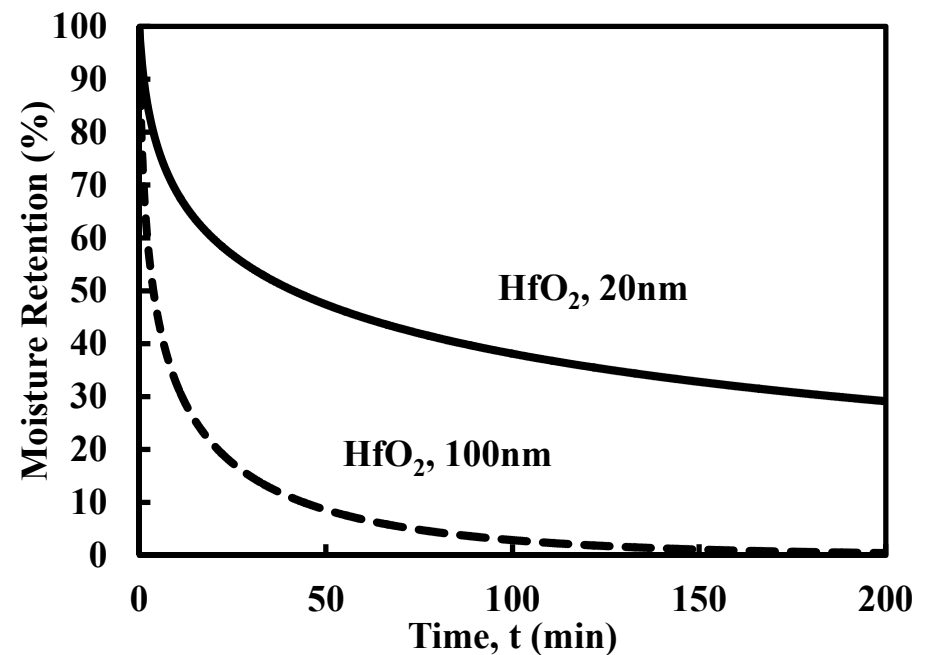
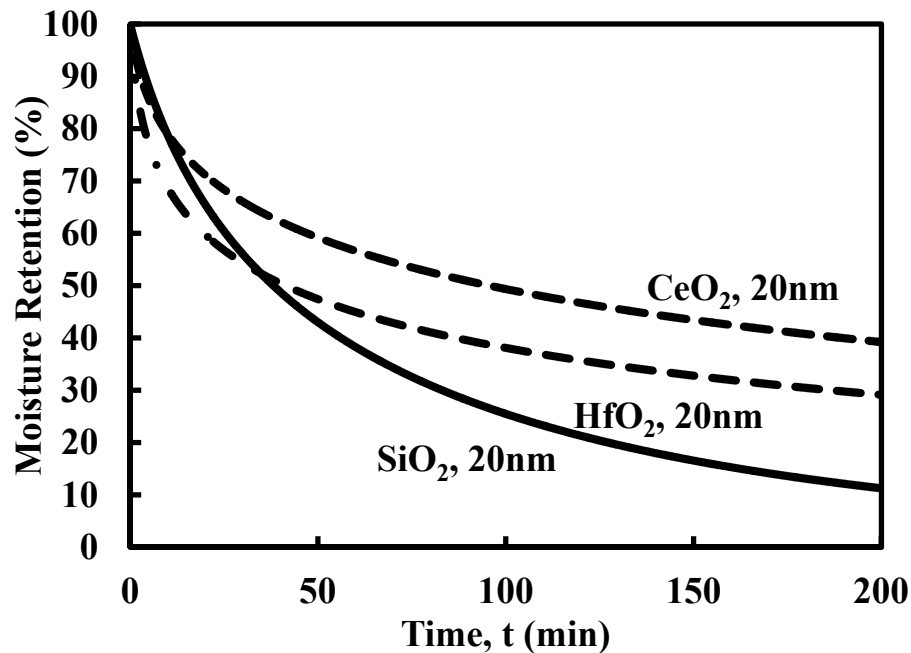
$D_e$  effective diffusivity,  $\text{m}^2 \cdot \text{s}^{-1}$



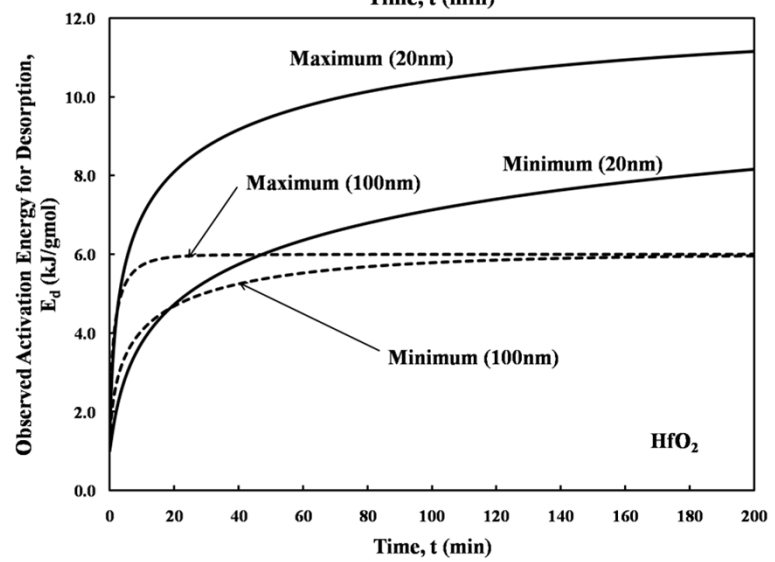
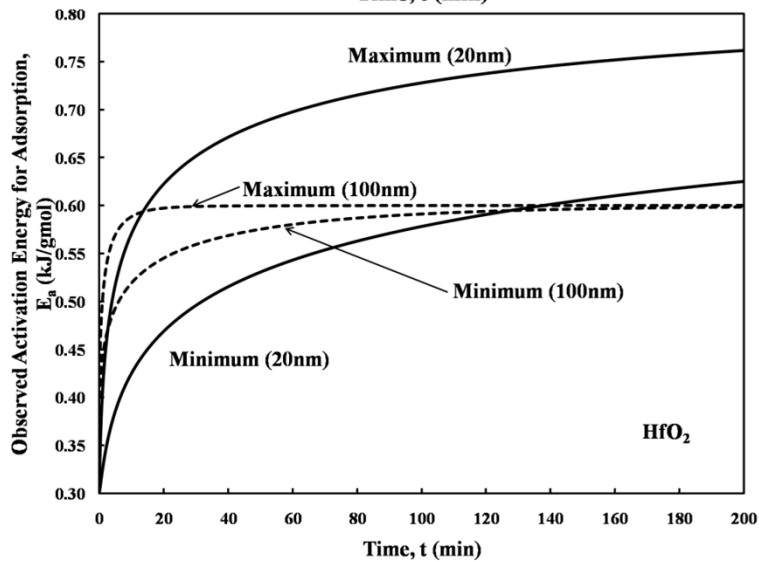
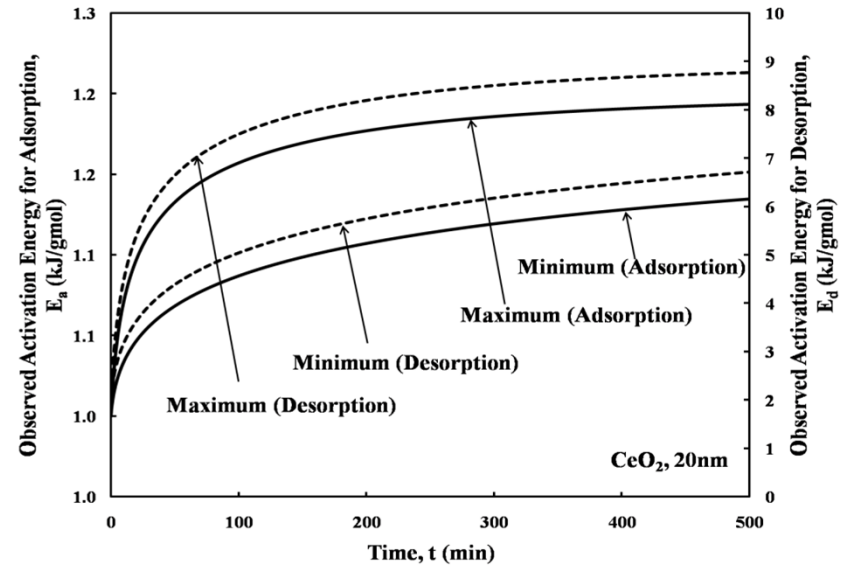
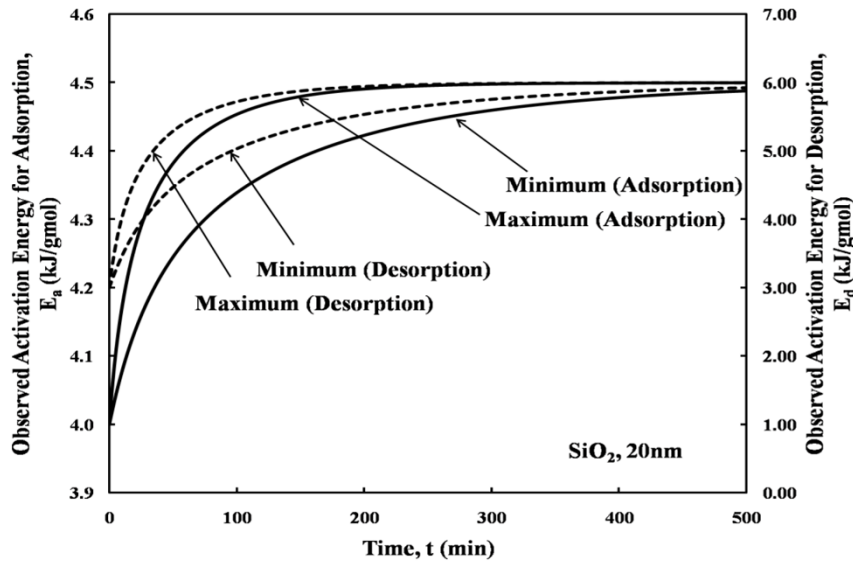
# Comparison of Adsorption Profiles of NPs



# Effect of NP Material and Size on Surface Retention



# Activation Energy of Surface Processes



# Summary and Conclusions

- Hydroxylation is a powerful method for characterization of capture and retention (adsorption/desorption) properties of NPs.
- The surface retention characteristics depend on the material as well as on the particle size.
- The affinity of nanoparticles for adsorption and retention decreases in the order:  $\text{CeO}_2 > \text{HfO}_2 > \text{SiO}_2$ . The surface available sites under certain challenge concentrations decreases in the order:  $\text{SiO}_2 > \text{HfO}_2 > \text{CeO}_2$ .
- Nanoparticles with smaller size will have larger density of surface sites and larger surface retention capacity for most cases. They also have higher affinity for retention of contaminants.

# **Fate of Nanoparticles in Porous Media**

**PhD student: Jeff Rottman**

**Chemical and Environmental Engineering**

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

# **Fate of Nanoparticles in Porous Media**

## **Objectives**

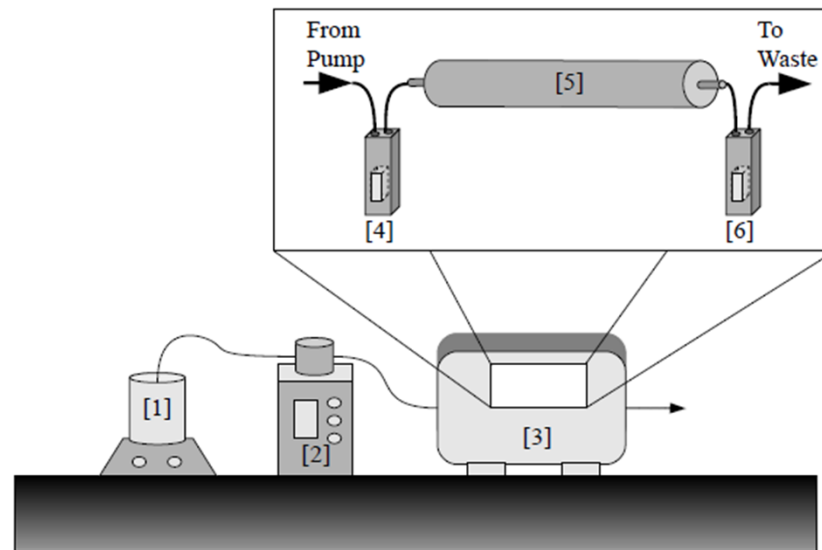
- Determine the fate of nanoparticles in porous media.
- Model the transport of nanoparticles in porous media.
- Establish techniques to enhance abatement.

## **Means**

- Develop an apparatus for the rapid measurement of nanoparticle retention in porous media.
- Develop a model to elucidate the controlling parameters.
- Utilize the model to develop an enhanced method of removal.

# Method of Measurement

- New experimental apparatus allows for a fully online measurement of NP removal by porous media.
- Accomplished by utilization of both reference and measurement cell of standard UV-Vis spectrophotometer.



**Experimental Apparatus:** NP suspension [1], pump [2], UV-Vis spectrophotometer [3], flow through cuvettes [4,6], column [5]



# Modeling Nanoparticle Breakthrough

$$\frac{\partial \Gamma}{\partial \tau} = \frac{1}{Pe} \frac{\partial^2 \Gamma}{\partial x^2} - \frac{\partial \Gamma}{\partial x} - \alpha [K_a \Gamma (1 - \theta) - K_d \theta]$$

$$\frac{\partial \theta}{\partial \tau} = K_a \Gamma (1 - \theta) - K_d \theta$$

$\Gamma$  = Nanoparticle Liquid Concentration

$\theta$  = Nanoparticle Surface Concentration

$\tau$  = Time

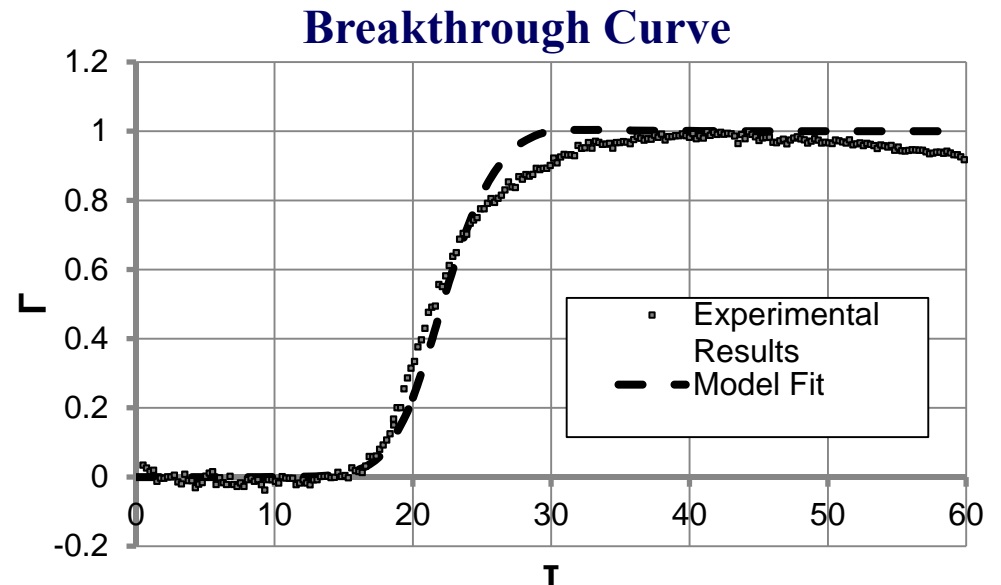
$x$  = Column Dimension

$Pe$  = Peclet Number

$\alpha$  = Capacity Factor

$K_a$  = Adsorption Mass Transfer Coefficient

$K_d$  = Desorption Mass Transfer Coefficient



This model is the basis for all further analysis. Determining the principle solution and bed parameters responsible for influencing  $K_a$  and  $K_d$  will allow for the design of a system capable of effectively removing NPs in suspension.

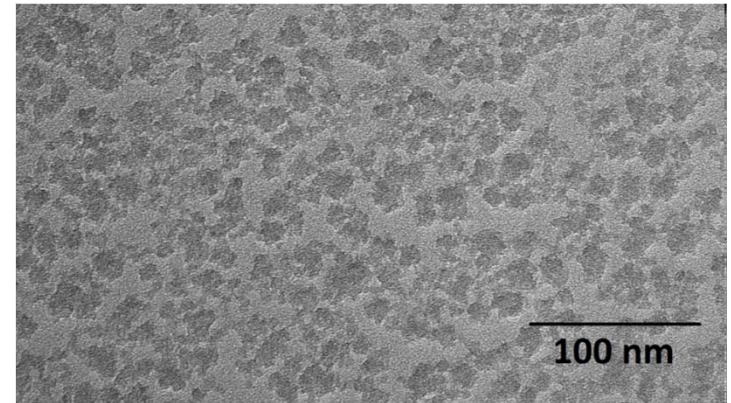
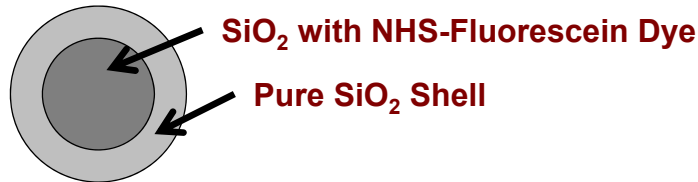
# Synthesis of Fluorescent Silica Nanoparticles

## Method

- Build a fluorescent core by conjugating APTES with NHS-fluorescein, then reacting with TEOS in an ethanol/ ammonia solution

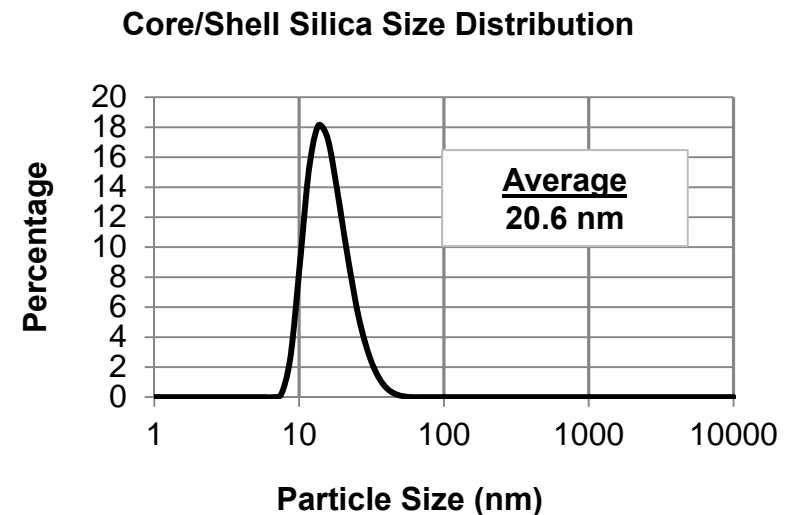


- Coat with pure SiO<sub>2</sub> by sequential addition of TEOS aliquots



## Advantages

- Maintains surface chemistry of pure silica NPs
- Easy to monitor
- Low detection limit
- Final size can be adjusted



# **Conclusions**

- **A rapid method for measuring in real time the retention of NP by porous media was developed. This method eliminates potential causes of error due to sampling.**
- **A mathematical model was developed to predict NP removal by porous media. Further definition of the retention model will reveal the major factors affecting removal.**
- **The synthesis of the fluorescent silica NP will allow for in situ studies of a nanomaterial widely used in semiconductor manufacturing.**
- **Preparation of fluorescent NPs with different average size will allow assessment of the impact of particle size on removal efficiency.**

# **Dispersion of Nanoparticles in Biological Media and Characterization of Contaminant Adsorption onto Nanoparticles Used in SC Manufacturing**

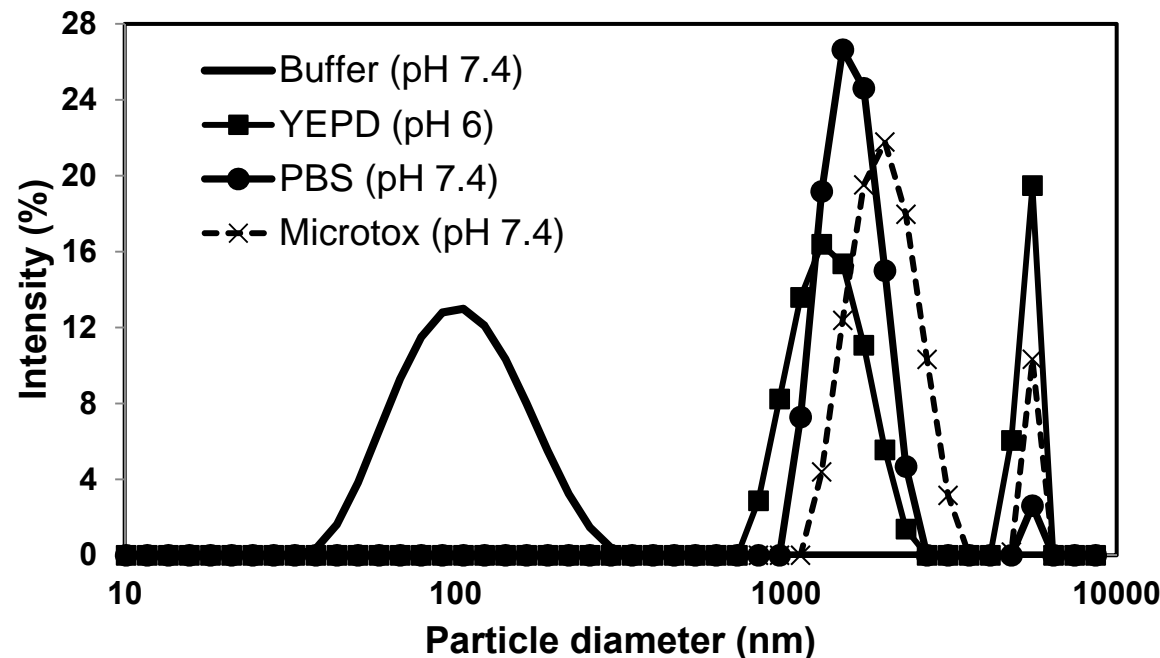
**PhD student: Isabel Barbero**

**MSc student: Monica Rodriguez**

**Postdoc: Antonia Luna Velasco**

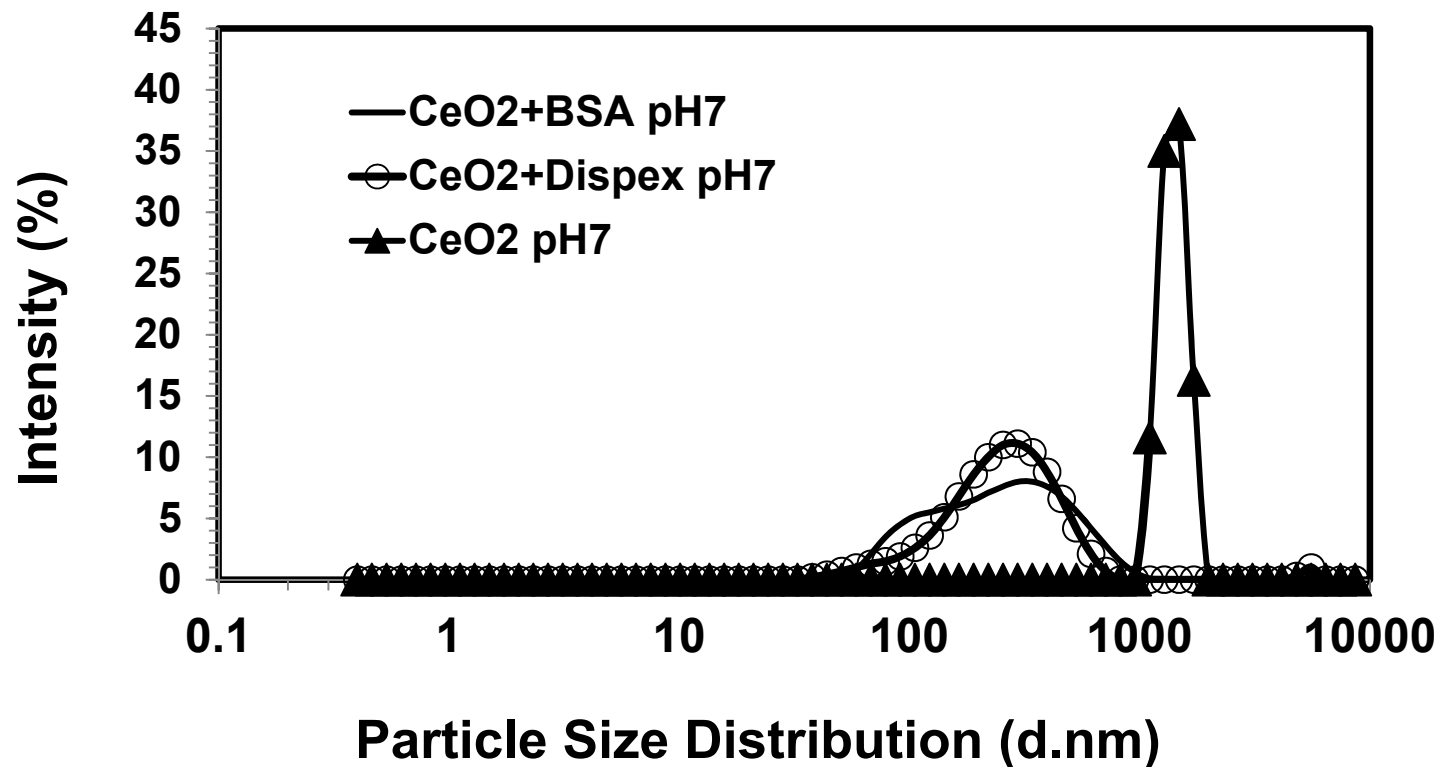
**Chemical and Environmental Engineering**

# NPs Dispersions Often Tend to Aggregate in Biological Medium



Particle size distribution of CeO<sub>2</sub> NP in different biological medium at pH 7  
(YPD= Yeast extract peptone dextrose, PBS= Phosphate saline solution,  
Medium used in the Microtox assay.

# Non-toxic Polyacrylate Surfactants and Proteins Useful for Enhancing Dispersion of Inorganic Oxide NPs in Biological Medium

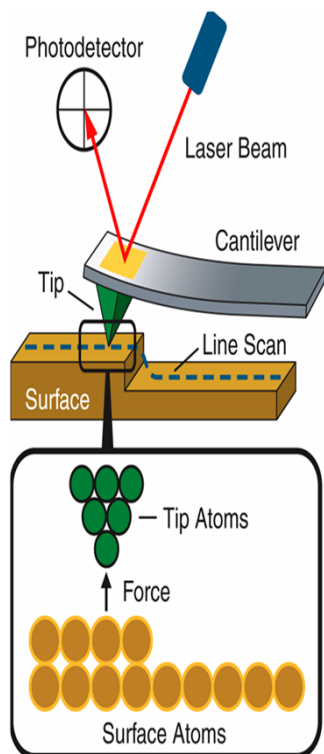


**BSA=** Protein Bovine Serum Albumin

**Dispex=** Commercial polyacrylate dispersants

Measurements were conducted at pH 6.5

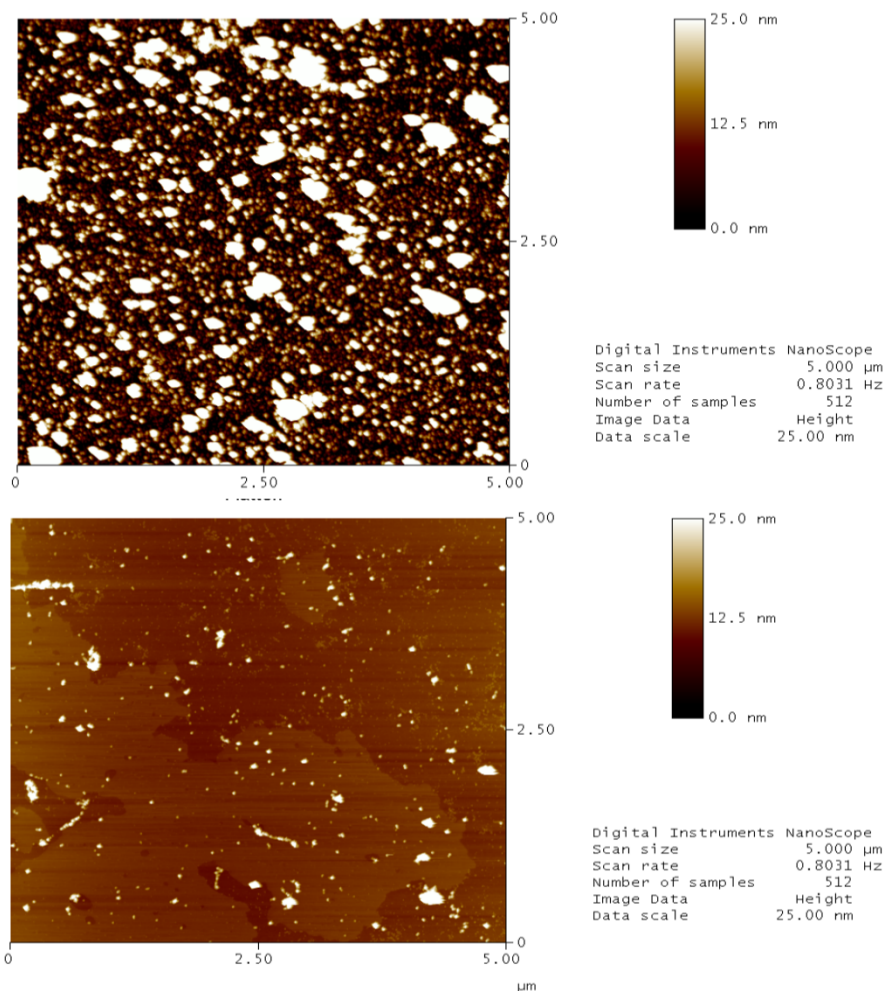
# Non-toxic Polyacrylate Surfactants Enhance the Dispersion of Inorganic Oxide NPs



Atomic Force  
Microscope (AFM)

AFM images:

$\text{CeO}_2$

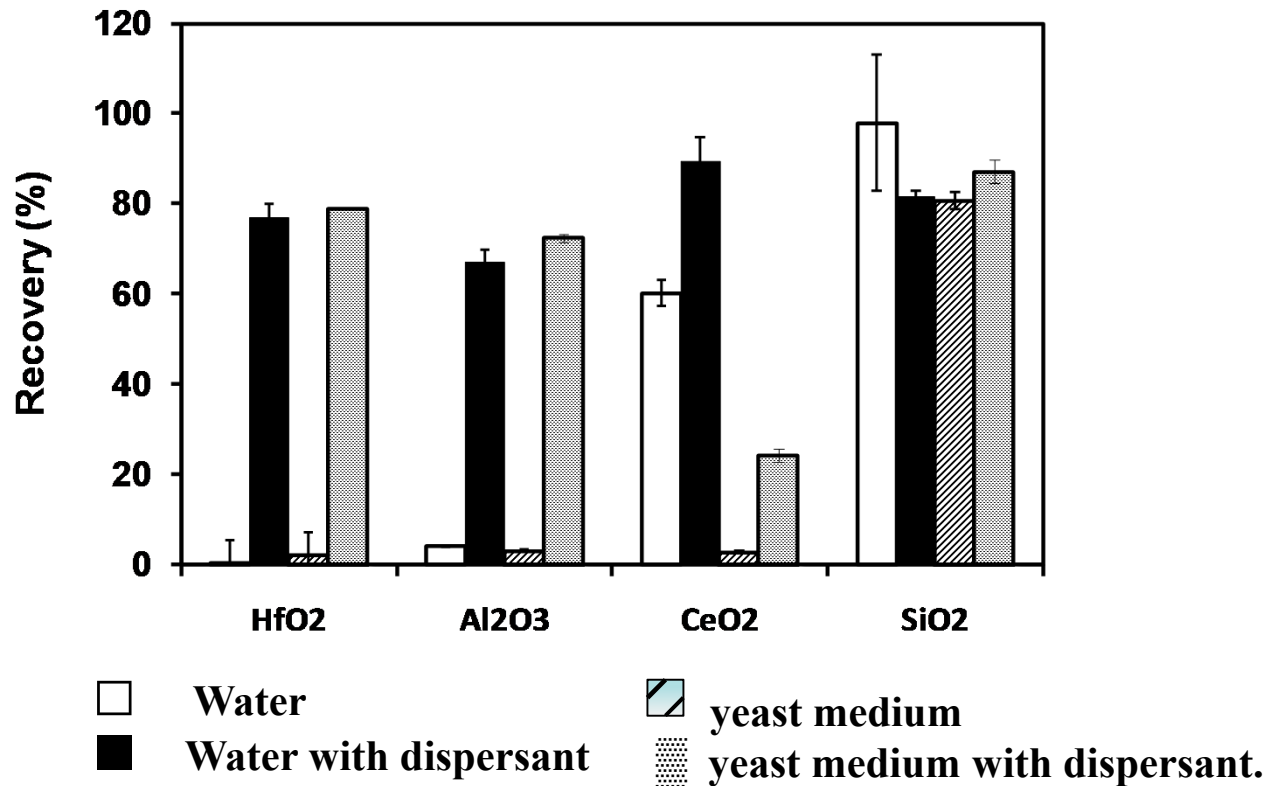


$\text{CeO}_2$  +  
Dispersant

mrmr011811ceo2dispex\_ph3.008

# Non-toxic Polyacrylate Surfactants Useful for Enhancing Dispersion of Inorganic Oxide NPs in Biological Medium

Concentration of inorganic oxide in the supernatant (dispersed)

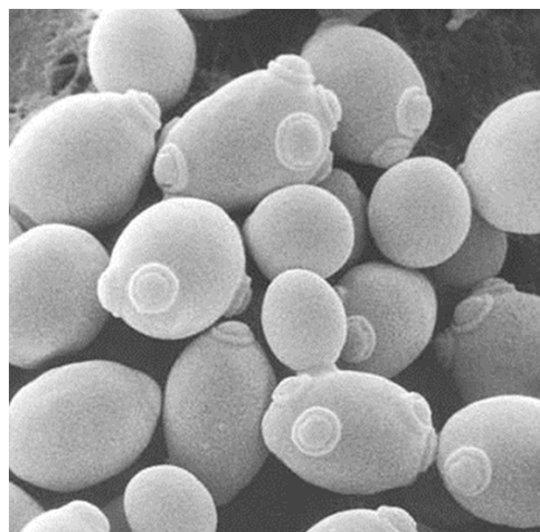
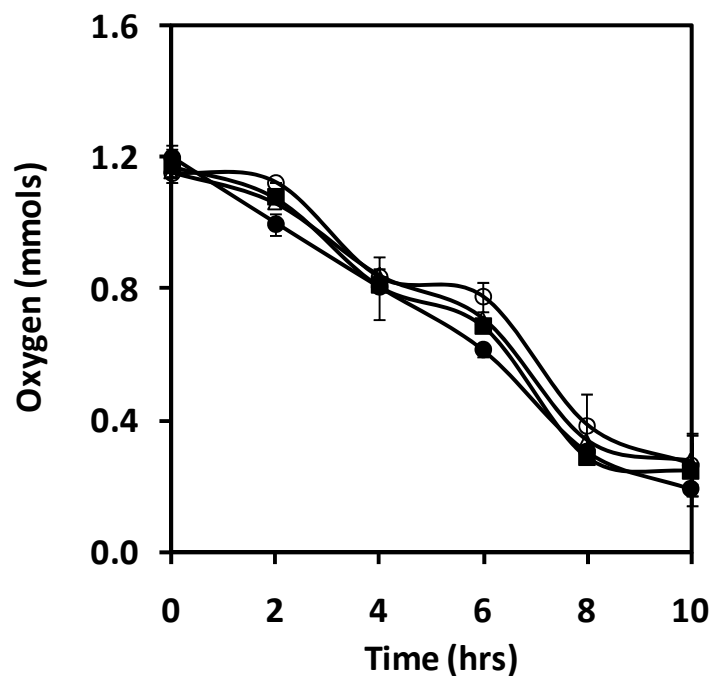


The polyacrylate dispersant, Displex, enhanced NP dispersion in water and biological medium.



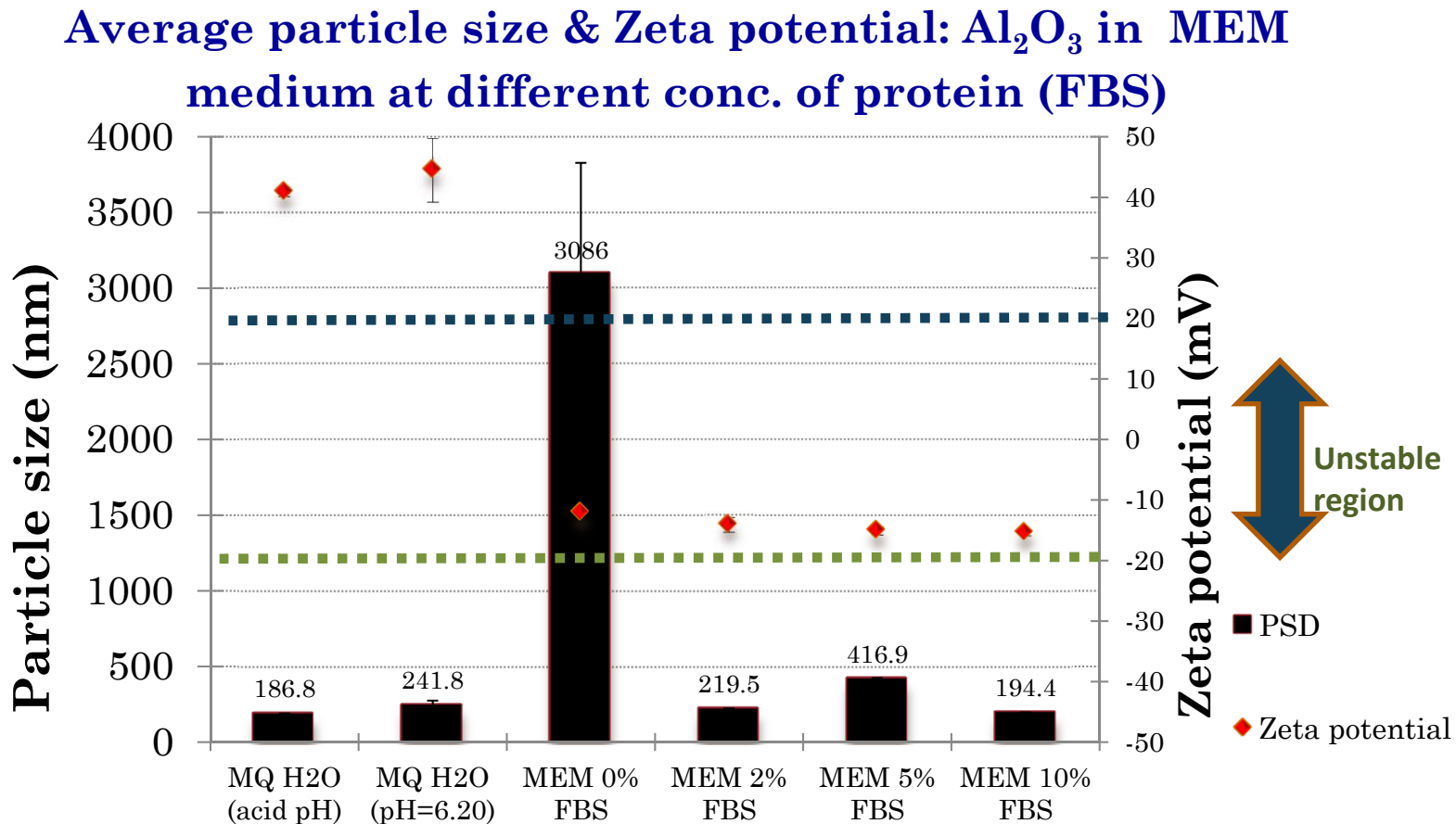
# The Polyacrylate Surfactant, Dispex, Was Not Toxic at Concentrations < 100 mg/L

Time course of oxygen consumption by the yeast, *C. saccharomyces*, in the presence of different dispersant concentrations (in mg/L); 0 (●), 10 (■), 50 (△) and 100 (○).



Bioassays with yeast and bacterial cells indicated that Dispex (< 100 mg/L) was not cytotoxic.

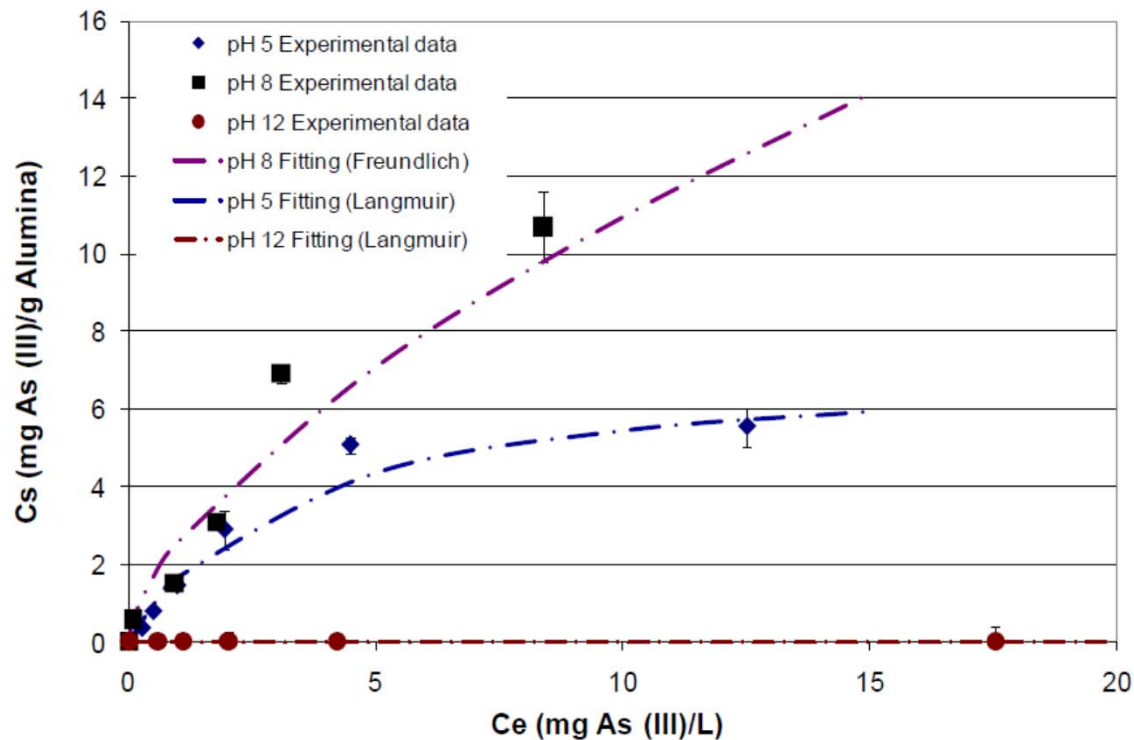
# Protein (Fetal Bovine Serum, FBS) Addition Increases the Stability of NPs Dispersions in Biological Medium



28

**Protein (FBS) addition increases the stability of NP dispersions in biological medium**

# NPs Can Adsorb High Levels of Toxic Contaminants



Adsorption isotherm of As(III) on Al<sub>2</sub>O<sub>3</sub> NPs at pH 5, 8 and 12. The graph shows the mass of As adsorbed per gram Al<sub>2</sub>O<sub>3</sub> (C<sub>s</sub>) as a function of the aqueous As equilibrium concentration (C<sub>e</sub>).

# **Outcomes**

- **Physico-chemical characterization of NPs utilized in toxicity testing.**
- **Assessment of stability and aggregation of NPs dispersions in biological medium, and development of approaches to enhance dispersion.**
- **Preparation of NPs contaminated with selected pollutants for toxicity testing, and determination of sorption isotherms at different pH values.**

# Industrial Interactions and Technology Transfer

- **ISMI-Sematech (Steve Trammell, Laurie Beu)**
- **AMD (Reed Content)**
- **IBM (Arthur T. Fong)**
- **Intel (Steve W. Brown, Mansour Moinpour)**

# Future Plans

## Next Year Plans

- Physico-chemical characterization of NPs utilized in toxicity studies.
- Continue characterization of interactions between NPs-biological media (e.g., state of aggregation, adsorption of contaminants, dissolution, redox changes, etc).
- Synthesis of fluorescently-labeled NPs to facilitate study of cell-NP interactions and NP detection in other studies.
- Investigate the behavior of NP used in semiconductor manufacturing in porous media.

## Long-Term Plans

- Rapid screening protocols of for assessing NP toxicity.
- Development of methods for NP removal.

# Publications, Presentations & Awards

## Publications

- Wang H, Yao J., Shadman F. 2011. Characterization of the surface properties of nanoparticles used in semiconductor manufacturing. (*Submitted*)
- Garcia-Saucedo C, Field JA, Otero L, Sierra-Alvarez. R 2011. Toxicity of HfO<sub>2</sub>, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and CeO<sub>2</sub> nanoparticles to the yeast, *Saccharomyces cerevisiae*. (*Submitted*)
- Field JA, Luna-Velasco A, Boitano SA, Shadman F, Ratner BD, Barnes C, Sierra-Alvarez R. 2011. Cytotoxicity and physicochemical properties of hafnium oxide nanoparticles. (*Submitted*)
- Gomez-Rivera F, Field JA, Brown D, Sierra-Alvarez R. 2011. Fate of cerium dioxide (CeO<sub>2</sub>) nanoparticles in municipal wastewater during activated sludge treatment. (*Submitted*)
- Rottman J, Shadman S, Sierra-Alvarez R. 2010. Interactions of CMP nanoparticles and sewage sludge. *SESHA Journal*, Summer 2010. Pp. 8
- Gomez-Rivera P, Brown D, Field JA, Shadman F, Sierra-Alvarez, R. 2010. Fate of CeO<sub>2</sub> nanoparticles during laboratory-scale activated sludge treatment. *SESHA Journal*, Summer 2010. Pp. 10.

## Conference Presentations

- Field JA, Luna-Velasco A, Garcia C, Otero L, Sierra-Alvarez R. 2010. Toxicity and environmental fate of nanoparticles. 2010 Nano Monterrey Forum: Nanotechnology Industrial Applications. 2010. Nov. 18-19, Monterrey, Mexico. [ORAL]
- Rottman J, Barbero I, Rodriguez M, Sierra-Alvarez R, Shadman F. 2010. Fate of CMP nanoparticles in municipal wastewater treatment. TECHCON Conference: Technology and Talent for the 21st Century. Austin, TX. Sept. 13-14. **Prize for best presentation in the Environmental session.** [ORAL]
- Gomez-Rivera, P., Brown, D. , Field JA, Shadman F, Sierra-Alvarez, R. 2010. Fate of CeO<sub>2</sub> Nanoparticles During Laboratory-Scale Activated Sludge Treatment. 32<sup>nd</sup> Semiconductor Environmental, Safety & Health Association (SESHA) Annual Int. High Technology ESH Symp. Exhibition, Scottsdale, AZ, April 26-29, 2010. **Prize for 3<sup>rd</sup> best student presentation.** [ORAL]
- Rottman J, Barbero I, Rodriguez M, Shadman F, Sierra Alvarez R. 2010. Fate of CMP nanoparticles during municipal wastewater treatment. 32<sup>nd</sup> SESH Annual Int. High Technology ESH Symp. Exhibition, Scottsdale, AZ, April 26-29, 2010. **Prize for 2<sup>nd</sup> best student presentation.** [ORAL]

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# Publications, Presentations & Awards

## Conference Presentations

- Rottman J, Barbero I, Rodriguez M, Shadman F, Sierra Alvarez R. 2010. Fate of CMP nanoparticles during municipal wastewater treatment. 32<sup>nd</sup> SESA Annual Int. High Technology ESH Symp. Exhibition, Scottsdale, AZ, April 26-29, 2010. **Prize for 2<sup>nd</sup> best student presentation** [ORAL]
- Rodriguez M, Barbero I, Luna A, Shadman F, Field JA, Sierra-Alvarez R. 2010. Impact of Wastewater Components on the Aggregation Behavior of CMP Nanoparticles 32<sup>nd</sup> SESA Annual Int. High Technology ESH Symp. Exhibition, Scottsdale, AZ, April 26-29, 2010. [ORAL]
- Field JA, Gomez-Rivera F, Barbero I, Rottman J, Rodríguez M, Luna A, Shadman F, Sierra-Alvarez R. 2010. Fate of Inorganic Oxide Nanoparticles in Semiconductor Manufacturing Effluents during Activated Sludge Treatment. 10<sup>th</sup> American Inst. Chemical Engineers (AIChE) Annual Meeting, Salt Lake City, UT, Nov. 7-12, 2010. [ORAL]
- Gomez-Rivera F, Barbero I, Rodríguez M, Luna-Velasco A, Shadman F, Field JA, Sierra-Alvarez R. 2010. Interactions Between Inorganic Oxide Nanoparticles and Municipal Wastewater Constituents: Implications for Nanoparticle Removal during Biological Wastewater Treatment. Proc. Leading Edge Technology 2010, Phoenix (AZ), June 2-4, p. 55 [Poster]
- Sierra-Alvarez R, Barbero I, Rottman J, Rodríguez M, Luna-Velasco A, Shadman F, Field JA. 2010. Removal of CeO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> Nanoparticles in Semiconductor Manufacturing Effluents during Activated Sludge Treatment. Proc. Leading Edge Technology 2010, Phoenix (AZ), June 2-4 p. 48. [Poster]
- Rottman J, Barbero I, Rodríguez M, Shadman F, Sierra-Alvarez R. 2010. Fate of metal oxide nanoparticles in municipal wastewater treatment. WSP Water Forum: Our Water Future. Nov. 22, 2010, Tucson, AZ. [Poster]
- Sierra-Alvarez R, Gomez F, Barbero I, Rottman J, Rodríguez M, Shadman F, Field JA. 2011. Removal of Inorganic Oxide Nanoparticles in Semiconductor Manufacturing Effluents during Activated Sludge Treatment. 2<sup>nd</sup> International Congress on Sustainability Science & Engineering (ICOSSE '11). Jan. 9-14, Tucson, AZ. [Poster]
- Ingato D., Field JA, Luna-Velasco A, Sierra-Alvarez R. 2009. Toxicity of Nanoparticles: Cerium and Hafnium Oxides. AIChE 2009 Annual Meeting. 8-13 de Nov., Nashville, TN. [Poster]

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# Publications, Presentations & Awards

## Seminars

- Rottman, J., Shadman F, Sierra-Alvarez R. 2010. Transport of Nanoparticles in Porous Media. Teleseminar series of Semiconductor Research Corporation/Sematech Eng. Research Center for Environ. Benign Semiconductor Manuf. Nov. 4th, Tucson, AZ.
- Wang H, Yao J, Shadman F. 2010. Physicochemical and Surface Characteristics Study of Nanoparticles related to ESH Impact of Emerging Nanoparticles and Byproduct in Semiconductor Manufacturing. Teleseminar series of Semiconductor Research Corporation/Sematech Eng. Research Center for Environ. Benign Semiconductor Manuf. Nov. 4<sup>th</sup>, Tucson, AZ.
- Garcia-Saucedo C, Otero L, Field JA, Sierra-Alvarez R. 2010. Developing a Yeast Cell Assay for Measuring the Toxicity of Inorganic Oxide Nanoparticles. Teleseminar series of Semiconductor Research Corporation/Sematech Eng. Research Center for Environ. Benign Semiconductor Manuf. May 6th, Tucson, AZ.
- Otero L, Garcia-Saucedo C., Field JA, Sierra-Alvarez, R 2010. Comparison of Nanoparticle Toxicity to Yeast Cells and Human Lung Epithelial Cells. Teleseminar series of Semiconductor Research Corporation/Sematech Eng. Research Center for Environ. Benign Semiconductor Manufacturing. Dec. 2, 2010, Tucson, AZ.
- Sierra-Alvarez R. 2009. Toxicity characterization of HfO<sub>2</sub> nanoparticles. SRC/Sematech Eng. Research Center for Environ. Benign Semiconductor Manufacturing Teleseminar Series. Aug. 6.

**Environmental Safety and Health (ESH) Impacts of Emerging  
Nanoparticles and Byproducts from Semiconductor  
Manufacturing-Preparation and Characterization of  
Nanoparticles: Subtask 2  
(Task #: 425.023)**

**PI:**

- Buddy Ratner, Bioengineering and Chemical Engineering, UW

**Graduate Student:**

- Rosa Daneshvar: PhD student, Chemical Engineering, UW

**Cost Share (other than core ERC funding):**

- \$10K from University of Washington Engineered Biomaterials (UWEB)

# Objectives

- Nanoparticle toxicity assessed by a human foreskin organ culture model
- Surface chemical characterization of nanoparticles
  - ESCA (XPS)
  - SIMS (static ToF-SIMS)
  - TEM

# **ESH Metrics and Impact 1.**

## **Nanoparticle toxicity in an organ culture model**

*Investigate the contribution of nanoparticles surface chemical structure to their toxicity with organ culture model*

*Nanoparticles will be applied subcutaneously to neonatal foreskin and changes due to presence of nanoparticles in the specimens will be investigated*

**Metrics:** magnitude of change of dermal cell structure measure measured by histology and TEM

**Impact:** the human foreskin organ culture model is highly relevant for toxicity assessment, does not require animals and has not yet been explored for nanotoxicity assessment

## ESH Metrics and Impact 2.

### Surface species and nanoparticle toxicity

*Hypothesis: toxicity of nanoparticles may be the result of interactions of surface species coating these particles with biological species*

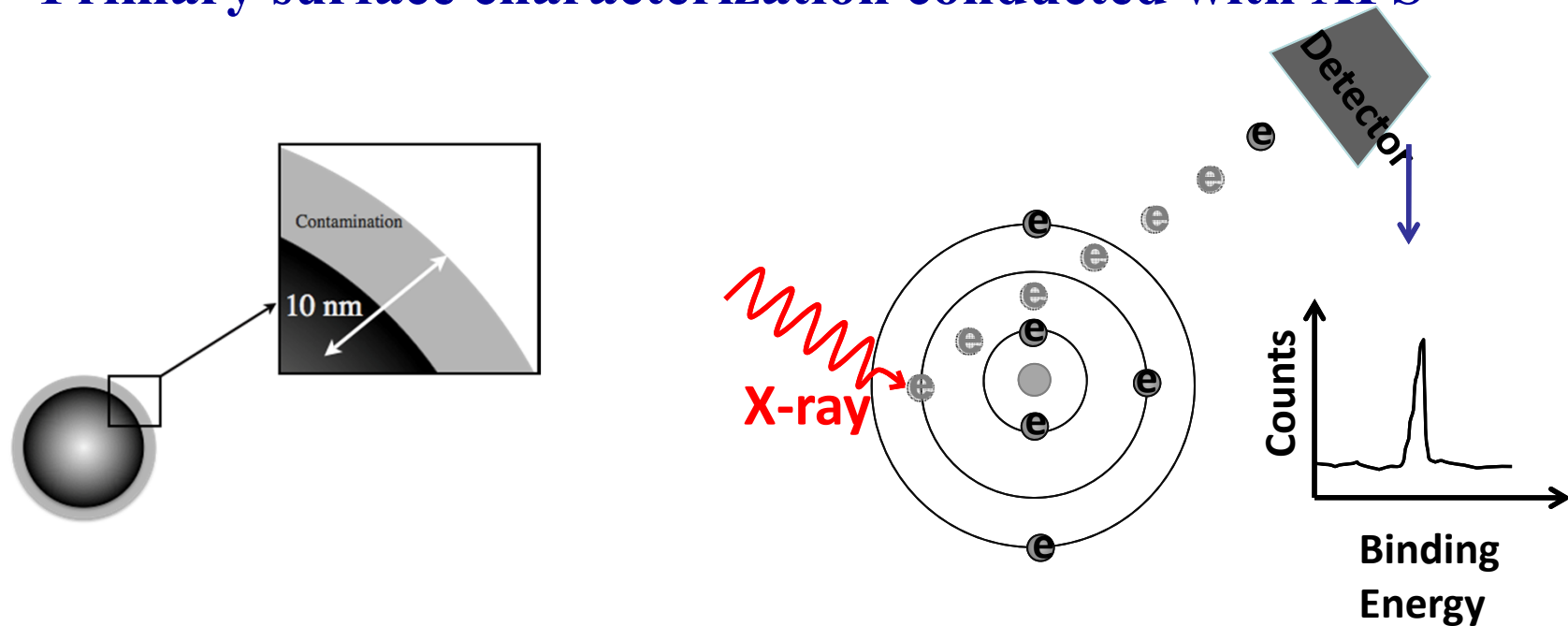
*To evaluate this hypothesis, nanoparticles surface species will be characterized with x-ray photoelectron spectroscopy (XPS or ESCA) and time of flight secondary ion mass spectrometry (ToF-SIMS)*

**Metrics:** Nature and concentrations of surface species on nanoparticles (XPS 8 nm sampling depth; SIMS 1.5 nm sampling depth)

**Impact:** SIMS and ESCA are rarely done on nanoparticles. This data could explain nanotoxicity, and could lead to manufacturing methods for safer nanoparticles

# X-ray photoelectron spectroscopy (XPS)

- XPS gives elemental composition and the chemical state information of outermost 8 nm layer of nanoparticles
- Primary surface characterization conducted with XPS



In XPS analysis, an X-ray excites a core electron. Binding energy of the excited electron is determined by detected characteristic kinetic energy.

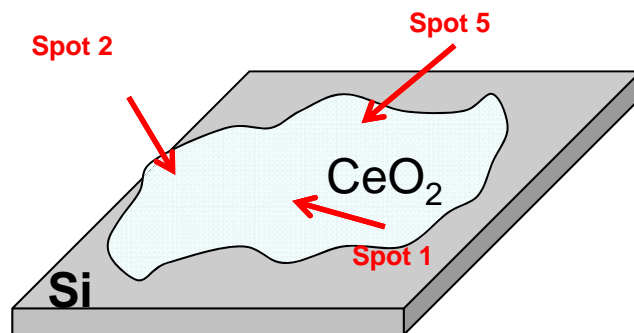
# Sample preparation

- About 40  $\mu\text{l}$  10 wt.%  $\text{CeO}_2$  in water solution was dropped on a silicon chip. Sample was covered with a KimWipe suspended above the drop, fastened with a rubber band and left in a fume hood for several days in order to dry



# Data nomenclature

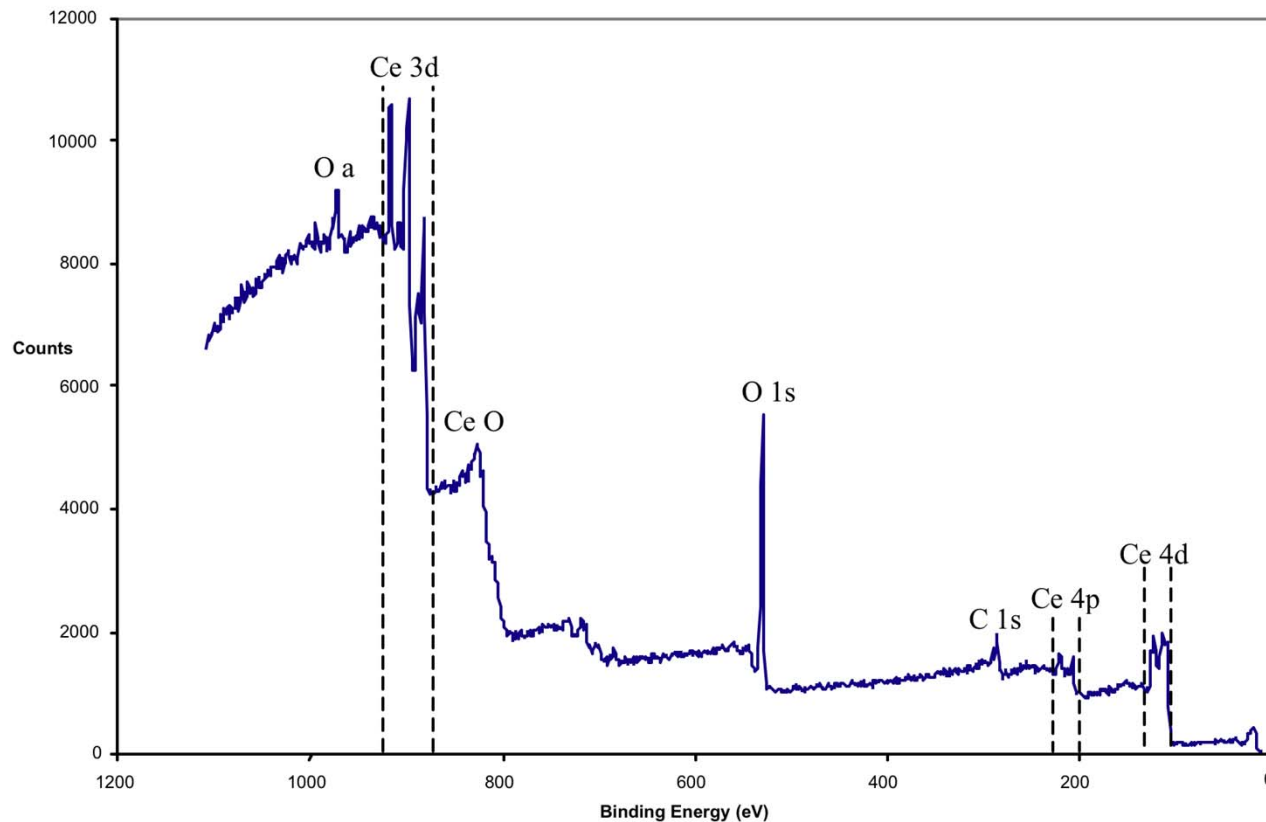
- Overall five different spots of one sample were analyzed by XPS
- Survey and detailed scans were conducted on 2 spots
- High resolution scans were conducted on 3 spots



Schematic diagram of spots characterized by XPS



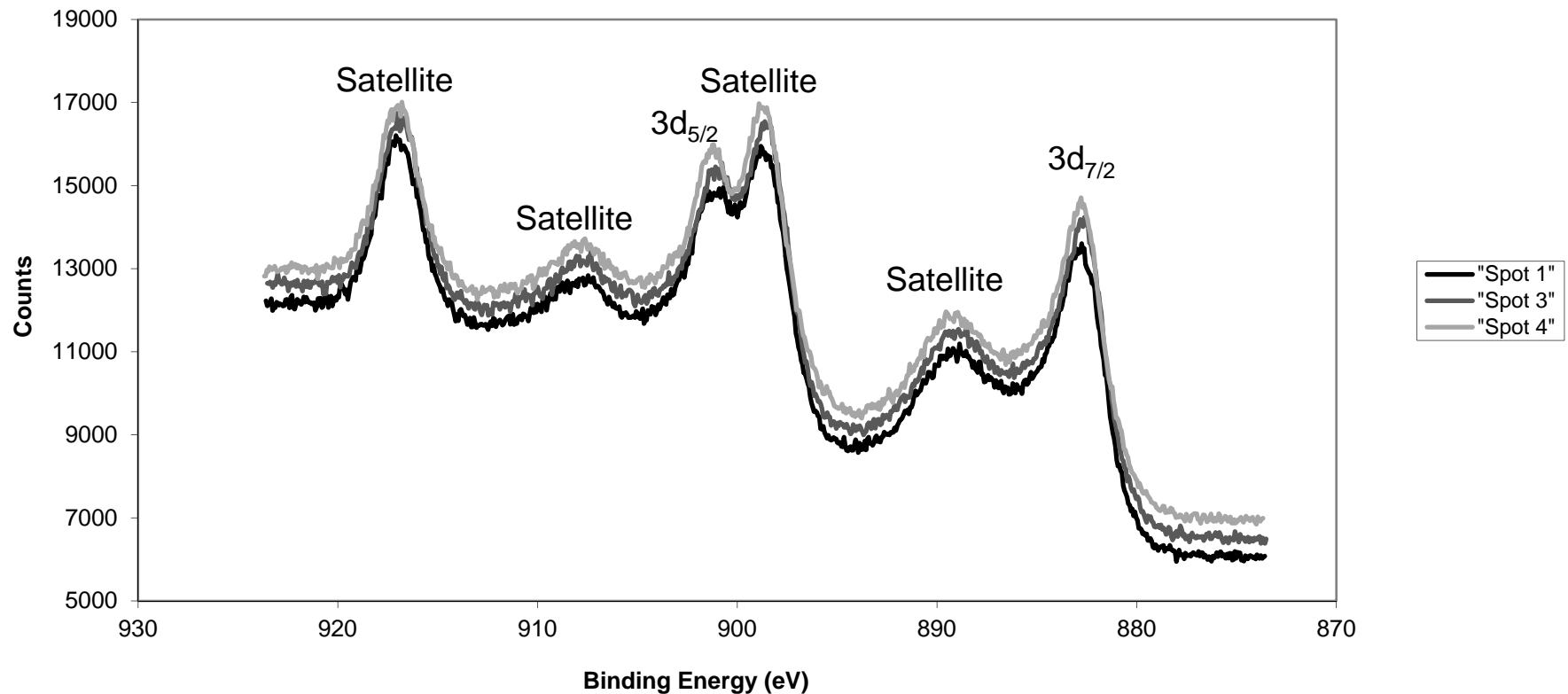
# Survey scan



Survey scan of 10 wt. %  $\text{CeO}_2$  in water, spot 2

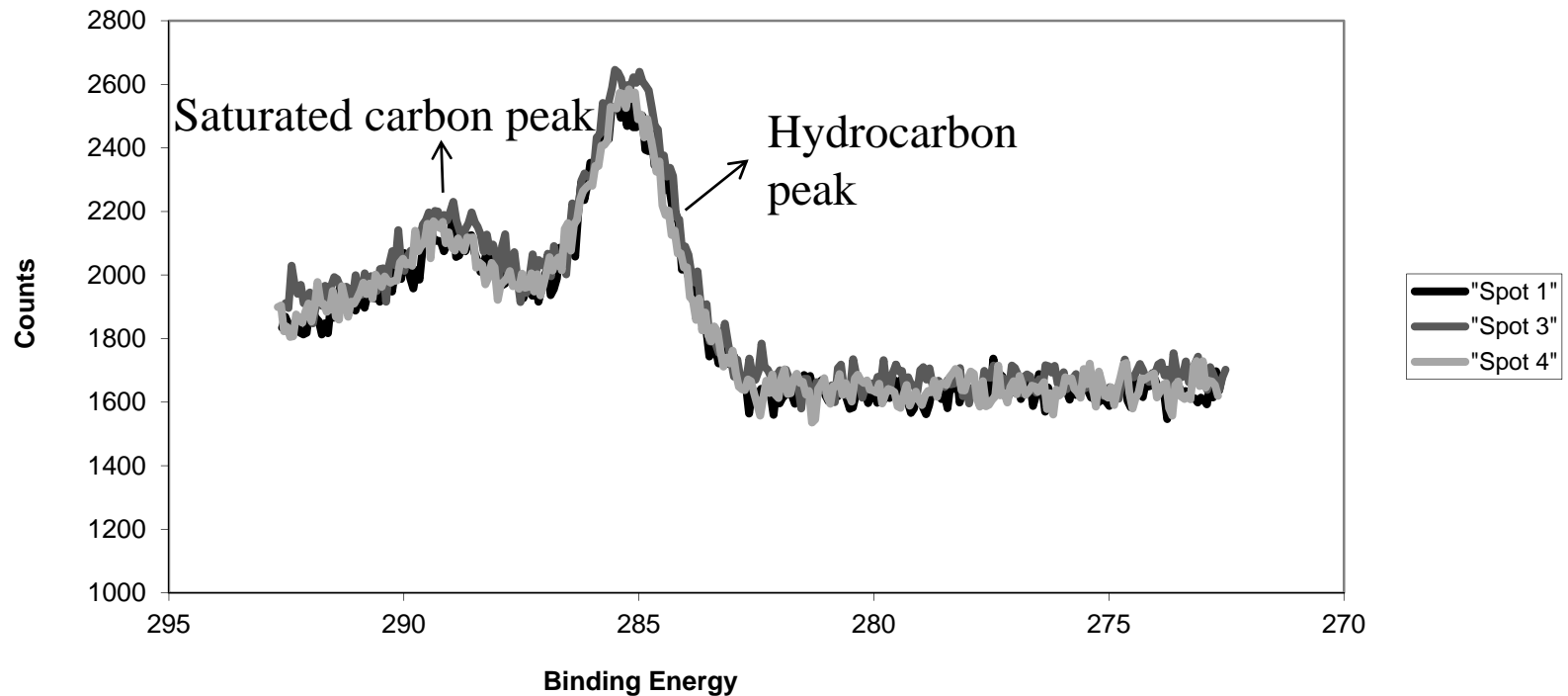
Survey scan spectra shows that the elements present on the outermost 10 nm layer of nanoparticles are Ce, C, and O

# High resolution spectra Ce 3d



The same trend of the high resolution spectra of the three spots analyzed indicates that Ce is in the same oxidation states in all analyzed spots

# High resolution C1s



- The overlap of the three spectra indicates that nanoparticles have homogenous surface chemical species
- High resolution C1s peak consists of hydrocarbon and unsaturated carbon peak
- Unsaturated C1s peak with a 4 eV shift from hydrocarbon peak could be associated with either carboxylate, or, less likely, carbonate

## Surface elemental ratio

- Surface elemental ratios were calculated based on detailed scan of the sample
- Hydrocarbon and unsaturated carbon contents are calculated from the ratio of their respective area under the detailed scan peaks

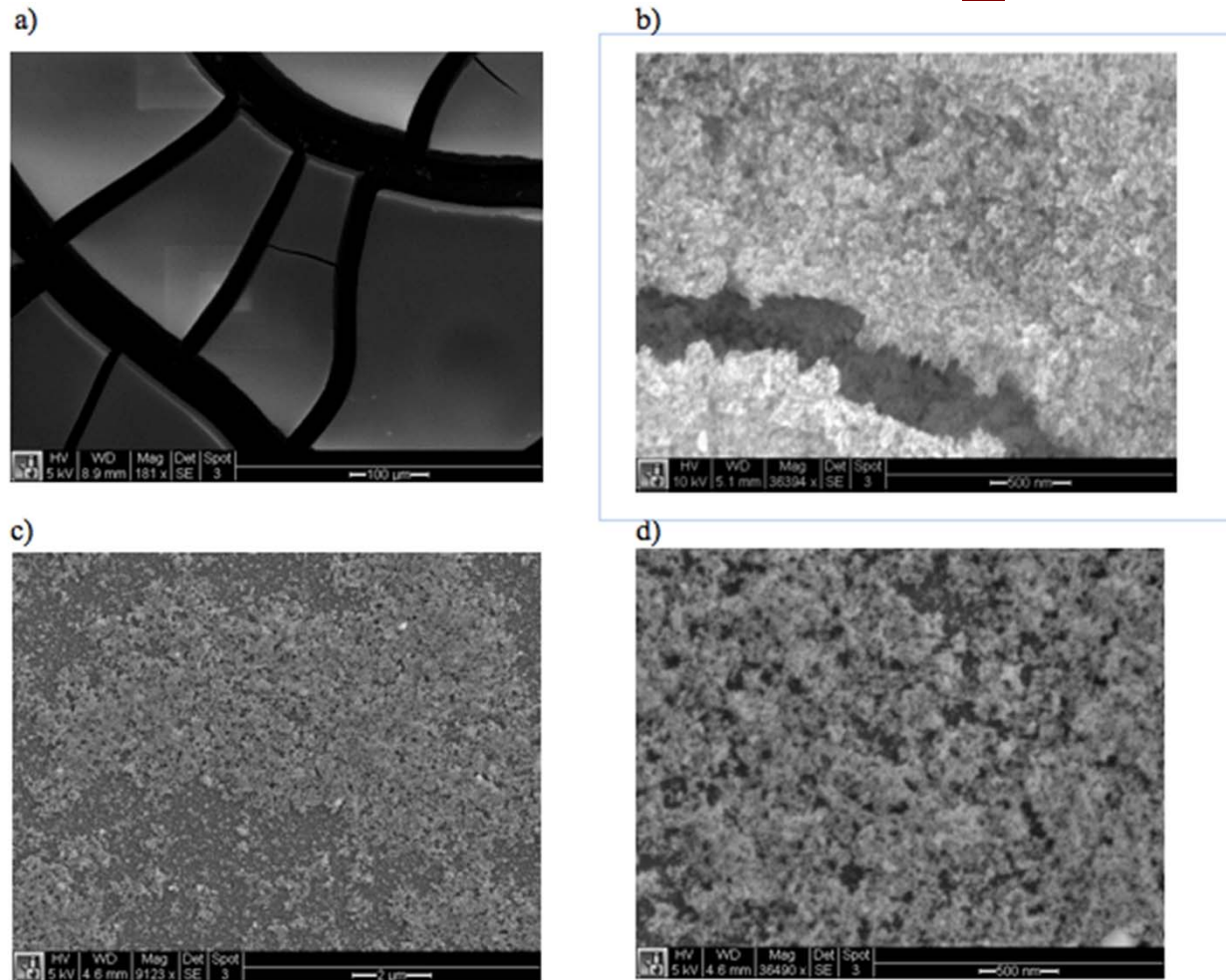
	Ce %	O%	Total C%	Unsaturated Carbon%	Hydrocarbon %
Spot 2	19.3	60.2	20.5	4.7	15.8
Spot 5	17.1	54.4	28.5	9.1	19.4

# Possible surface chemical species

- Oxygen to carbon ratio calculated from the detailed scan spectra serves as a guide to find potential surface chemical species
- Exact determination of chemical structure is achievable with complementary techniques (i.e. time of flight secondary ion mass spectrometry ToF-SIMS)

	Total O (%)	O in CeO <sub>2</sub> (%)	O in unsaturated carbon (%)	$\frac{O}{UnsaturatedC}$ (%)
Spot 2	60.2	38.6	21.6	4.6
Spot 5	54.4	34.2	20.3	2.2

# SEM characterization of CeO<sub>2</sub> sample



SEM micrographs of CeO<sub>2</sub> nanoparticles. a. 10 wt.% CeO<sub>2</sub> (the original sample concentration) b. Surface between cracks shown in a. c,d. Diluted sample (0.5 wt. % )

## Dynamic light scattering (DLS) characterization of CeO<sub>2</sub> sample

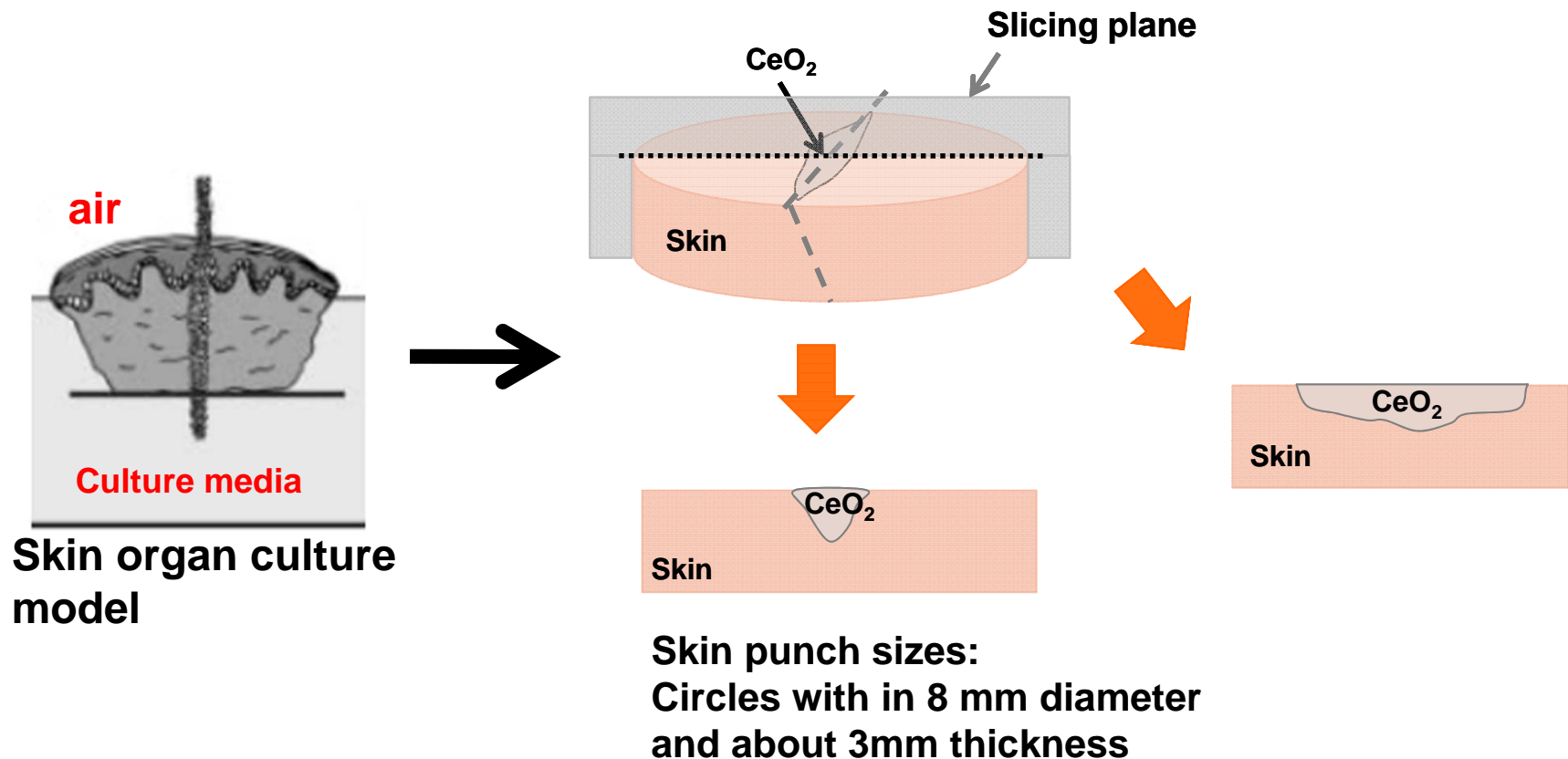
Dynamic light scattering (DLS) hydrodynamic diameter for 0.0125 wt. % CeO<sub>2</sub>

	Not <u>sonicated</u>	<u>Sonicated</u> 10s	<u>Sonicated</u> 5 min
Hydrodynamic diameter (nm)	305.3±2.4	110.6±2.9	89.6±0.5

**Conclusion:** the particles, even after sonication, are much larger than the “as purchased” specification

# Organ Culture Model for Nanotoxicity

Rosa Daneshvar (Ph.D. student) has received training on the organ culture model, is ordering all needed supplies, and is in training for the TEM analysis. She has started control H&E staining for histology. We now await receiving the skin samples.





# Summary

- Nanoparticle surface chemical structure was characterized by XPS
- Nanoparticles surface were homogenous with respect to elemental species
- Oxidation state of  $\text{Ce}^{4+}$  was homogenous in the examined spots
- Carboxylate and carbonate might be present on nanoparticles surface
- Exact determination of chemical structure is achievable with complementary techniques (i.e. time of flight secondary ion mass spectrometry ToF-SIMS)

# Industrial Interactions and Technology Transfer

- Telephone conference calls

# **Future Plans**

## **Next Year Plans**

- **Conduct surface chemical characterization for CeO<sub>2</sub> of different size CeO<sub>2</sub> particles**
- **Conduct surface chemical characterization of different type of nanoparticles (i.e. gold nanoparticle)**
- **Compare the toxicity of two types of nanoparticles in three different sizes with organ culture model**

## **Long-Term Plans**

- **Characterize surface chemical species of three different sizes of CeO<sub>2</sub> and gold nanoparticles**
- **Evaluate and compare the toxicity of characterized nanoparticles by organ culture model**

# Publications, Presentations, and Recognitions/Awards

## Publication:

**“Cytotoxicity and Physicochemical Properties of Hafnium Oxide Nanoparticles”**

**James A Field, Antonia Luna-Velasco, Scott A. Boitano, Farhang Shadman, Buddy D. Ratner, Chris Barnes and Reyes Sierra-Alvarez**

**(submitted to Chemosphere)**

## Award:

 **BUDDY RATNER TO BE PRESENTED WITH HIGHEST HONOR FOR BIOMEDICAL ENGINEERING,  
2011 PIERRE GALLETTI AWARD**

**Posted on January 27, 2011**



AMERICAN INSTITUTE FOR MEDICAL  
AND BIOLOGICAL ENGINEERING

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

# **Environmental Safety and Health (ESH) Impacts of Emerging Nanoparticles and Byproducts from Semiconductor Manufacturing - Toxicity Assessment (Task # 425.024)**

## **PIs:**

- **Jim A Field, Dept. Chemical and Environmental Engineering, UA**
- **Reyes Sierra-Alvarez, Dept. Chemical and Environmental Engineering, UA**
- **Scott Boitano, Dept. of Physiology and The Arizona Respiratory Center, UA**

## **Graduate Students:**

- **Lila Otero, PhD candidate, Chemical and Environmental Engineering, UA**
- **Isabel Barbero, PhD candidate, Chemical and Environmental Engineering, UA**
- **Jorge Gonzalez, PhD candidate, Chemical and Environmental Engineering, UA**
- **Mia McCorkel, PhD candidate, Dept. of Physiology, UA**

## **Other Researchers:**

- **Antonia Luna, Postdoctoral Fellow, Chemical and Environmental Engineering, UA**
- **Citlali Garcia, Postdoctoral Fellow, Chemical and Environmental Engineering, UA**
- **Angel Cobo-Curiel, Exchange Student, University of Valladolid, Spain**

## **Cost Share (other than core ERC funding):**

- **\$80k from UA Water Sustainability Program**
- **\$150k to purchase real-time toxicity monitoring system (UA Water Sustainability Program)**
- **Postdoctoral fellowship to C. Garcia (Mexican Science Foundation, CONACyT)**
- **Doctoral fellowship to J Gonzalez (Mexican Science Foundation, CONACyT)**
- **Doctoral fellowship to M McCorkel (SRC graduate fellowship program)**

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

# Overall Objectives

- **Characterize toxicity of current and emerging nanoparticles (NP) & NP byproducts**
- **Develop new rapid methodologies for assessing and predicting toxicity**

# **ESH Metrics and Impact**

1. *Reduction in the use or replacement of ESH-problematic materials*

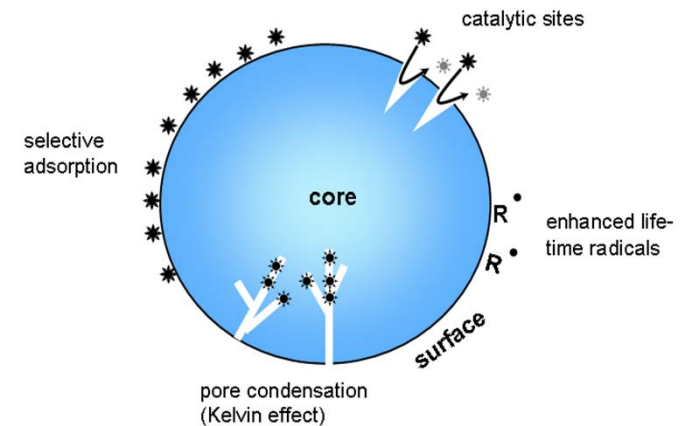
**This project will evaluate the toxicity of various types of nanoparticles utilized or considered for application in semiconductor manufacturing, and the impact of manufacturing steps on their toxicity. This information can assist in selecting materials which are candidates for replacement or use reduction.**

2. *Reduction in emission of ESH-problematic material to environment*

**The knowledge gained can be utilized to modify the manufacture of nanoparticles so that they have a lowered toxicity and thus a lowered environmental impact.**

# Hypotheses

- Surface chemistry plays an important role in NP toxicity
- The size of NPs intrinsically makes reactive surfaces



➤ reactive with medium components

- ☐ forming reactive oxygen species (ROS)
- ☐ oxidize biomolecules

➤ particle – particle interaction

- ☐ agglomeration and dispersion impacting stability NP suspension

➤ dissolution of toxic species

➤ adsorption of toxic species



# Toxicity Assessment and Prediction

## Objectives

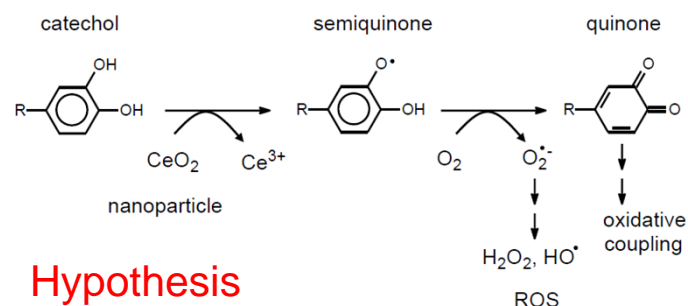
- Establish role for reactive oxygen species (ROS) and oxidative stress as a potential marker for NP toxicity assessment.
- Develop predictable models of toxicity based on physico-chemical properties elucidated by advanced surface analysis techniques.

# **Experiments Past Year**

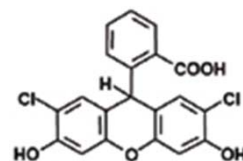
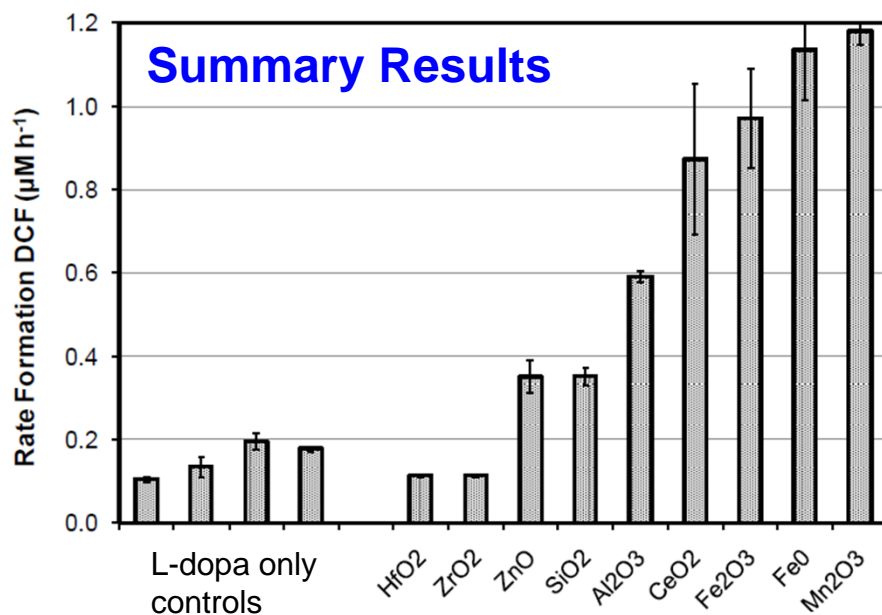
- **Completed study on chemical ROS production.**
- **Completed study on yeast O<sub>2</sub> uptake assay.**
- **Evaluated flow-cytometry for yeast membrane integrity assay.**
- **Impedance-based Real Time Cell Analysis (RTCA) for high throughput screening.**

# Experiments: Chemical ROS - 1

Monitor chemical ROS production caused NP oxidation of L-dopa

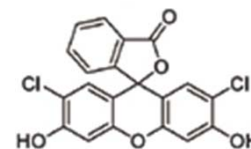


Hypothesis



2',7'-dichlorodihydrofluorescein (DCFH)

ROS



2',7'-dichlorofluorescein (DCF)

fluorescent

Fluorescence spectrometer

Measurement

New findings since last year

- Mn<sub>2</sub>O<sub>3</sub> directly oxidizes DCFH (O<sub>2</sub> not required)
- Mn<sub>2</sub>O<sub>3</sub> caused large effects in ppm range
- Completed screening

Conclusions

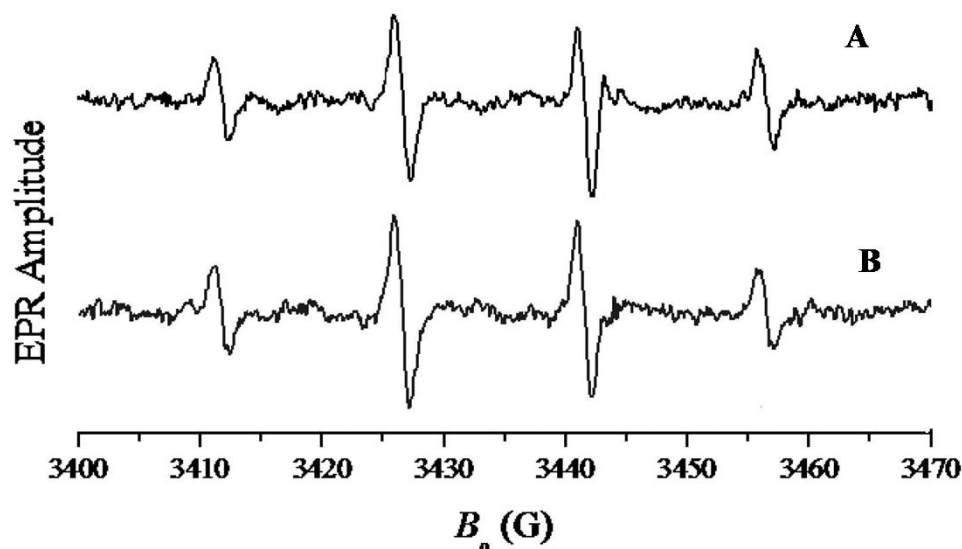
- Mn<sub>2</sub>O<sub>3</sub>, most reactive and directly oxidizes DCFH (L-dopa is competitive inhibitor)
- CeO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub> and Fe<sup>0</sup> react with L-dopa and O<sub>2</sub> to greatly enhance ROS formation
- ZnO, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> react with L-dopa and O<sub>2</sub> to enhance ROS formation to a lesser extent
- HfO<sub>2</sub>, ZrO<sub>2</sub> do not enhance ROS production (inert)

# Experiments: Chemical ROS - 2

## Electron Spin Resonance (ESR) evidence ROS

Spin Trap: 5,5-dimethyl-1-pyrroline N-oxide (DMPO)

Signals correspond to DMPO-OH; however DMPO-OH can also form from DMPO-OOH so evidence is for OH• and/or O<sub>2</sub><sup>-•</sup> radicals



**A:** 1,000 mg/L CeO<sub>2</sub> and 0.02 mM DMPO in pH 7 water

**B:** 1,000 mg/L Mn<sub>2</sub>O<sub>3</sub> and 0.02 mM DMPO in pH 7 water

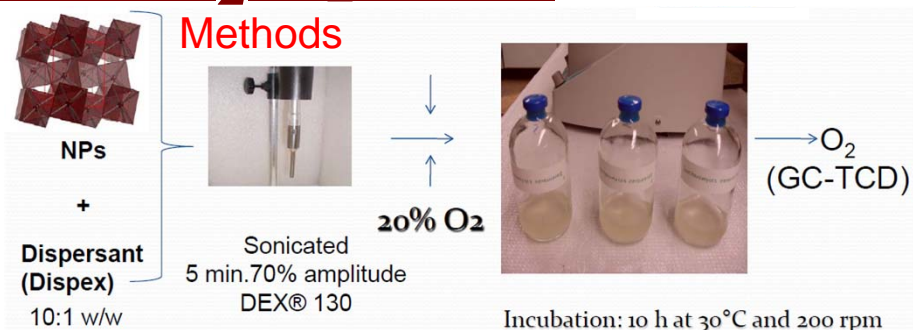
### **Conclusions:**

**CeO<sub>2</sub> and MnO<sub>2</sub> form OH• and/or O<sub>2</sub><sup>-•</sup> radicals**

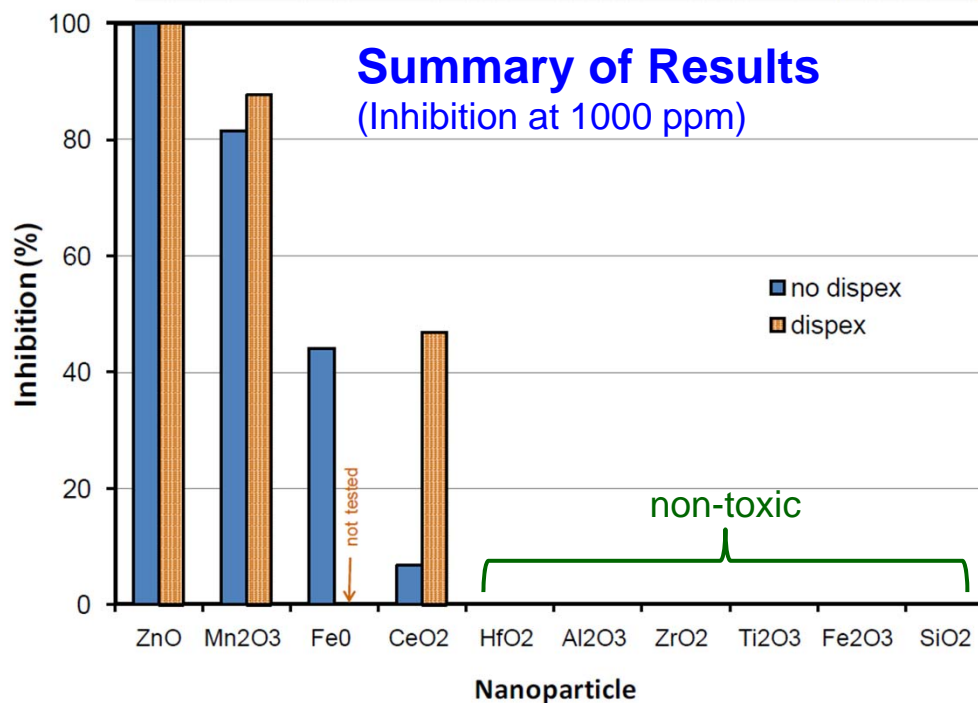
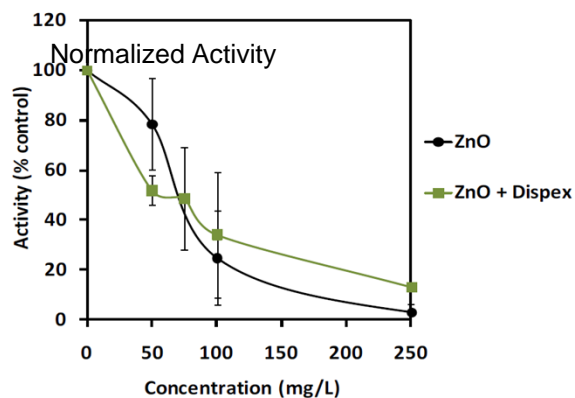
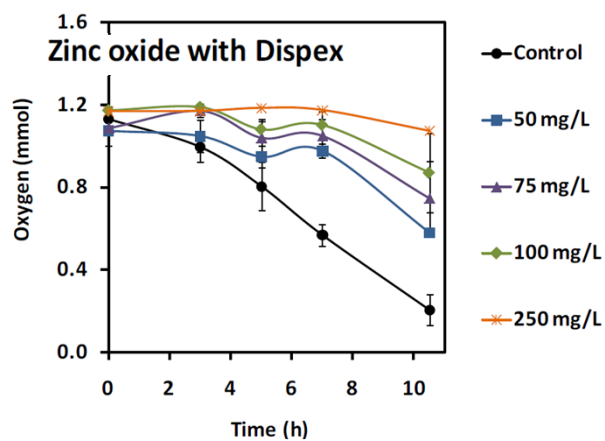
**To a lesser extent Fe<sup>0</sup> also formed OH• and/or O<sub>2</sub><sup>-•</sup> radicals**

# Experiments: Yeast O<sub>2</sub> uptake

Monitor O<sub>2</sub> uptake by yeast *S. cerevisiae* in pH 6.5 Yeast Extract Peptone Dextrose (YEPD) medium (effect dispersant, Dispex)



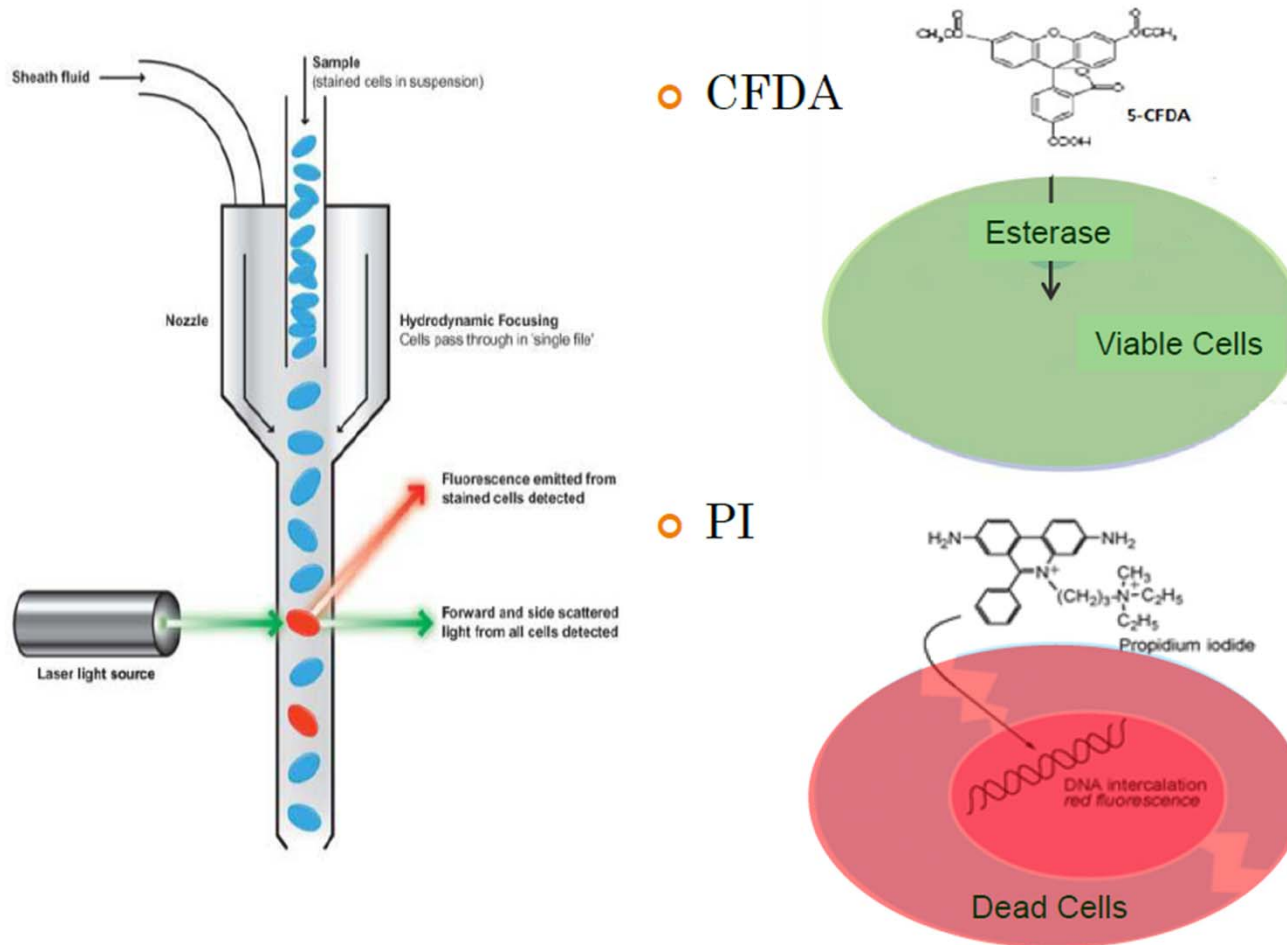
## Example Time Course



**Conclusions:** ZnO most toxic, due to solubilization of Zn<sup>+2</sup>  
Mn<sub>2</sub>O<sub>3</sub>, Fe<sup>0</sup> & CeO<sub>2</sub> toxic, due to oxidative stress  
CeO<sub>2</sub> toxicity increased by better dispersion

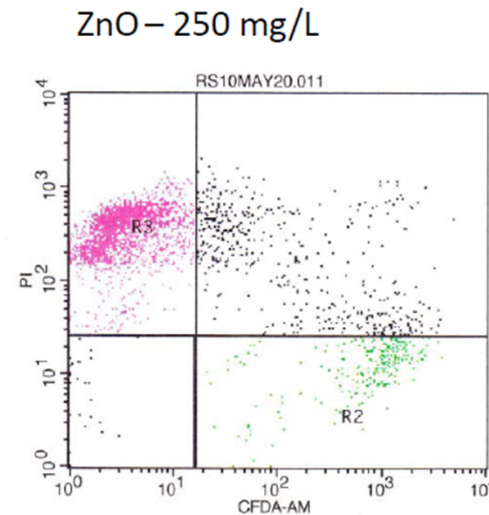
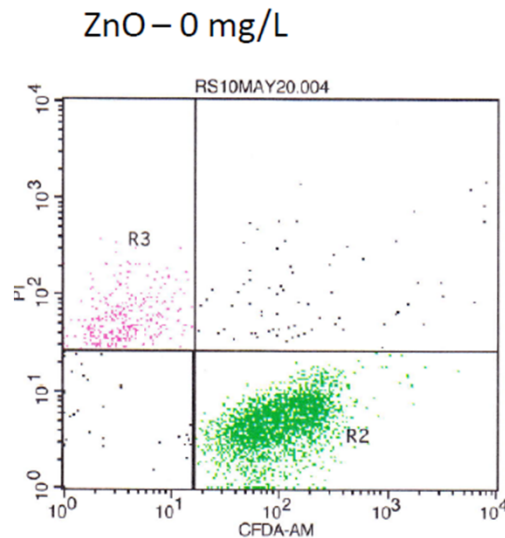
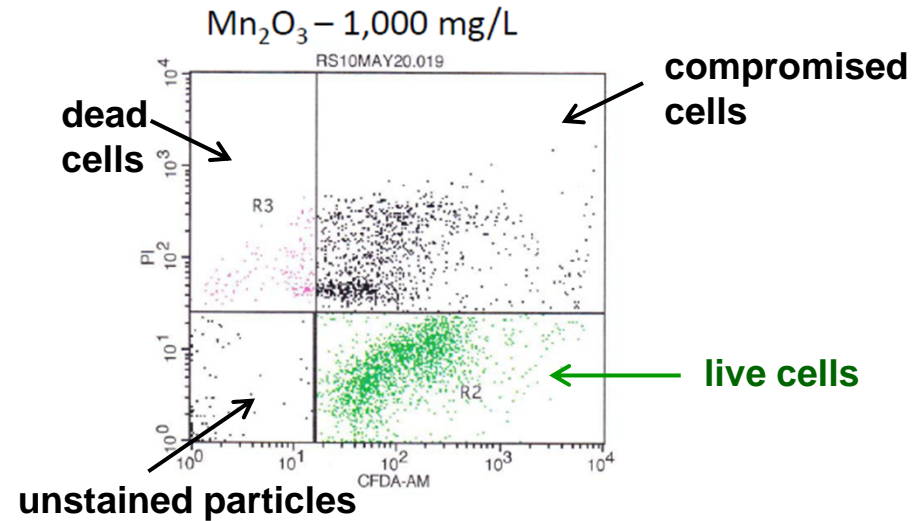
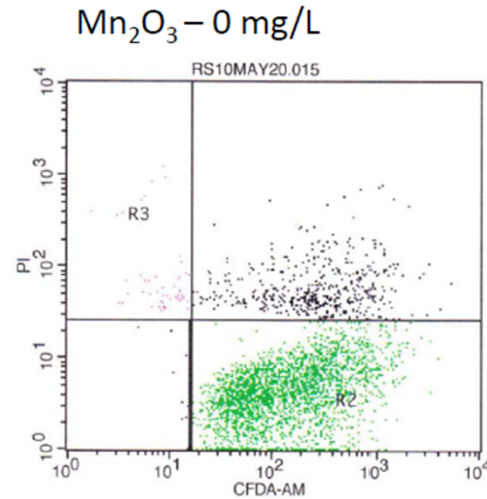
# Experiments: Yeast Flow Cytometry - 1

Flow cytometry for assaying membrane integrity of yeast *S. cerevisiae* in pH 6.5 Yeast Extract Peptone Dextrose (YEPD) medium exposed to NP dispersed in Dispex



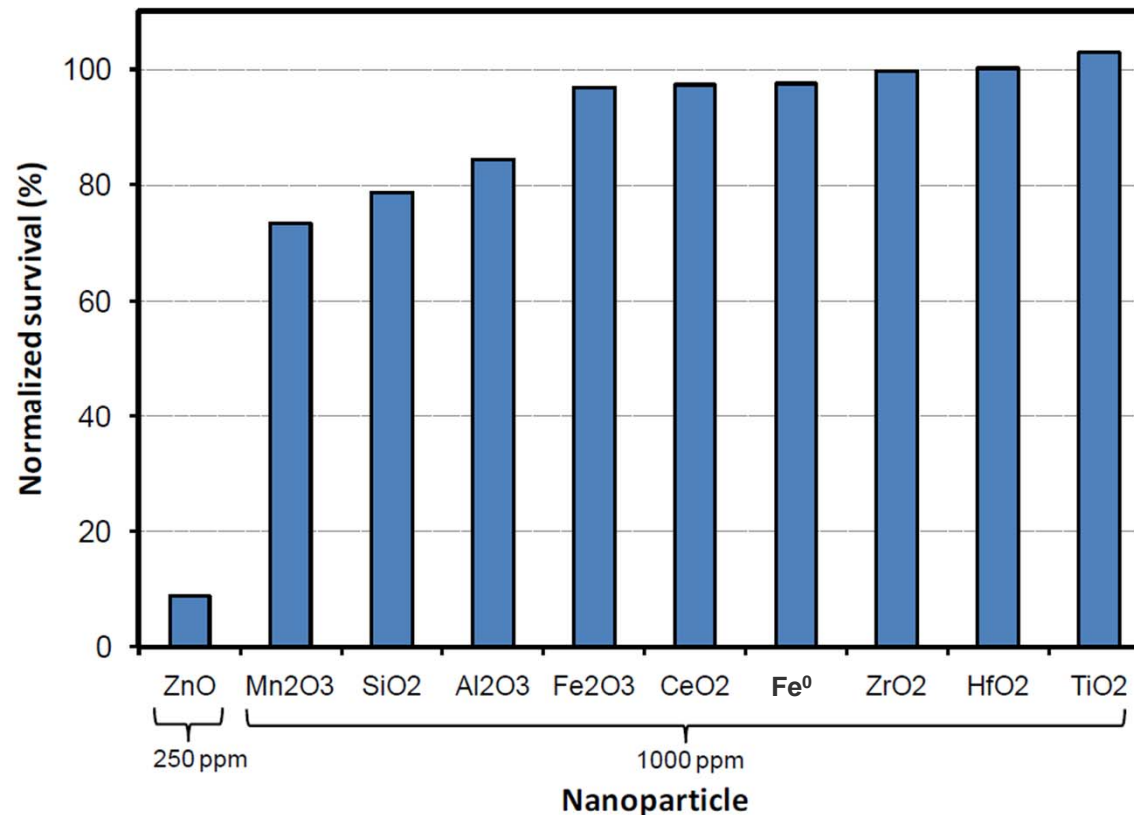
# Experiments: Yeast Flow Cytometry - 2

Flow cytometry example plots (upper right plot with explanation of quadrants)



# Experiments: Yeast Flow Cytometry - 3

## Flow Cytometry Summary of Results



### Conclusions:

ZnO most toxic, due to solubilization of toxic  $Zn^{+}$  salt

$Mn_2O_3$ ,  $SiO_2$  and  $Al_2O_3$  significant but low toxicity at 1000 ppm

All other NPs did not disrupt membrane

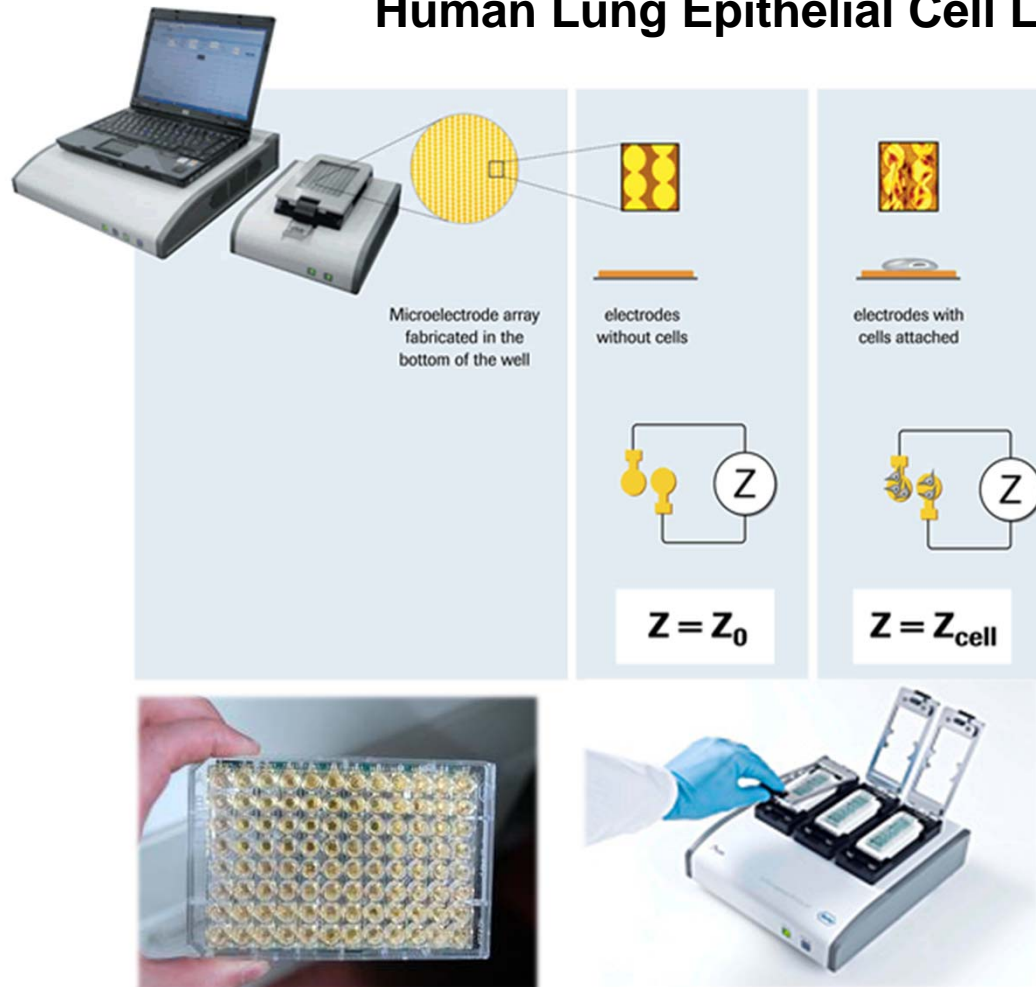
} membrane damage



# Experiments: xCELLigence - 1

Monitor Impedance Based Real Time Cell Assay (RTCA) with xCELLigence (Roche)

Human Lung Epithelial Cell Line, 16HBE14o-

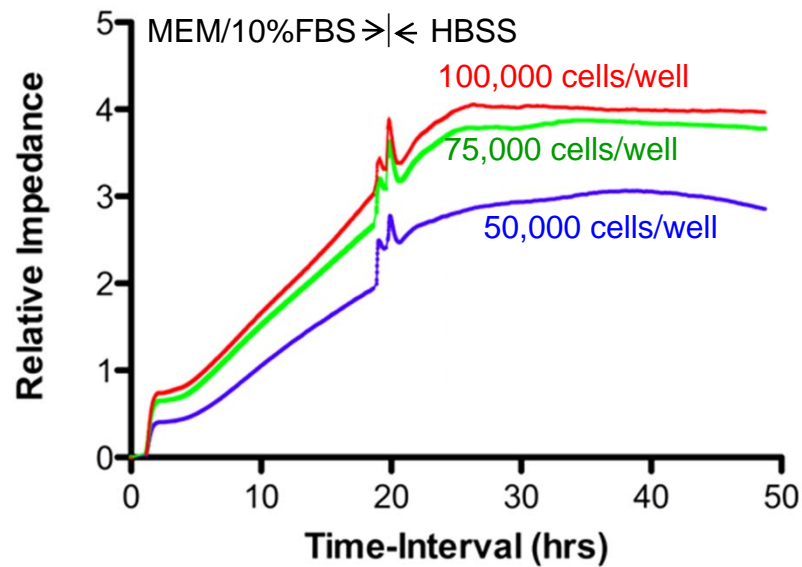


- The xCELLigence System measures **electrical impedance** across interdigitated micro-electrodes integrated on the bottom of tissue culture E-Plates.
- The impedance provides information about the **biological status** of the cells.
- The xCELLigence system does **not** need **fluorescent labels**.

# Experiments: xCELLigence - 2

## RTCA Optimization

### Number of Cells

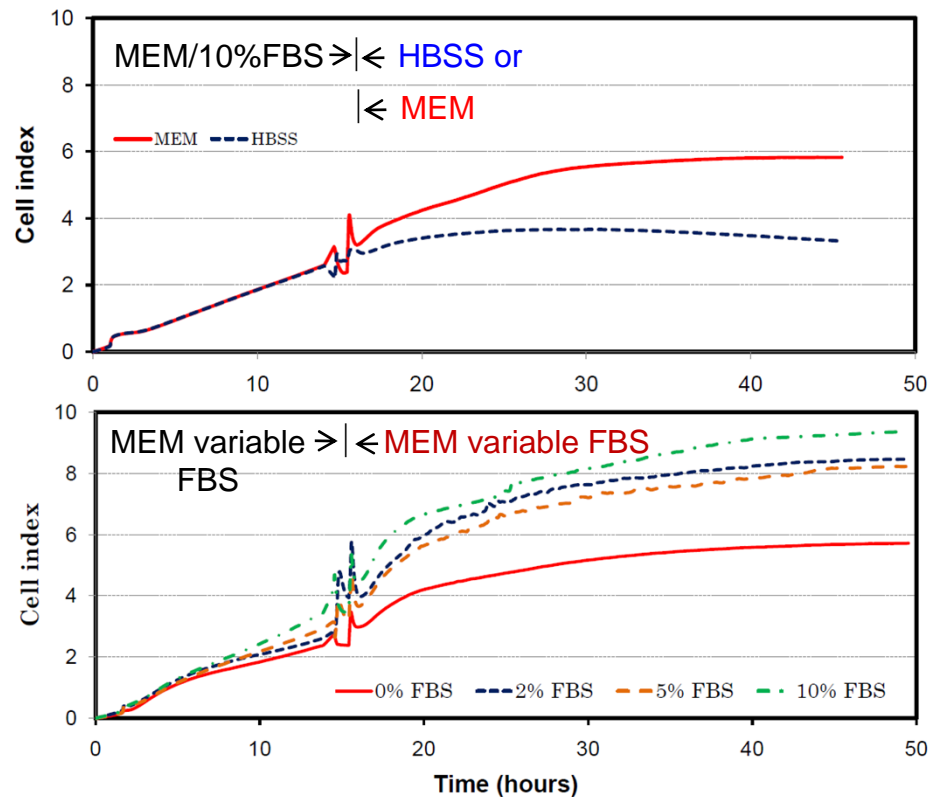


MEM = Minimum Essential Medium Eagle

HBSS = Hanks balanced salt solution

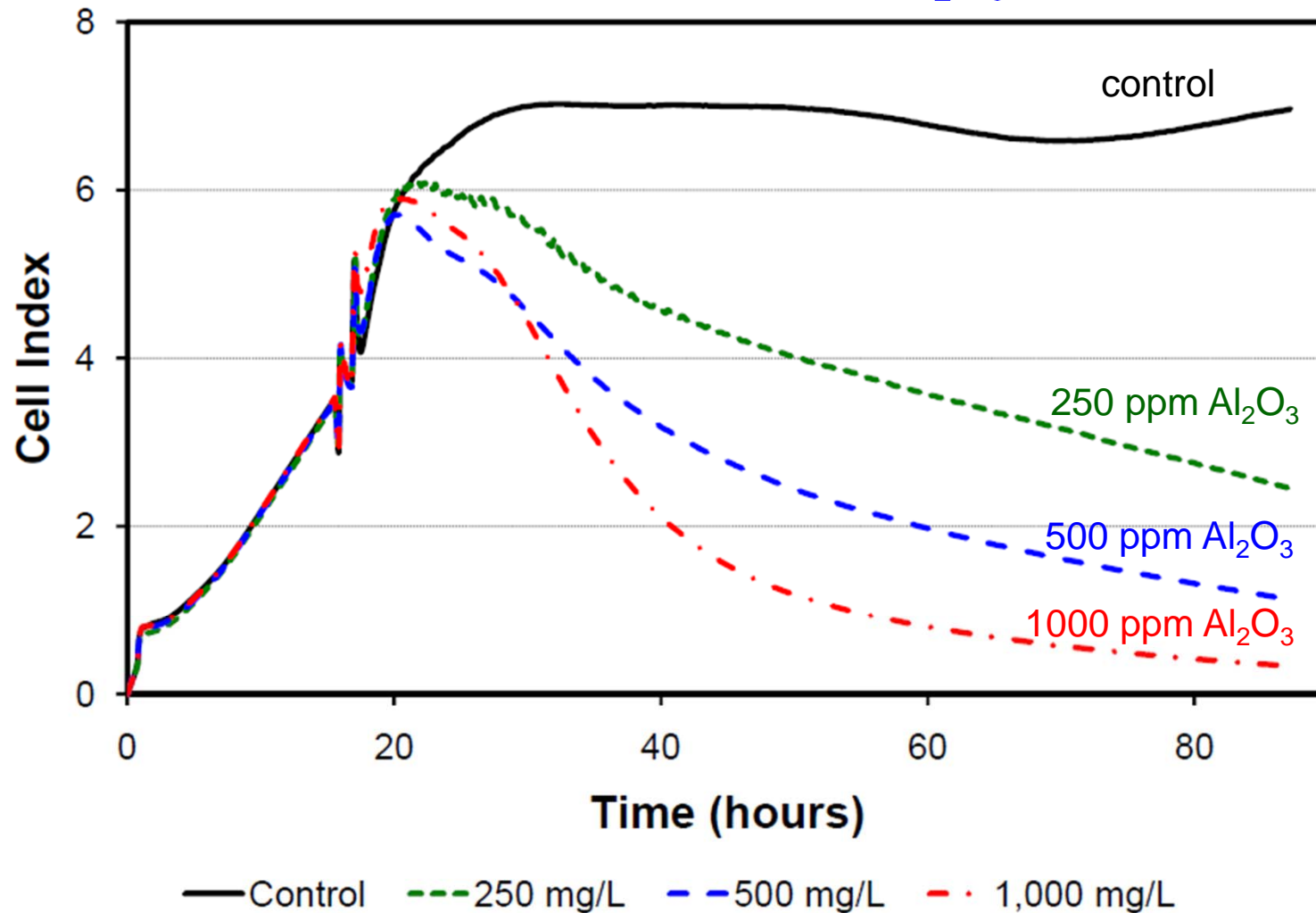
FBS = Fetal bovine serum (protein)

### Medium Composition



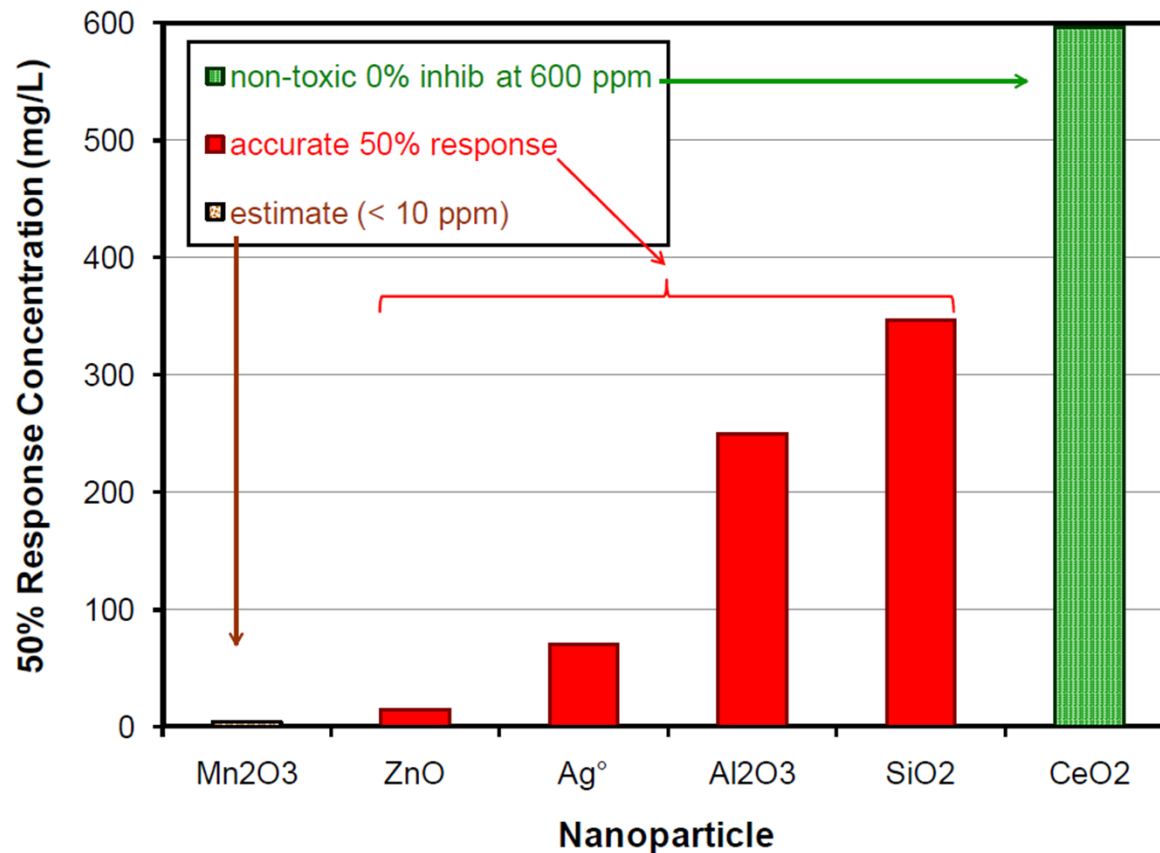
# Experiments: xCELLigence - 3

Example Output RTCA with  $\text{Al}_2\text{O}_3$  NPs



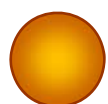
# Experiments: xCELLigence 4

50% Response Concentrations from all RTCA experiments with NPs



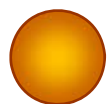
**Conclusions:** Mn<sub>2</sub>O<sub>3</sub> most toxic (estim. 3.5 ppm 50% response) oxidative  
ZnO and Ag<sup>0</sup> also highly toxic solubilization Zn<sup>+2</sup> and Ag<sup>+</sup>  
Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> moderate toxicity stability of NP suspensions

# Experiments: Conclusions



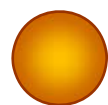
## **Most toxic NPs: ZnO, Ag<sup>0</sup> and Mn<sub>2</sub>O<sub>3</sub>**

- ZnO and Ag<sup>0</sup> NPs solubilize during the assays and are almost equivalent in toxicity to Zn<sup>+2</sup> and Ag<sup>+</sup> salts.
- Mn<sub>2</sub>O<sub>3</sub> is oxidative (directly oxidizes ROS-dye, can also form ROS, oxidized BSA protein and had a detectable impact in yeast membrane integrity test).



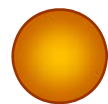
## **Consistently moderately toxic NPs: Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub>**

- Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> had good NP stability in assay media utilized.
- Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> also have moderate to low chemical ROS production.



## **Sometimes moderately toxic NPs: CeO<sub>2</sub> and Fe<sup>0</sup>**

- CeO<sub>2</sub> and Fe<sup>0</sup> strongly enhance chemical ROS production.

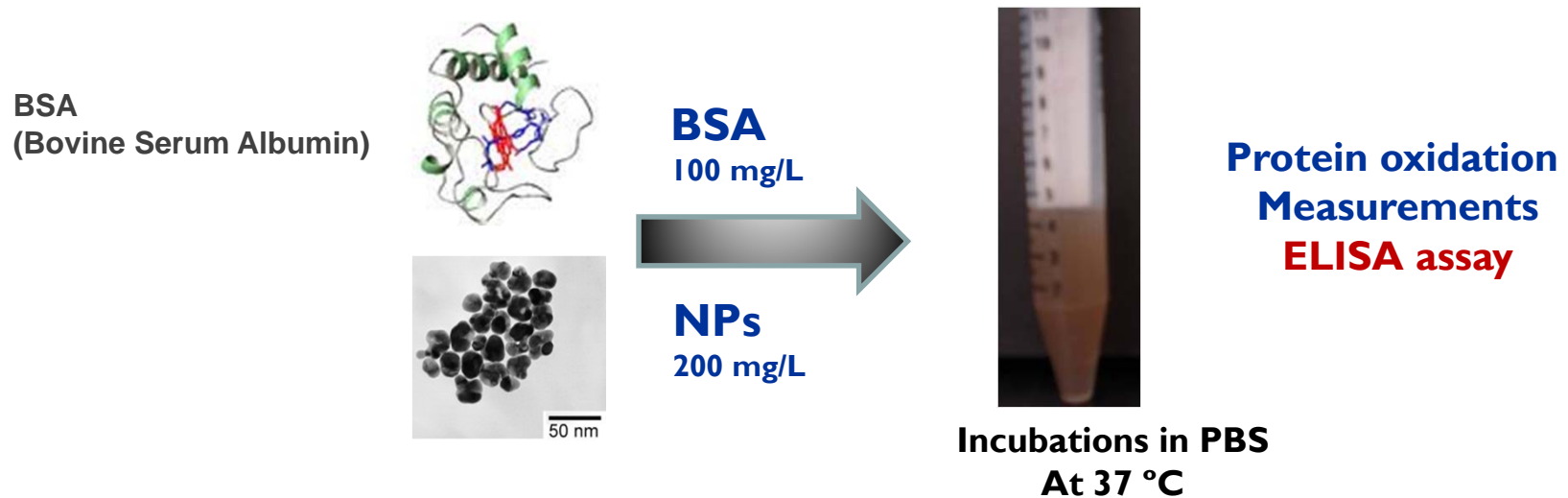


## **Consistently non-toxic NPs: ZrO<sub>2</sub> and HfO<sub>2</sub>**

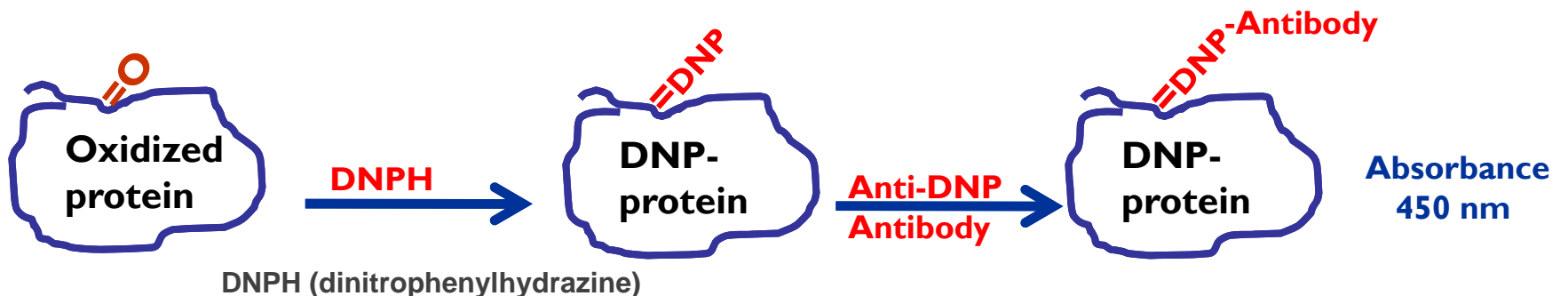
- inert

# New Experiments - 1

## Protein Oxidation by Nanoparticles

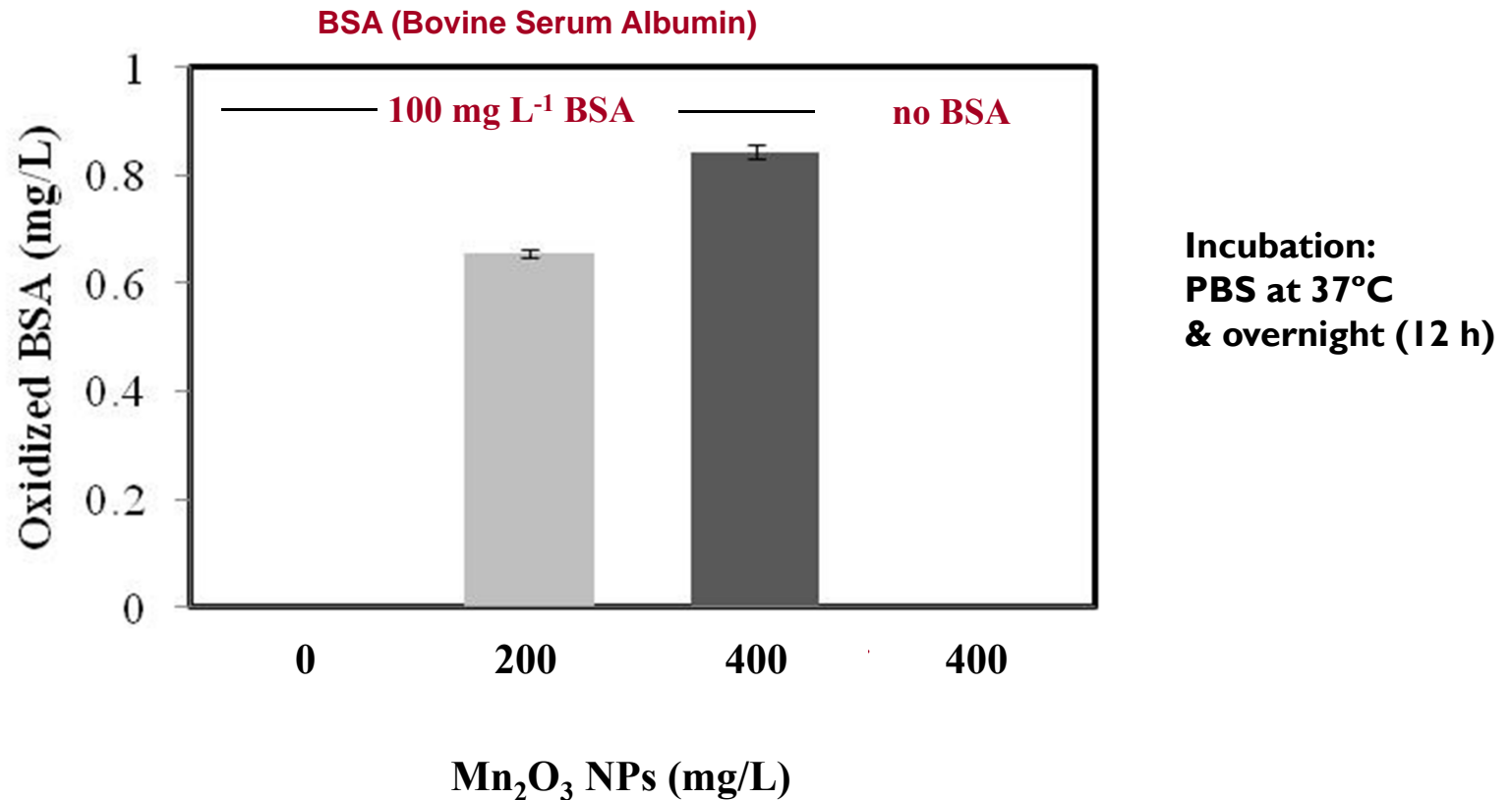


Rapid detection/quantification of protein carbonyls as an index of oxidized proteins with ELISA test



# New Experiments - 2

## Preliminary Result BSA protein oxidation by NPs



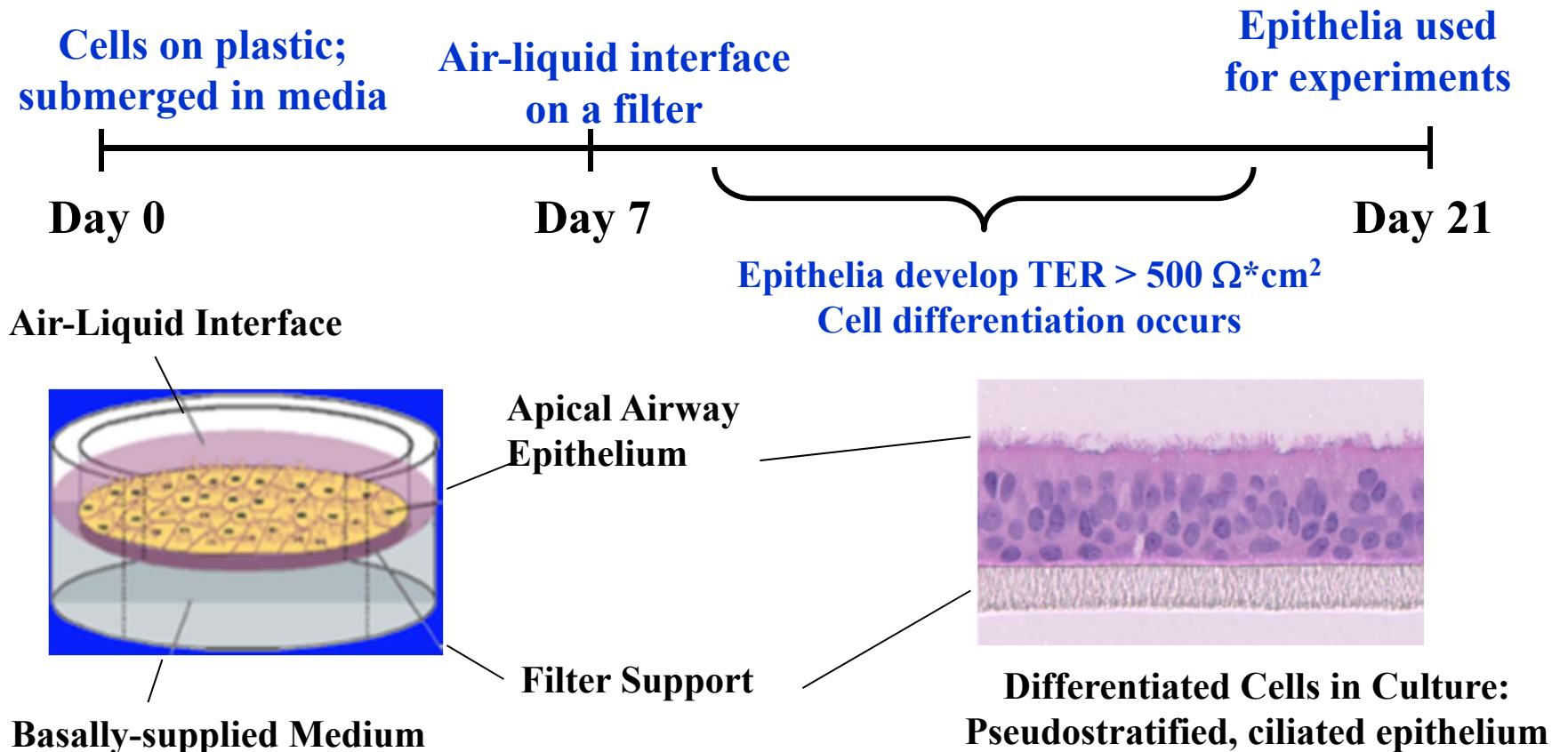
### Ongoing Experiments:

Longer incubation times (2 & 7 days) to determine if they have more oxidative effect

# New Experiments - 3

## Development of Well-Differentiated Human Airway Epithelia (Organ Cultures) to Better Evaluate in vivo Effects of NPs

Tracheobronchial tissues (National Disease Research Interchange) are subjected to the following:





# Long Term Project Outcomes

- **Assessment of stability and aggregation of NPs dispersions in biological medium, and development of approaches to enhance dispersion.**
- **Clues on how to reduce and eliminate toxicity due to unavoidable surface contamination.**
- **Predictive correlations between toxicity data and physicochemical parameters.**

# **Industrial Interactions and Technology Transfer**

- **ISMI-Sematech (Steve Trammell, Laurie Beu)**
- **AMD (Reed Content)**
- **IBM (Arthur T. Fong)**
- **Intel (Steve W. Brown, Mansour Moinpour)**

# **Future Plans**

## **Next Year Plans**

- **Fractionation of NPs for toxicity study size fractions**
- **Oxidation of large biomolecules (proteins, etc)**
- **Correlation multiple parameters to measured toxicity**
- **Assay reactive oxygen species/cellular signaling pathways altered by NPs**
- **NP toxicity to well-differentiated human airway epithelia**

## **Long-Term Plans**

- **Rapid screening protocols of for assessing NP toxicity**

# Publications & Presentations

## Journal Publications from Project

- Luna-Velasco A, Field JA, Cobo-Curiel A, Sierra-Alvarez R. 2011. Inorganic nanoparticles enhance the production of reactive oxygen species (ROS) during the autoxidation of L-3,4-dihydroxyphenylalanine (L-Dopa). J. Haz. Mat. (Submitted)
- Garcia-Saucedo C, Field JA, Otero L, Sierra-Alvarez R. 2011. Toxicity of HfO<sub>2</sub>, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and CeO<sub>2</sub> nanoparticles to the yeast, *Saccharomyces cerevisiae*. J. Haz. Mat. (Submitted)
- Field JA, Luna-Velasco A, Boitano SA, Shadman F, Ratner BD, Barnes C, Sierra-Alvarez R. 2011. Cytotoxicity and physicochemical properties of hafnium oxide nanoparticles. Chemosphere (Submitted)
- Gomez-Rivera F, Field JA, Brown D, Sierra-Alvarez R. 2011. Fate of cerium dioxide (CeO<sub>2</sub>) nanoparticles in municipal wastewater during activated sludge treatment Bioresource Technol. (Submitted)

## Conference Papers from Project

- Rottman J, Shadman S, Sierra-Alvarez R. 2010. Interactions of CMP nanoparticles and sewage sludge. SESHA Journal, Summer 2010. Pp. 8
- Gomez-Rivera P, Brown D, Field JA, Shadman F, Sierra-Alvarez, R. 2010. Fate of CeO<sub>2</sub> nanoparticles during laboratory-scale activated sludge treatment. SESHA Journal, Summer 2010. Pp. 10.

# Publications & Presentations

## Conference Presentations

- Field JA, Luna-Velasco A, Garcia C, Otero L, Sierra-Alvarez R. 2010. Toxicity and environmental fate of nanoparticles. 2010 Nano Monterrey Forum: Nanotechnology Industrial Applications. 2010. Nov. 18-19, Monterrey, Mexico. [ORAL]
- Rottman J, Barbero I, Rodriguez M, Sierra-Alvarez R, Shadman F. 2010. Fate of CMP nanoparticles in municipal wastewater treatment. TECHCON Conference: Technology and Talent for the 21st Century. Austin, TX. Sept. 13-14. **Prize for best presentation in the Environmental session.** [ORAL]
- Gomez-Rivera, P., Brown, D. , Field JA, Shadman F, Sierra-Alvarez, R. 2010. Fate of CeO<sub>2</sub> Nanoparticles During Laboratory-Scale Activated Sludge Treatment. 32<sup>nd</sup> Semiconductor Environmental, Safety & Health Association (SESHA) Annual Int. High Technology ESH Symp. Exhibition, Scottsdale, AZ, April 26-29. **Prize for 3rd best student presentation.** [ORAL]
- Rottman J, Barbero I, Rodriguez M, Shadman F, Sierra Alvarez R. 2010. Fate of CMP nanoparticles during municipal wastewater treatment. 32<sup>nd</sup> SESA Annual Int. High Technology ESH Symp. Exhibition, Scottsdale, AZ, April 26-29, 2010. **Prize for 2<sup>nd</sup> best student presentation** [ORAL]
- Rottman J, Barbero I, Rodriguez M, Shadman F, Sierra Alvarez R. 2010. Fate of CMP nanoparticles during municipal wastewater treatment. 32<sup>nd</sup> SESA Annual Int. High Technology ESH Symp. Exhibition, Scottsdale, AZ, April 26-29, 2010. **Prize for 2<sup>nd</sup> best student presentation** [ORAL]
- Rodriguez M, Barbero I, Luna A, Shadman F, Field JA, Sierra-Alvarez R. 2010. Impact of Wastewater Components on the Aggregation Behavior of CMP Nanoparticles 32<sup>nd</sup> SESA Annual Int. High Technology ESH Symp. Exhibition, Scottsdale, AZ, April 26-29, 2010. [ORAL]
- Field JA, Gomez-Rivera F, Barbero I, Rottman J, Rodríguez M, Luna A, Shadman F, Sierra-Alvarez R. 2010. Fate of Inorganic Oxide Nanoparticles in Semiconductor Manufacturing Effluents during Activated Sludge Treatment. 10<sup>th</sup> American Inst. Chemical Engineers (AIChE) Annual Meeting, Salt Lake City, UT, Nov. 7-12, 2010. [ORAL]
- Rottman J, Barbero I, Rodríguez M, Shadman F, Sierra-Alvarez R. 2010. Fate of metal oxide nanoparticles in municipal wastewater treatment. WSP Water Forum: Our Water Future. Nov. 22, 2010, Tucson, AZ. [Poster]

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# Publications & Presentations

## Conferences Presentations

- Gomez-Rivera F, Barbero I, Rodríguez M, Luna-Velasco A, Shadman F, Field JA, Sierra-Alvarez R. 2010. Interactions Between Inorganic Oxide Nanoparticles and Municipal Wastewater Constituents: Implications for Nanoparticle Removal during Biological Wastewater Treatment. Proc. Leading Edge Technology 2010, Phoenix (AZ), June 2-4. p. 55 [Poster]
- Sierra-Alvarez R, I. Barbero, J. Rottman, M. Rodríguez, A. Luna-Velasco, F. Shadman, JA Field. Removal of CeO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> Nanoparticles in Semiconductor Manufacturing Effluents during Activated Sludge Treatment. Proc. Leading Edge Technology 2010, Phoenix (AZ), USA, 2-4 June 2010. p. 48. [Poster]
- Boitano S, M. McCorkel, I. Barbero, JA Field, R. Sierra-Alvarez. 2010. Nanoparticle Toxicity: Chemical Adsorbents Increase Cytotoxicity. TECHCON Conf.:Technology & Talent for the 21<sup>st</sup> Century. Austin, TX. Sept. 13-14. Pub. ID: P056590. [Poster]
- Sierra-Alvarez R, Gomez F, Barbero I, Rottman J, Rodríguez M, Shadman F, Field JA. 2011. Removal of Inorganic Oxide Nanoparticles in Semiconductor Manufacturing Effluents during Activated Sludge Treatment. 2<sup>nd</sup> International Congress on Sustainability Science & Engineering (ICOSSE '11). Jan. 9-14, Tucson, AZ. [Poster]
- Boitano S, Sherwood CL, Flynn AN, McCorkel M, Field JA, Sierra-Alvarez R. 2010. Use of xCELLigence RTCA to assay cellular signaling and nanocytotoxicity responses in an adherent human bronchial epithelial cell line. Mountain 28<sup>th</sup> Annual Regional Chapter Meeting of the Mountain West Society of Toxicology, Tucson, AZ, Sept. 9 –10, 2010. [Poster].
- McCorkel M, Boitano S. 2011. Nanoparticle toxicity on airway epithelial cells. Society of Toxicology, Washington, D.C. March 6-10. [Poster].

# Publications & Presentations

## Seminars

- Field JA, Sierra-Alvarez R. 2010. Brownbag presentation: Nanoparticle Interaction with Biological Wastewater Treatment Processes, Water Sustainability Program, Phoenix, Arizona. Jan . 2010 at Arizona Cooperative Extension.
- Garcia-Saucedo C, Otero L, Field JA, Sierra-Alvarez R. 2010. Developing a Yeast Cell Assay for Measuring the Toxicity of Inorganic Oxide Nanoparticles. Teleseminar series of Semiconductor Research Corporation/Sematech Eng. Research Center for Environ. Benign Semiconductor Manuf. May 6th, Tucson, AZ.
- Otero, L., Garcia-Saucedo, C., Field JA, Sierra-Alvarez, R. 2010. Comparison of Nanoparticle Toxicity to Yeast Cells and Human Lung Epithelial Cells. ERC Teleseminar series. Dec. 2, 2010, Tucson, AZ>
- Boitano, S. 2009. Measuring cytotoxicity of nanoparticles in human cells. ERC Teleseminar Series. Sept. 17, Tucson, AZ.
- Sierra-Alvarez, R. 2009. Toxicity characterization of HfO<sub>2</sub> nanoparticles. ERC Teleseminar Series, Aug. 6, 2009. Tucson, AZ.

# Task Title:



## **Predicting, Testing, and Neutralizing Nanoparticle Toxicity**

(The University of Texas at Dallas: *Task Number: 425.027*)

### PIs:

- Steven O. Nielsen (PI)<sup>1,2</sup>, Rockford K. Draper (co-PI)<sup>1,2,3</sup>, Paul Pantano<sup>1,2</sup> (co-PI), Inga H. Musselman (co-PI)<sup>1,2</sup>, Gregg R. Dieckmann (co-PI)<sup>1,2</sup>

### Graduate Students:

- Chi-cheng Chiu<sup>1</sup> (Ph.D. defended 2010, 100% funded), Udayana Ranatunga<sup>1</sup> (Ph.D. candidate, 100% funded), David K. Bushdiecker<sup>1</sup> (Ph.D. candidate, not funded), Priya Richards<sup>3</sup> (Ph.D. candidate, not funded)

### Undergraduate Students:

- Sri Magali<sup>1</sup>, Nancy Jacobsen<sup>1</sup>, Prashant Raghavendran<sup>3</sup>, Simon Beck<sup>3</sup>

### High School Students:

- Synyoung Li, Jesuit College Preparatory School of Dallas, Srivenkatesh Perumal, Plano ISD

### Other Researchers:

- Ruhung Wang<sup>1,3</sup> (Postdoc, 100% funded), Carole Mikoryak<sup>3</sup> (not funded)

### Year 2 Cost Share (other than core ERC funding):

- \$25K from UTD Engineering School for RA support
- \$20K from UTD Vice President of Research for supplies

<sup>1</sup>Department of Chemistry

<sup>2</sup>Alan G. MacDiarmid NanoTech Institute

<sup>3</sup>Department of Molecular & Cell Biology

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## Year 2 Deliverables & Objectives

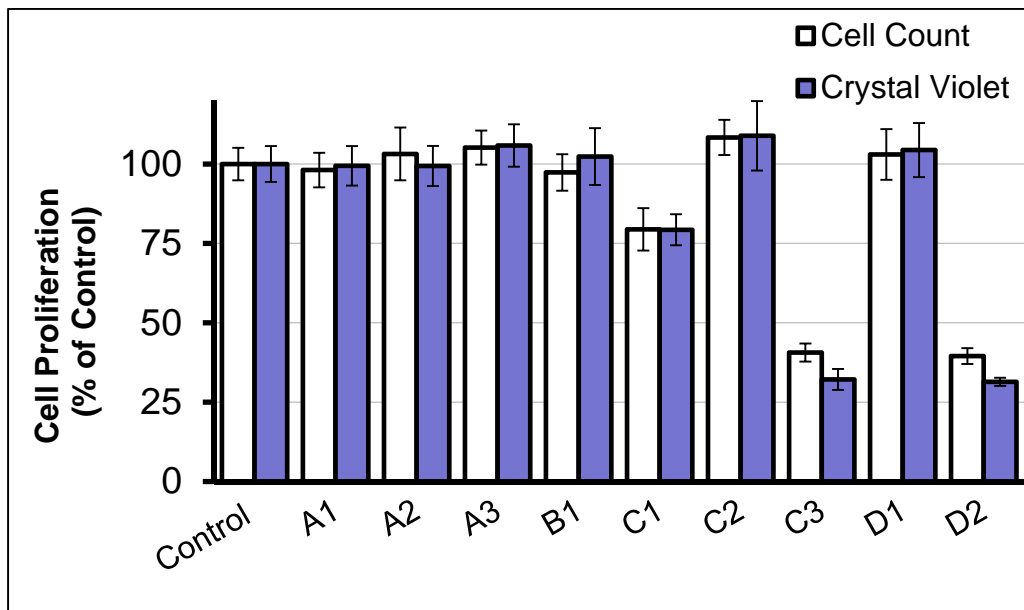
- Obtain and validate data on the physical and chemical characteristics of CNT and CMP nanoparticles with an initial attempt to correlate with structural modeling, interaction with model mammalian cells, toxicity, and bioactivity.

# ESH Metrics and Impact

1. *Reduction in emission of ESH problematic material to environment:*
  - Reduced the toxic material associated with commercial preparations of a variety of single-wall and multiwall CNT types to a level such that the final CNT materials display minimal toxicity to cells in a sensitive model cell culture system.
2. *Identification of inherent material ESH properties and any process by-products:*
  - Assessed inherent ESH properties of single-wall CNTs, multiwall CNTs, graphene oxide, CMP ceria, and separable by-products.
  - Demonstrated that single-wall CNTs and multiwall CNTs themselves have little inherent toxicity in cell culture models, and that observed toxicity is due to by-products that can be separated from the CNTs.
3. *Establish dose metrics:*
  - Dose metrics established using cultured mammalian cells for single-wall CNTs, multiwall CNTs, graphene oxide, and CMP ceria.
4. *Develop analytical tools to measure trace levels of materials in process effluents:*
  - Developed sensitive methods to detect CNTs, functionalized CNTs, graphene oxide, and CMP ceria using their unique Raman signatures.
  - Improved the accuracy of the UV-VIS spectroscopy method to quantify the percentages of semi-conducting and metallic CNTs
5. *Predictive materials modeling and development of nanoparticle-bio interaction studies:*
  - Developed predictive DLVO theory for CNTs and computer models for CNT-bio and C60-bio interactions.

# *In Vitro* Cytotoxicity Comparison of Various Single-walled Carbon Nanotubes (SWNTs)

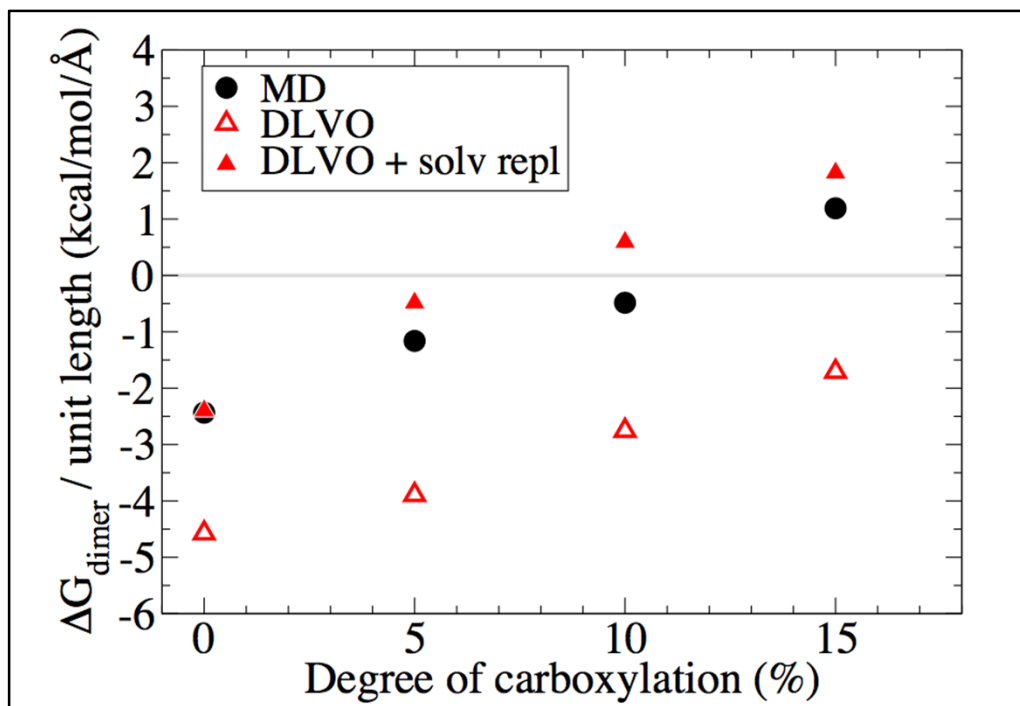
This work started in year one and carried over to year two. The sample size has been increased from **four SWNT** samples obtained from **two commercial vendors** to **nine samples** (coded in the graph below by letters and numbers) from **five different vendors**. Cytotoxicity was assessed by both direct cell counting and a high throughput crystal violet colorimetric assay which quantifies DNA content.



**Significant toxicity was detected only in cells treated with samples C3 and D2. These were the only vendor-carboxylated SWNTs in the test samples. The toxic material could be removed by filtration or centrifugation and co-purified with amorphous carbon contaminants in the SWNT samples.**

**These data suggest that small carbon fragments are the most toxic material in SWNT samples and provide guidance on how to reduce toxicity by removing the small contaminants. This work has been submitted to the SRC (P058949) in anticipation of publication.**

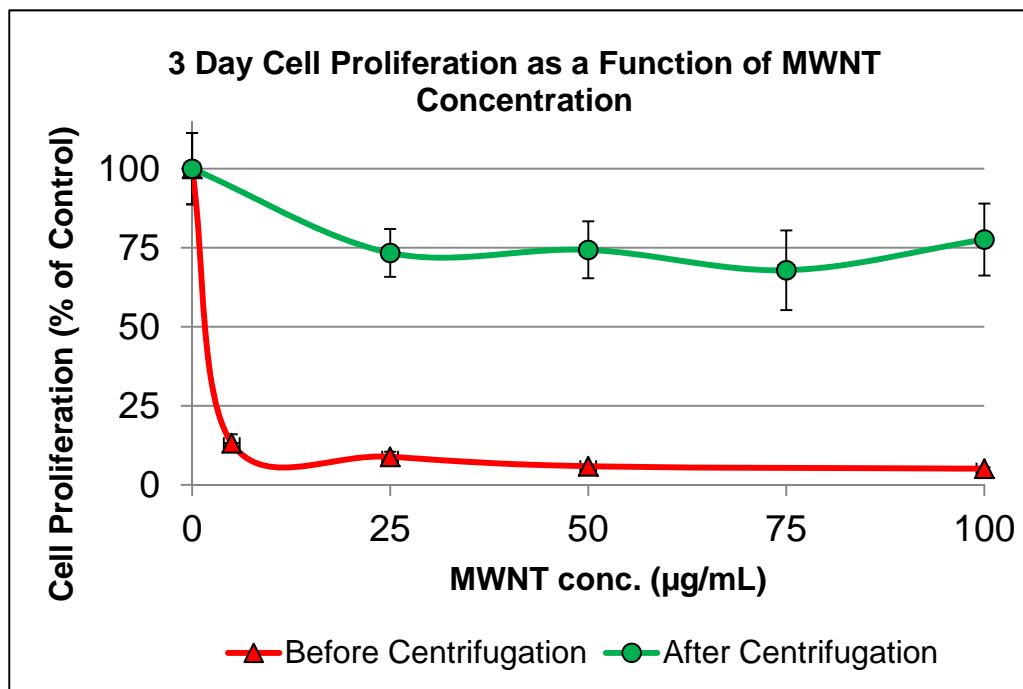
# Predictive Materials Modeling of SWNTs



We developed computer simulation models of both pristine and carboxylated SWNTs which are validated against experimental dispersion data. In addition, we presented the first ever Derjaguin, Landau, Verwey, and Overbeek (DLVO) analysis of the colloidal stability of SWNTs, and we established that the solvent-induced repulsion between fullerenes, which is not considered in classical DLVO theory, is crucial to obtain a correct physical picture of SWNT dispersibility. These results provided physical insight into the colloidal stability of SWNTs, and are being applied to large-scale computer simulation studies of nano-bio systems including SWNT-cell membrane interactions.

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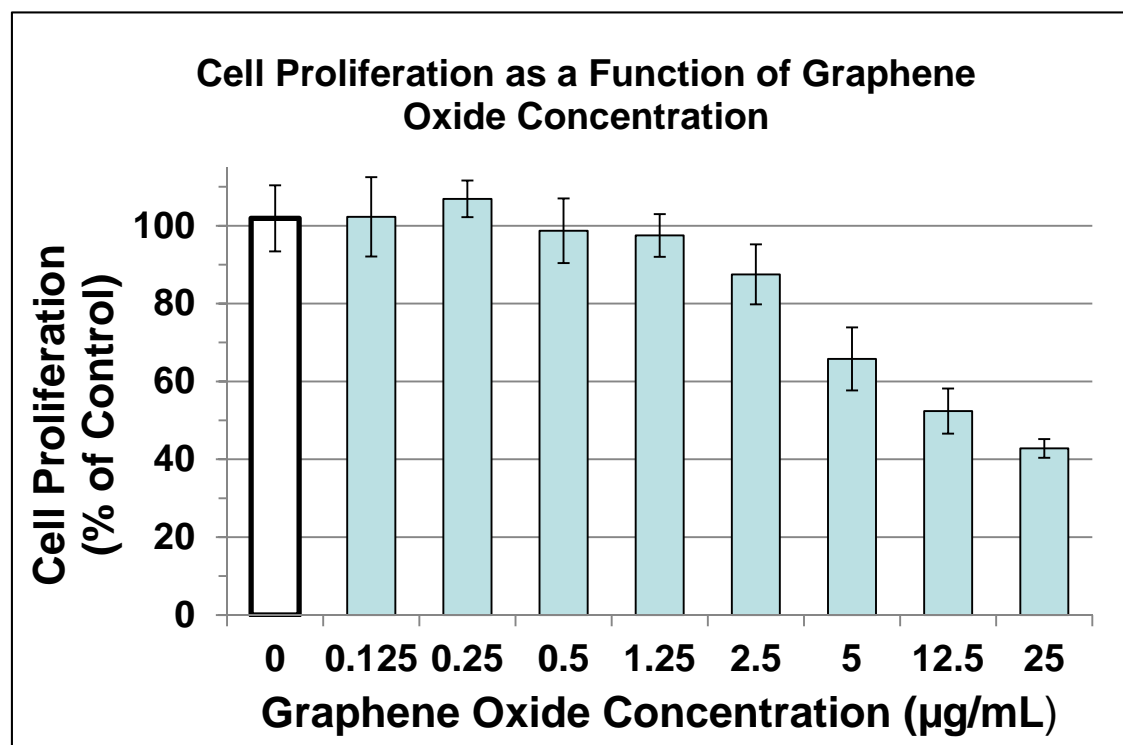
# Characterization and *In Vitro* Toxicity Testing of Multiwalled Carbon Nanotubes (MWNTs)



Carboxylated MWNT samples were dispersed in biocompatible surfactants and tested for toxicity as a function of MWNT dose before and after centrifugation at 20,000 x g for 5 min. Before centrifugation, the MWNT samples were highly toxic. Centrifugation, however, drastically reduced toxicity.

These data suggest that much of the toxic material in MWNT samples can be efficiently removed by centrifugation. This work will be expanded in year three to include a wide variety of MWNT samples from different vendors. The identity of the toxic material will be investigated in year three of the project.

# *In Vitro* Toxicity Testing of Graphene Oxide



The toxicity of graphene oxide samples to mammalian cells in proliferation studies was measured as a function of dose. The  $IC_{50}$  was  $\sim 12$   $\mu\text{g/mL}$ . In addition, it was demonstrated that graphene oxide entered mammalian cells and appeared to localize in lysosomes.

In summary, graphene oxide entered mammalian cells and inhibited cell proliferation. The toxic material in the graphene oxide samples has not yet been identified, but will be studied in year three of the project.

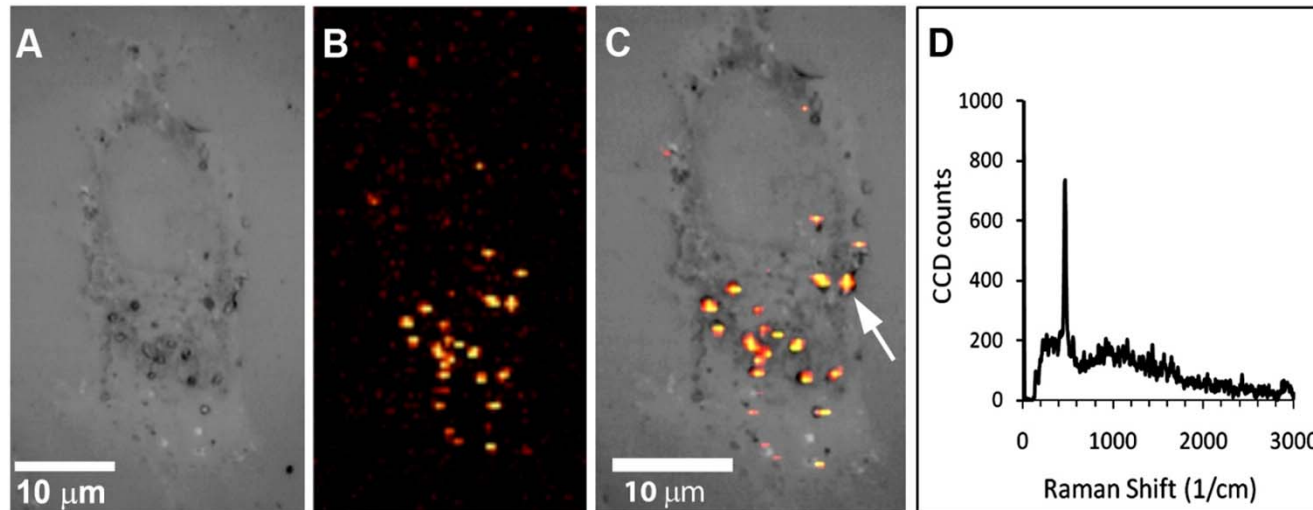
# Characterization and *In Vitro* Toxicity

## Testing of a CMP Particle: The Case of Ceria

This work was undertaken as part of an ERC-member study to compare results on the properties and toxicity of a single ceria sample. Our full report was submitted on Dec. 9, 2010 to the ERC nanotox researchers and key industrial contacts. The main conclusions of our study were:

1. The particle size and zeta potential of ceria was studied by dynamic light scattering and both depended on the pH, salt concentration, and the presence of proteins. The particle diameter in H<sub>2</sub>O was ~97 nm at pH 5 and was ~2500 nm at pH 7. The particle size in PBS (pH 7.2) was ~1173 nm and was reduced to ~290 nm in the presence of 10% fetal bovine serum (protein). The zeta potential in H<sub>2</sub>O at pH 5 was ~+55 mV and at pH 7 was ~+50 mV. In PBS at pH 7.2, the zeta potential was ~-30 mV irrespective of the presence of serum.
2. Ceria at concentrations <1 mg/mL showed no significant toxic effect on a model mammalian cell line (normal rat kidney NRK cells) after continuous exposure for up to 4 days.
3. Ceria was directly detected within NRK cells by confocal scanning Raman microscopy using the distinct ceria Raman band at 465 cm<sup>-1</sup>. Images showing the intracellular locations are on the next slide.

# Uptake of Ceria CMP Particles into Subcellular Vesicles in Mammalian Cells



(A) Optical image of a typical NRK cell that was incubated with 1 mg/mL ceria for 2 days and then fixed on a glass cover slip. (B) Raman scan of the cell where the false-color represents the ceria Raman signal intensity. (C) Overlay of panels A and B to show co-localization of the ceria Raman signals with vesicles. (D) Background-corrected Raman spectrum taken from one pixel in the hot spot indicated by the white arrow in C to verify the presence of the intense ceria peak at 465 cm<sup>-1</sup>.

**The main conclusion from these studies is that, even though ceria enters mammalian cells, it shows little toxicity *in vitro*.**



# Industrial Interactions and Technology Transfer

- Leveraged core ERC funding to obtain Small Business Technology Transfer (STTR) grant from the NIH (Dan Herr, SRC wrote a key supporting letter).
  - CNT toxicity.
- Initiated MWNT studies due to industrial interest by Intel, TI, and others.
  - ESH of MWNTs.
- Submitted “round robin” report to ERC nanotox researchers and industrial affiliates.
  - ESH of ceria CMP.

# Future Plans

## Year Three Plans

- Obtain data on physical and chemical characteristics of CNT and CMP nanoparticles, correlating structural modeling to interactions with model mammalian cells, toxicity, and bioactivity. (Deliverables Final Report, 2012).
- Using our in-house, nitric acid-functionalized CNTs, we will perform a detailed assessment of CNT toxicity vs. percent carboxylation and will correlate this to DLVO theory and MD computer simulation studies.
- Investigate the toxic contaminant in acid-purified SWNTs, MWNTs, and graphene oxide samples.

## Long-Term Plans

- Catalog what contaminants are being seen among various manufacturers of SWNTs, MWNTs, and other nanoparticles of interest to the SRC community.
- ESH of packaging. (Mario Bolanos-Avila, TI: Strategic Packaging Research Manager).

# Publications

- **SRC Publication P056398** C. Chiu, G.R. Dieckmann, P. Pantano , I. Musselman, R. Draper, S. Nielsen, “Computer Simulations of the Interaction between Carbon-Based Nanoparticles and Biological Membranes”, 11-Jun-2010.
- **SRC Publication P055218** C. Chiu, R. DeVane, M. Klein, W. Shinoda, P. Moore, S. Nielsen, “Coarse Grained Potential Models for Phenyl Based Molecules: II. Application to Fullerenes”, J. Phys. Chem. B 114, 6394-6400 (2010).
- **SRC Publication P058919** P. Pantano, N. Jacobsen, “Determining the Percentages of Semi-conducting and Metallic Single-walled Carbon Nanotubes in Bulk Soot”, Carbon (in press).
- **SRC Publication P058918** R. DeVane, M. Klein, W. Shinoda, P. Moore, S. Nielsen, C. Chiu, “Effect of Carboxylation on Carbon Nanotube Aqueous Dispersibility – A Predictive Coarse Grained Molecular Dynamics Approach”, 24-Jan-2011.
- **SRC Publication P056717** C. Chiu, “Molecular Dynamics Simulations of Nanoscale Interfaces: From Simple Liquids to Biological Systems”, Ph.D. Thesis (UT Dallas, 2010)
- **SRC Publication P057837** S. Nielsen, C. Chiu, R. DeVane, A. Jusufi, P. Moore, M. Klein, W. Shinoda, “Parametrization and Application of a Coarse Grained Forcefield for Benzene/Fullerene Interactions with Lipids”, J. Phys. Chem. B 114, 16364-16372 (2010).
- **SRC Publication P058949** R. Wang, C. Mikoryak, S. Li, R. Draper, D. Bushdiecker, I. Musselman, P. Pantano, “Cytotoxicity Screening of Single-Walled Carbon Nanotubes: Detection and Removal of Cytotoxic Contaminants from Carboxylated Carbon Nanotubes”, 31-Jan-2011.

## **Presentations**

- C. Chiu, “Computer Simulations of the Interaction between Carbon-Based Nanoparticles and Biological Membranes”, SRC TECHCON 2010, September 14, 2010.
- R. Wang, “Physical Characterization and In Vitro Toxicity Testing of Commercially Purchased Single-walled Carbon Nanotubes”, ERC Teleseminar, April 22, 2010.
- P. Pantano, “Confocal Raman Imaging of Carbon Nanomaterials Taken-up by Living Cells”, 66th SouthWest Regional ACS Meeting, Dec 2010.

## **Awards**

- *2010 Simon Karecki Award*: graduate student Chi-cheng Chiu.

# **Development of Quantitative Structure-Activity Relationship for Prediction of Biological Effects of Nanoparticles Associated with Semiconductor Industries** *(Task Number: 425.025)*

**PIs:** Yongsheng Chen, Environmental Engineering, Georgia Institute of Technology (GIT)

**Graduate Students:**

- Wen Zhang and Kungang Li: PhD student, Environmental Engineering, GIT
- Yang Li: Ph.D exchange student, Environmental Engineering, GIT
- Nicole Sullivan: Master student, Environmental Engineering, GIT
- Steven Klein: PhD student, Mechanical engineering, ASU

**Other Researchers:**

- Jonathan Posner, Mechanical Engineering, ASU
- Trevor J. Thornton, Electric Engineering, ASU
- Ying Huang and Ying Chen Visiting Scholar, GIT

**Cost Share (other than core ERC funding):**

- \$25 k start-up fund from ASU
- \$48.6 k Chinese Education and Scholar Exchange Fellowships
- \$200k funds from GIT for AFM and other lab instrument purchase

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# **Objectives**

**Develop a quantitative structure-activity relationships (QSARs) model for prediction of the biological effects of engineered nanoparticles (NPs) associated with semiconductor industries. To pursue this goal, our approach mainly includes:**

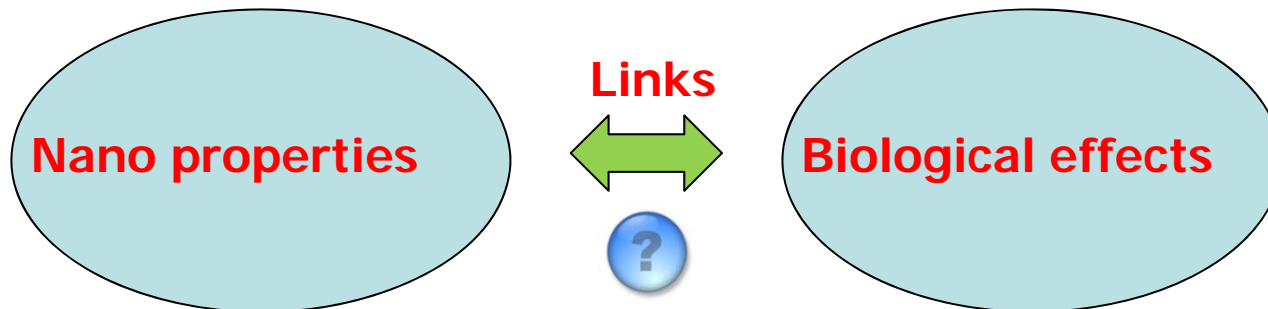
- Establish a comprehensive understanding of relevant physiochemical properties of semiconductor nanomaterials that govern their fate, transport and biological interactions.**
- Collect sufficient experimental and theoretical data to describe the environmental behaviors of semiconductor nanomaterials and their associated biological consequences.**

# **ESH Metrics and Impact**

- 1. Our work aims at development of fundamental understanding of cytotoxicity of semiconductor NPs to human health and provides a comprehensive database and clear definition of ESH-problematic manufactured nanomaterials.*
- 2. Based on the quantitative structure-activity relationship (QSAR) model we plan to establish, problematic nanomaterials from industrial manufacturers could be predicted, identified, and effectively modified to produce more environmental benign semiconductor nanomaterials.*

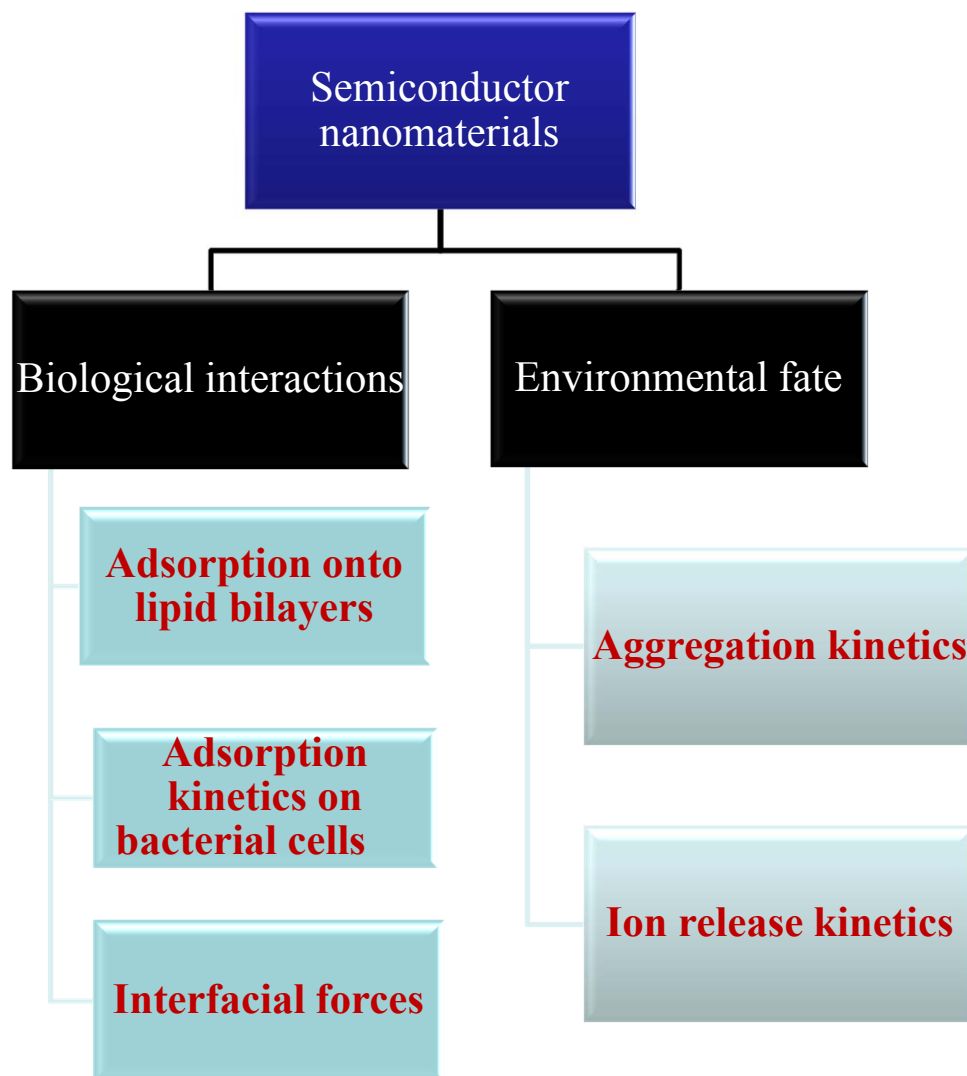
# Motivation

- **Insufficient knowledge** of the environmental fate, transport, transformation, and biological interactions;
- **Lack of effective and valid characterization tools** for characterizing bio-nano interactions;
- **New criteria** that are used to categorize and prioritize nanomaterials and their relevant properties.





# Summary of our work

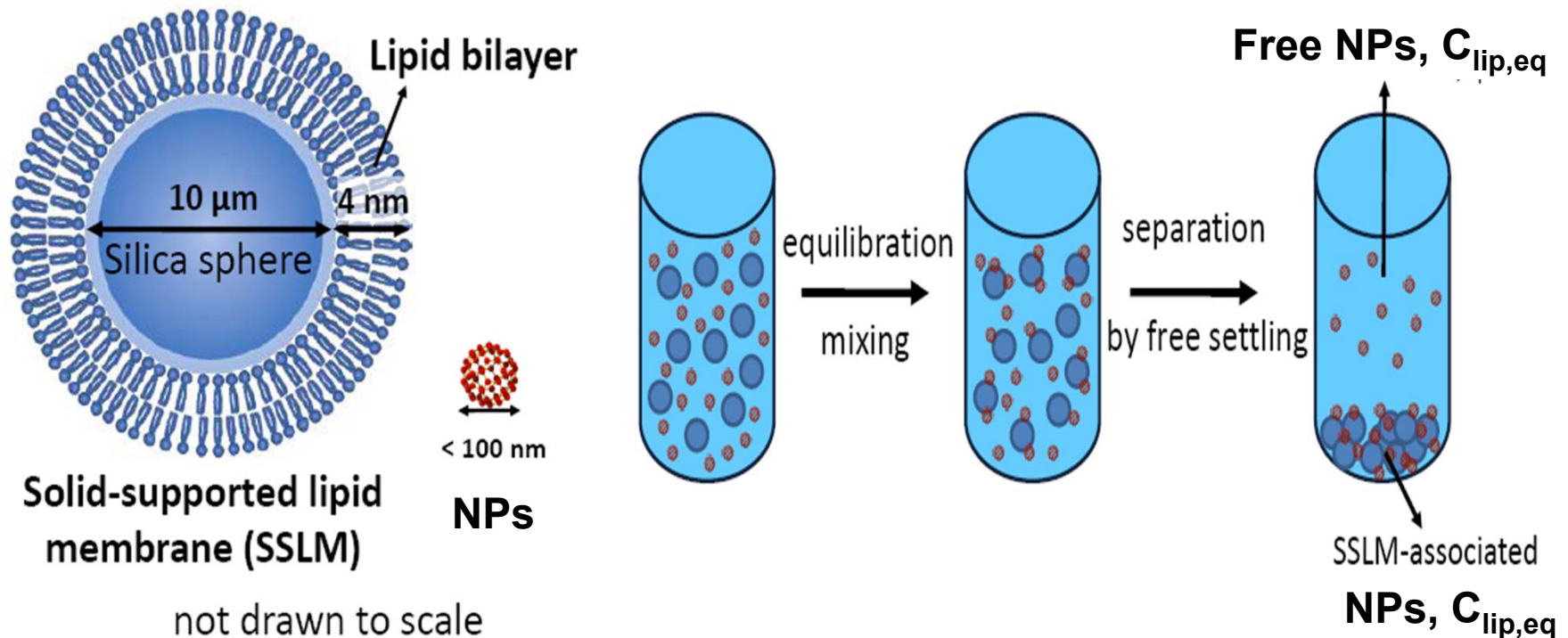


Hematite ( $\alpha\text{-Fe}_2\text{O}_3$ )
$\text{CeO}_2$
$\text{TiO}_2$
$\text{ZnO}$
$\text{Al}_2\text{O}_3$
$\text{CuO}$
$\text{SiO}_2$
QDs
Au
Ag

## **Technical data that are presented in detail in this report**

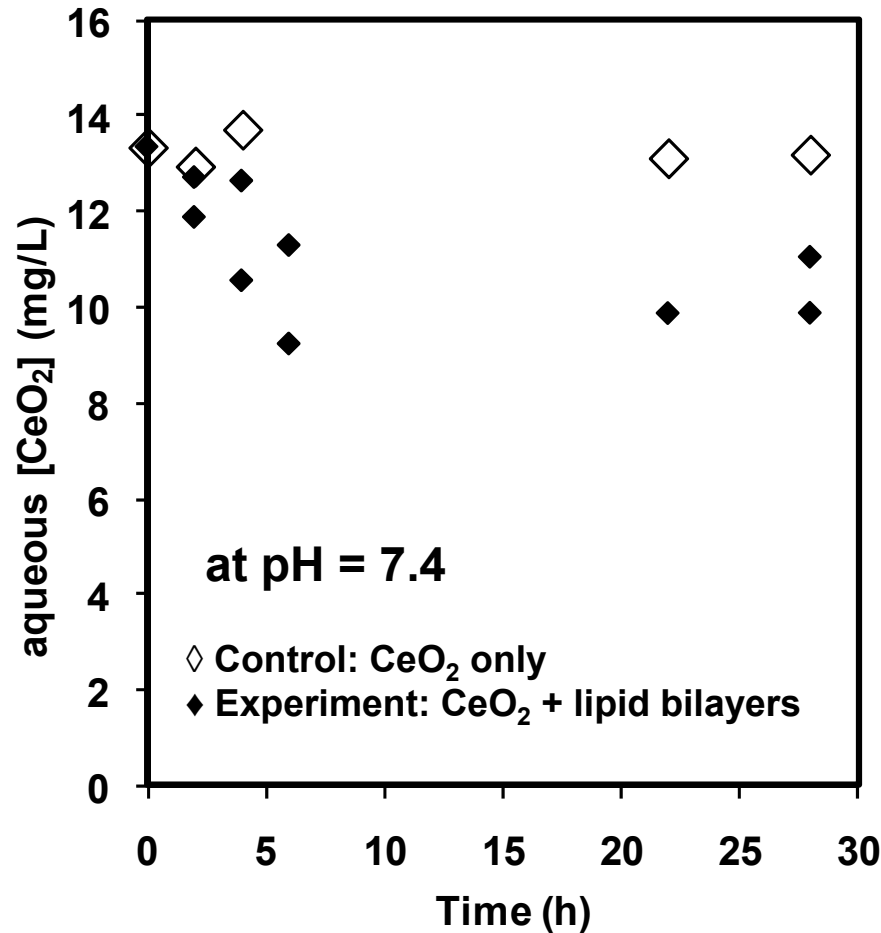
- 1. Quantifying adsorption kinetics of NPs to lipid bilayers supported on 10 micron silica spheres;**
- 2. Aggregation kinetics of metal oxide or metal NPs in aqueous solution;**
- 3. Ion release kinetics of AgNPs: size and concentration effects.**

# Adsorption kinetics of NPs to lipid



Schematic of adsorption of NPs to lipid bilayers supported on 10 micron silica spheres. These commercially available solid-supported lipid membranes (SSLM) greatly improve the speed and accuracy of measurements and enable the quantification of lipid surface area. Varied concentrations of SSLM and ENMs are placed in glass vials and mixed on a rotary mixer in an end-over-end action. At equilibrium, vials will be sit quiescently, allowing the SSLM beads to settle to the bottom and the supernatants containing free ENMs will be drawn for analysis of concentrations.

# CeO<sub>2</sub> adsorption kinetics onto lipid bilayers



Calculation of lipid bilayer-water distribution coefficients ( $K_{lipw}$ )

$$K_{lipw} = \frac{C_{lip,eq}}{C_{w,eq}} (L / kg) \text{ where}$$

$$C_{lip,eq} = \frac{(C_{w,ref} - C_{w,eq})(mg / L)}{m_{lip} (kg / L)}$$

$C_{w,ref}$  = [ENMs] in the control samples

$C_{w,eq}$  = free [ENMs] in supernatants at equilibrium

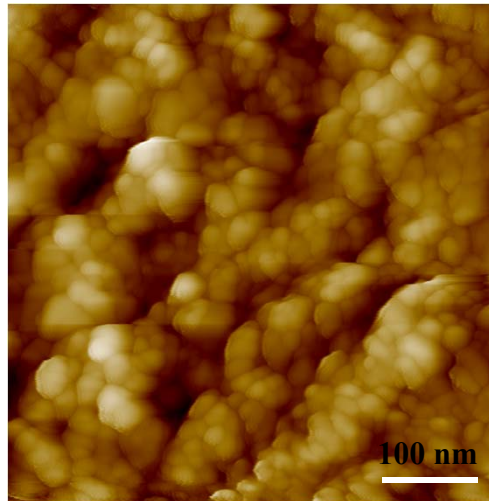
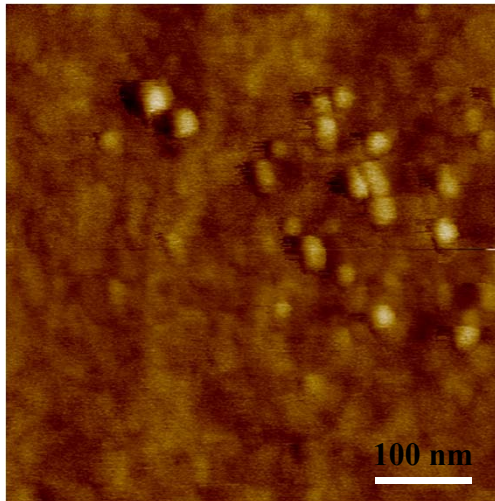
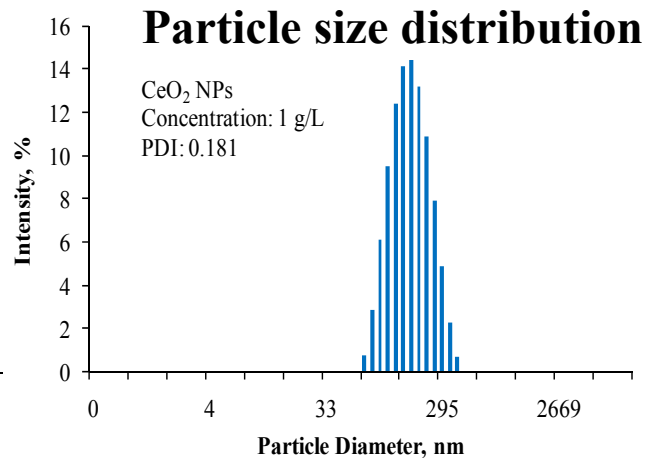
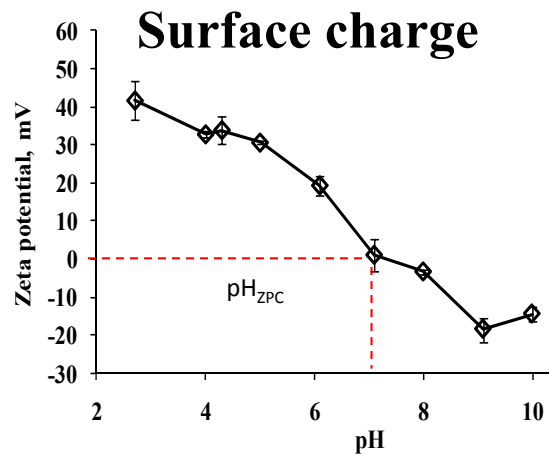
$m_{lip}$  = lipid concentration

Validated using a reference compound (2,4,6-trichlorophenol).

$\log K_{lipw} = 3.89 \pm 0.03$  (L/kg), close to 3.90 reported by Escher et al. (ES&T, 1996)

$$K_{lipw} = \frac{\text{aqueous [CeO}_2\text{] at equilibrium (mg/L)}}{\text{lipid phase [CeO}_2\text{] at equilibrium (mg/kg lipid)}} = 600$$

# CeO<sub>2</sub> NP aggregation kinetics in aqueous solution



➤ CeO<sub>2</sub> nanoparticles (and most other metal oxide, e.g., Fe<sub>2</sub>O<sub>3</sub>, CuO) carry positive charge in neutral pH;

➤ Hydrodynamic radius is much larger than their actual radius as in their solid state;

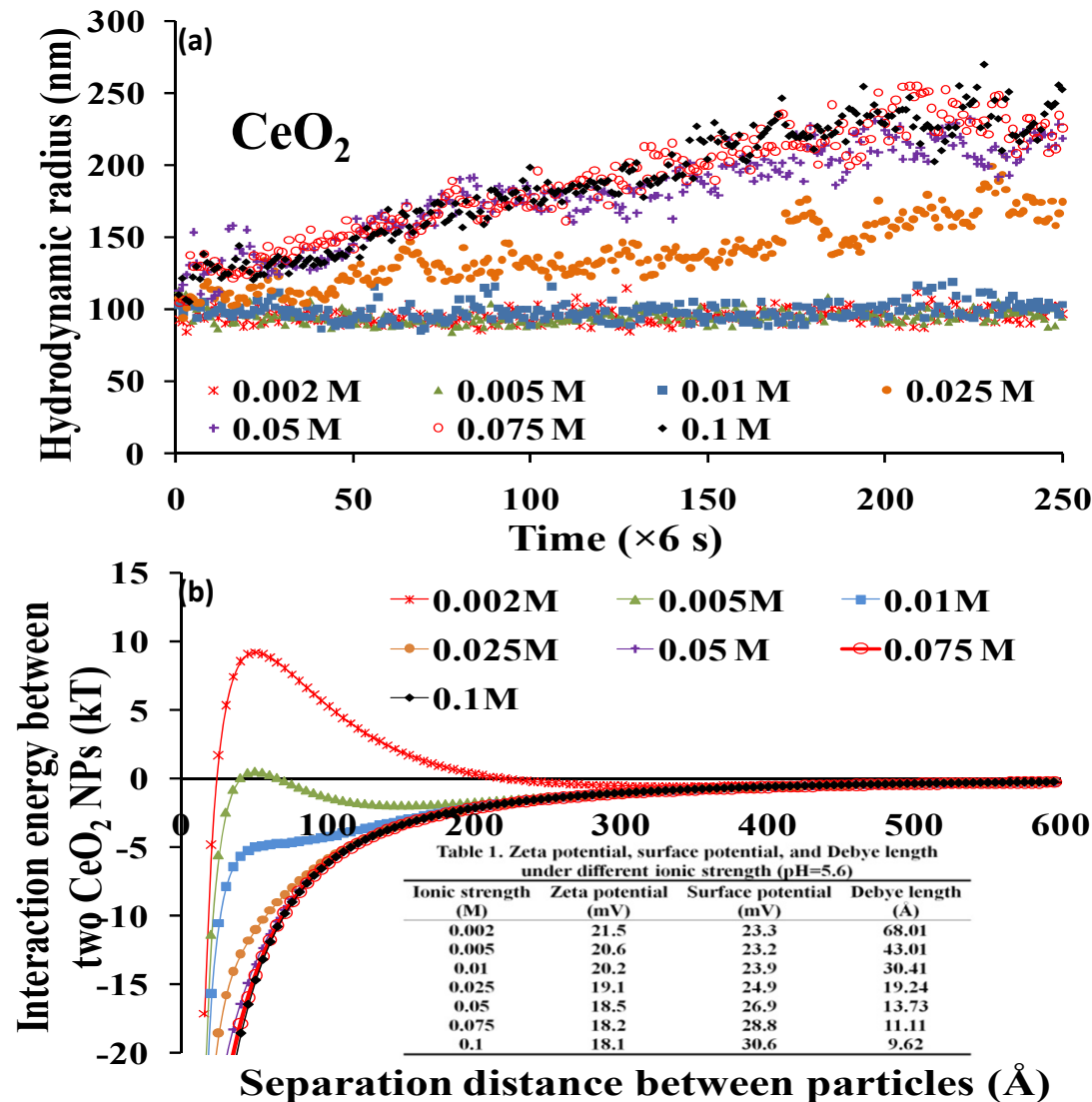
➤ Aggregation takes place and gets faster with increasing ionic strength.

Individual scattered nanoparticles    Aggregated nanoparticles

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

Kungang Li, Wen Zhang, Ying Huang, and Yongsheng Chen, Modeling the aggregation kinetics of CeO<sub>2</sub> nanoparticles in monovalent and divalent electrolytes with EDLVO theory, *Colloids and Surfaces A*, Under review.

# CeO<sub>2</sub> NP aggregation kinetics in aqueous solution-continued



**Key findings:**

➤ Aggregation kinetics show the dependencies of particle size and ionic strength;

➤ DLVO theory interprets the effects of particle size and ionic strength on interaction energy successfully;

➤ Aggregation kinetics is hard to quantitatively describe with DLVO theory alone.

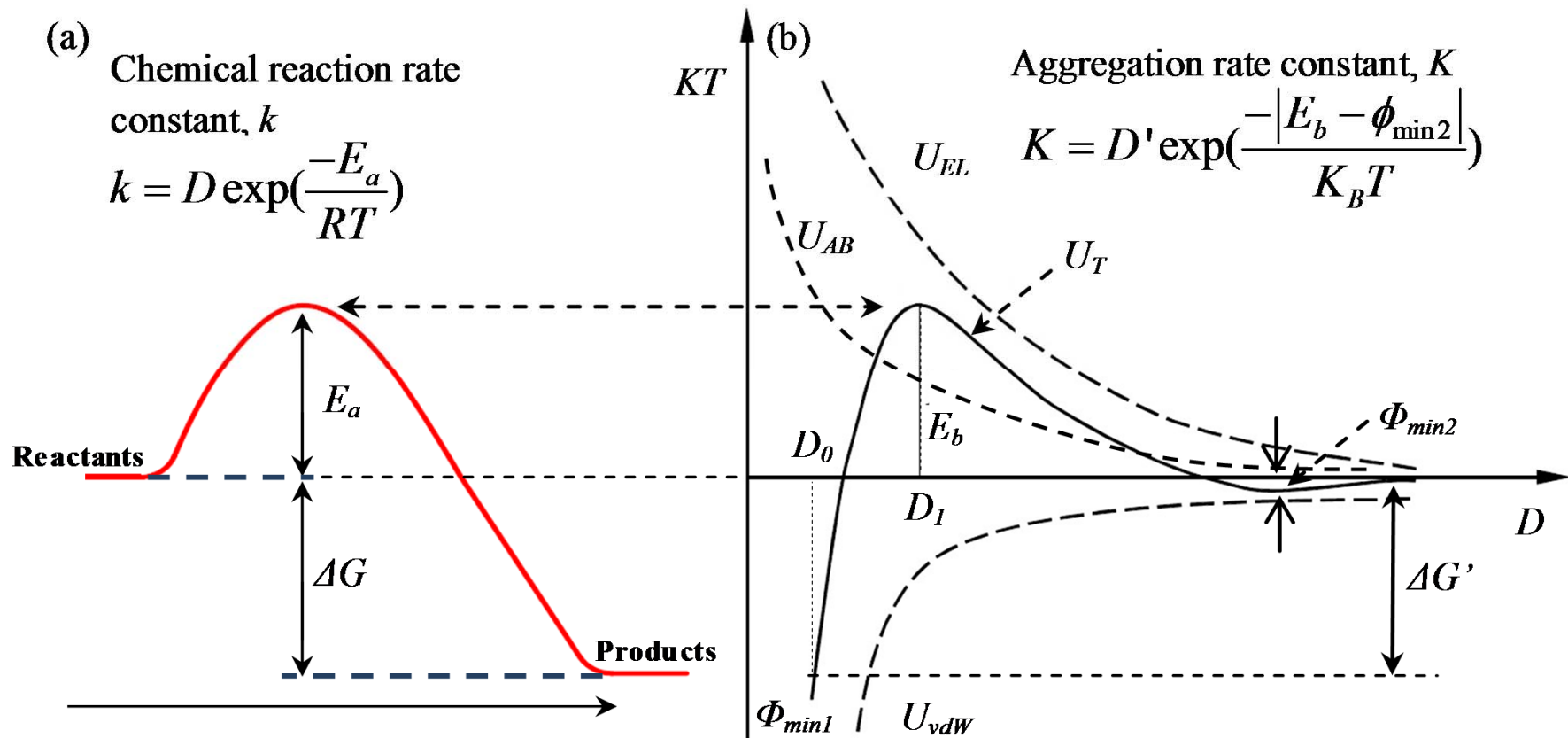
*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

Kungang Li, Wen Zhang, Ying Huang, and Yongsheng Chen, Modeling the aggregation kinetics of CeO<sub>2</sub> nanoparticles in monovalent and divalent electrolytes with EDLVO theory, *Colloids and Surfaces A*, Under review.



# CeO<sub>2</sub> NP Aggregation kinetics in aqueous solution-continued

Aggregation may be a pseudo-2<sup>nd</sup> reaction kinetics and the rate constant has an Arrhenius form at low particle concentration.

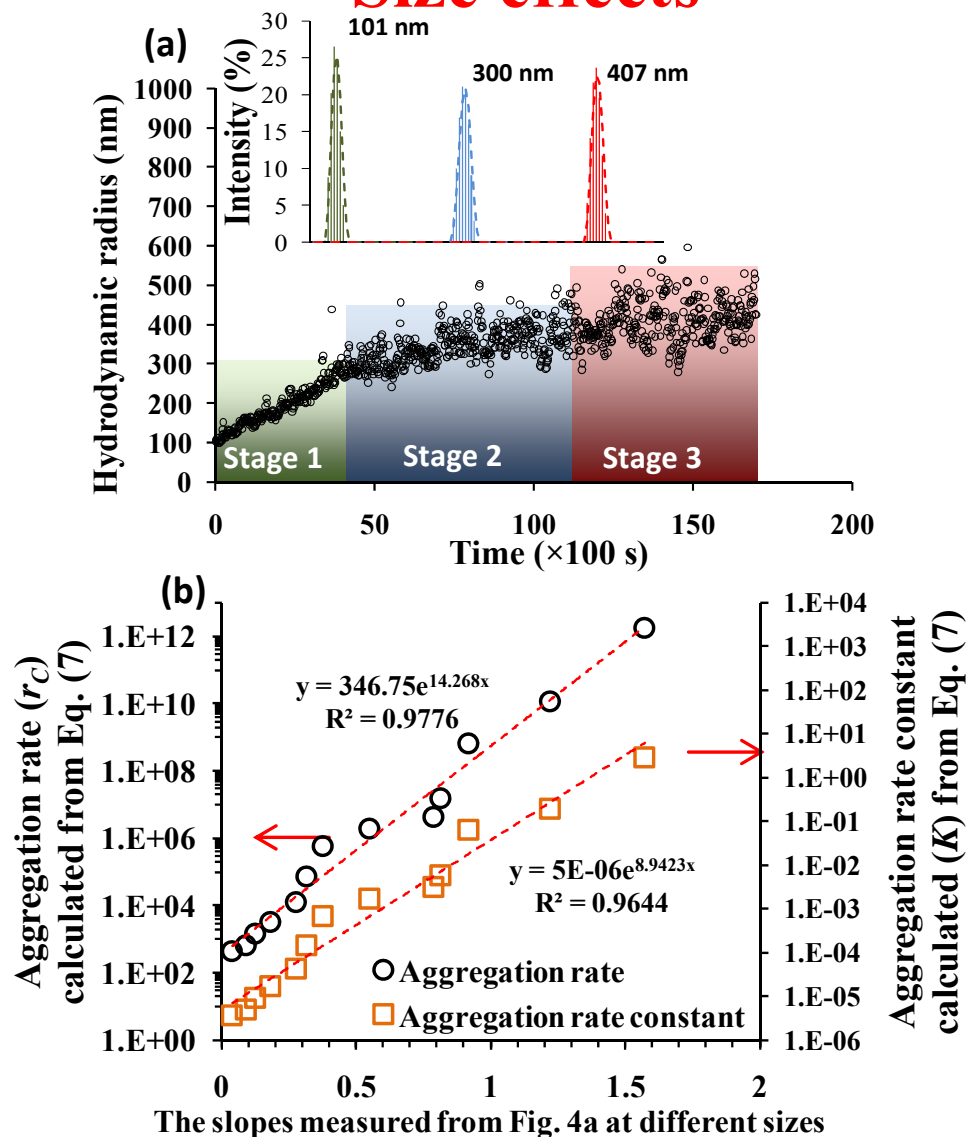


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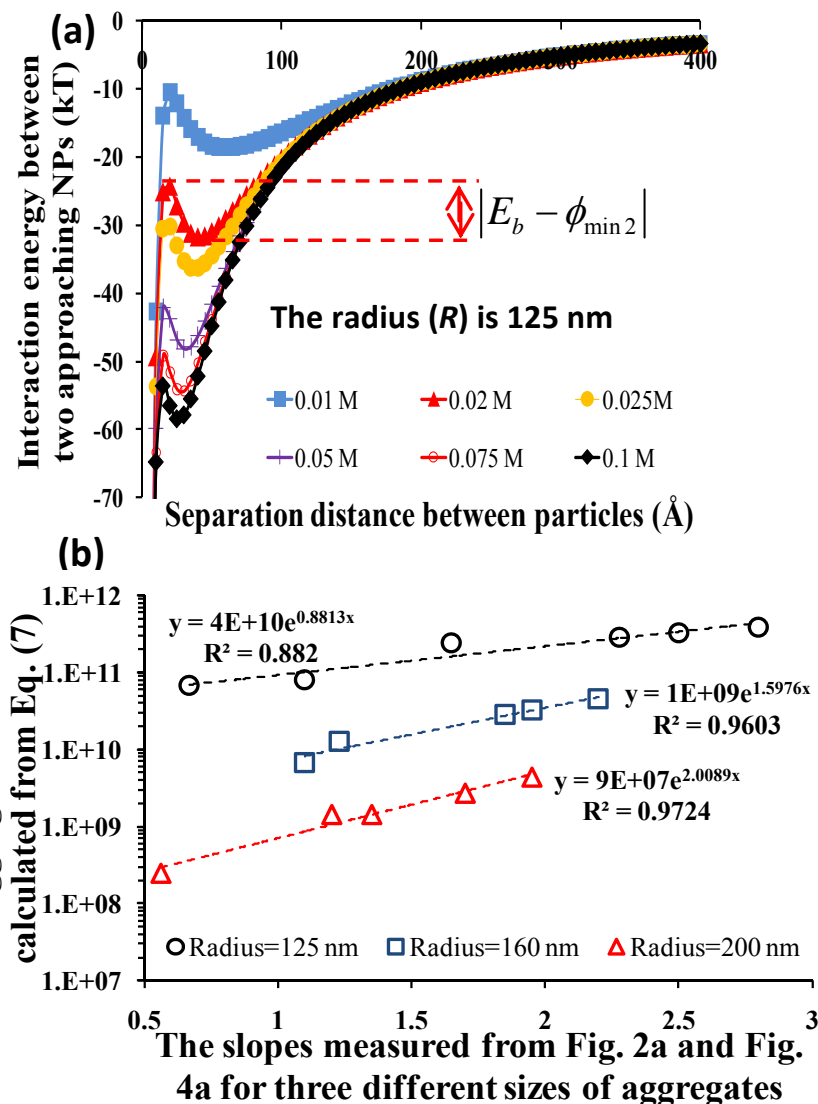
Kungang Li, Wen Zhang, Ying Huang, and Yongsheng Chen, Modeling the aggregation kinetics of CeO<sub>2</sub> nanoparticles in monovalent and divalent electrolytes with EDLVO theory, *Colloids and Surfaces A*, Under review.

# CeO<sub>2</sub> NP Aggregation kinetics in aqueous solution-continued

## Size effects



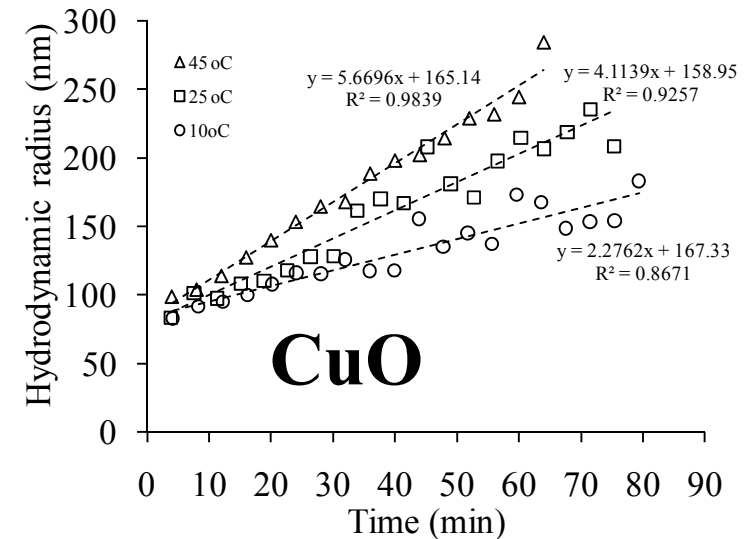
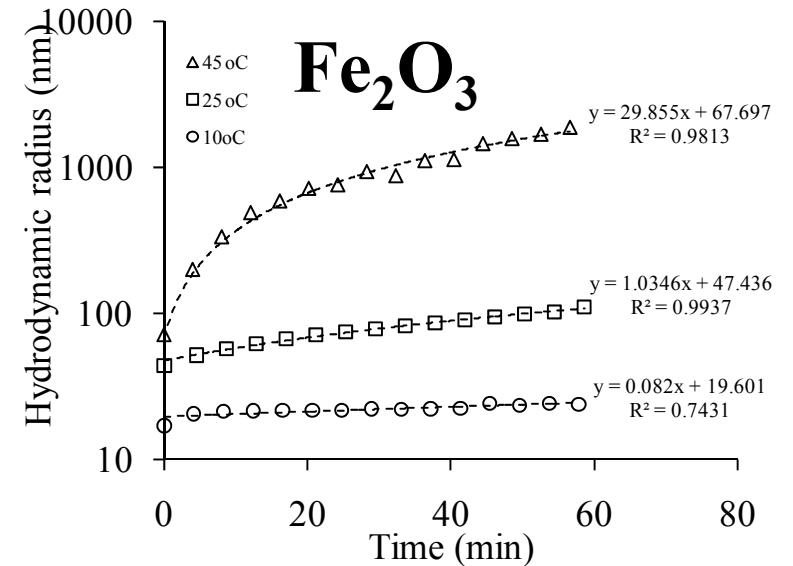
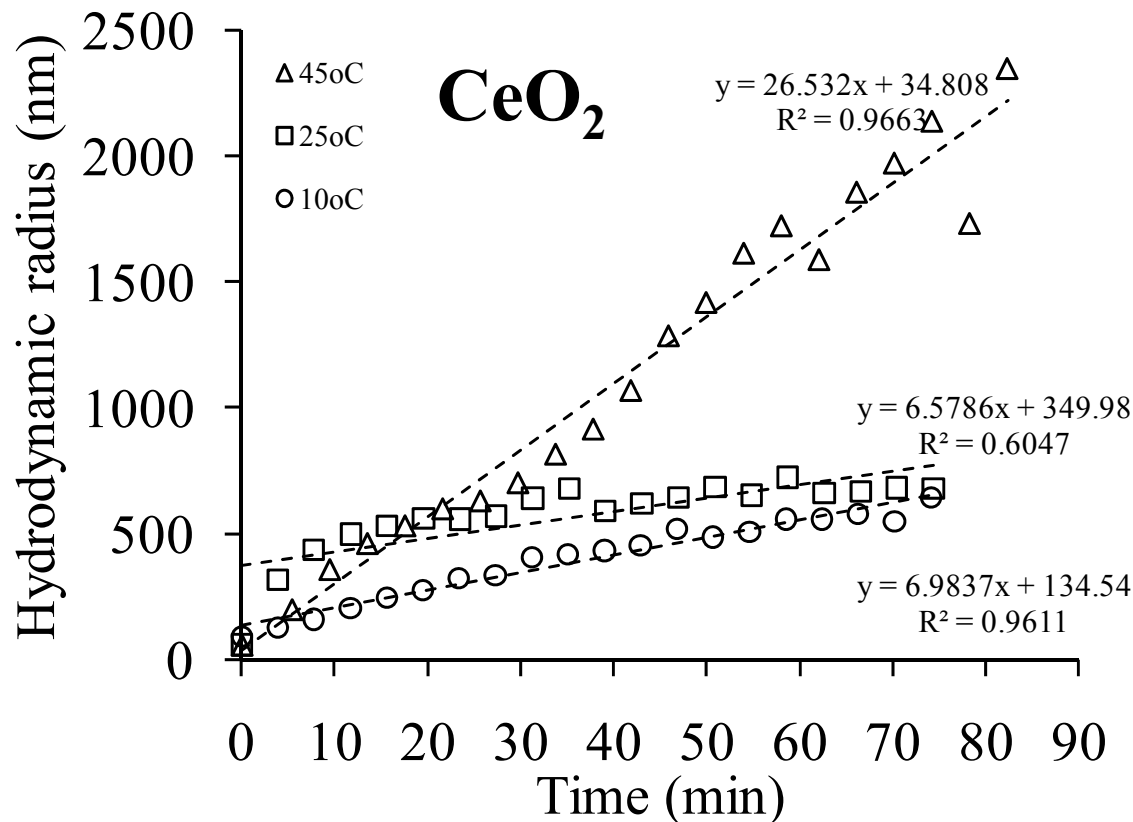
## Ionic strength effects





# CeO<sub>2</sub> NP aggregation kinetics in aqueous solution-continued

## Temperature effect

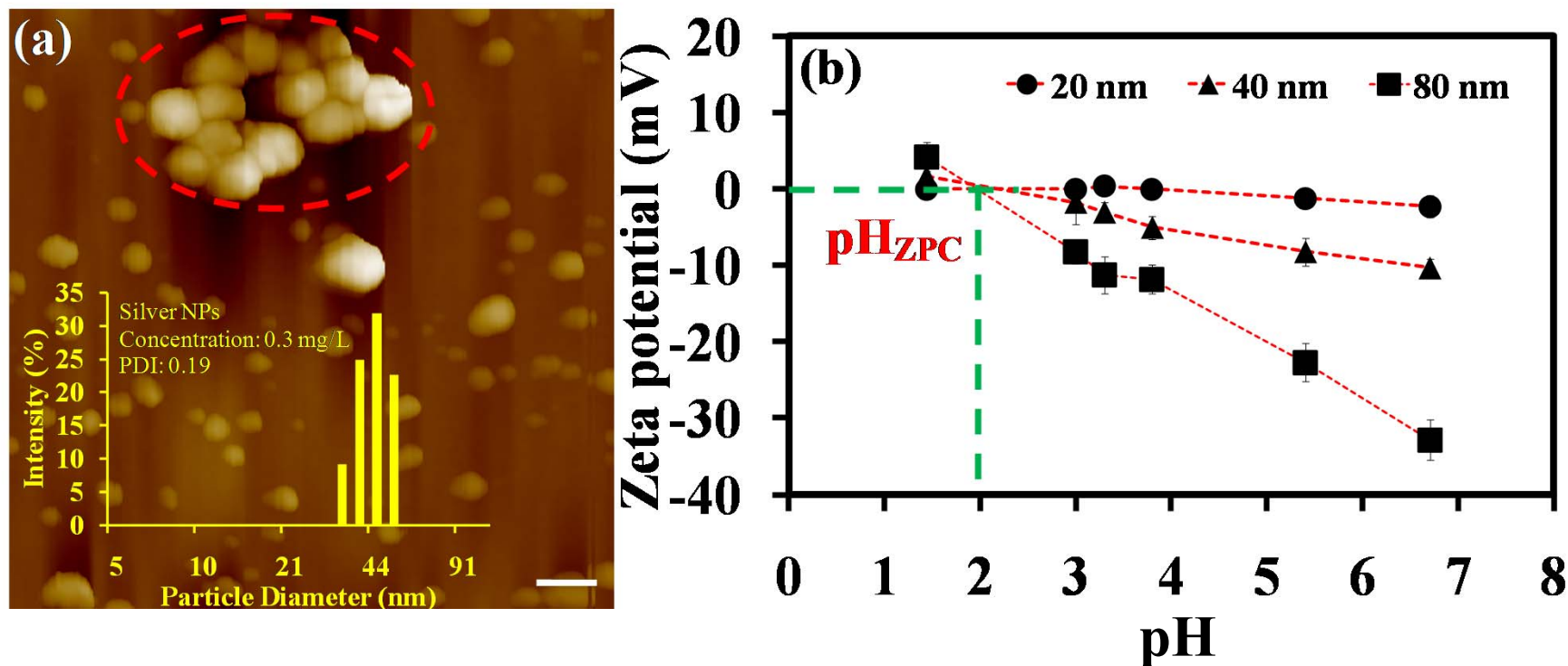


SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

Kungang Li, Wen Zhang, Ying Huang, and Yongsheng Chen, Modeling the aggregation kinetics of CeO<sub>2</sub> nanoparticles in monovalent and divalent electrolytes with EDLVO theory, *Colloids and Surfaces A*, Under review.

# AgNPs aggregation kinetics in open and closed systems

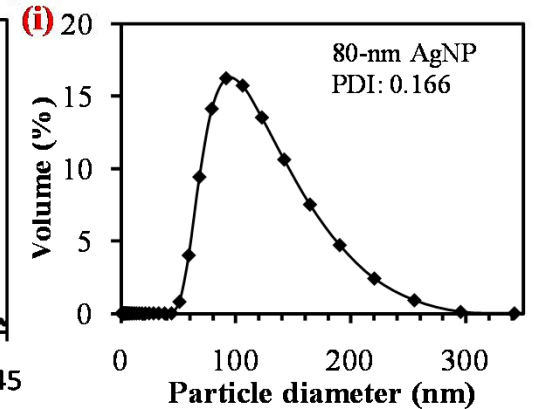
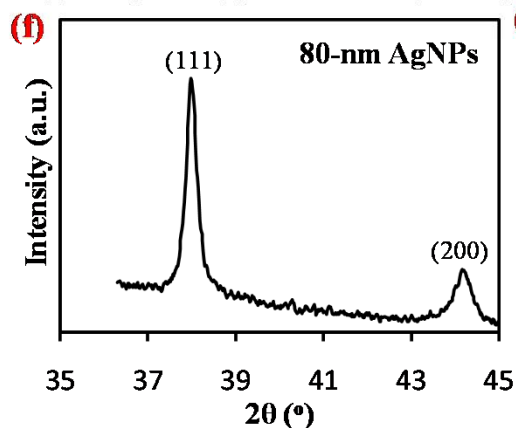
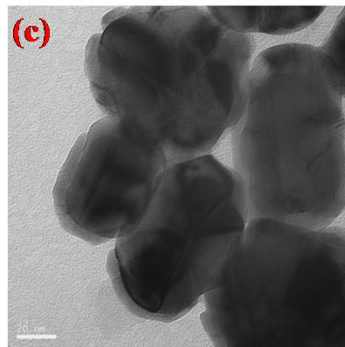
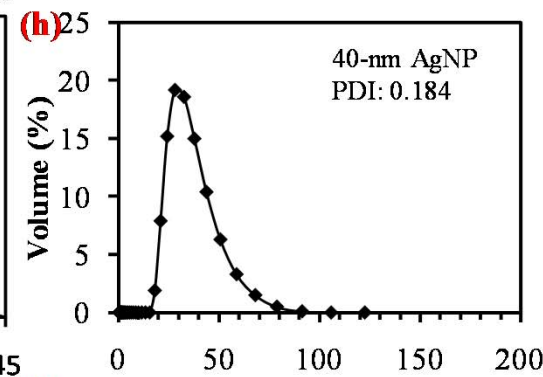
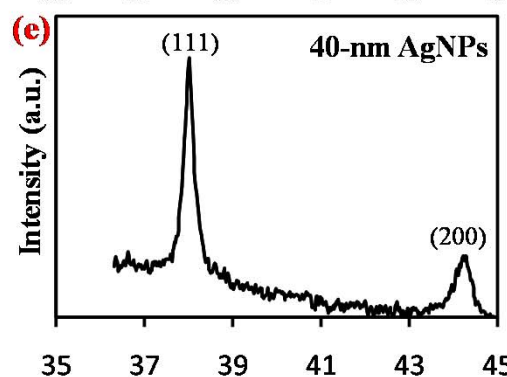
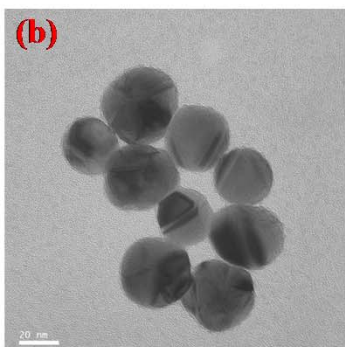
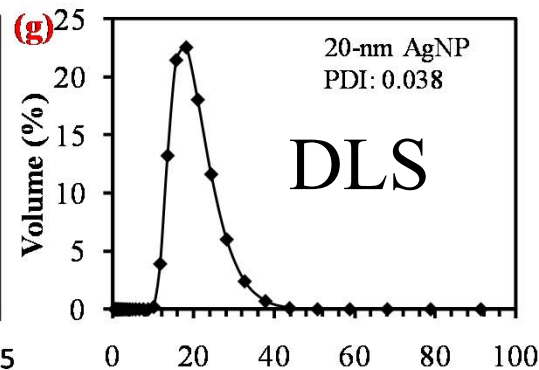
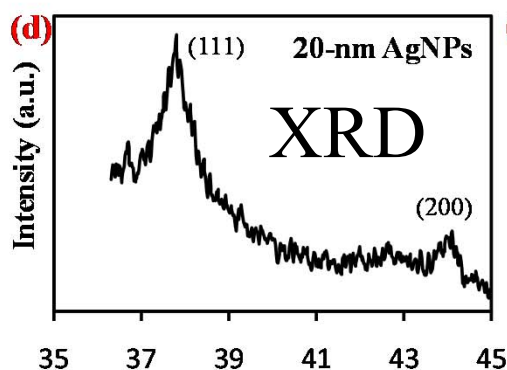
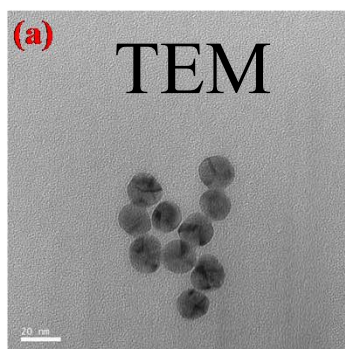
Morphology, size, size distribution, and zeta potentials of different sizes of AgNPs.



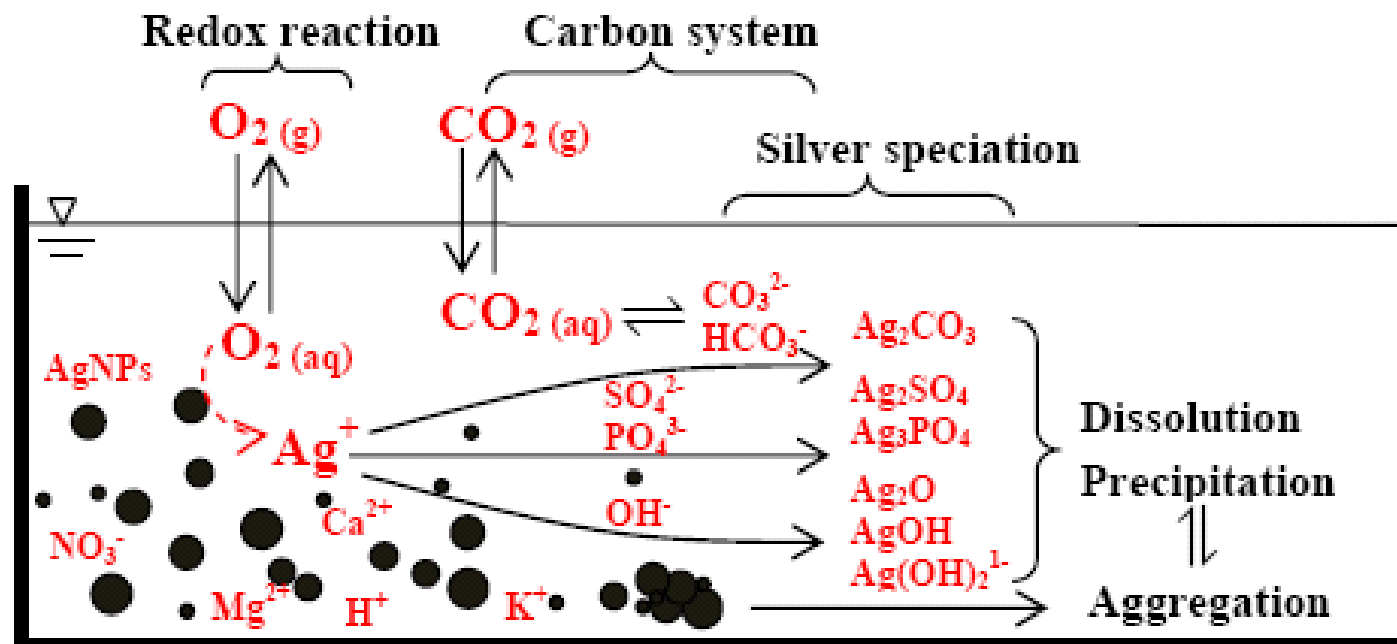
*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

Wen Zhang, Ying Yao, Kungang Li, Ying Huang, Yongsheng Chen. Aggregation kinetics of silver nanoparticles in open and close systems. *Environmental Science and Technology*. Under review.

# AgNPs aggregation kinetics in open and closed systems-continued

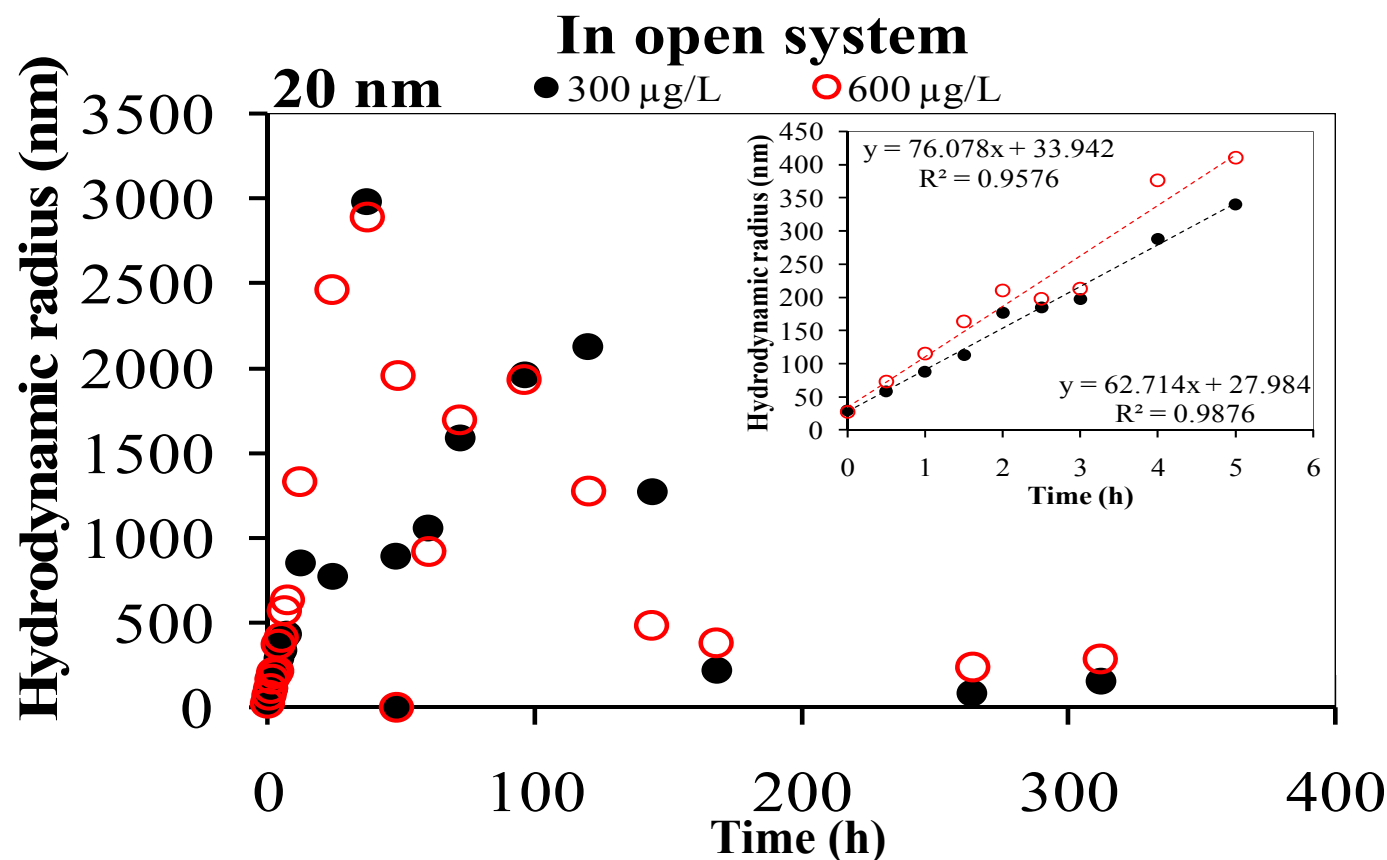


# AgNPs aggregation kinetics in open and closed systems-continued



Open and closed systems make a difference in silver nanoparticle aggregation due to the different physiochemical processes that occur concurrently.

# AgNPs aggregation kinetics in open and closed systems- *open system*

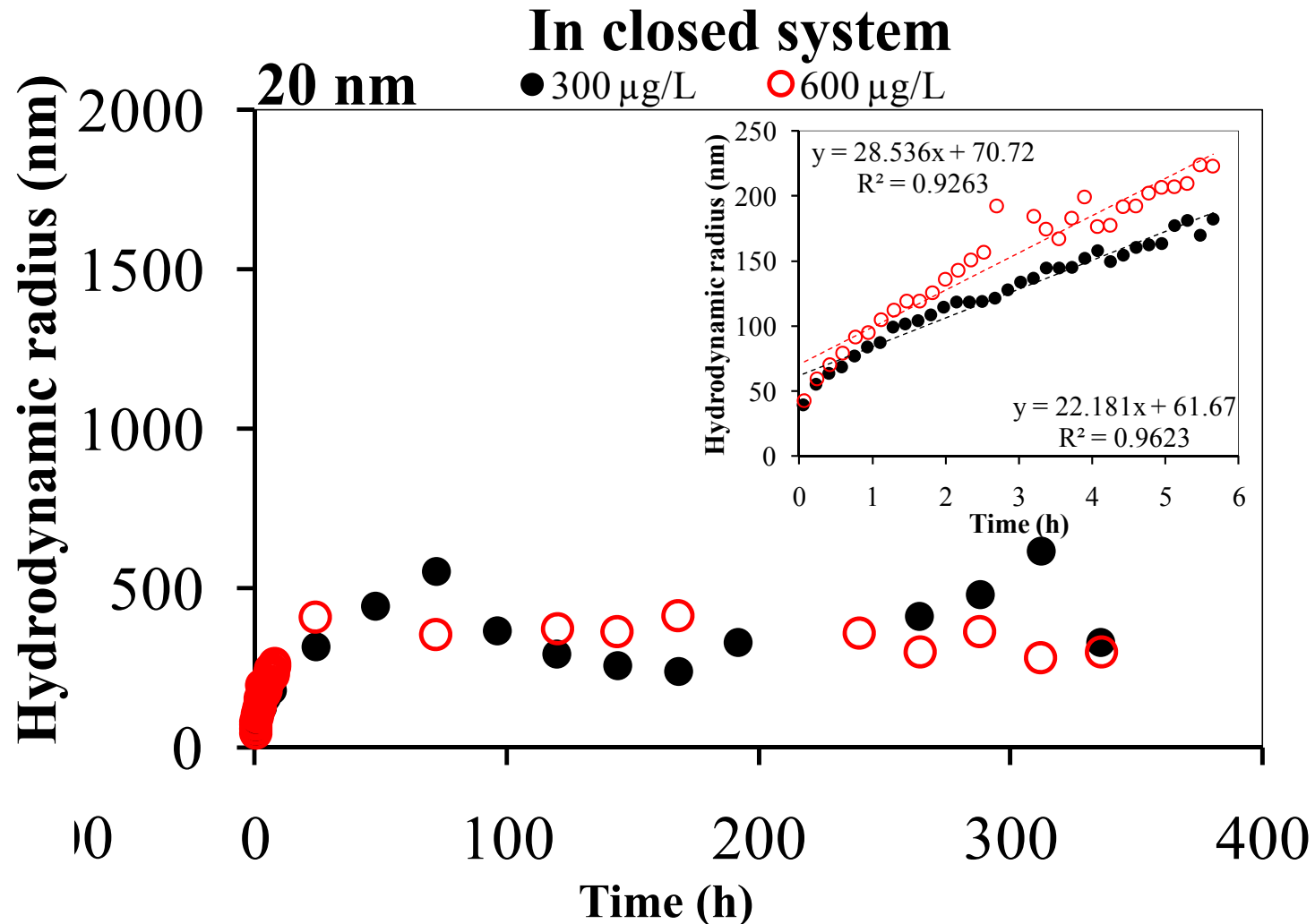


- Aggregation rates of AgNPs in open systems were approximately 3-8 times higher than those in closed systems depending on the original sizes (20, 40, and 80 nm);
- After the linear growth, the changes in the hydrodynamic radii became random in open systems, whereas in closed systems the growth of hydrodynamic radii was relatively smooth.

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

Wen Zhang, Ying Yao, Kungang Li, Ying Huang, Yongsheng Chen. Aggregation kinetics of silver nanoparticles in open and close systems. *Environmental Science and Technology*. Under review.

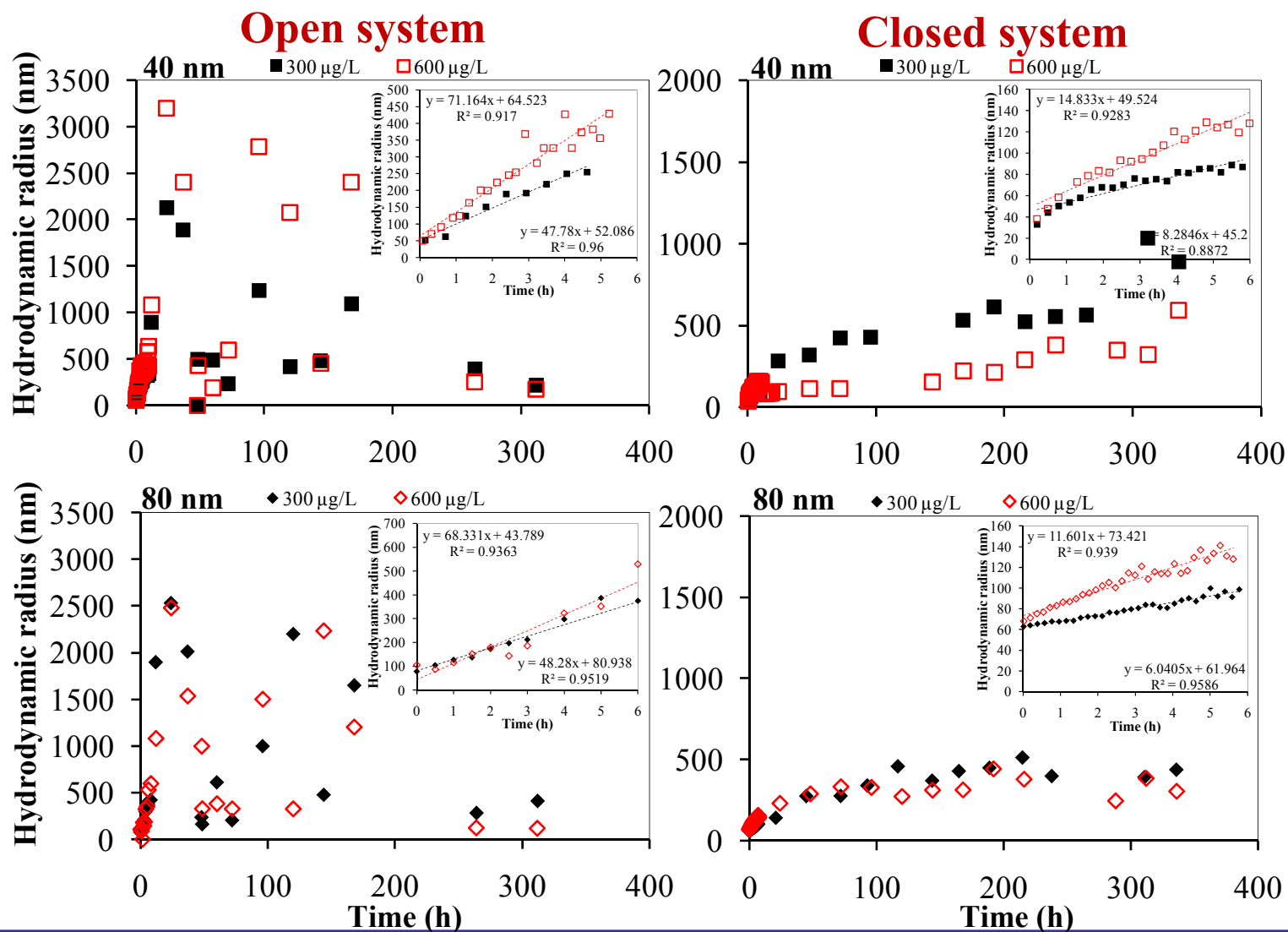
# AgNPs aggregation kinetics in open and closed systems- *closed system*



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Wen Zhang, Ying Yao, Kungang Li, Ying Huang, Yongsheng Chen. Aggregation kinetics of silver nanoparticles in open and close systems. *Environmental Science and Technology*. Under review.

# AgNPs aggregation kinetics in open and closed systems-40 and 80 nm

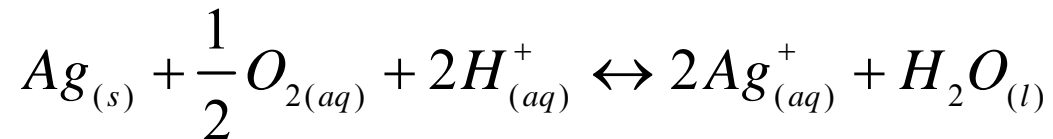


SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

Wen Zhang, Ying Yao, Kungang Li, Ying Huang, Yongsheng Chen. Aggregation kinetics of silver nanoparticles in open and close systems. *Environmental Science and Technology*. Under review.

# AgNPs ion release kinetics: primary particle size and concentration effects.

**Reaction stoichiometry:**



**Hard sphere theory and Arrhenius equation are used to derive the silver ion release rate:**

$$\gamma_{Ag^+} = \frac{3}{4} \left( \frac{8\pi k_B T}{m_B} \right)^{1/2} \cdot \rho^{-1} \cdot \exp\left(\frac{-E_a}{k_B T}\right) \cdot [Ag] \cdot r^{-1} \cdot [O_2]^{0.5} \cdot [H^+]^2$$

$$[Ag^+]_{released} \approx \frac{1}{6}a^3t^3 + \left(\frac{1}{2}a^2bt^2 - \frac{1}{2}a^2t^2\right) + (at - abt + \frac{1}{2}ab^2t) + \left\{[Ag^+]_{initial} - 1 + b - \frac{1}{2}b^2 + \frac{1}{6}b^3\right\}$$

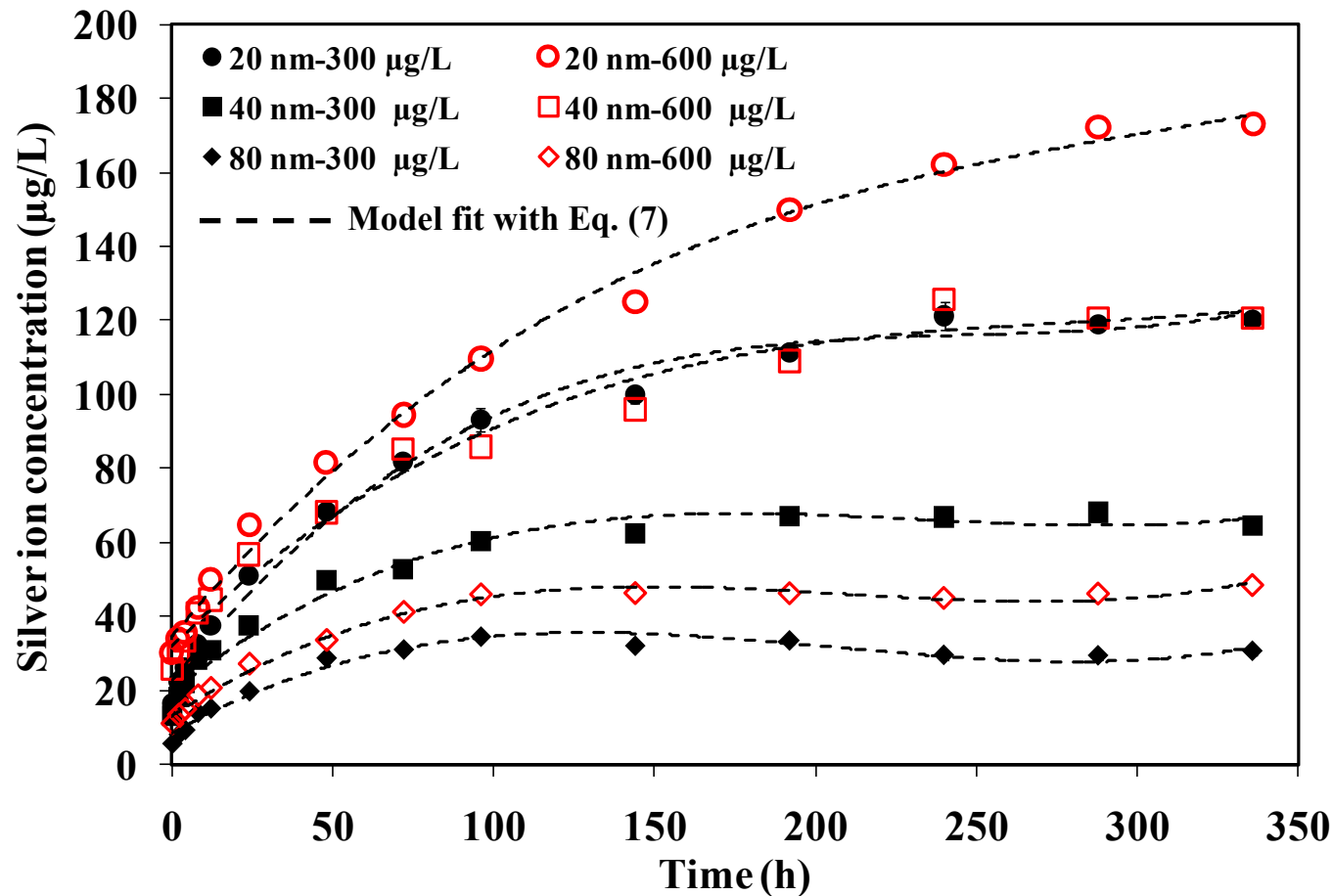
**Released silver ion concentration is a function of time, particle size, oxygen and proton concentrations, temperature and “activation energy”.**

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

Wen Zhang, Ying Yao, Nicole Sullivan, Yongsheng Chen. Kinetics modeling of ion release silver NPs in the environment. *Environmental Science and Technology*. Revision submitted.



# AgNPs ion release kinetics: primary particle size and concentration effects-continued



Size and concentration	Correlation coefficient ( $R^2$ )
20 nm-300 µg/L	0.9914
20 nm-600 µg/L	0.9947
40 nm-300 µg/L	0.9732
40 nm-600 µg/L	0.9812
80 nm-300 µg/L	0.9737
80 nm-600 µg/L	0.9924

➤ **Primary particle size determines the ion release kinetics, not hydrodynamic or aggregate's size**

# Cellular and subcellular impairment by exposure to NPs

**Caco-2 cells**

- Hematite NPs of different sizes
- Surface disruption and cell penetration

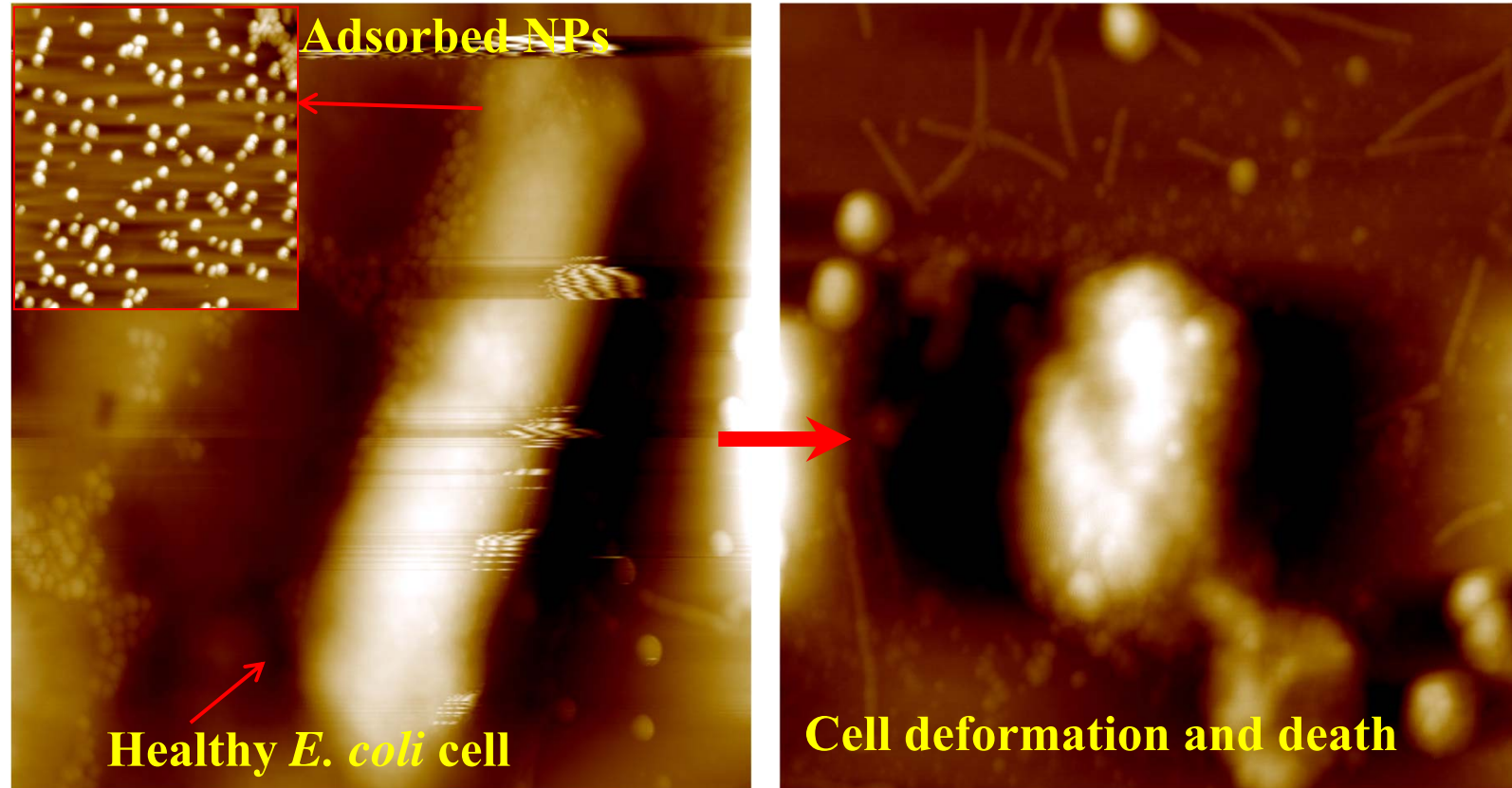
***E. Coli* cells**

- Hematite NPs of different sizes
- Surface adsorption, and surface disruption

***E. Coli* cells**

- QDs
- Cell growth inhibition, DNA binding and visualization

# Adsorption, surface disruption, and adsorption kinetics modeling of hematite NPs on *E. coli* cells

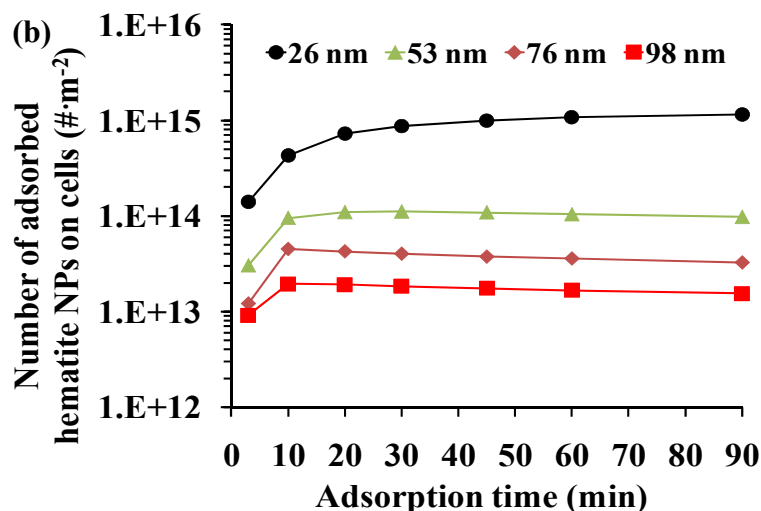
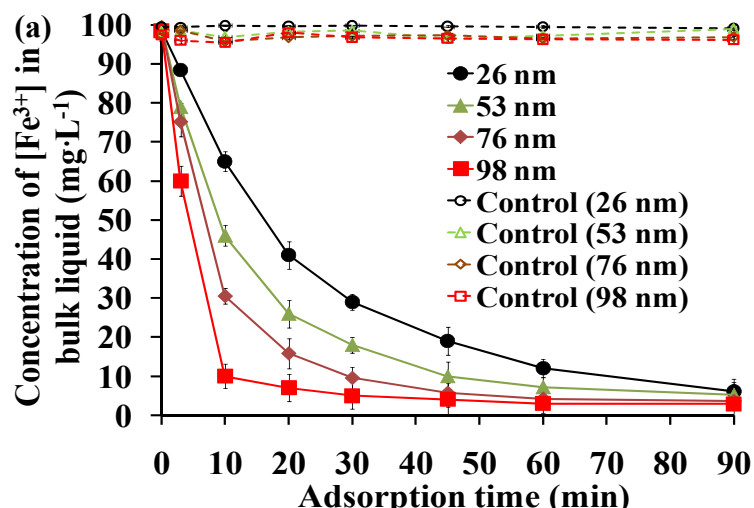


Exposure impairment of hematite NPs on *E. coli* cells.

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

Wen Zhang, Bruce Rittmann, and Yongsheng Chen. Size effects on adsorption kinetics of hematite NPs on *E. coli* cells. *Environmental Science and Technology*. Revision resubmitted.

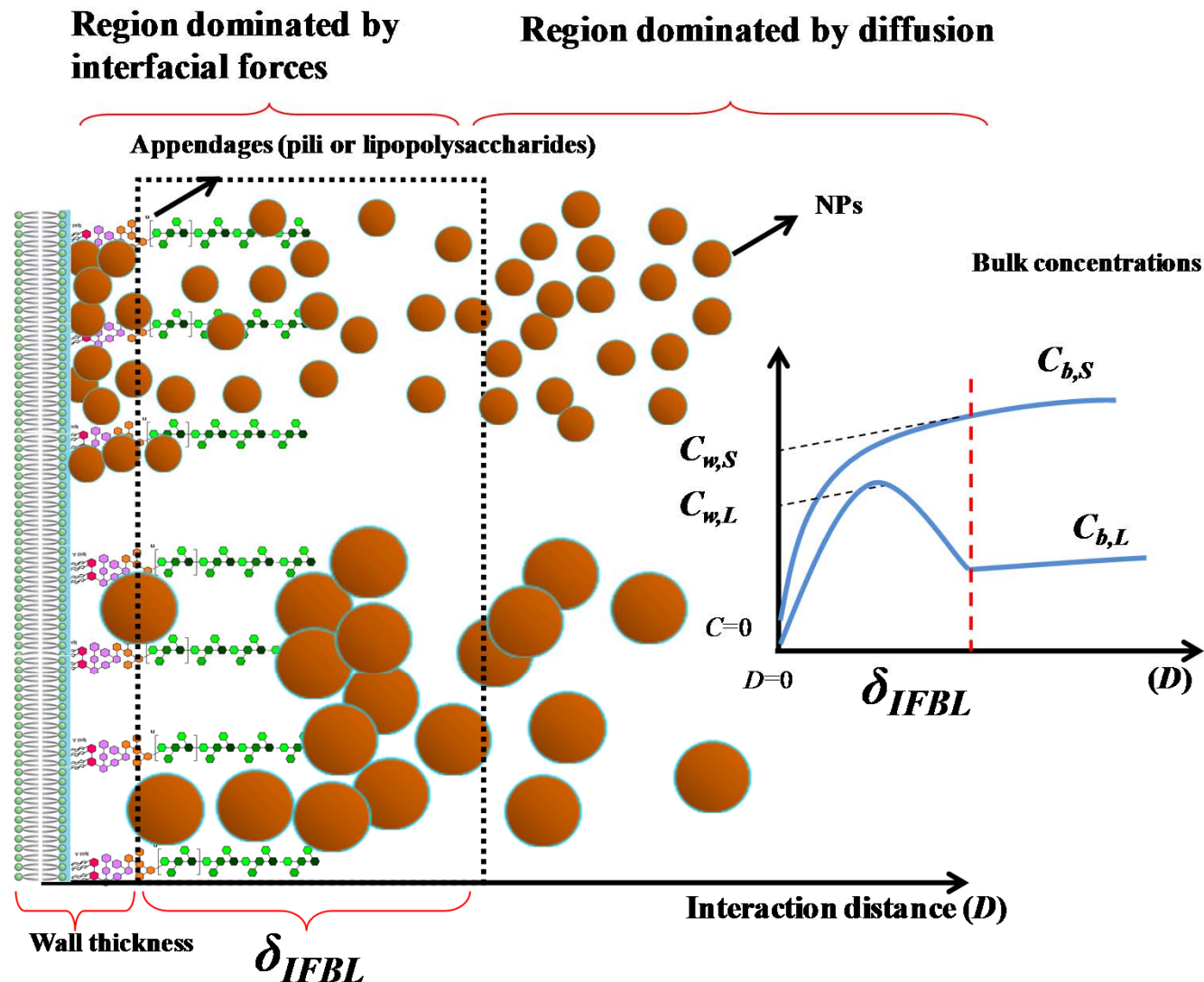
# Adsorption, surface disruption, and adsorption kinetics modeling of hematite NPs on *E. coli* cells



## Key findings:

- Adsorption kinetics also show the dependency of particle size;
- The adsorption rates expressed as  $\text{mg Fe}\cdot\text{L}^{-1}\cdot\text{s}^{-1}$  decreased in the order of  $98 \text{ nm} > 76 \text{ nm} > 53 \text{ nm} > 26 \text{ nm}$ .
- The adsorption rates expressed as the number of adsorbed hematite NPs per unit cell surface area ( $\# \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ) were faster for small NPs than those for large NPs;
- The contradiction in the adsorption kinetics when expressed by mass-based concentration and number-based concentration can be interpreted with IFBL theory.

# Adsorption, surface disruption, and adsorption kinetics modeling of hematite NPs on *E. coli* cells



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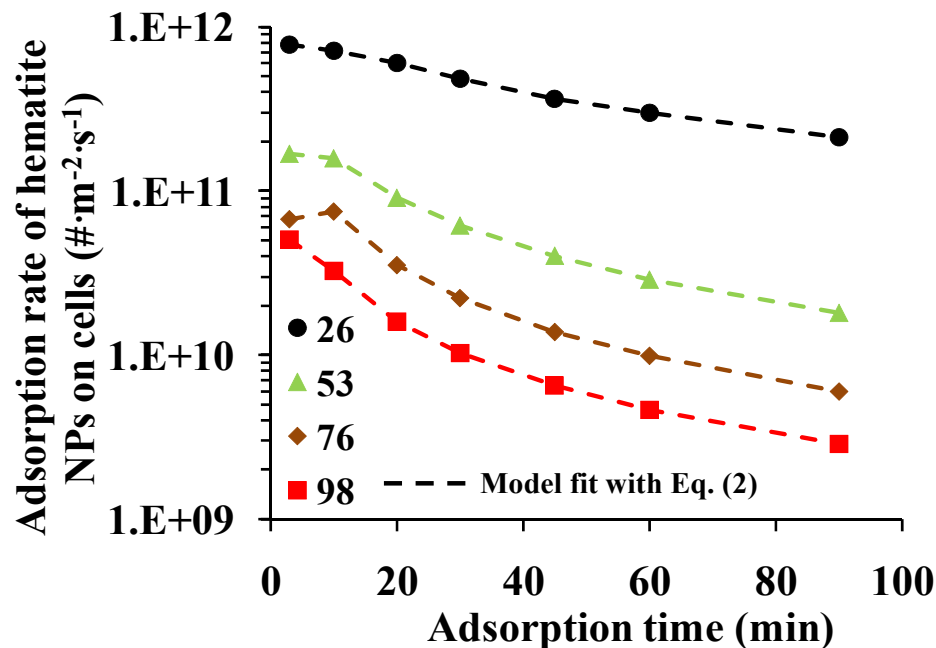
Wen Zhang, Bruce Rittmann, and Yongsheng Chen. Size effects on adsorption kinetics of hematite NPs on *E. coli* cells. *Environmental Science and Technology*. Revision resubmitted.

# Adsorption, surface disruption, and adsorption kinetics modeling of hematite NPs on *E. coli* cells

Modeling particle adsorption kinetics using interaction force boundary layer (IFBL) theory, :

$$\frac{dC_{sorption}}{dt} = k_a C_w$$

$$k_a = \frac{\text{Diffusion}}{\int_{D=0}^{D=\delta_{diffusion}} [(1 + \frac{R_H}{D}) \exp(\frac{U_{TOT}^{EDLVO}(D)}{k_B T}) - 1] dD}$$

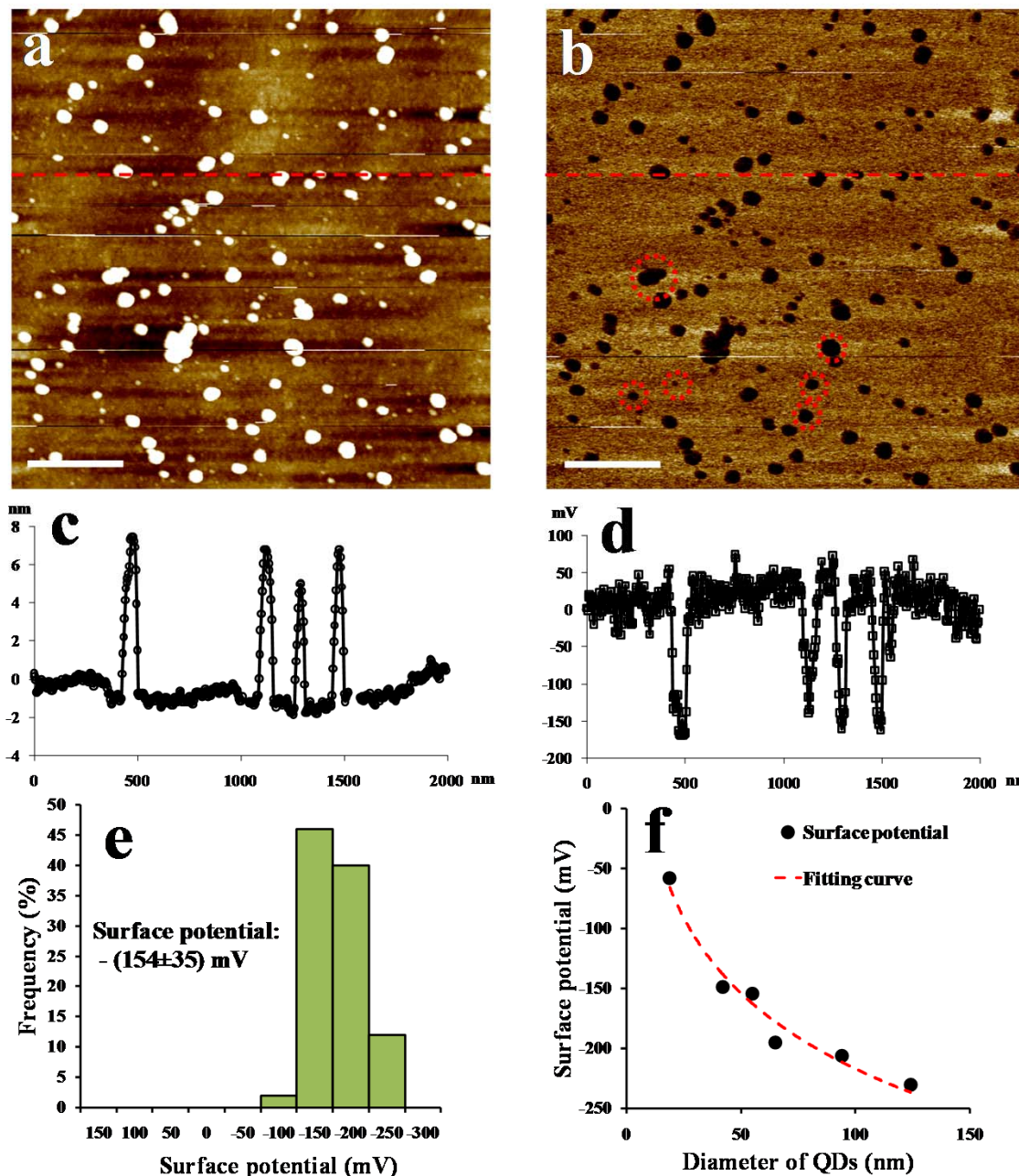


➤ **Faster adsorption kinetics for smaller NPs could be attributed to higher particle diffusivity and lower energy barriers in the total interaction energy.**



# Permeation of QDs into *E. coli* cells and binding with DNA

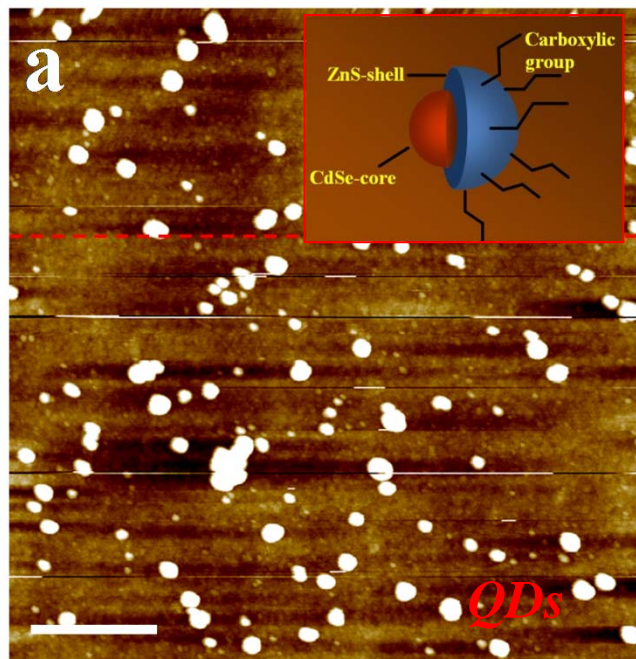
QDs characterization:  
CdSe-ZnS core-shell,  
15-25 nm in diameter,  
Citric acid coating.



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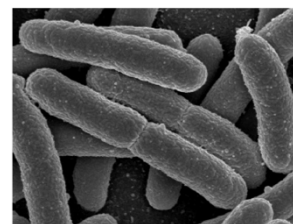
Wen Zhang, Ying Yao, and Yongsheng Chen Quantifying and Imaging the Morphology and Nanoelectric Properties of Soluble Quantum Dot Nanoparticles Interacting with DNA.  
*Journal of Physical Chemistry C*. DOI: 10.1021/jp107676h.

# Permeation of QDs into *E. coli* cells and binding with DNA-continued

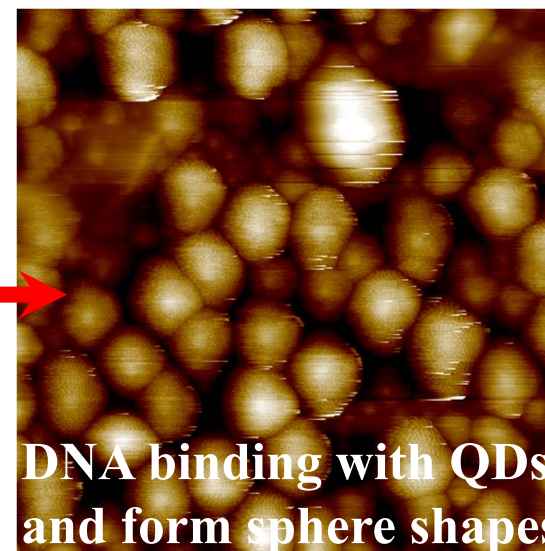
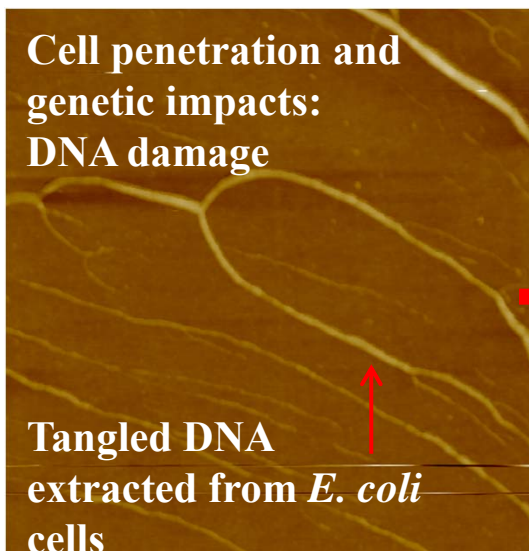


**Ultrasmall QDs (CdSe-ZnS) can permeate into *E. coli* cells and unintentionally bind with DNA**

**Permeate  
into**



**Bind with**

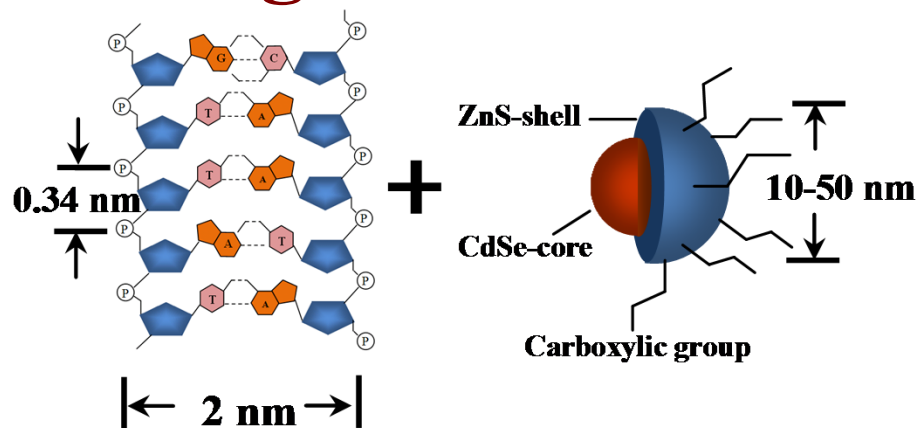


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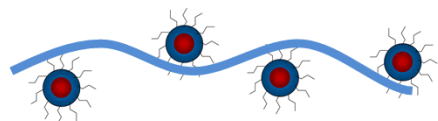
Wen Zhang, Ying Yao, and Yongsheng Chen Quantifying and Imaging the Morphology and Nanoelectric Properties of Soluble Quantum Dot Nanoparticles Interacting with DNA. *Journal of Physical Chemistry C*. DOI: 10.1021/jp107676h.



# Permeation of QDs into *E. coli* cells and binding with DNA-continued



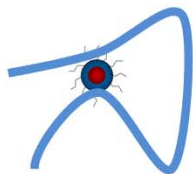
1. Attachment of QDs on DNA



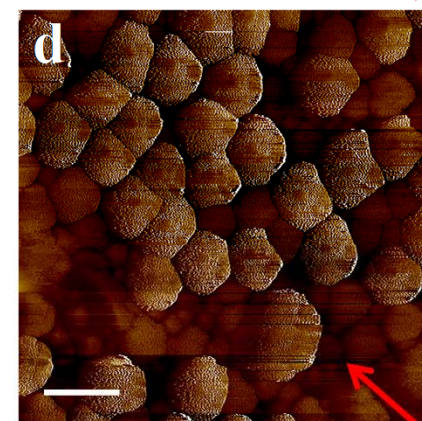
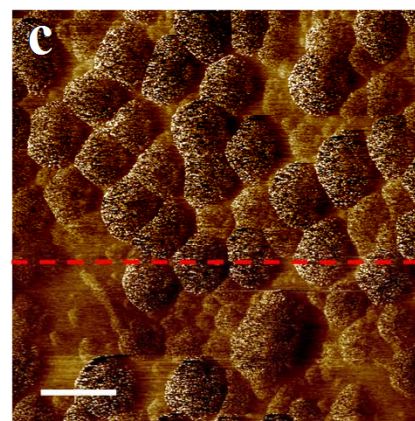
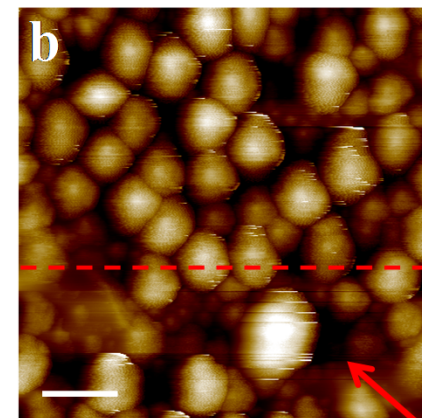
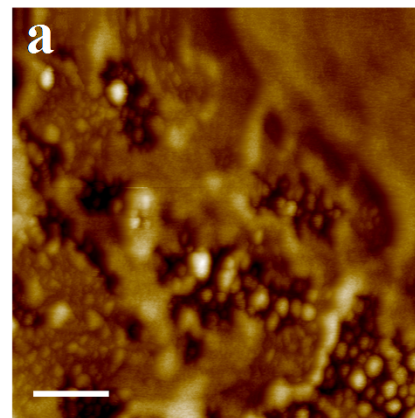
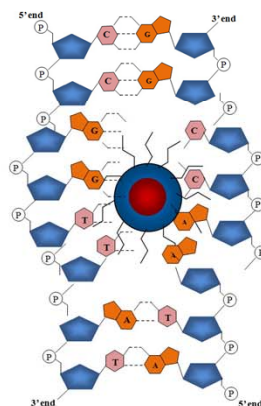
2. Attachment of DNA on QDs



3. Cross-linked DNA



4. Incision of QDs into DNA helix



**Sphere-shaped DNA conformation after binding with QDs.**

SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

Wen Zhang, Ying Yao, and Yongsheng Chen Quantifying and Imaging the Morphology and Nanoelectric Properties of Soluble Quantum Dot Nanoparticles Interacting with DNA. *Journal of Physical Chemistry C*. DOI: 10.1021/jp107676h.

# **Future Plans**

## **Next Year Plans**

- **Systematical study of important relevant physiochemical properties of semiconductor nanomaterials, specifically on size, shape and surface properties on biological and environmental interactions.**
- **Continue cytotoxicity tests with various typical cells (e.g., *E. coli*) at cellular and genetic levels and semiconductor nanoparticles of high interest (e.g., CeO<sub>2</sub>);**
- **Development AFM-based imaging tools for visualization of cellular disruption by exposure to NPs;**

## **Long-Term Plans**

- **Accumulating sufficient data to categorize and prioritize relevant nanoparticles and their characteristics that are used for establishing robust and accurate predictive QSAR models.**
- **Provide fundamental information for manufacturing environmental benign semiconductor nanomaterials for industries.**

# Publications, Presentations, and Recognitions/Awards

## ➤ Publication

1. Wen Zhang, Madhavi Kalive, David G Capco, and Yongsheng Chen, Adsorption of hematite nanoparticles onto Caco-2 cells and the cellular impairments: effect of particle size. *Nanotechnology*. 2010, 21, 355103.
2. Wen Zhang, Andrew Stack, and Yongsheng Chen, Interaction force measurement between E. coli cells and nanoparticles immobilized surfaces by using AFM. *Colloids and Surfaces B: Biointerfaces*. 10.1016/j.colsurfb.2010.09.003.
3. Wen Zhang, Ying Yao, and Yongsheng Chen Quantifying and Imaging the Morphology and Nanoelectric Properties of Soluble Quantum Dot Nanoparticles Interacting with DNA. *Journal of Physical Chemistry C*. DOI: 10.1021/jp107676h.
4. Wen Zhang, Ying Yao, Nicole Sullivan, Yongsheng Chen. Kinetics modeling of ion release silver NPs in the environment. *Environmental Science and Technology*. Revision submitted.
5. Wen Zhang, Bruce Rittmann, and Yongsheng Chen. Size effects on adsorption kinetics of hematite NPs on *E. coli* cells. *Environmental Science and Technology*. Revision requested.
6. Wen Zhang, Ying Yao, Ching-Hua Huang, and Yongsheng Chen. Measurement of trace level metal based nanoparticles by ICP-MS without sample digestion. *Environmental Pollution*. Under review.
7. Wen Zhang, Ying Yao, Kungang Li, Ying Huang, Yongsheng Chen. Aggregation kinetics of silver nanoparticles in open and close systems. *Environmental Science and Technology*. Under review.
8. Kungang Li, Wen Zhang, Ying Huang, and Yongsheng Chen, Modeling the aggregation kinetics of CeO<sub>2</sub> nanoparticles in monovalent and divalent electrolytes with EDLVO theory, *Colloids and Surfaces A*, Under review.

## ➤ Presentation

During year 2008-2010, I attended and made oral presentations in 8 national conferences, including ASM, ACS, USEPA grantees meetings, ICEIN, SRC, IENC, and etc.

## ➤ Recognitions/Awards

News report for our research: <http://nanotechweb.org/cws/article/lab/43670>

SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

# High-Throughput Cellular-Based Toxicity Assays for Manufactured Nanoparticles and Nanostructure-Toxicity Relationship Models

*(Task Number: 425.035)*

Subtask 1: “High Throughput Screening”

Subtask 2: “Computational Models”

## PIs:

- **Subtask 1 Leader: Dr. Russell J. Mumper, Center for Nanotechnology in Drug Delivery, UNC Eshelman School of Pharmacy, UNC-Chapel Hill**
- **Subtask 2 Leader: Dr. Alexander Tropsha, Division of Medicinal Chemistry and Natural Products, UNC Eshelman School of Pharmacy, UNC-Chapel Hill**

## Graduate Students and Postdoctoral Fellows:

- **Shalini Minocha, PhD Candidate, Center for Nanotechnology in Drug Delivery, UNC Eshelman School of Pharmacy, UNC-Chapel Hill**
- **John Pu, PhD Candidate, Laboratory for Molecular Modeling, UNC Eshelman School of Pharmacy, UNC-Chapel Hill**
- **Denis Fourches, Postdoctoral Fellow, Laboratory for Molecular Modeling, UNC Eshelman School of Pharmacy, UNC-Chapel Hill**

# Objectives

## Subtask 1:

- **Validation of high-throughput cellular-based toxicity assays for MNP assessment.**
- **Test QNTR (Quantitative Nanostructure Toxicity Relationship) model using the predictive models developed in subtask 2.**

## Subtask 2:

- **Develop QNTR models that correlate the compositional/physical/chemical/geometrical and biological descriptors of MNPs with known toxicological endpoints.**
- **Improve the prediction performance of QNTR models with the availability of new experimental data from subtask 1.**

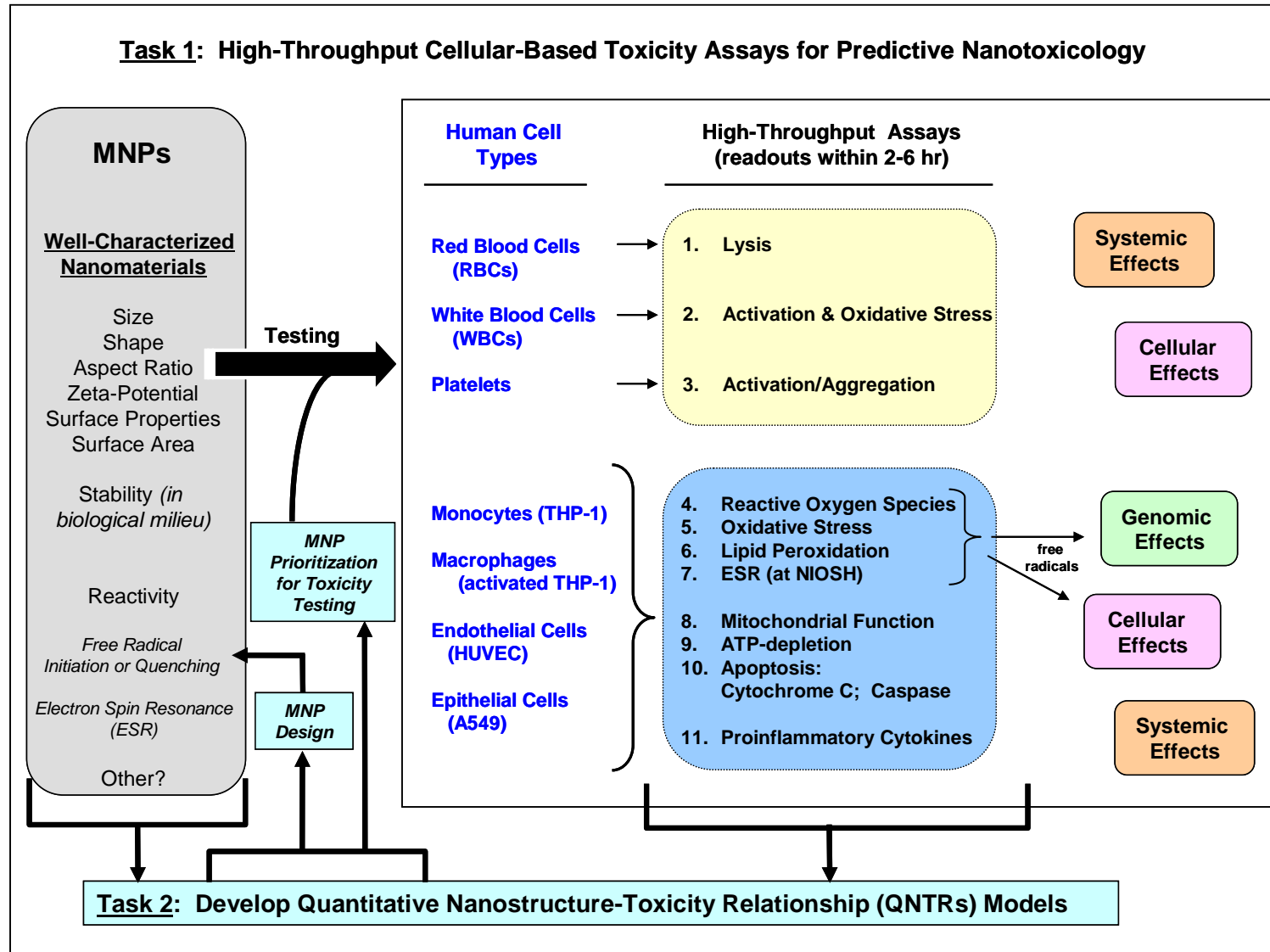
# ESH Metrics and Impact

- 1. Obtain predictive knowledge of the physical and chemical properties of manufactured nanoparticles.*
- 2. Develop relevant in-vitro assays utilizing human cells to predict the toxicity of manufactured nanoparticles.*
- 3. Develop predictive computational models that correlate physical-chemical descriptors of MNPs with their toxic effects.*

*Impact: Utilize the knowledge gained through above three metrics for improved MNP experimental design and prioritized toxicity testing toward the manufacturing of safe nanomaterials.*



# General Framework of the Proposed Approach



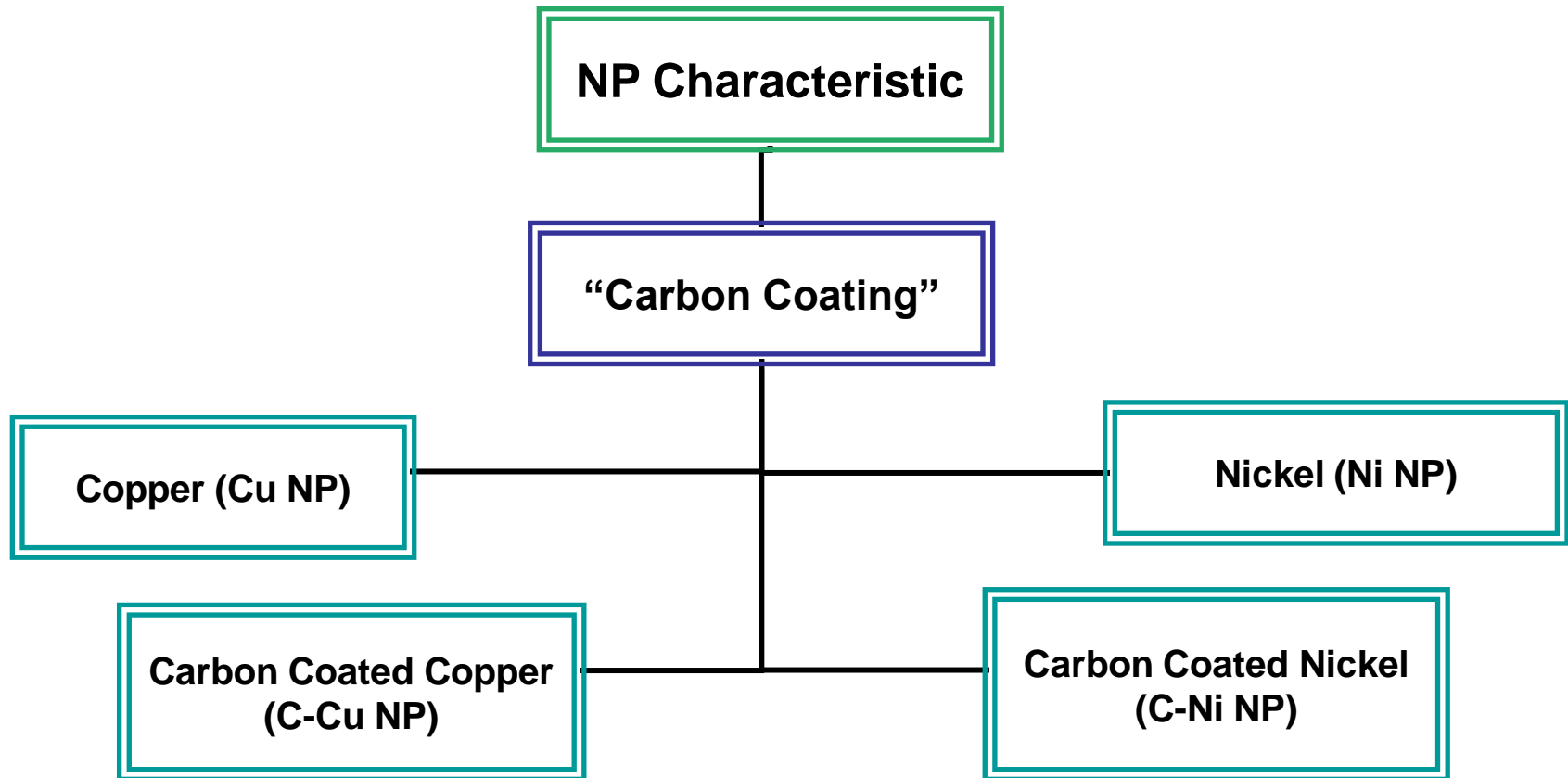
# Subtask 1: Potential Cellular-based Assays

Human Cells	Assay	Description
Red Blood Cells (RBCs)	Lysis	Measure oxyhemoglobin at 540 nm
White Blood Cells (WBCs)	Activation	Measure reduction of ferricytochrome c caused by produced superoxide anions
	Oxidative Stress	Measure intracellular GSSG/GSH ratio; where GSSG is oxidized glutathione and GSH is reduced glutathione
Platelets	Activation	Flow cytometry to measure PAC-1-FITC binding to activated platelets
	Aggregation	Whole Blood Impedance Aggregometry

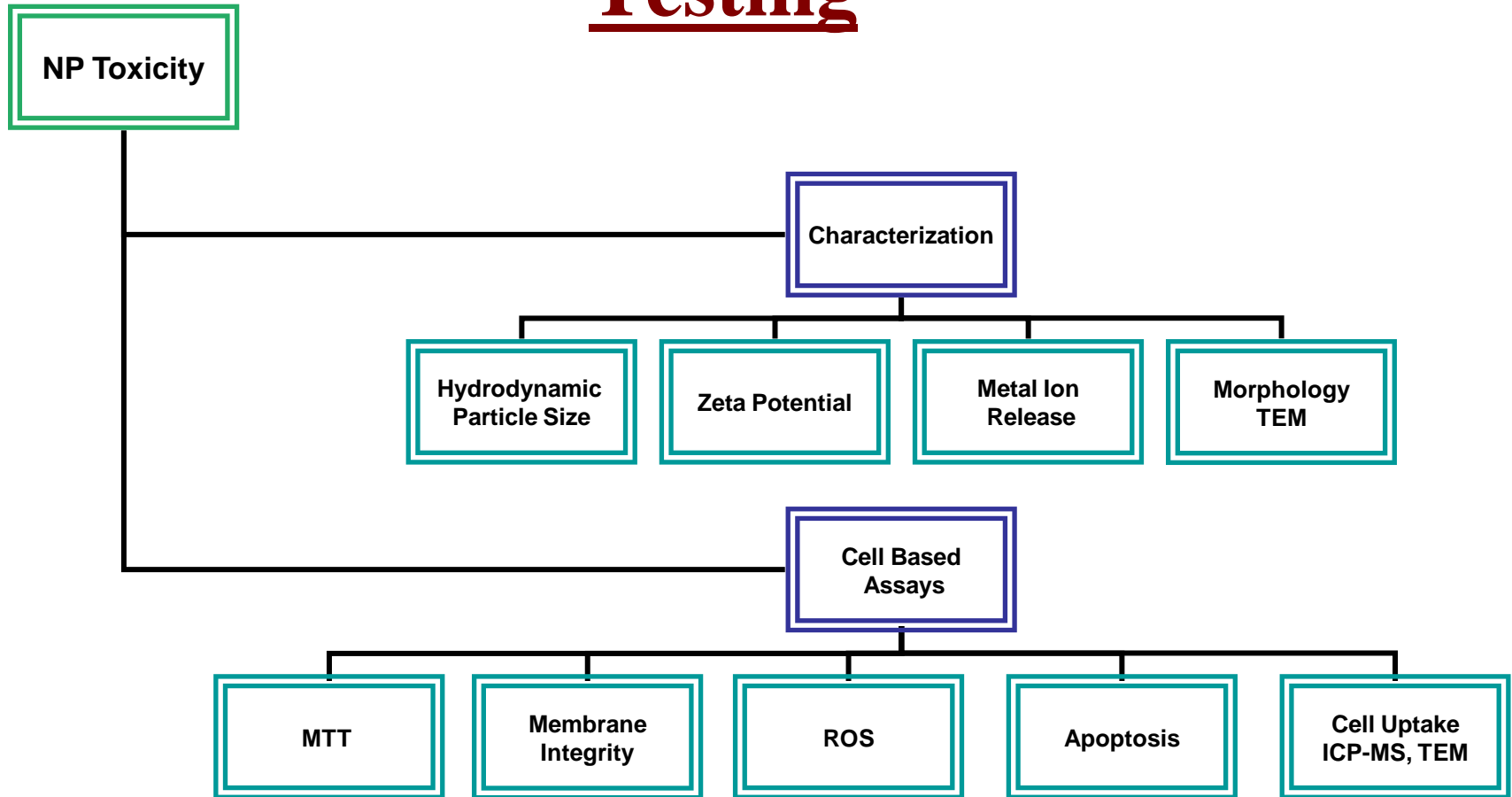
Human Cells	Assay	Description
<b>Monocytes (THP-1)</b> <b>Macrophages (activated THP-1)</b> <b>Endothelial Cells (HUVEC)</b> <b>Epithelial Cells (A549)</b>	Reactive Oxygen Species	1) Measure intracellular fluorescence produced with H <sub>2</sub> DCFDA or carboxy-H <sub>2</sub> DCFDA loaded cells; 2) Measure (a) cellular ESR
	Oxidative Stress	Measure intracellular GSSG/GSH ratio; where GSSG is oxidized glutathione and GSH is reduced glutathione
	Lipid Peroxidation	Lipid Hydroperoxide (LPO) Assay
	Mitochondrial Function	MTT assay & JC-1 assay
	ATP-depletion	ATPlite 1step® Assay Kit (PerkinElmer)
	Apoptosis:	
	Cytochrome C	Cytochrome C immunoassay
	Caspase-3	Caspase-3 Fluorometric Assay (R&D Systems); Quantify caspase-3 activation by cleavage of DEVD-AFC substrate
	Proinflammatory Cytokines	Cytokine assays by ELISA; NFκB, IL-1β, TNF-α, IFN-γ, IL-8



# Subtask 1: Current Method Approach



# Subtask 1: Current Scheme for Toxicity Testing



Cell Line Model:

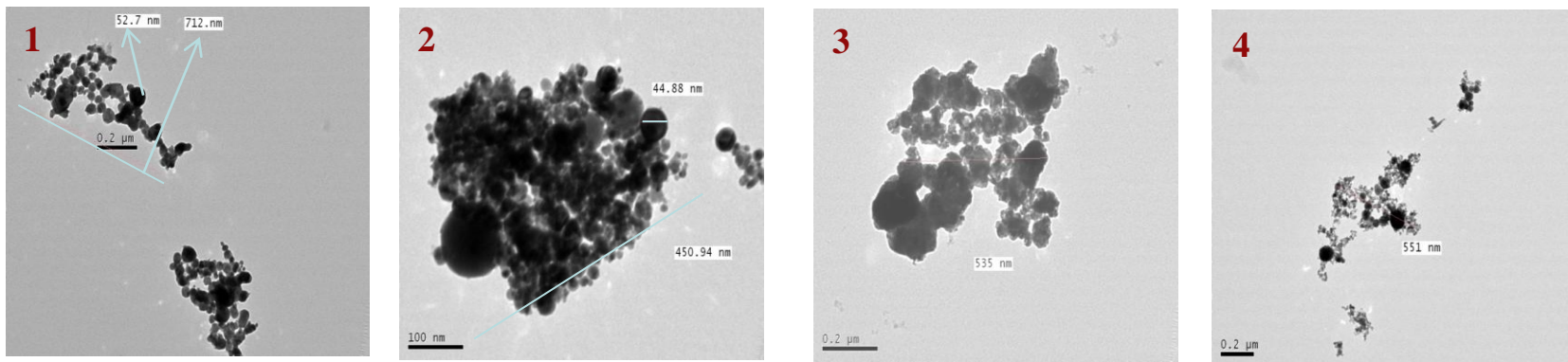
A549 alveolar epithelial cells

# Characterization: MNPs

NP Type	Manufacturer	Particle Size* Range (nm)	Particle Size in DI water (nm)	Zeta Potential (mV)
Nickel	NanoAmor	20	$834.6 \pm 495.1$	$2.76 \pm 0.7$
Carbon coated Nickel	NanoAmor	20	$466.6 \pm 179.6$	$-16.4 \pm 1.8$
Copper	NanoAmor	25	$662.2 \pm 139.3$	$-9.0 \pm 2.4$
Carbon coated Copper	NanoAmor	25	$412.1 \pm 210.9$	$-6.21 \pm 0.7$

\* Provided by Manufacturer

Sample preparation: 1 mg/ml suspensions in DI water; bath sonicated for 6 x30 sec

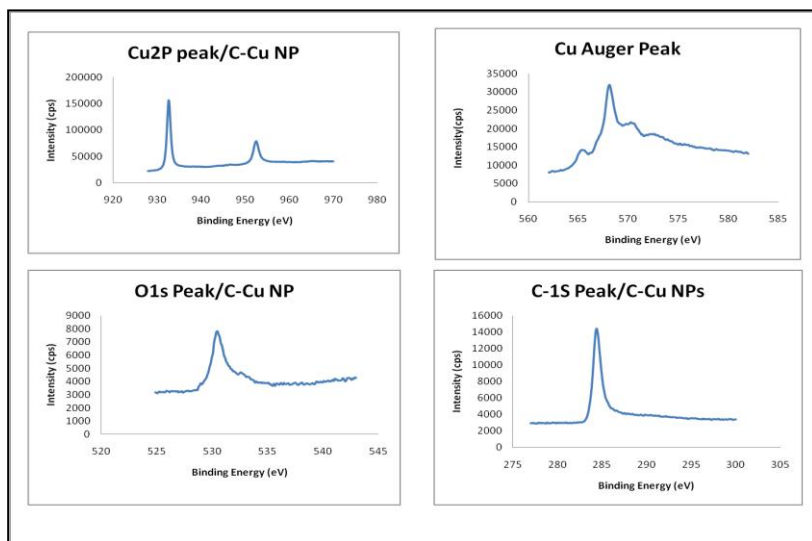


1. Ni 2. C-Ni 3. Cu 4. C-Cu MNPs. Nanoparticles were suspended at concentration of 10  $\mu\text{g/ml}$  in DI water for this analysis. The average particle sizes measured by TEM correlates with the dynamic light scattering data.

# XPS Analysis: Cu NP and C-Cu NP

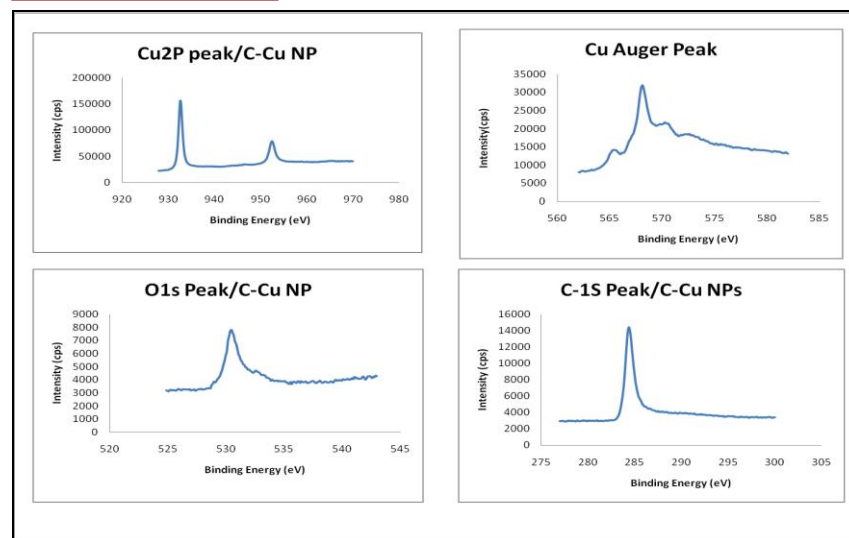
XPS analysis was carried out for analyzing the composition of top 5 nm of the nanoparticles

## C-Cu NP



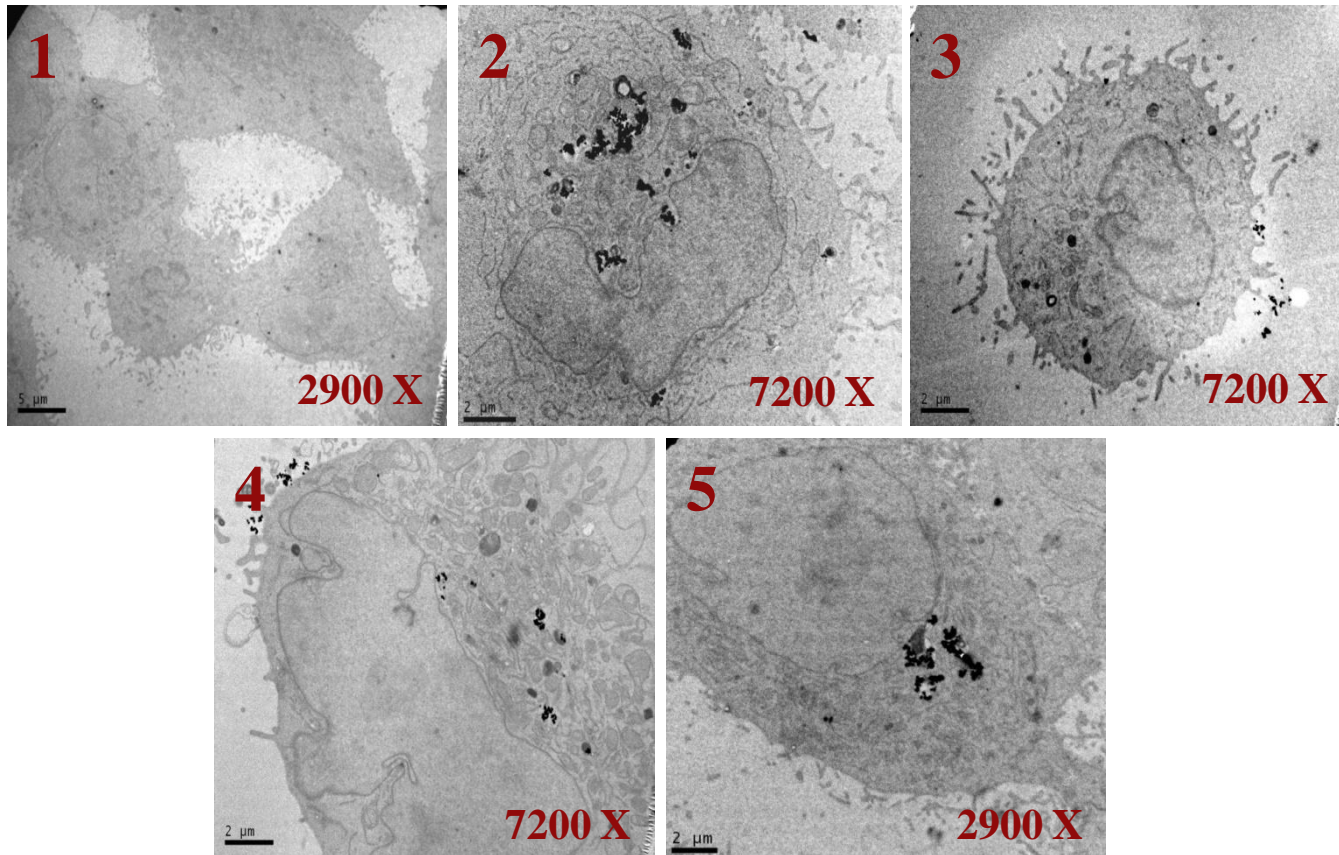
Cu 2P peak was observed at 932.7 eV and Cu Auger peak was observed at 568.07 eV. The relative percent atomic concentrations of various elements were Cu 2P (48.33), C1S (17.67) and O1S (34).

## Cu NP



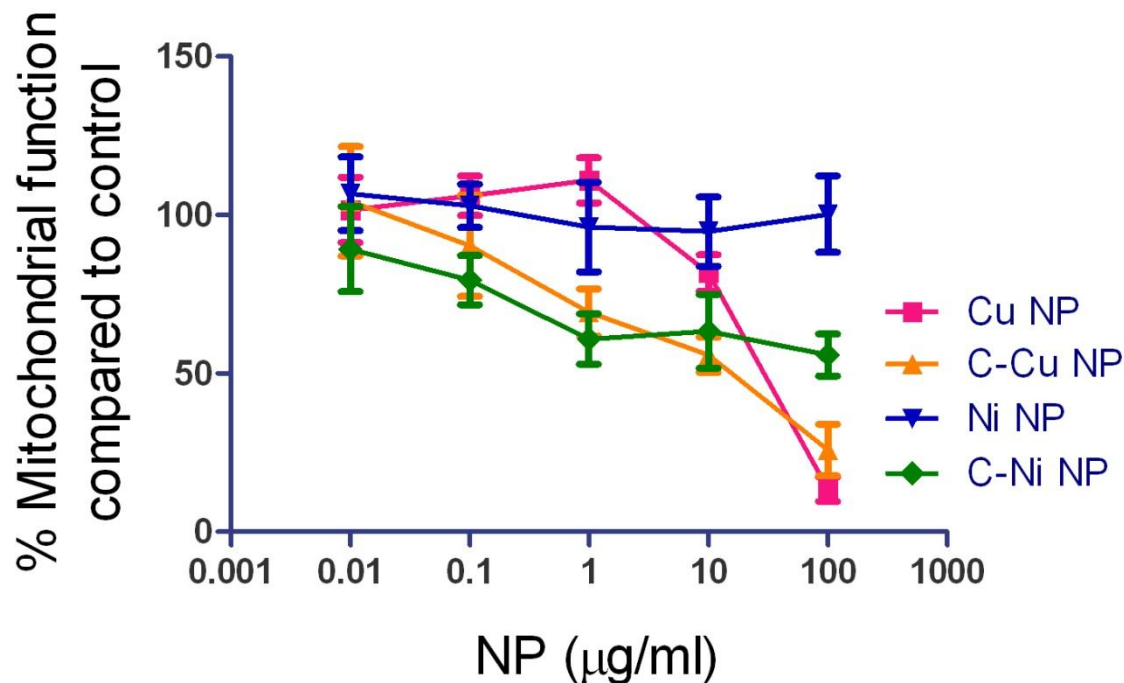
Cu 2P peak was observed at 932.7 eV and Cu Auger peak was observed at 570.3 eV. The relative percent atomic concentrations of various elements were Cu 2P (36.3), C1S (54.95) and O1S (8.68).

# Cell Uptake Analysis by TEM



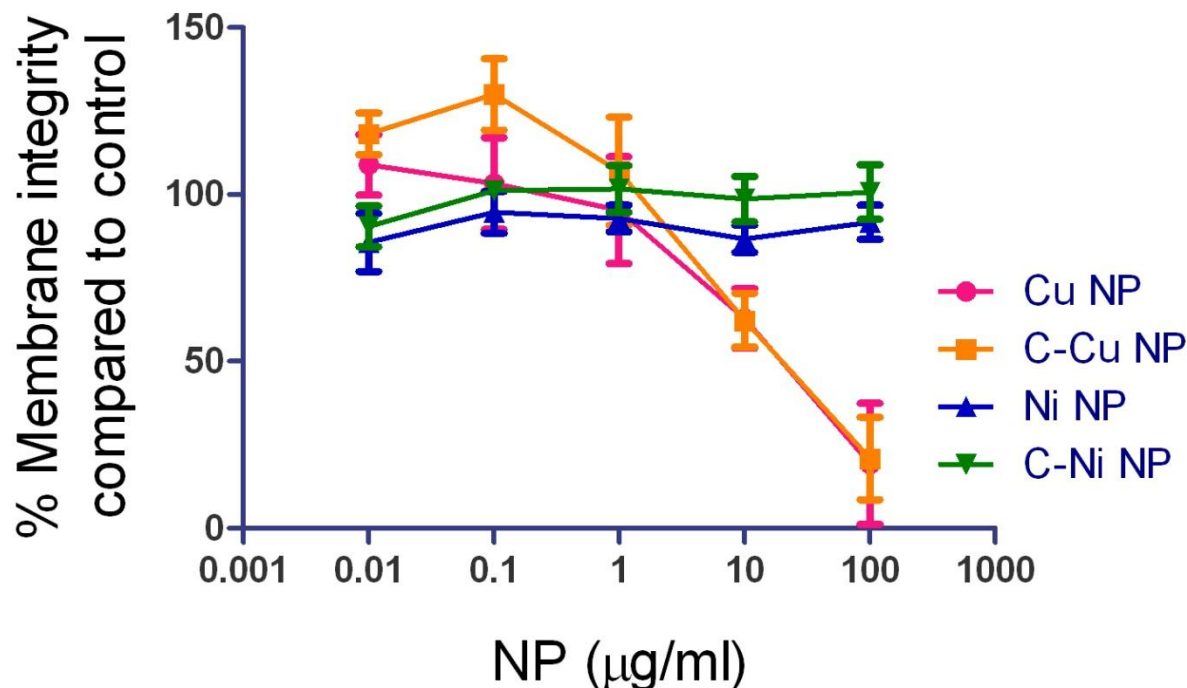
1. Control A549 cells 2. Cu treated 3. C-Cu treated 4. Ni treated and 5. C-Ni treated A549 cells. Cells were treated with nanoparticles at concentration of 10  $\mu\text{g/ml}$  for 8 hr.

# Mitochondrial Function



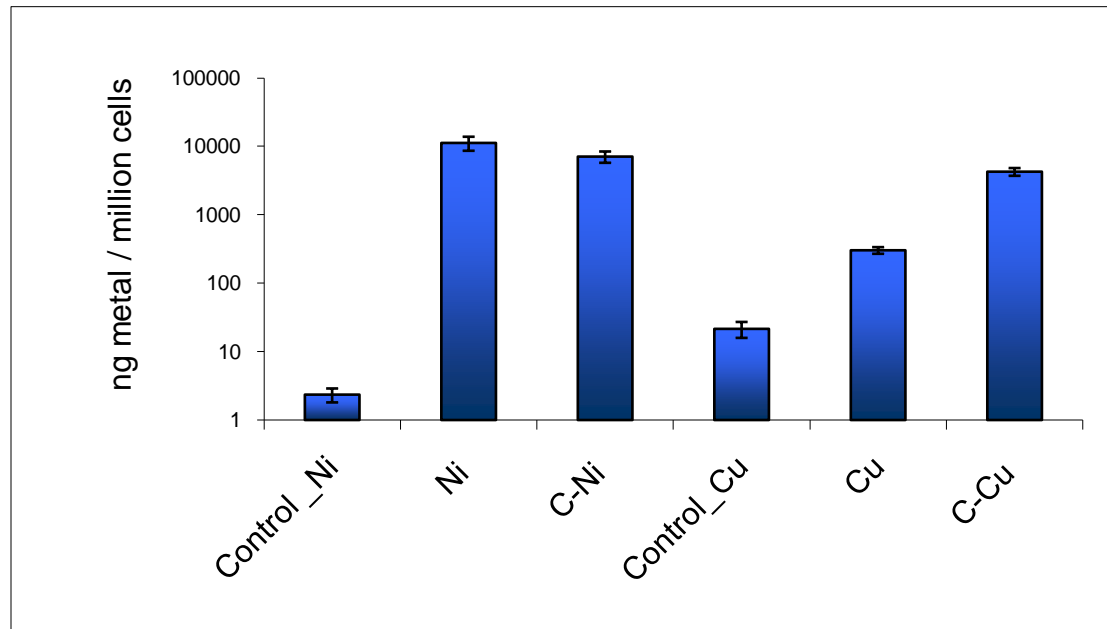
- A549 cells (25,000 per well), incubation with NPs for 24 hr.
- Data corrected for absorbance from blank NPs.
- Ni NPs significantly differ from C-Ni NPs at all doses.
- Cu NPs significantly differ from C-Cu NPs at 0.1, 1 and 10  $\mu\text{g/ml}$ .  
(  $p < 0.05$  as compared to control)

# Neutral Red Membrane Integrity Assay



- A549 cells (25,000 per well), incubation with NPs for 24 hr.
- Data corrected for absorbance from blank NPs.
- Ni NPs and C-Ni NPs do not alter membrane integrity.
- Cu NPs and C-Cu NPs were found to be equally toxic in this assay.

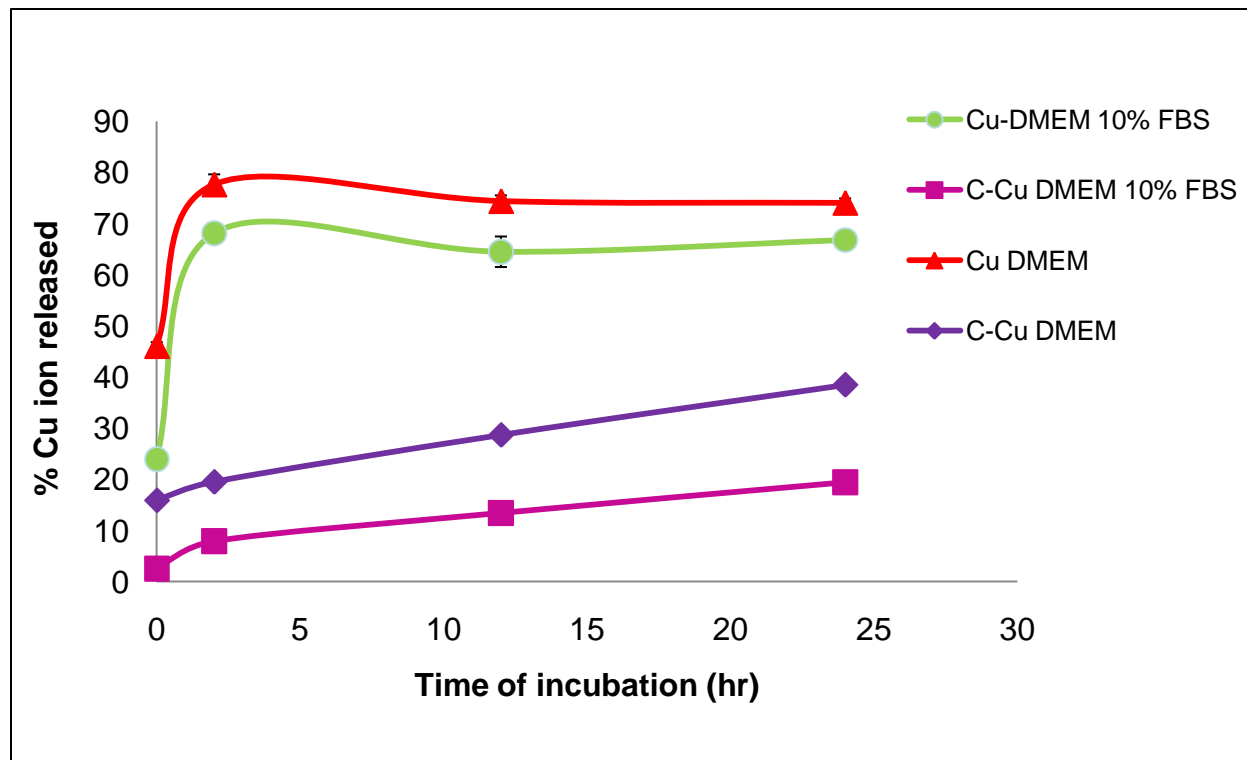
# Cell Uptake Analysis by ICP-MS



- Control\_Ni and Control\_Cu signify the amount of respective metal content in untreated control A549 cells.
- Nanoparticles were tested at concentrations of 10  $\mu\text{g/ml}$  for 8 hr in A549 cells.
- Ni uptake from Ni and C-Ni NPs is comparable.
- Cu uptake from C-Cu NPs is an order of magnitude higher than uptake from Cu NPs.

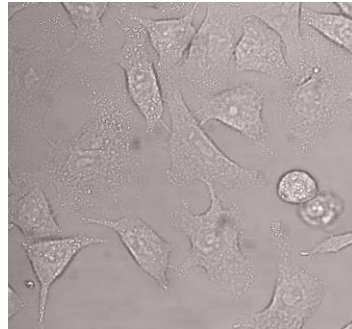


# Cu Ion Release from Cu and C-Cu NPs

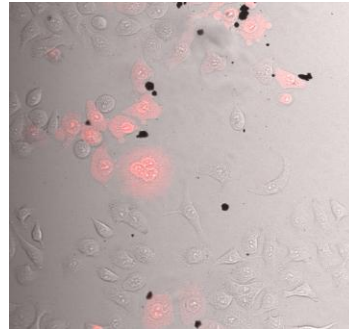


Kinetic analysis of Cu ion release quantified from Cu and C-Cu NPs at 50  $\mu\text{g/ml}$  concentration in 2 ml cell culture medium with and without 10% FBS at 37° C. C-Cu NP releases on average 6-7 fold lower amount of Cu when compared to C-Cu NPs due to carbon coating. Coating of nanoparticle surface due to presence of proteins in FBS may be responsible for lower release of Cu from both Cu and C-Cu NPs

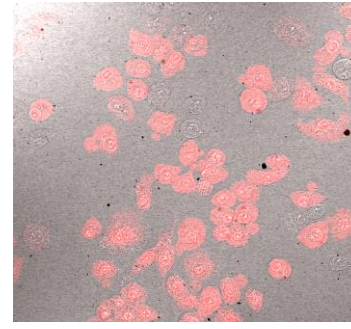
# Propidium Iodide (PI) Uptake in Cells after Treatment with Cu and C-Cu NPs



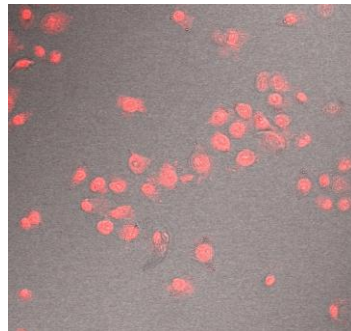
**Negative Control**



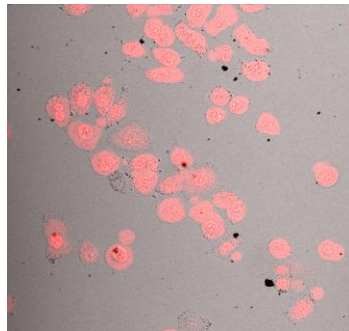
**C-Cu NP 10 µg/ml**



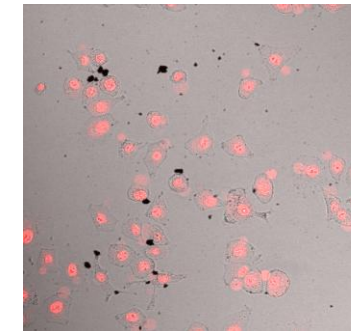
**C-Cu NP 50 µg/ml**



**CuCl<sub>2</sub> eq to 50 µg/ml Cu**



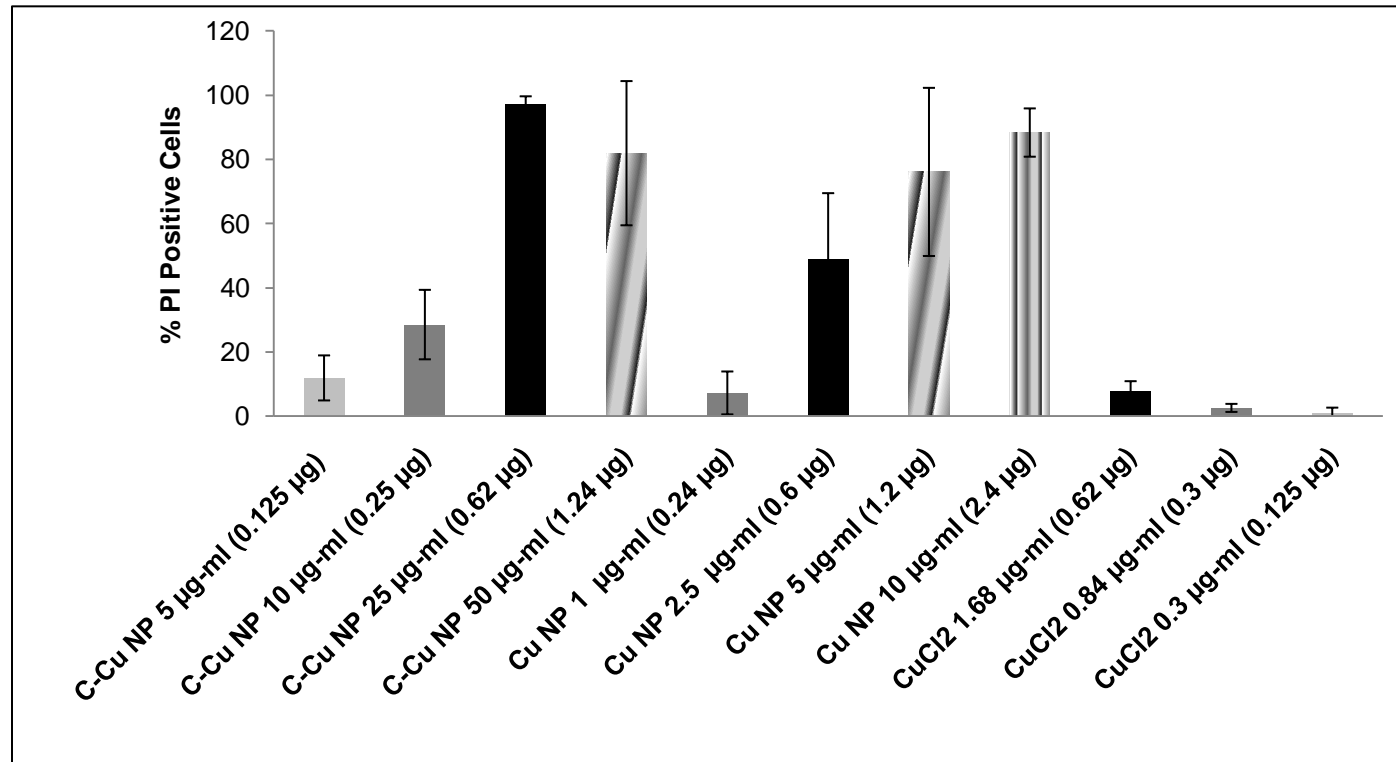
**Cu NP 10 µg/ml**



**Cu NP 50 µg/ml**

A549 cells were treated with Cu NP and C-Cu NP at 10 µg/ml and 50 µg/ml for 1 min and checked for damage to plasma membrane integrity by incubation with a membrane impermeable dye ; Propidium Iodide (PI). Surprisingly, Cu NP induces membrane damage immediately at 10 µg/ml and 50 µg/ml (seen as red fluorescence in cells due to PI uptake)

# PI Uptake Analysis after Treatment with Cu and C-Cu NPs



A549 cells were treated with Cu NP, C-Cu NP and  $\text{CuCl}_2$  at various doses for 1 min and membrane damage was determined by PI uptake. In order to identify if the immediate membrane damage was induced by released Cu ions, the amount of released Cu in each treatment (mentioned in brackets in the fig) was compared. The data above shows that membrane damage is mostly due to NP effect (see black bars above). Also, Cu NP at 5  $\mu\text{g/ml}$  shows equivalent membrane damage as compared to 25  $\mu\text{g/ml}$  dose of C-Cu NPs.

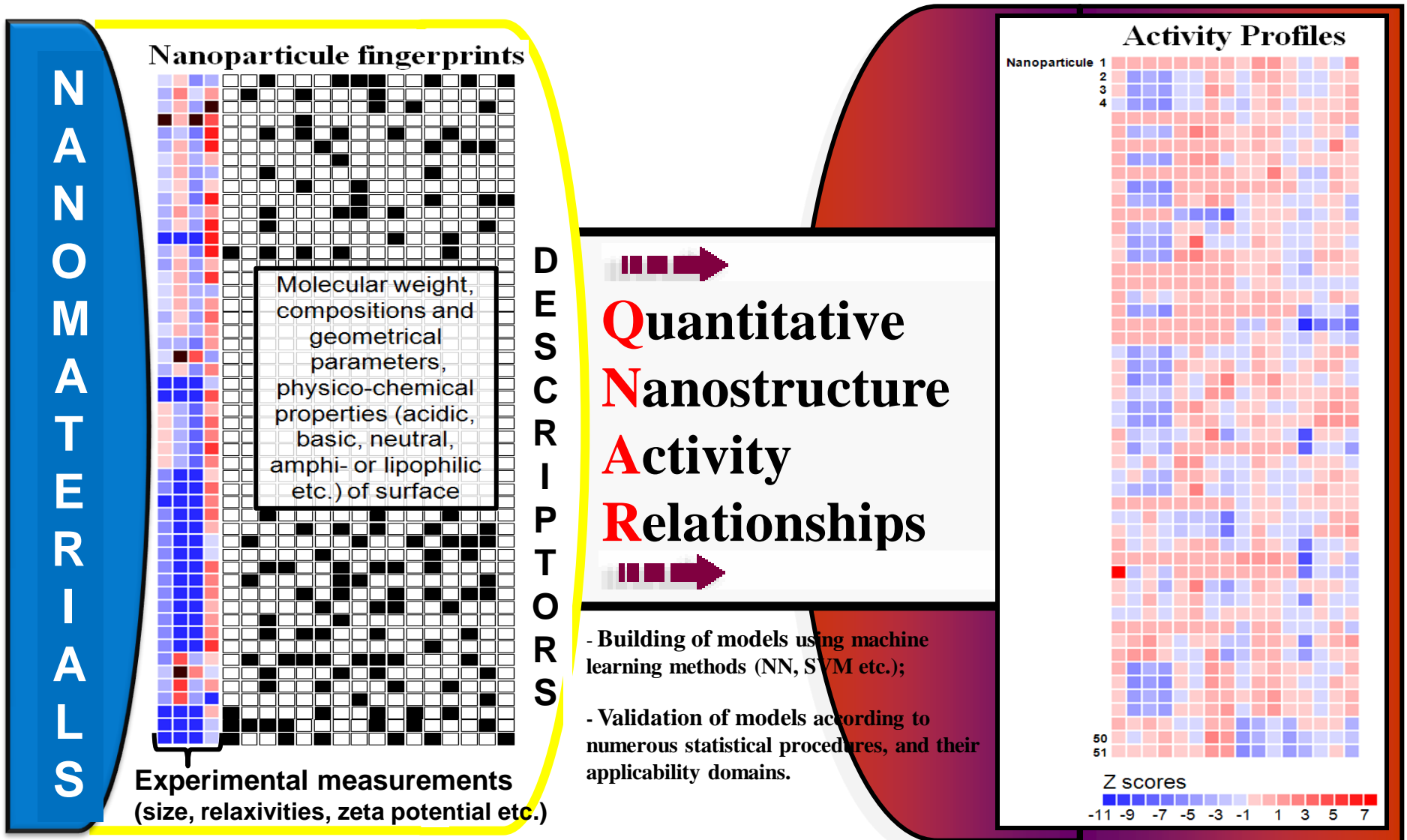
# Conclusions of Task 1 studies

- NPs were characterized for particle size, charge, morphology, quantitative and qualitative cell uptake.
- Particle size analysis shows that the NP sizes were about 20 fold higher than the average particle size provided by the manufacturer. Surface composition analysis confirmed the presence of carbon coating on the surface of C-Cu and C-Ni NPs.
- Cu and C-Cu NPs were found to be more toxic than Ni and C-Ni NPs.
- For C-Cu NPs, the presence of carbon coating retards the release of Cu ions and facilitates cell uptake. Although, both Cu and C-Cu NPs are eventually toxic; Cu NPs induce equivalent membrane damage as C-Cu NPs but at a five fold lower dose.
- The characterization and toxicity data suggests that the presence of carbon coating interferes with the interaction of C-Cu NPs with the cell surface and alters the mechanism of toxicity of Cu NPs and C-Cu NPs. At least at doses lower than 10  $\mu\text{g/ml}$  for C-Cu NPs, the mechanism of toxicity seems to be initiated primarily as a result of uptake of C-Cu NPs into the cells resulting in mitochondrial damage. Whereas for Cu NPs, as low as 2.5  $\mu\text{g/ml}$  dose induces membrane damage and therefore Cu NPs seem to act primarily by damaging the cell membrane surface.

# Subtask 2: Research Hypothesis

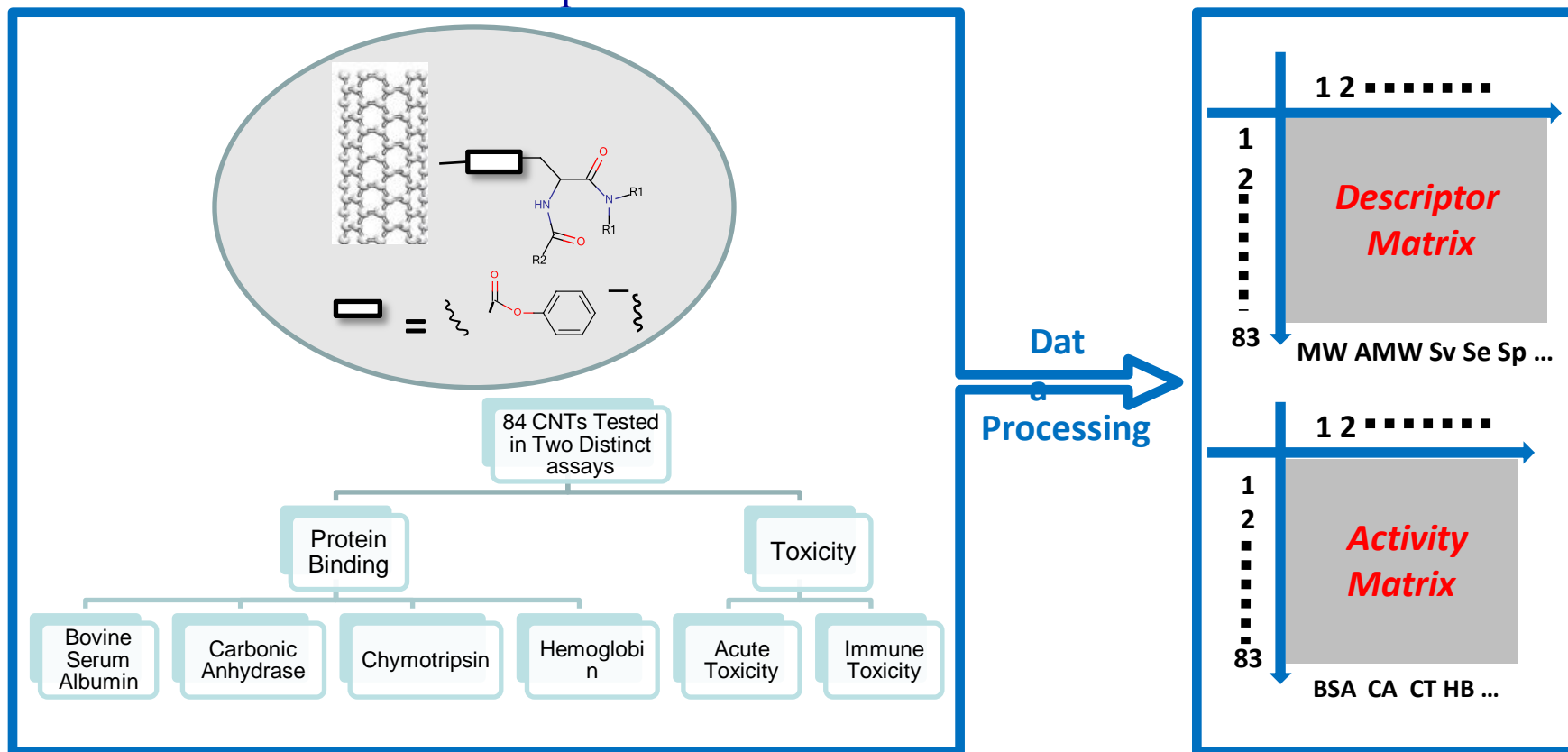
- The biological/toxicological properties of carbon nanotubes (CNTs) depend on the compositional/physical/chemical/geometrical properties of the CNTs.
- Toxicological data obtained from *in-vitro* cellular-based toxicity assays will correlate reasonably with *in-vivo* findings.
- Surface chemistry could provide sufficient information in predicting the behavior of CNTs in both in vitro and in vivo assays.
- Using physical/chemical characterization and toxicological screens for an ensemble of MNPs, it will be possible to develop **predictive Quantitative Nanostructure – Activity (QNAR) models**.

# Subtask 2: QNAR Scheme



# Subtask 2: Data Retrieving and Processing

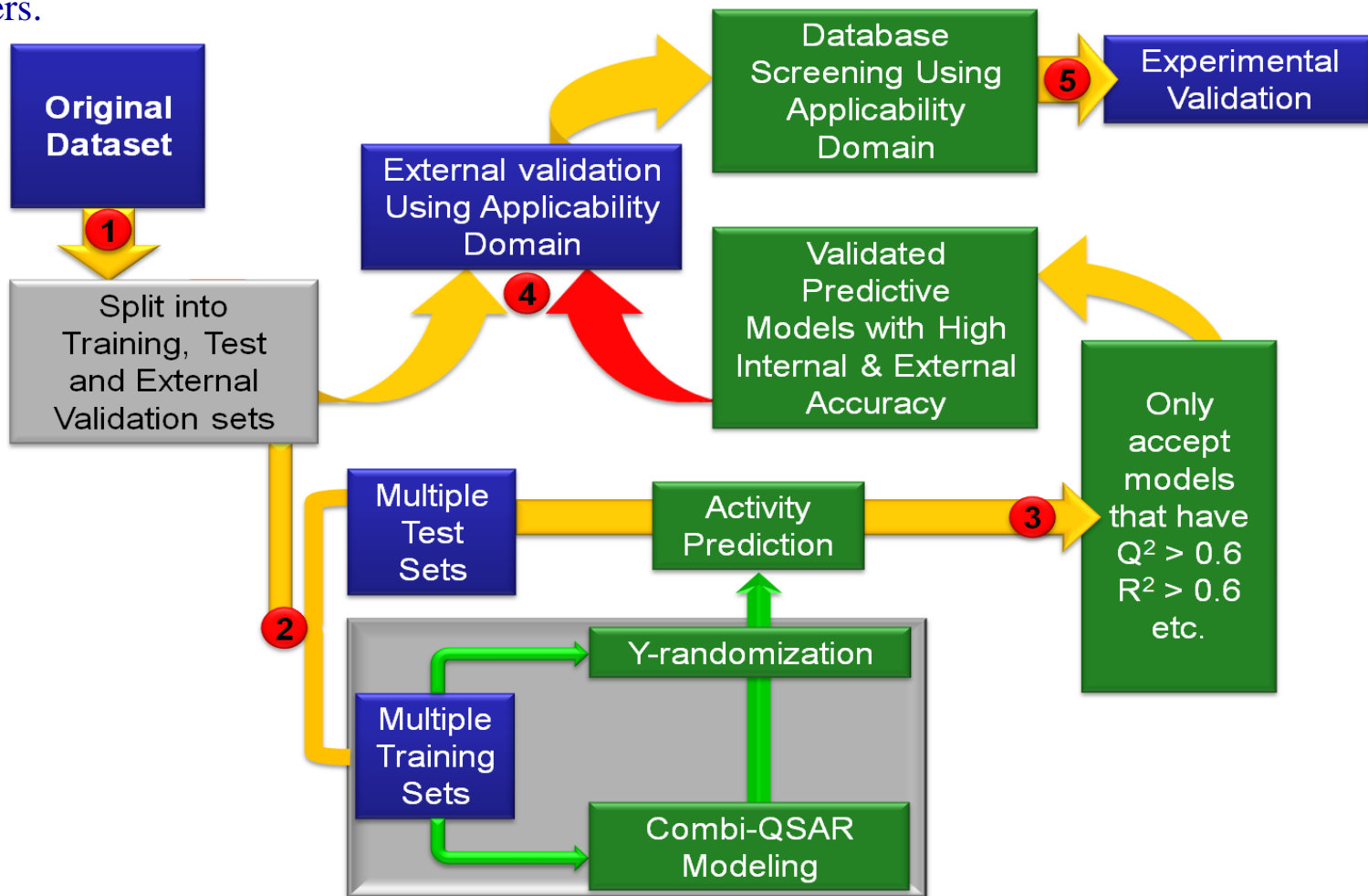
Recently\*, a series of 84 CNTs decorated with surface organic molecules were tested in protein binding, acute toxicity and immune toxicity assays in Dr. Bing Yan's group at St. Jude Children's Research Hospital.



\*Zhou, H., et al. A nano-combinatorial library strategy for the discovery of nanotubes with reduced protein-binding, cytotoxicity, and immune response. *Nano. Lett.*, 2008, 8, 859-865.

# Subtask 2: Validated QNAR Workflow

We followed a standardized, predictive QSAR workflow previously established by our group\*. Models' prediction power is assessed by external cross-validation techniques as well as rigorous statistical parameters.



\* Tropsha, A. *Best Practices for QSAR Model Development, Validation, and Exploitation* Mol. Inf., 2010, 29, 476 – 488).



# **Subtask 2: Research Methods**

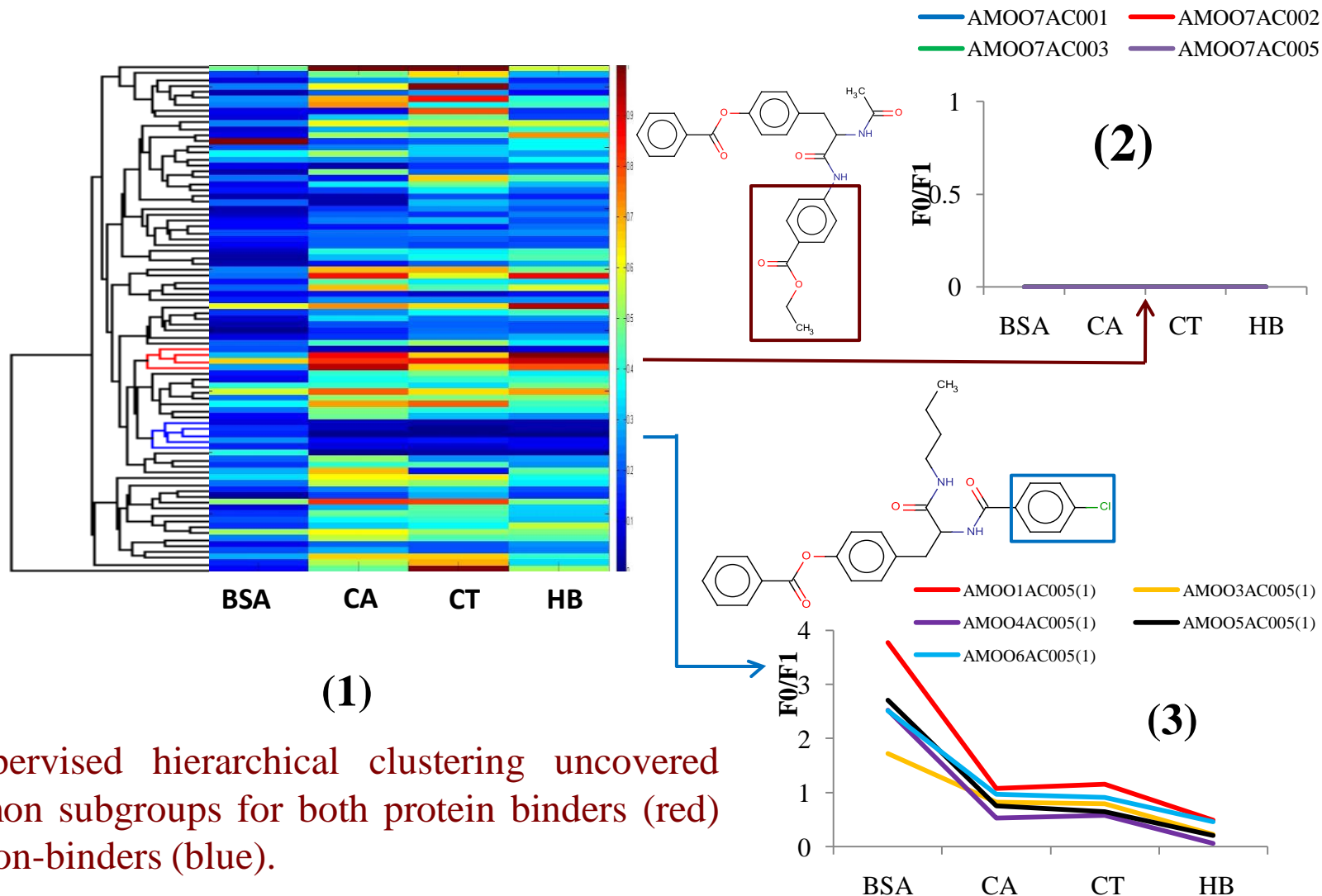
- Descriptors:

Each carbon nanotube was represented by a single copy of its surface molecule. Molecular descriptors were calculated for each CNT using Dragon and MOE software.

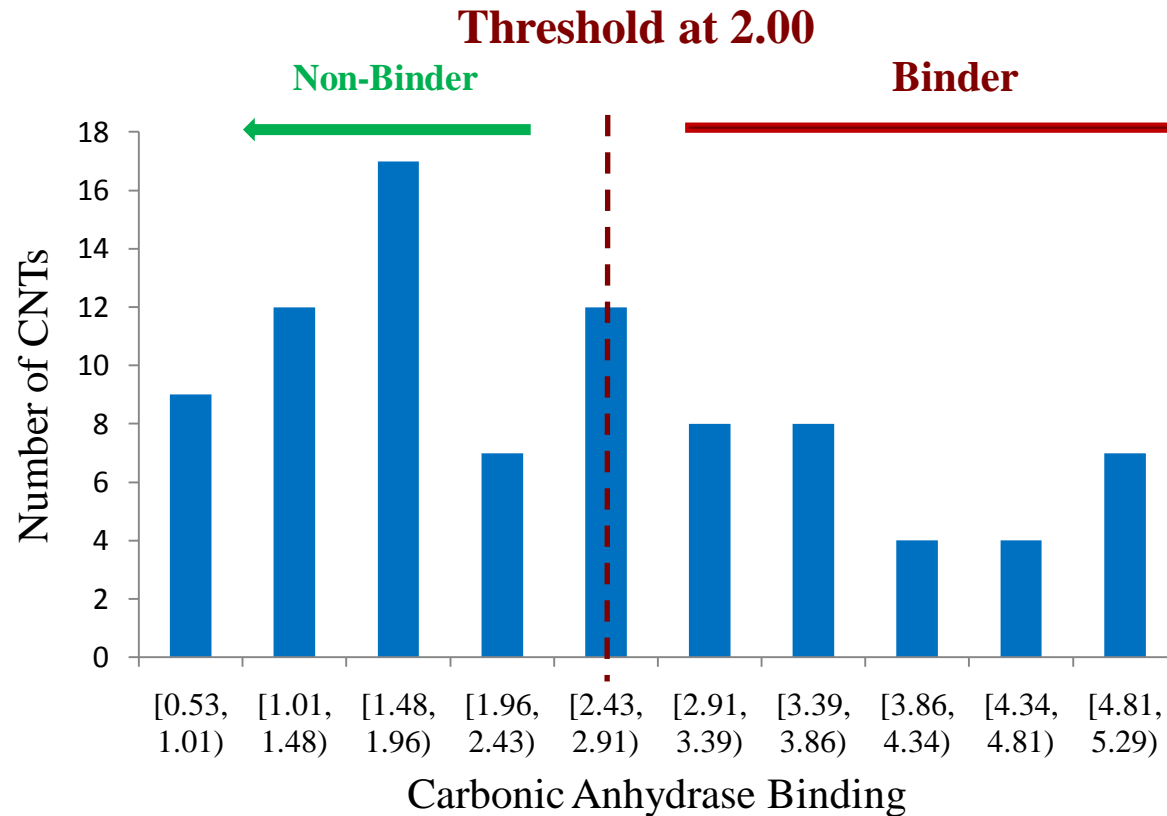
- Modeling technique:

Consensus modeling approach was used by combining different machine learning methods (k nearest neighbors, support vector machine and random forest) with different sets of chemical descriptors.

# Subtask 2: Clustering Analysis of Protein Binding Profile



# Subtask 2: QNAR Modeling of Carbonic Anhydrase Binding



CNTs with carbonic anhydrase binding affinity greater than 2 were labeled as binders, and otherwise non-binders.

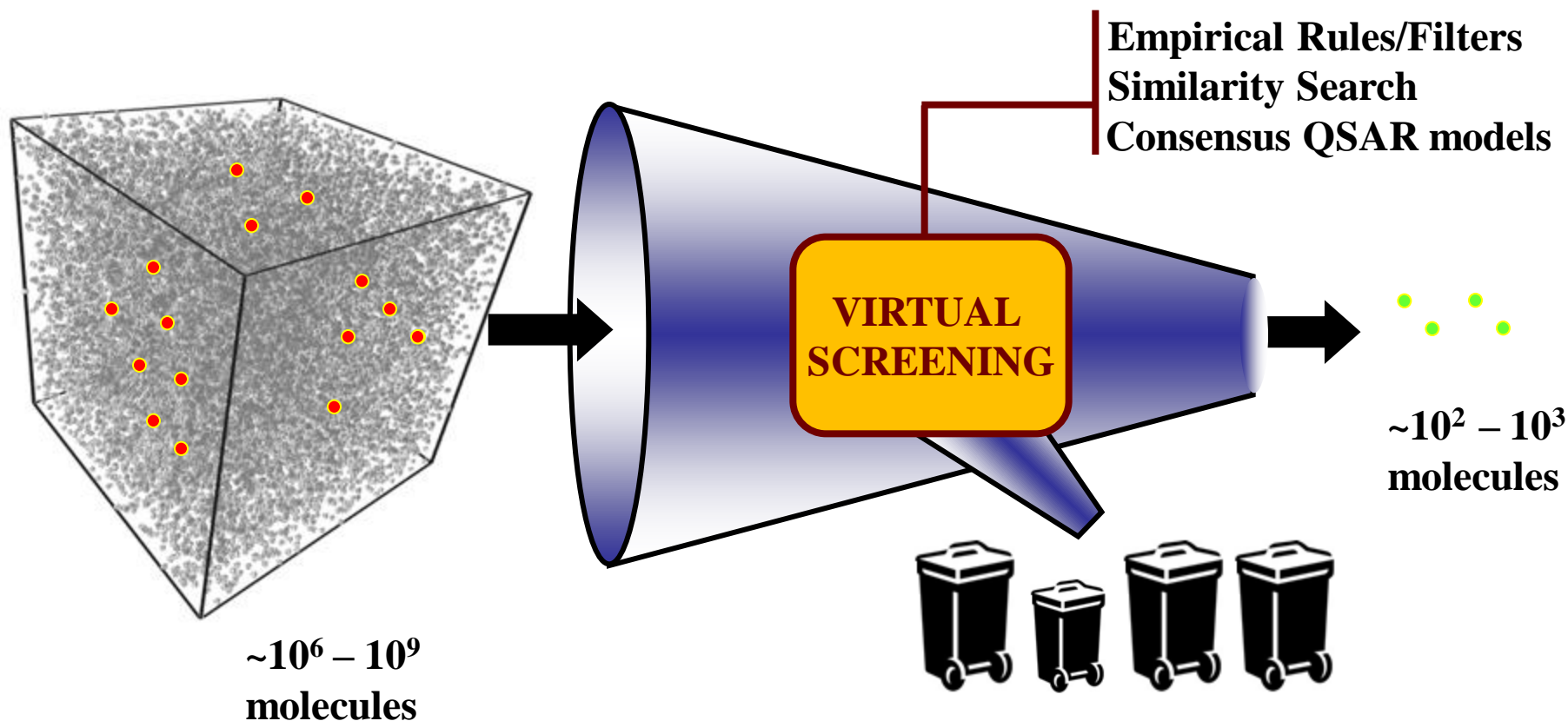
## Subtask 2: QNAR Modeling of CA Binding

		kNN-Dragon	SVM-Dragon	RF-Dragon	kNN-MOE	SVM-MOE	RF-MOE
<b>F0</b>	Sens.	0.70	0.70	0.70	0.70	0.70	0.70
	Spec.	0.83	0.83	0.83	0.83	0.67	0.83
	Accr.	0.75	0.75	0.75	0.75	0.69	0.75
<b>F1</b>	Sens.	0.80	0.60	0.80	0.80	0.70	0.80
	Spec.	1.00	1.00	1.00	1.00	0.67	1.00
	Accr.	0.88	0.75	0.88	0.88	0.69	0.88
<b>F2</b>	Sens.	0.88	0.75	0.75	0.50	0.63	0.75
	Spec.	0.63	0.44	0.75	0.63	0.50	0.50
	Accr.	0.75	0.63	0.75	0.56	0.56	0.63
<b>F3</b>	Sens.	0.86	0.86	0.86	0.86	0.86	0.43
	Spec.	0.67	0.56	0.67	0.67	0.44	0.67
	Accr.	0.75	0.69	0.75	0.75	0.63	0.56
<b>F4</b>	Sens.	0.63	0.63	0.63	0.63	0.50	0.63
	Spec.	0.64	0.64	0.55	0.45	0.64	0.55
	Accr.	0.63	0.63	0.58	0.53	0.58	0.58
<b>Overall</b>	Sens.	0.77	0.70	0.74	0.70	0.67	0.67
	Spec.	0.73	0.68	0.73	0.68	0.58	0.68
	Accr.	<b>0.75</b>	0.69	<b>0.73</b>	0.69	0.63	0.67

Acceptable models can thus be applied to virtual screening

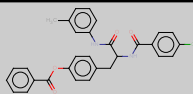
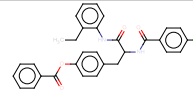
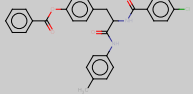
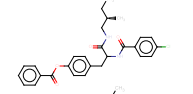
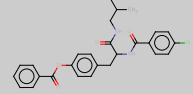
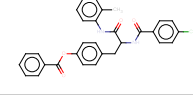
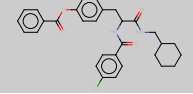
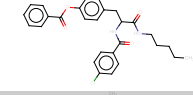
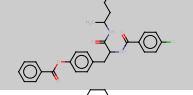
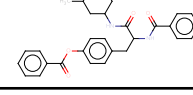
*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

# Subtask 2: Virtual Screening of External Library



240,000 *in silico* designed small molecules which are considered attachable have been subjected to VS seeking for non-toxic NPs or non-binders.

## Subtask 2: Virtual Hits of CA Non-Binders

ID	Structure	kNN	RF	SVM
128836		0.012	0	0
124236		0.014	0	0
164836		0.015	0	0
40436		0.020	0	0
10836		0.020	0	0
152036		0.023	0	0
5636		0.024	0	0.02
12236		0.024	0	0
51836		0.025	0	0
49236		0.027	0	0

Lower prediction score means lower predicted protein binding affinity

# Subtask 2: Conclusions

- Chemical scaffolds have been found by clustering analysis that lead to high/low protein profile
- Endpoint-specific QNAR models have been developed for a series of functional carbon nanotubes
- Virtually confirmed hits were identified and experimental verification is under investigation.

# Industrial Interactions and Technology Transfer

- **Round Robin Effort:**

Carried out characterization and toxicity analysis of CeO<sub>2</sub> nanoparticles at UNC-CH as part of coordinated effort to test the nanoparticles across different universities.

Active participation in the teleconference with academic and industrial partners.

- **TECHCON 2010:**

Discussion with Brian Raley (Global Foundaries) and SRC members

- The study in subtask 1 provides insights into differential physicochemical properties of the nanoparticles due to surface carbon coating which was also linked to the differences observed in the toxicity mechanisms of these nanoparticles. Furthermore a dose dependent and kinetic analysis of toxicity of Cu and C-Cu NPs is provided to aid informed decisions on the use and monitoring concentrations of these nanoparticles in semiconductor manufacturing operations as the toxicity was not just a function of the released Cu ion fraction.
- Chemical identities of CNT modifiers predicted to favor lower protein binding were transferred to Dr. Bing Yan for experimental validation



# Future Plans

## Next Year Plans

- Subtask 1:
  - Complete the metal ion release and membrane damage assays for Ni and C-Ni nanoparticles.
  - Apply the established set of methods to evaluate the toxicity of nanoparticles that are of interest to SRC member companies.
- Subtask 2:
  - Establish a database of experimental nanotoxicity data
  - Develop extended QNTR models of all available nanotoxicity data (e.g., new datasets are being collected by colleagues at EPA and NTP)
  - Validate current models by confirmatory experiments

## Long-Term Plans

- Obtain predictive knowledge of physical and chemical properties of MNPs that affect human cells and utilize this knowledge for improved MNP experimental design and prioritized toxicity testing.

# Publications, Presentations, and Recognitions/Awards

- “Effect of Carbon Coating on the Physicochemical Characteristics and Toxicity Mechanisms of Carbon Coated and Non Coated Copper and Nickel Nanoparticles” Research manuscript in preparation for submission to ACS Nano.
- Shalini Minocha, Anuraag Sarangi, Alexander Tropsha, Russell J. Mumper. “Physicochemical Characterization and Toxicity Evaluation of Metal-Based Manufactured Nanoparticles.” Oral and poster presentation at TECHCON 2010, Austin, TX, September 12-15, **2010**.
- Shalini Minocha and Russell J. Mumper, “In-vitro Assays to Assess the Toxic Potential of Manufactured Nanoparticles”, 2009 AAPS Annual Meeting and Exposition, Los Angeles CA, November 8-12, **2009**.
- Denis Fourches, Lin Ye, Russell J. Mumper and Alexander Tropsha. Assessing the Biological Effects of Nanoparticles Using Quantitative Nanostructure – Activity Relationships. Spring 2009 ACS Meeting and Exposition, Salt Lake City, UT, March 22-26, **2009**.
- Dongqiuye Pu, Denis Fourches, Alexander Tropsha. Quantitative Nanostructure-Toxicity Relationship (QNTR) Modeling. CMMI Conference, Atlanta, GA, Jan. 4-7, <http://www.nanowerk.com/spotlight/spotid=18875.php>.

# Publications, Presentations, and Recognitions/Awards (cont.)

- Denis Fourches, Dongqiuye Pu, Russell J. Mumper and Alexander Tropsha. Quantitative Nanostructure-Toxicity Relationship (QNTR) Modeling. *ACS nano*. **2010** Oct 26;4(10): 5703-12. **NOTE: This paper was a subject of spotlight in Nanowerk,**  
**<http://www.nanowerk.com/spotlight/spotid=18875.php>.**
- Denis Fourches, Dongqiuye Pu, Alexander Tropsha. Exploring Quantitative Nanostructure-Activity Relationships (QNAR) Modeling as a Tool for Predicting Biological Effects of Manufactured Nanoparticles. *Combinatorial Chemistry & High Throughput Screening*, **2011**, in presss..

# Low ESH-impact Gate Stack Fabrication by Selective Surface Chemistry

*(Task Number: 425.026)*

Shawn Miller and Anthony Muscat

Department of Chemical and Environmental Engineering

University of Arizona, Tucson, AZ 85721



ERC Review Meeting  
March 10-11, 2011  
Tucson, AZ

Industrial partners:  
Sematech  
ASM

# Low ESH-impact Gate Stack Fabrication by Selective Surface Chemistry

*(Task Number: 425.026)*

## PI:

- Anthony Muscat, Chemical and Environmental Engineering, UA

## Graduate Students:

- Shawn Miller, MS candidate, Optical Science and Engineering, UA

## Cost Share (other than core ERC funding):

- ASM

## Industrial Interactions and Technology Transfer

- Biweekly project updates to ASM
  - Eric Shero
  - Mohith Verghese

## Presentations

- “Improvements in self-assembled monolayer quality and time scale,” American Vacuum Society, ALD: Dielectrics for Semiconductors, October 19, 2010, Albuquerque, NM

## Mentors

- Joel M. Barnett, SEMATECH
- Willy Rachmady, Intel

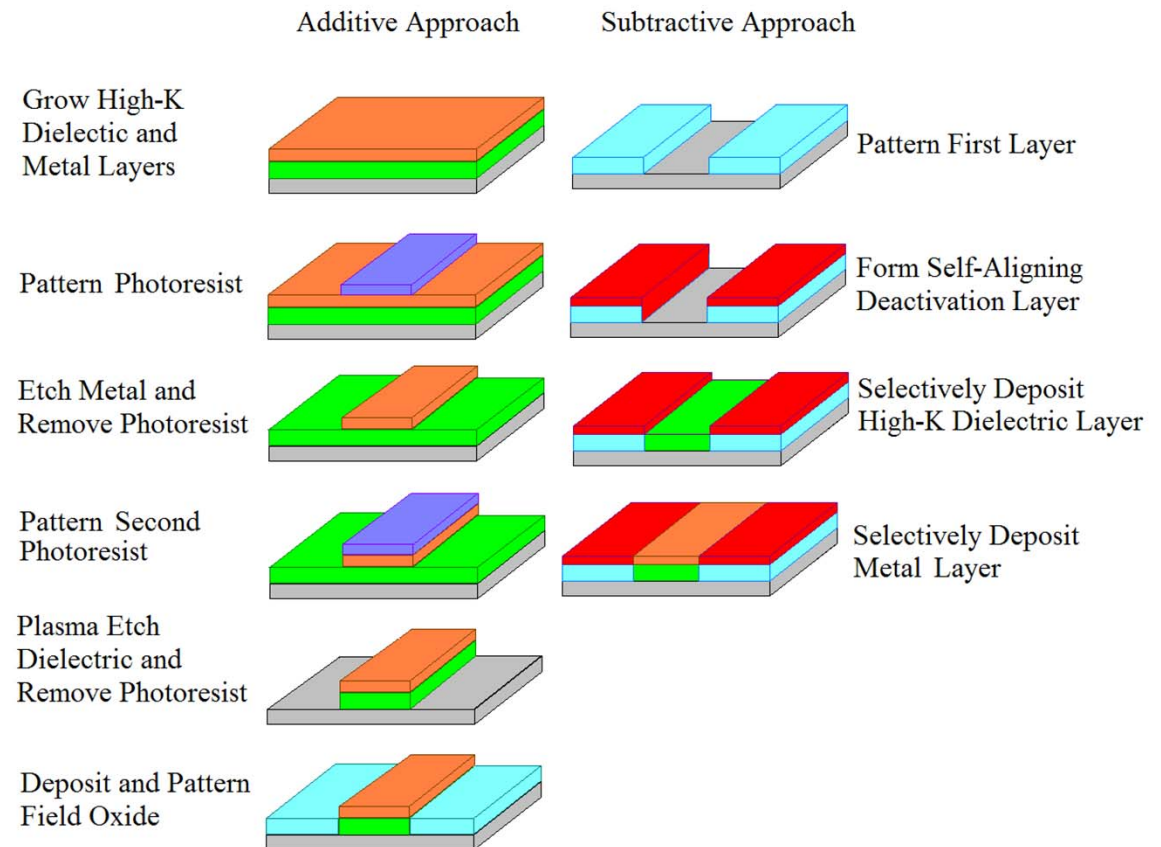
# Overall Objectives

- **Simplify multistep subtractive processing used in microelectronic device manufacturing**

- Develop new additive processes that can be integrated into current devices flows
- Minimize water, energy, chemicals, and materials consumption
- Reduce processing steps and costs

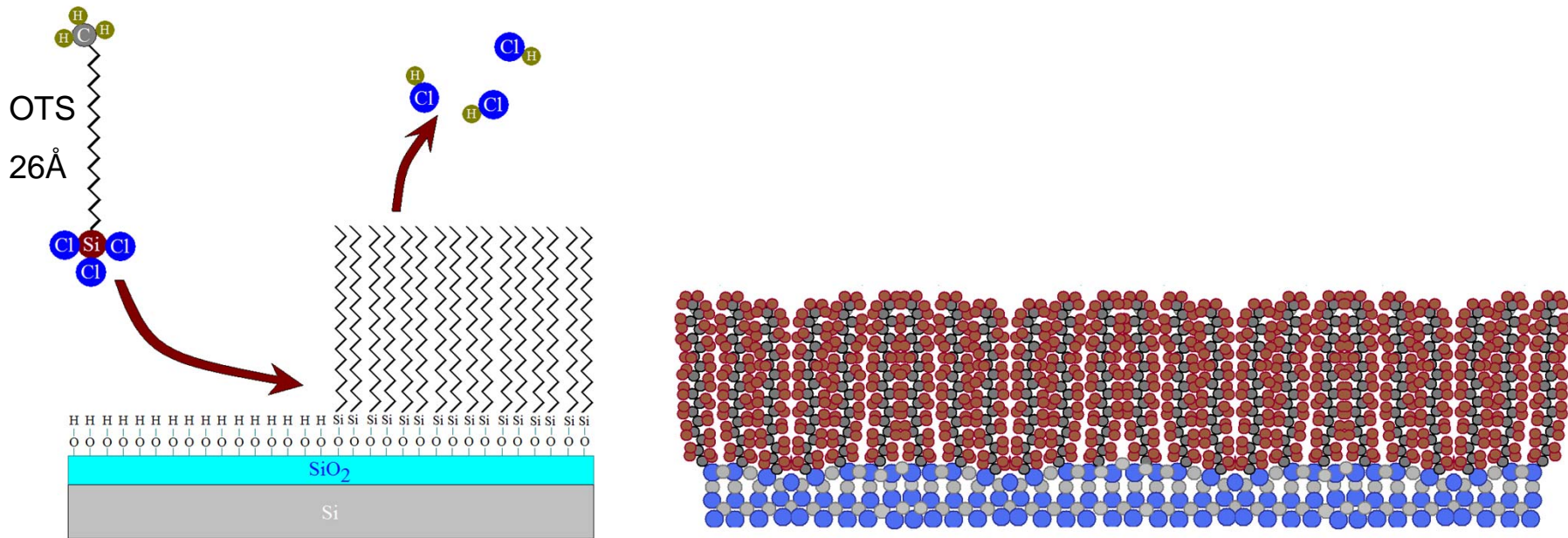
- **Focus on high-k gate stack testbed**

- Fabricate low defect high-k/semiconductor interfaces





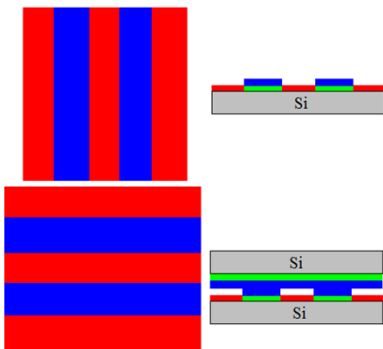
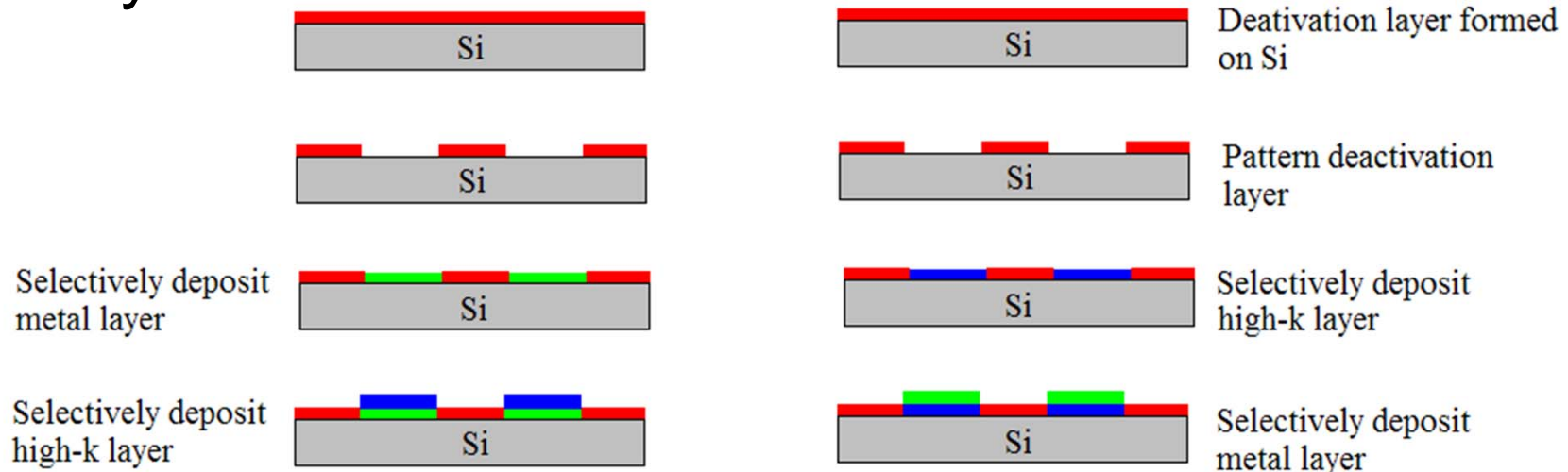
# Technical objective



- Use a self-assembled monolayer (SAM) which acts as a chemically inert layer on reactor surfaces preventing ALD deposition from occurring
  - Identify and solve defects in SAM layers which result in deactivation failure (completed)
  - Pattern SAM layer for device manufacturing
  - Provide in-situ vapor phase formation of the SAM layer

# Novel Device Manufacturing

- Single patterning step for deactivation layer
- Use selective ALD of metal and high-k dielectric layer



Xia, Q., "Memristor-CMOS Hybrid Integrated Circuits for Reconfigurable Logic", Nano Letters, Vol.9, No.10, 3640-3645, 2009.

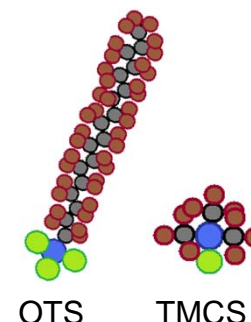
Coll, M., "Formation of Silicon-Based Molecular Electronic Structures Using Flip-Chip Lamination" J. AM. CHEM. SOC., 131, 12451-12457, 2009



# ESH Metrics and Impact:

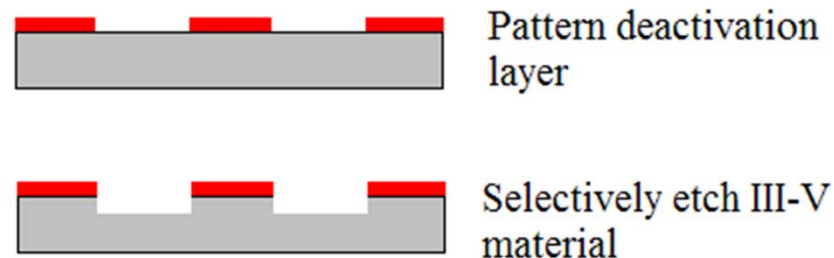
## Cost Reduction

- Safety of SAM solution
  - Chlorosilanes dissolved in toluene
    - Chlorosilanes reacts with water, air sensitive, and combustible
      - OTS (octadecyltrichlorosilane)
      - TMCS (trimethylchlorosilane)
    - **Batch processing must be done in vented environment with controlled humidity and no spark or open flame**
    - **Vapor process could eliminate solvent**
  - Carbon and HCl are only byproducts of the surface reaction
- Reduce number of manufacturing steps and costs
  - Additive processing
  - Minimize chemical usage and reduce chemical waste
  - Single photoresist patterning step for both metal and dielectric
    - Possible elimination of PR patterning
  - Dielectric and metal deposition done in same reactor
  - No plasma etching steps for dielectric or metal layer
  - Vapor phase SAM formation lowers material/waste/environmental impact
- Additional benefits of hydrophobic surface
  - SAM coating prevents aqueous solutions from interacting with surfaces
    - Coating metal parts or work surfaces which are exposed to water-based solution reduces the need for cleaning such tools/equipment
    - Coat ALD reactor walls with SAM to extend up-time, reduce cleaning, and improve throughput

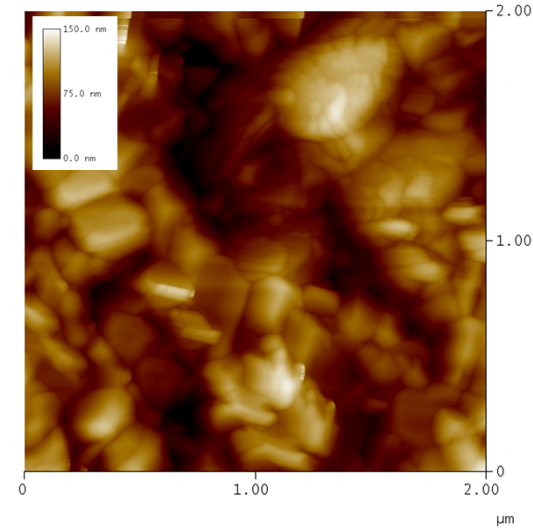
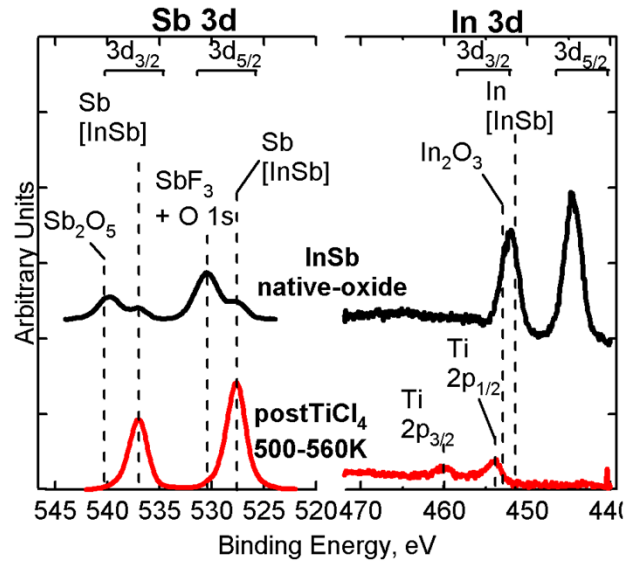


# Etching Control

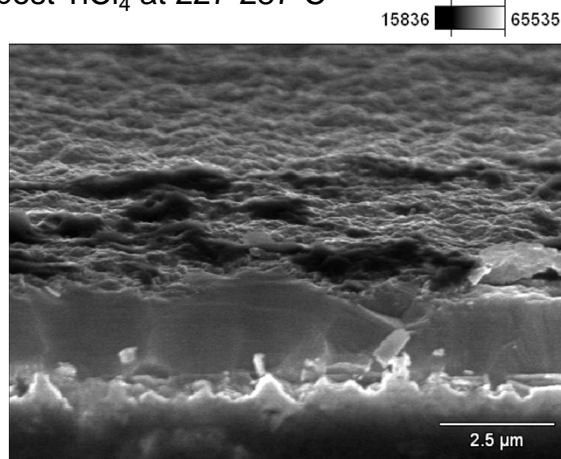
- Deactivation layer can be patterned on III-V semiconductors
  - Controlled chemical etching
  - Deactivation layer resistant to many liquid and vapor phase chemistries



# InSb(100) – TiCl<sub>4</sub> exposure



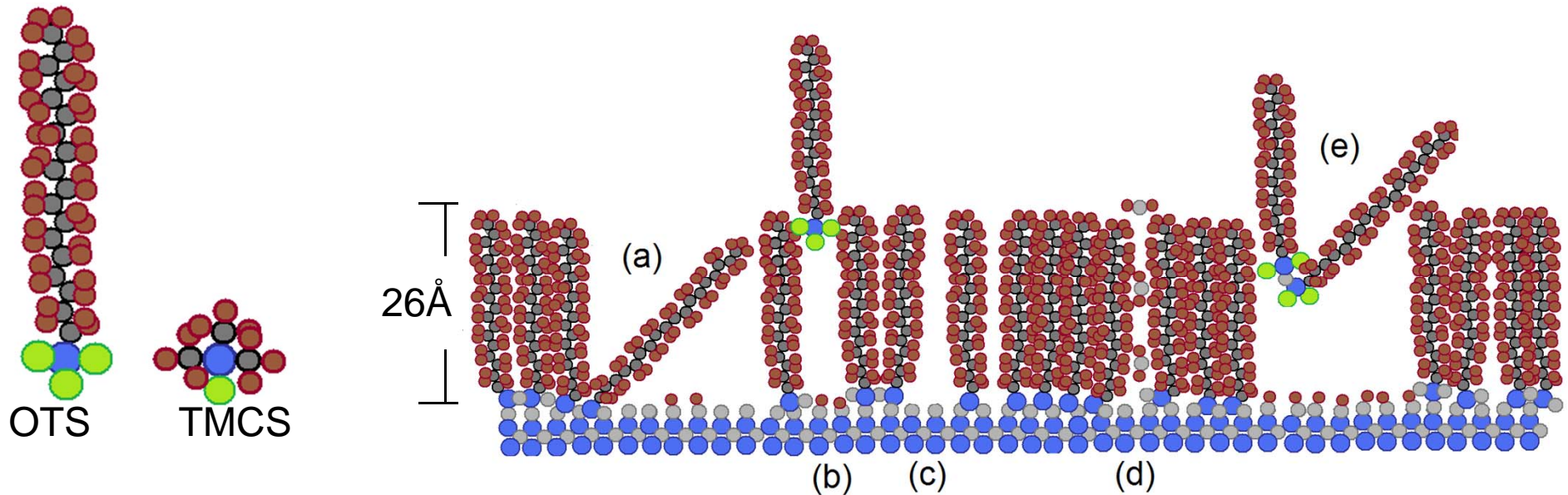
SEM post TiCl<sub>4</sub> at 227-287°C



RMS = 33.4 nm

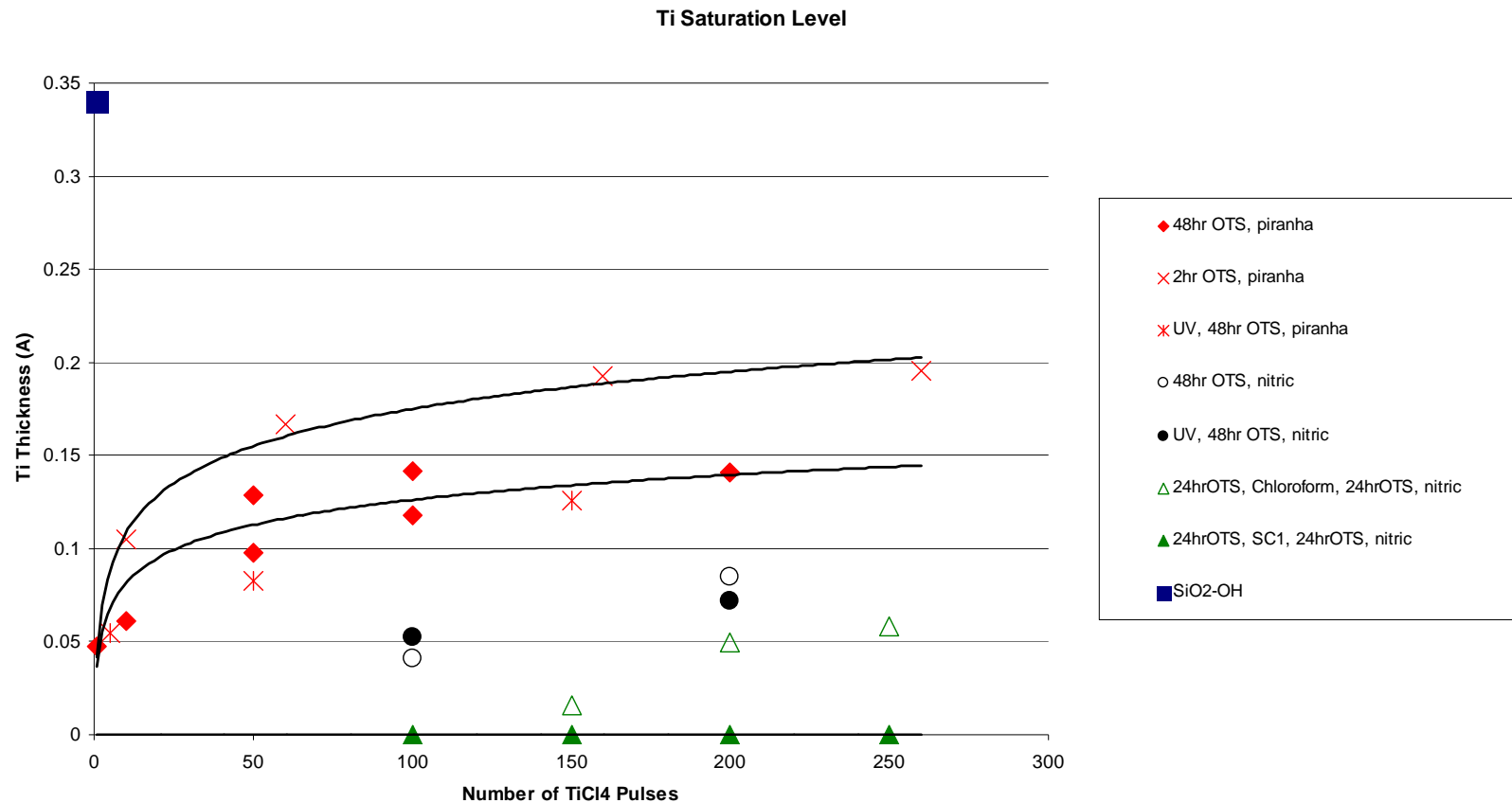
- Effect of chlorine-based metal precursor on III-V surfaces investigated
  - Expose native oxide covered InSb(100) to TiCl<sub>4</sub> at 10<sup>-7</sup> Torr and 227-287°C
- Chlorine based precursor selectively etched In at 227° C
  - Removed native oxide completely
  - Roughened surface

# SAM Defects



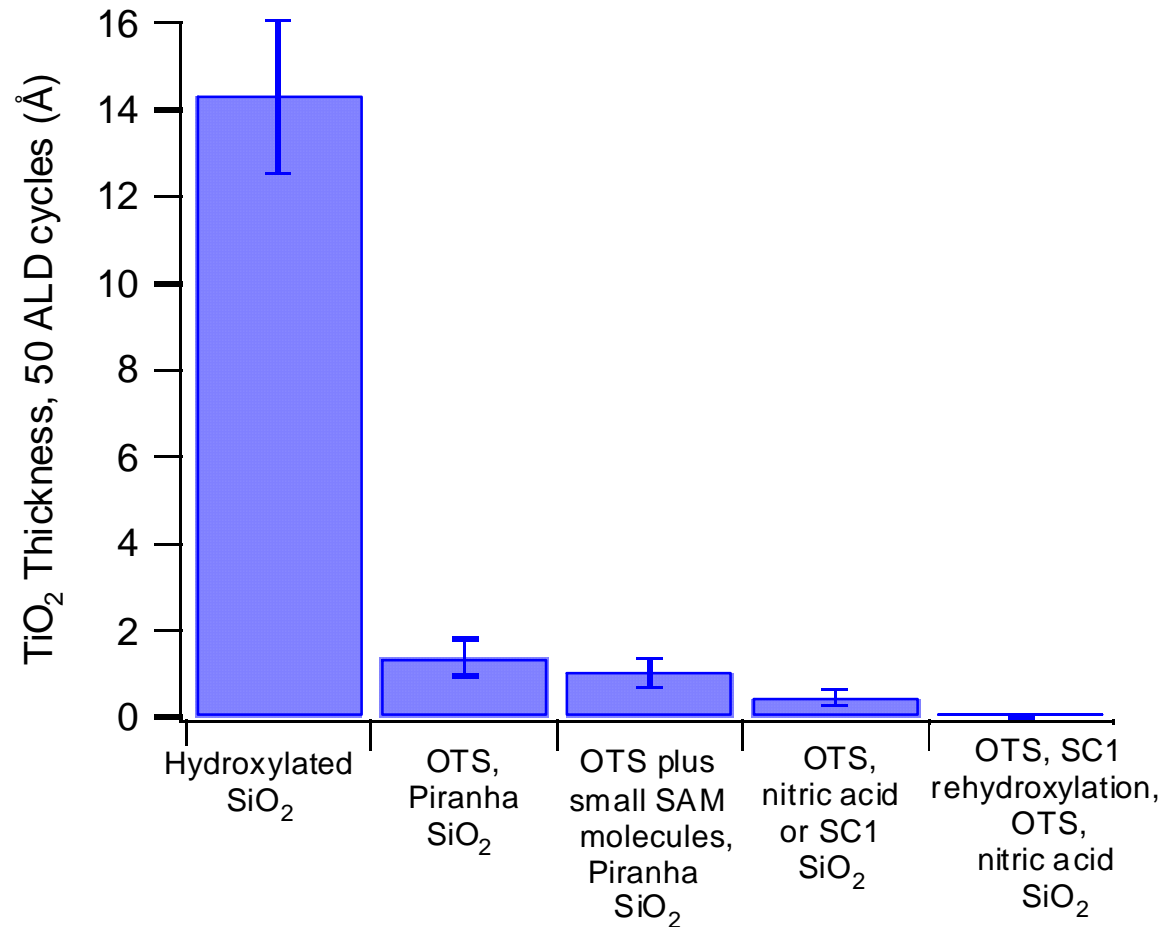
- (A) Poor alignment at island boundaries block surface sites (poor uniformity)
- (B,C) Gaps in SAM too small for primary SAM molecule
- (D) Water absorbed/adsorbed in SAM layer
  - Either during SAM formation or during ALD process
- (E) Polymerized SAM molecules on surface
  - Block surface sites
  - Excess polymer increases thickness and water contact angle
  - Could generate particles

# Defect monitoring using $\text{TiCl}_4$ pulses



- Defect level in SC1 re-hydroxylated samples was below XPS limit for up to 250 seconds of  $\text{TiCl}_4$  exposure

# Deactivation results



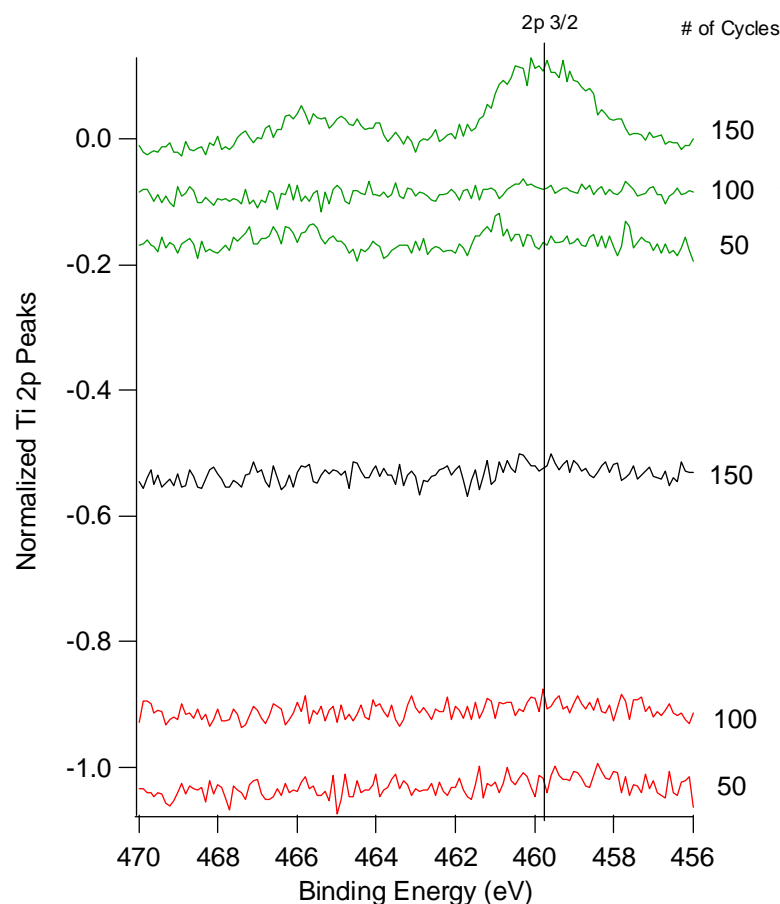
- Up to 200 Cycle deactivation achieved for TiO<sub>2</sub>
  - Previous best was 50 cycles for HfO<sub>2</sub> after 48hrs
- Providing more hydroxyl groups is key to continuing to increase density

# Time scale reduction with re-hydroxylation

- Samples removed from OTS every hour and treated with SC1 re-hydroxylation

- Deactivation for up to 100 cycles was achieved after only 1hr in OTS solution and 1hr in TMCS (trimethylchlorosilane) solution

– 1/24<sup>th</sup> original time scale

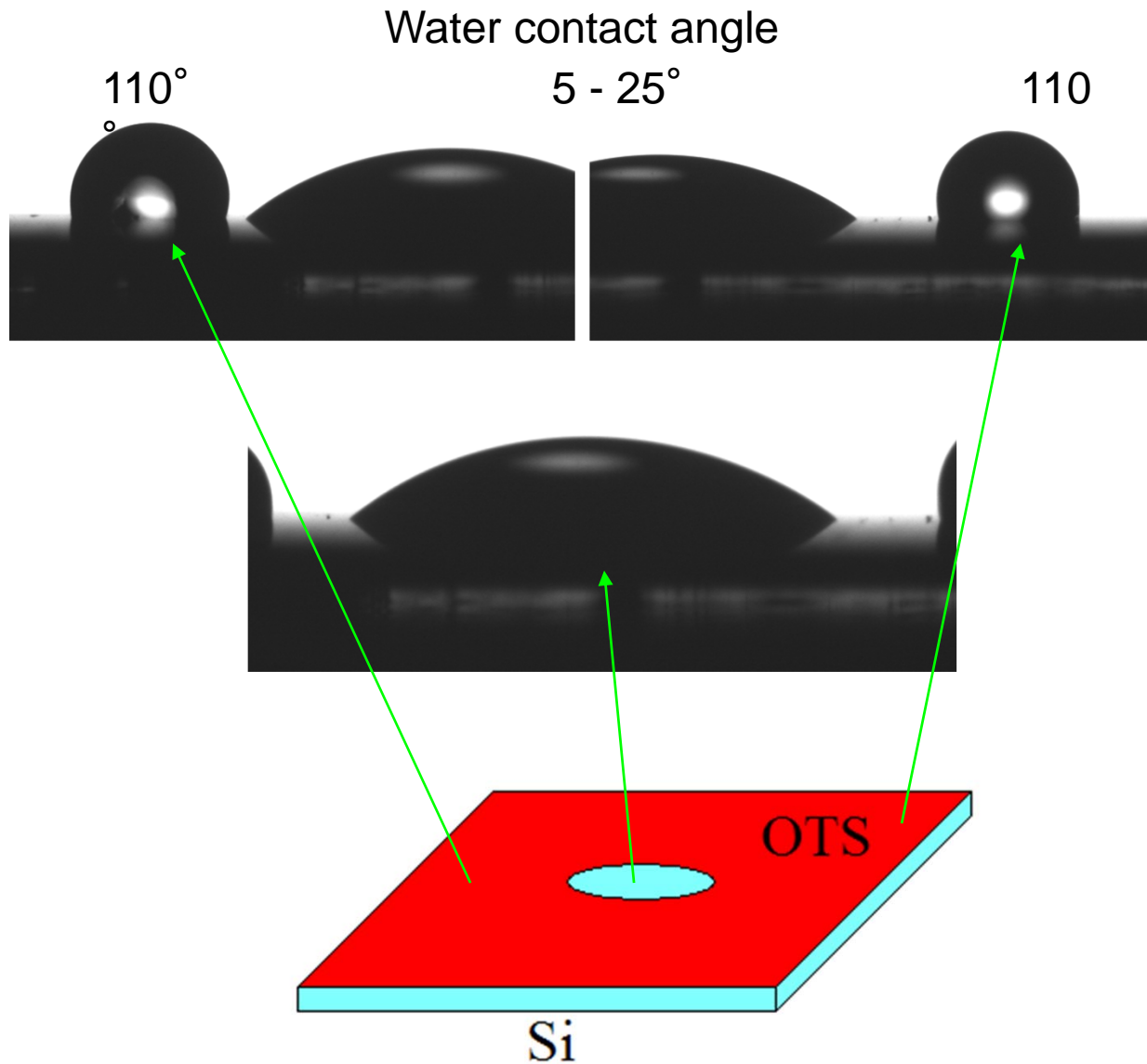


4 - 1hr OTS w/3 SC1 re-hydroxylations

4 - 1hr OTS w/4 SC1 re-hydroxylations  
+ 1hr TMCS

1hr OTS, SC1 re-hydroxylation, 1hr TMCS

# Selective high-k deposition

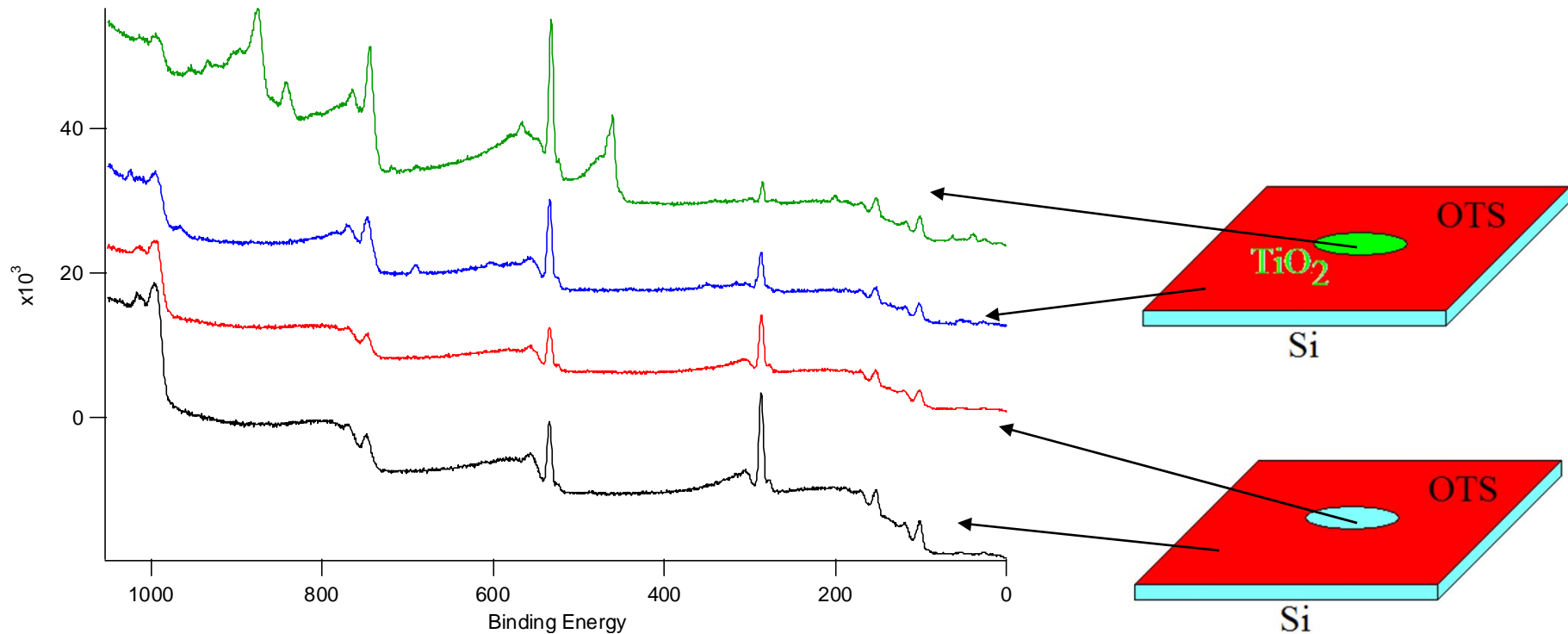


- SAM surfaces exposed to UV in air for 2.5 h through a simple mask
- Removal of SAM occurred only in UV/air exposed areas
- Surface was hydrophilic in UV/air exposed areas and hydrophobic on remaining OTS areas

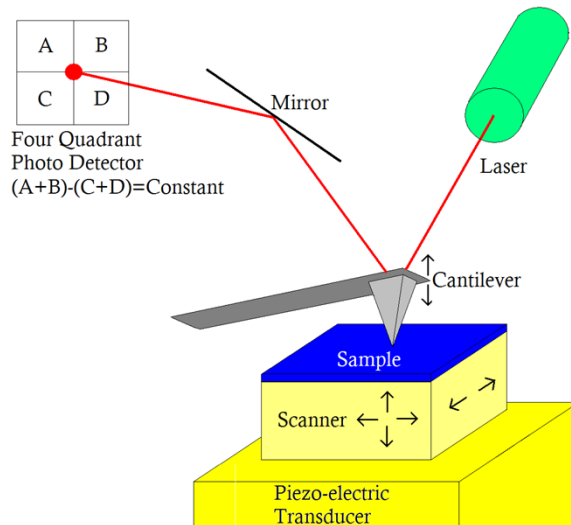


# Direct SAM patterning

- Selectively deposited 15Å of  $\text{TiO}_2$  only in open areas of OTS coated Si surface
- Pattern formed without photoresist



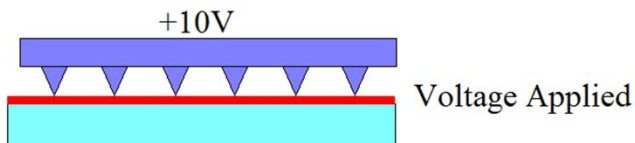
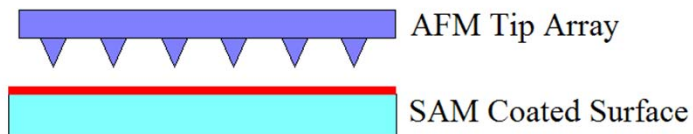
# Alternate patterning approach



- Conductive atomic force microscopy (AFM) removes SAM

- Multiple tip arrays can be used to make detailed nm scale patterns

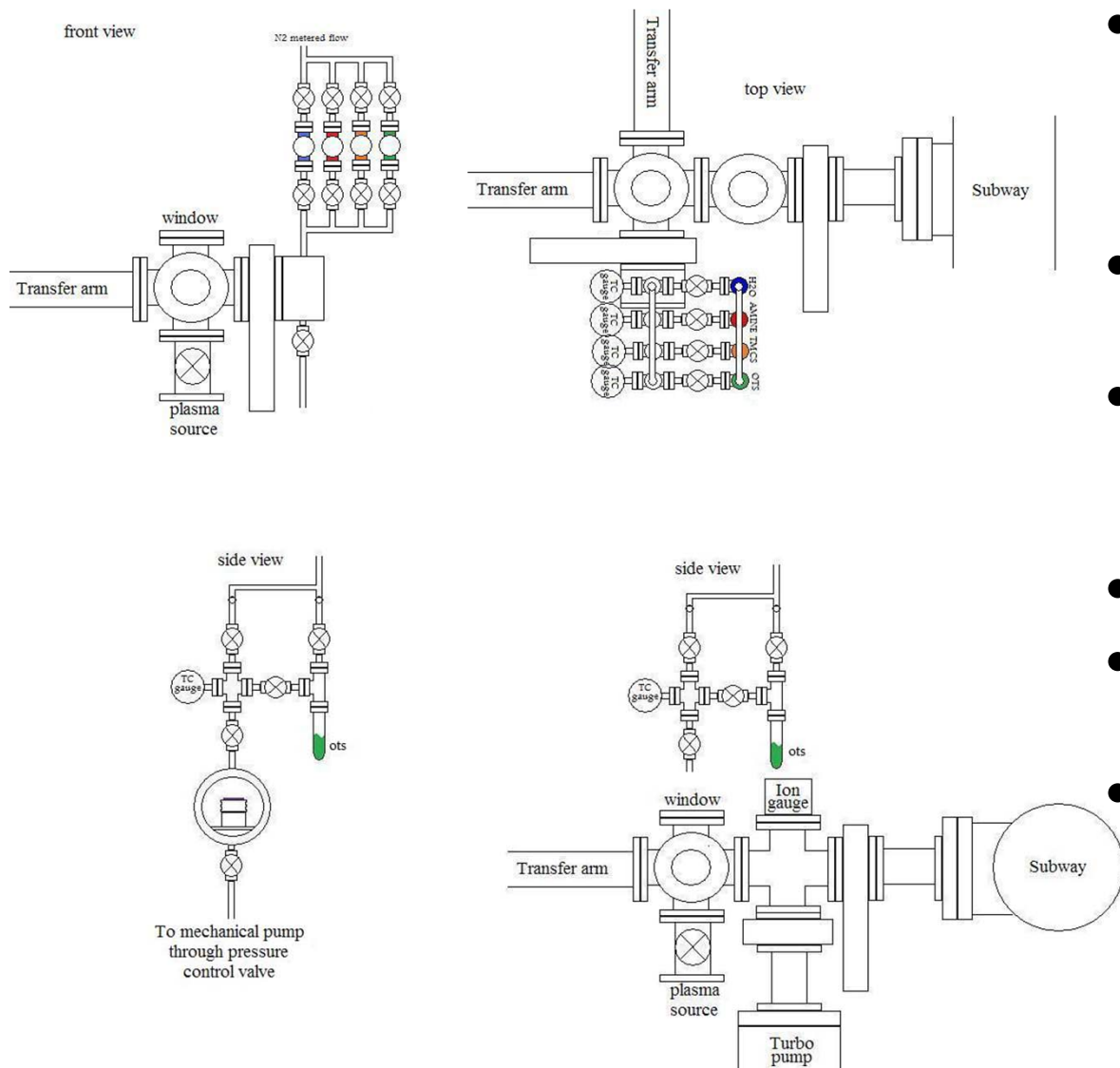
- No need for photoresist



# Important Learning from Liquid Phase

- Surface Hydroxylation proven to be the most important parameter in forming a high quality OTS SAM
  - OTS deposits quickly with abundant hydroxyl groups
    - Primary layer formed in first hour
  - OTS has difficulty finding small gaps once primary layer is formed
    - Same effect achieved with 1 hour TMCS exposure as with 3 1 hour OTS exposures and re-hydroxylations

# New SAM Vapor/In-situ Hydroxylation Reactor



- Safe to install on cluster apparatus
  - Polymerization not seen in previous reactor
- Provides more versatile vapor delivery
- Allows higher temperature testing
  - 300° C
- In-situ hydroxylation
- Connected in-situ to ALD reactor
- Vials are well isolated from other chemicals

# Conclusions

- It is possible to selectively control deposition of metal and high-k layers
  - 2 hr SAM formation time scale
  - Reduced SAM defects (100+ ALD cycles)
  - Only one patterning step required for metal and dielectric deposition (self-aligning high-k growth)
- Simplifies the front end gate stack manufacturing process
  - Reduced cost
  - Reduced material usage
  - Improve environmental performance

# Industrial Interactions and Technology Transfer

- Biweekly project updates to ASM
  - Eric Shero
  - Mohith Verghese

# Future Work

- Determine the line spreading and line edge roughness for different patterning approaches
- Determine usable lifetime of SAM solution
- Develop an industrially viable method for vapor phase delivery of SAM molecules
  - Pulse and purge both water and SAM molecules as opposed to sealing vapor in a reactor for extended time
  - Extend extraction process to vapor phase SAMs
- Investigate vapor phase ozone and gas phase HF/vapor treatment to increase and control hydroxylation of oxide surfaces
- Characterize SAM layers
  - Thermal stability for deactivation
  - Durability for large numbers of ALD cycles
  - Lifetime of SAM solution
- Investigate selective deposition/etching method on III-V semiconductor surfaces

# Lowering the Environmental Impact of High-k and Metal Gate-Stack Surface Preparation Processes

*(Task Number: 425.028)*

## PIs:

- **Yoshio Nishi, Electrical Engineering, Stanford University**
- **Srini Raghavan, Materials Science and Engineering, University of Arizona**
- **Bert Vermeire, Electrical Engineering, Arizona State University**
- **Farhang Shadman, Chemical Engineering, University of Arizona**

## Research Scientists:

- **Manish Keswani, Materials Science and Engineering, University of Arizona**
- **Jun Yan, Chemical Engineering, University of Arizona**

## Graduate Students:

- **Kedar Dhane, graduated; currently with Intel**
- **Gaurav Thareja, Electrical Engineering, Stanford University**
- **Davoud Zamani, Chemical Engineering, University of Arizona**
- **Xu Zhang, Electrical Engineering, Arizona State University**

## Cost Share (other than core ERC funding):

- **\$50k from Stanford CIS**
- **\$20k from WSP**

*SRC/Sematech Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*



# Objectives

- **Development of non-fluoride based etch chemistries for hafnium based high-k materials**
- **Elimination of galvanic corrosion between metal gate and polysilicon during wet etching**
- **Significant reduction of water and energy (hot water) usage during rinse**
- **Determination of chemical and electrical characterization methodology for surface preparation of high k dielectric films.**
- **Validation of low resource-usage processes using metal - high-k device fabrication and electrical characterization.**

# **ESH Metrics and Impact**

- **Reduction in the usage of HF and HCl; development of environmentally friendly, non-fluoride based etch chemistries for hafnium-based high-k materials**
- **Significant reduction in water usage during rinse**
- **Significant reduction in energy (hot water) usage during rinse**
- **Reduction of rinse time leading to increase in throughput and decrease in resource usage**

# **Subtask 1: Environmentally Friendly Chemical Systems for Patterning Silicates and Hafnium Oxide**

## **BACKGROUND**

- In the formation of high k- metal gate structures by the “gate first” process, etching of high k material after ‘P-metal’ removal to prepare the surface for ‘N- metal’ deposition is required. Additionally, selective etching of high k material with respect to  $\text{SiO}_2$  is also needed
- Currently used chemical system for etching Hf based high-k materials is dilute HF containing HCl; however, these high k materials become very difficult to etch when subjected to a thermal treatment
- HF based systems appear to induce galvanic corrosion of polysilicon, which is in contact with metal gate materials; reducing the oxygen level of HF has been recommended to reduce corrosion

# Materials and Experimental Procedures

- Materials

300 mm ALD  $\text{HfSi}_{0.74}\text{O}_{3.42}$  wafers:

- Provided by ASM
- Film Thickness:  $\sim 240 \text{ \AA}$

- Experimental Procedures:

- Wafer was cleaved into 2 x 2 cm samples for experiments
- Samples cleaned by IPA, rinsed with DI water and dried by  $\text{N}_2$
- Reduction of hafnium silicate film was carried out separately in gaseous phase system ( $\text{N}_2/\text{H}_2$ ,  $\text{CO}/\text{CO}_2$ ,  $\text{CO}/\text{N}_2$  and  $\text{CO}/\text{CO}_2/\text{N}_2$  gas mixtures at temperatures of 100 to 600 °C ) as well as in liquid phase system (Hydroxylamine 5 wt% aqueous solution)
- Samples were etched in hydrofluoric acid and ammonium hydroxide based aqueous solutions containing TIRON and EDTA as chelating agents post-reduction treatment
- Average etch rates of hafnium silicate film were calculated from thickness measurements determined using spectroscopic ellipsometer (J. A. Woollam Co.) at 5 different locations on the sample

# ESH Gain in Etching of Hafnium Silicate

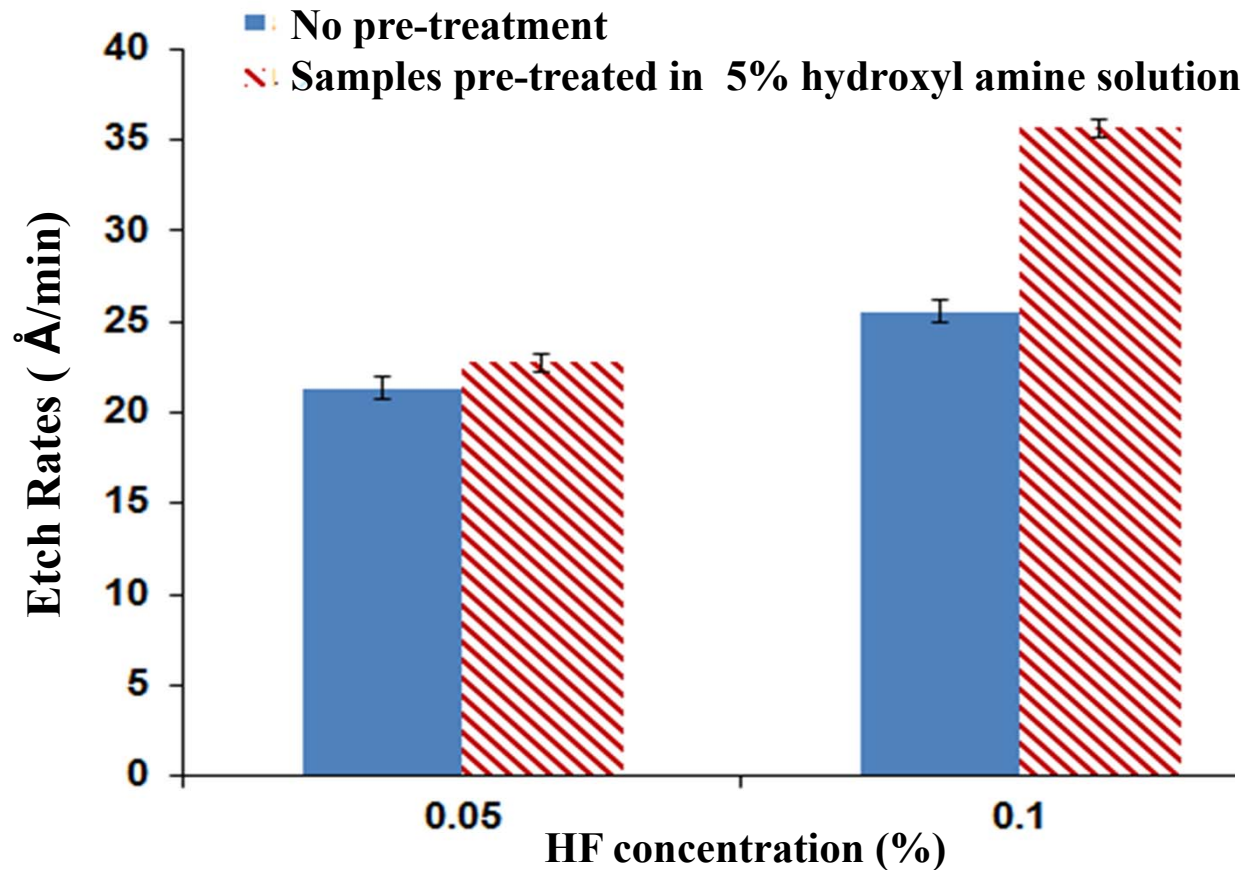
**Etching  $\text{HfSi}_{0.74}\text{O}_{3.42}$  in ammonia and HF based solutions after reduction treatment**

<b>Reduction Temperature (°C)</b>	100 - 600			
<b>Reduction Time (min)</b>	15 - 180			
<b>Reduction Atmosphere</b>	$\text{CO}/\text{CO}_2/\text{N}_2$	$\text{CO}/\text{N}_2$	$\text{CO}/\text{CO}_2$	$\text{N}_2/\text{H}_2$
<b>Etching Solutions</b>	$\text{NH}_4\text{OH}:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (1:1:5)	$\text{NH}_4\text{OH}$ (0-29%)	HF (0.1 & 1%)	

**Reduction of hafnium silicate using various gases at different temperatures was found to be ineffective in improving the etch rates of the film either in ammonium hydroxide or HF based aqueous solutions.**

# ESH Gain in Etching of Hafnium Silicate

Etching of  $\text{HfSi}_{0.74}\text{O}_{3.42}$  in DHF after treatment in 5 % aqueous hydroxyl amine solution



**Pretreatment of hafnium silicate in 5 % hydroxyl amine solution improves the etch rate of the film by 40 % in 0.1 % HF solution.**

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## **Subtask 2: Low-Water and Low-Energy New Rinse and Drying Recipes and Methodologies**

### **BACKGROUND**

- **Formation of high-k metal gate structures requires cleaning of fine geometries containing materials not traditionally used by the semiconductor industry. Wet etching must be quenched at the appropriate time**
- **More single wafer tools are used for cleaning, rinsing and drying because of better yield. Optimization of cycle time is critical for throughput and reduced resource usage**
- **Elucidating rate-limiting mechanisms to make possible multi-stage, resource-efficient recipes requires in-situ and real-time measurements and accurate simulation capabilities**
- **Validation of low resource-usage processes for high-volume manufacturing using electrical test structures**

# Quartz Crystal Microbalance Set Up



$$\Delta f = \frac{-2\Delta m f_0^2}{nA\sqrt{\mu\rho}}$$





# Process Model for DHF Interaction with HfO<sub>2</sub>

$$\frac{dC_s}{dt} = K_a C_b (S_0 - C_s) - K_d (C_s) \quad (1)$$

$$-\frac{1}{A} \frac{dM}{dt} = -(Mw_{HF}) \frac{dC_s}{dt} + (Mw_{HfO_2}) K_e C_b (S_0 - C_s) \quad (2)$$

$$\frac{1}{A} (M - M_0) = [C_b S_0 (Mw_{HF} K_a - Mw_{HfO_2} K_e) + \quad (3)$$
$$(Mw_{HfO_2} K_e C_b - Mw_{HF} K_a C_b - Mw_{HF} K_d) \times$$

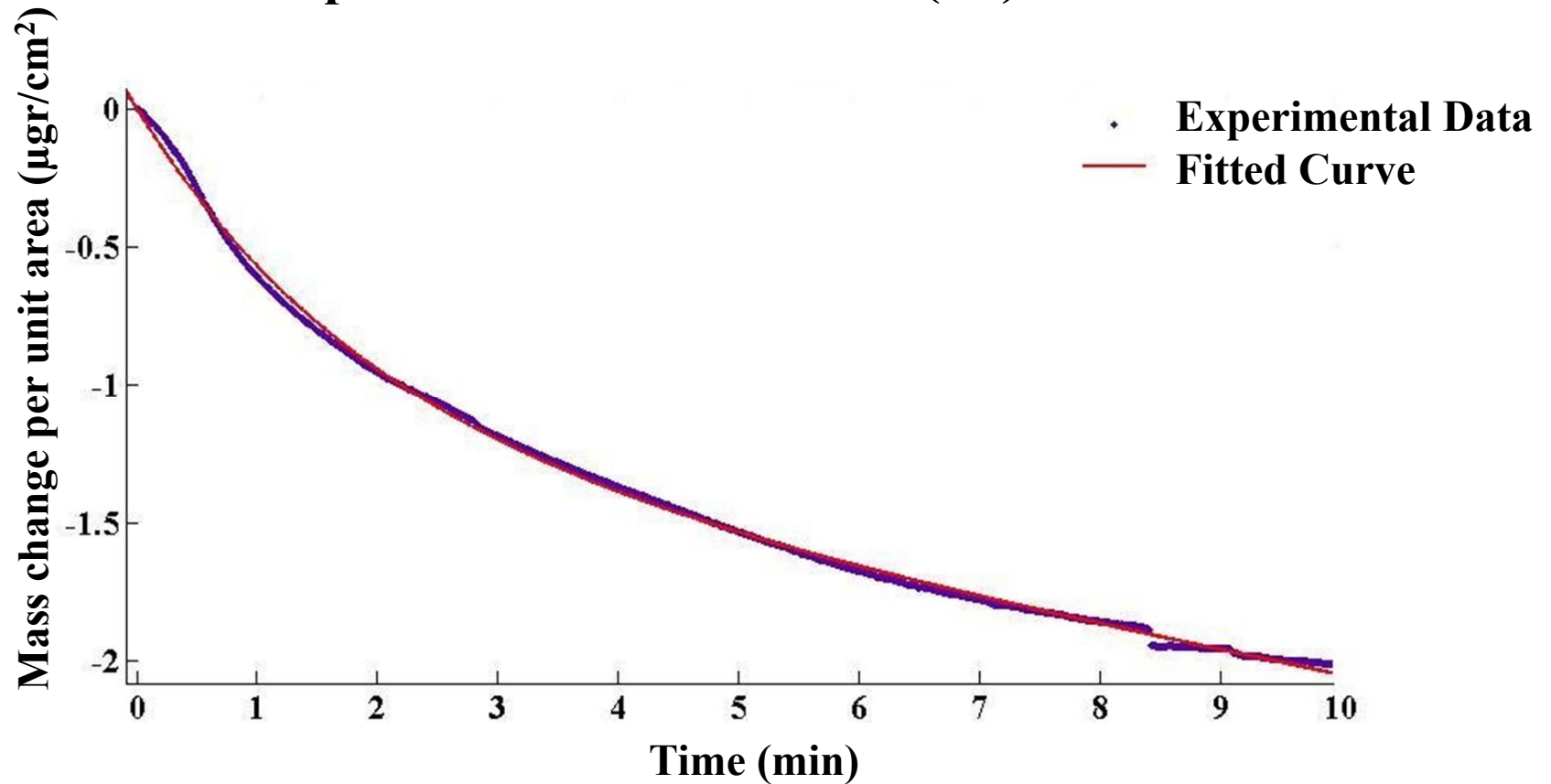
$$\frac{K_a C_b S_0}{K_a C_b + K_d}] t + [(Mw_{HfO_2} K_e C_b - Mw_{HF} K_a C_b - Mw_{HF} K_d) \times$$

$$\frac{K_a C_b S_0}{(K_a C_b + K_d)^2}] (\exp - (K_a C_b + K_d) t - 1)$$

# Model Validation Using Experimental Data

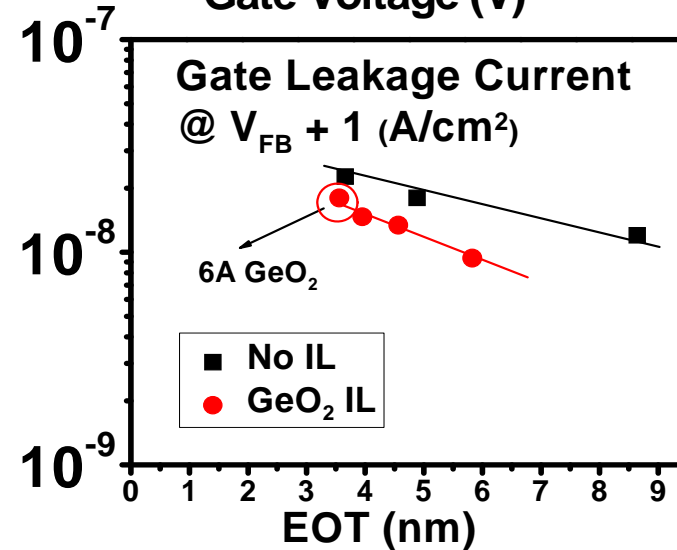
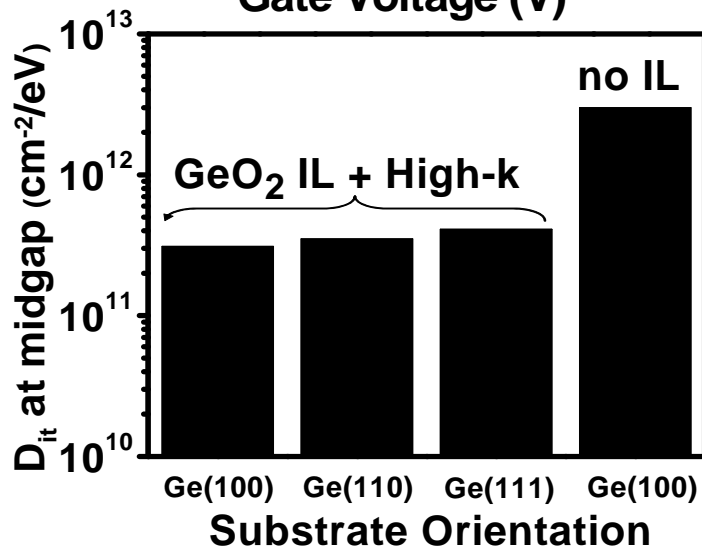
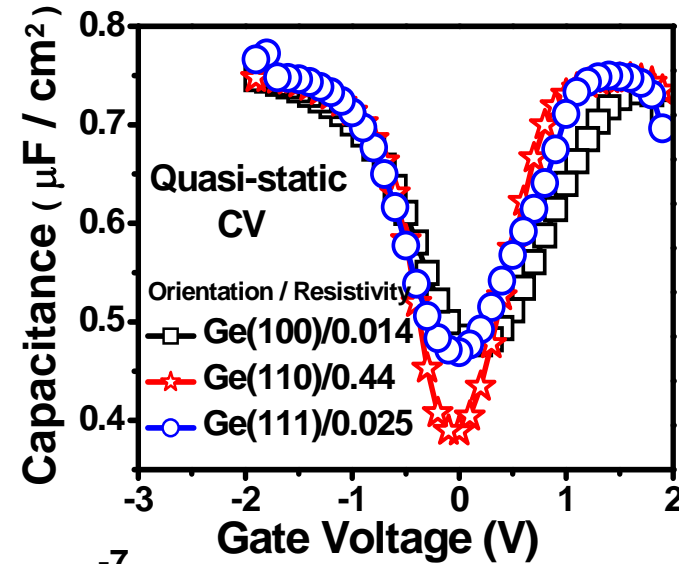
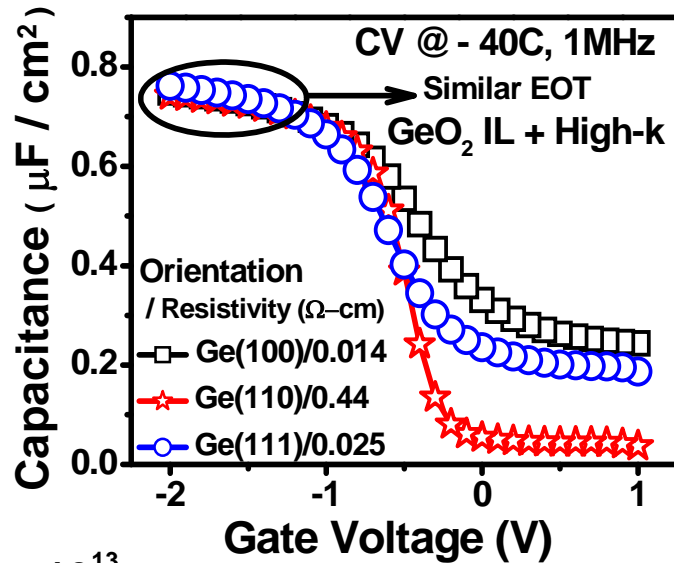
**Adsorption constant rate: 132.962 (lit/mole.s)**

**Desorption constant rate: 0.001 (1/s)**

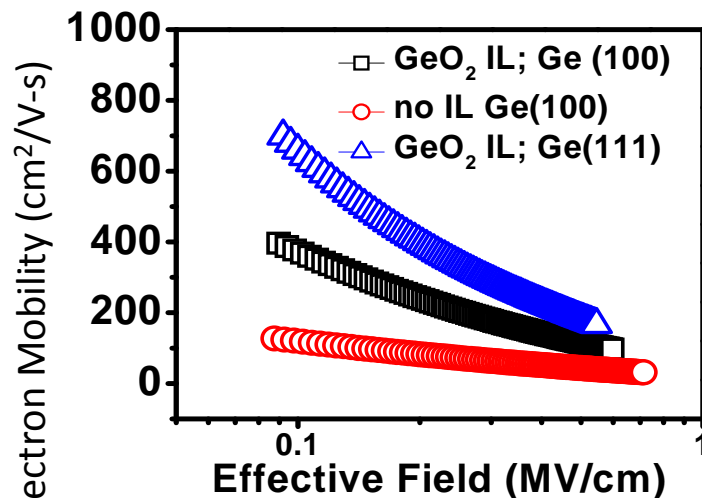
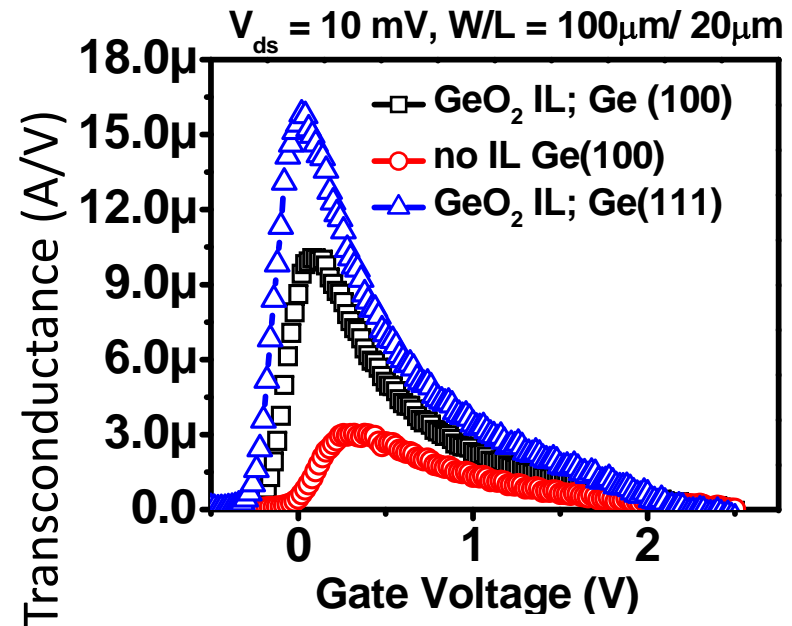
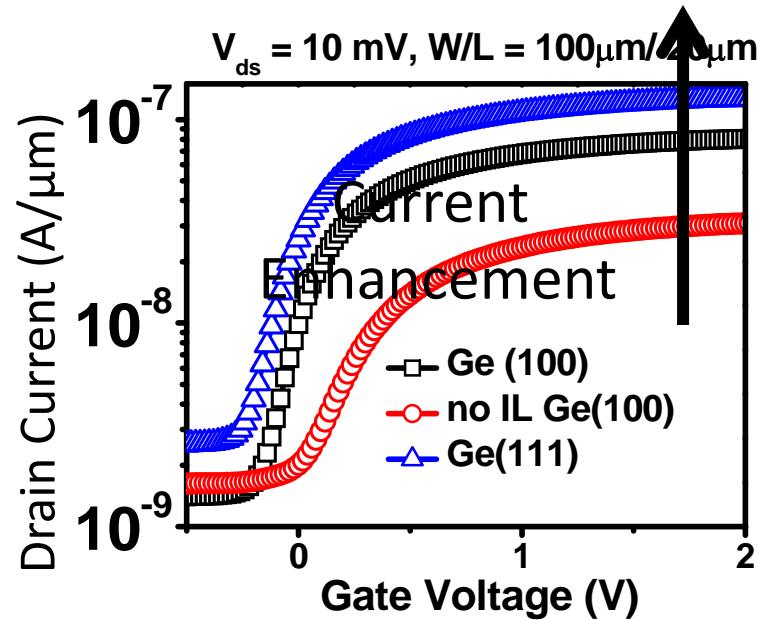


# Subtask 3: Test Structure

## GeO<sub>2</sub> : Growth Rate, D<sub>it</sub>, Scalability

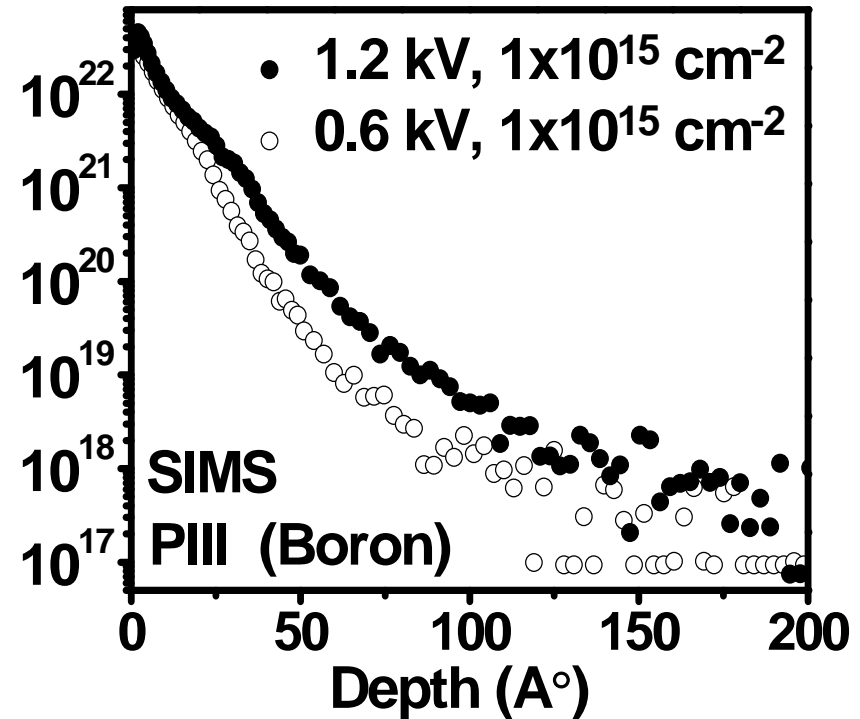
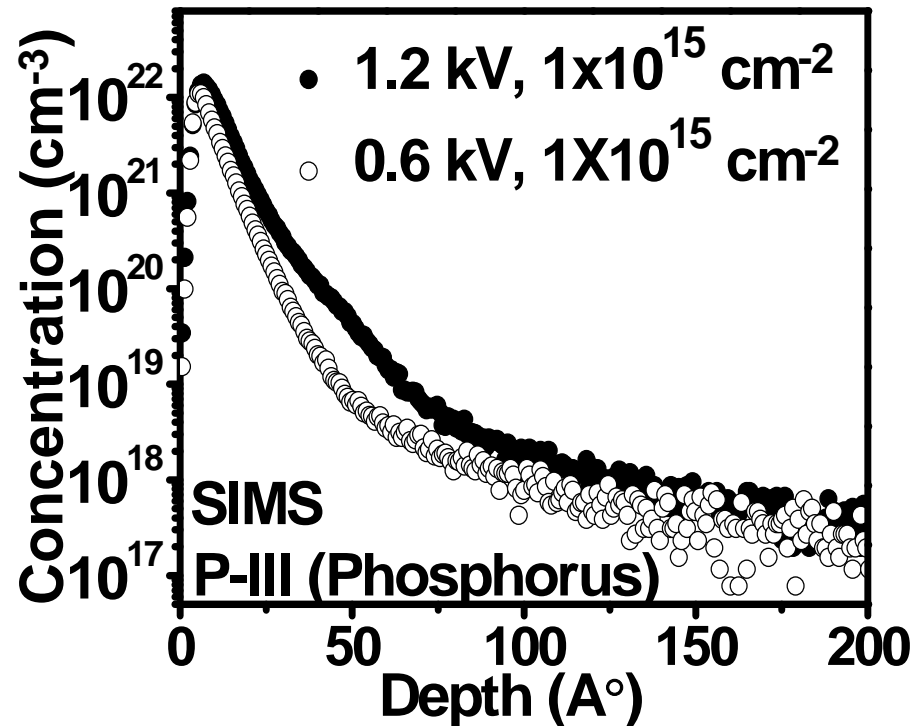


# Drive Current, Mobility Enhancement



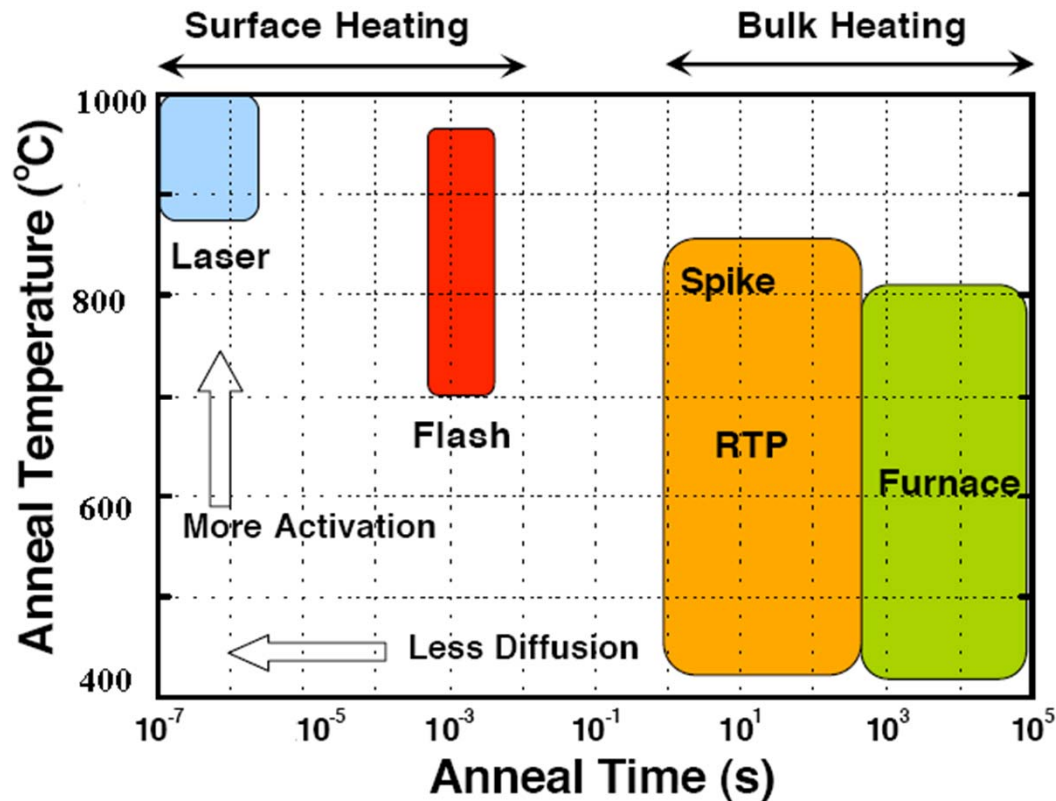
Ge(111) has higher mobility – lower  $m^*$   
 Samples without GeO<sub>2</sub> – poor mobility –  
 interface/coulomb scattering

# Plasma Doping in Ge



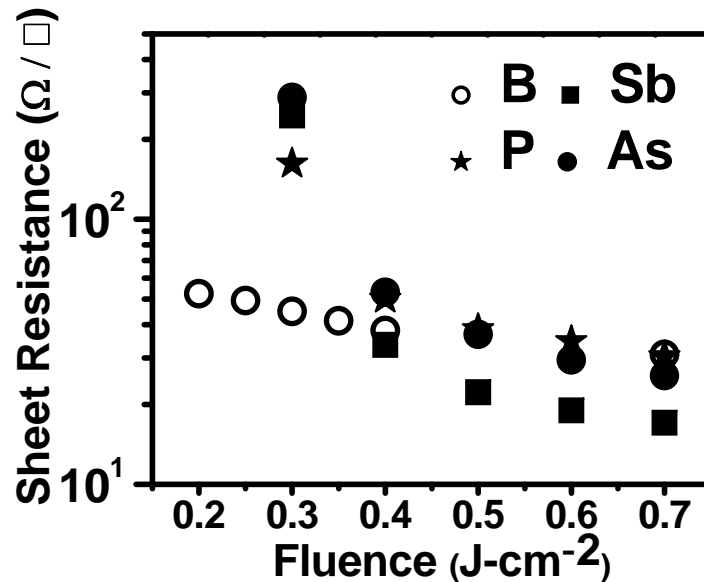
- $X_j < 10 \text{ nm}$  @  $5 \times 10^{18} \text{ cm}^{-3}$
- Shallower junctions possible
  - Scaling the voltage
  - Using arsenic species

# Dopant Activation for USJ in Ge

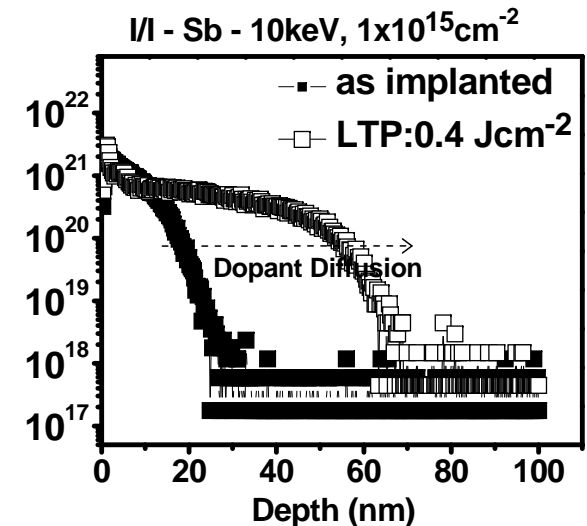
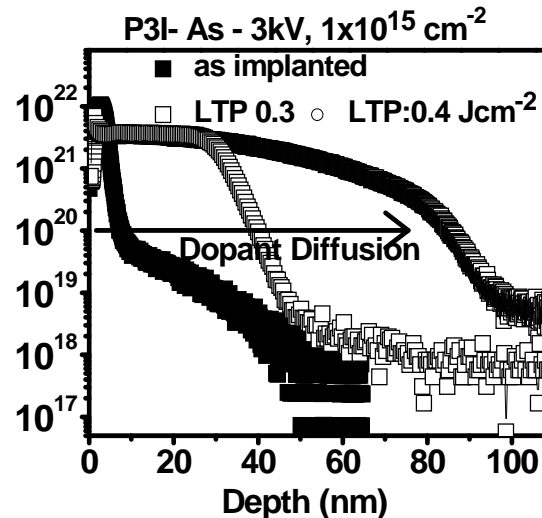
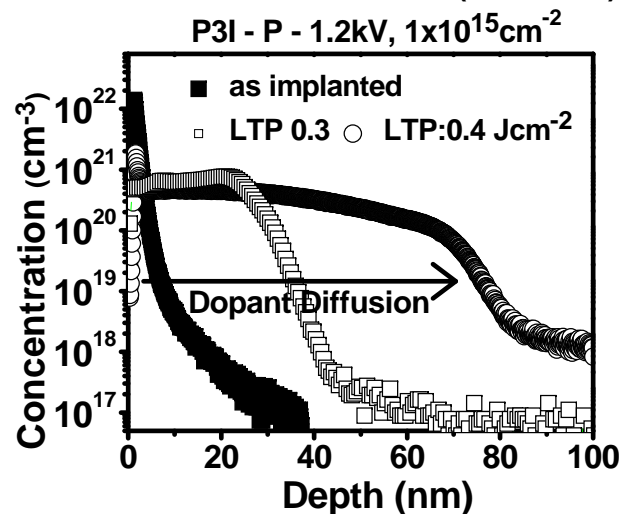


- Laser Thermal Processing (LTP)
  - High dopant activation
  - Reduced diffusion
  - Implantation damage annihilation (Melt – Regrowth)

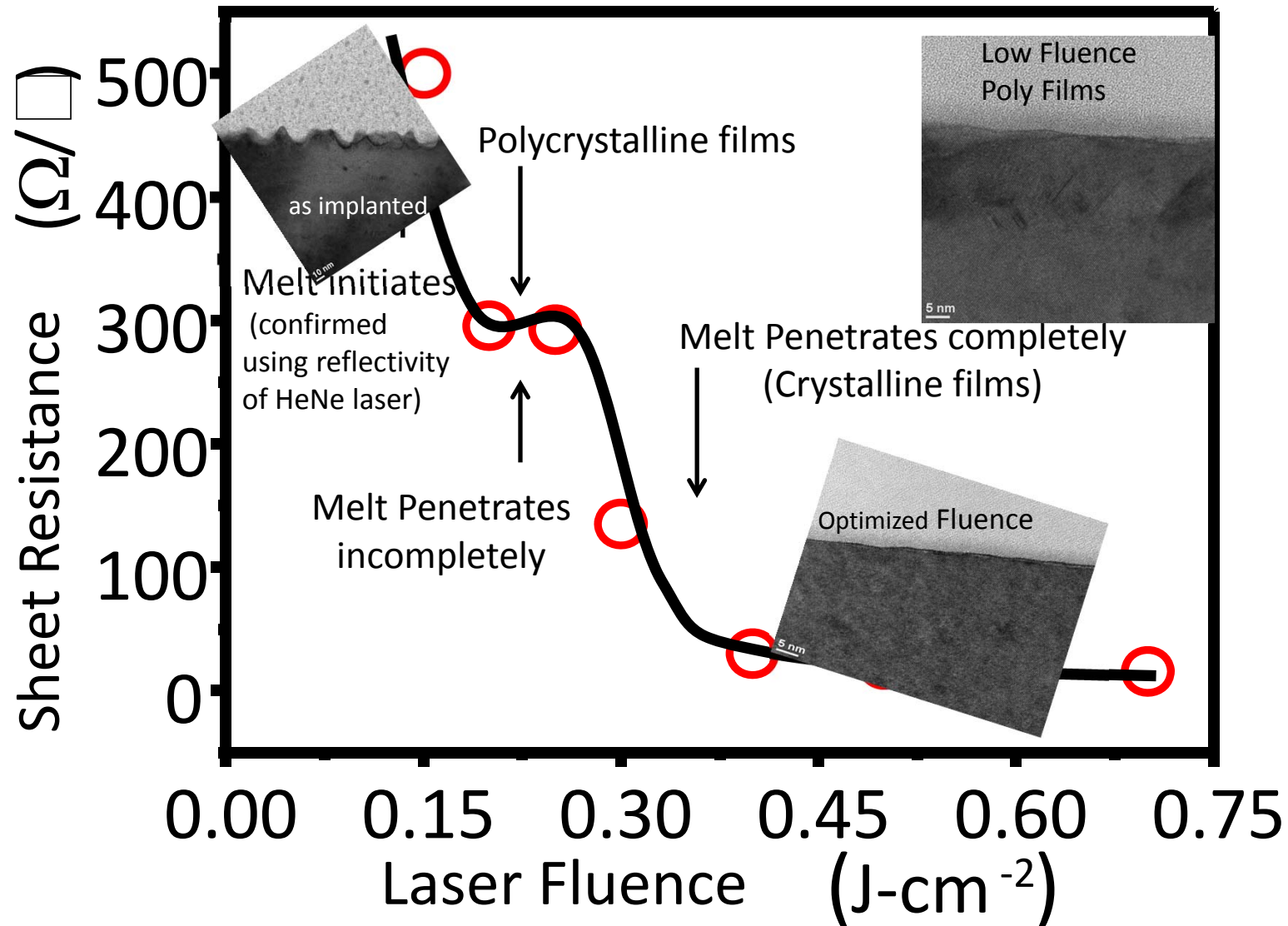
# Sheet Resistance & SIMS



Laser Fluence  $\uparrow$   
 Dopant diffusion  $\uparrow$   
 Sheet Resistance  $\downarrow$

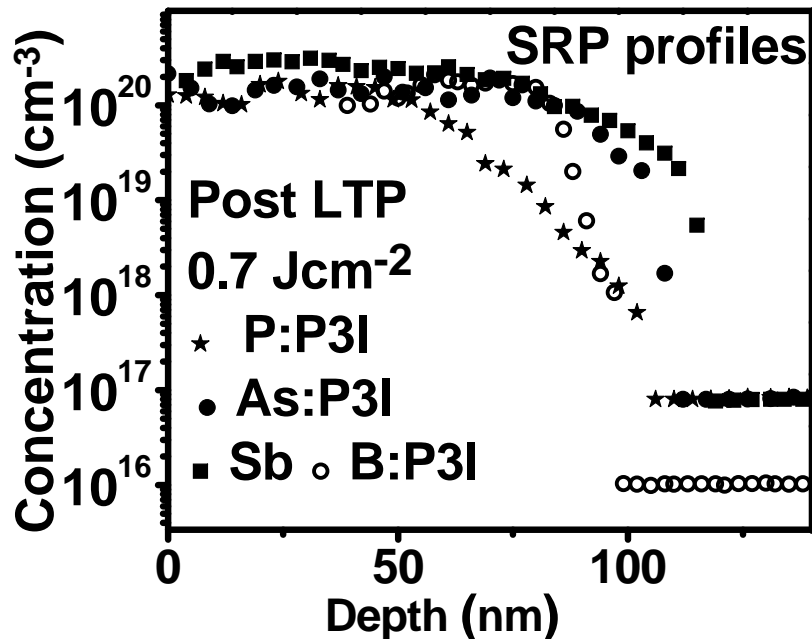


# Sheet Resistance and TEM





# Dopant Activation using LTP

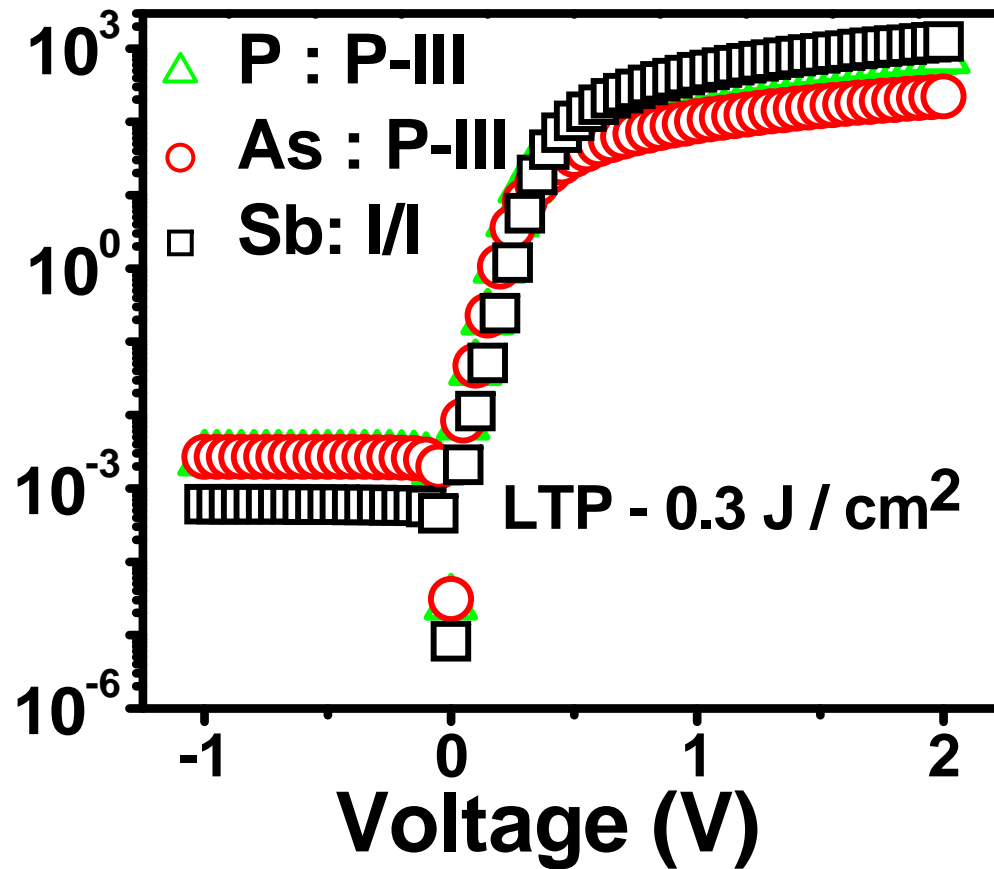


Annealing Technique	Dopant	Electrical Activation (cm <sup>-3</sup> )
Furnace Anneal <sup>[1]</sup>	P	8 x 10 <sup>18</sup>
Rapid Thermal Anneal (RTA) <sup>[2]</sup>	P / As / Sb / B	2 x 10 <sup>19</sup> / 8x10 <sup>18</sup> 8x 10 <sup>18</sup> / 1x10 <sup>20</sup>
Flash Anneal <sup>[3]</sup>	P	6x10 <sup>19</sup>
In-situ doping <sup>[4]</sup>	P	1x10 <sup>19</sup>
<b>This Work (LTP)</b>	<b>P / As / Sb / B</b>	<b>&gt; 1 x 10<sup>20</sup></b>

Dopant Activation > 1 x 10<sup>20</sup> cm<sup>-3</sup>

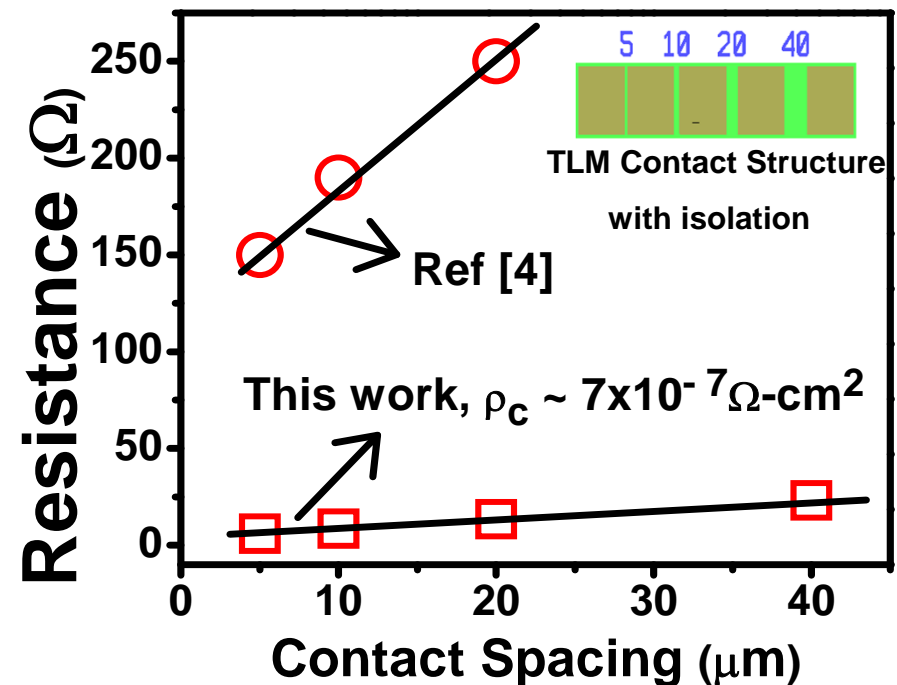
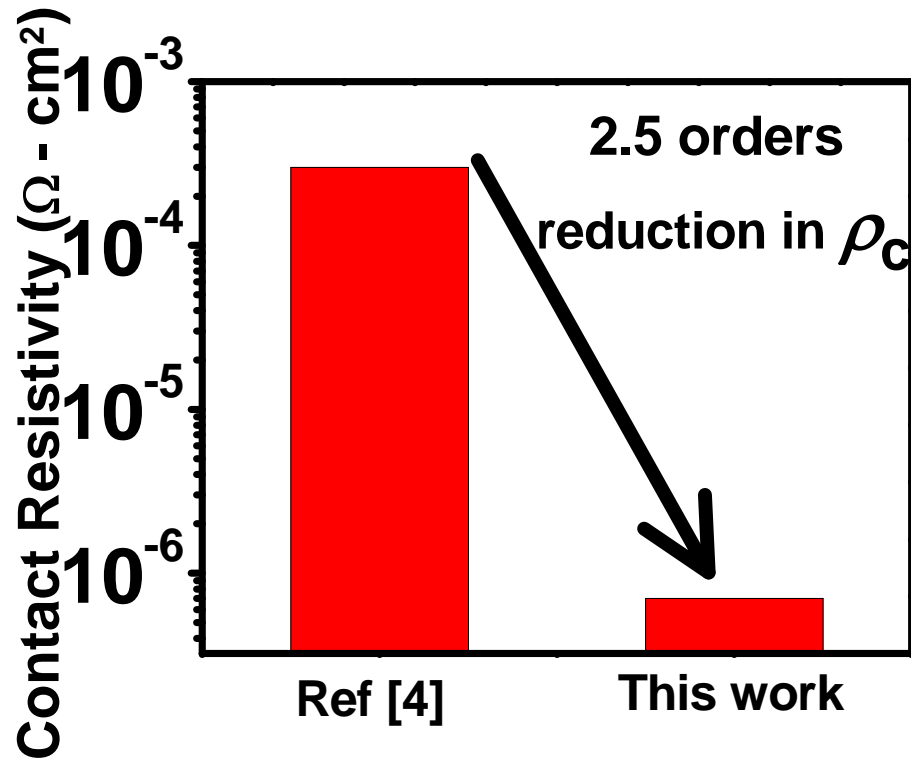
- [1] D.Kuzum, et al., IEDM, 2009, 453, [2] C.O.Chui, et al. APL, 83, 3275, 2003,  
[3] C. Wundisch, et al. 95, 252107, 2009, [4]H.-Y. Yu, et al. 685, IEDM 2009

# High Performance N<sup>+</sup>/P Ge Diodes



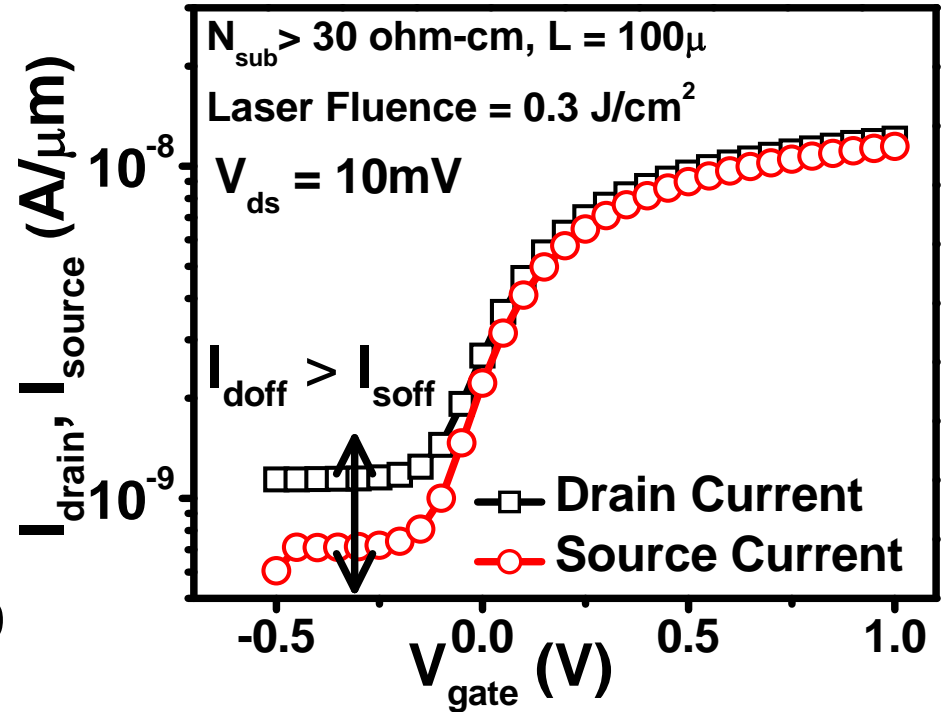
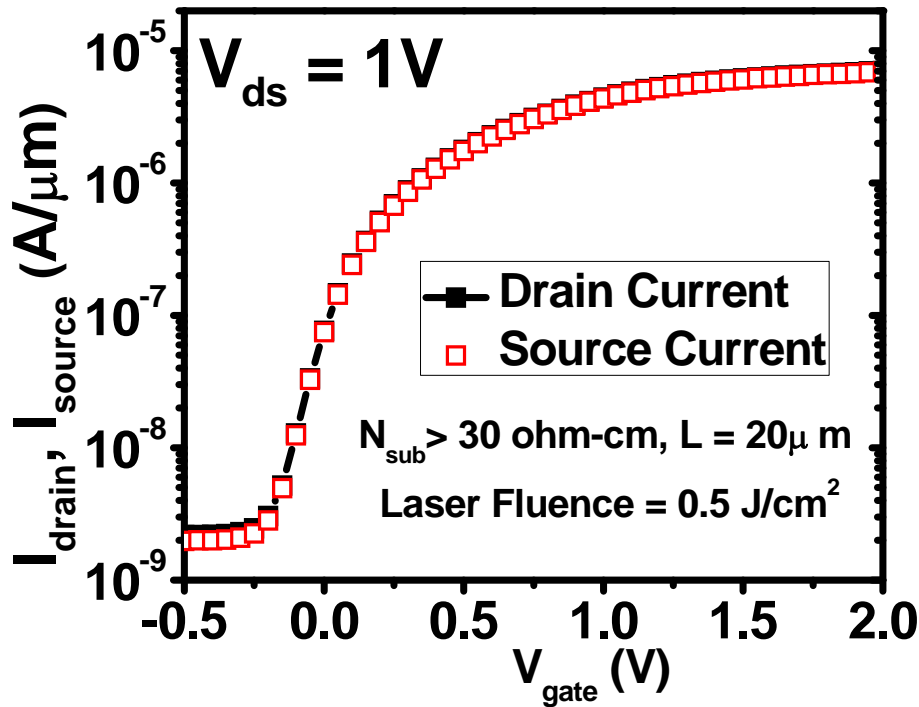
$$I_{\text{on}} / I_{\text{off}} > 1 \times 10^5, \eta < 1.2$$

# Contact Resistivity ( $\rho_c$ ) & Benchmark



Significant reduction in Metal /  $\text{N}^+ \text{Ge}$   $\rho_c$  of  $7 \times 10^{-7} \Omega \cdot \text{cm}^2$

# MOSFET results



Unoptimized laser fluence causes discrepancy between  $I_{\text{drain}}$  and  $I_{\text{source}}$  due to high diode leakage

# Contributions

- First demonstration of
  - High dopant activation ( $> 1 \times 10^{20} \text{ cm}^{-3}$ ) using Sb dopants (n-type) in Ge
    - Well behaved  $n^+/p$  diodes ( $I_{\text{on}}/I_{\text{off}} > 1 \times 10^5$ ,  $\eta < 1.2$ ) and MOSFETs.
    - Lowest contact resistivity for metal(Ti/Al)- $n^+$  Ge contacts ( $7 \times 10^{-7} \Omega\text{-cm}^2$ )
  - Ultra Shallow Junctions ( $X_j < 10\text{nm}$ ) for Ge
  - Scalable  $\text{GeO}_2$  Interfacial Layers (IL) (sub -1nm) for Ge MOS with performance enhancement for Ge NMOSFET
  - Substrate orientation independent growth rate and  $D_{\text{it}}$  for  $\text{GeO}_2$  engineered using SPA oxide

# Summary

- Conducted baseline etch tests on ALD  $\text{HfO}_2$  and  $\text{HfSi}_x\text{O}_y$  in dilute HF
- Investigated the feasibility of etching the materials in ammonium hydroxide solutions after a pre-reduction treatment in  $\text{H}_2/\text{N}_2$  gas mixtures
- Determined the rinse process parameters that are needed and will be used in developing reliable and robust low-water rinse recipes for cleaning of heterogeneous nano-structures.
- Test structure: First demonstration of high dopant activation ( $> 1 \times 10^{20} \text{ cm}^{-3}$ ) using Sb dopants (n-type) in Ge

# Publications and Presentations

- G. Thareja, J. Liang, S. Chopra, B. Adams, N. Patil, A. Nainani, E. Tasyurek, S.-L. Cheng, Y. Kim, S. Moffatt, R. Brennan, J. McVittie, T. Kamins, H-S.P. Wong, K. Saraswat and Y. Nishi, “High Performance Germanium N-MOSFET with Antimony Dopant Activation Beyond  $1 \times 10^{20} \text{ cm}^{-3}$ ”, IEDM, December 6, 2010
- Masaharu Kobayashi, Gaurav Thareja, Masato Ishibashi, Yun Sun, Peter Griffin, Jim McVittie, Piero Pianetta, Krishna Saraswat, Yoshio Nishi, “Radical oxidation of germanium for interface gate dielectric  $\text{GeO}_2$  formation in metal-insulator-semiconductor gate stack,” *Journal of Applied Physics*, 106, 104117, 2009.
- X. Zhang, J. Yan, B. Vermeire, F. Shadman, and J. Chae, “Passive Wireless Monitoring of Wafer Cleanliness During Rinsing of Semiconductor Wafers,” *IEEE Sensors Journal*, 10 (6), 1048, 2010.

# **Publications and Presentations**

- **K. Dhane, J. Han, J. Yan, O. Mahdavi, D. Zamani, B. Vermeire, and F. Shadman, “Dynamics of Cleaning and Rinsing of Micro and Nano Structures in Single-Wafer Cleaning Tools,” IEEE Transactions on Semiconductor Manufacturing, 24 (1), 125, 2011**
- **Jun Yan, “Water Usage Reduction and Water Reuse in Semiconductor manufacturing”, the Second International Congress on Sustainability Science and Engineering, Water Re-Use Workshop, January 14, 2011, Tucson, Arizona, USA (Invited Presentation)**



# **Industrial Interactions and Technology Transfer**

- **Collaborative interactions with Initiative for Nanoscale Materials and Processes, INMP, at Stanford which is supported by 7 semiconductor and semiconductor equipment manufacturing companies.**
- **Interactions with ASM (Eric Shero and Eric Liu) for preparation of high-k test samples**

# **Sugar-Based Photoacid Generators (“Sweet” PAGs):** **Environmentally Friendly Materials for Next** **Generation Photolithography** *(Task Number: 425.029)*

## **PIs:**

- Christopher K. Ober, Materials Science and Engineering, Cornell University
- Reyes Sierra, Chemical and Environmental Engineering, UA

## **Graduate Students:**

- Lila Otero, PhD candidate, Chemical & Environmental Engineering, UA
- Marie Krysak, PhD candidate, Materials Science & Engineering, Cornell University

## **Undergraduate Students:**

- Lily Milner, Chemical & Environmental Engineering, UA

## **Other Researchers:**

- Youngjin Cho, Postdoctoral Fellow, Materials Science & Eng., Cornell University
- Wenjie Sun, Postdoctoral Fellow, Chemical & Environmental Engineering, UA

## **Cost Share (other than core ERC funding):**

- UofA GIGA fellowship (1 year) to Lila Otero.

# Objectives

- **Develop PFOS-free and environmentally friendly PAGs with superior imaging performance. The novel PAGs will be based on biological units such as sugars and cholic acids for chemically amplified resist application**
- **Identify modeling tools to predict the environmental fate of novel PAGs**
- **Evaluate the environmental aspects of new PAGs**

# **ESH Metrics and Impact**

## **1. Reduction in the use or replacement of ESH-problematic materials**

**Complete replacement of perfluorooctanesulfonate (PFOS) structures including metal salts and photoacid generators in photoresist formulations.**

## **2. Reduction in emission of ESH-problematic material to environment**

**Develop new PAGs that can be readily disposed of in ESH friendly manner.**

## **3. Reduction in the use of natural resources (water and energy)**

**New PAGs prepared using simple, energy reduced chemistry in high yields and purity to reduce water use and the use of organic solvents.**

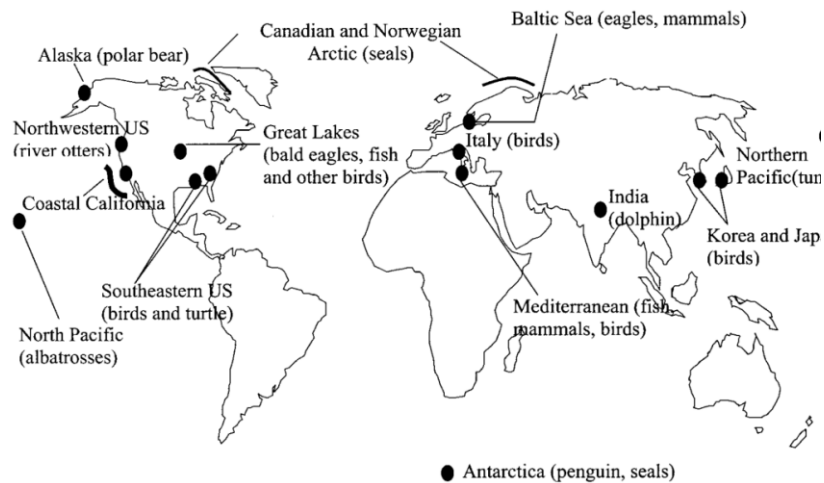
## **4. Reduction in the use of chemicals**

**Reduction in the use of fluorinated chemicals.**

# PFOS IS A PERSISTENT, TOXIC and Bioaccumulative (PBT) Contaminant

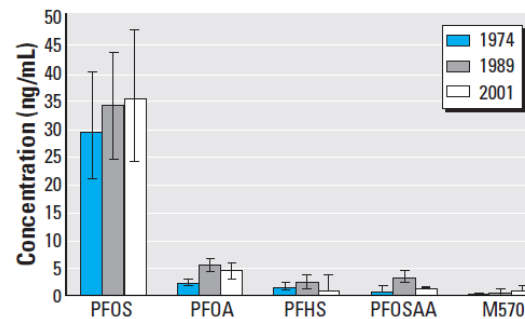
➤ **PFOS and PFOS-related materials are potentially environmentally hazardous**

## Global Distribution of PFOS in Wildlife



*Environ. Sci. Technol.* 2001, 35, 1339.

## PFOS in human blood



**Figure 1.** Median fluorochemical concentrations and IQRs for blood samples collected in Washington County, Maryland, from adults living in proximity in 1974 ( $n = 178$  serum samples) and 1989 ( $n = 178$  plasma samples) and in the county in 2001 ( $n = 108$  serum samples; Olsen et al. 2003c).

*Environ. Health Perspect.* 2005, 113, 539.

## PFOS in drinking water



PFOS and other PFCs detected in drinking water resources worldwide

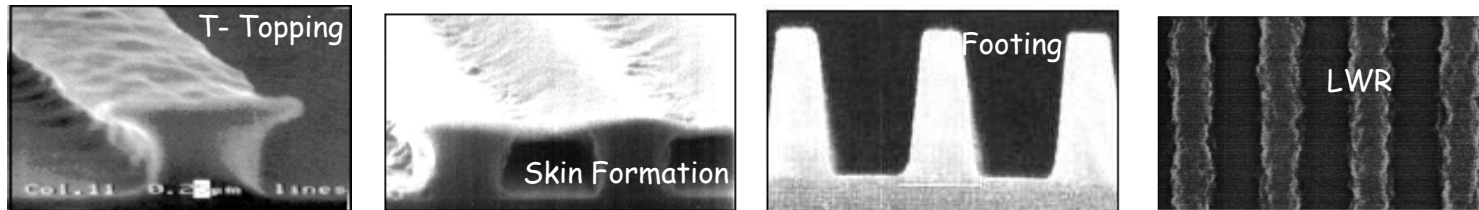
- **PFOS banned for most application is the US and EU.**
- **PFOS listed as chemical for regulation within the Stockholm Convention on Persistent Organic Pollutants (POPs)**
- **EPA Provisional Health Advisory Levels for PFOS 200 ng L<sup>-1</sup>**

**Next Generation PAGs — environmentally friendly**

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

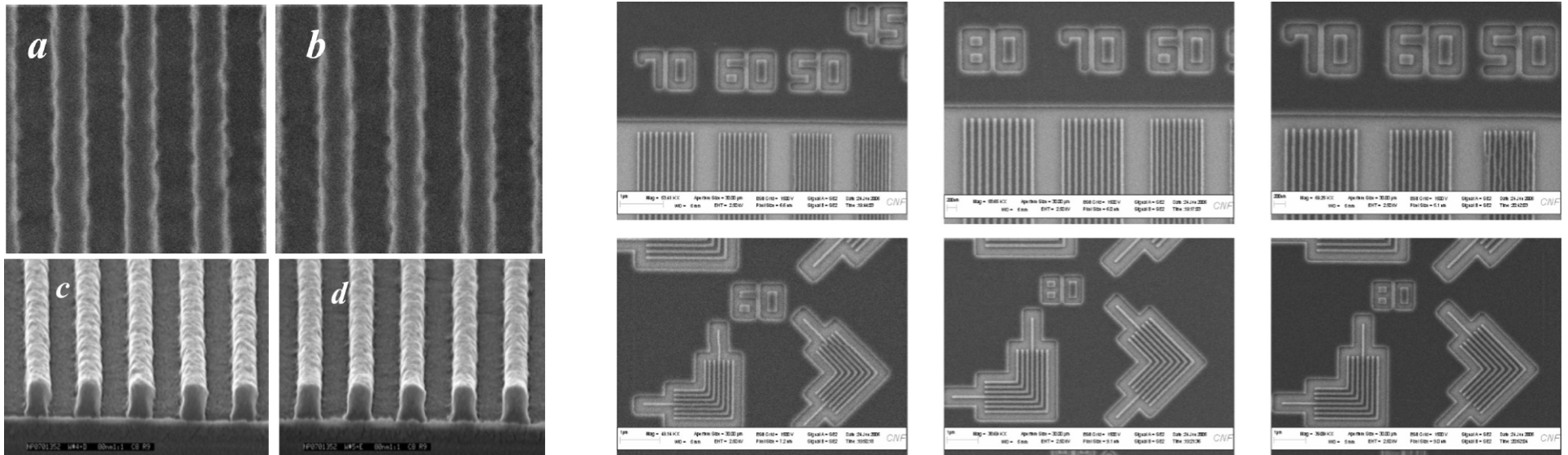
# PFOS PAG Performance Issues

## “Segregation or non-uniform distribution of PAG”



➡ Surface segregation increases with increase in fluorine content

## “PFOS free new PAG”: high resolution patterning



Top-down and cross-sectional SEM images of 90 nm dense lines of resist films of TPS NB (a and c) and the sweet PAG (b and d) patterned by 193 nm lithography. Esize (mJ/cm<sup>2</sup>): a, 23.8; b, 27.3. LER (nm): a, 5.8; b, 6.5.

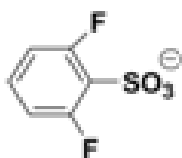
Top-down SEM images of resist films of poly(GBLMA-co-MAdMA) blended separately with TPSGB (left column), TPSNB (middle column), and TPS PFBS (right column) patterned by EUV lithography.

C.K. Ober et al., *Chem. Mater.* (2009); C.K. Ober et al., *JPST* (1999); J. L. Lenhart et al., *Langumir* (2005); W. Hinsberg et al., *SPIE* (2004); M. D. Stewart et al., *JVSTB* (2002)

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

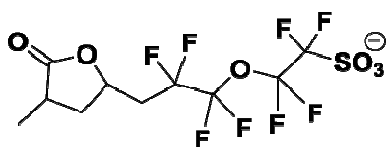
# Environmental Compatibility of New Non-PFOS PAG Anions

## Selected examples:



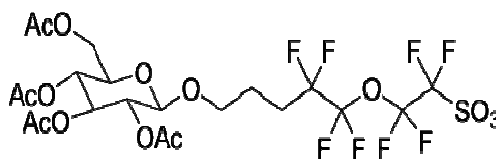
1<sup>st</sup> generation

(Aromatic structure)



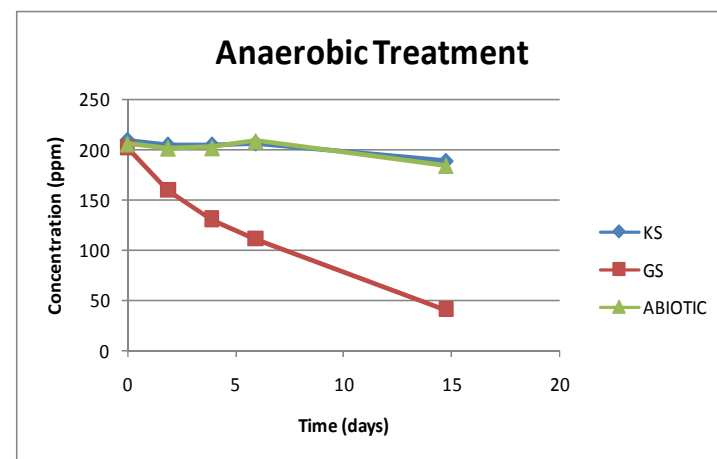
2<sup>nd</sup> generation

(Aliphatic structure)



3<sup>rd</sup> generation

(Sugar structure)



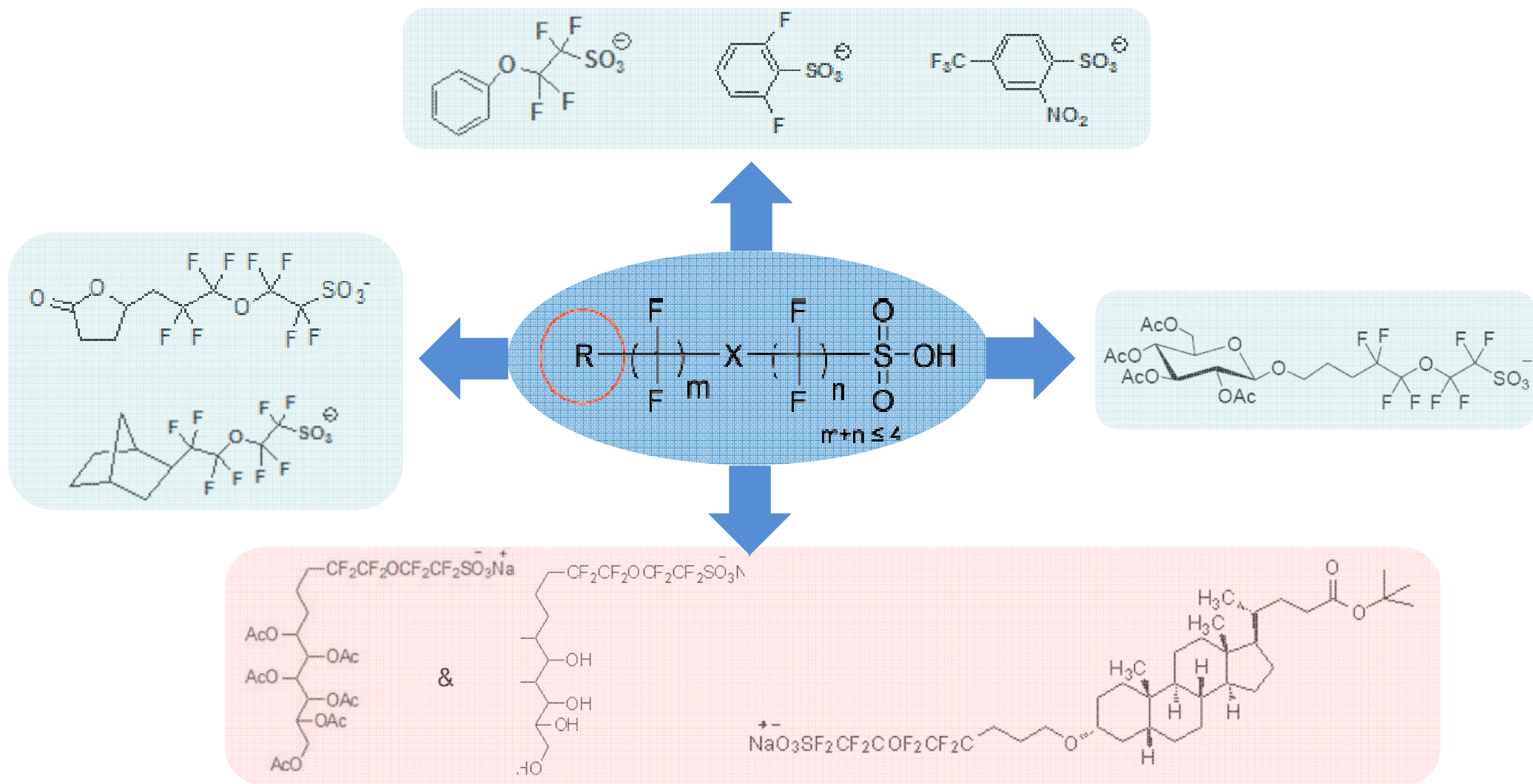
Degradation for 2<sup>nd</sup> generation PAG in anaerobic batch bioassays. (KS) Abiotic sterilized control; (GS) complete treatment with active sludge; (ABIOTIC) sterile, non-inoculated control.

- **1<sup>st</sup> Generation Non-PFOS PAGs:** Low toxicity and low bioaccumulation potential but relatively persistent to microbial degradation.
- **2<sup>nd</sup> Generation Non-PFOS PAGs:** Preliminary results show that replacing the phenyl group with a UV-transparent alicyclic moiety increases the susceptibility of the PAG compound to biodegradation.
- **3<sup>rd</sup> Generation Non-PFOS PAGs:** Replacing with sugar and natural groups is expected to increase biodegradation.



# Molecular Design of New PAGs: PFOS-free salts

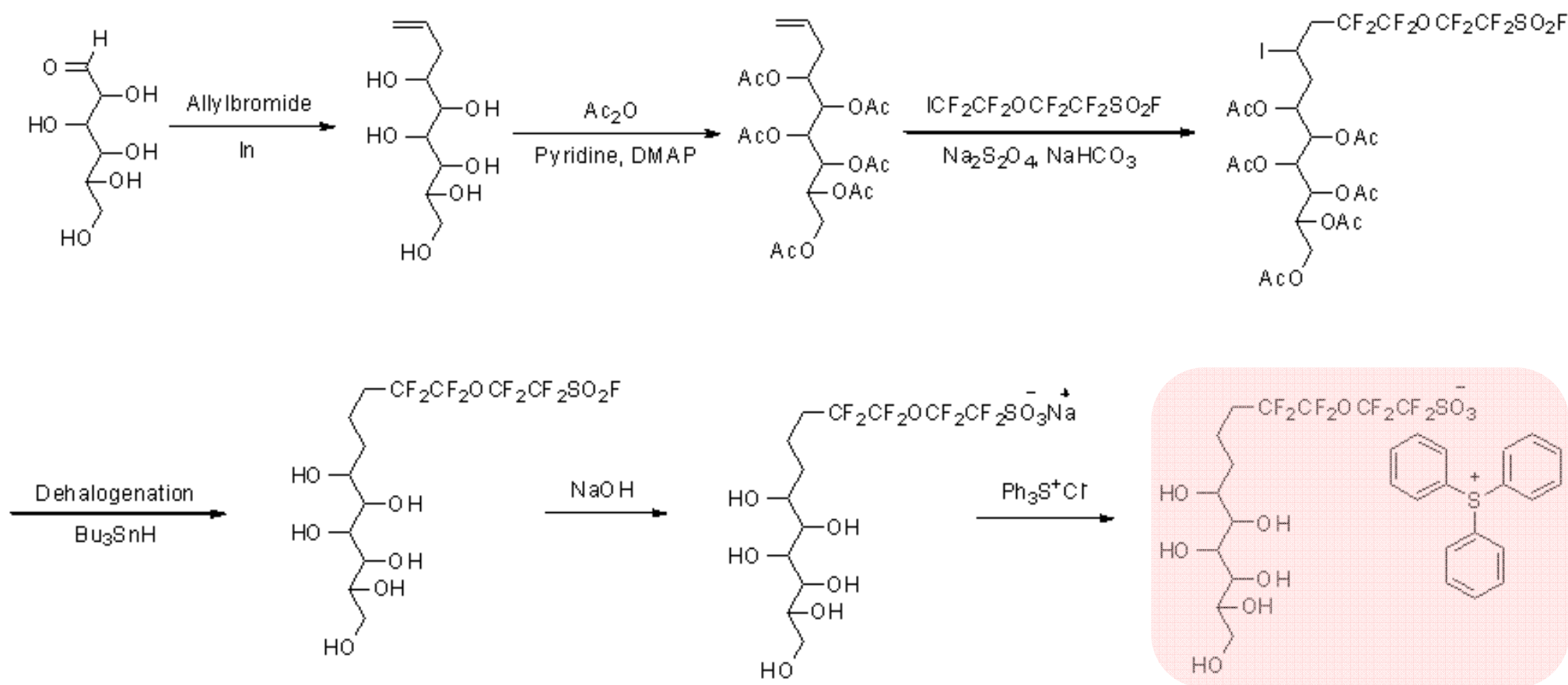
**For environmentally friendly and excellent performance:**





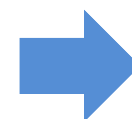
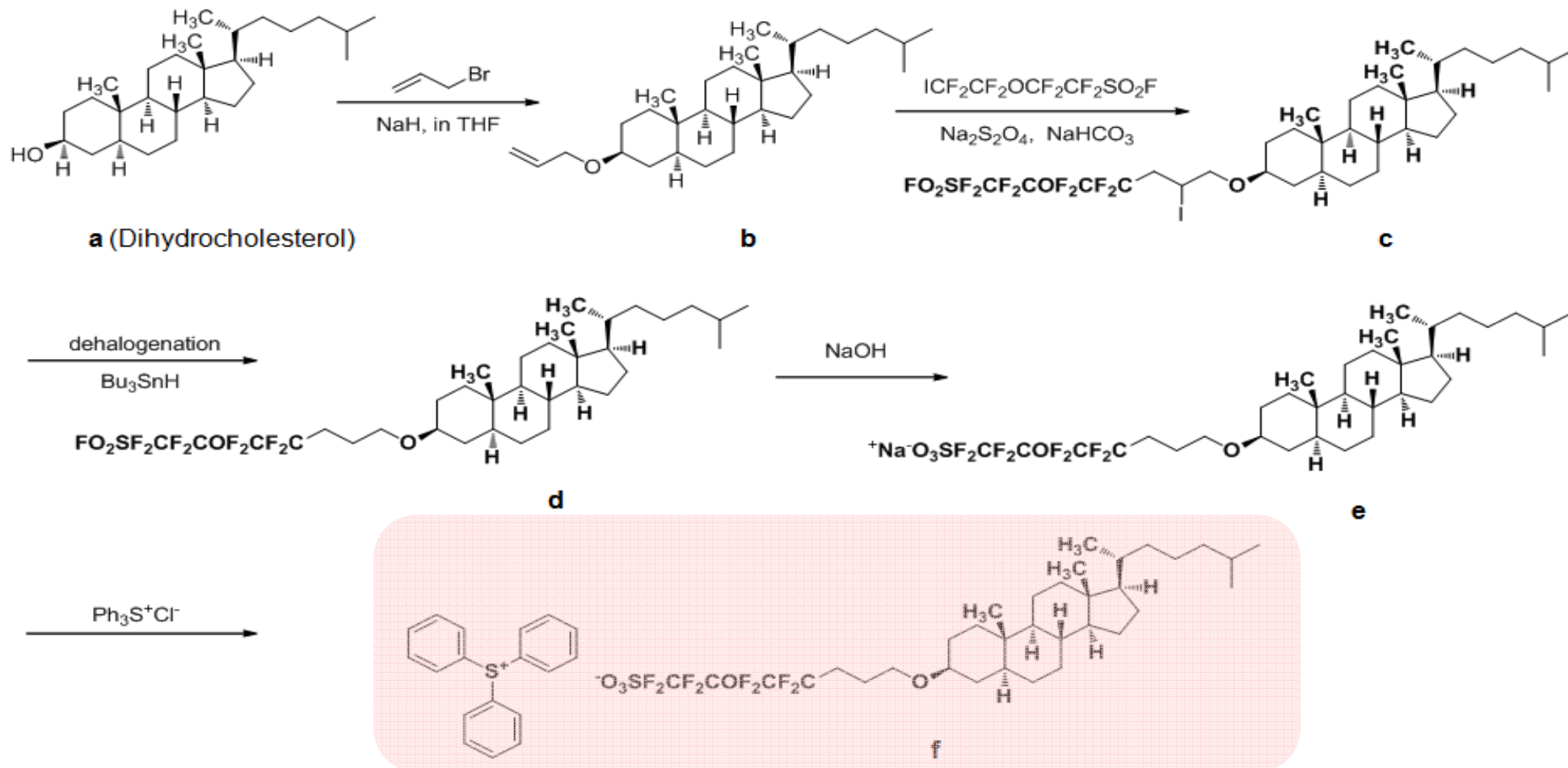
# Synthesis of linear type “Sweet” PAG

## ❖ Synthetic scheme of deacetylated linear type Sweet PAG:



# Synthesis of “Biocompatible” PAGs

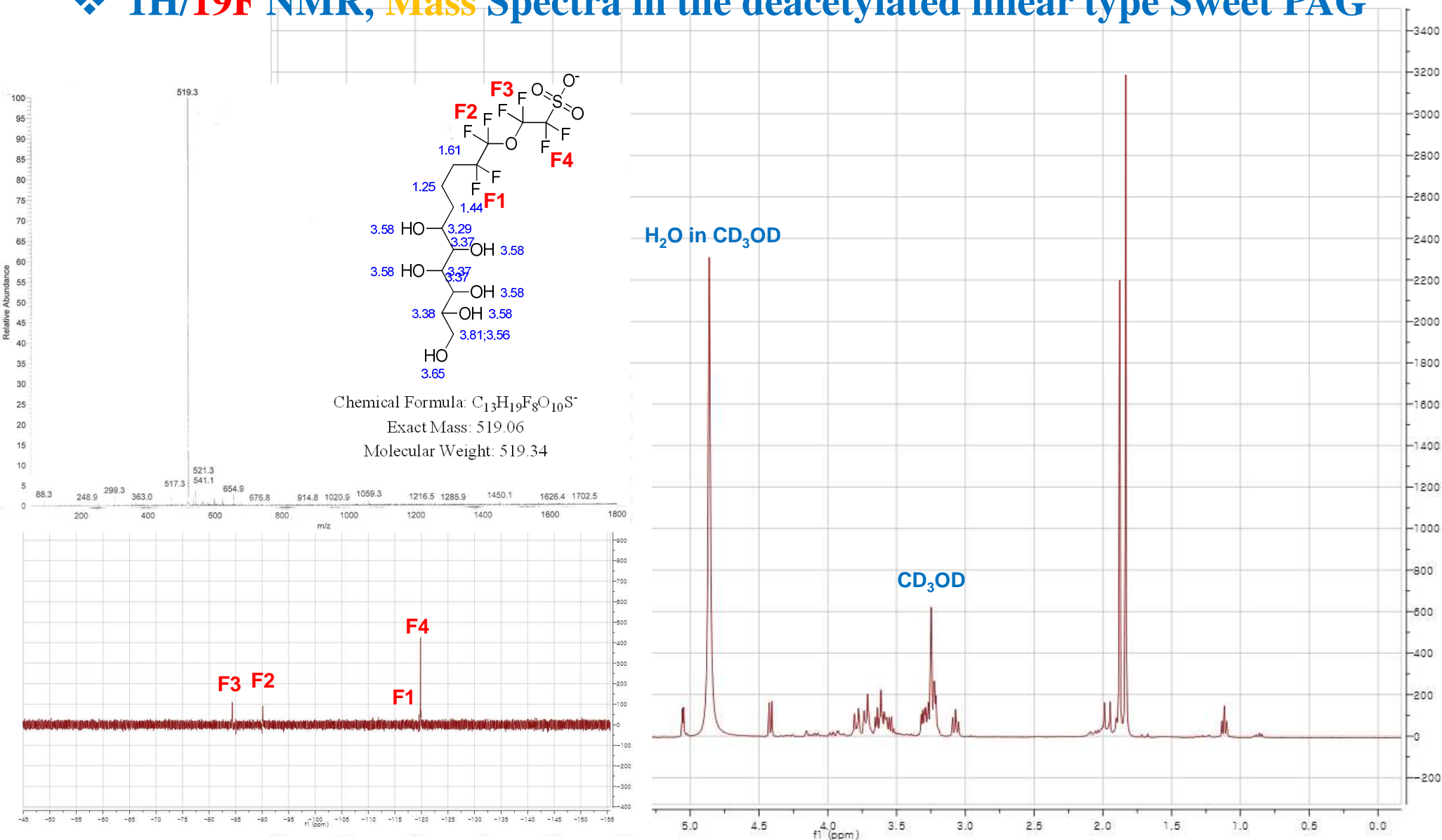
## ❖ Synthetic scheme of Dihydrocholesterol based PAG:



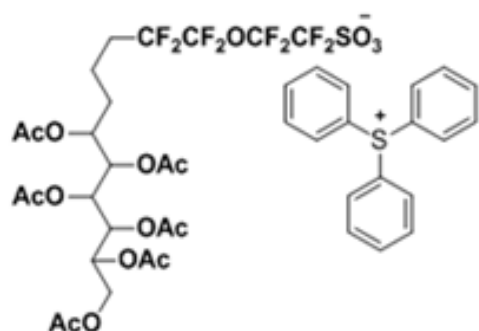
Ongoing..

# Characterizations of New PAGs

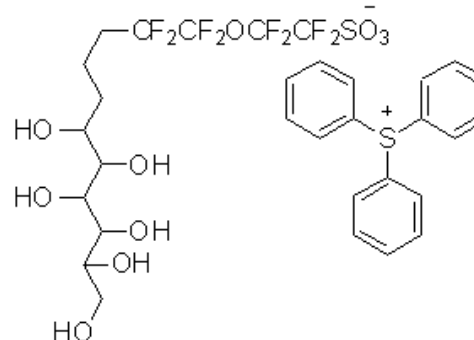
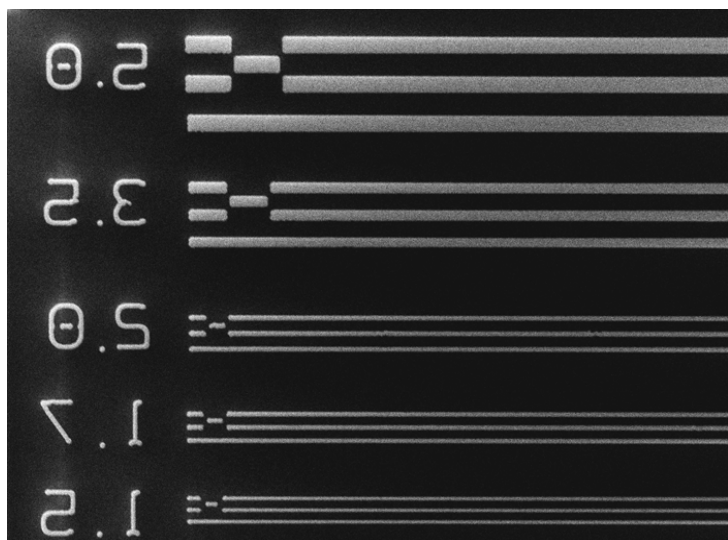
## ❖ $^1\text{H}/^{19}\text{F}$ NMR, Mass Spectra in the deacetylated linear type Sweet PAG



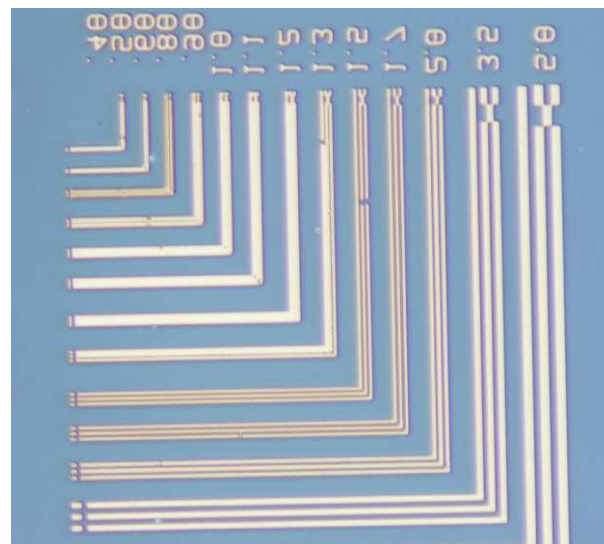
# Evaluation of Lithographic Performance



The conditions:  
 50mg ESCAP  
 2.5mg PAG (5%)  
 1.0g PEGMA (5% solution)  
 PAB: 130°C/60s  
 PEB: 130°C/60s  
 Exposure: 20 mJ/cm<sup>2</sup> at 254nm  
 Development: 0.26 N TMAH/60s



The conditions:  
 50mg ESCAP  
 2.5mg PAG (5%)  
 1.0g Ethyl lactate (5% solution)  
 PAB: 130°C/60s  
 PEB: 130°C/60s  
 Exposure: 20 mJ/cm<sup>2</sup> at 254nm  
 Development: 0.26 N TMAH/60s



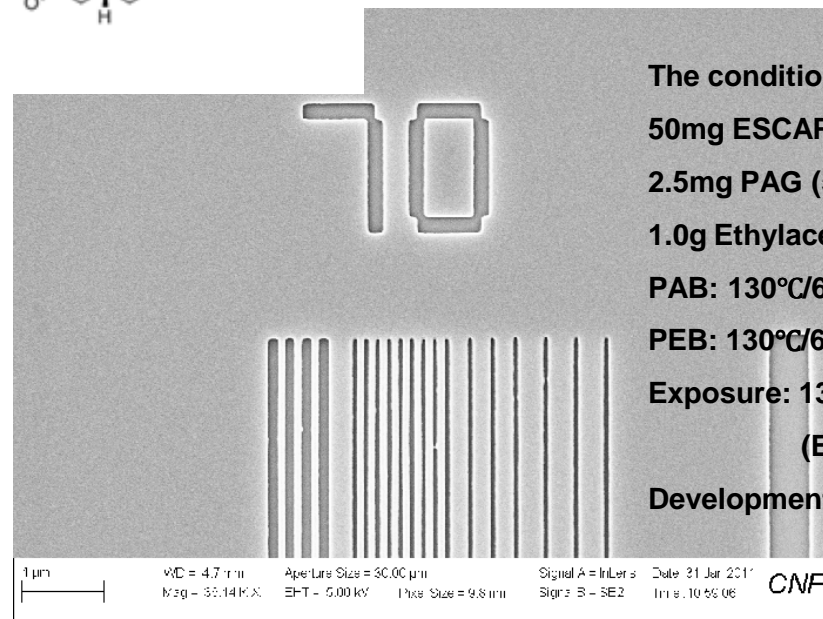
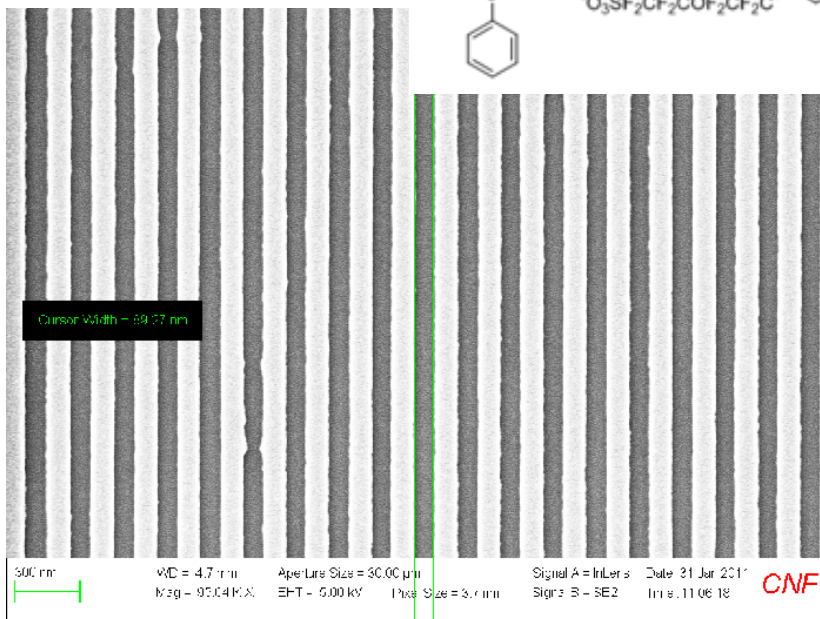
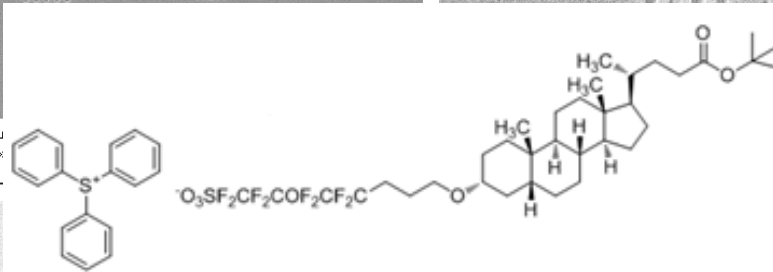
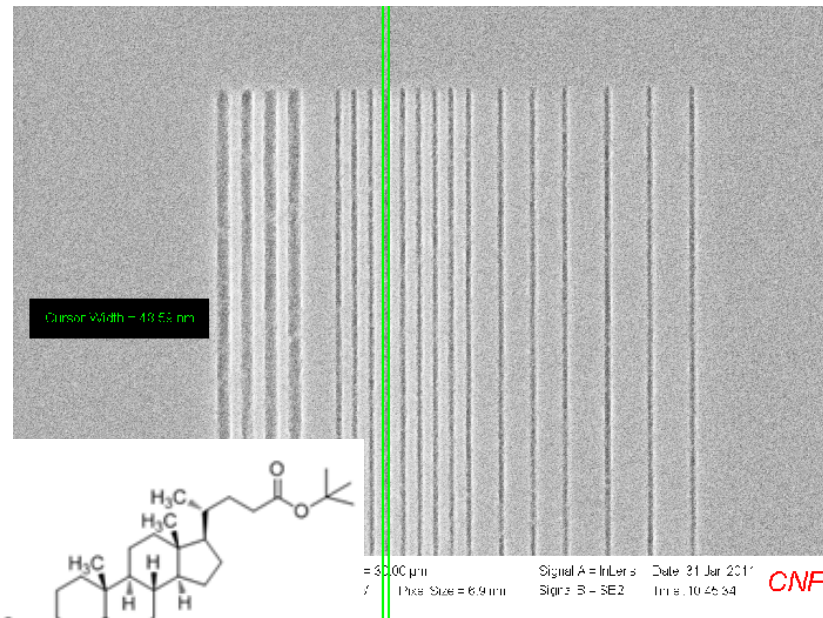
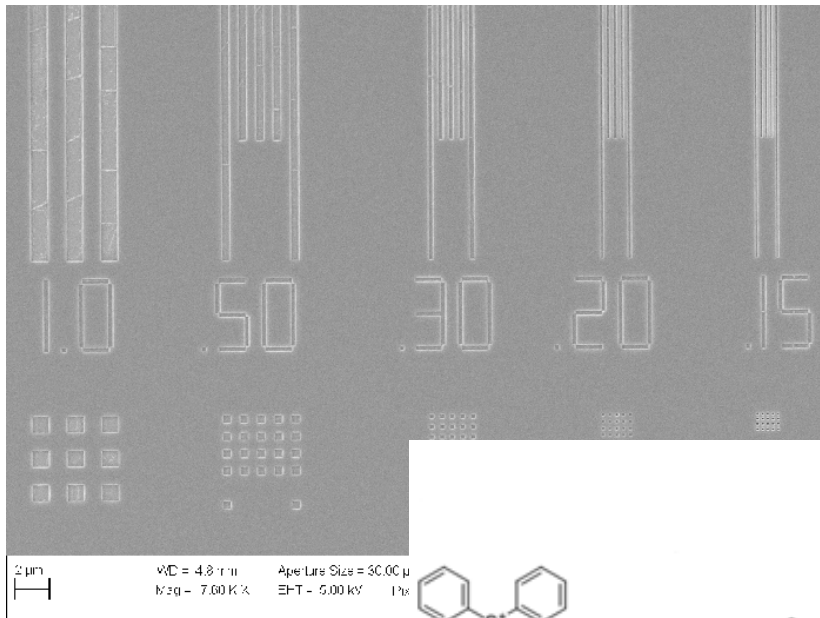
Solvent	PGMEA	Butanone	Ethyl lactate
Solubility of PAG	△	△	O



**Some issues with solubility of deacetylated linear type Sweet PAG**



# E-beam Lithographic Performance



**The conditions:**

- 50mg ESCAP
- 2.5mg PAG (5%)
- 1.0g Ethylacetate (5% solution)
- PAB: 130°C/60s
- PEB: 130°C/60s
- Exposure: 130 μc/cm<sup>2</sup> at 100Kev (E-beam)
- Development: 0.26 N TMAH/60s

# **Industrial Interactions and Technology Transfer**

- **Collaboration with Dow Electronic Materials for photolithography tests of Sweet PAG concluded**
- **Samples provided to Orthogonal, Inc. – a small startup**
- **Performance at 193 nm and EUV evaluated with the assistance of International Sematech**
- **Ongoing interactions with Intel on LER issues**

# Future Plans

## Next Year's Plans :

- Prepare next generation PAGs (several more compounds) based on biomolecules.
- Evaluate the lithographic performance of new PAGs.
- Modify sulfonium cationic groups.
- Reduce synthetic steps and use more environmentally friendly chemicals.
- Summarize previous studies and submit manuscripts for transfer of know-how to technical community.

## Long-Term Plans :

- Establish the relationship between photoacid generators' structure and their environmental properties

# **Environmental Compatibility of New Non-PFOS PAG Anions**

**PhD student: Lila Otero**

**Undergraduate student: Lily Milner**

**Postdoc: Wenjie Sun**

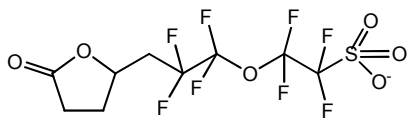


# **Environmental Compatibility of New Non-PFOS PAG Anions**

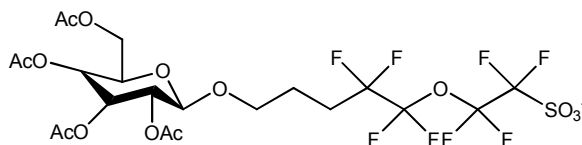
## **Tasks:**

- **Evaluate the environmental compatibility of new PAGs**
- **Evaluation of selected computer models to predict the environmental fate of new PAGs.**

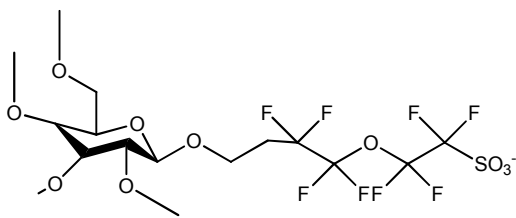
# Environmental Compatibility of New Non-PFOS PAG Anions



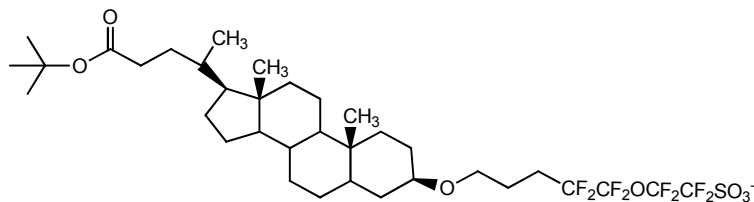
Lactone PAG



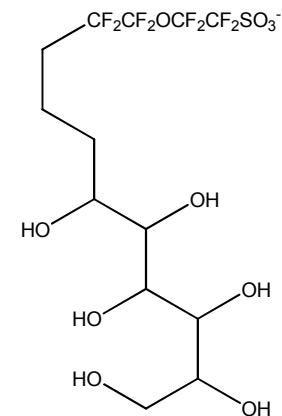
Sugar Sweet PAG



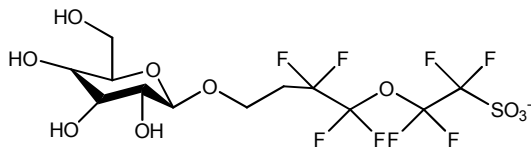
Methoxy Sugar B Sweet PAG



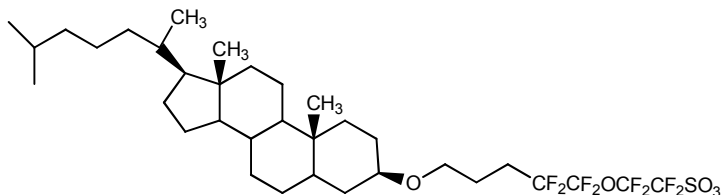
Lithocholic acid PAG



Deactylated linear sweet PAG-K



Hydroxy Sugar B Sweet PAG



Dihydrocholesterol PAG

■ **3<sup>rd</sup> Generation Non-PFOS PAGs included in the testing program**

# Environmental Compatibility

- **Biodegradation**
  - Batch bioassays: aerobic and anaerobic conditions
- **Toxicity**
  - Microbial inhibition (aerobic and anaerobic microorganisms)
  - Aquatic toxicity (Microtox<sup>R</sup> w. bacterium, *Vibrio fischeri*)
  - MTT test (mitochondrion activity)
  - Real time cell analysis (xCELLigence)
- **Bioaccumulation**
  - $K_{ow}$ : water-octanol partition coefficient



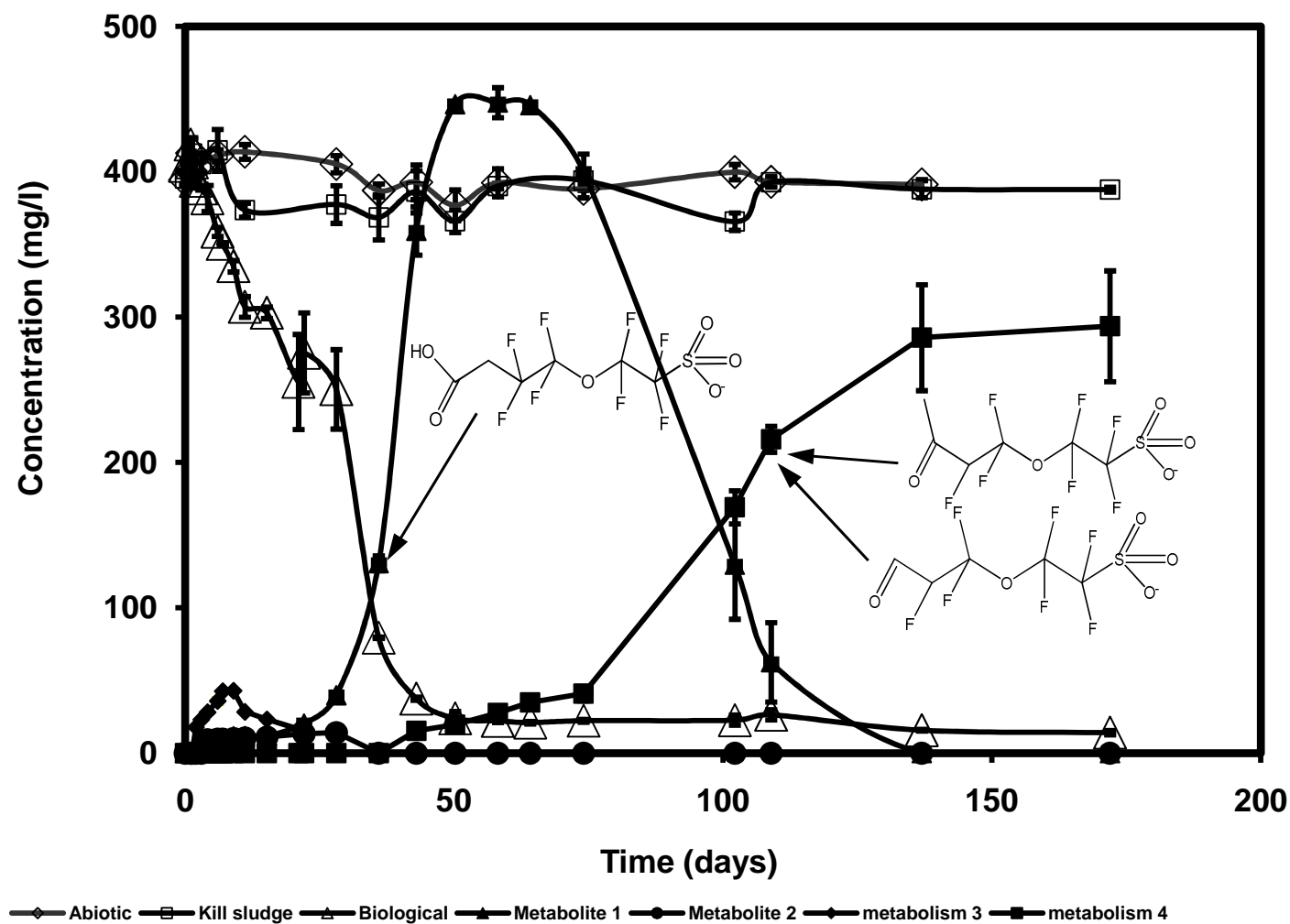
# Microbial Degradation of New Generation PAGs

Compounds	Aerobic Degradation	Anaerobic Degradation
Sweet PAG	YES	YES
Lactone PAG	YES	NO
Linear sweet PAG	YES	NO
Lithocholic acid	In progress	In progress
PFOS	NO	NO
PFBS	NO	NO

**Biomolecule-based PAGs are degraded by microorganisms in activated sludge.  
High PAG removals anticipated in conventional wastewater treatment systems**

# Microbial Degradation of New Generation PAGs

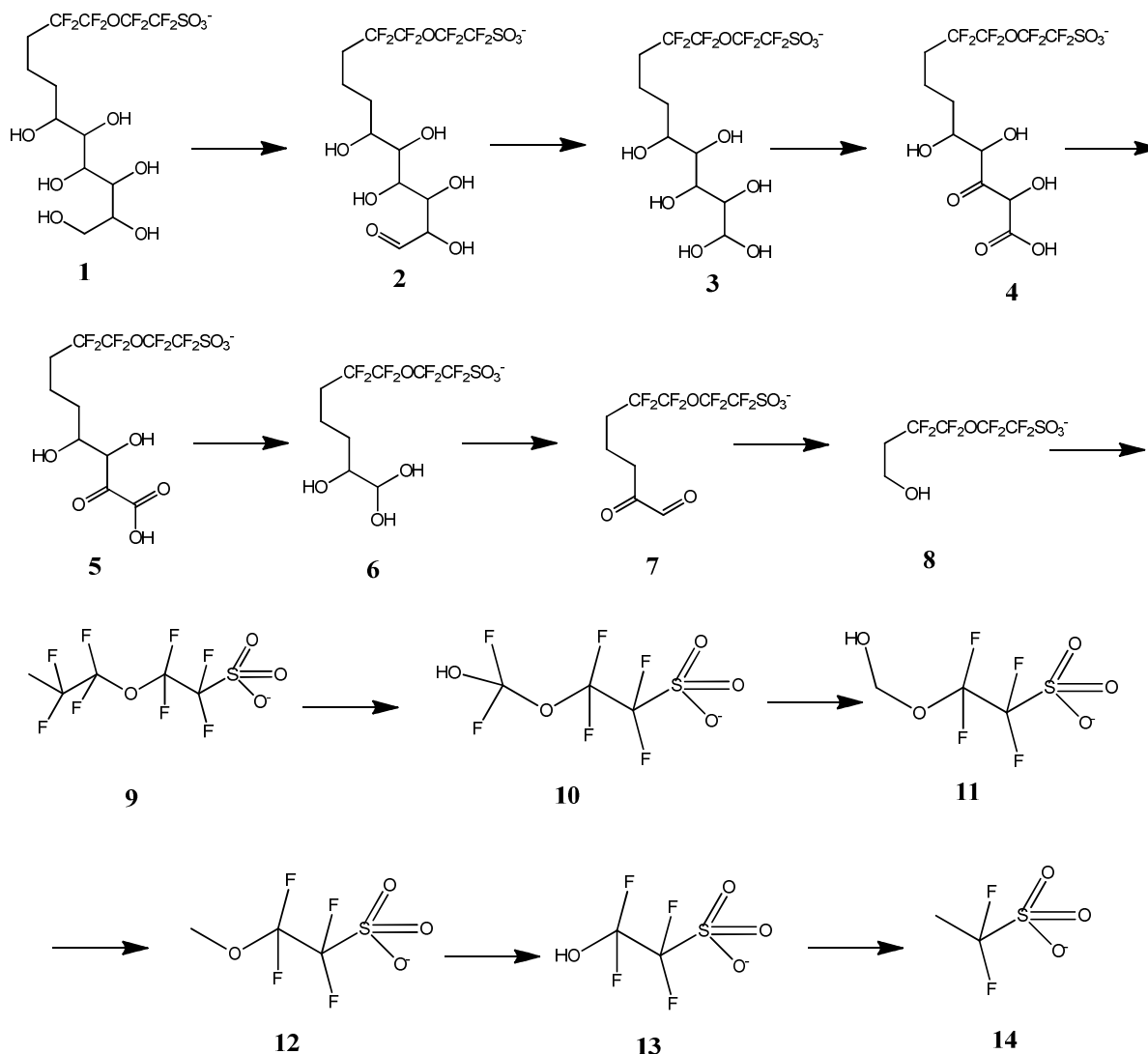
## Biodegradation of the “lactone PAG” by aerobic microorganisms vs. time



**Biomolecule-based PAGs are readily degradable by aerobic bacteria in activated sludge.**

# Microbial Degradation of New Generation PAGs

## Aerobic biodegradation pathway for the Linear Sweet PAG

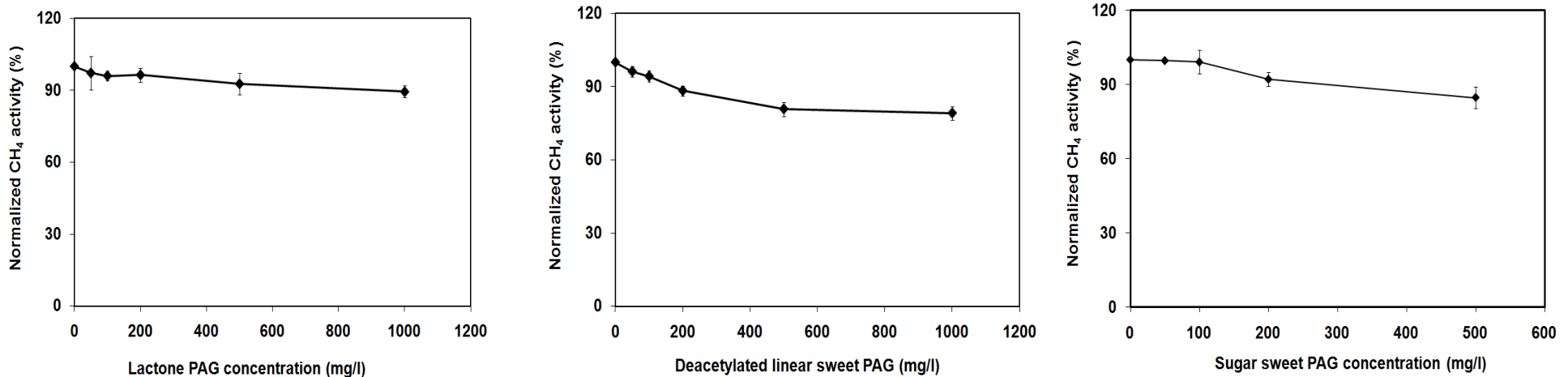


**Biomolecule-based PAGs are susceptible to aerobic degradation.**

**Microbial attack of the perfluorinated backbone observed in the assay with linear sweet PAG.**

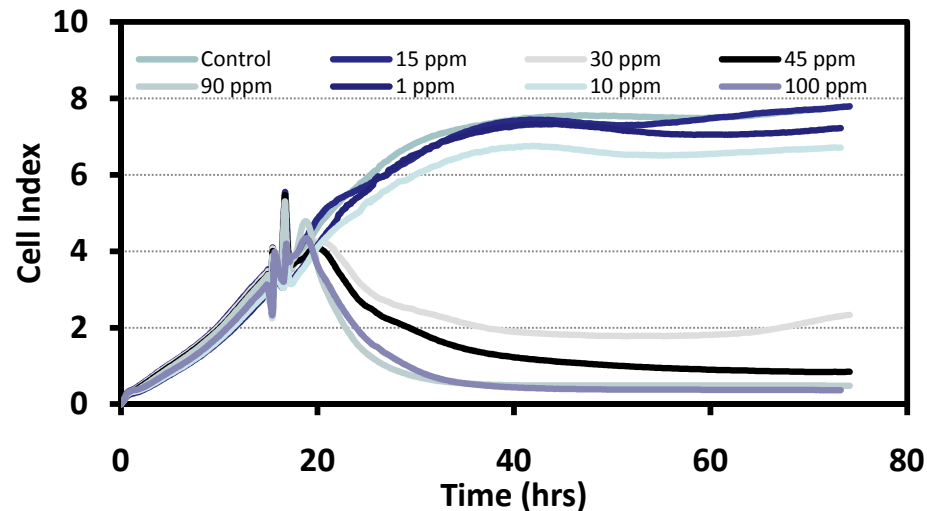
# Cytotoxicity of New Generation PAGs

## Inhibitory effect of different new PAG compounds towards acetoclastic activity in anaerobic biofilms



**PAG compounds are not toxic to anaerobic wastewater treatment biofilms.**

## Cytotoxicity of sugar Sweet PAG in assays with lung epithelial 16HBE14o- cells (RTCA with xCELLigence)



**Some PAGs showed intermediate toxicity towards lung epithelial 16HBE14o- cells (RTCA)**

# Cytotoxicity of New Generation PAGs

## Summary of inhibitory concentrations determined for the PAG compounds in different toxicity assays

Compounds	Microtox		Methanogenic $\pm$		RTCA (xCELLigence)	
	IC50* (mg/l)	Max Conc. Tested (mg/l)	IC50 (mg/l)	Max Conc. Tested (mg/l)	IC50 (mg/l)	Max Conc. Tested (mg/l)
PAG compounds						
PFOS	GMC	250	GMC*	250	50.5	63
PFBS	GMC	3,375	GMC	500	85.2	100
Lactone PAG	GMC	1,000	GMC	1,000	GMC	100
Sugar Sweet PAG	3.6	2,500	GMC	500	25.7	100
Linear Sweet PAG	5.6	1,000	GMC	1,000	11.5	100
Lithocholic acid PAG	0.44	200	GMC	100	12.2	100

\*GMC= Greater than maximum concentration tested. \*: Based on the results after exposure time of 30 min.

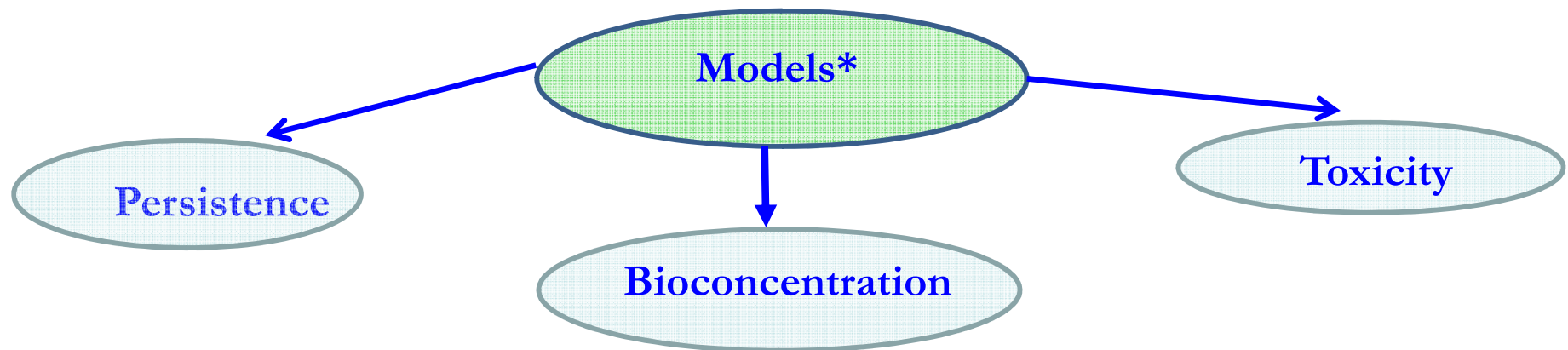
$\pm$ : Based on results of two experiments with hydrogen and acetate as electron donor, respectively. \$ Testing in progress

- PAG compounds were not toxic to anaerobic wastewater treatment biofilms.
- Some PAG compounds showed high toxicity towards the bacterium *V. fischeri* (Microtox) and intermediate toxicity towards lung epithelial 16HBE14o- cells (RTCA with xCELLigence system)



# Prediction of Toxicity and Environmental Fate using Computer Models

- Strategies to increase (bio)degradability: Biodegradation testing of structurally-related compounds modified with selected functionalities.
- Testing the validity of selected models to predict the toxicity, (bio)degradation potential and other properties determining the environmental fate of PAGs.



# Prediction of Toxicity and Environmental Fate using Computer Models

- University of Minnesota Biocatalysis/ Biodegradation Database (UMB-BD<sup>[1]</sup>) →  
Biodegradation potential and breakdown pathways
- CATABOL<sup>[2]</sup> program →  
Biodegradation potential of fluorinated compounds
- EPA Persistence-Bioaccumulation-Toxicity profiler (PBT)<sup>[3]</sup> →  
Estimates persistence, bioaccumulation potential, and chronic fish toxicity based on chemical structure
- EPA Estimation Program Interface (EPI) Suite<sup>[4]</sup> →  
Bioaccumulation potential
- EPA-ECOSAR<sup>[4]</sup> →  
Acute and chronic toxicity to fish, daphnids and green algae using an extensive set of structure-activity relationships (SARs)
- EPA-BIOWIN<sup>[4]</sup> →  
Estimates aerobic and anaerobic biodegradability of organic chemicals using 7 different models
- EPA-AOP<sup>[4]</sup> →  
Compound susceptibility to advanced oxidation of hydroxyl radicals

[1] <http://umbbd.msi.umn.edu/index.html>, [2] *SAK and QSAR in Environ. Res.*, 2004, 15: 69. [3] <http://www.pbtprofiler.net/>

[4] <http://www.epa.gov/oppt/exposure/pubs/episuite.htm>

# Toxicity: Predicted vs. Measured Levels

	PBT	ECOSAR		Experimental		
	Fish Chronic Tox	Aquatic Chronic Tox	Aquatic Acute Tox	Microtox	Methanogenic biofilms	Xcelligence
PFOS	high	intermediate	intermediate	Low	Low	Intermediate
PFBS	low	low	low	Low	Low	Intermediate
Lactone PAG	low	low	low	High	Low	Low
Sugar sweet PAG	low	low	low	High	Low	intermediate
Linear sweet PAG	low	low	low	High	low	intermediate
Lithocholic PAG	NE*	High	High	High	Low	intermediate
Dihydrocholesterol PAG	NE	High	High	planned	planned	planned
Counterion- TPS	high	High	High	high	high	planned

\* NE = not estimated

- **PBT and ECOSAR models showed performed poorly to predict experimental toxicity data.**
- **Poor fit could be related to the use of different test organisms in models (fish, algae, and/or water fleas) and experimental work (wastewater treatment microorganisms, human cell lines, bioluminescent bacteria in Microtox assay), and/or the structural complexity of the PAG compounds.**

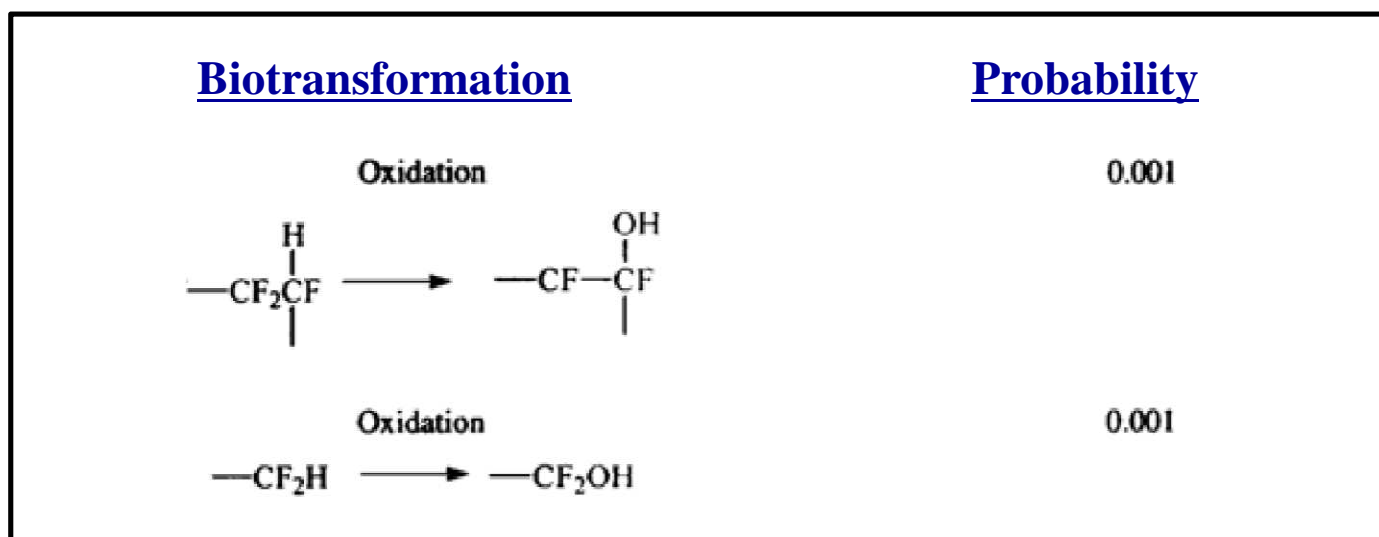
# Biodegradation Potential: Model Predictions vs. Experimental Data

Compounds	Anaerobic		Aerobic	
	BIOWIN	Experimental	BIOWIN	Experimental
PFOS	LOW	LOW	LOW	LOW
PFBS	LOW	LOW	LOW	LOW
PFOA	LOW	LOW	Intermediate	LOW
Lactone PAG	LOW	LOW	Intermediate	HIGH
Sugar sweet PAG	LOW	HIGH	HIGH	HIGH
Linear sweet PAG	LOW	LOW	HIGH	HIGH
Lithocholic PAG	LOW	Ongoing	LOW	Ongoing
Dihydrocholesterol PAG	LOW	Ongoing	LOW	Ongoing
Counter ion- TPS	LOW	LOW	LOW	LOW

- **BIOWIN** generally provided good predictions of aerobic and anaerobic biodegradation potential

# Other Models to Predict Biodegradability Pathways

- University of Minnesota Biocatalysis/ Biodegradation Database (UMB-BD<sup>[1]</sup>) →  
The rules used by the database do not accurately predict the unique characteristics of highly fluorinated compounds.
- CATABOL<sup>[2]</sup> program → The software relies on a set of principal transformations and assigns a probability to each of them. An example is shown below:



Very low probability values for the biodegradation of perfluorinated backbones (<0.001), intermediate/low probabilities for transformation of functional group substituents of highly fluorinated chains.

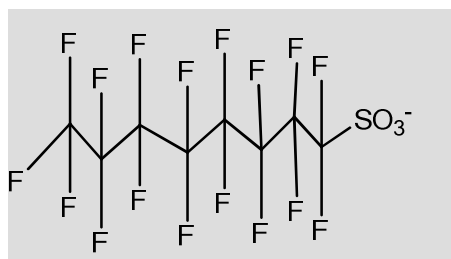
# Prediction of Removal by Advanced Oxidation Processes

Compounds	Removal by Advanced Oxidation Processes	
	AOP Model	Experimental
PFOS	NO	NO
PFBS	NO	NO
PFOA	NO	NO
Lactone PAG	YES	YES
Sugar sweet PAG	YES	YES
Linear sweet PAG	YES	planned
Lithocholic PAG	YES	planned
Dihydrocholesterol PAG	YES	planned
Counter ion: TPS	YES	YES

- AOP provided good predictions of compound susceptibility to oxidative attack by hydroxyl radicals.

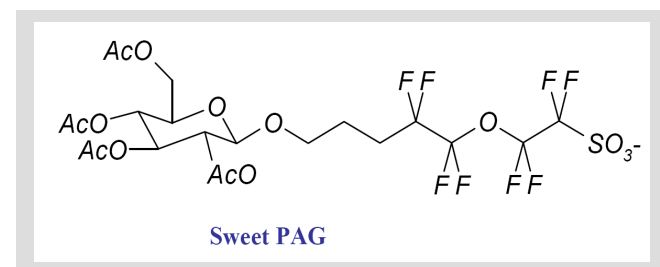
# Conclusions

**The newly developed, biomolecule-based PAGs present significant ESH advantages compared to PFOS-based PAGs.**



**PFOS**

(Perfluoroalkyl sulfonate)



Sweet PAG

**New generation PAGs**

(Biomolecule-based)

Biodegradability	NO	YES (aerobic)
Chemical Degradation	NO	YES
Methanogenic toxicity	Low	Low
Cytotoxicity	YES	+ / -- (depends on PAG)
Bioaccumulation	YES	NO

# **Future Plans**

## **Next Year's Plans :**

- **Complete environmental evaluation of the new PAGs**
- **Evaluate the removal of novel PAGs using conventional wastewater treatment and selected physico-chemical techniques.**
- **Summarize previous studies and submit manuscripts for transfer of know-how to technical community**

## **Long-Term Plans :**

- **Establish the relationship between photoacid generators' structure and their environmental properties**



# Task Deliverables

- Report on the preparation of new "Sweet" PAG Gen 2 materials (Jan 10)  
- *completed*
- Report on the lithographic evaluation of new "Sweet" PAG Gen 2 materials (July 10)  
- *completed*
- Report on the assessment of the environmental compatibility of 2nd generation "Sweet" PAGs (Jan 11)  
- *completed*
- Report on the evaluation of selected computer models to predict PAG environmental fate (Jan 11)  
- *completed*
- Report on the preparation of new "Sweet" PAG Gen 3 materials (Jan 11)  
- *completed*

# Publications, Presentations, and Recognitions/Awards

## **Publications**

- Cho Y., Ouyang C. Y., Sun W., Sierra-Alvarez R., Ober C. K. “Environmentally Friendly Natural Molecules Based Photoacid Generators for the Next Generation Photolithography” *Proc. SPIE*, 2011.
- Yi Y, Ayothi R, Wang Y, Li M, Barclay G, Sierra-Alvarez R, Ober CK. 2009. Sulfonium Salts of Alicyclic Group Functionalized Semifluorinated Alkyl Ether Sulfonates As Photoacid Generators” *Chem. Mater.* 2009, 21, 4037.
- Jing Sha, Byungki Jung, Michael O. Thompson, and Christopher K. Ober. 2009. Submillisecond post-exposure bake of chemically amplified resists by CO<sub>2</sub> laser spike annealing. *J. Vac. Sci. Technol. B*, 27(6), 3020-3024.
- Ayothi R, Yi Y, Cao HB, Wang Y, Putna S, Ober CK. 2007. Arylonium Photoacid Generators Containing Environmentally Compatible Aryloxyperfluoroalkanesulfonate Groups” *Chem. Mater.* 2007, 19, 1434.
- Ober CK, Yi Y, Ayothi R. 2007. Photoacid generator compounds and compositions. *PCT Application* WO2007124092.

## **Presentations and Conference Proceedings**

- Condensed Matter and Materials Physics (CMMP 10). Warwick, UK, Dec. 14-16, 2010. “Will Polymers Be Used to Make the Next Generation Nano World?”, invited plenary talk.
- 2010 MRS Fall Meeting, Boston, MA, November 29-December 3, 2010. “Striving for Sub-30 nm Resolution: Directed Assembly Meets Self Assembly”, invited talk.
- 1st RX Branch Distinguished Lecture, Air Force Research Laboratory, Dayton, OH, Nov. 1 – 5, 2010.
  - “The convergence of top down and bottom up patterning applied to microelectronics and the life sciences”
- 2010 MRS Spring Meeting, San Francisco, CA, April 5-9, 2010. “Striving for Sub-30 nm Resolution: Using Directed or Self Assembly”, invited talk.
- Spring 2010 ACS National Meeting, San Francisco, CA, March 21-25, 2010 “Self-assembly and directed assembly: Tools for current challenges in nanofabrication”, invited talk – Lovinger Award Symposium.
- CNF Synergies in NanoScale Manufacturing & Research Workshop, Ithaca, NY, Jan. 29, 2010. “Orthogonal Processing: A New Strategy for Patterning Organic Electronics”, invited talk.

# **Publications, Presentations, and Recognitions/Awards**

## **Presentations and Conference Proceedings**

- Sun W, Cho Y, Ober CK, Field JA, Sierra Alvarez R. 2010. Sugar-Based Photoacid Generators ("Sweet" PAGs): Environmentally Friendly Materials for Next Generation Photolithography TECHCON Conference: Technology and Talent for the 21<sup>st</sup> Century. Austin, TX. Sept. 13-14.
- Sun W, Sierra-Alvarez R, Ober C, Cho Y. 2011. Environmentally Friendly Sugar or Natural Materials Based Photoacid Generators for Next Generation Photolithography. 2<sup>nd</sup> International Congress on Sustainability Science and Engineering. Jan. 9-14, Tucson, AZ.

## **Recognitions/Awards**

- 2009 Gutenberg Research Awards for C. K. Ober
- 2009 Fellow of the American Chemical Society for C. K. Ober

# **Students on Task 425.029**

- **Graduated Students and Current Affiliation**
  - Nelson Felix, IBM, Dec 2007
  - Victor Gamez, CH2M Hill, May 2009
  - Evan Schwartz, 3M
  - Jing Sha, Intel
- **Internships (Task and related students)**
  - Marie Krysak, Intel
  - Evan Schwartz, Intel & Bayreuth
  - Anuja de Silva, IBM (now at IBM)
  - Jing Sha, NIST

# Supercritical Carbon Dioxide Compatible Additives: Design, Synthesis, and Application of an Environmentally Friendly Development Process to Next Generation Lithography *(Task Number: 425.030)*

## PI:

- Christopher K. Ober, Materials Science and Engineering, Cornell University

## Collaborator:

- Juan de Pablo, Chemical and Biological Engineering, University of Wisconsin-Madison

## Graduate Student:

- Christine Ouyang: PhD candidate, Materials Science and Engineering, Cornell University
- Gregory Toepperwein, PhD candidate, Chemical Engineering, University of Wisconsin



SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing



# Objectives

- To reduce the use of organic solvents and water in the development process by using environmentally benign solvents
- To reduce pattern collapse by using low surface tension fluids
- To demonstrate environmentally benign development of conventional photoresists using  $\text{scCO}_2$  and silicone fluids
- To achieve high resolution and high aspect-ratio patterning with molecular glass photoresists

# ESH Metrics and Impact

## **1. Reduction in the use or replacement of ESH-problematic materials**

100% reduction in the use of aqueous base TMAH developer

## **2. Reduction in emission of ESH-problematic material to environment**

Up to 100% reduction in VOCs and HAPs emission

## **3. Reduction in the use of natural resources (water and energy)**

Eliminate water usage

Reduction in energy for water treatment and purification

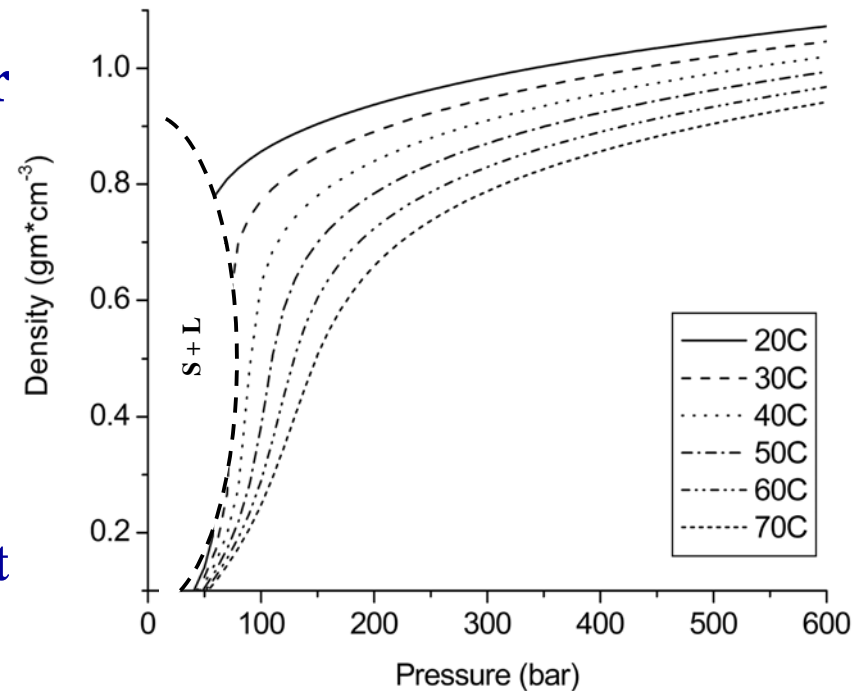
## **4. Reduction in the use of chemicals**

Minimal use of organic solvents

# Why a Non-Aqueous Developer Solvent?

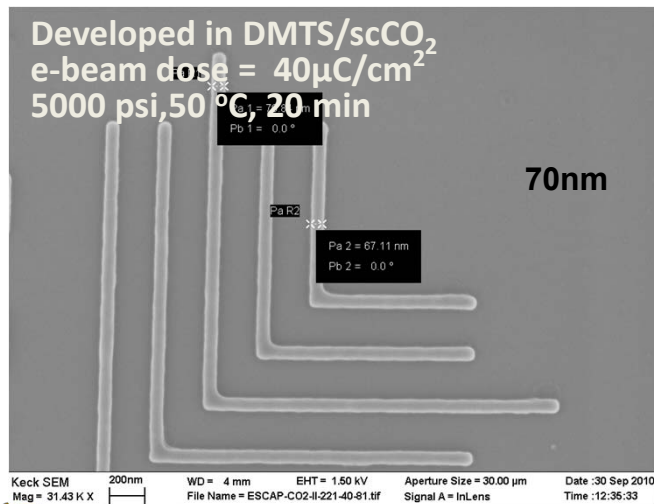
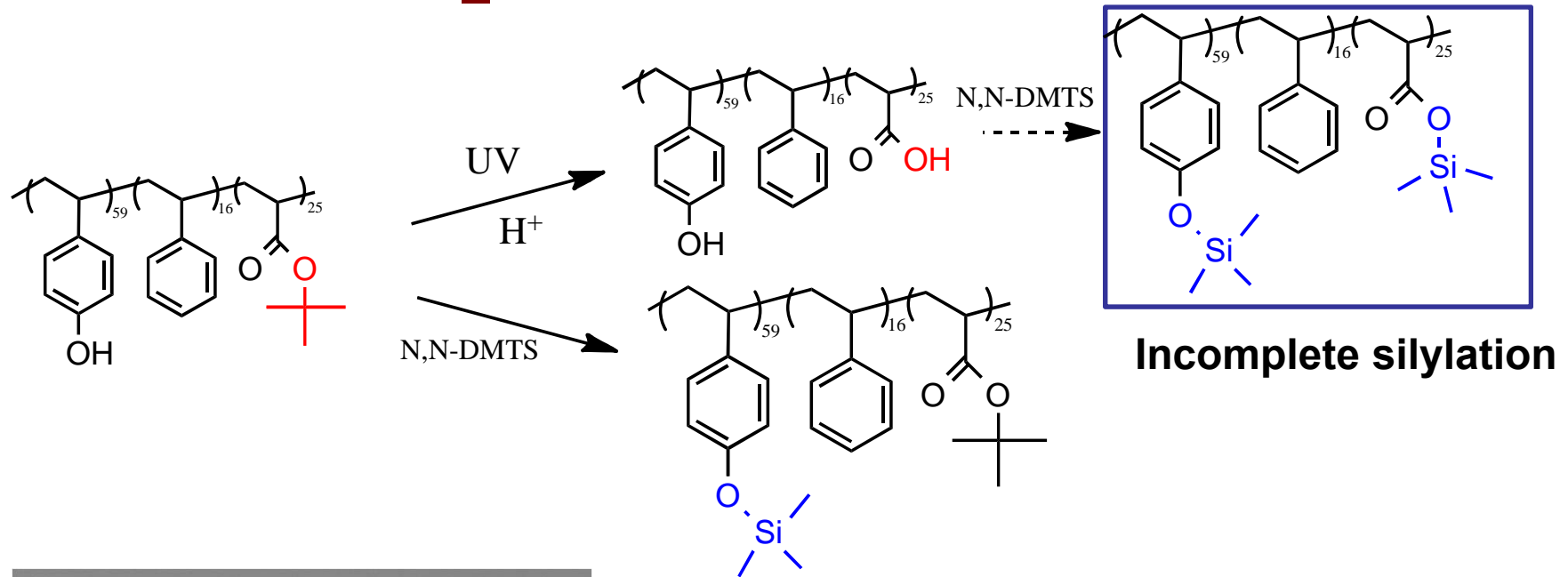
## Environmental and Performance Advantages of scCO<sub>2</sub>

- Environmentally friendly, zero VOC solvent
- Highly tunable solvating power
  - $\rho(T,P)$
  - Leaves no residue
  - Clean separations
- One-phase fluid
  - Zero surface tension
  - Transport, viscosity between that of liquid and gas
- Nonpolar, inert character
- Potential to reduce LER and eliminate pattern collapse

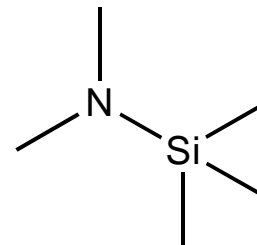




# scCO<sub>2</sub> Development of ESCAP

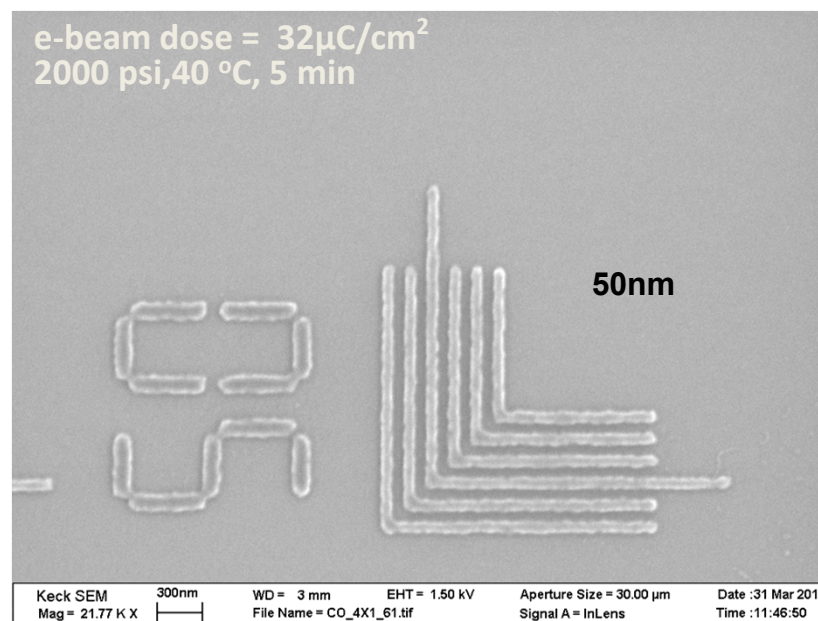
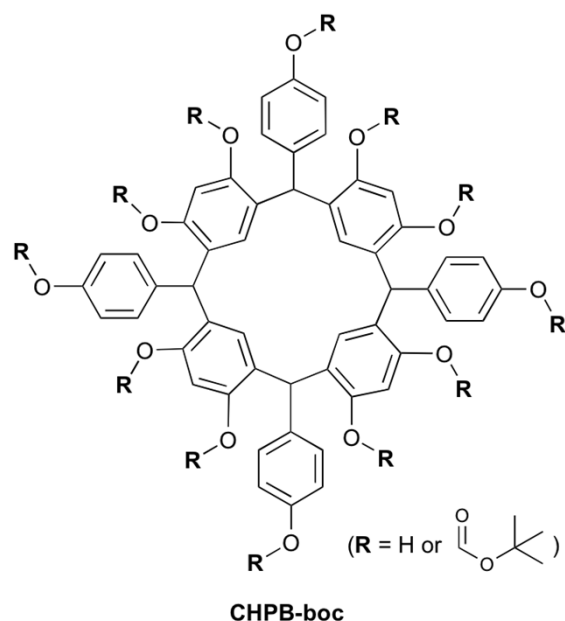


•Silicone-containing additive



(N,N-Dimethyl)trimethyl  
silane (N,N-DMTS)

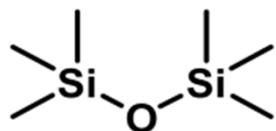
# scCO<sub>2</sub> Development of Calixarene Resist



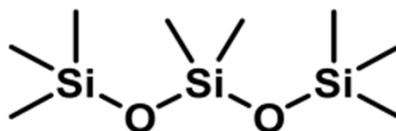
- Soluble in scCO<sub>2</sub> due to small size
- Potential to reduce LER and achieve higher resolution

# Silicone Fluids-Linear Methyl Siloxanes

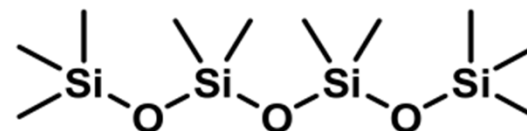
- Low in toxicity
  - Environmentally friendly
  - VOC exempt
- Contribute little to global warming
- Non-ozone depleting
  - replacement for Ozone Depleting Substances
- Low surface tension
  - potential to eliminate patterns collapse
- Can be recycled
  - degrade to naturally occurring chemical species



Hexamethyldisiloxane



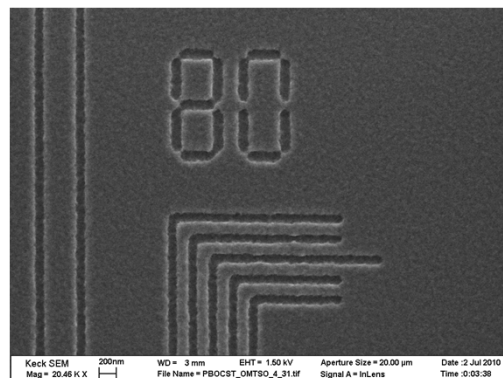
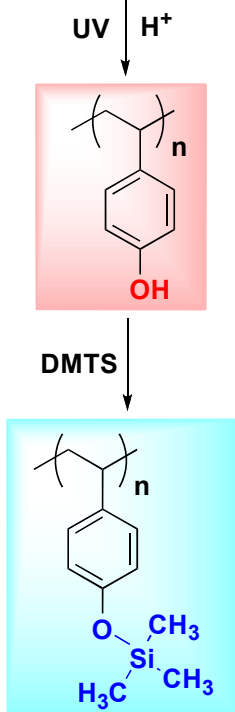
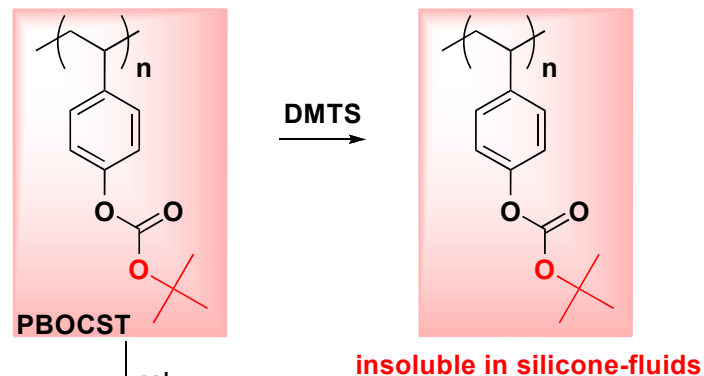
Octamethyltrisiloxane



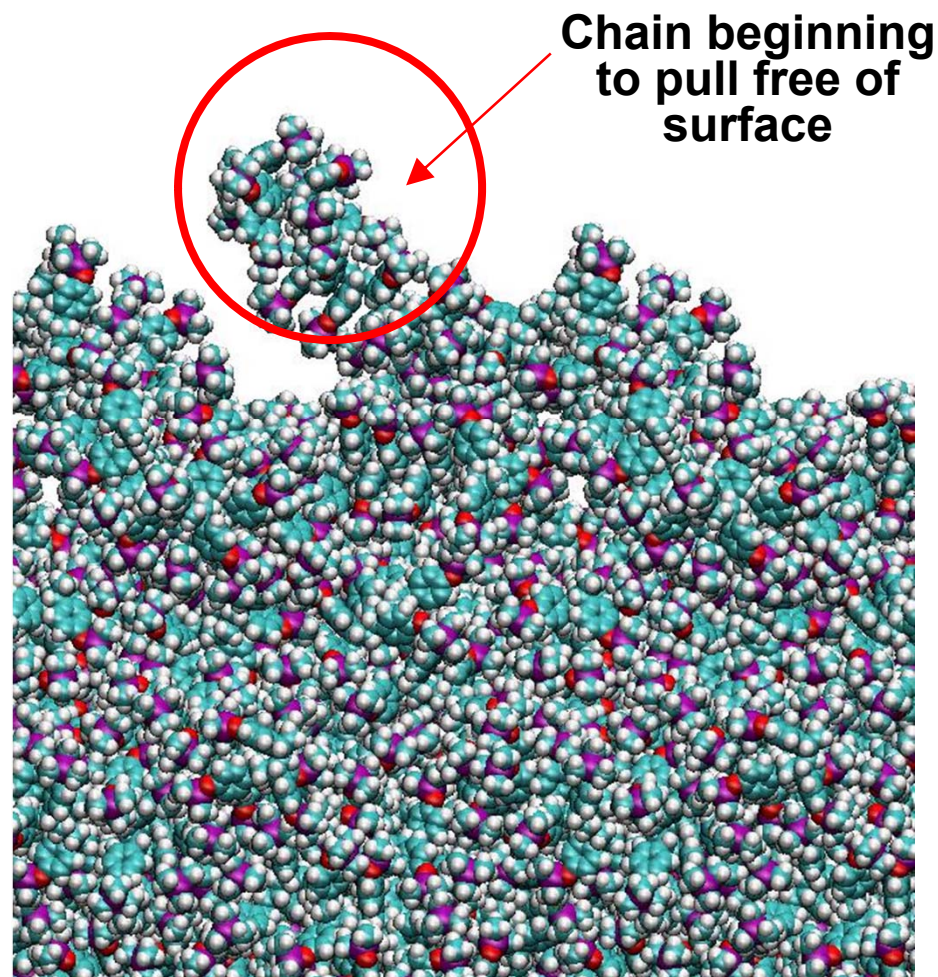
Decamethyltetrasiloxane

D. E. Williams, *ACS Symposium Series*, 2000, 767, 244-257.

# Development of PBOCST in Silicone Fluids

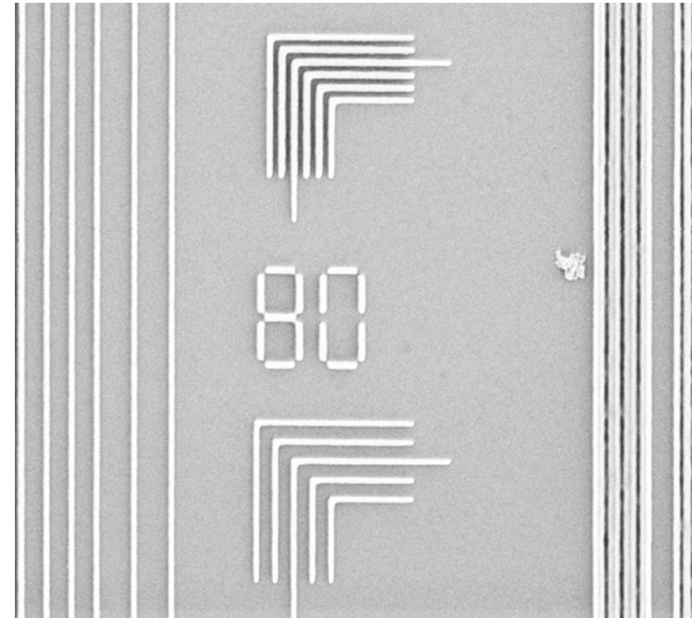
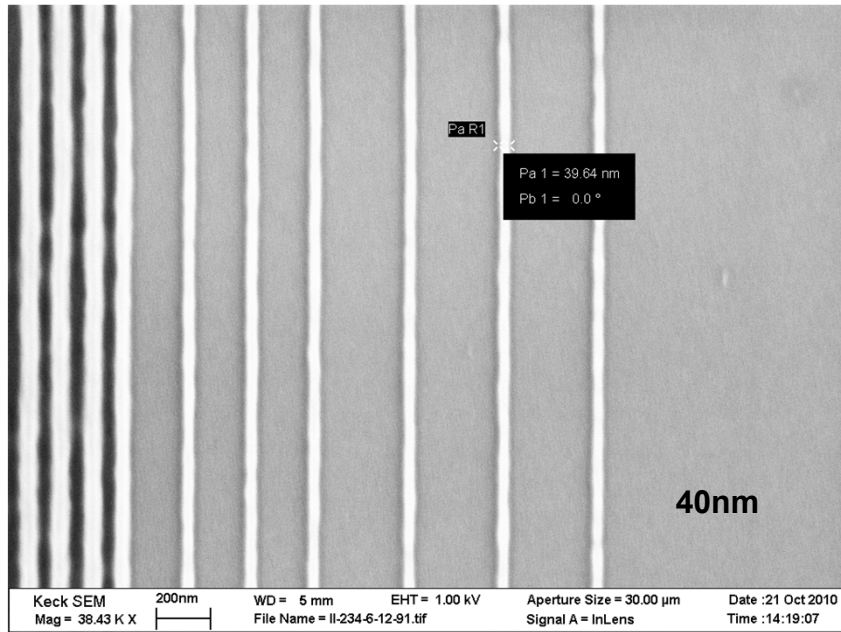


Solvent: DMTS/Octamethyltrisiloxane  
 e-beam dose = 100 $\mu\text{C}/\text{cm}^2$





# Electron-Beam Patterning and Silicone Fluid Development of Conventional Photoresists



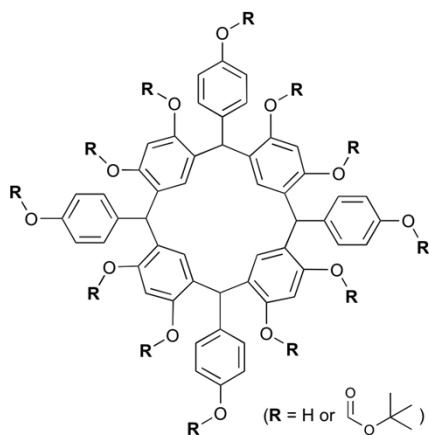
**TOK photoresist**

**DMTS: HMDSO=1:20 at 40°C for 40 minutes**

**Resist film thickness ~350 nm**

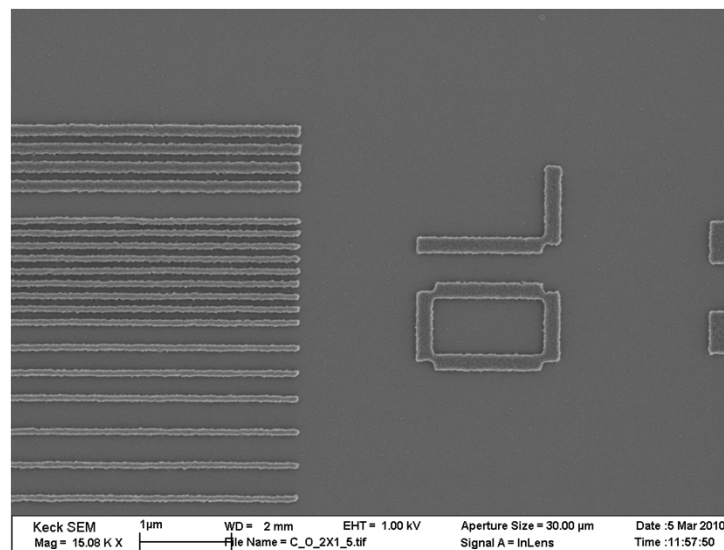
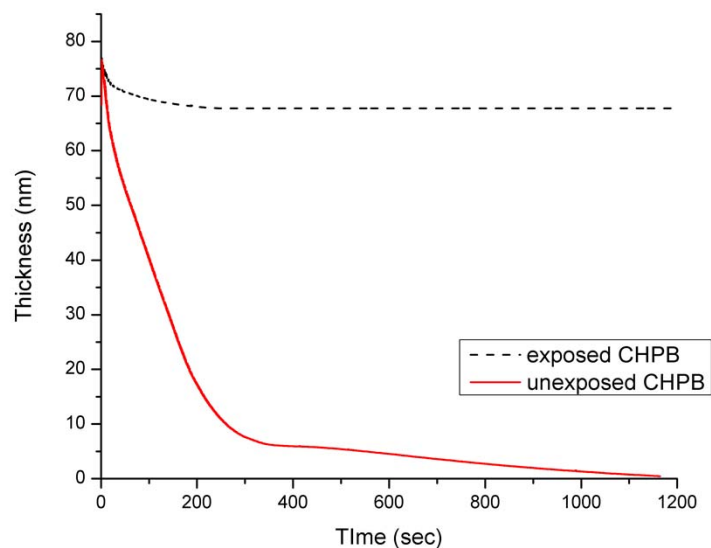
# Electron-Beam Patterning and Silicone Fluid

## Development of Calixarene Resist



CHPB-boc

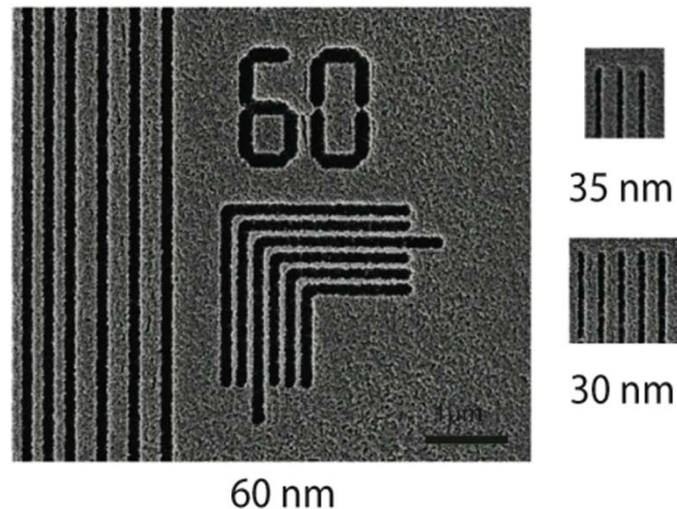
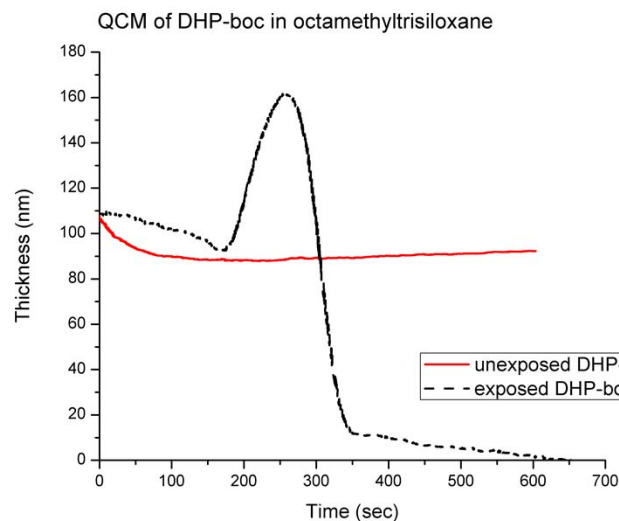
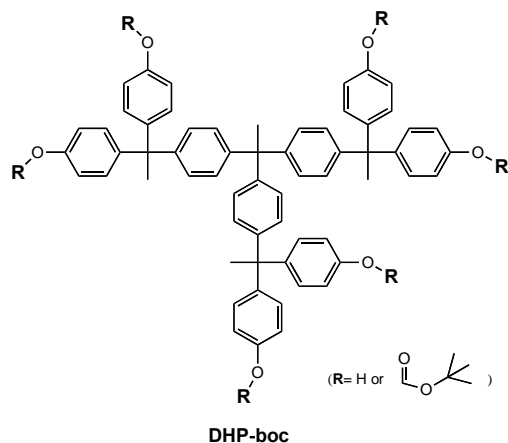
QCM of CHPB in hexamethyldisiloxane



**Solvent: Octamethyltrisiloxane**  
**e-beam dose =  $32 \mu\text{C}/\text{cm}^2$**

# Electron-Beam Patterning and Silicone Fluid

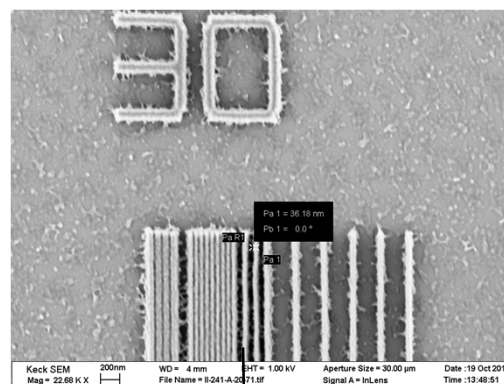
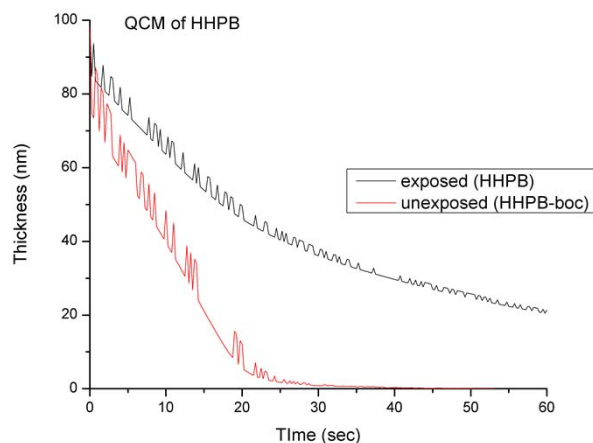
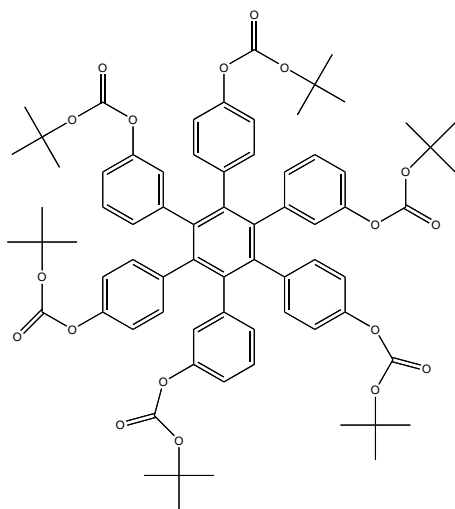
## Development of Molecular Glass Resist



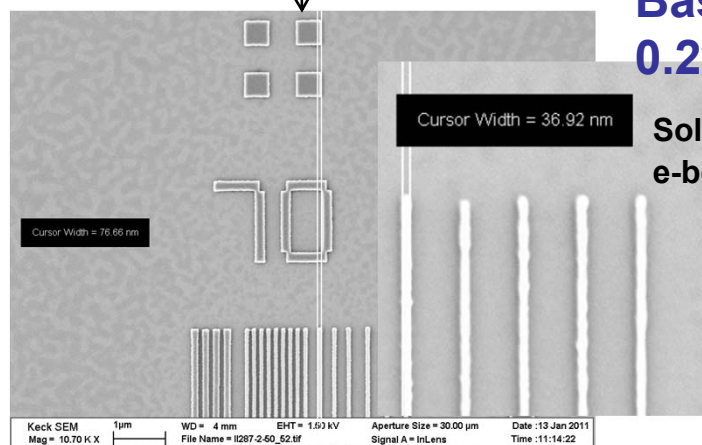
**Solvent:** DMTS/octamethyltetrasiloxane  
**e-beam dose:**  $40\mu\text{C}/\text{cm}^2$   
**Aspect ratio~6:1**

# Electron-Beam Patterning and Silicone Fluid Development of Molecular Glass

## Photoresist



Solvent: Octamethyltrisiloxane  
e-beam dose =  $20 \mu\text{C}/\text{cm}^2$   
microbridging

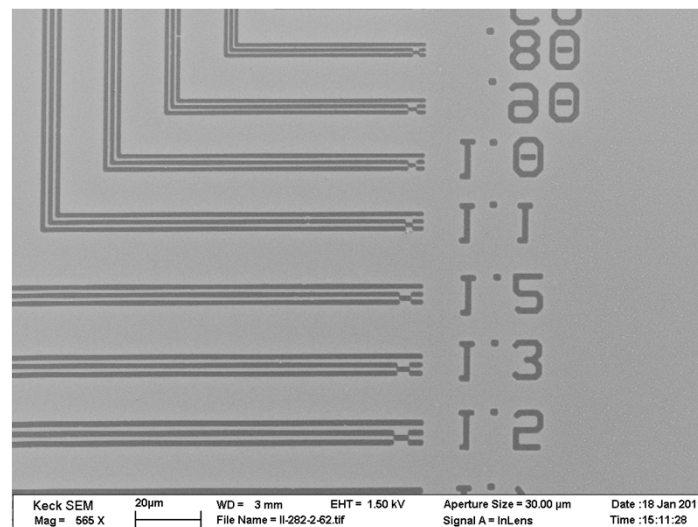
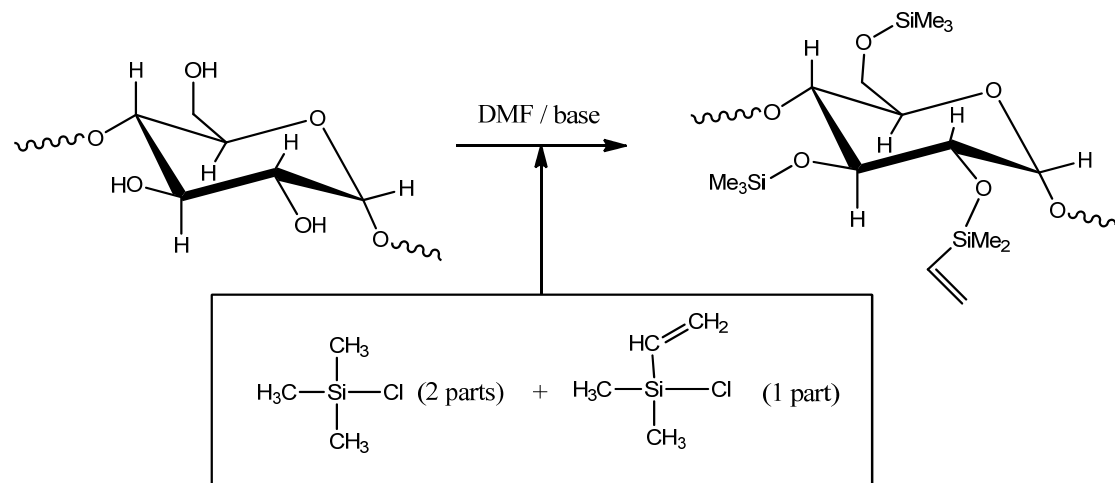


Base quencher  
0.2wt % trioctylamine

Solvent: octamethyltrisiloxane  
e-beam dose =  $50 \mu\text{C}/\text{cm}^2$



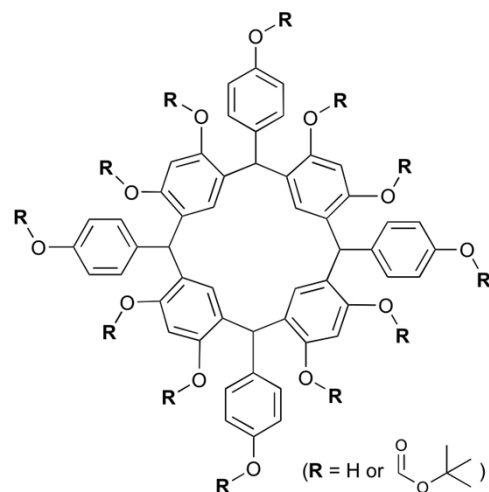
# Development of Maltodextrin Photoresists



- Based on natural materials
- Si-containing groups to increase etch resistance and solubility in silicone fluid
- Unexposed form soluble in silicone fluids

**Solvent: Octamethyltrisiloxane**  
**254 nm UV light**  
**Dose: 10.2 mJ/cm<sup>2</sup>**

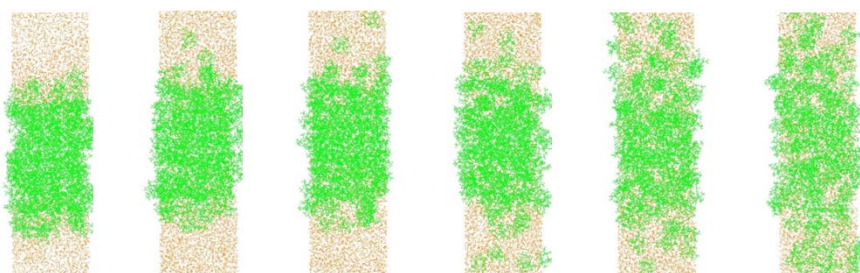
# Interactions with de Pablo Group



CHPB-boc

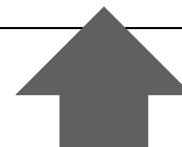


Time (1-2ns between images) →



## Ober Group

- Provide experimental results
- Development process
- Synthesize photoresists



monthly teleconference



- Computer Simulations
- Pre-screening of possible photoresist structures
- Provide information on dissolution mechanism at a molecular level

## de Pablo Group

# Future Plans

## Next Year Plans (seed effort)

- Continue successful studies of  $\text{scCO}_2$  and silicone fluid processable photoresists with computational studies as a guide for new photoresist structures
- Expand range of environmentally friendly solvents with excellent performance
- Examine unique solubility characteristics of molecular glasses as photoresists for non-polar solvent development
- Explore environmentally benign, naturally occurring cores (e.g. cyclodextrin) for next generation high-resolution molecular glass photoresists

## Long-Term Plans

- Identify additional additives for  $\text{scCO}_2$  and environmentally friendly silicone fluids to develop other conventional photoresists
- Create new chemistries for patterning and functionalizing small, non-polar molecules in  $\text{scCO}_2$  and silicone fluids



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# Industrial Interactions and Technology Transfer

- Discussions with Dow electronics on non-polar solvent development
- Interactions with Robert Allen from IBM
- Interactions with Kenji Yoshimoto from Global Foundry
- Former student (N. Felix) hired by IBM Fishkill Research Center
- Jing Sha hired by Intel
- Collaboration with Albany Nanotech for EUV exposures



# Publications, Presentations, and Recognitions/Awards

## **Publications**

- C. Y. Ouyang, J.-K. Lee, J. Sha, C. K. Ober, “*Environmentally Friendly Processing of Photoresists in  $scCO_2$  and decamethyltetrasiloxanes*”, *Proceedings of SPIE* (2010), 7639
- C. K. Ober, C. Y. Ouyang, J.-K. Lee, J. Sha, “*Green Processing of Photoresists in non-polar fluids for high resolution patterning*”, ACS preprints (2010)
- J. Sha and C. K. Ober, “*Fluorine- and Siloxane-Containing Polymers for Supercritical Carbon Dioxide Lithography*”, *Polymer International* (2009), 58(3), 302-306.
- A. Rastogi, M. Tanaka, G. N. Toepperwein, R. A. Riggelman, J. J. dePablo, C. K. Ober, “*Fluorinated Quaternary Ammonium Salts as Dissolution Aids for Polar Polymers in Environmentally Benign Supercritical Carbon Dioxide*”, *Chem. Mater.* (2009), 21(14), 3121-3135.
- J. Sha, J-K Lee, C. K. Ober, “*Molecular Glass Resists Developable in Supercritical  $CO_2$  for 193-nm Lithography*”, *Proceedings of SPIE* (2009), 7273, 72732T.

## **Presentations**

- Advances in Resist Materials and Processing Technology XXVI conference (part of the SPIE Symposium on Advanced Lithography) (Feb 2010). “*Environmentally Friendly Processing of Photoresists in  $scCO_2$  and decamethyltetrasiloxane*”
- ERC Teleseminar (Mar 2010). “*Green Processing in Lithography*”
- 240<sup>th</sup> ACS National Meeting (Aug 2010). “*Green Processing of Photoresists in Non-Polar Fluids for High-Resolution Patterning*”

# Supercritical Carbon Dioxide

## Compatible Additives:

### Design, Synthesis, and Application of an Environmentally Friendly Development Process to Next Generation Lithography

*(Task Number: 425.031)*

#### PIs:

- **Juan J. dePablo, Chemical and Biological Engineering, University of Wisconsin**
- **Christopher K. Ober, Materials Science and Engineering, Cornell University**

#### Graduate Students:

- **Gregory N. Toepperwein: 5<sup>th</sup> year PhD candidate, Chemical and Biological Engineering, University of Wisconsin**
- **Christine Ouyang: 3<sup>rd</sup> year PhD candidate, Materials Science and Engineering, Cornell University**

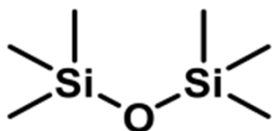
#### Undergraduate Students:

- **Dan Rynearson, Chemical and Biological Engineering, University of Wisconsin**

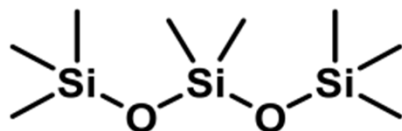
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# Objectives

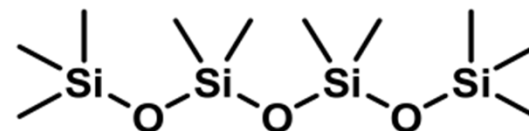
- Develop environmentally benign chemistry platforms for traditional photoresists using alternative solvents: Siloxanes and scCO<sub>2</sub>



Hexamethyldisiloxane

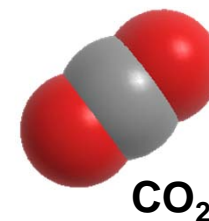


Octamethyltrisiloxane



Decamethyltetrasiloxane

- Generate the definitive molecular model for siloxane solvents
  - Complete parameterization of all bonds, torsions, charges, etc.
  - Reproduction of experimentally-obtained chemical properties (density, heat of vaporization, etc.)
- Study behavior of traditional photoresists in new solvents and supercritical carbon dioxide



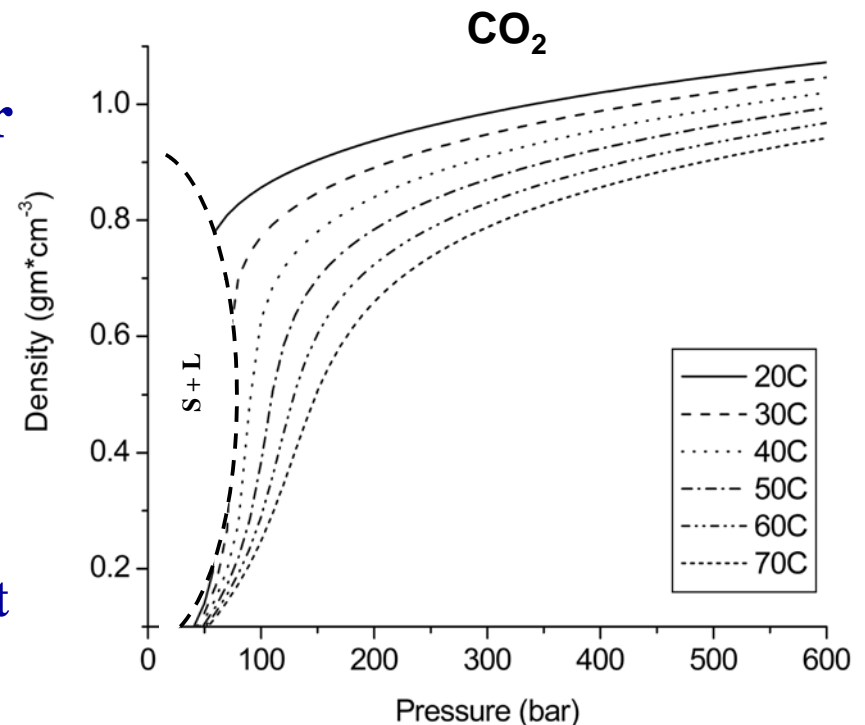
# **ESH Metrics and Impact**

- 1. Reduction in the use or replacement of ESH-problematic materials**  
**100% reduction in the use of aqueous base TMAH developer**
- 2. Reduction in emission of ESH-problematic material to environment**  
**Up to 100% reduction in VOCs and HAPs emission**
- 3. Reduction in the use of natural resources (water and energy)**  
**Eliminate water usage**  
**Reduction in energy for water treatment and purification**
- 4. Reduction in the use of chemicals**  
**Minimal use of organic solvents**



# Why a Non-Aqueous Developer Solvent?

- Environmentally friendly, zero VOC solvent
- Highly tunable solvating power
  - $\rho(T,P)$
  - Leaves no residue
  - Clean separations
- One-phase fluid
  - Zero surface tension
  - Transport, viscosity between that of liquid and gas
- Nonpolar, inert character
- Potential to reduce LER and eliminate pattern collapse



# Model

- Chose functional form consistent with generic formalism to enable transferability
- Parameters derived from quantum mechanical calculation and experimental analysis
- Modeled six elementary building blocks from which an arbitrary structure can be created

Model Formalism:

$$V_{Total} = \underbrace{V_{LJ} + V_{Coul}}_{\text{Intermolecular}} + \underbrace{V_{Bond} + V_{Ang} + V_{Tors}}_{\text{Intramolecular}}$$

$$V_{LJ} = 4\epsilon \left[ \left( \frac{\sigma}{r} \right)^{12} - \left( \frac{\sigma}{r} \right)^6 \right]$$

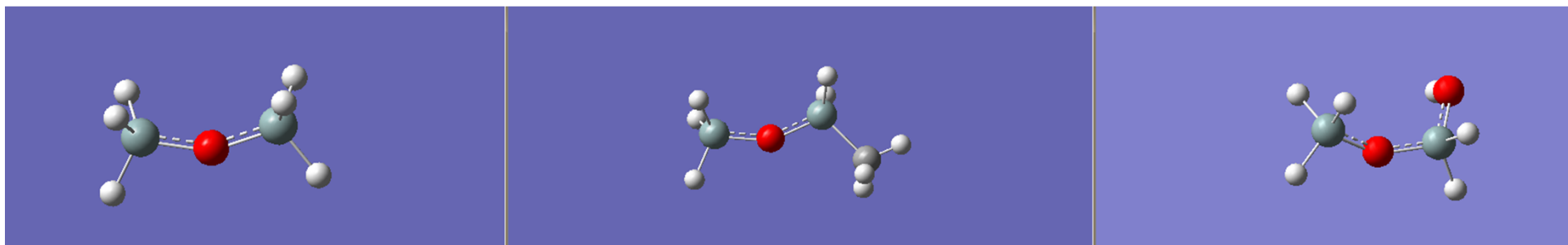
$$V_{Coul} = \frac{q_i q_j}{4\epsilon_0 \epsilon r}$$

$$V_{Bond} = \frac{1}{2} k_{Bond} (r - r_0)^2$$

$$V_{Ang} = \frac{1}{2} k_{Ang} (\theta - \theta_0)^2$$

$$V_{Tors} = \sum_{n=0}^5 c_n \cdot \cos(\phi)^n$$

Sample elementary building blocks:



**Si-O-Si-H**

**Si-O-Si-C**

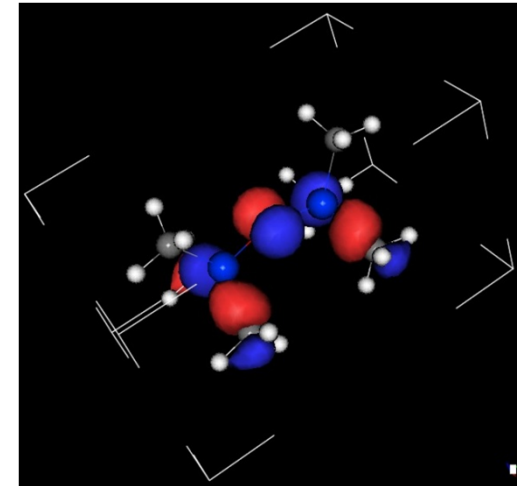
**Si-O-Si-O**

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# Quantum Mechanics

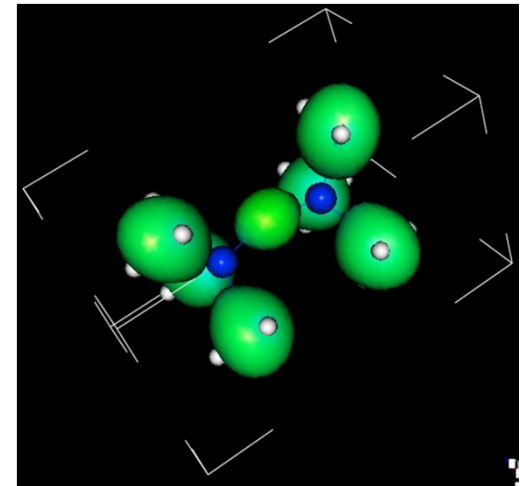
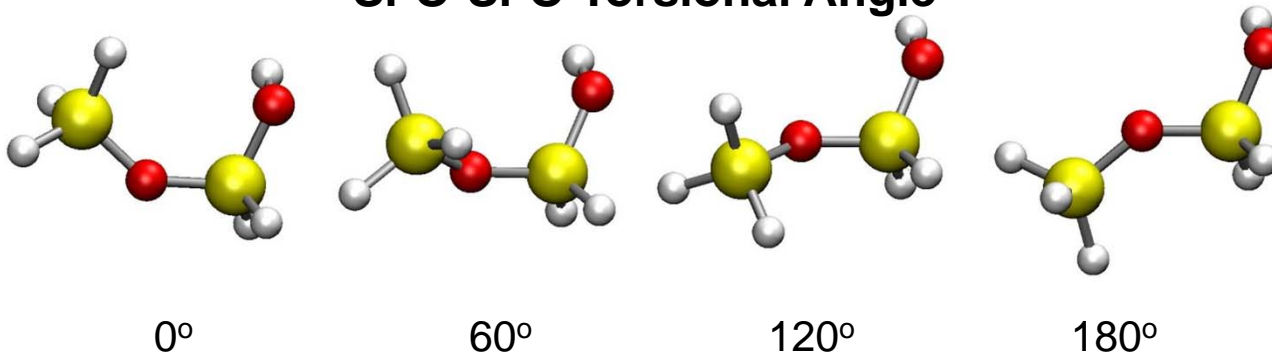
## HMD Siloxane

- Provides a detailed description of electron position as we probe different configurations
  - Can determine charges ( $q_i$ ) directly
  - Map energy as a function torsion angle, etc.
  - rb3lyp model with 6-311+g(2d,p) basis set



HOMO

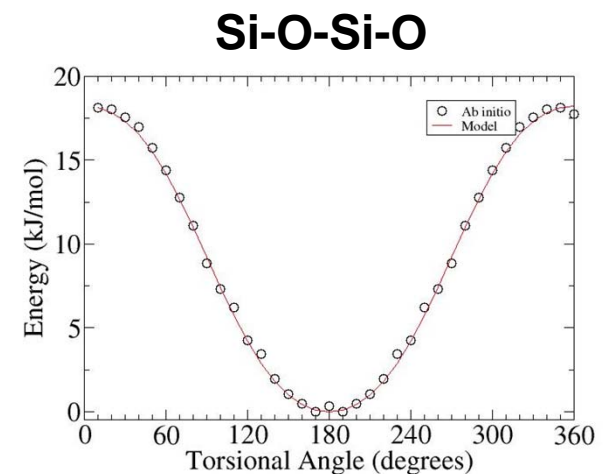
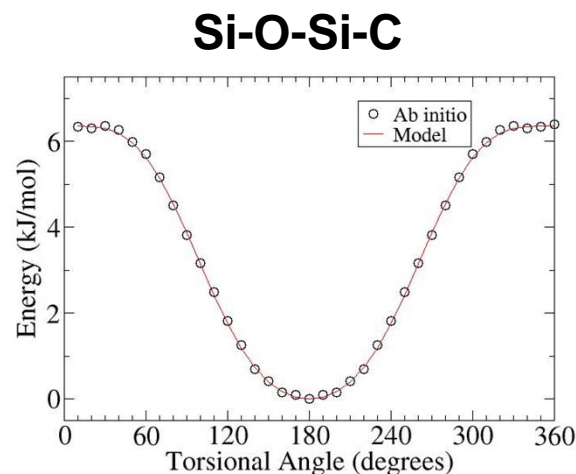
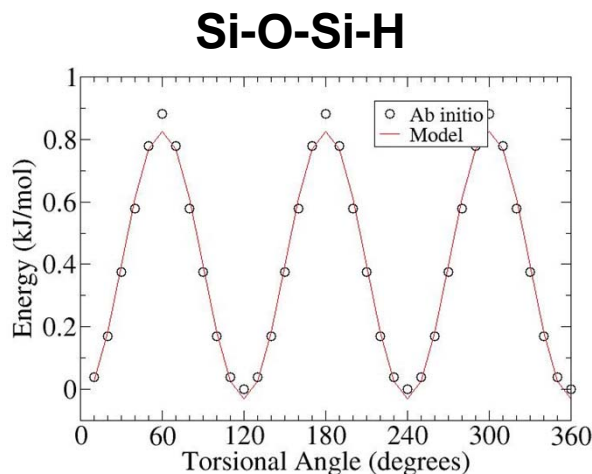
### Si-O-Si-O Torsional Angle



LUMO

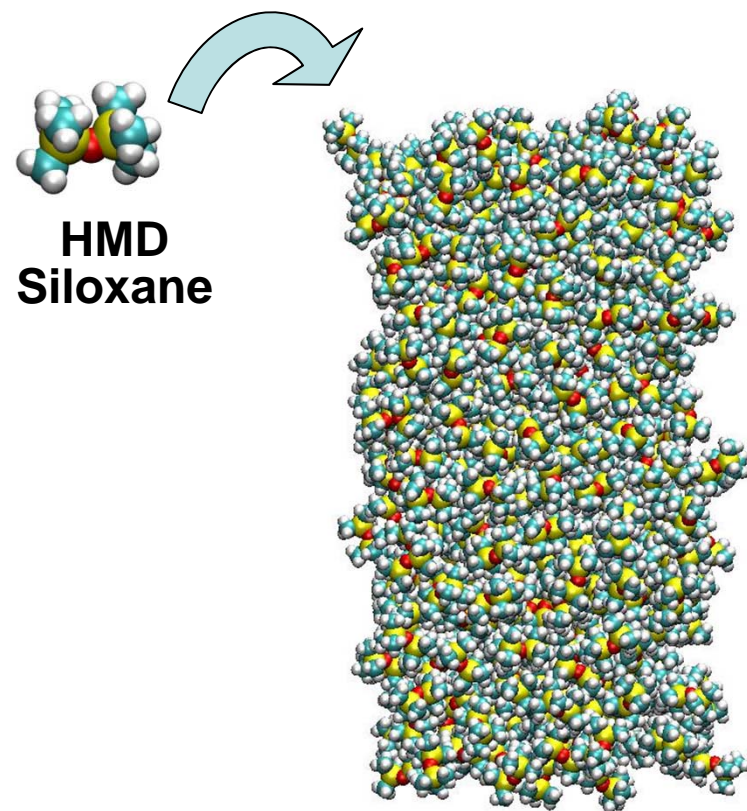
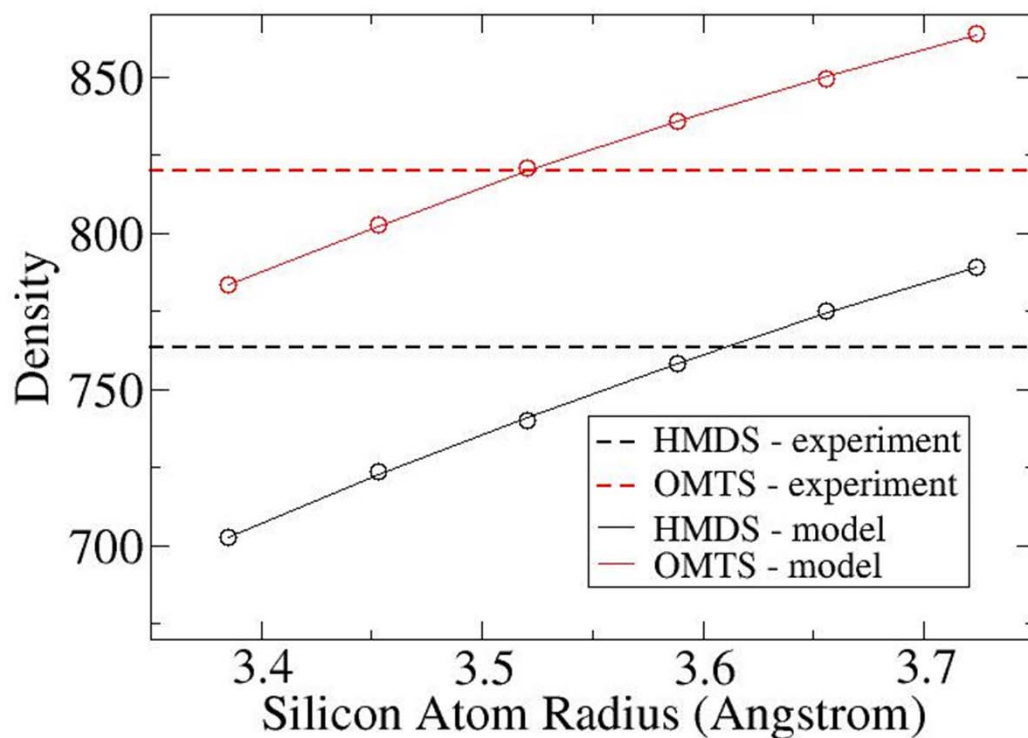
# Potential Fitting – Torsional Sample

- **Si-O-Si-C** and **Si-O-Si-O** torsions most important parameters in determining shape of the solvents
- Torsional parameters fit to capture difference between quantum mechanical results and non-bonded interactions




# Intermolecular Interactions

- Having built a complete intramolecular model from quantum mechanics, we now tune intermolecular many-body interactions to match experiment



# Experimental Measurables

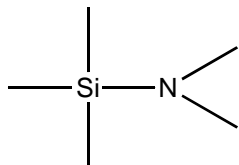
	HMD Siloxane		OMT Siloxane		DMT Siloxane	
	Experimental	Model	Experimental	Model	Experimental	Model
Heat of Vaporization (kcal/mol)	7.2	7.1	 40.4	10.1	12.0	13.2
Specific Heat (cal/g*K)	0.46	0.21	0.29	0.42	0.41	0.65
Density (g/ml)	0.764	0.758	0.820	0.836	0.854	0.85
Dipole Moment (Debye)	Unknown	1.016	Unknown	1.203	Unknown	2.0553
Dielectric Constant	Unknown	1.339	Unknown	1.400	Unknown	1.875

- **Good agreement with known properties**
- **Model suggested error in literature of OMTSiloxane heat of vaporization, repeat of measurement confirmed model was correct**

# Application of Siloxane Model: ESCAP

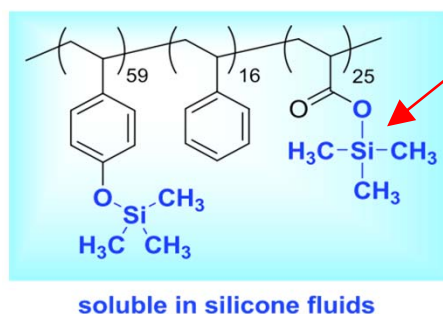
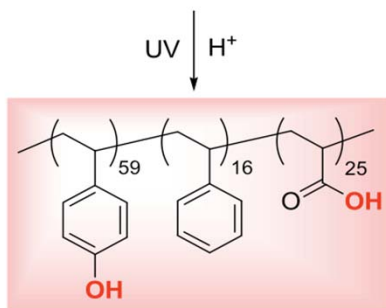
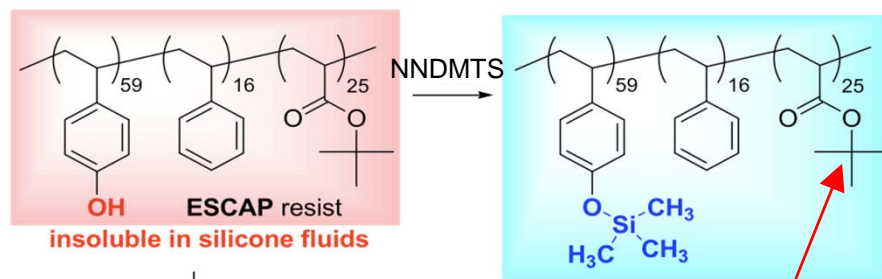
- ESCAP is our model EUV photoresist
  - Model previously developed and tested for  $\text{scCO}_2$

- In experiment, chemically modified by NNDMTS:



(N,N-Dimethyl)trimethyl silane

- Similarity between exposed and unexposed form makes ESCAP a serious test of model sensitivity



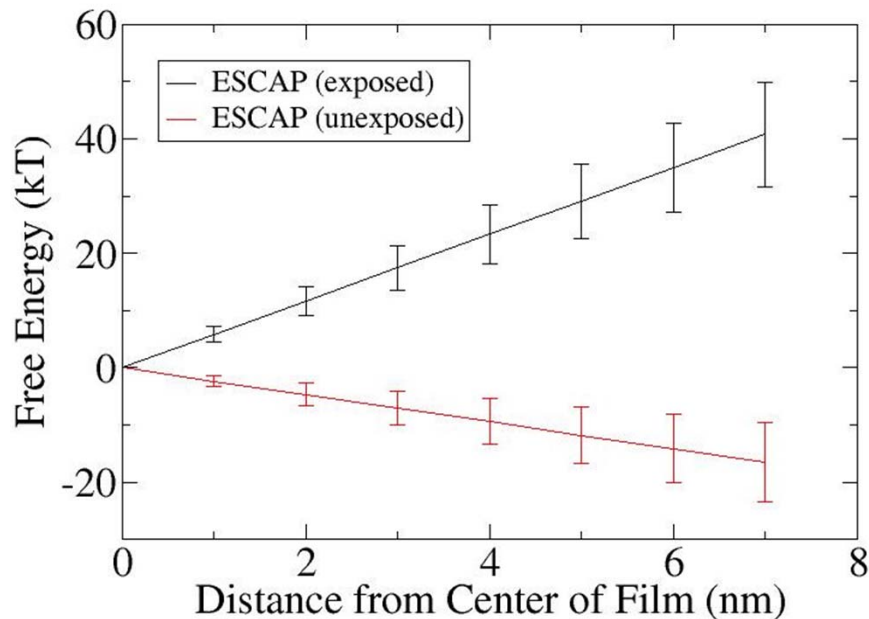
**Identical Topology**  
Si atom makes group slightly bulkier, makes group more polar

**Chemistry shown independent of specific siloxane solvent used**

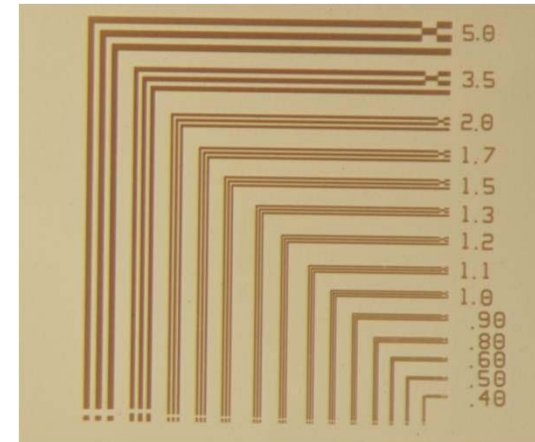


# ESCAP Result

- Model predicts only unexposed films to be unstable:
  - Negative Tone
- Results from experimental collaborator corroborate result



**Solvent: Hexamethyldisiloxane**



**Photoresist: ESCAP**

**Chemical modifier:  
NNDMTS**

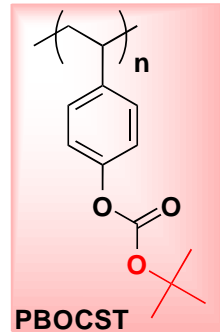
**Solvent:  
Octamethyltrisiloxane**

**Dose = 50 mJ/cm<sup>2</sup>**

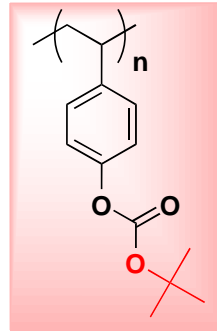
**PEB: 115 °C, 60 sec**



# PHOST Result

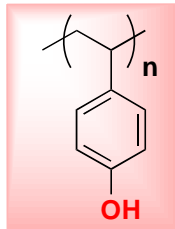


DMTS

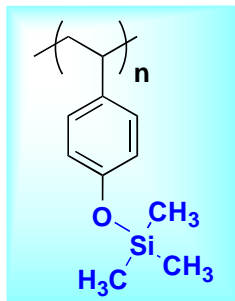


insoluble in silicone-fluids

UV  $H^+$



DMTS

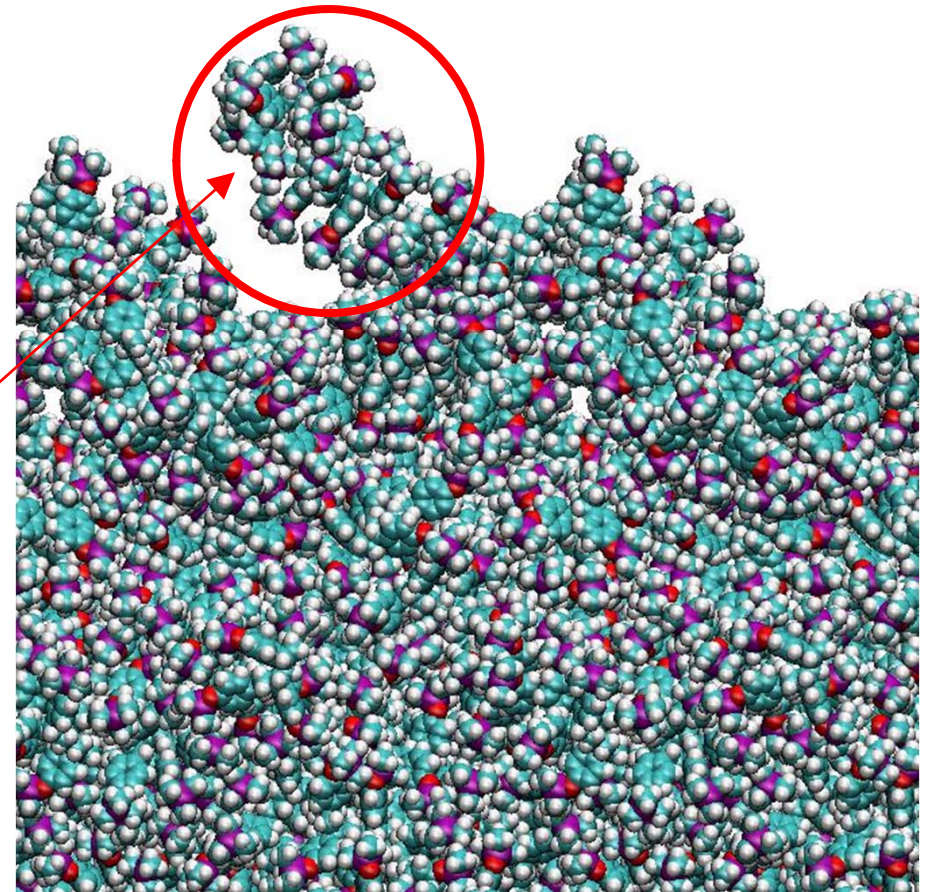


soluble in silicone-fluids

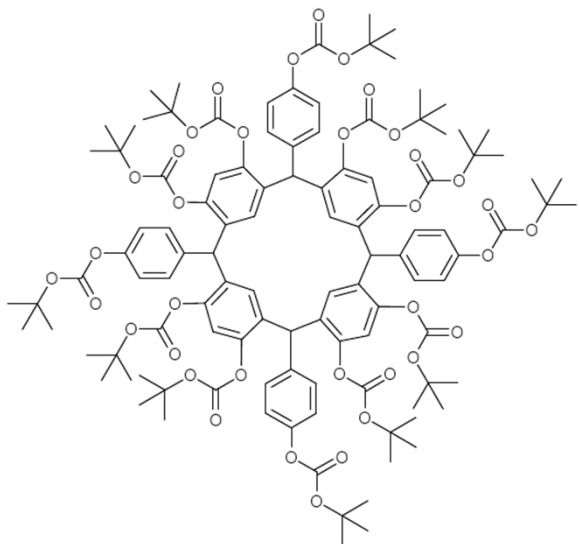
Chain beginning  
to pull free of  
surface

(exposed form  
in HMDSiloxane)

- Other EUV model photoresist predicted to be positive tone resist and confirmed by experiment

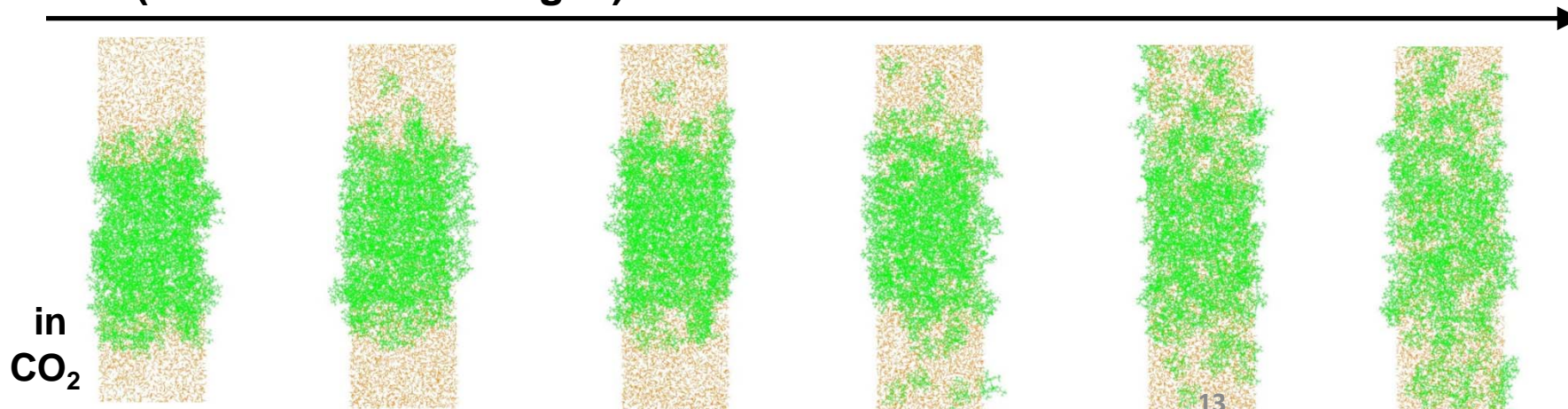


# Predictive Power of Simulation: Calixarene



- Molecular glass photoresist capable of high-resolution patterns (low LER)
- Last January we demonstrated potential of this via simulation **BEFORE** experiment
- Capable of dissolution in scCO<sub>2</sub> without any additive (first material to show this property, shown below)
- Viable in siloxane-based solvents also

Time (1-2 ns between images)



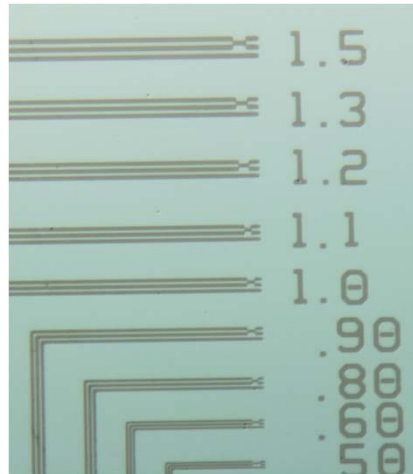
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# Calixarene Experimental Results

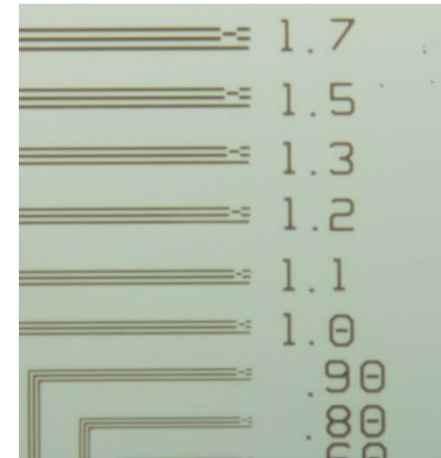
- Collaborators have demonstrated true potential of this compound in siloxane solvents (negative tone resist)
- Preliminary results with Siloxane model in agreement



**OMT Siloxane**  
**Dose: 250 mJ/cm<sup>2</sup>**  
**PEB: 90°C, 30 sec**



**HMD Siloxane**  
**Dose: 350 mJ/cm<sup>2</sup>**  
**PEB: 90°C, 30 sec**



**DMT Siloxane**  
**Dose: 300 mJ/cm<sup>2</sup>**  
**PEB: 90°C, 30 sec**

# Industrial Interactions and Technology Transfer

- Regular discussions with Intel via Richard Schenker
- Interactions with Dario Goldfarb from IBM
- Interactions with Kenji Yoshimoto from Global Foundry



# **Future Plans**

## **Next Year Plans (seed effort)**

- Continue successful studies of  $\text{scCO}_2$  and silicone fluid processable photoresists with computational studies as a guide for new photoresist structures
- Expand range of environmentally friendly solvents with excellent performance
- Examine unique solubility characteristics of molecular glasses as photoresists for non-polar solvent development
- Explore environmentally benign, naturally occurring cores (e.g. cyclodextrin) for next generation high-resolution molecular glass photoresists

## **Long-Term Plans**

- Identify additional additives for  $\text{scCO}_2$  and environmentally friendly silicone fluids to develop other conventional photoresists
- Create new chemistries for patterning and functionalizing small, non-polar molecules in  $\text{scCO}_2$  and silicone fluids



# Publications, Presentations, and Recognitions/Awards

## **Publications**

- C. Y. Ouyang, J.-K. Lee, J. Sha, C. K. Ober, “*Environmentally Friendly Processing of Photoresists in  $scCO_2$  and decamethyltetrasiloxanes*”, *Proceedings of SPIE* (2010), 7639
- C. K. Ober, C. Y. Ouyang, J.-K. Lee, J. Sha, “*Green Processing of Photoresists in non-polar fluids for high resolution patterning*”, ACS preprints (2010)
- J. Sha and C. K. Ober, “*Fluorine- and Siloxane-Containing Polymers for Supercritical Carbon Dioxide Lithography*”, *Polymer International* (2009), 58(3), 302-306.
- A. Rastogi, M. Tanaka, G. N. Toepperwein, R. A. Riggleman, J. J. dePablo, C. K. Ober, “*Fluorinated Quaternary Ammonium Salts as Dissolution Aids for Polar Polymers in Environmentally Benign Supercritical Carbon Dioxide*”, *Chem. Mater.* (2009), 21(14), 3121-3135.
- J. Sha, J-K Lee, C. K. Ober, “*Molecular Glass Resists Developable in Supercritical  $CO_2$  for 193-nm Lithography*”, *Proceedings of SPIE* (2009), 7273, 72732T.

## **Presentations**

- Advances in Resist Materials and Processing Technology XXVI conference (part of the SPIE Symposium on Advanced Lithography) (Feb 2010). “*Environmentally Friendly Processing of Photoresists in  $scCO_2$  and decamethyltetrasiloxane*”
- ERC Teleseminar (Mar 2010). “*Green Processing in Lithography*”
- 240<sup>th</sup> ACS National Meeting (Aug 2010). “*Green Processing of Photoresists in Non-Polar Fluids for High-Resolution Patterning*”

# **Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry**

*(Task 425.032)*

## **Subtask 1: Effect of Retaining Ring Geometry on Slurry Flow and Pad Micro-Texture**

### **PI:**

- Ara Philipossian, Chemical and Environment Engineering, UA

### **Graduate Students:**

- Xiaoyan Liao, PhD candidate, Chemical and Environmental Engineering, UA
- Xiaomin Wei, PhD candidate, Chemical and Environment Engineering, UA
- Anand Meled , PhD candidate, Chemical and Environment Engineering, UA

### **Undergraduate Student:**

- Adam Rice, Chemical and Environment Engineering, UA

# Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry

*(Task 425.032)*

## Subtask 1: Effect of Retaining Ring Geometry on Slurry Flow and Pad Micro-Texture

### Other Researchers:

- Yasa Sampurno, Postdoctoral Fellow, Chemical and Environment Engineering, UA
- Yun Zhuang, Postdoctoral Fellow, Chemical and Environment Engineering, UA

### Cost Share (other than core ERC funding):

- In-kind donation (pads) from Cabot Microelectronics Corporation
- In-kind donation (retaining rings) from Entegris, Inc.
- In-Kind deonation (diamond discs) from Ehwa



# Primary Anticipated Results

- **Understand how pad micro-texture and slurry availability are fundamentally affected by:**
  - Pad type (i.e. porous vs. non-porous, and various degrees of hardness)
  - Diamond disc type (i.e. grain size, and morphology)
  - Retaining ring slot designs
  - Slurry flow rate and injection schemes
- **Via die-scale and wafer-scale empirical, theoretical and numerical methods, gain a deeper understanding of how the above:**
  - Interact with one another
  - Affect polishing outcomes (on 200 and 300 mm rotary platforms)
  - Extendible to 450 mm rotary processes (theoretically)
- **Ultimately, our goal is for this work to lead to new designs of polishing protocols and consumables with superior performance (i.e. wafer-level topography, uniformity, consumable durability, throughput ...) and more environmentally benign consequences.**

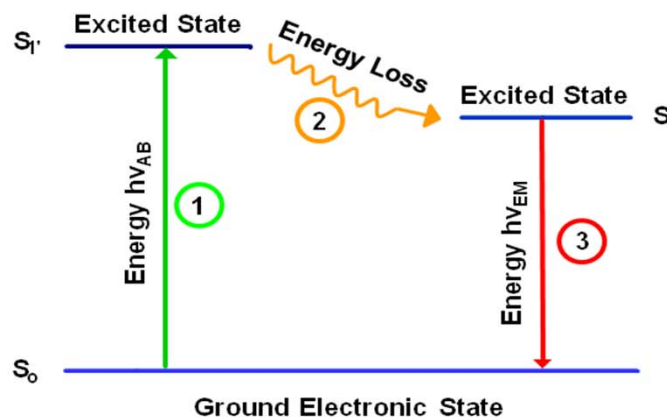
# Specific Objectives and EHS Impact

- **Develop UV enhanced fluorescence system and quantify the extent of fluorescent light emitted by the slurry**
- **Employ the fluorescent light data to rapidly assess slurry flow patterns as a function of retaining ring designs, slurry flow rates, pad groove designs, and tool kinematics**
- **Investigate the effect of retaining ring slot design and polishing conditions including pad/retaining ring sliding velocity, retaining ring pressure and slurry flow rate on fluid dynamics at the bow wave**

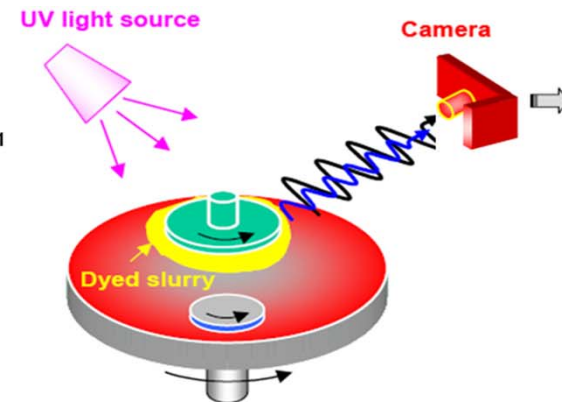
**Reduce slurry consumption by 40 percent**

# General Approach

- Tag slurry with a special set of fluorescent dyes
- Use UV – LED as light sources to excite the dyes in the slurry causing them to emit fluorescent light
- Employ a high resolution CCD camera to record the emission of fluorescent light
- Develop software and quantitatively assess the flow pattern using the movie from CCD camera



Jablonski Energy Level Diagram

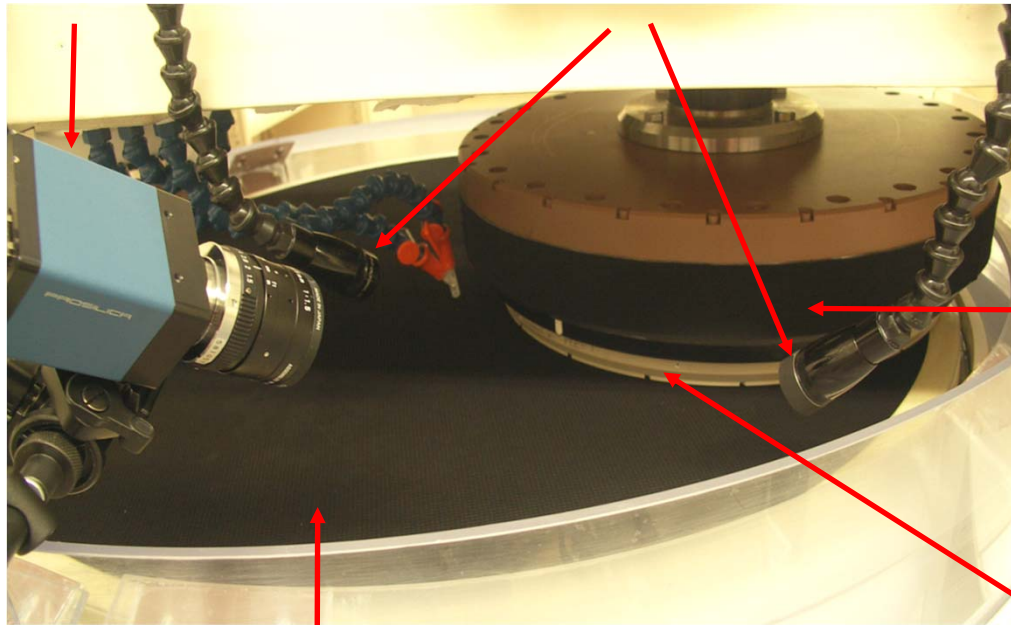


UV Fluorescence Technique

# Experimental Setup

**HD CCD Camera**

**UV Lights**



Polisher	: Araca APD – 800®
Camera shutter	: 0.02 sec
Frequency	: 5 Hz
Frames per run	: 50 frames

**Carrier Head**

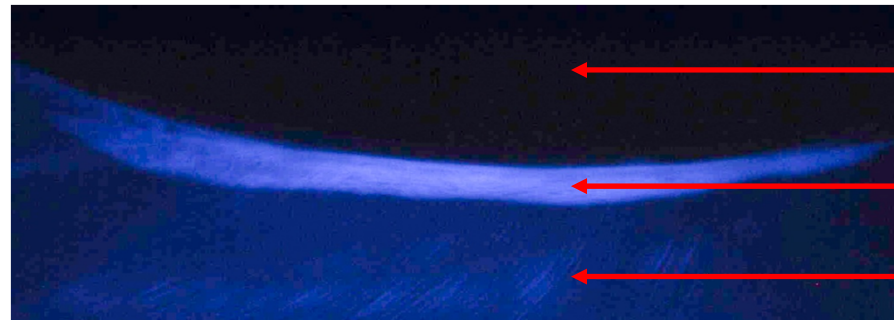


**Retaining Ring**

**Politex Pad**

# Image Analysis Procedure

**Raw Image**

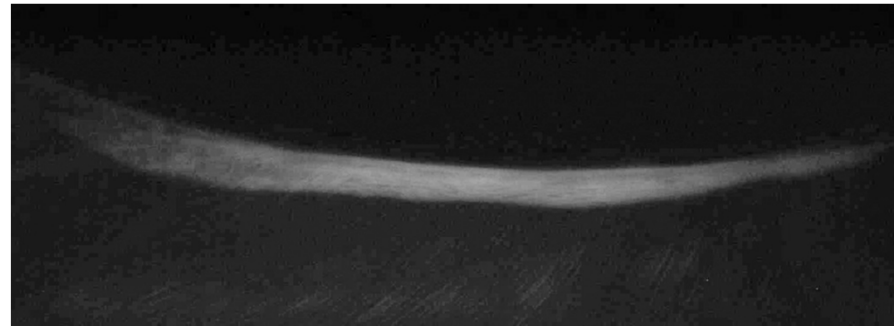


**Carrier Head**

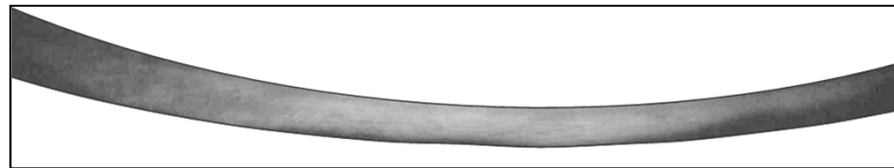
**Bow wave**

**Pad**

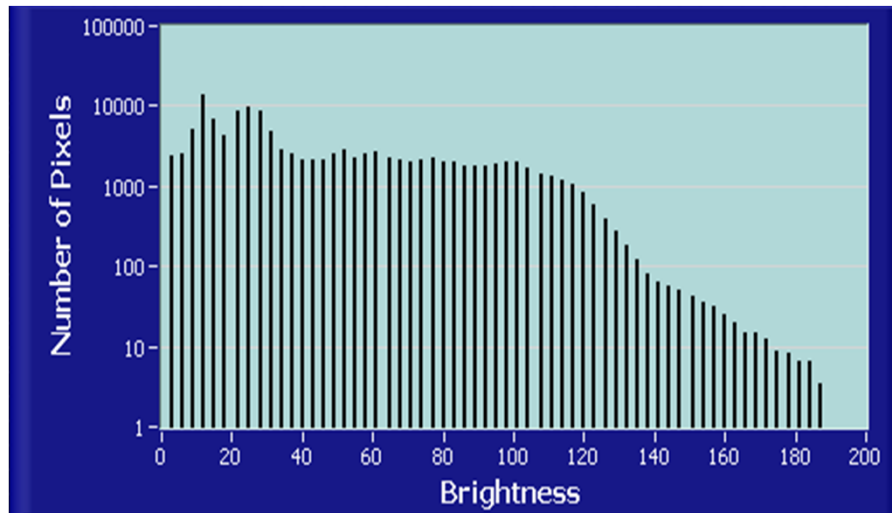
**Grey Scale Image**



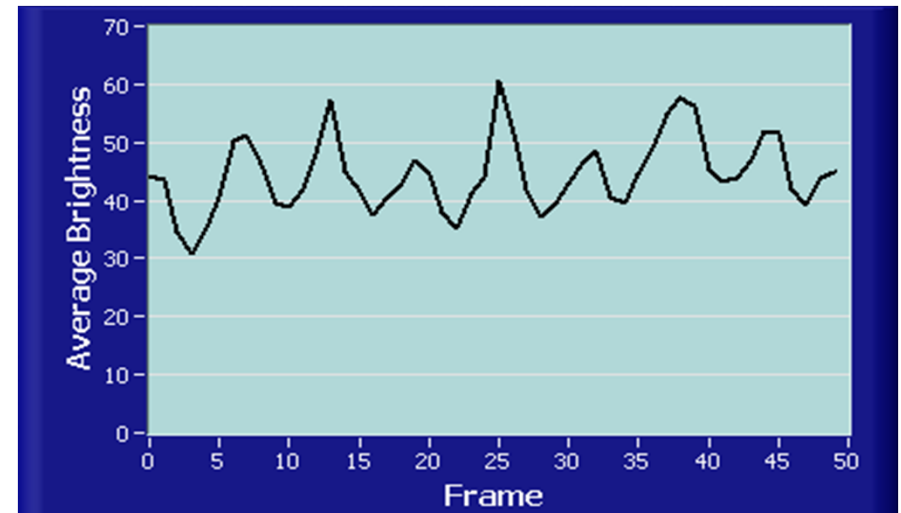
**Cropped Image**



# Image Analysis – Effect of Pressure



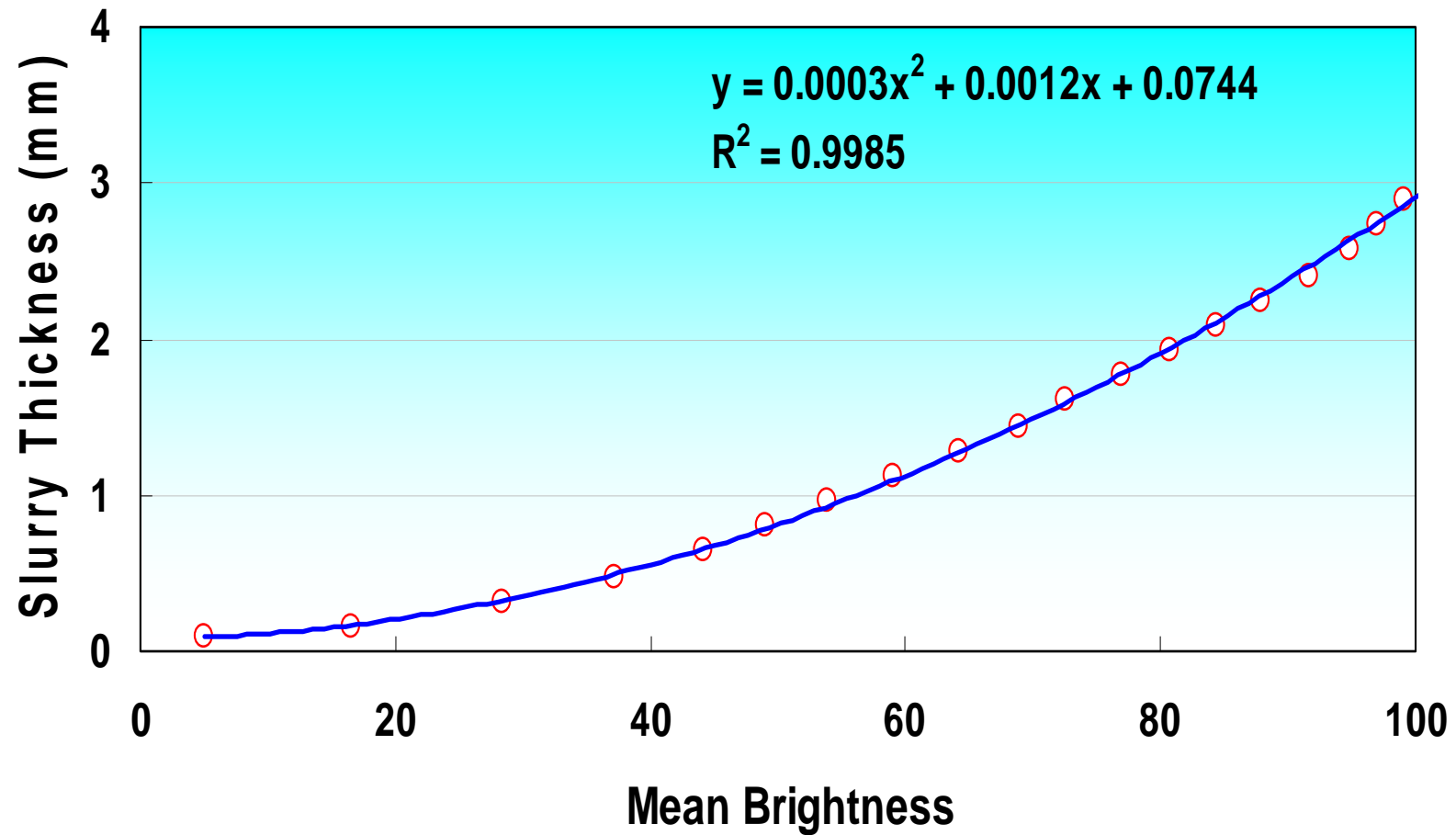
**Brightness Data of One Image**



**Average Brightness Calculation**

**Mean brightness: 44.5**  
**Standard deviation: 6.4**

# Slurry Film Thickness Calibration Curve

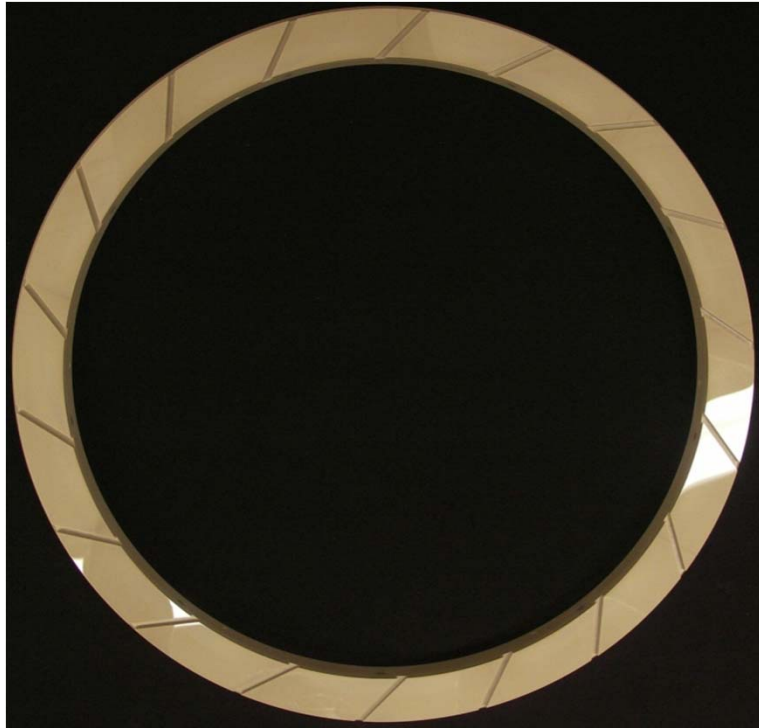


# Experimental Conditions

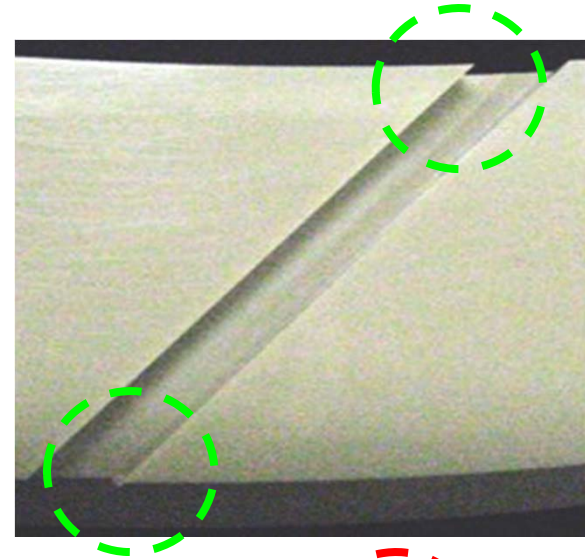
- **Retaining Ring Designs**
  - PEEK-1 and PEEK-2
- **Sliding Velocities**
  - 0.6 and 1.2 m/s
- **Ring Pressures**
  - 1.4 and 2.8 PSI
- **Slurry Flow Rates**
  - 150 and 300 ml/min
- **Pad**
  - Dow Electronic Materials Politex REG
- **Pad Conditioning**
  - In-situ conditioning at 3 lb<sub>f</sub> by 3M PB32A brush
- **Slurry**
  - 1 part of Fujimi PL-7103 slurry + 4 parts of DI H<sub>2</sub>O + 0.5 g/L Coumarin (4-Methyl-umbelliferone)
- **Polishing Time**
  - 20 seconds



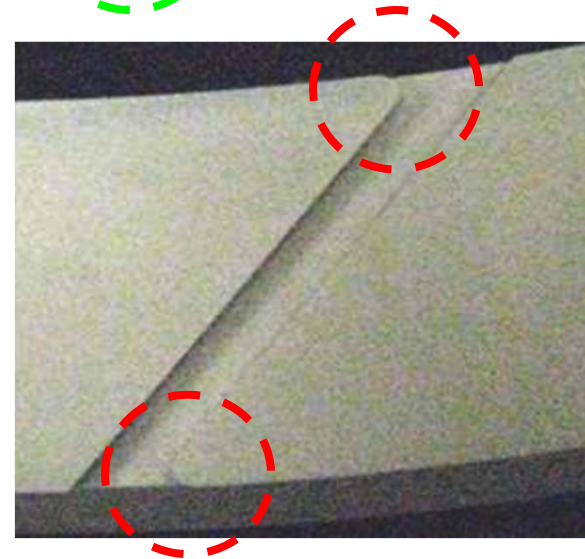
# Retaining Ring Slot Designs



**Retaining Ring for 300-mm Wafer Process**



**PEEK-1**



**PEEK-2**

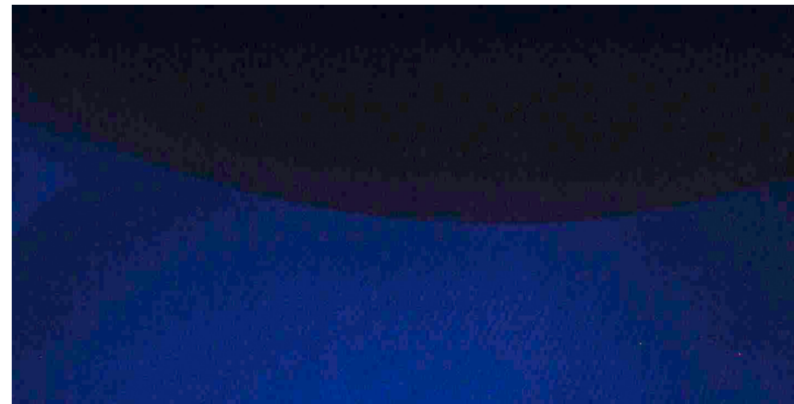
# Example – Effect of Retaining Ring Designs

**0.6 m/s, 2.8 PSI, 300 ml/min**



**PEEK-1**

**Mean slurry film thickness: 0.71 mm**

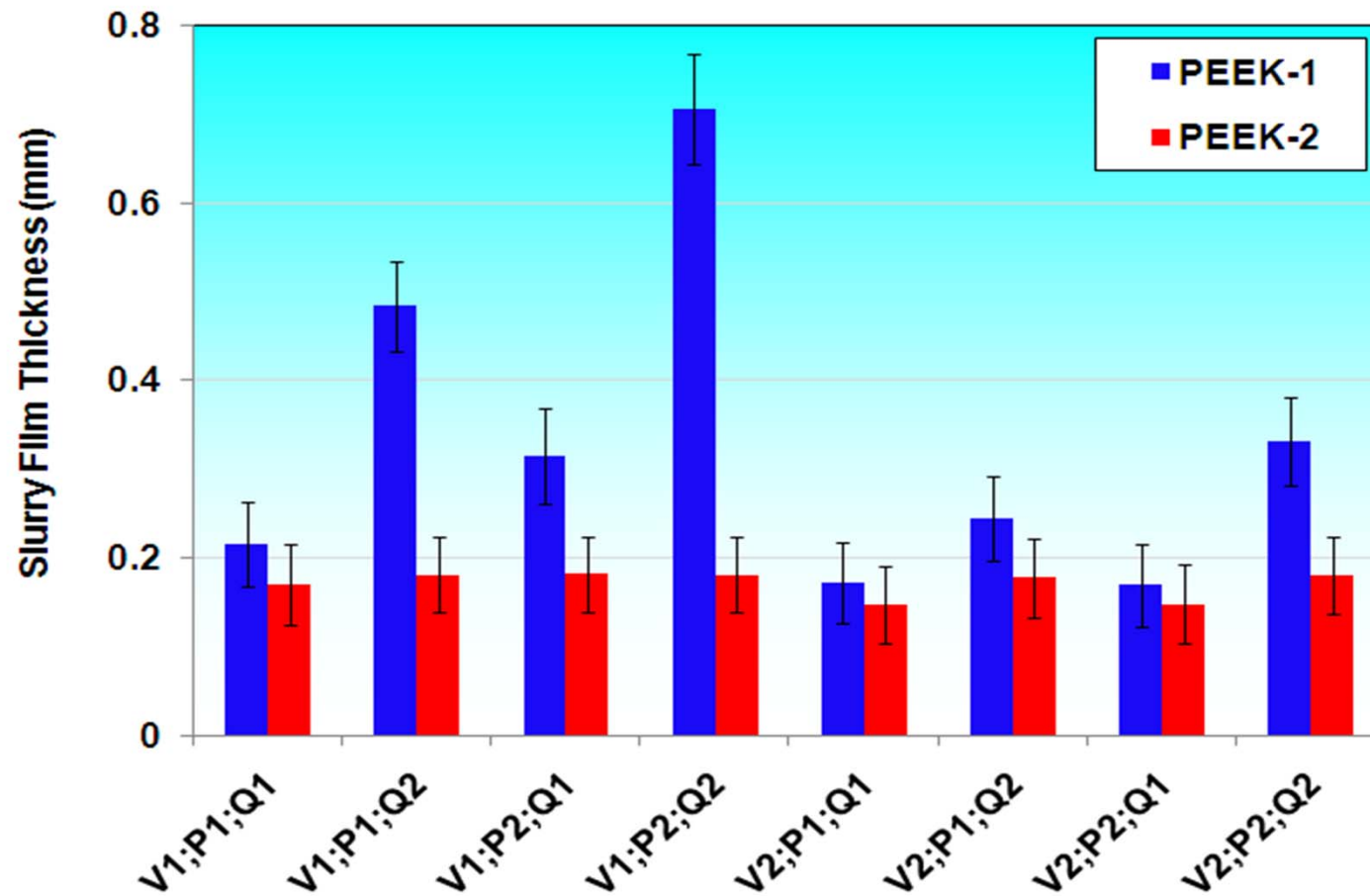


**PEEK-2**

**Mean slurry film thickness: 0.18 mm**

# Bow Wave Slurry Film Thickness

## Effect of Retaining Ring Design

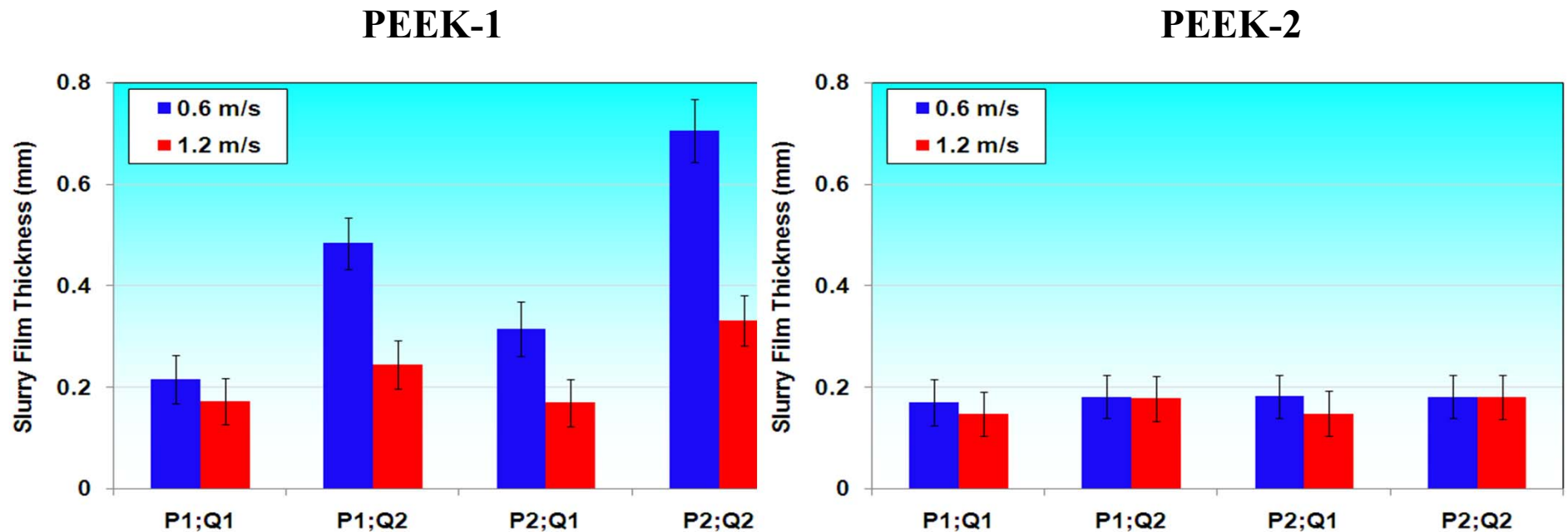


**V1 = 0.6 m/s, V2 = 1.2 m/s, P1 = 1.4 PSI, P2 = 2.8 PSI, Q1 = 150 ml/min, Q2 = 300 ml/min**

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# Bow Wave Slurry Film Thickness

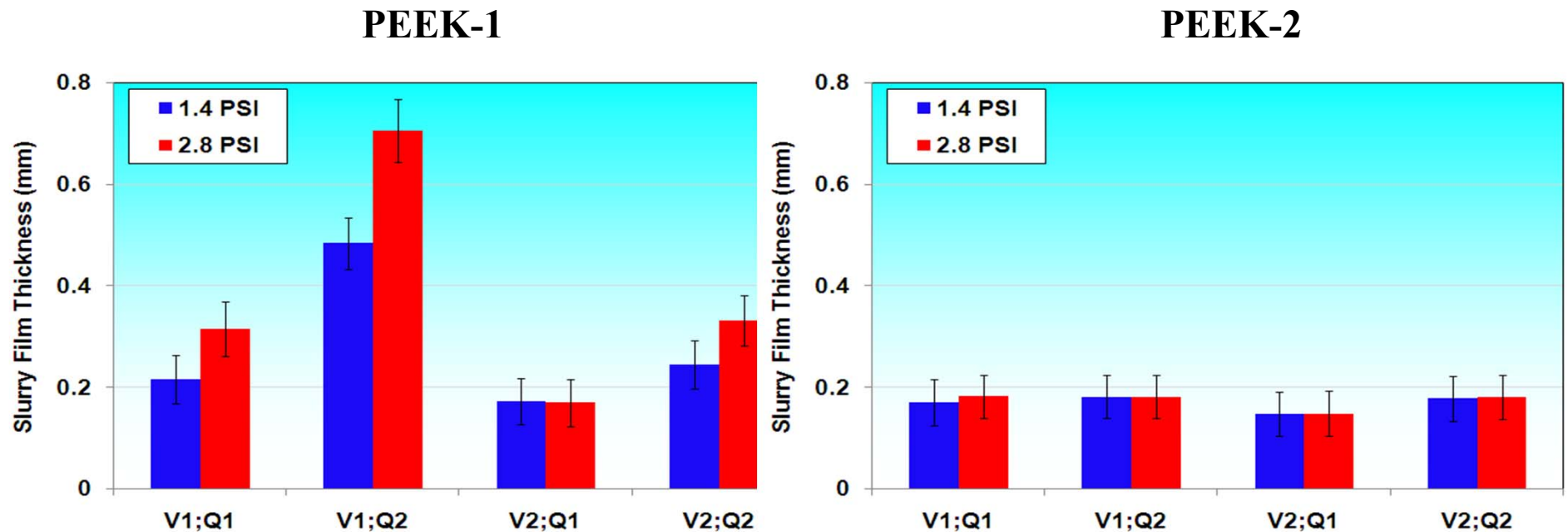
## Effect of Sliding Velocity



P1 = 1.4 PSI, P2 = 2.8 PSI, Q1 = 150 ml/min, Q2 = 300 ml/min

# Bow Wave Slurry Film Thickness

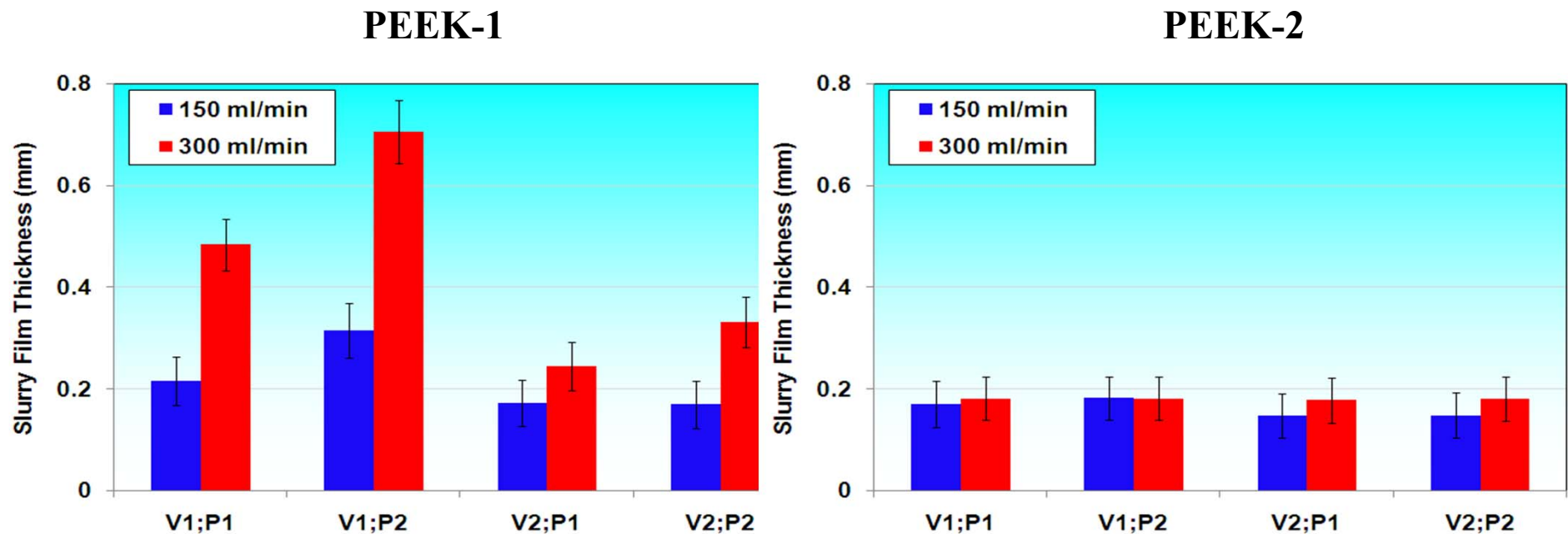
## Effect of Retaining Ring Pressure



$V1 = 0.6 \text{ m/s}$ ,  $V2 = 1.2 \text{ m/s}$ ,  $Q1 = 150 \text{ ml/min}$ ,  $Q2 = 300 \text{ ml/min}$

# Bow Wave Slurry Film Thickness

## Effect of Slurry Flow Rate



**V1 = 0.6 m/s, V2 = 1.2 m/s, P1 = 1.4 PSI, P2 = 2.8 PSI**

# Summary

- Slurry film thickness at the bow wave was successfully measured by the UVIZ - 100<sup>®</sup> system using UV fluorescence methods.
- Results indicated that the retaining ring with the sharp angle slot design (PEEK-1) generated significantly thicker slurry film at the bow wave than its counterpart with the round angle slot design (PEEK-2), as such, we believe PEEK-2 is more efficient in slurry transport.
- For PEEK-1, slurry film thickness at the bow wave increased with increasing flow rate and ring pressure while it decreased with increasing pad/retaining ring sliding velocity.
- For PEEK-2, slurry film thickness at the bow wave did not change significantly under different polishing conditions indicating an apparent robustness of the PEEK-2 design to various operating conditions.

# **Future Plans**

- **Next year plan: investigate the effect of slurry injection scheme on bow wave characteristics, slurry availability and pad micro-texture**
- **Long-term plan: develop fundamental understanding of the effect of retaining ring and injection scheme on slurry flow and polishing performance to overcome difficult challenges in environmental and manufacturing efficiency.**



# Industrial Interactions and Technology Transfer

## **Industrial mentors and contacts:**

- **Christopher Wargo (Entegris)**
- **Cliff Spiro (Cabot Microelectronics)**
- **Peter Ojerholm (Ehwa)**

# **Publications and Presentations**

- **Effect of Retaining Ring Slot Design on Slurry Film Thickness during CMP. X. Wei, Y. Sampurno, Y. Zhuang, R. Dittler, A. Meled, J. Cheng, C. Wargo, R. Stankowski and A. Philipossian. Electrochemical and Solid-State Letters, 13(4), H119-H121 (2010).**
- **Tribological, Thermal and Wear Characteristics of Polyphenylen Sulfied and Polyetheretherketone Retaining Rings in Inter-Layer Dielectric CMP. X. Wei, Y. Zhuang, Y. Sampurno, F. Sudargho, C. Wargo, L. Borucki and A. Philipossian. Electrochemical and Solid-State Letters, 13(11), H391-H395 (2010).**
- **Effect of Retaining Ring Slot Design and Polishing Conditions on Slurry Flow Dynamics at Bow Wave. X. Liao, Y. Sampurno, A. Rice, Y. Zhuang and A. Philipossian. 2010 International Conference on Planarization/CMP Technology Proceedings, 31-35 (2010).**
- **Effect of Retaining Ring Slot Design and Polishing Conditions on Slurry Flow Dynamics at Bow Wave. X. Liao, Y. Sampurno, A. Rice, Y. Zhuang and A. Philipossian. 2010 International Conference on Planarization/CMP Technology, Phoenix, Arizona, November 14-17 (2010).**

# Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry

*(Task 425.032)*

## Subtask 2: Effect of Pad Conditioning on Pad Micro-Texture and Polishing Performance

### PI:

- Ara Philipossian, Chemical and Environment Engineering, UA
- Duane Boning, Electrical Engineering and Computer Science, MIT

### Graduate Students:

- Xiaoyan Liao, Ph. D. candidate, Chemical and Environment Engineering, UA
- Yubo Jiao, Ph. D. candidate, Chemical and Environment Engineering, UA
- Zhenxing Han, Ph. D. candidate, Chemical and Environment Engineering, UA
- Anand Meled, Ph. D. candidate, Chemical and Environment Engineering, UA
- Changhong Wu, Ph. D. candidate, Chemical and Environment Engineering, UA
- Wei Fan, Ph. D. candidate, Electrical Engineering and Computer Science, MIT

# Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry

*(Task 425.032)*

## Subtask 2: Effect of Pad Conditioning on Pad Micro-Texture and Polishing Performance

### Other Researchers:

- Yun Zhuang, Post-doctoral Fellow, Chemical and Environment Engineering, UA
- Yasa Sampurno, Post-doctoral Fellow, Chemical and Environment Engineering, UA

### Cost Share (other than core ERC funding):

- In-kind donation (slurry) from Hitachi Chemical
- In-kind donation (diamond discs) from 3M Corporate
- In-kind donation (diamond discs) from Mitsubishi Materials Corporation
- In-kind support (confocal microscopy) from Araca, Inc.

# **Objectives**

- Investigate the effect of pad conditioning on pad surface micro-texture, as well as frictional force, removal rate, and wafer topography (dishing) during copper CMP process
- Characterize pad asperity modulus using nanoindentation
- Characterize pad asperity height using micro profilometry
- Understand how pad properties change during CMP process

# ESH Metrics and Impact

1. *Reduce CMP consumable consumption (pad, slurry, UPW, chemicals, pad conditioner, and retaining ring) by increasing yield through 1-3X dishing and erosion reduction*

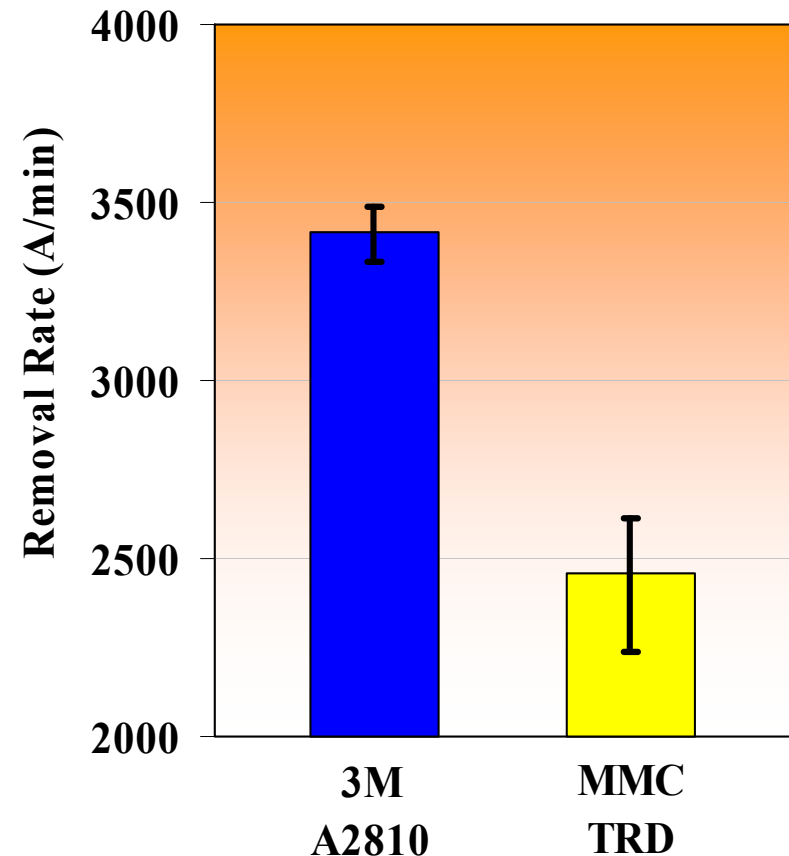
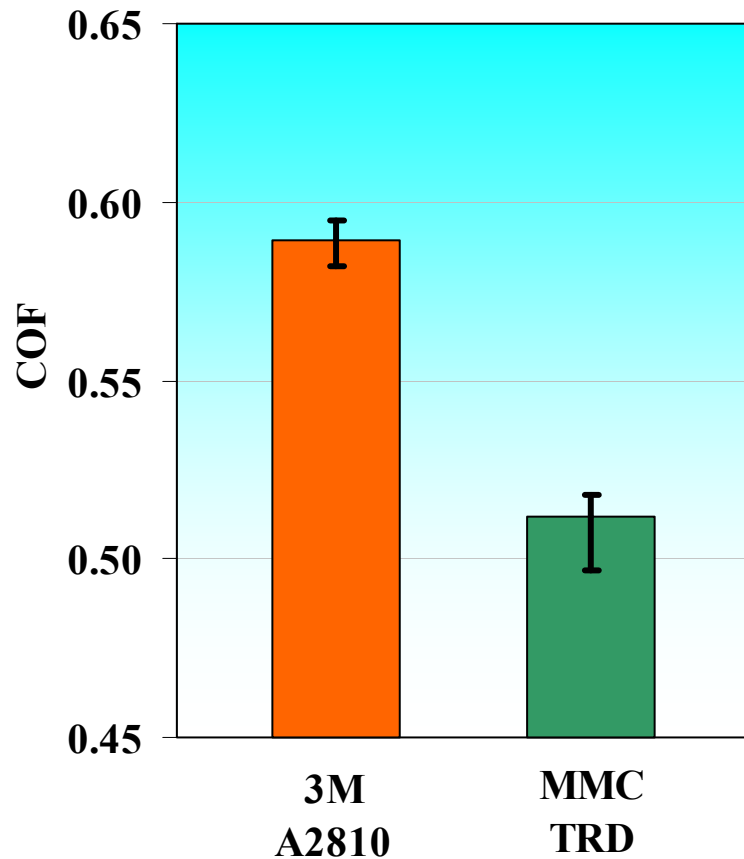
# General Approach

**Polish 200-mm blanket copper and patterned SEMATECH 854 wafers with a 3M A2810 disc and a Mitsubishi Materials Corporation 100-grit TRD disc, and analyze pad micro-texture through laser confocal microscopy:**

- Blanket wafer polishing: frictional force and removal rate**
- Patterned wafer polishing: dishing**
- Pad micro-texture analyses: contact area, near contact area, and summit curvature**

# COF and Removal Rate Comparison

## Blanket Wafer Polishing



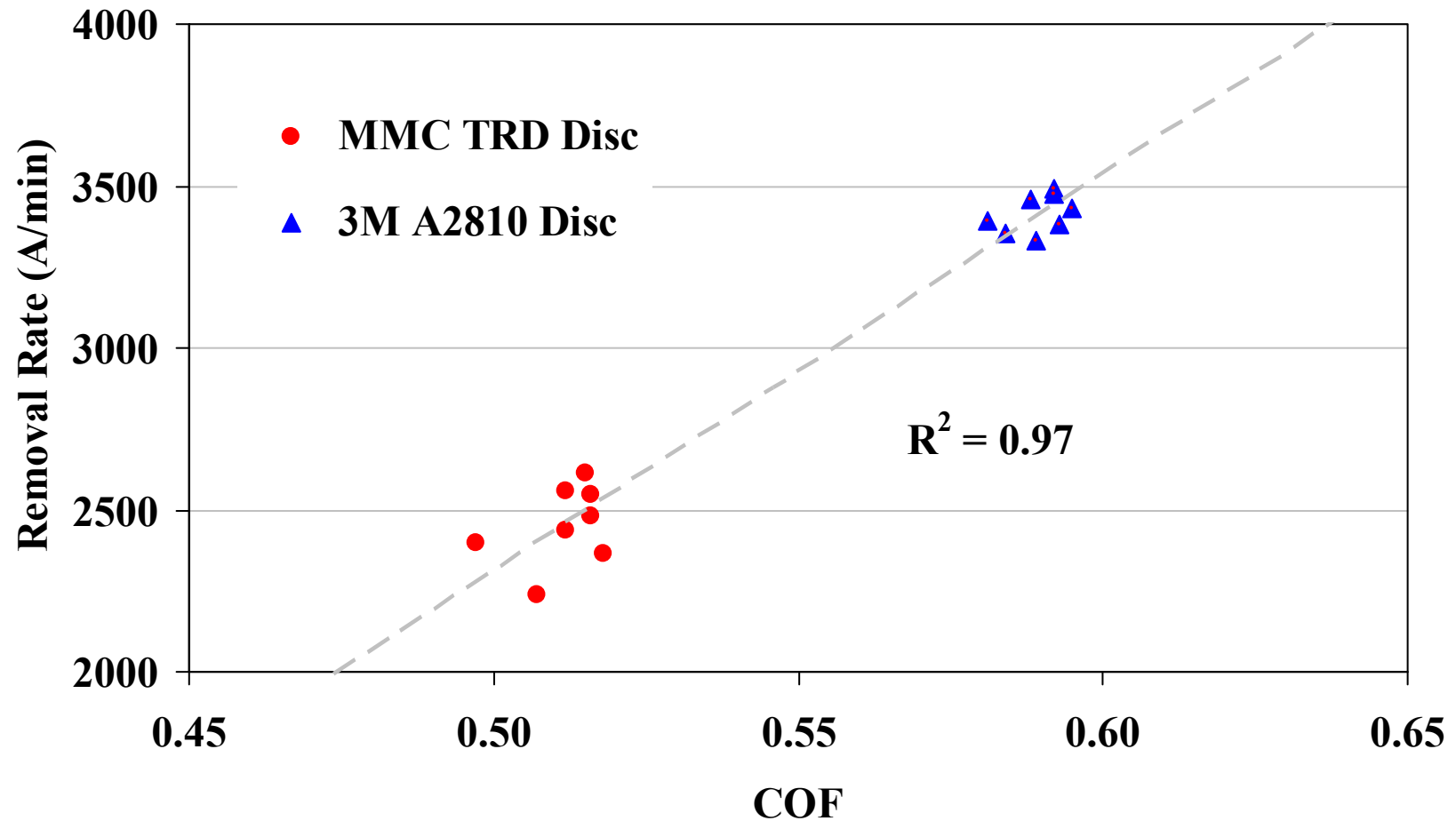
$$COF_{3M\ A2810} > COF_{MMC\ TRD}$$

$$RR_{3M\ A2810} > RR_{MMC\ TRD}$$



# Removal Rate vs. COF

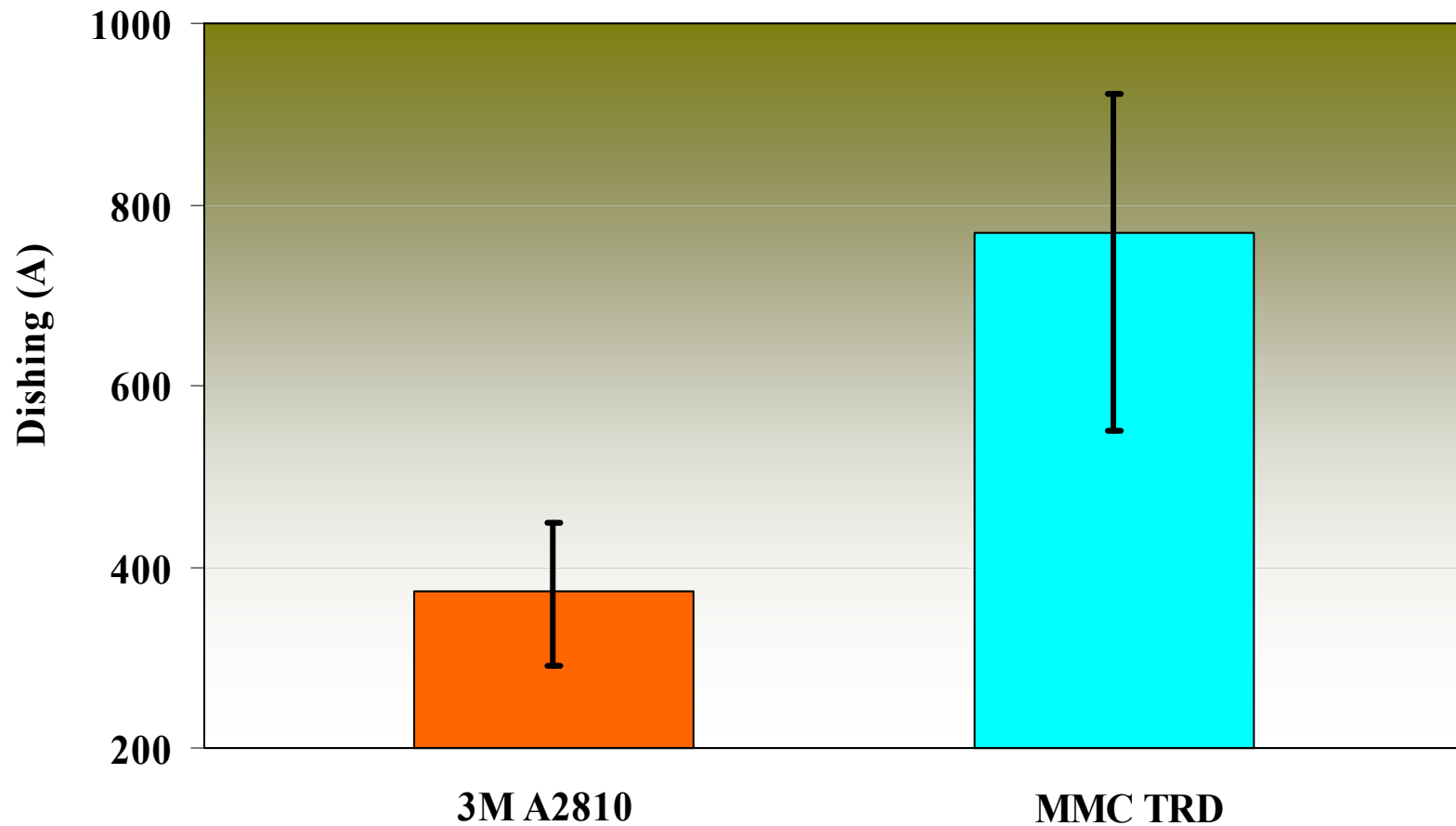
## Blanket Wafer Polishing



**As expected, removal rate increased with COF.**

# Dishing Comparison

Patterned Wafer Polishing, Center Die, 100/100 Micron Feature



**Dishing<sub>3M A2810</sub> < Dishing<sub>MMC TRD</sub>**

# Laser Confocal Microscopy



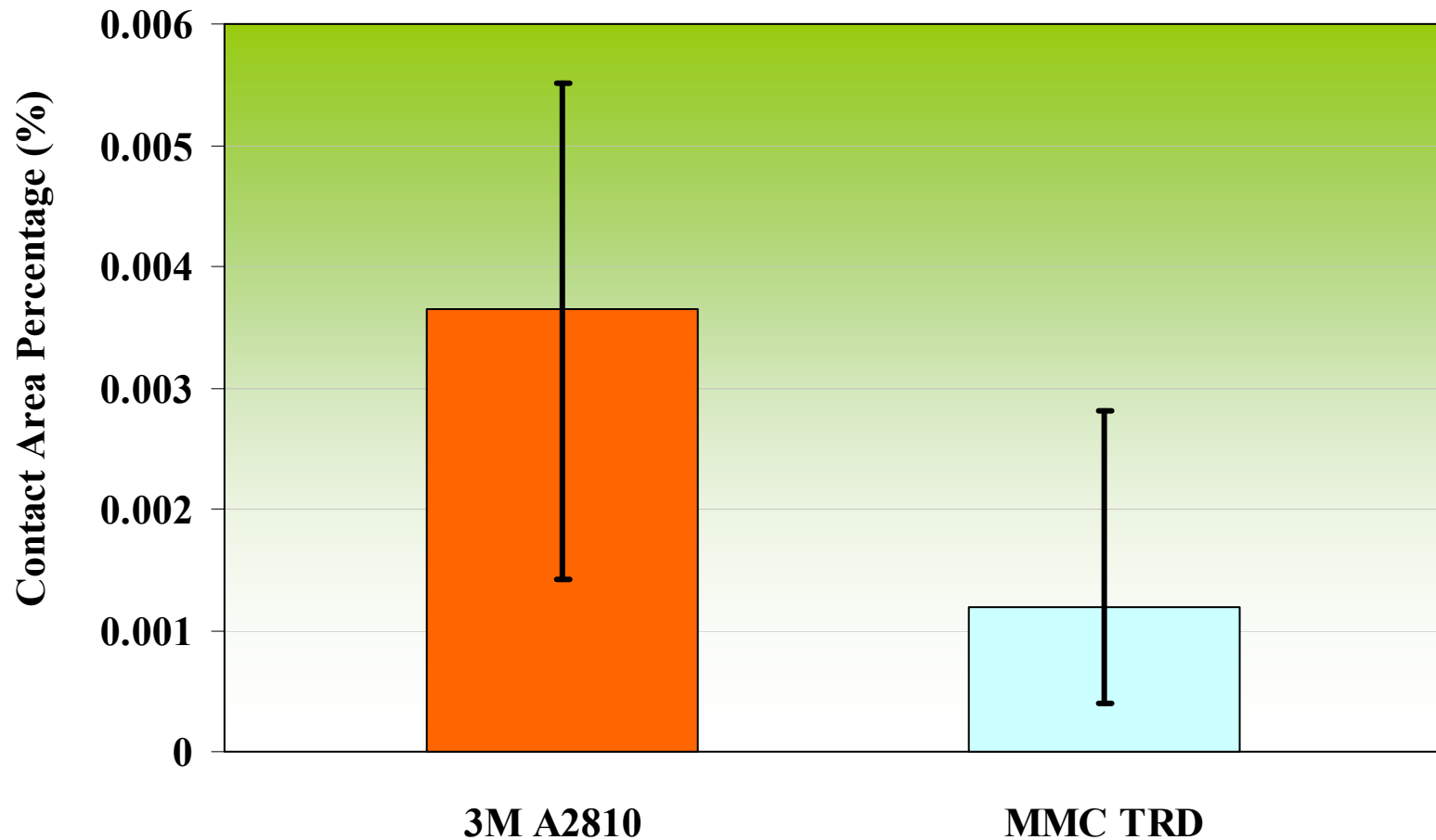
Zeiss LSM 510 Meta NLO

**Pad surface contact area and topography analyses were performed through laser confocal microscopy.**

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# Pad Surface Contact Area Comparison

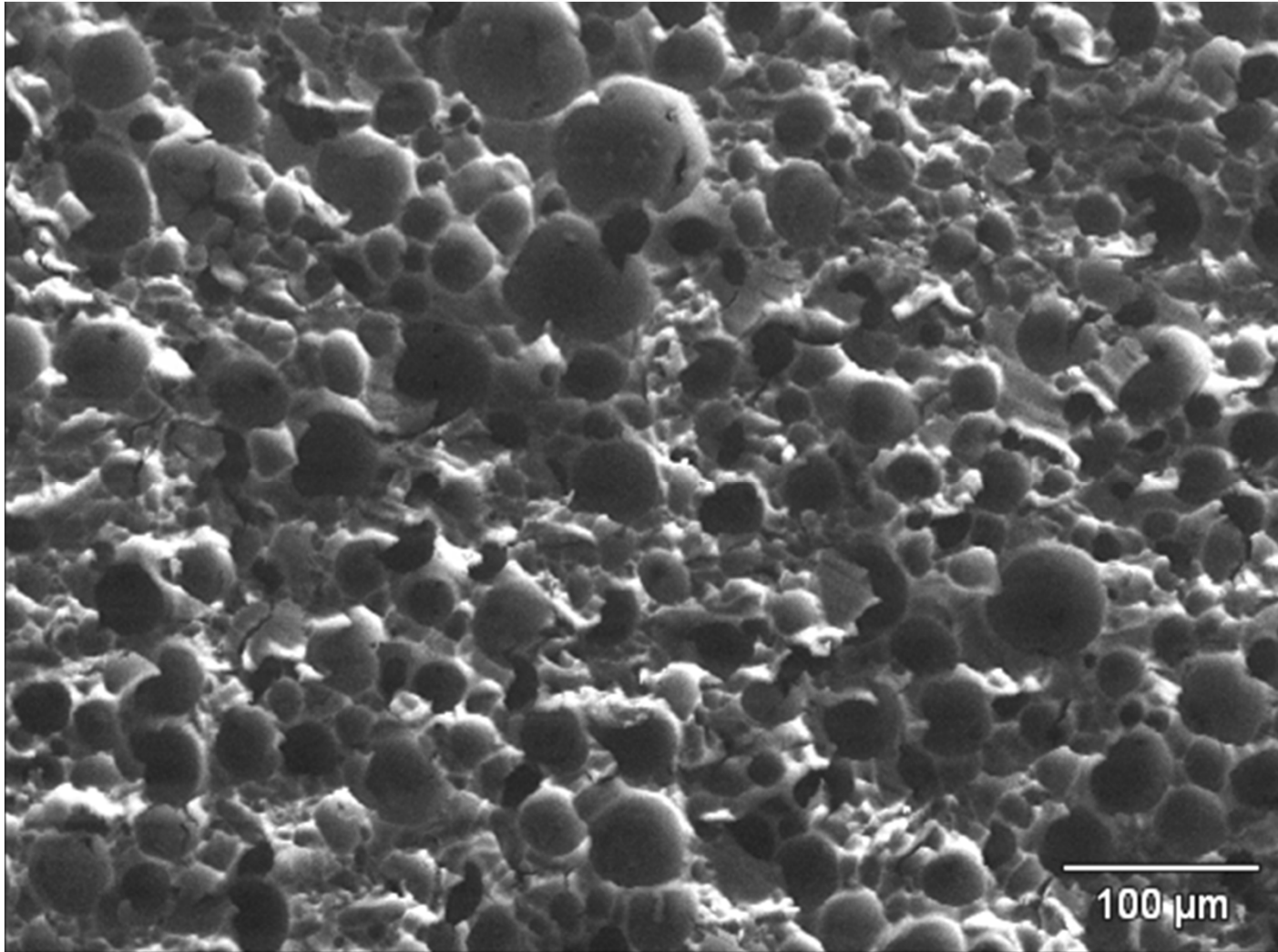
## Blanket Wafer Polishing



**Contact Area Percentage<sub>3M A2810</sub> > Contact Area Percentage<sub>MMC TRD</sub>**

# Pad Surface SEM Image

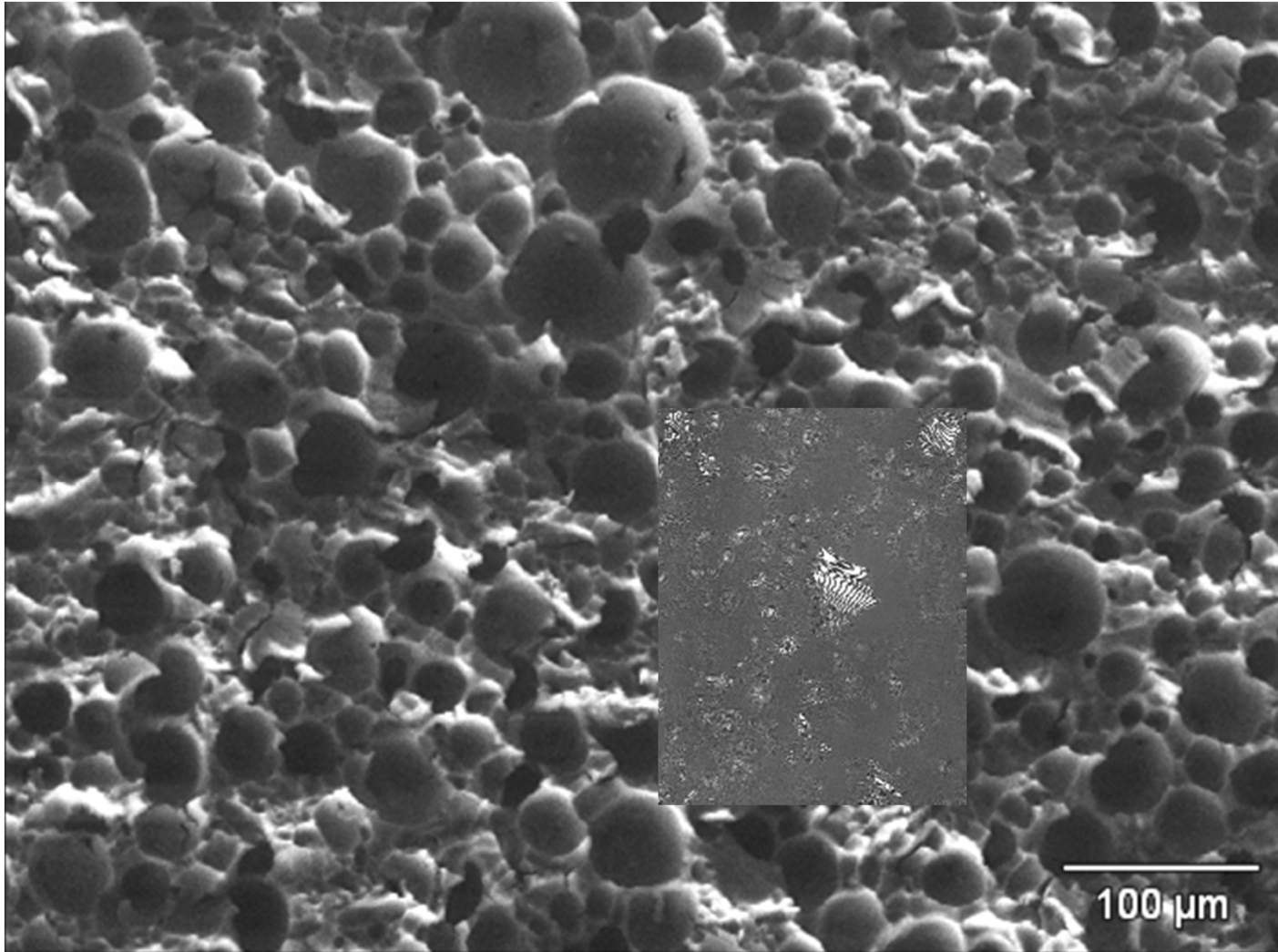
## Blanket Wafer Polishing, MMC TRD Disc



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# Pad Surface SEM and Contact Images

## Blanket Wafer Polishing, MMC TRD Disc

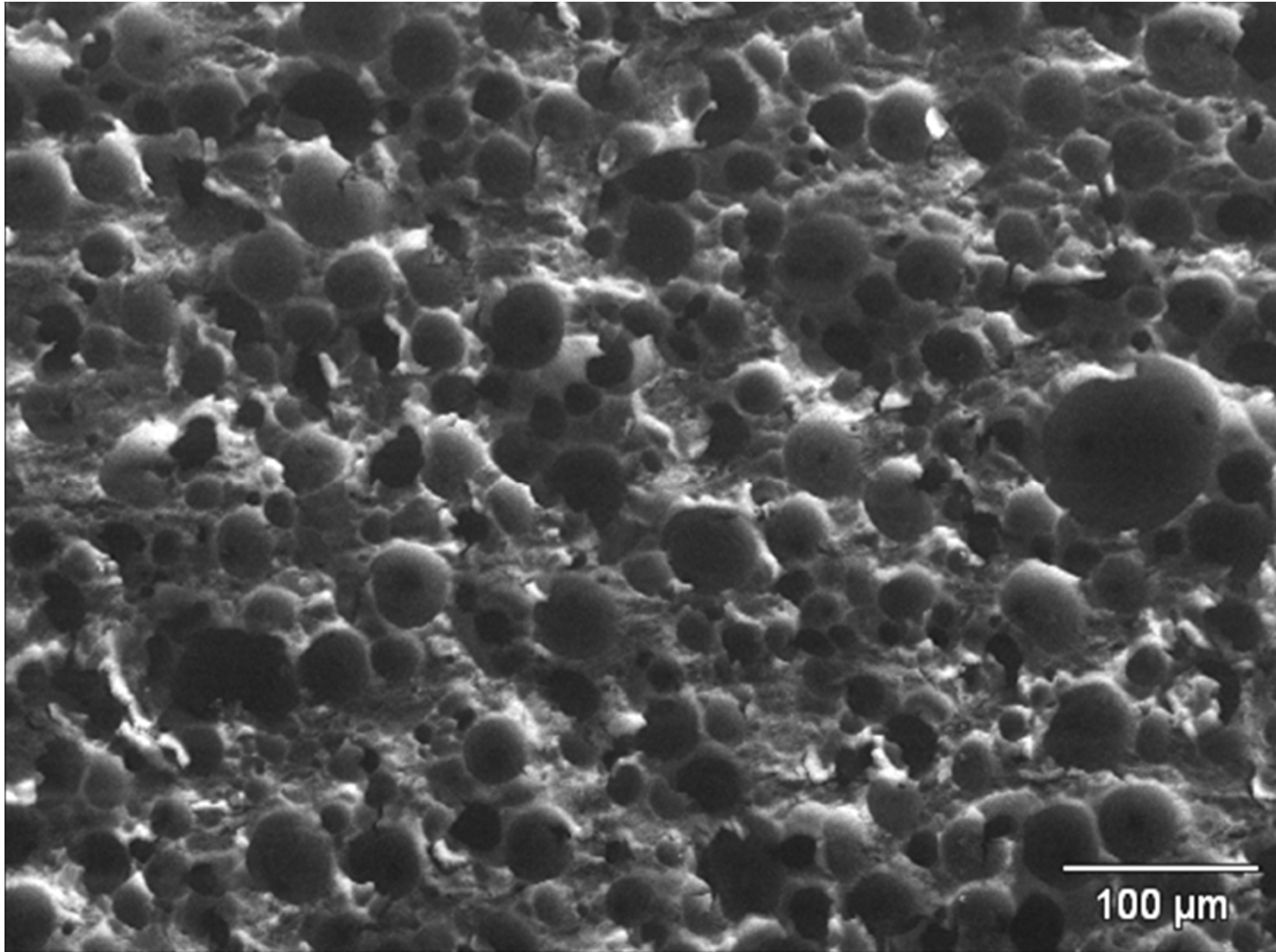


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# Pad Surface SEM Image

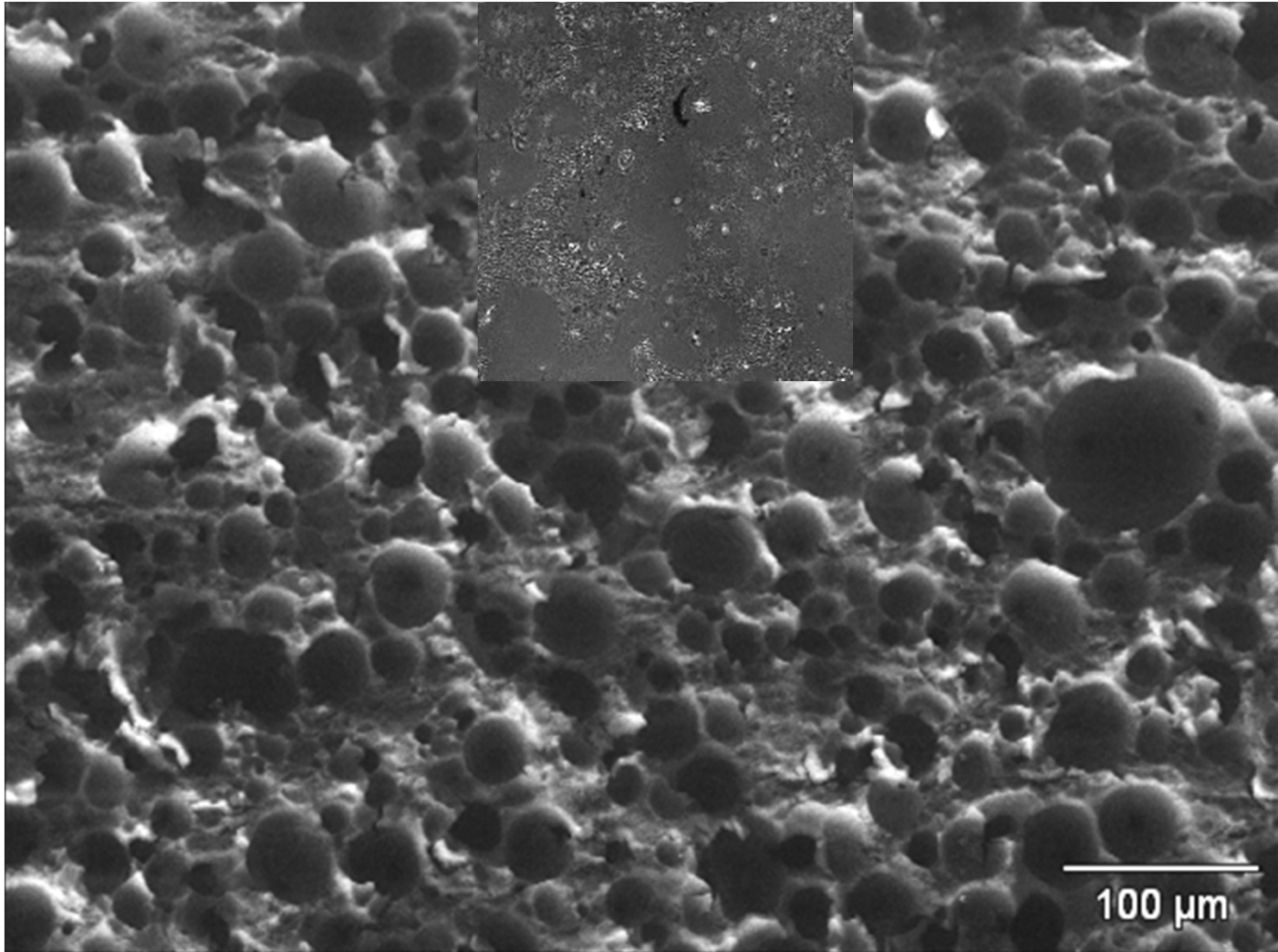
## Blanket Wafer Polishing, 3M A2810 Disc



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# Pad Surface SEM and Contact Images

Blanket Wafer Polishing, 3M A2810 Disc

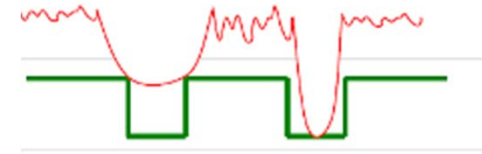
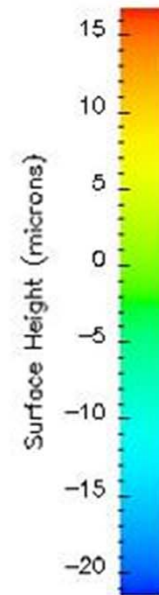
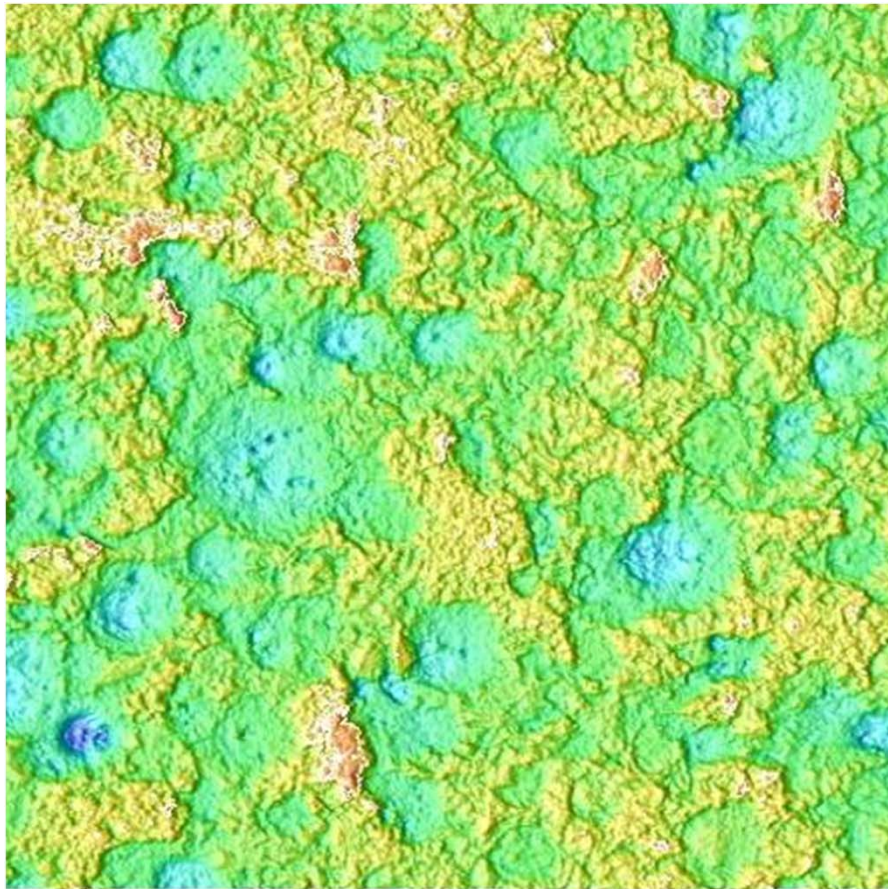


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# Pad Surface Summit Curvature Comparison

## Patterned Wafer Polishing



Disc	$K_s$ (micron <sup>-1</sup> )
3M A2810	1.80
MMC TRD	2.13

**Higher summit curvatures correspond to sharper pad asperities.**

*SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing*

# Summary

During blanket copper wafer polishing, MMC TRD disc generated **fewer pad surface contact areas** than 3M A2810 disc.

In addition, MMC TRD disc generated much **larger flat near contact areas** corresponding to **conditioning debris and pore walls that had been fractured and collapsed**.

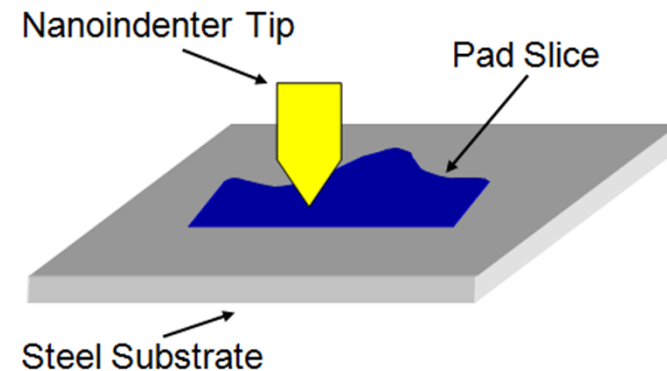
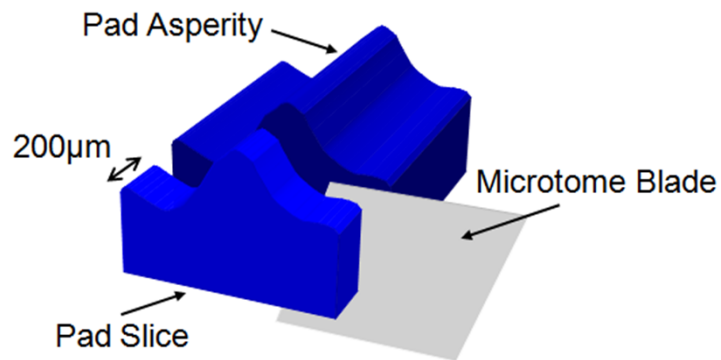
The conditioning debris and fractured/collapsed pore walls partly covered the adjacent pores, **making the pad surface more lubricated and rendering a lower COF and removal rate** compared with the 3M A2810 disc.

During patterned copper wafer polishing, MMC TRD disc generated **a higher mean summit curvature** than 3M A2810 disc.

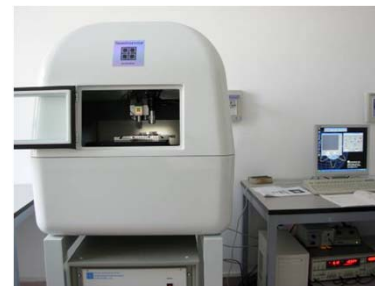
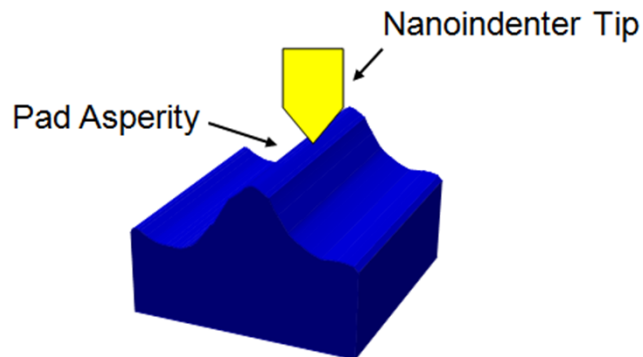
**Sharper pad summits** contributed to **higher dishing** for MMC TRD disc.

# Pad Modulus Measurement: Nanoindentation

- **Pad slice nanoindentation:**



- **Pad asperity nanoindentation:**



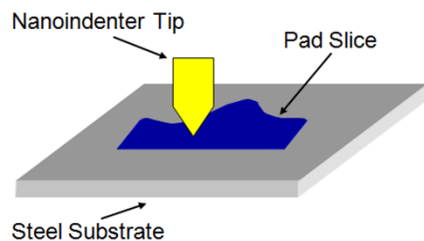
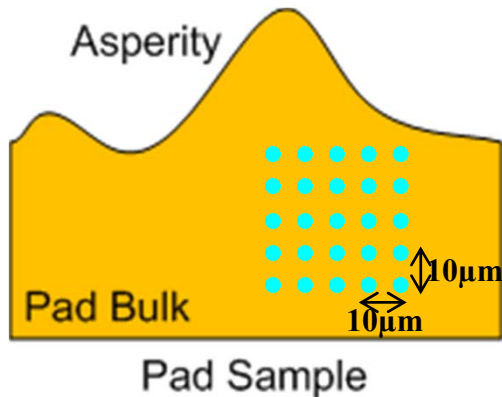
Hysitron TriboIndenter

Indent Working Mode

Max Force	10 mN
Force Resolution	2 nN
Min Contact Force	<100 nN
Force Load Rate	>50 mN/s
Max Displacement	5 µm
Displacement Resolution	0.04 nm

# Pad Slice: Contour Plot of Reduced Modulus

Test Pattern: slice, multiple points

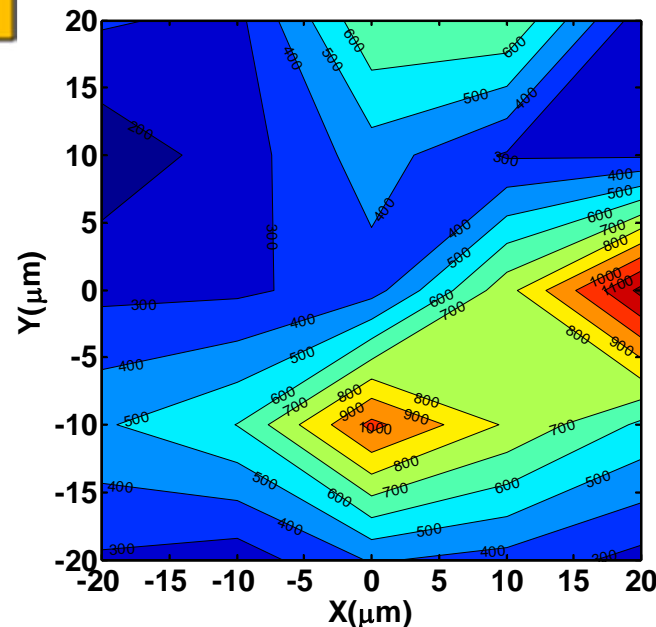


Example: JSR pad slice, same test area, repeat twice

1<sup>st</sup> test

Mean: 462.69MPa

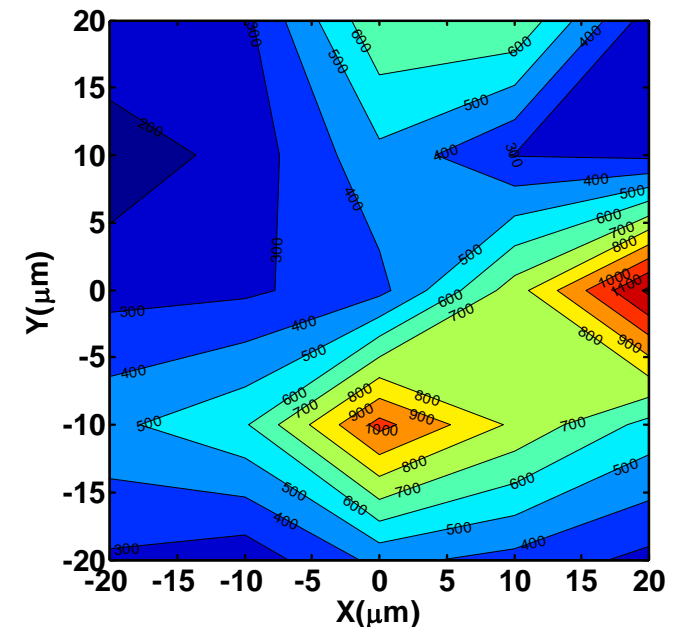
Standard Deviation: 272.44MPa



2<sup>nd</sup> test (same position on the sample)

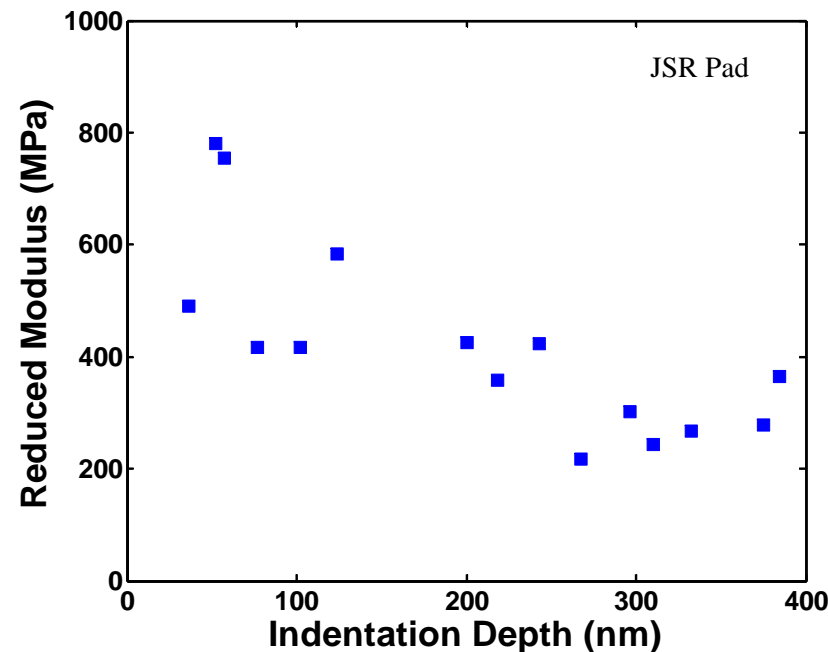
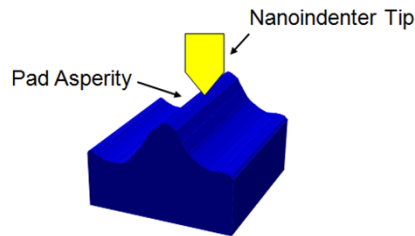
Mean: 460.93MPa

Standard Deviation: 270.58MPa



- There is spatial variation in pad mechanical properties

# Pad Asperity: Depth Dependence of Reduced Modulus

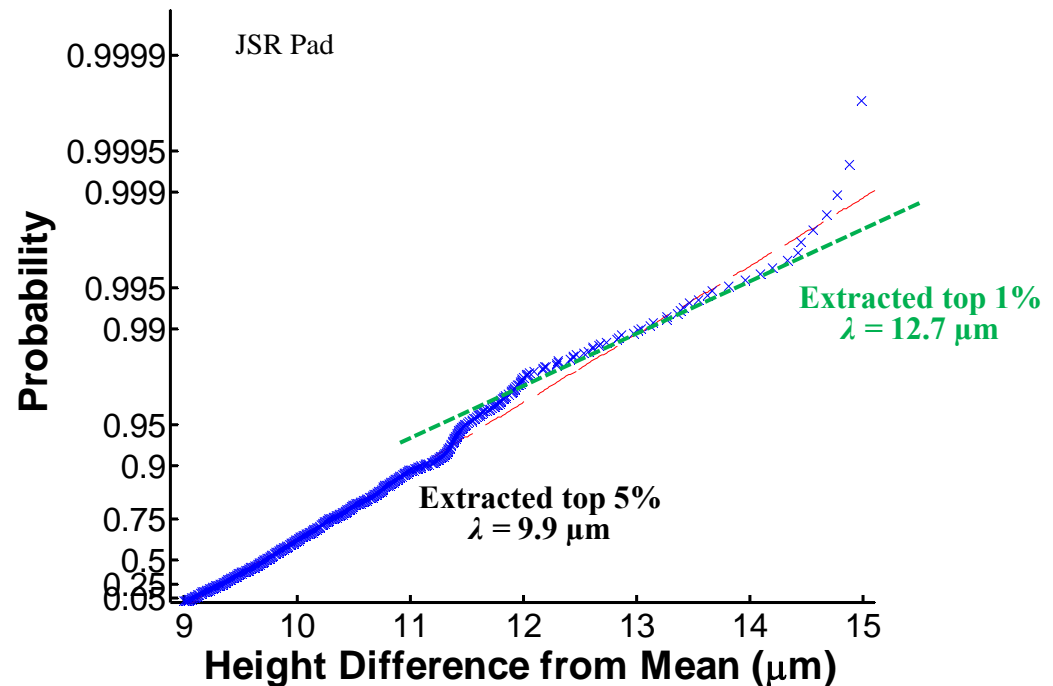
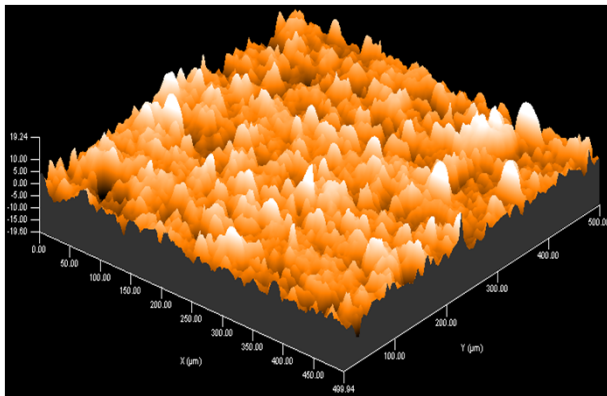


*Boning and Fan, MRS  
Spring Meeting, April 2010.*

- **Deep indentation ( $> 300$  nm):**
  - Asperity modulus approaches bulk modulus
  - Bulk estimate = 291 MPa (depth  $> 300$  nm)
- **Shallow indentation ( $< 100$  nm):**
  - Substantially higher modulus,  $\sim 2\times$  or greater the bulk value
  - Surface estimate = 572 MPa (depth  $< 100$  nm)

# Pad Asperity Height Distribution

Pad Surface Profilometry



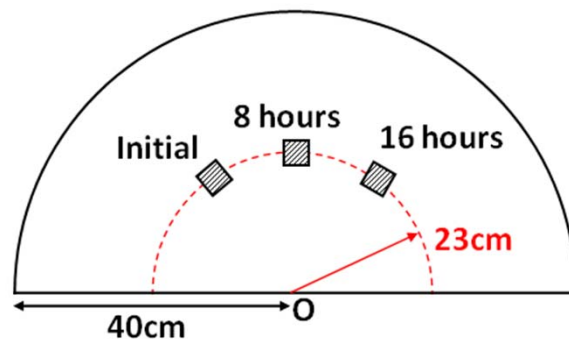
- **Consistent with an exponential height distribution**
  - Exponential in the tail of the distribution, i.e., for heights substantially greater than the mean height
  - A very small number of very tall asperities (i.e. fewer than 0.05%). We ignore these.
  - Possibility of a **bimodal** (exponential) distribution; useful to extract both.



# Pad Aging Experiment

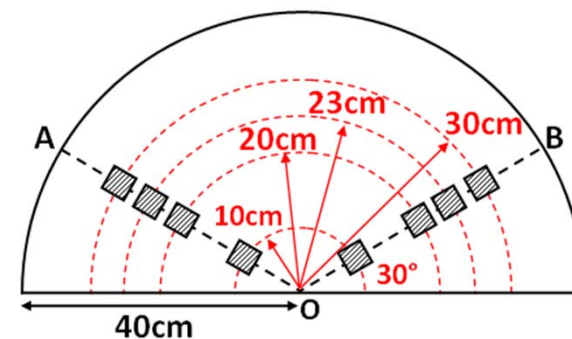
- **Cu wafer polishing with JSR WSP pad**
  - **Polisher:** Araca APD-800
  - **Polishing head speed:** 25 rpm
  - **Polishing pressure:** 1.5 psi
  - **Condition head speed:** 95 rpm
  - **Conditioner down force:** 8 lbF
- **Pad sample collection**

**Aging samples:**



Sample size: 2.5cm × 2.5cm

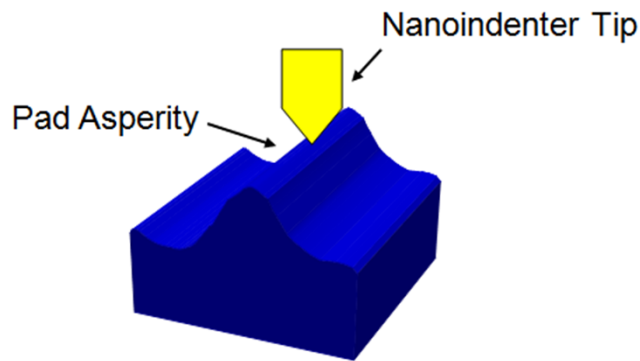
**Spatial samples after 16 hours:**



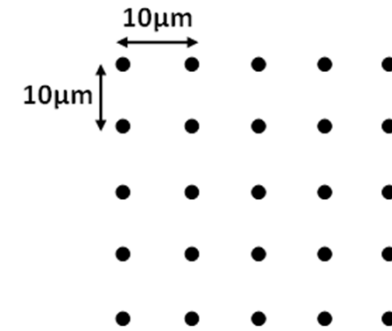
Sample size: 1.5cm × 1.5cm

# Pad Properties: Pad Asperity Indentation

- Pad asperity nanoindentation:



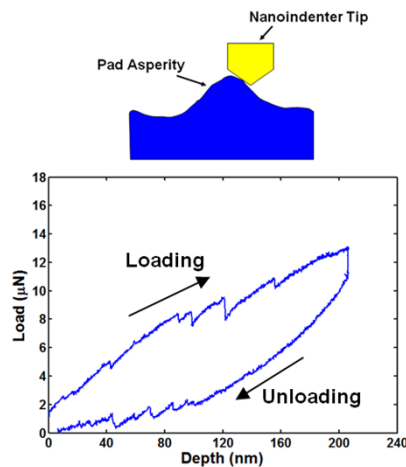
Hysitron TriboIndenter



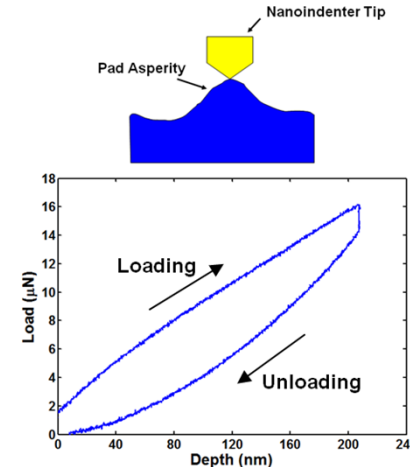
Test Pattern Applied

- Indentation curves:

Failed test: indenter tip sliding

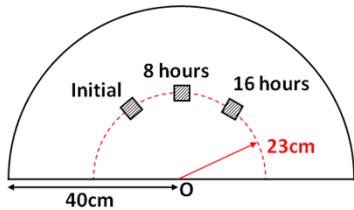


Successful test: solid contact

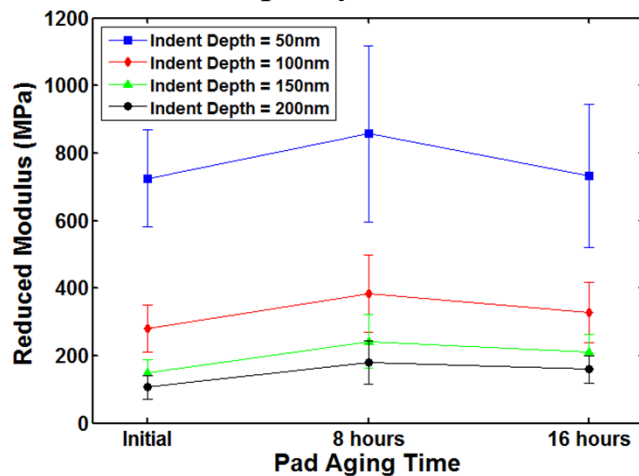




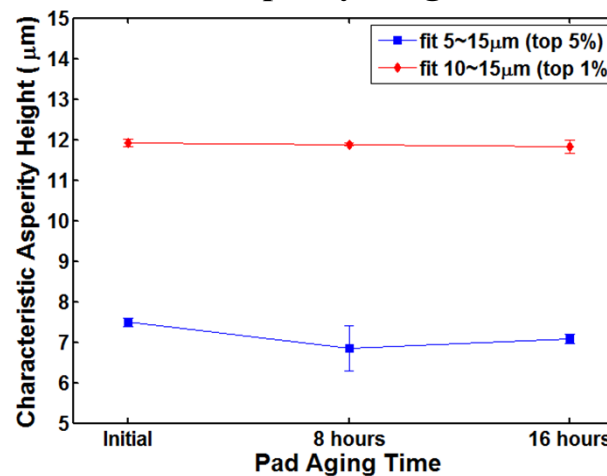
# Pad Aging Results



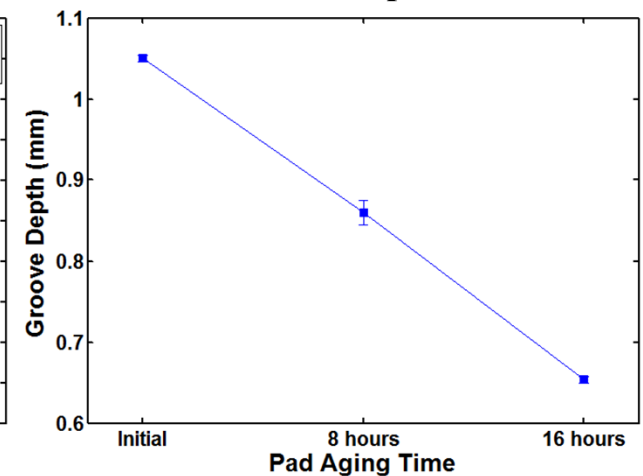
Asperity Modulus



Asperity Height

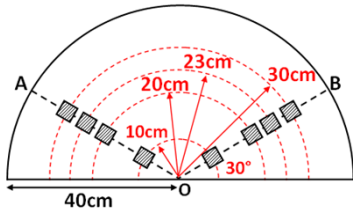


Groove Depth

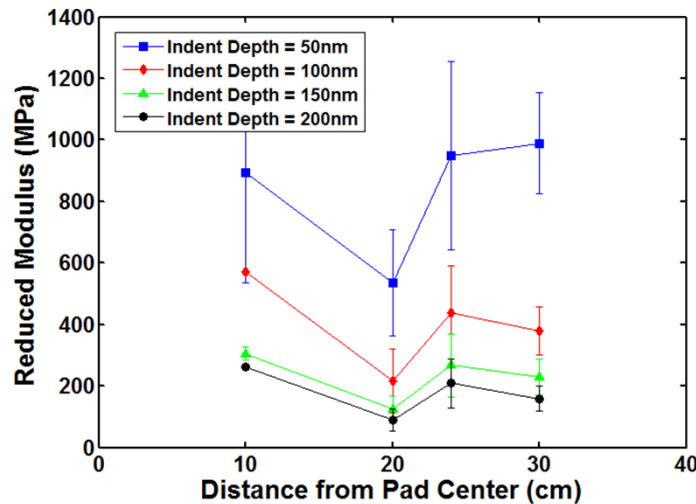


- Asperity modulus and asperity height distribution are both consistent across polishing/conditioning times
- Depth dependence of modulus
  - Deep indentation: asperity modulus approaches bulk modulus (<200 MPa)
  - Shallow indentation: substantially higher modulus, ~2x or greater the bulk value
- Substantial pad wear during CMP process: groove depth decreases linearly with polish time

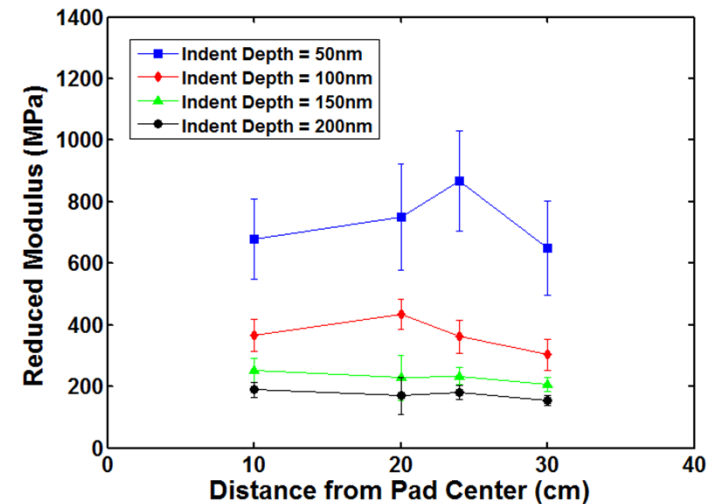
# Spatial Results: Asperity Modulus



**OA direction:**

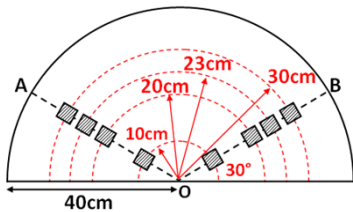


**OB direction:**

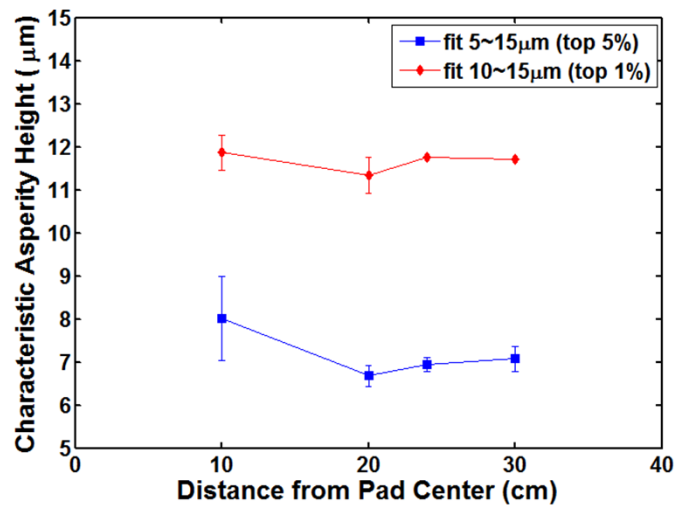


- **No strong radial dependence of asperity reduced modulus**
- **Depth dependence of modulus**
  - Deep indentation: asperity modulus approaches bulk modulus (<200 MPa)
  - Shallow indentation: substantially higher modulus, ~2x or greater the bulk value

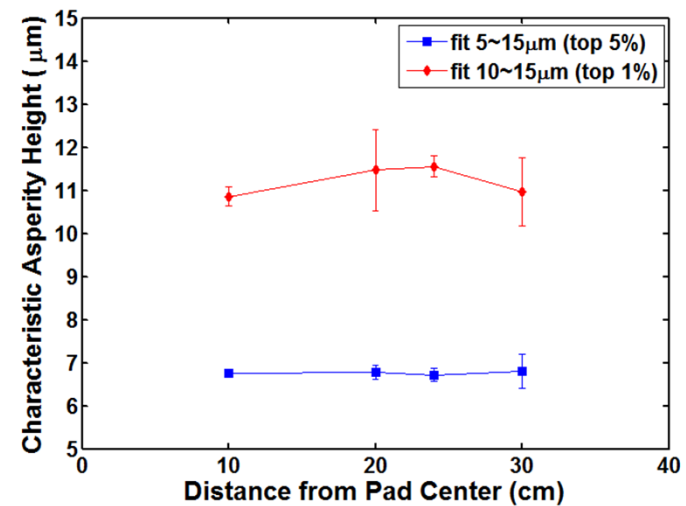
# Spatial Results: Asperity Height



**OA direction:**



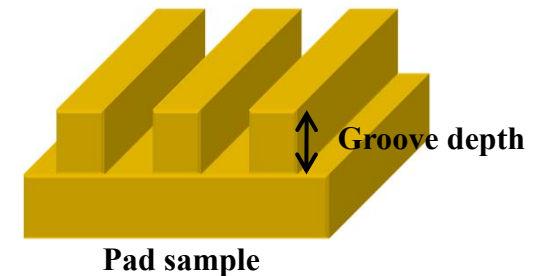
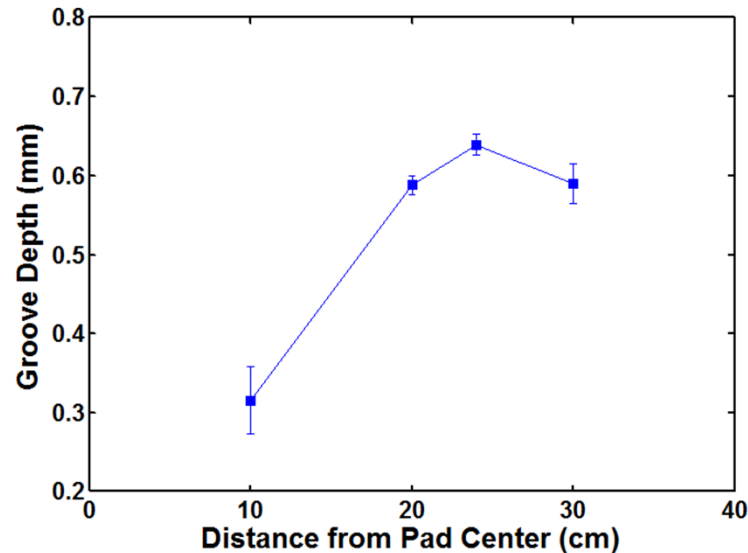
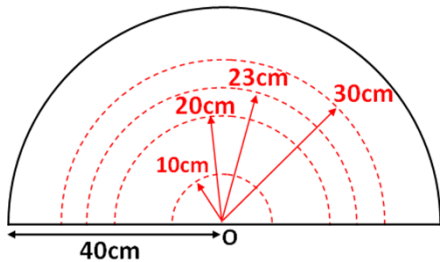
**OB direction:**



After 16 hours polishing (with conditioning)

- **No strong radial dependence of asperity height distribution: good spatial uniformity of asperity heights with conditioning**

# Spatial Results: Groove Depth



After 16 hours polishing (with conditioning)

- Groove depth has a strong radial dependence: more pad wear near the center (in this non-optimized process)
- Despite large and non-uniform pad wear, pad surface properties are maintained

# Industrial Interactions and Technology Transfer

## **Industrial mentors and contacts:**

- **Lenoard Borucki (Araca)**
- **Toranosuke Ashizawa (Hitachi Chemical)**

# Future Plans

- **Next year plan:** continue to investigate the effect of pad conditioning on pad surface micro-texture, as well as frictional force, removal rate, and wafer topography (dishing/erosion) during copper and oxide/STI CMP processes.
- **Long-term plan:** develop fundamental understanding of the effect of pad conditioning and pad-wafer contact in CMP processes.

# **Publications**

- **Investigating the effect of diamond size and conditioning force on chemical mechanical planarization pad topography. T. Sun, L. Borucki, Y. Zhuang and A. Philipossian. Microelectronic Engineering, 87, 553-559 (2010).**
- **Investigating the Effect of Conditioner Aggressiveness on Removal Rate during Inter-Layer Dielectric CMP through Confocal Microscopy and Dual Emission UV Enhanced Fluorescence Imaging. T. Sun, L. Borucki, Y. Zhuang, Y. Sampurno, F. Sudargho, X. Wei, S. Anjur and A. Philipossian. Japanese Journal of Applied Physics, 49(2), 026501 (2010).**
- **Slurry Induced Pad Wear Rate in Chemical Mechanical Planarization. A. Meled, Y. Sampurno, Y. Zhuang and A. Philipossian. Electrochemical and Solid-State Letters, 13(3), H52-H54 (2010).**
- **Analyses of Diamond Disc Substrate Wear and Diamond Micro-Wear in Copper Chemical Mechanical Planarization Process. A. Meled, Y. Zhuang, X. Wei, J. Cheng, Y. Sampurno, L. Borucki, M. Moinpour, D. Hooper and A. Philipossian. Journal of The Electrochemical Society, 157(3), H250-H255 (2010).**
- **Studying the Effect of Temperature on the Copper Oxidation Process Using Hydrogen Peroxide for Use in Multi-Step CMP Models. D. DeNardis, D. Rosales-Yeomans, L. Borucki and A. Philipossian. Thin Solid Films, 518, 3903-3909 (2010).**

# **Publications**

- **A Three-Step Copper CMP Model Including the Dissolution Effects of a Commercial Slurry Dissolution.** D. DeNardis, D. Rosales-Yeomans, L. Borucki and A. Philipossian. *Thin Solid Films*, 518, 3910-3916 (2010).
- **Optical and Mechanical Characterization of Chemical Mechanical Planarization of Pad Surfaces.** T. Sun, Y. Zhuang, L. Borucki and A. Philipossian. *Japanese Journal of Applied Physics*, 49(4), 046501 (2010).
- **End-Point Detection of Ta/TaN Chemical Mechanical Planarization via Forces Analysis.** Y. Sampurno, X. Gu, T. Nemoto, Y. Zhuang, A. Teramoto, A. Philipossian and T. Ohmi. *Japanese Journal of Applied Physics*, 05FC01 (2010).
- **Characterization of Pad-Wafer Contact in CMP Using Confocal Microscopy.** T. Sun, Y. Zhuang, L. Borucki and A. Philipossian. *Japanese Journal of Applied Physics*, 49(6), 066501 (2010).
- **Novel Diamond Disc Diagnostic Method Based on 'Dry' Coefficient of Friction Measurements.** A. Meled, Y. Sampurno, F. Sudargho, Y. Zhuang and A. Philipossian. *Electrochemical and Solid-State Letters*, 13(12), H457-H459 (2010).



# **Presentations**

- **The Nature of Large Contact Areas in Chemical-Mechanical Planarization. L. Borucki, Y. Zhuang, Y. Sampurno and A. Philipossian. The International Semiconductor Technology Conference / China Semiconductor Technology International Conference (ISTC/CSTIC 2010), Pudong, Shanghai, China, March 18-19 (2010).**
- **Tribological and Kinetic Characterization of 300-mm Copper Chemical Mechanical Planarization Process. Z. Han, Y. Zhuang, Y. Sampurno, A. Meled, Y. Jiao, X. Wei, J. Cheng, M. Moinpour, D. Hooper and A. Philipossian. The International Semiconductor Technology Conference / China Semiconductor Technology International Conference (ISTC/CSTIC 2010), Pudong, Shanghai, China, March 18-19 (2010).**
- **Effect of Pad Micro-Texture on Frictional Force, Removal Rate, and Wafer Topography during Copper CMP Process. Y. Zhuang, X. Liao, L. Borucki, S. Theng, X. Wei, T. Ashizawa and A. Philipossian. The International Semiconductor Technology Conference / China Semiconductor Technology International Conference (ISTC/CSTIC 2010), Pudong, Shanghai, China, March 18-19 (2010).**
- **Novel Diamond Disc Diagnostic Method Based on ‘Dry’ Coefficient of Friction Measurements. Y. Sampurno, F. Sudargho, A. Meled, Y. Zhuang and A. Philipossian. The International Semiconductor Technology Conference / China Semiconductor Technology International Conference (ISTC/CSTIC 2010), Pudong, Shanghai, China, March 18-19 (2010).**

# **Presentations**

- **Method for Ultra-rapid Determination of the Lubrication Mechanism of CMP Processes. Y. Sampurno, S. Theng, F. Sudargho, Y. Zhuang and A. Philipossian. 2010 Materials Research Society Spring Meeting, San Francisco, California, April 5-7 (2010).**
- **Tribological and Kinetic Characterization of 300-mm Copper Chemical Mechanical Planarization Process. Y. Jiao, A. Meled, X. Wei, Z. Han, J. Cheng, Y. Sampurno, Y. Zhuang, M. Moinpour, D. Hooper and A. Philipossian. 2010 Materials Research Society Spring Meeting, San Francisco, California, April 5-7 (2010).**
- **Overcoming Some of the Challenges Associated with Slurry Injection in CMP. A Philipossian, L. Borucki, Y. Zhuang and Y. Sampurno. 2010 Materials Research Society Spring Meeting, San Francisco, California, April 5-7 (2010).**
- **Characterization and Modeling of Pad Asperity Response in CMP. D. Boning and W. Fan. 2010 Materials Research Society Spring Meeting, San Francisco, California, April 5-7 (2010).**
- **Tribological, Thermal, and Kinetic Characterization of 300-mm Copper CMP Process. Y. Zhuang, Z. Han, Y. Sampurno, A. Meled, Y. Jiao, X. Wei, J. Cheng, M. Moinpour, D. Hooper and A. Philipossian. The fifteenth International Symposium on Chemical-mechanical Planarization, Lake Placid, New York, August 8-11 (2010).**

# **Presentations**

- **Characterization of CMP Pad Surface Properties. W. Fan, D. Boning, Y. Zhuang, Y. Sampurno, A. Philipossian, D. Hooper and M. Moinpour. The fifteenth International Symposium on Chemical-mechanical Planarization, Lake Placid, New York, August 8-11 (2010).**
- **Tribological, Thermal and Kinetic Studies of Ti and TiN CMP. R. Duyos-Mateo, X. Gu, T. Nemoto, S. Sugawa, T. Ohmi, Z. Han, Y. Zhuang, Y. Sampurno and A. Philipossian. 2010 International Conference on Planarization/CMP Technology, Phoenix, Arizona, November 14-17 (2010).**

# Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry

*(Task 425.032)*

## Subtask 3: Implementation of an Extended Die-Level and Wafer-Level CMP Model

### PI:

- Duane Boning, Electrical Engineering and Computer Science, MIT

### Graduate Students:

- Wei Fan, Ph.D. candidate, EECS, MIT
- Joy Johnson, Ph.D. candidate, EECS, MIT

### Cost Share (other than core ERC funding):

- Experimental support, Intel

SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

# **Objectives**

**Goal: Improve fundamental understanding of CMP thru modeling and experimentation of CMP consumables to:**

- Reduce use of high-cost engineered consumables**
- Reduce generation of by-product wastes**
- Save processing times requiring significant energy**
- Enable better process control**

**1. Nano-scale model for pad-wafer contact:**

- Analyze mechanical response of pad asperities**
- Understand pad-wafer interaction**

**2. Slurry agglomeration/wafer-level CMP modeling:**

- Understand how slurry abrasive particles, pad debris, and wafer debris affect agglomeration**
- Understand how agglomeration relates to process efficiency, planarization capability, and defectivity**

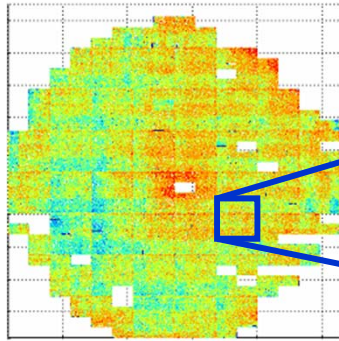
# ESH Metrics and Impact

**Driving principle and goals: Joint improvement in CMP performance and ESH performance**

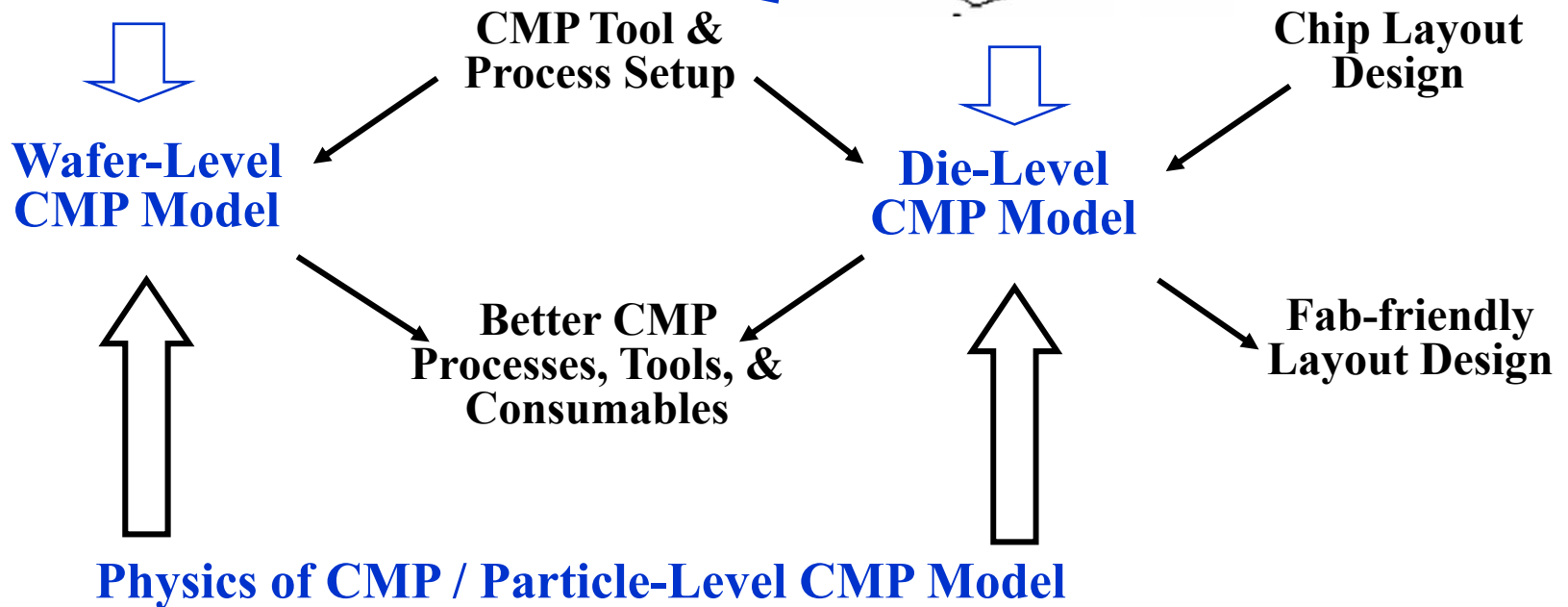
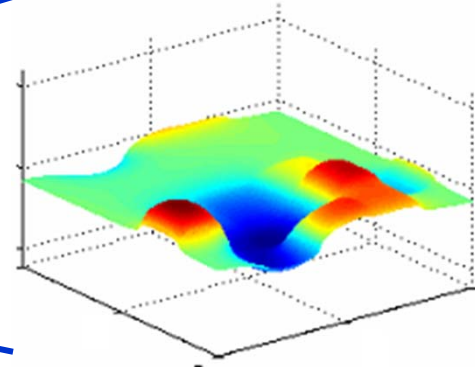
- 1. Reduction in the use or replacement of ESH-problematic materials*
- 2. Reduction in emission of ESH-problematic material to environment*
  - Reduce slurry particle use and Cu solid waste by 20-50%
- 3. Reduction in the use of natural resources (water and energy)*
  - Shorten CMP polish times (copper, barrier) by 20-50%
  - Improve yield (multiplication over all inputs/outputs) by 1-2%
- 4. Reduction in the use of chemicals*
  - Reduce slurry usage by 20%
  - Improve pad lifetime by 20-50%

# Motivation: CMP Models

**Wafer-Level Non-Uniformity**

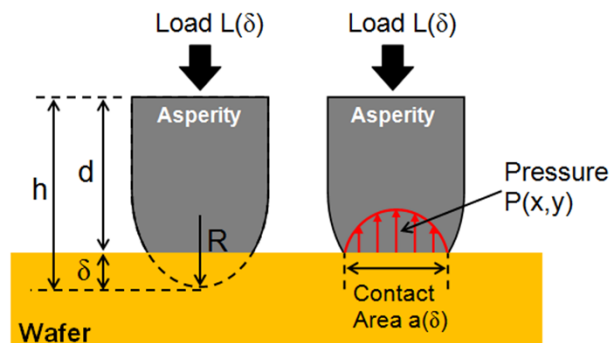


**Die-Level Non-Uniformity**



# 1. Summary of Pad-Wafer Interaction Model

- **Greenwood Williamson approach**
  - Asperities have spherical surfaces with same radius
  - Elastic Hertzian contact
- **Single asperity compression**



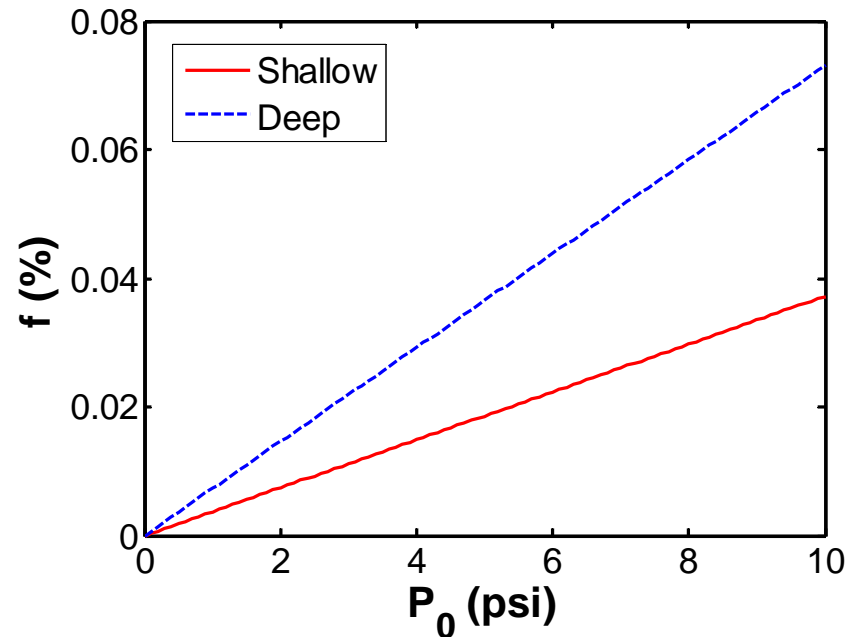
- **Exponential asperity height distribution**  $\xi(h) = \frac{1}{\lambda} e^{-\frac{h}{\lambda}}$
- **Result: Predict contact area fraction  $f$**

$$f(P_0) = \frac{P_0}{E} \sqrt{\frac{\pi R}{\lambda}}$$

$E$ : asperity reduced modulus  
 $P_0$ : reference pressure



# Model Trend: Contact Area vs. Reference Pressure



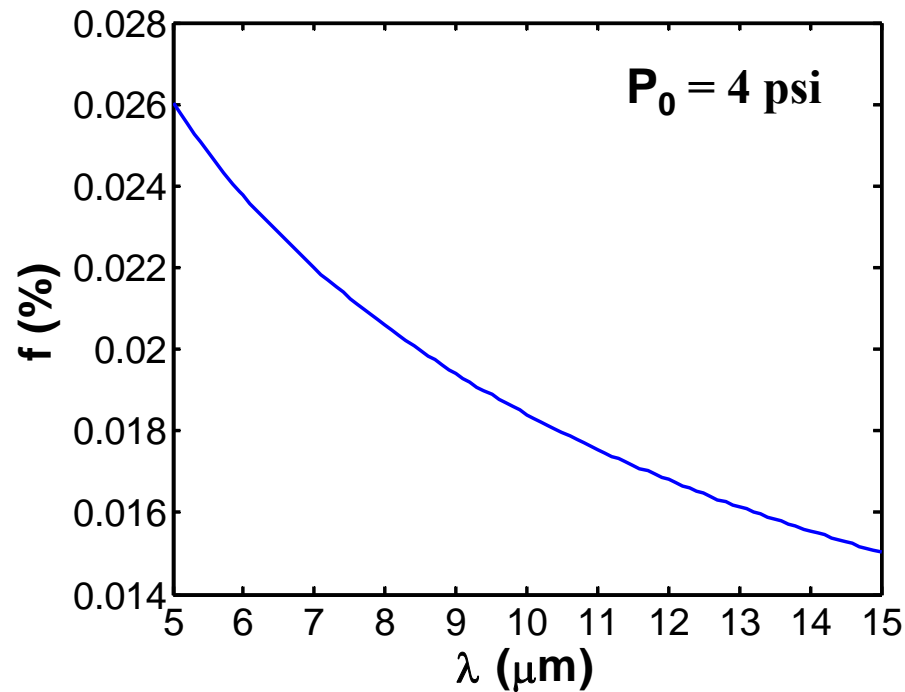
$E = 291 \text{ MPa}$

$E = 572 \text{ MPa}$

$$f(P_0) = \frac{P_0}{E} \sqrt{\frac{\pi R}{\lambda}}$$

- **Contact area increases linearly with  $P_0$** 
  - Depends on reduced pad modulus
  - Using shallow modulus average (stiffer asperities): smaller  $f\%$  for same pressure
  - Using deep modulus average (asperities same as bulk): predicts larger  $f\%$  for same pressure

# Model Trend: Contact Area vs. Characteristic Asperity Height

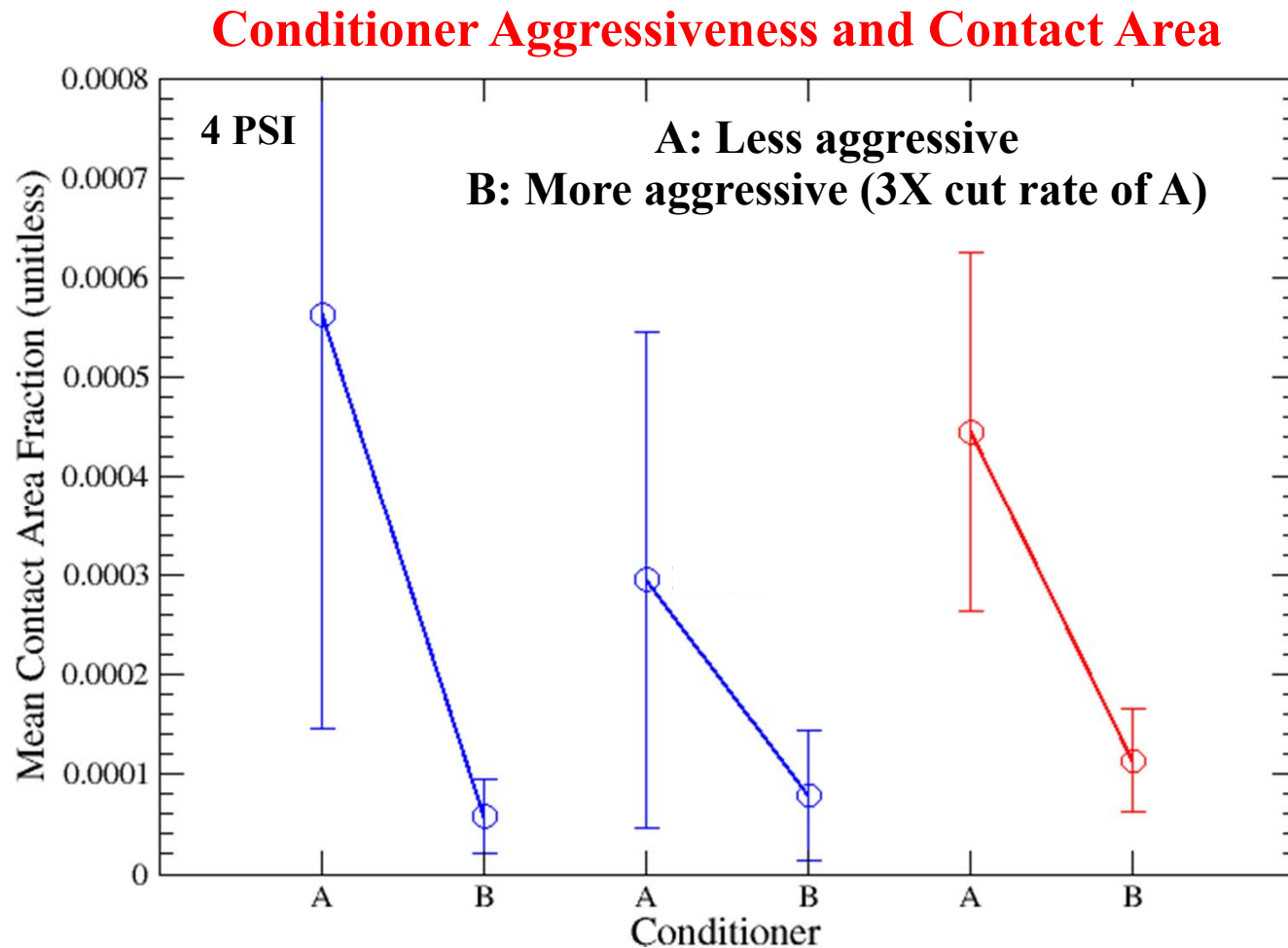


$$f(P_0) = \frac{P_0}{E} \sqrt{\frac{\pi R}{\lambda}}$$

$$\xi(h) = \frac{1}{\lambda} e^{-\frac{h}{\lambda}}$$

- **Contact area decreases with larger  $\lambda$** 
  - Larger  $\lambda$  implies wider distribution (more taller asperities)
  - For wider distribution, a smaller number of tall asperities bear the load, reducing the contact area percent

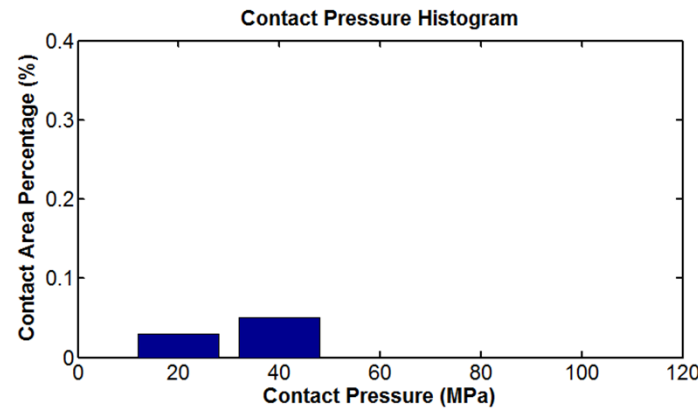
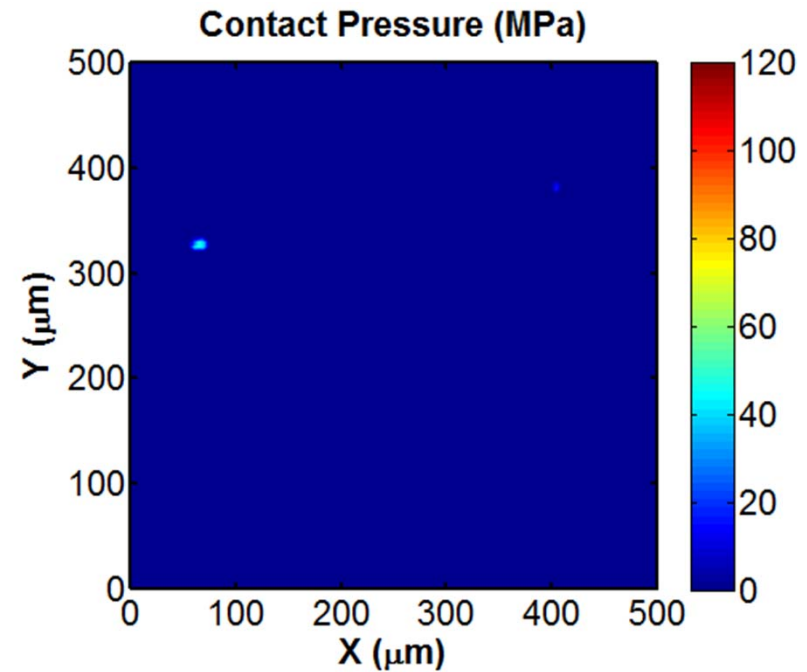
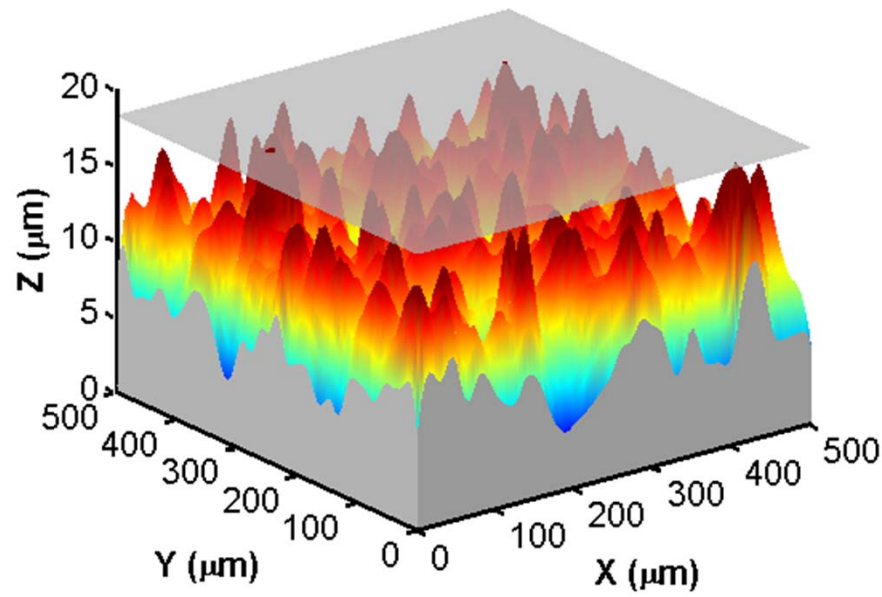
# Consistent with Conditioning/Contact Area Data



*L. Borucki et al., CSITC, March 2010.*

# Simulated Pad-Wafer Interaction

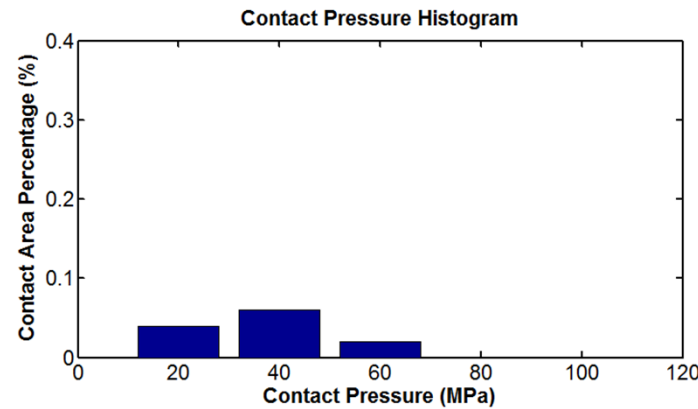
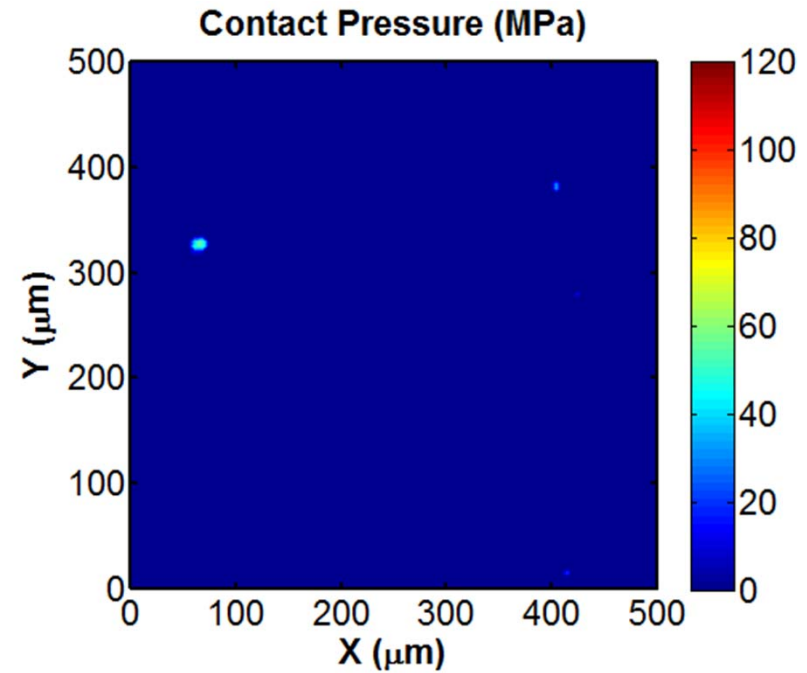
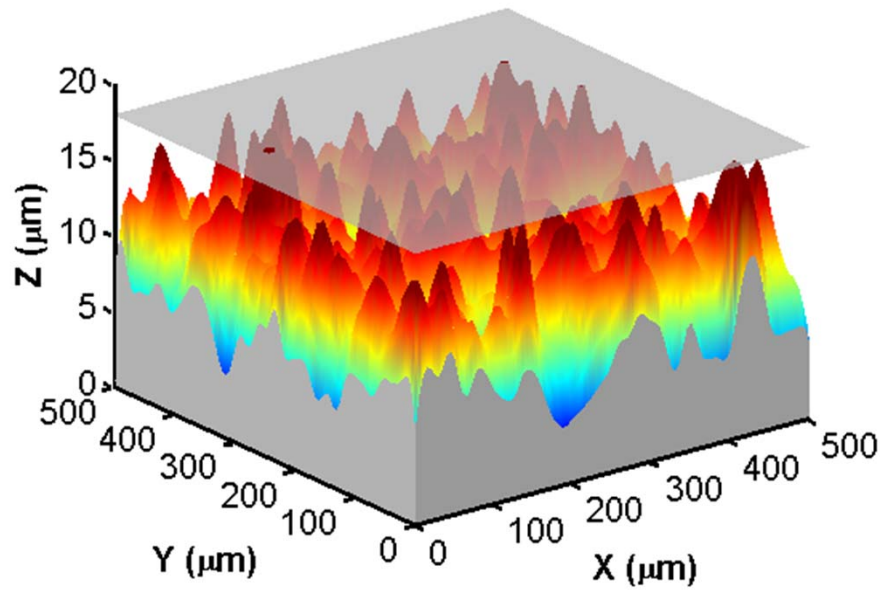
$P_0 = 5 \text{ psi}$



$\lambda = 11.8 \mu\text{m}$   
 $E = 460 \text{ MPa}$

# Simulated Pad-Wafer Interaction

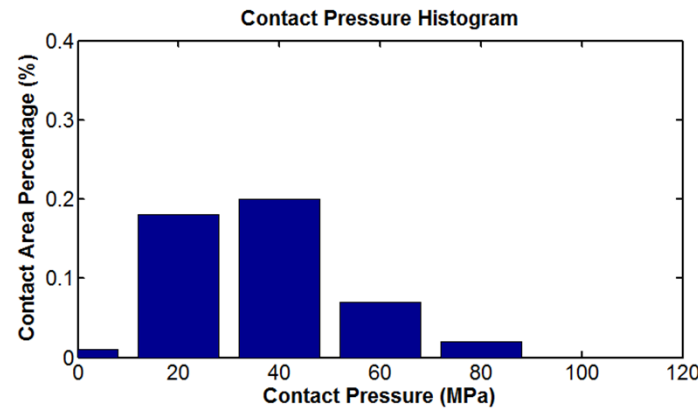
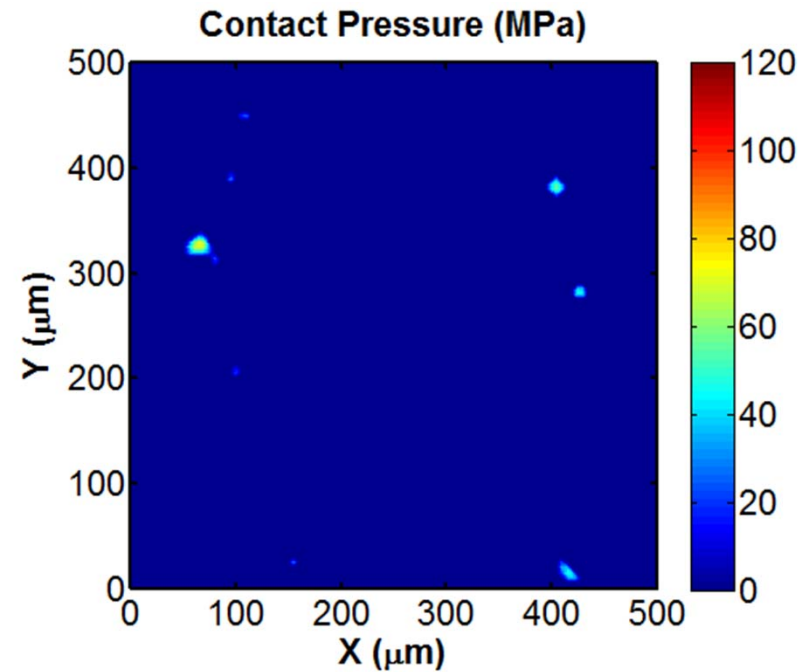
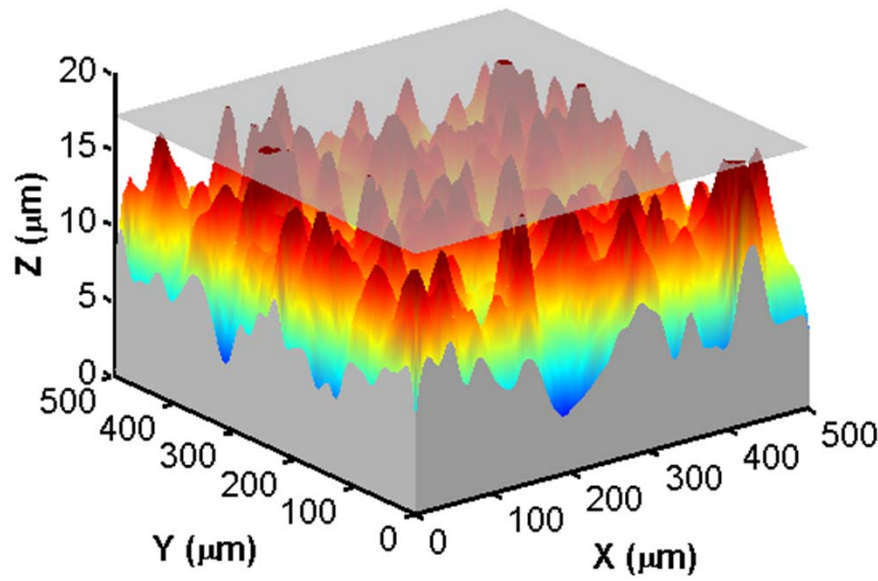
$P_0 = 10$  psi



$\lambda = 11.8 \mu\text{m}$   
 $E = 460 \text{ MPa}$

# Simulated Pad-Wafer Interaction

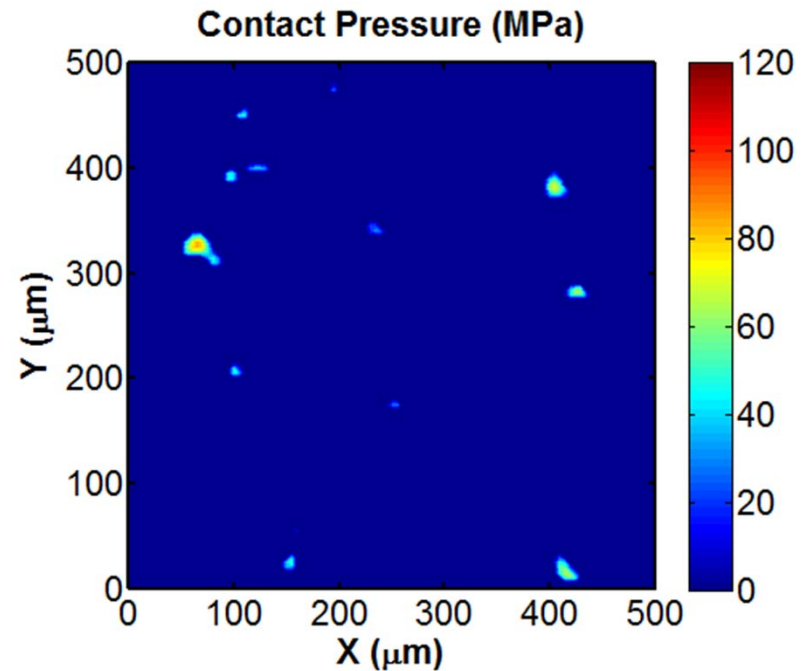
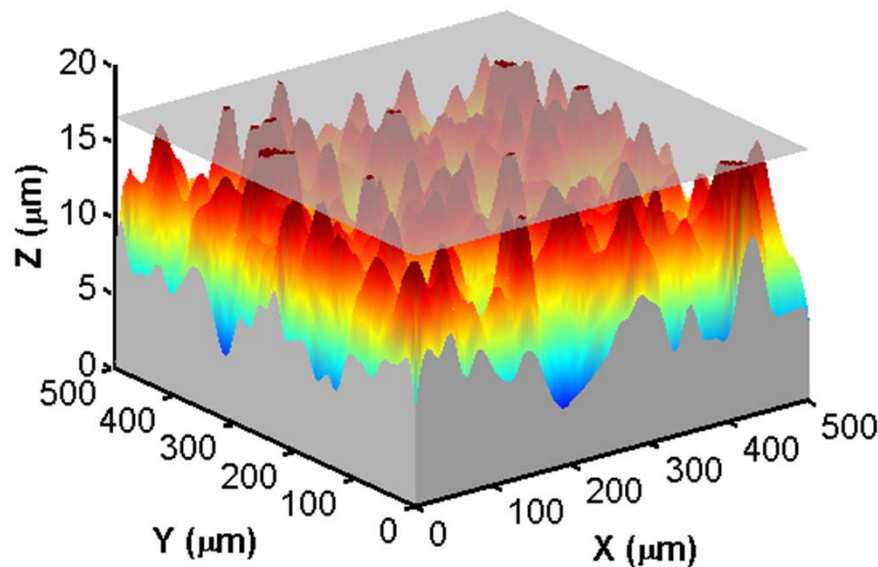
$P_0 = 50$  psi



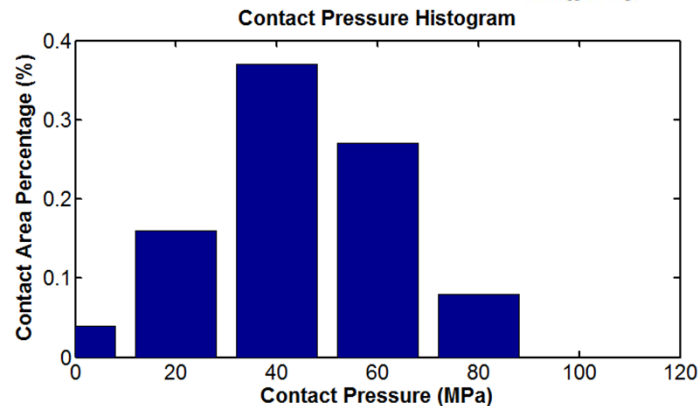
$\lambda = 11.8 \mu\text{m}$   
 $E = 460 \text{ MPa}$

# Simulated Pad-Wafer Interaction

$P_0 = 150$  psi



- Contact area changes with overall applied pressure
- There is also a distribution of asperity contact pressures



$\lambda = 11.8 \mu\text{m}$   
 $E = 460 \text{ MPa}$

## **Next Steps**

- **Extended die-level CMP model including detailed properties**
  - Integrate physical die-level CMP model with nano-scale pad-wafer contact model
  - Consider implications of shallow indentation modulus
  - Understand material removal mechanism using 3-body contact model
- **Extended wafer-level CMP model including polishing tool effects**
  - Retaining ring slot design: effects on wafer/ring edge pressure distributions
  - Pad thickness changes: examine pattern wafer effects due to finite (and changing) pad thickness



## **2. Slurry Agglomeration/Wafer-Level CMP Modeling:**

**Issue: Slurry chemistry, process conditions, and tool design affect slurry particle size and agglomeration**

- **Model how/when slurry abrasive particles form agglomerates**
- **Understand how agglomeration relates to process efficiency, planarization capability, and defectivity**
  - **agglomerate (particle) size distribution, slurry stability**
  - **dependency of wafer-scale uniformity (pattern density)**
- **Integrate with *wafer- and die-scale* models:**
  - **Pressure/velocity (shear) impact on slurry**
  - **Pad microstructure and slurry interactions**

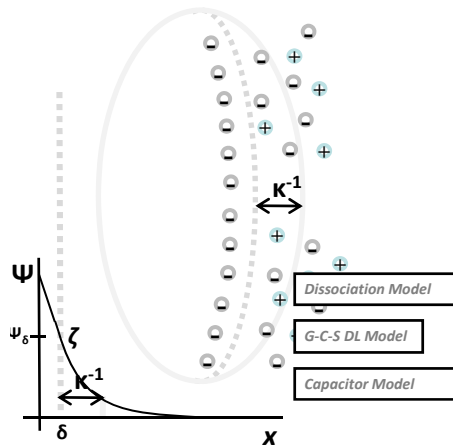
# **Accomplishments and Current Work:**

## **Slurry Agglomeration Model**

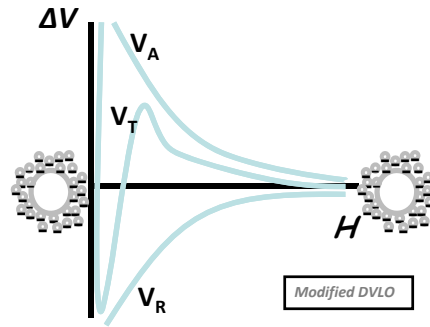
- **Agglomeration model development:**
  - Account for slurry particles, and wafer debris in the creation of agglomerates (respective of size and composition)
  - Account for slurry stability based on agglomerates, chemical composition, and shear forces during CMP
  - Calculate probability of agglomerate size distribution and corresponding stability
- **CMP model/experimental preliminary investigations:**
  - Slurry particle size distribution and stability
- **CMP wafer-scale model application**
  - Studies of planarization and defectivity as a function of slurry agglomerates
  - Possible integration of agglomeration model metrics in planarization model on wafer scale

# Agglomeration Model Validation

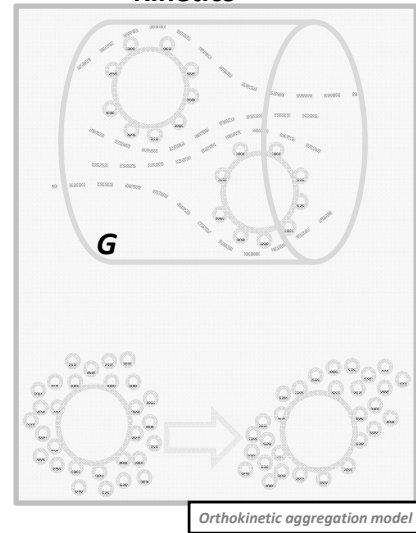
## Surface Chemistry



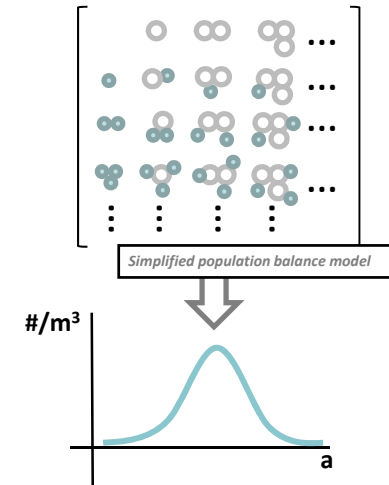
## Inter-Particle Interactions



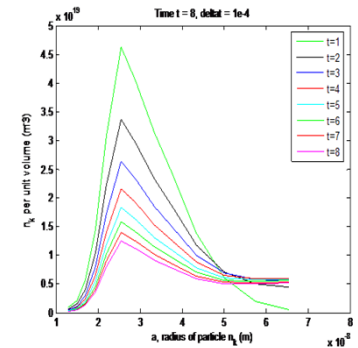
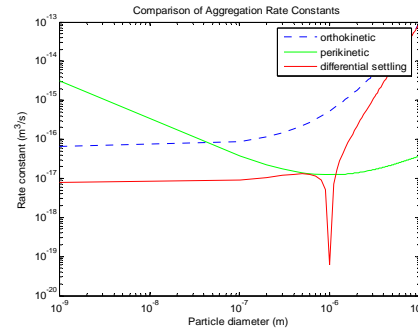
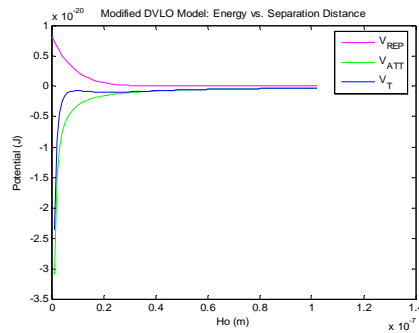
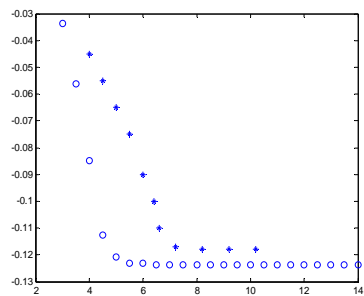
## Kinetics



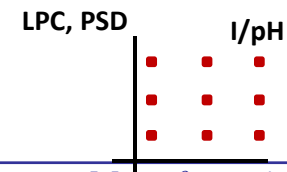
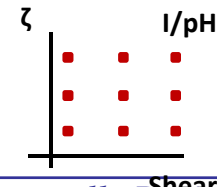
## Population Balance



theory



model



experiments

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Shear

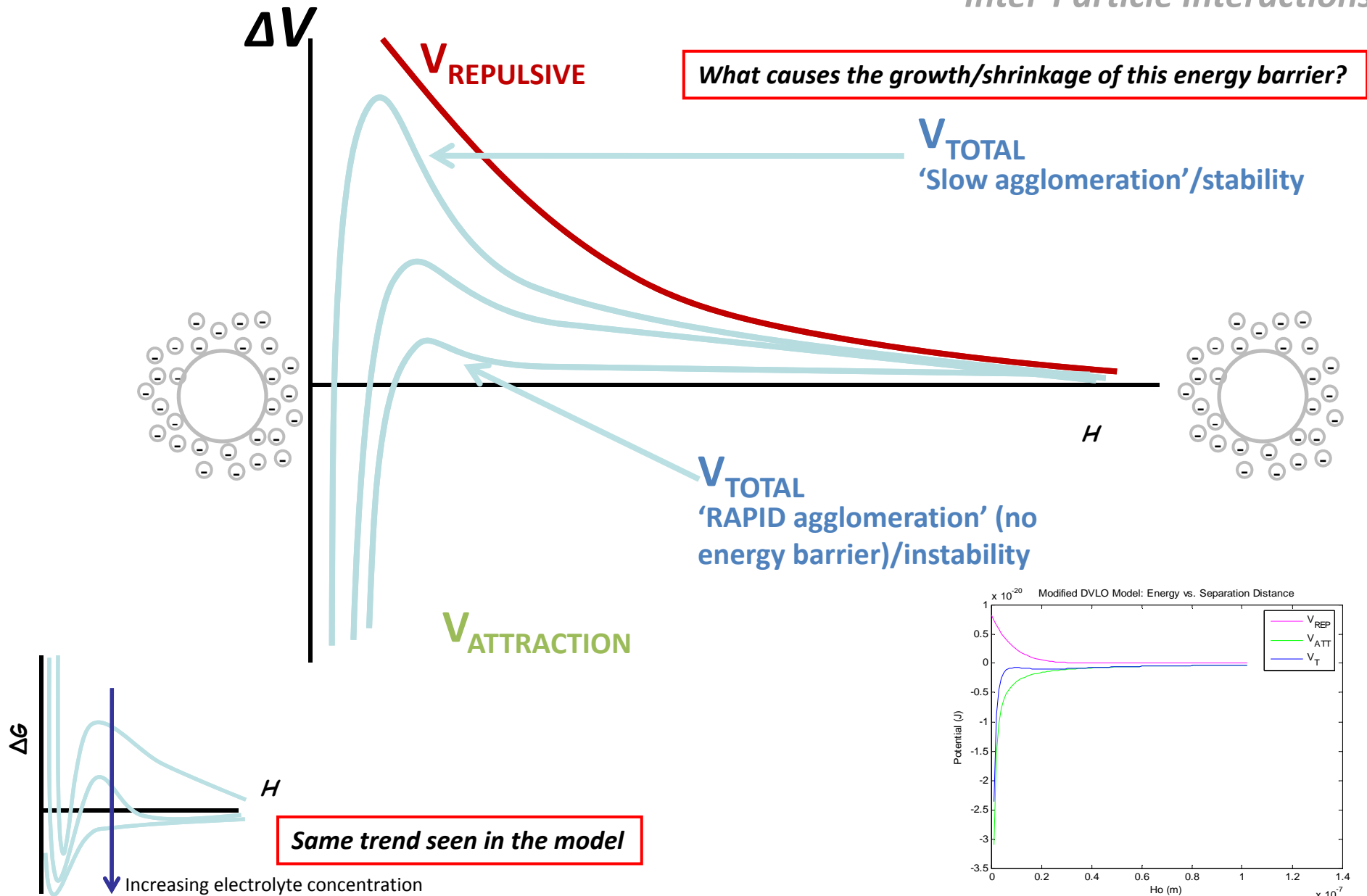
Shear

length scale

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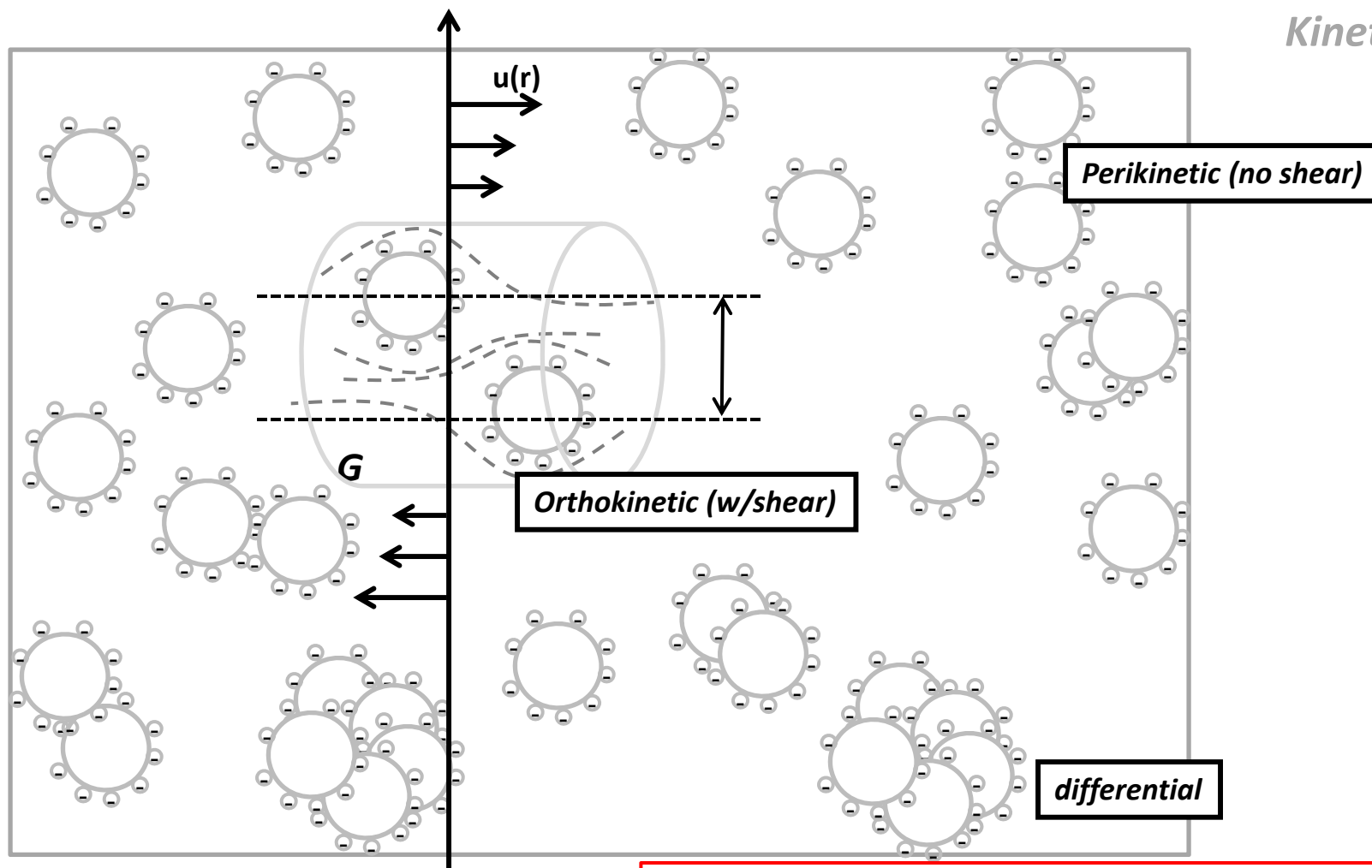
*The Surface Chemistry Model provides a calculation of surface charge density and zeta potential.*

# Inter-Particle Interactions



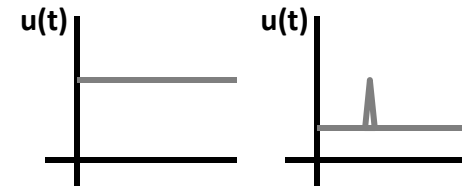
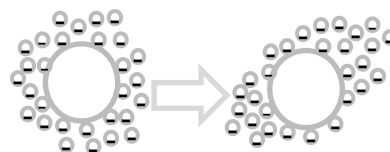
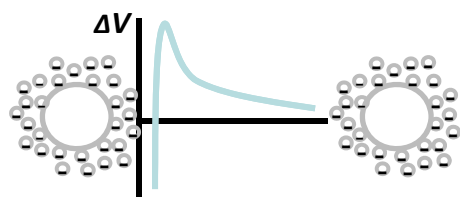
SRC/SEMATECH Engineering Research Center for Env

The modified DVLO Model provides a calculation of interaction energy as it relates to the surface chemistry.



## Additional Variables:

The Orthokinetic Aggregation Model provides a calculation of agglomeration rate as a function of shear



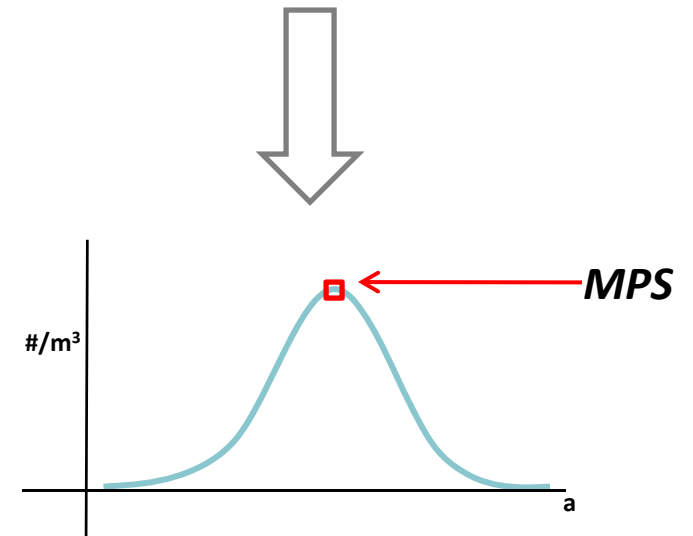
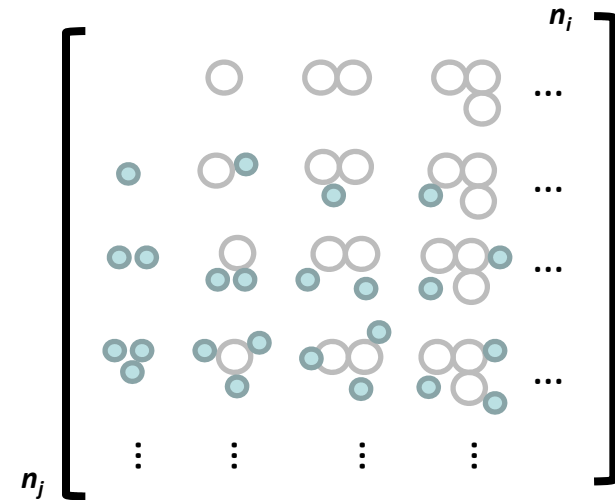
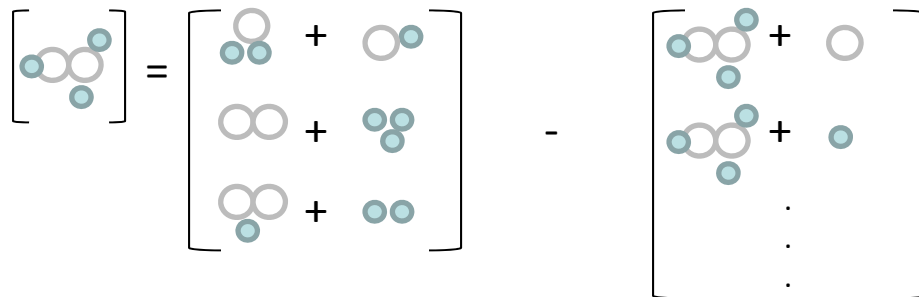
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How do these variables reduce/increase the shear effects on agglomeration?

## Simplified Population Balance Model of the Orthokinetic Agglomeration rate

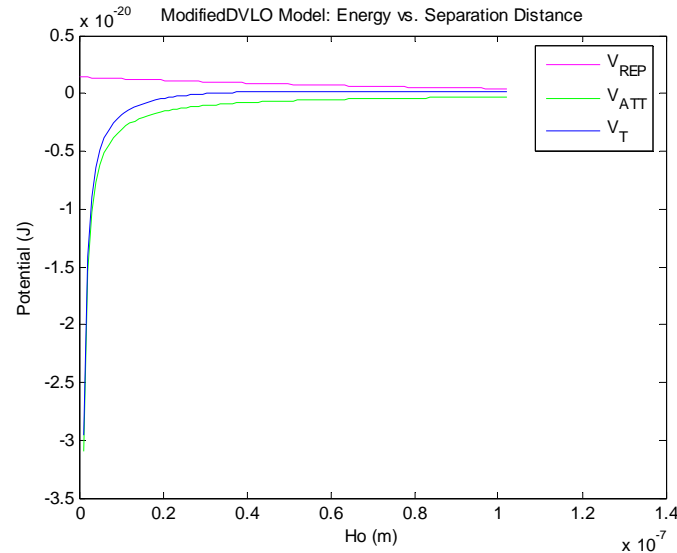
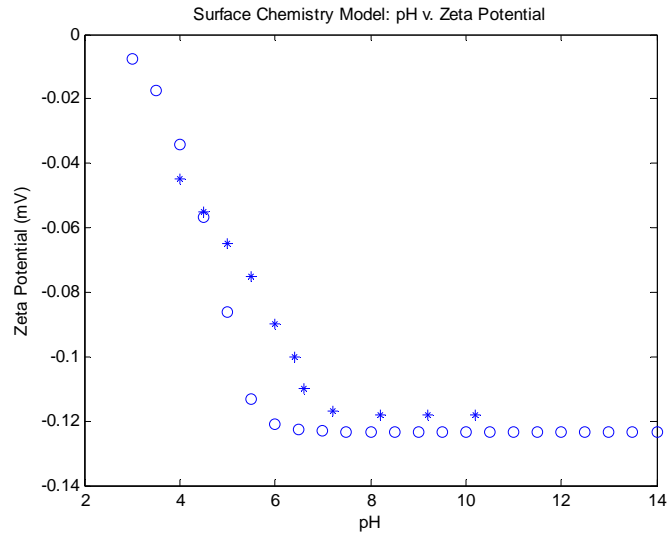
$$\frac{dn_k}{dt} = \frac{1}{2} \sum_{i+j=k}^{i=k} k_{ij} n_i n_j - n_k \sum_{k=1}^{\infty} k_{ik} n_i$$

Birth rate of  $n_k$                       Death rate of  $n_k$

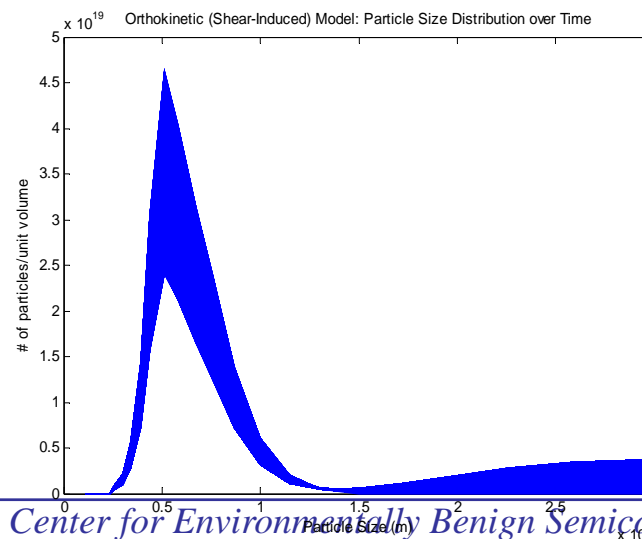
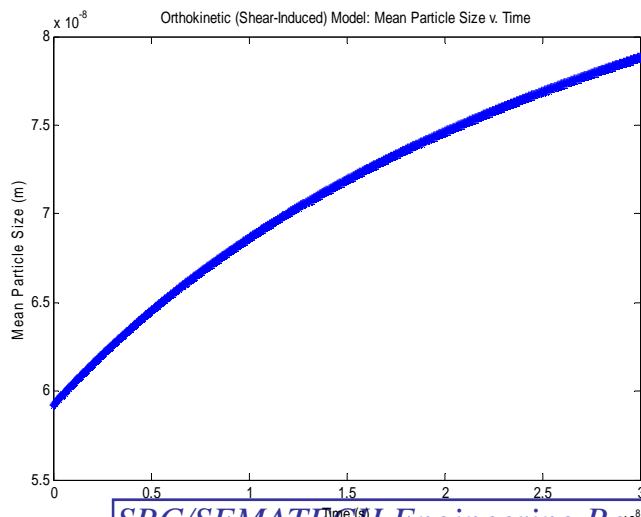


# Standard Case

## Population Balance



- **Input Params:**
  - $I = 0.001M$
  - $pH = 4$
  - $particletype = 'silica'$
  - $MPS = .051\mu m$
  - $PSD$  (initial measured  $PSD$ )

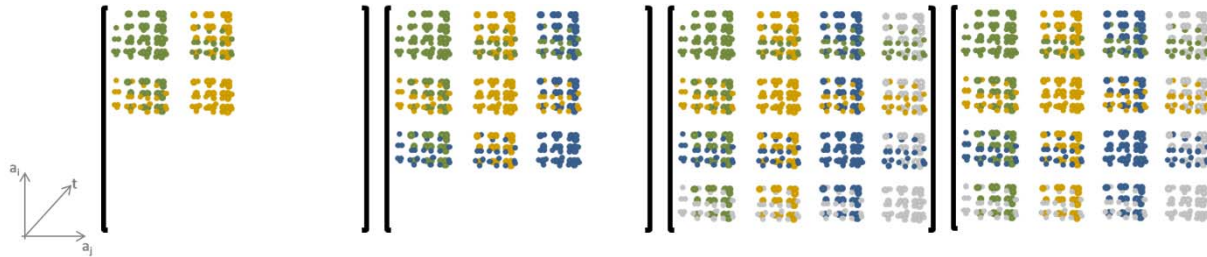




# Future Plans

## Next Year Plans

- Complete agglomeration experiments (in collaboration with Intel)
- Explore model paths for multi-particle systems in both conventional CMP and alternative pad particle-based processes



- Explore alternative pad-particle CMP, in comparison to conventional CMP

# **Pad/Slurry Alternative: Controlled Pad Particles vs. Pad Surface Asperities**

**Opportunity: Explore a recently proposed approach that uses pad “particles” or beads suspended in a slurry to replace CMP pad asperities**

- **Gain fundamental physical understanding of key planarizing mechanisms, e.g. random pad asperities vs. controlled size of pad particles**
- **Understand environmental, cost, performance benefits, as well as viability of new approach**
- **Integrate with slurry particle agglomeration models to predict effects of new particles in the slurry**

# Initial Experimentation:

- Explore *proof of principle* baseline experiments on a bench top polisher
- Experiment with appropriate:
  - slurry composition: bead type, wt %, size distribution, surfactant
  - counter face: composition type and/or preparation (grooved/flat)

		Counter face composition/preparation					
Slurry composition	A						
	B						
	C						
	D						
		Type A		Type B		Type C	

Chose best metric for more intensive planarization studies to compare with conventional CMP process

# Industrial Interactions and Technology Transfer

- Intel
  - Conducting experiments for agglomeration model metrics and verification.

# **Publications and Presentations**

- 1. D. Boning and J. Johnson, “Slurry Particle Agglomeration Model for Chemical Mechanical Planarization (CMP),” CMP Symposium, MRS Spring Meeting, April 2010.**
- 2. W. Fan, J. Johnson, and D. Boning, “Wafer-level Modeling of Electrochemical-Mechanical Planarization (ECMP),” International Conference on Planarization Technology (ICPT), Phoenix, AZ, Oct. 2010.**
- 3. D. Boning, “CMP Mechanisms and Models: Progress and Challenges,” Keynote, Symposium V: CMP and Post-CMP Cleaning, China Semiconductor Technology International Conference (CSTIC), Shanghai, China, March 18-19, 2010.**

# Development of an All-Wet Benign Process for Stripping of Implanted State-of-the-Art Deep UV Resists

*(Task number: 425.033)*

## *Experimental Investigation of Catalyzed Hydrogen Peroxide (CHP) System For HDIS*

### PI:

- Sriniraghavan, Department of Materials Science and Engineering, UA

### Graduate Student:

- R. Govindarajan, PhD candidate,  
Department of Materials Science and Engineering, UA

### Cost Share (other than core ERC funding):

- In-kind donation of ion-implanted resist wafers by *Sematech*(~ \$ 5,000 )

# Objectives

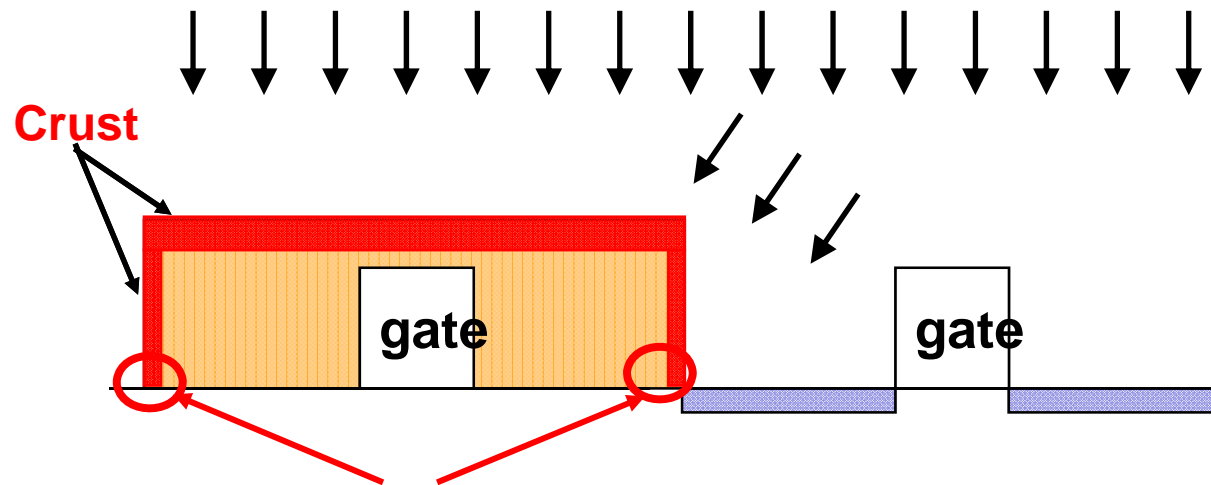
## **Overall Objective:**

- Development of an environmentally friendly process for stripping high dose implanted resists using catalyzed hydrogen peroxide system (CHP)

## **Current Year Goals:**

- Eliminate/reduce the use of iron in Catalyzed hydrogen peroxide (CHP) system
- Investigate the use of UV activated Hydrogen Peroxide system for disrupting crust formed on resist layers exposed to high dose of ions ( $\geq 10^{15}$  /cm<sup>2</sup>)

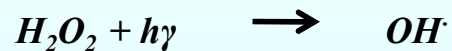
# Stripping Implanted Photoresist



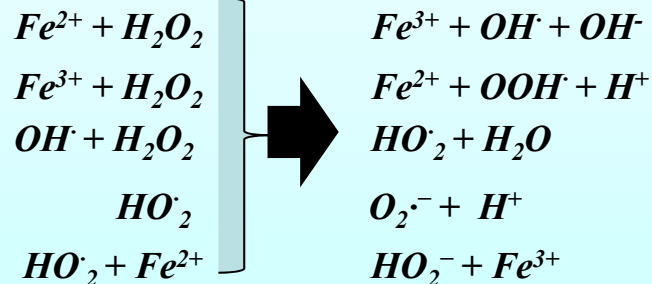
➤ Currently, high temperature ( $>200^{\circ}\text{C}$ ) SPM is used to attack crust & resist

Most challenging where crust is fused to wafer surface; also near EBR region

## $\text{H}_2\text{O}_2$ Activation by UV light



## Catalyzed $\text{H}_2\text{O}_2$ Propagation



➤ Radicals- strong oxidants  
➤ CHP system disrupts crust and provides access to SPM



# ESH Metrics and Impact

## ➤ SPM solution

- Requires high temperature ( $> 200^{\circ}\text{C}$ ) for stripping high dose implanted resists

## ➤ Comparison of toxicity of ingredients in CHP and SPM

Compound	LD <sub>50</sub>	Carcinogenic
Ferrous sulfate	1520mg/kg (mouse)	NO
Peroxide	2000 mg/kg (mouse)	NO
Sulfuric acid	90 ml/kg (rat)	Yes
UV light (216nm)	3 mJ/cm <sup>2</sup> (Bacteria)	Yes

## ➤ ESH Impact

- By using low temperature ( $< 120^{\circ}\text{C}$ ) SPM as a secondary chemical, *energy and safety issues related to the use of very hot SPM can be significantly reduced*

## **Current Year Activities**

- **Carried out studies on spin tool for disrupting crusted resist using Catalyzed Hydrogen Peroxide (CHP) system**
- **Explored the use of UV activated Hydrogen Peroxide system for disrupting crust that typically forms on high dose implanted resists**
- **With permission from FSI. characterized wafers subjected to their proprietary steam activated SPM process (ViPR) and used the study to evaluate the effectiveness of CHP/SPM process**

# **Experimental Approach**

## **➤Materials**

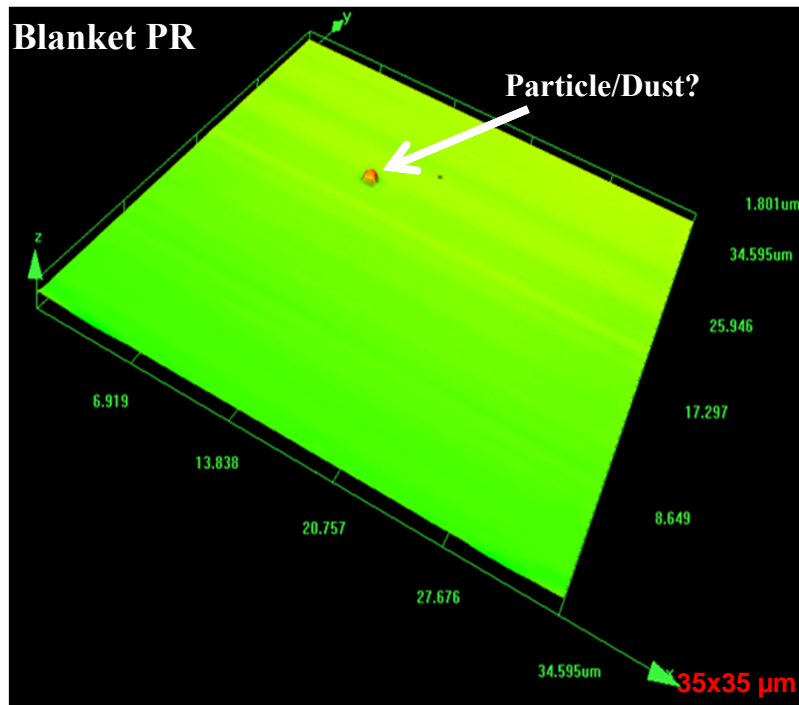
- **Implanted resist films ( $1\text{E}16 \text{ As /cm}^2$  ;  $\sim 1.5 \mu\text{m}$ ) donated by Sematech, ( $1\text{E}15 \text{ As /cm}^2 \sim 1.0 \mu\text{m}$ ) FSI International**
- **UV light source (Wavelength: 254nm; Intensity :  $12.2 \text{ mW/cm}^2$  at 3")**
- **Ferrous Sulfate ( $\text{FeSO}_4 \cdot 6\text{H}_2\text{O}$ ) , 99.998% pure**
- **Hydrogen Peroxide (30%)**

## **➤Methods**

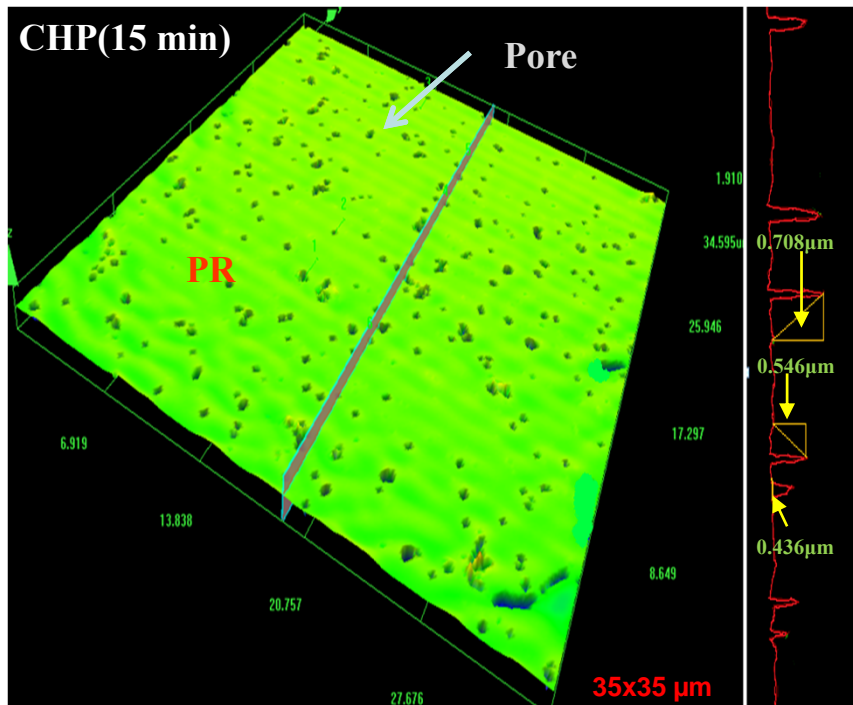
- **Experiments conducted on Laurell Spinner using puddle method (dispensing solution, allowing it to stay, followed by spinning)**
- **Morphological changes after CHP treatment were characterized using Leica DM4000B microscope operated using QCapture Pro 5.0 software, Leeds Confocal microscope, FESEM and XPS**

# Confocal Microscopic Characterization of Implanted PR

## 3D Confocal Micrographs



**AS IMPLANTED**

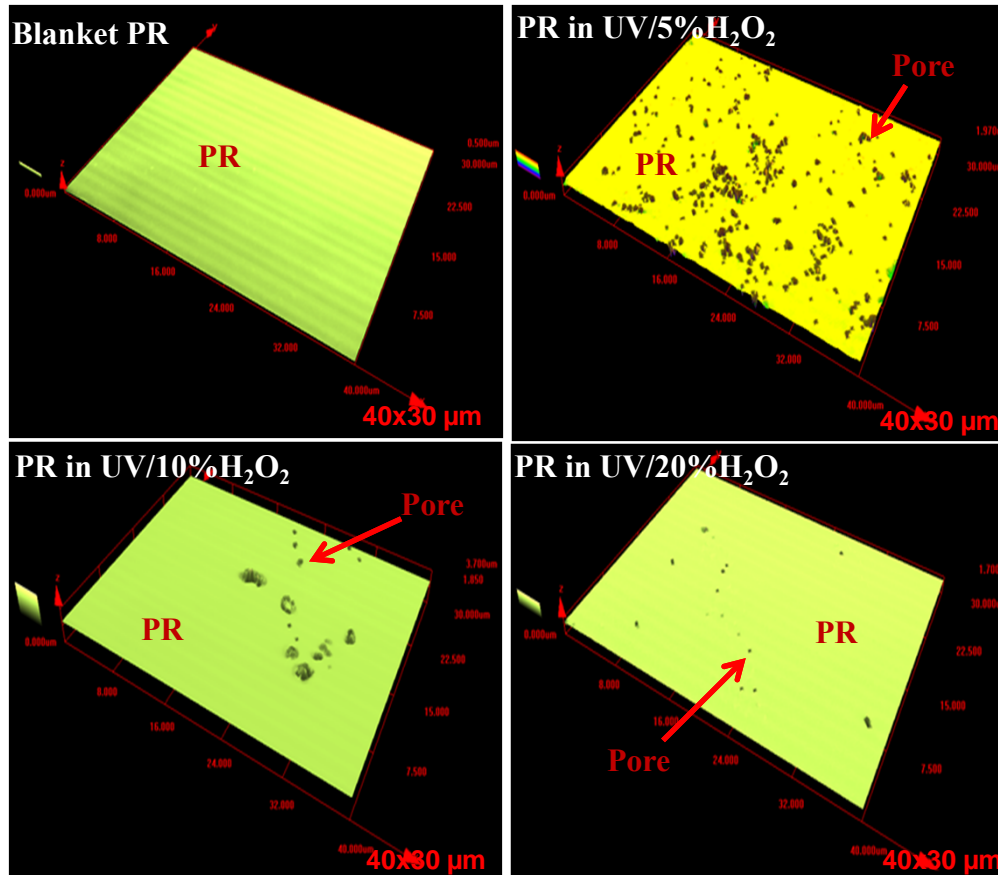


**TREATED WITH CHP**

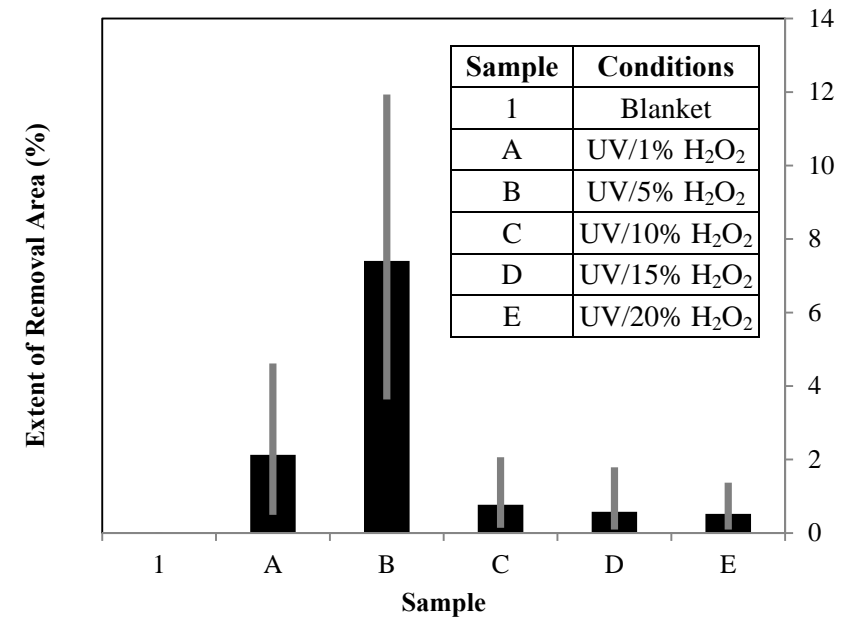
- Blanket PR (dose:  $1\text{E}16 \text{ As/cm}^2$ ) is smooth without any pores
  - CHP ( $5\text{mM Fe}^{2+}$ , 20%  $\text{H}_2\text{O}_2$ ) treatment @  $25^\circ\text{C}$  for 15 minutes shows localized attack
- PR surface has pores of depth  $< 700 \text{ nm}$  and size  $< 1.5 \mu\text{m}$

# Effect of UV Activated $H_2O_2$ on Implanted PR

## 3D Confocal Micrographs



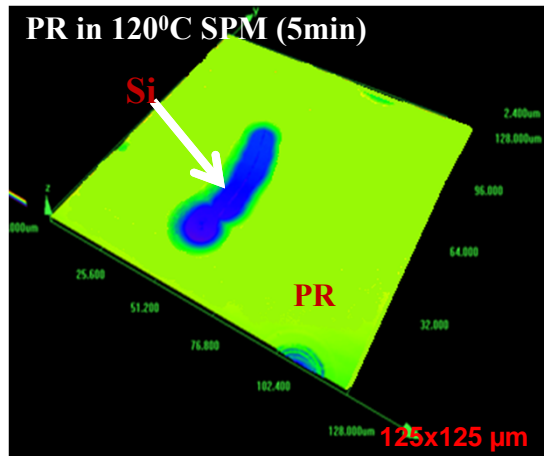
Effect of  $H_2O_2$  Concentration on PR disruption under UV irradiation



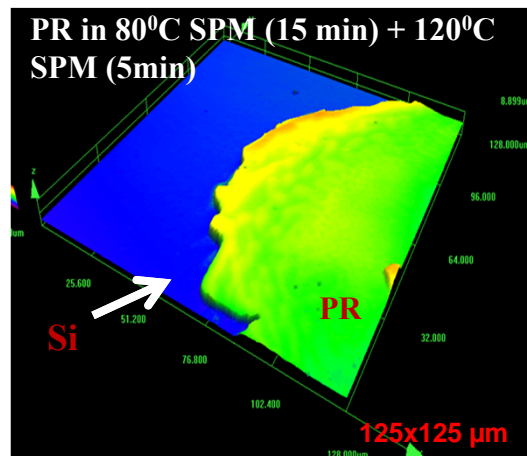
- PR (dose:  $1E 16$  As/cm<sup>2</sup>) exposed to UV irradiated  $H_2O_2$  at 40°C for 15 minutes
- Good attack observed with 5%  $H_2O_2$  activated by UV light
- Extent of disruption/attack depends on  $H_2O_2$  concentration

## Effect of SPM & Two Step CHP(or UV-Peroxide)/SPM Process

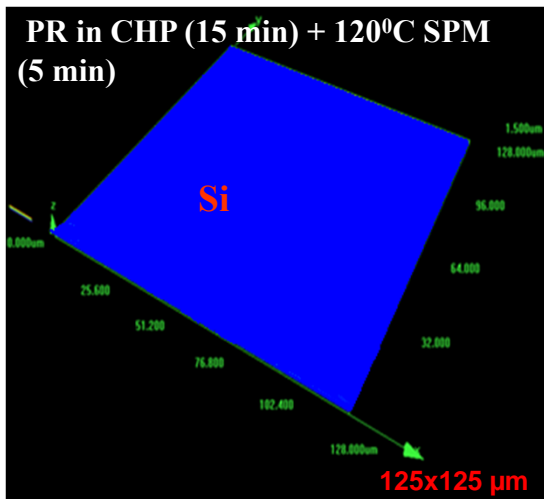
### 3D Confocal Micrographs



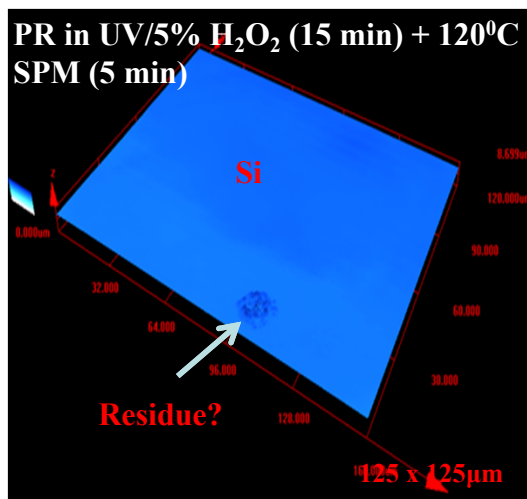
Inefficient removal



Reduced extent of removal



Complete removal

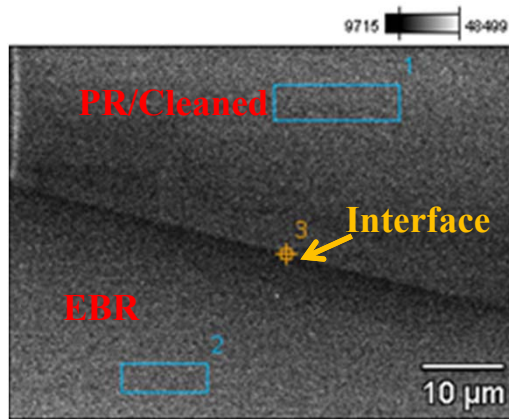


Residue?

➤ SPM treatment – localized PR removal (bare Si as blue color) 2:1 SPM: Preheated (80°C) H<sub>2</sub>SO<sub>4</sub> mixed with H<sub>2</sub>O<sub>2</sub>, solution dispensed at ~ 120°C

➤ *Two step process involving CHP or UV/ 5% H<sub>2</sub>O<sub>2</sub> exposure followed by 2:1 SPM (120 °C) treatment results in very good removal of PR*

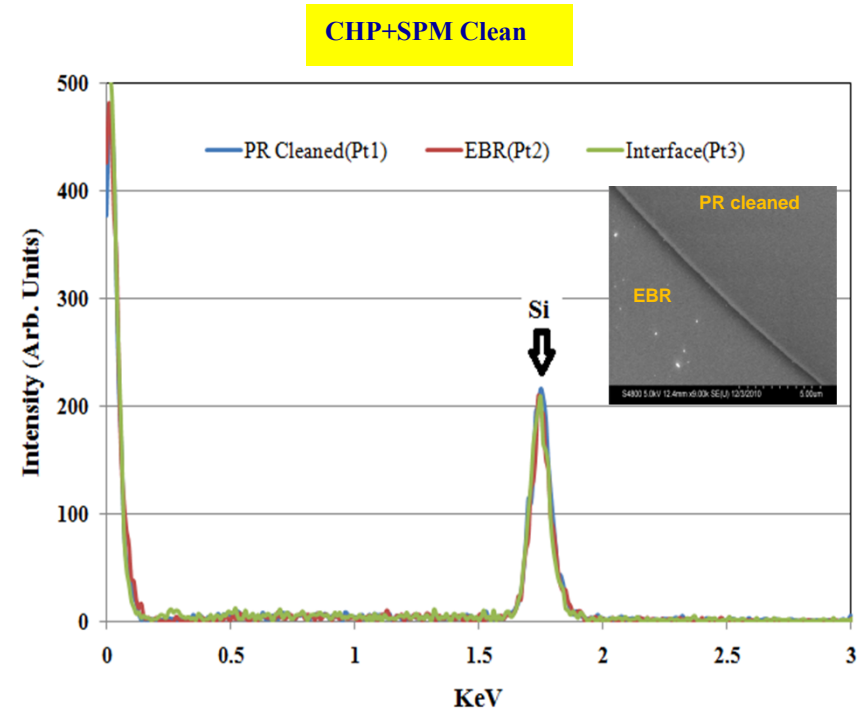
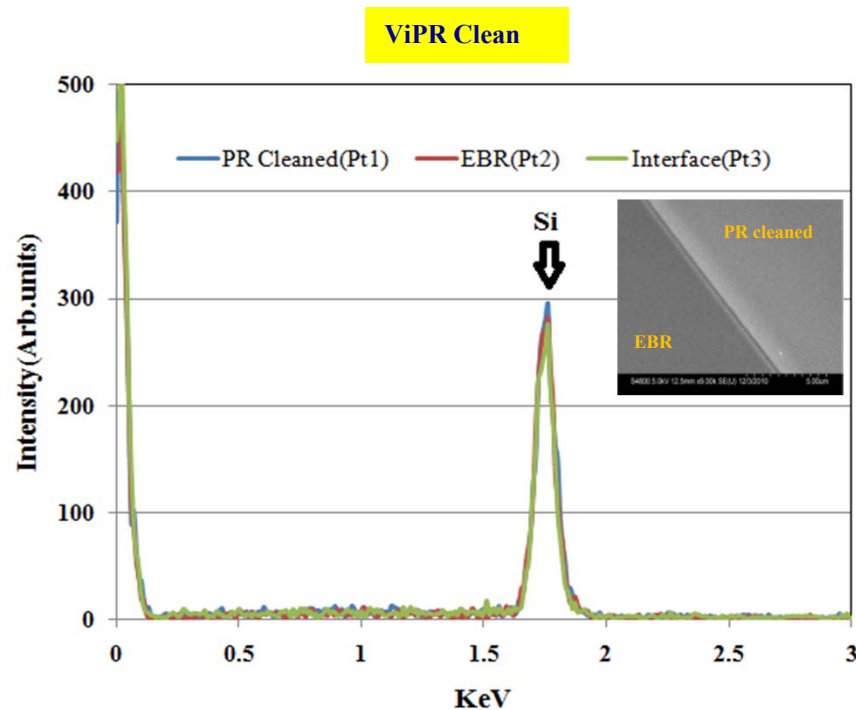
# EDS analysis of Samples (Dose: 1E15 As/cm<sup>2</sup> @ 10KeV) provided by FSI



➤ Most difficult to remove – Interface between EBR cleaned region and PR region

➤ Sample cleaned using ViPR process strips PR (*no C & O signal*)

➤ CHP treatment (15 mins) followed by 2:1 SPM (~120°C, 5 mins) *shows similar result as ViPR process*



# Summary

- **CHP system containing 5 mM  $\text{Fe}^{2+}$  and 20%  $\text{H}_2\text{O}_2$  at 25 °C and 5%  $\text{H}_2\text{O}_2$  exposed to UV at 40 °C create surface defects on high dose implanted PR**
- *Good removal of high dose implanted PR is possible by first exposing the resist in CHP or UV irradiated 5%  $\text{H}_2\text{O}_2$  solution for 15 minutes and then in 2:1 SPM at ~120 °C for 5 minutes under spin conditions*
- *Effectiveness of two step CHP/SPM process appears comparable to that of FSI's ViPR process*



# **Deliverables Status**

<b>Promised Deliverables</b>	<b>Y/N/IP</b>
Use of non-metal based catalyst to activate Hydrogen Peroxide	Yes; Using UV source
Work with Tool maker to test/compare the chemical system	Yes; For $1\text{E}15\text{ As/cm}^2$ implanted samples with FSI's ViPR process
Evaluation of two step (CHP and UV irradiated $\text{H}_2\text{O}_2$ followed by conventional SPM) process to strip films	Yes

# Future Plans

## Next Year Plans

- Optimization of UV activated hydrogen peroxide system to decrease the exposure time prior to conventional SPM treatment
- Explore the use of *non-metal catalysts* such as borates

## Long Term Plans

- Investigate the use of sulfuric acid alone as the second step

# Industrial Interactions and Technology Transfer

- Patent on “Enhanced Stripping of Implanted Resists”, was filed by SRC in December 2010 ( File No: US 12/981,073)
- R. Govindarajan, M. Keswani and S. Raghavan, "Development of an all wet benign process based on catalyzed hydrogen peroxide (CHP) chemical system for stripping of implanted state-of-the art Deep UV resists ", TECHCON Conference, Austin, TX, Sep 13-14 (2010)
- Interactions with Dr. Kanwal Singh of Intel on patterned wafers
- Technical discussions with Joel Barnett of Sematech on choice of samples and experimental direction
- Discussions with Jeff Butterbaugh on testing the process in FSI tools

## Acknowledgement

- Assistance of Bob Morris of Oclaro on Confocal microscopy
- Assistance of Steven Hernandez, University of Arizona on FESEM

# **Improvement of ESH Impact of Back End of Line (BEOL) Cleaning Formulations Using Ionic Liquids to Replace Traditional Solvents** *(Task Number: 425.034)*

## **PI:**

- **Srini Raghavan, Materials Science and Engineering, University of Arizona**

## **Graduate Students:**

- **Dinesh P R Thanu, PhD candidate, Materials Science and Engineering, University of Arizona**
- **Jenny Taubert, PhD candidate, Materials Science and Engineering, University of Arizona**

# Objectives

## **OVERALL OBJECTIVE**

- **Develop cleaning formulations based on electrically conductive deep eutectic solvents (DES) to replace traditional organic solvent based formulations for BEOL cleaning**

## **SPECIFIC OBJECTIVE FOR THE CURRENT CONTRACT YEAR**

- **Extend the work on removal of post etch residues (PER) formed on copper using choline chloride/urea (CC/U) DES**
- **Explore the use of choline chloride/malonic acid (CC/MA) DES in PER removal and compare with CC/U DES**

## **ESH Metrics and Impact**

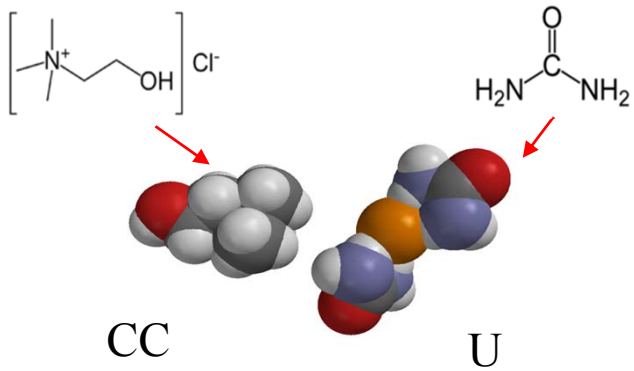
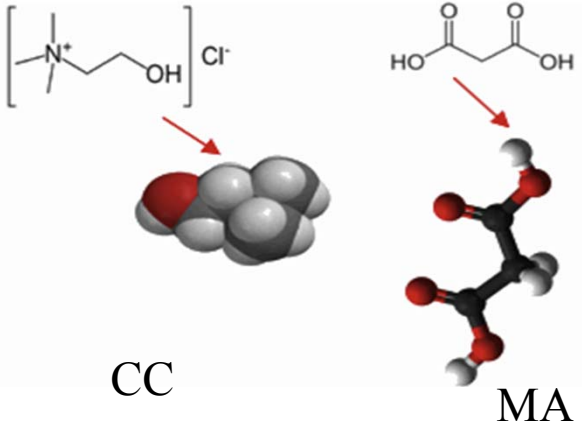
- ESH objective:* Replacement of organic solvents from BEOL cleaning formulations which generate a waste stream that is difficult to treat

<b>Solution components</b>	<b>Weight % in typical formulations</b>	<b>Formulation used in this study</b>
Traditional organic Solvent	> 60%	Eutectic composition of two benign compounds 100%
Water	< 40%	0%
Fluoride	~ 1-2%	0%

<b>Ingredients</b>	<b>LD<sub>50</sub> (Oral Rat) mg/kg</b>
Urea	<b>8471</b>
Choline Chloride	<b>5000</b>
Malonic Acid	<b>1310</b>

<b>Components</b>	<b>Vapor Pressure (@20°C) mm Hg</b>
<u>DES Components:</u>	
Choline Chloride (Solid)	<b>4.93 E-10 @25°C</b>
Urea (Solid)	<b>6.75 E-3</b>
Malonic Acid (Solid)	<b>NA</b>
<u>Conventional Solvents:</u>	
DMSO	<b>0.42</b>
N-Methyl Pyrrolidone	<b>0.29</b>
Sulfolane	<b>0.01</b>

# Comparison between CC/U and CC/MA DES

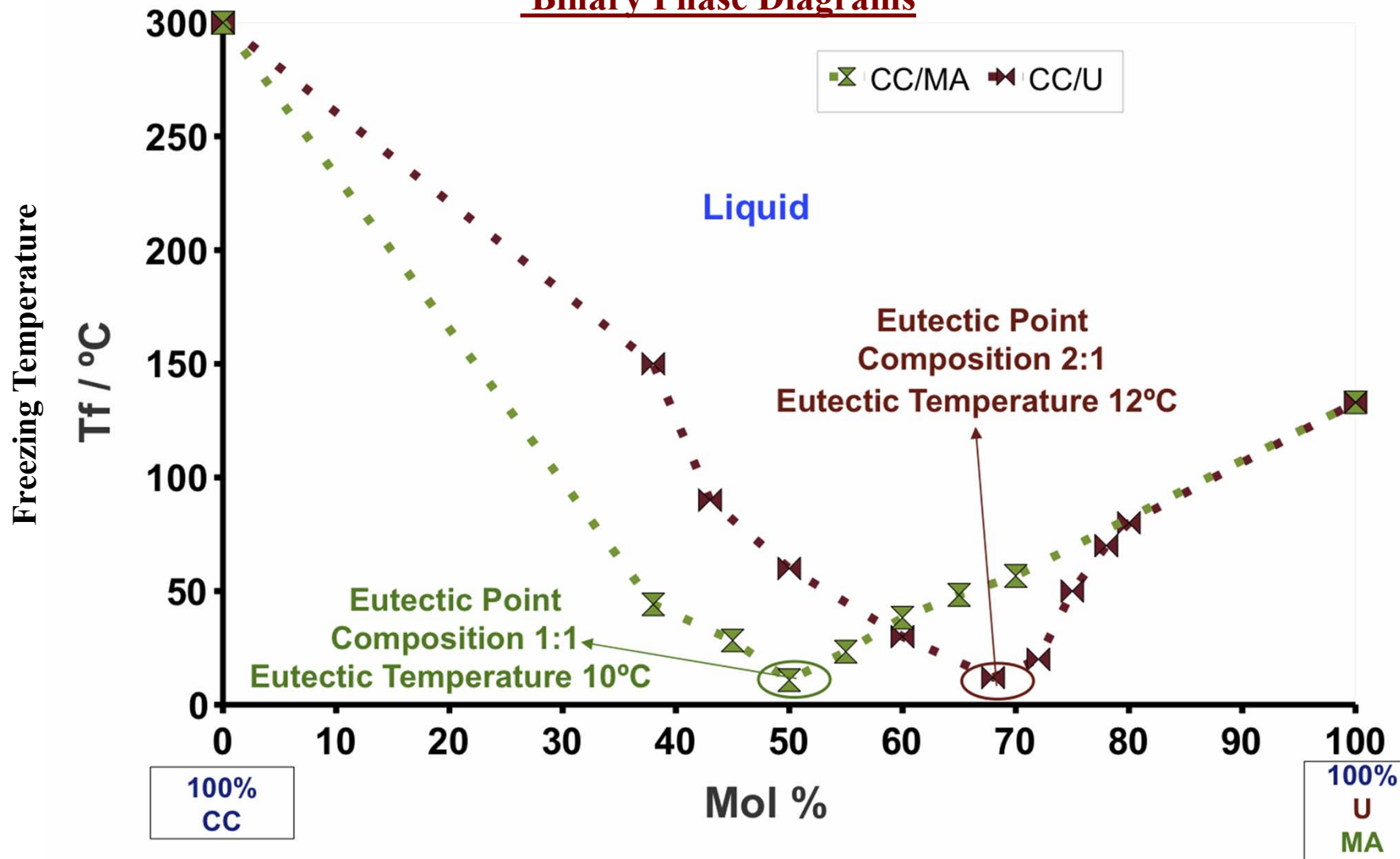
Properties	CC/U	CC/MA
Eutectic Temperature (°C)	12	10
Solubility of CuO (ppm)	~5	~14000
Solubility of Cu <sub>2</sub> O (ppm)	~200	~18000
Mechanism of Metal Oxide Removal	Complex formation [MClO. (Urea)] <sup>-</sup>	Chlorometalate formation MCl <sub>x</sub> <sup>-</sup>
Viscosity at 25°C (cP)	855	2260
Conductivity (mScm <sup>-1</sup> )	0.8	0.4
Water Soluble	Yes	Yes
	 <p>CC</p> <p>U</p>	 <p>CC</p> <p>MA</p>

A.P. Abbott, et al., J. Chem. Eng Data, 51, p.1280-1282 (2006)

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# Deep Eutectic Solvents (DES)

## Binary Phase Diagrams



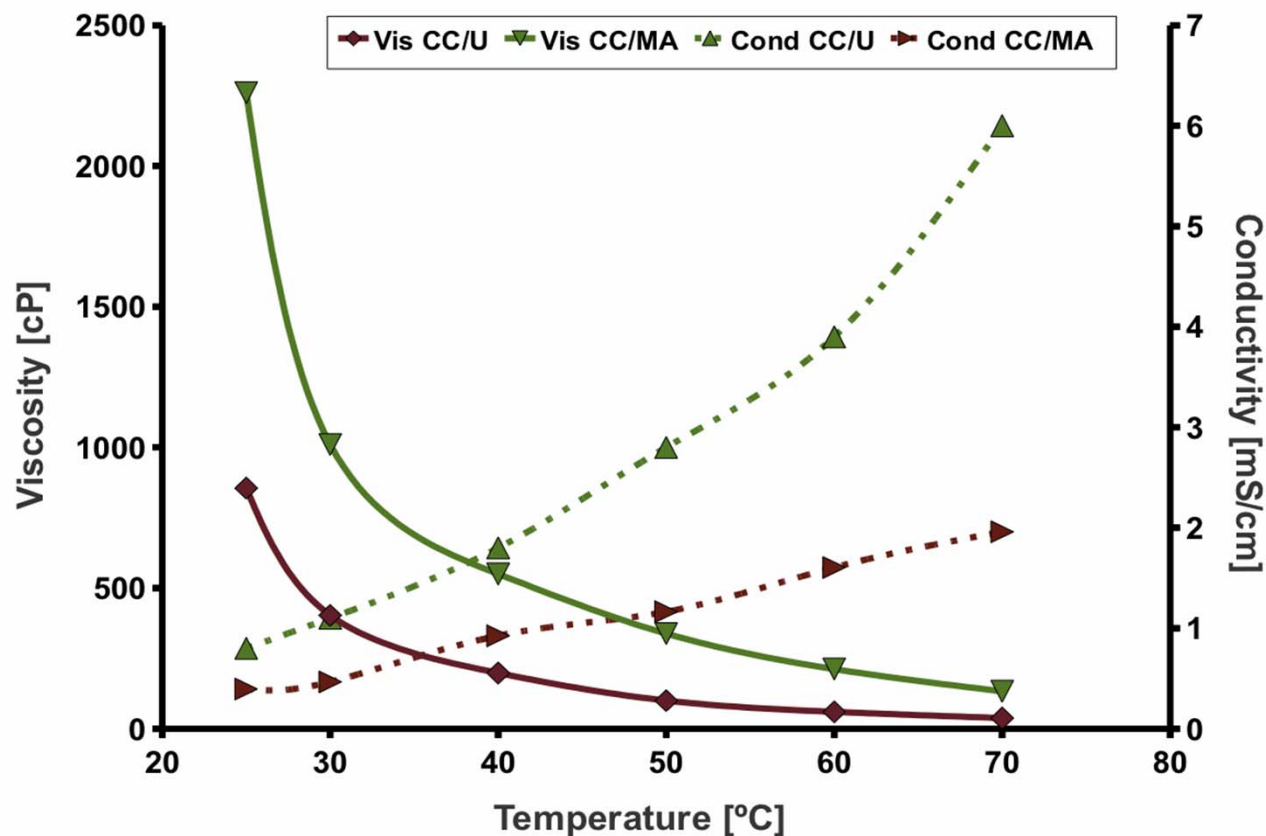
A.P. Abbott, et al., *Chemical Communications*, p. 70-71 (2003)

A.P. Abbott, et al., *Journal of the American Chemical Society*, 9 (126), p. 29 (2004)

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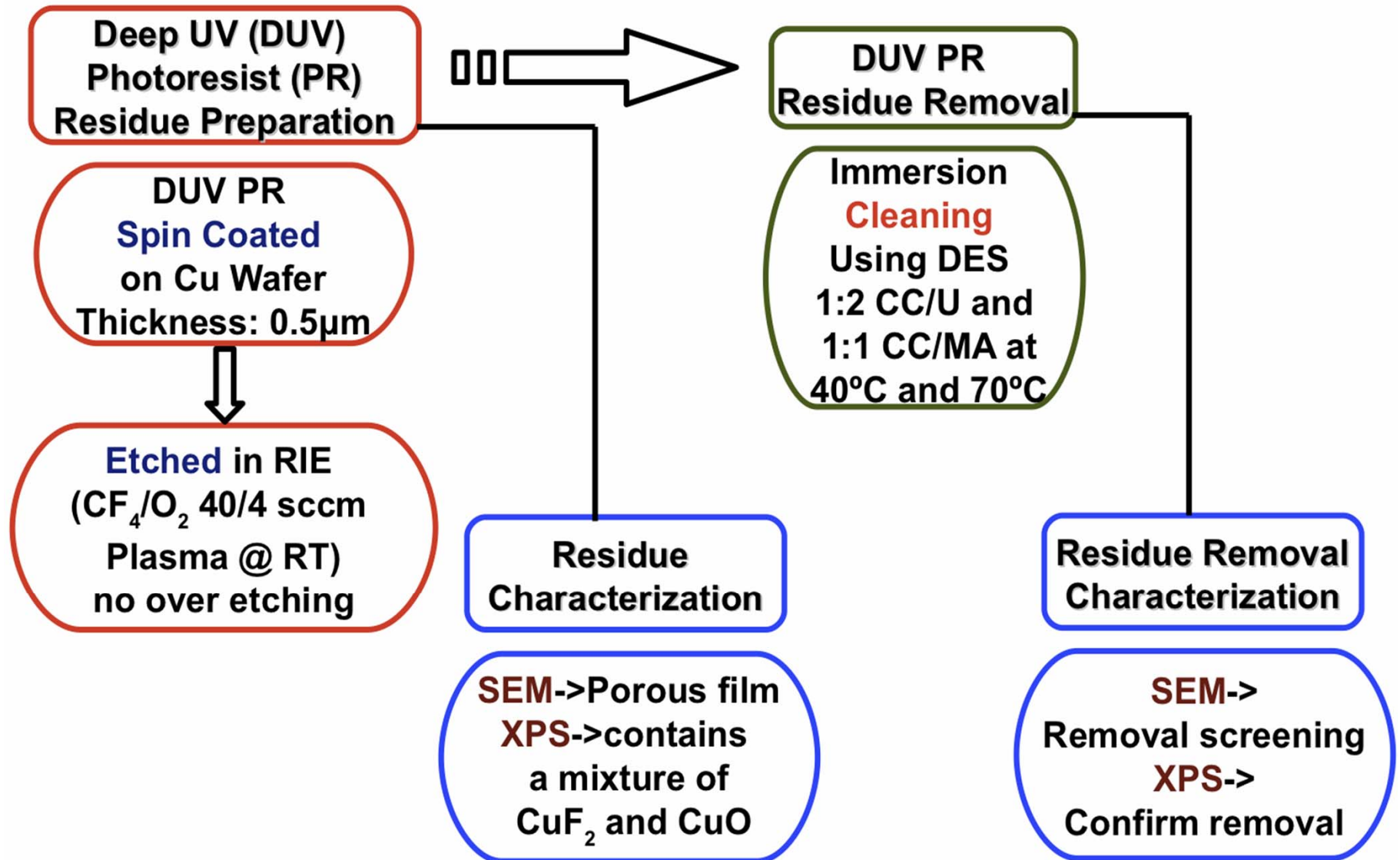


## Conductivity and Viscosity of DES Systems at Different Temperatures

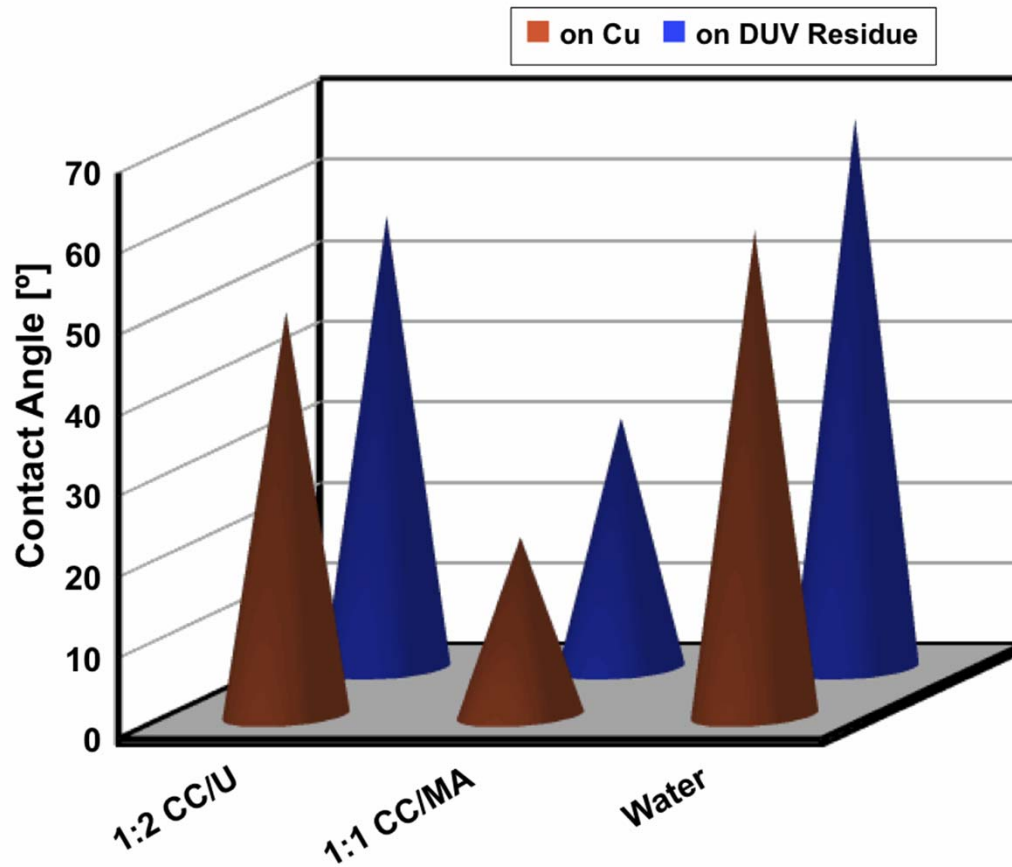


- Good conductivity at 25°C ( $\sim 1 \text{ mS cm}^{-1}$  for CC/U,  $\sim 0.4 \text{ mS cm}^{-1}$  for CC/MA) [Comparison: Conductivity of 250:1 dilute HF is  $\sim 5.2 \text{ mS cm}^{-1}$ ]
- Conductivity increases with temperature ( $6 \text{ mS cm}^{-1}$  for CC/U,  $2 \text{ mS cm}^{-1}$  for CC/MA @ 70°C)
- Viscosity high ( $> 1000 \text{ cP}$  at RT) but reduces to  $< 100 \text{ cP}$  at 70°C [ Comparison: Viscosity of 98 %  $\text{H}_2\text{SO}_4$  is  $\sim 30 \text{ cP}$  at RT]

# Experimental Approach



## Contact Angle of DES and Water on Copper and Residue Film

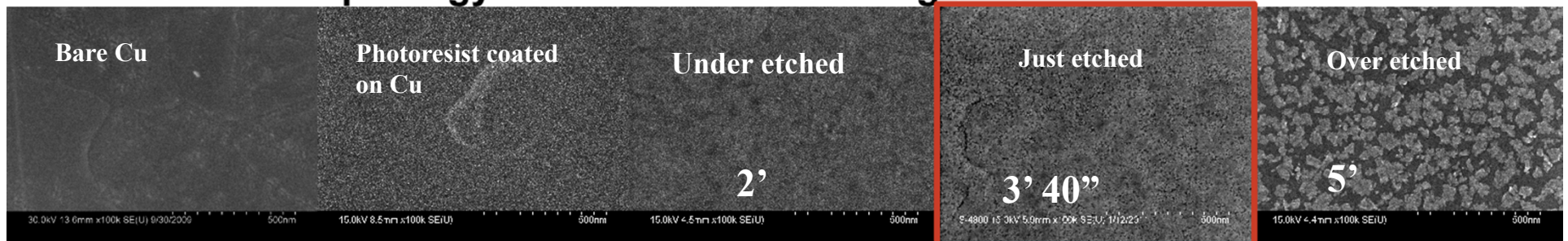


- Residue film is hydrophobic
- CC/U contact angle on copper and residue film comparable to water
- CC/MA showed better wetting than CC/U

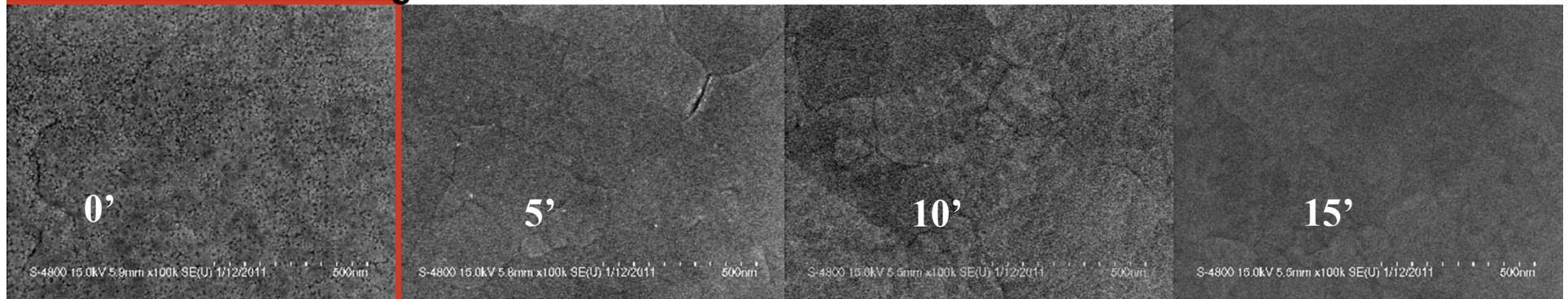


# SEM Characterization of Residue Removal

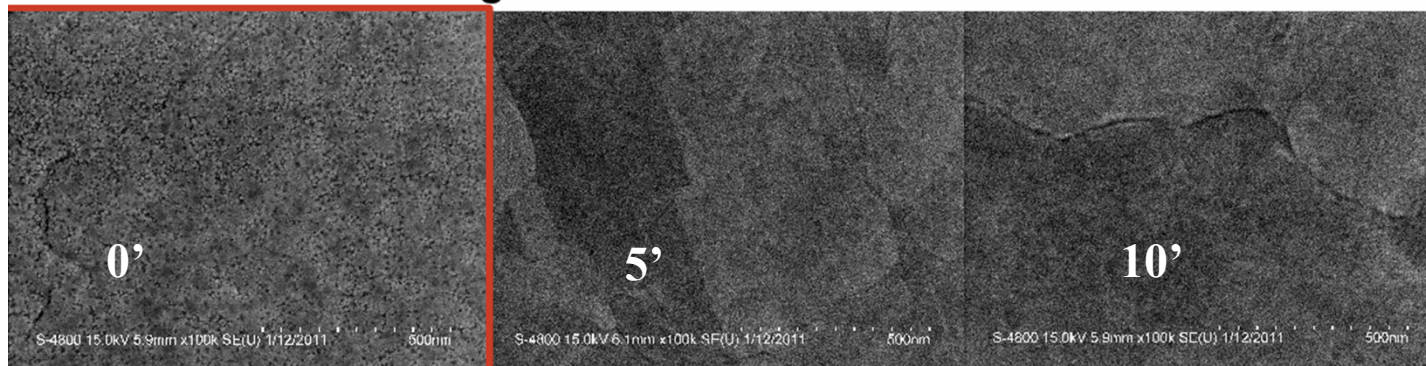
## DUV residue morphology as a function of etching time



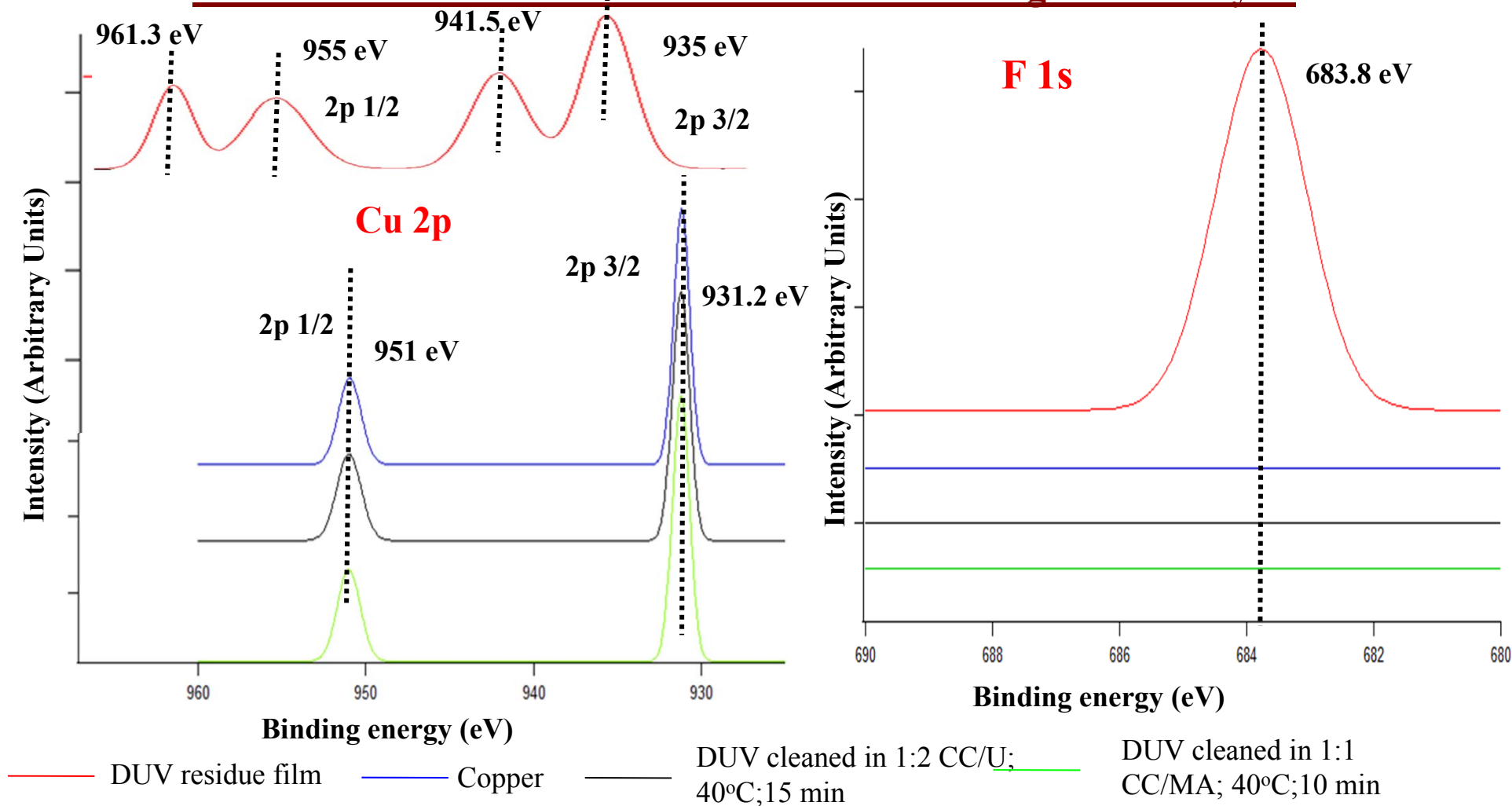
## Residue Removal using 1:2 CC/U as a function of time: Removal observed within 15'



## Residue Removal using 1:1 CC/MA as a function of time: Removal observed within 10'



## Confirmation of Residue Removal in DES using XPS Analysis



- Residue shows the presence of  $\text{Cu}^{+2}$  compounds

Cu 2p Spectrum: Cleaned samples show absence of  $\text{Cu}^{+2}$  compounds

F 1s Spectrum: Absence of fluorine peak in sample cleaned in DES –complete residue removal

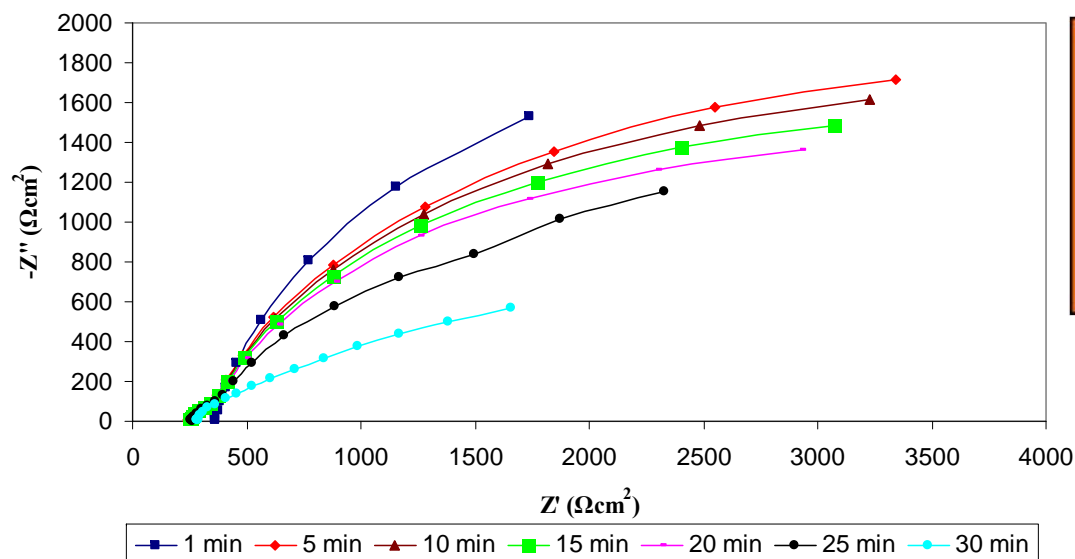
O 1s and C 1s spectrum are not shown. O 1s showed presence of native oxides and C 1s looked similar for all samples

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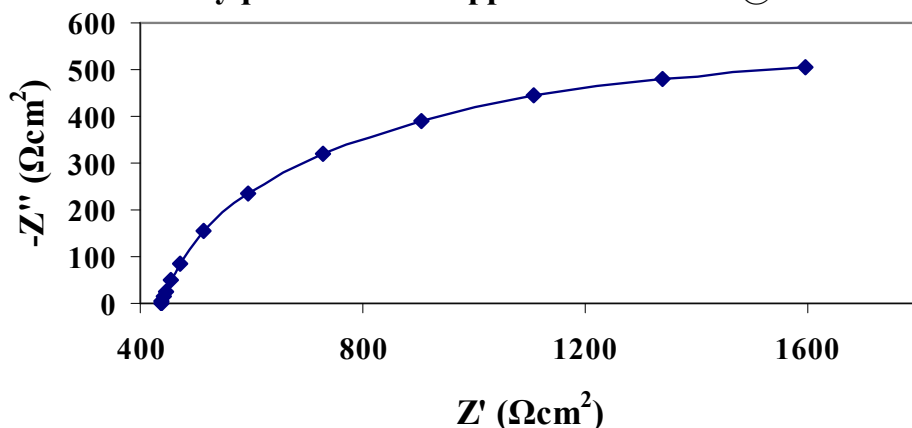
# Electrochemical Impedance Spectroscopy (EIS) Measurements

- Samples: Resist coated copper (overetched) and uncoated copper
- Electrolyte: 1:2 CC/U at 40°C

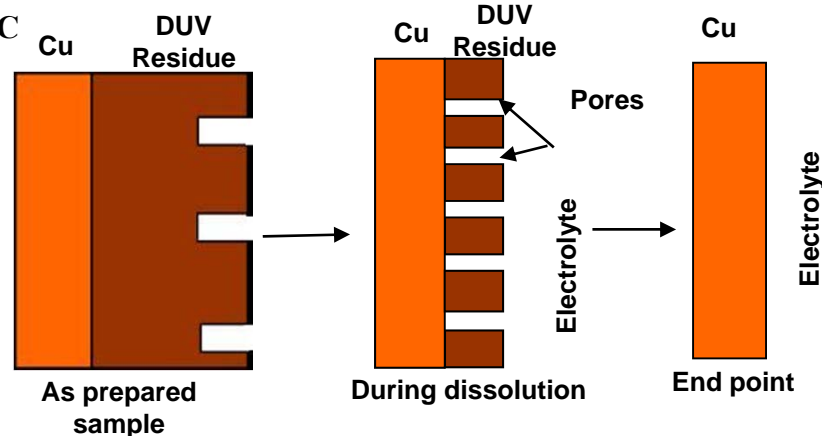
Nyquist Plot of Copper Coated with Residue Film in 1:2 CC/U @ 40°C



Nyquist Plot of Copper in 1:2 CC/U @40°C

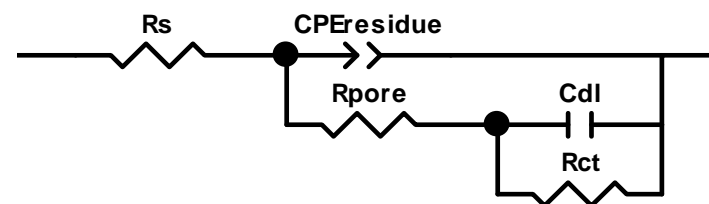


## Porous Film Model

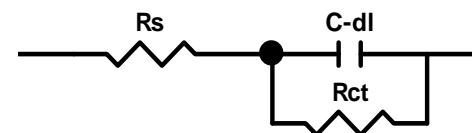


## Equivalent Circuits

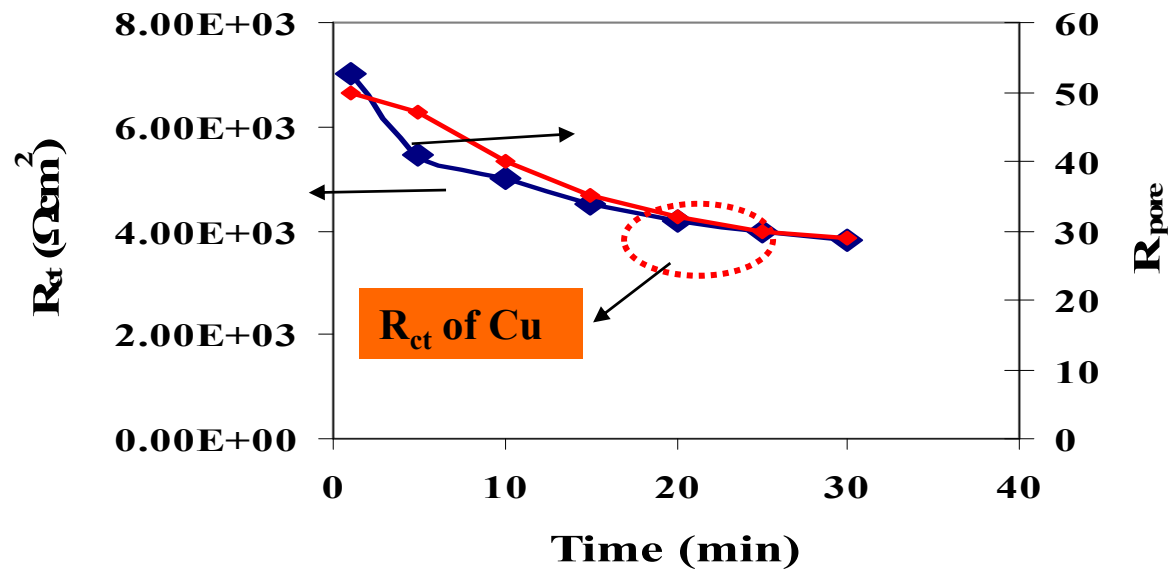
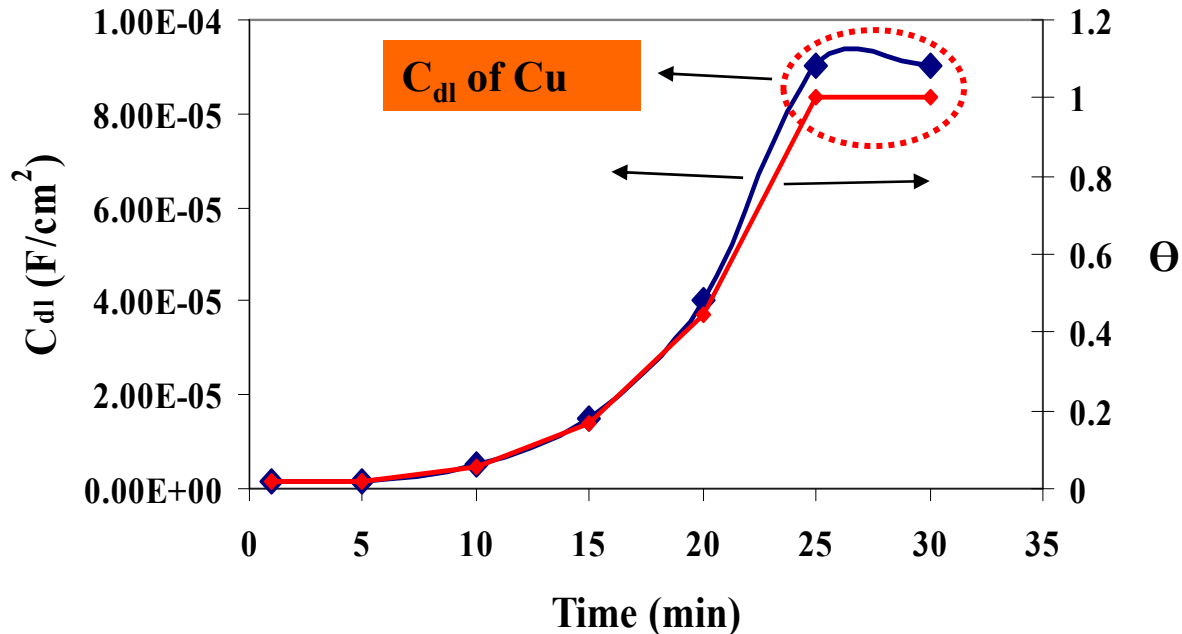
### For Porous Residue Film on Copper



### For Uncoated Copper



# Porous Film Model



## During dissolution

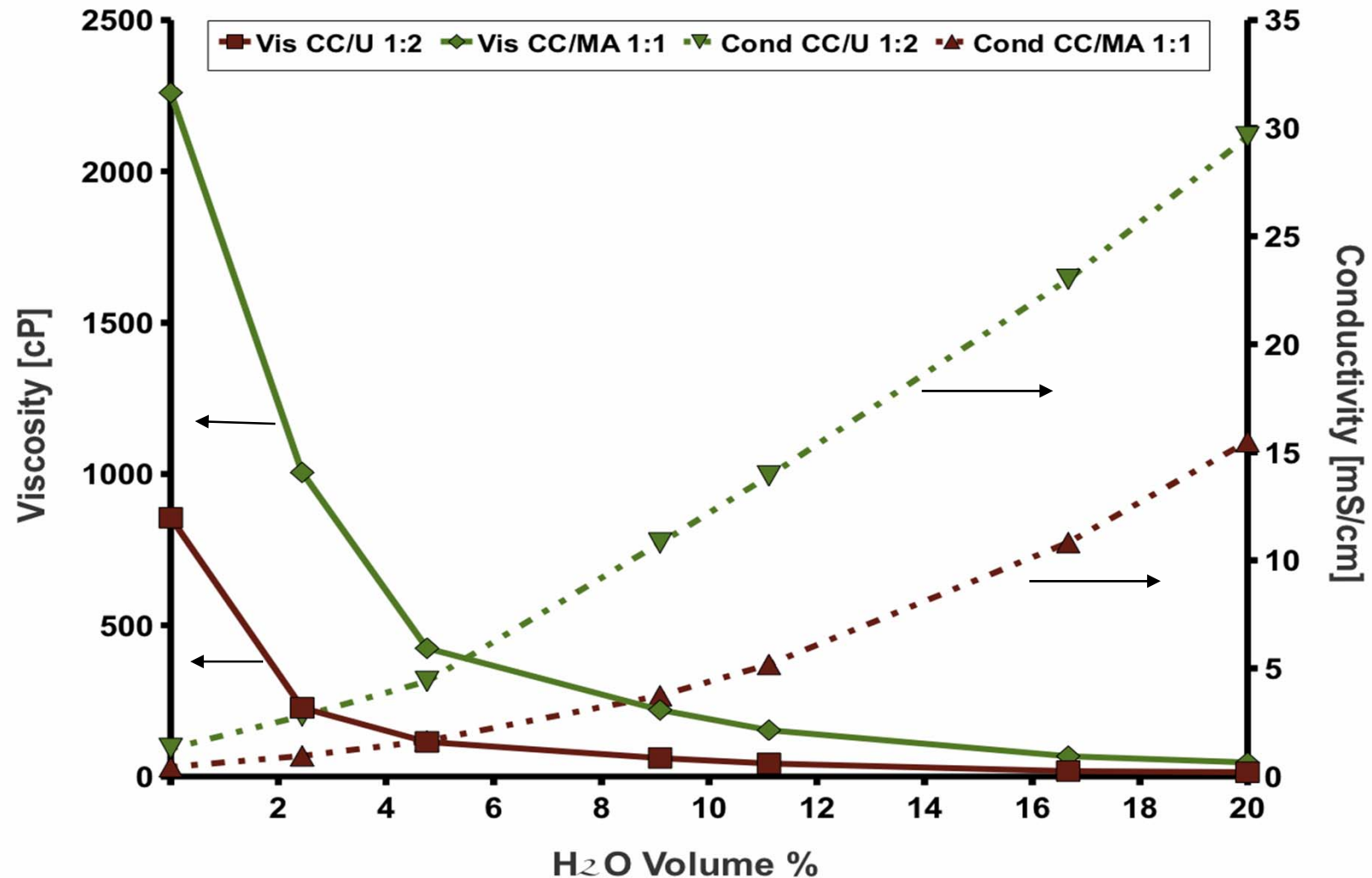
- $C_{dl}$  ↑ and  $R_{ct}$  ↓ due to increased Cu surface area
- $R_{pore}$  ↓ due to loss of residue

## At end point,

- $C_{dl}$  of residue film and  $R_{ct}$  values identical to that of bare Cu
- Area fraction of copper exposed reaches one where  $\Theta = C_{dl}(\text{residue}) / C_{dl}(\text{Cu})$
- EIS studies show complete removal in 30 min
- This agrees well with SEM and XPS characterization for overetched residue removal



## Viscosity Reduction By Addition of water @ 25°C



- Viscosity reduces considerably (855 to 14 cP for CC/U and 2260 to 46 cP for CC/MA) with addition of 20 vol% water



## Summary

Tasks Proposed Last Year	Accomplished Tasks	Work In Progress
<i>Refine CC/U DES</i>	2:1 DES @ 40 and 70°C effectively removed residue film on copper	<ul style="list-style-type: none"> <li>• Removal of under etched residue film on copper</li> <li>• Electrochemical impedance spectroscopy study of residue removal</li> </ul>
<i>Explore CC/MA DES</i>	<ul style="list-style-type: none"> <li>• 1:1 DES @ 40 and 70°C removed residue faster than CC/U</li> <li>• Better wetting characteristic than CC/U</li> </ul>	<ul style="list-style-type: none"> <li>• Removal of under etched residue film on copper</li> <li>• Electrochemical impedance spectroscopy study of residue removal</li> </ul>
<i>Viscosity reduction of DES</i>	Viscosity reduction achieved by addition of polar solvents like water	<ul style="list-style-type: none"> <li>• Investigation of residue removal using DES and water mixtures</li> <li>• Effect of IPA on viscosity reduction of DES</li> </ul>
<i>Spin cleaning</i>	-	<ul style="list-style-type: none"> <li>• Study of reduction of cleaning time</li> </ul>

# **Industrial Interactions and Technology Transfer**

- Teleconference with Dr. Kanwal Singh and Bob Turkot, Intel, to discuss results and seek advice on future direction
  - Investigation on the use of DES for crust and photoresist removal from Intel patterned structures
  - Teleconferences held on 9/28/2010, 11/4/2010 and 12/17/2010
- Collaboration with IMEC in testing the DES formulations for residue removal on low-k structures
- Invention disclosure filed on September 28, 2010 at University of Arizona

## **Acknowledgements**

- Dr. Kanwal Singh, Intel, SRC/GRC Industry Liaison
- Bob Turkot, Intel
- Dr. Manish Keswani, Assistant Research Professor, Materials Science and Engineering, University of Arizona

# **Future Plans**

## **Next Year Plans**

- **Removal study of post etch residues formed from CF<sub>4</sub>/Ar plasma gases on copper and low-k**
- **Work with Intel and IMEC to evaluate DES for residue removal on PR/low-k structures**
- **Effect of water rinsing of DES on copper corrosion**

## **Long-term Plans**

- **Develop a single step process of photoresist stripping and residue removal using DES**

# **Publications, Presentations, and Recognitions/Awards**

## **Publication**

- D. P. R. Thanu and S. Raghavan, “Benign Deep Eutectic Solvents (DES) for Replacement of Organic Solvents Based Cleaning Formulations in Back End of Line Cleaning”, TECHCON Proceedings, p.1-4, Sep 15, Austin, TX (2010)

## **Presentations**

- D. P. R. Thanu and S. Raghavan, “Benign Deep Eutectic Solvents (DES) for Replacement of Organic Solvents Based Cleaning Formulations in Back End of Line Cleaning”, TECHCON Oral Presentation and Poster, Sep 15, Austin, TX (2010)
- S.Raghavan and D. P. R. Thanu, “ Improvement of ESH Impacts of BEOL Formulations Using Ionic Liquids to Replace Traditional Solvents”, IMEC, Sep 2010, Leuven, Belgium
- D. P. R. Thanu and S. Raghavan, “Liquid Mixtures of Urea and Choline Chloride for Use in BEOL Cleaning”, SRC Teleseminar, Jan 27, 2011, Tucson, Arizona

# Integrated Electrochemical Treatment of CMP Waste Streams for Water Reclaim and Conservation (Customized Project ended April 2010)

## PIs:

- James Farrell, Chemical and Environmental Engineering, UA
- James C. Baygents, Chemical and Environmental Engineering, UA

## Graduate Students:

- Francis Dakubo, PhD candidate, Chemical and Environmental Engineering, UA
- Jake Davis, PhD candidate, Chemical and Environmental Engineering, UA
- David Hubler, PhD candidate, Chemical and Environmental Engineering, UA
- Mark Brown, MS candidate, Chemical and Environmental Engineering, UA
- Pui Foon Lai, MS candidate, Chemical and Environmental Engineering, UA

## Undergraduate Students:

- Ritika Mohan, Kyle Kryger, Chemical Engineering, UA

## Cost Share (other than core ERC funding):

- GEP Smith Fellowship (D. Hubler), Triffet Prize (D. Hubler), Mining Engineering Fellowship (F. Dakubo), NASA Space Grant Fellowship (K. Kryger, J. Davis), Water Sustainability Program Fellowship (R. Mohan), Water Resources Research Center (\$17K), SFAz Fellowship (\$46K)

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# Objectives

- **Develop an electrochemical method for removing  $\text{Cu}^{2+}$ ,  $\text{H}_2\text{O}_2$ , colloidal abrasives, chelating agents and corrosion inhibitors from wastewater generated during CMP.**
  - **Currently, this water is discharged to sewer untreated**
- **Compare contaminant removal with industry benchmarks for use of reclaimed water.**
- **Build a prototype reactor and pilot test on real CMP wastewater.**

# ESH Metrics and Impact

1. *Reduction in emission of ESH-problematic material to the environment*

- Eliminate the disposal problems associated with membrane concentrates.
- Eliminate the disposal of Cu-laden nanoparticles into hazardous waste landfills.

2. *Reduction in the use of natural resources (water and energy)*

- Reclaim CMP wastewater for use in mechanical systems.
- CMP wastewater accounts for up to 30% of fab water use.

3. *Reduction in the use of chemicals*

- Eliminate the need for pH adjusting chemicals and reducing agents that add to TDS load.
- Eliminate the need for activated carbon regeneration.

# Commercially-Available Technology

Siemens Copper Select™ process

- Ceramic membrane used to separate copper from wastewater
- Silica nanoparticles remain in wastewater
- Copper is concentrated on chelating ion exchange resin
- Resin regeneration performed offsite



*From [www.water.siemens.com](http://www.water.siemens.com)*

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# Major Findings

CuCMP wastewater treatment:

- Pyrolox ( $\text{MnO}_2$ ) is an effective catalyst for hydrogen peroxide destruction
- Better than GAC (is not fouled by chelators)
- Copper can be removed via ion exchange and ion exchange media can be regenerated, on-site, with moderate acids and small footprint
- No chemical addition needed

A remaining issue:

- Nanoparticles – must be removed or diverted from IX material (filtration costs up to \$3.50/1000 gallons [Pall Corporation estimate based on existing installations])
- High nanofiltration cost makes treating CMP wastewater

# Novel Ion Exchange Materials

New ion exchange materials can improve the process in several ways:

- Material structure eliminates need to remove nanoparticles
- Regeneration can be performed at pH values where nanoparticles do not dissolve
- Better mass transfer characteristics – regeneration can be faster



# New Approach

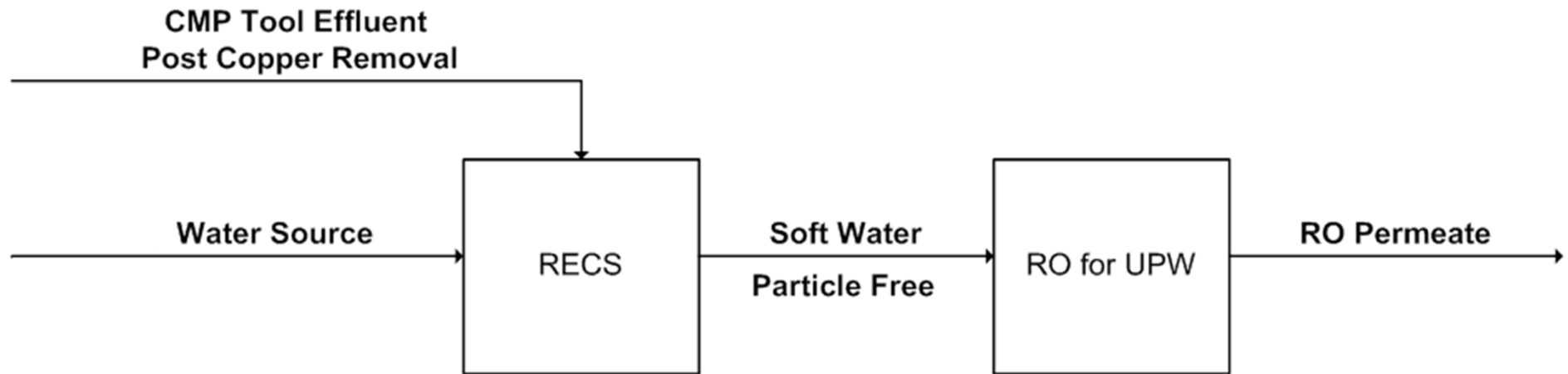
A new approach allows

- **low cost** removal of nanoparticles via **Rapid Electrochemical Crystallization Softening (RECS)**
- **on-site** ion exchange regeneration with copper recovery
- **elimination** of ion exchange softening prior to reverse osmosis

Economic advantages:

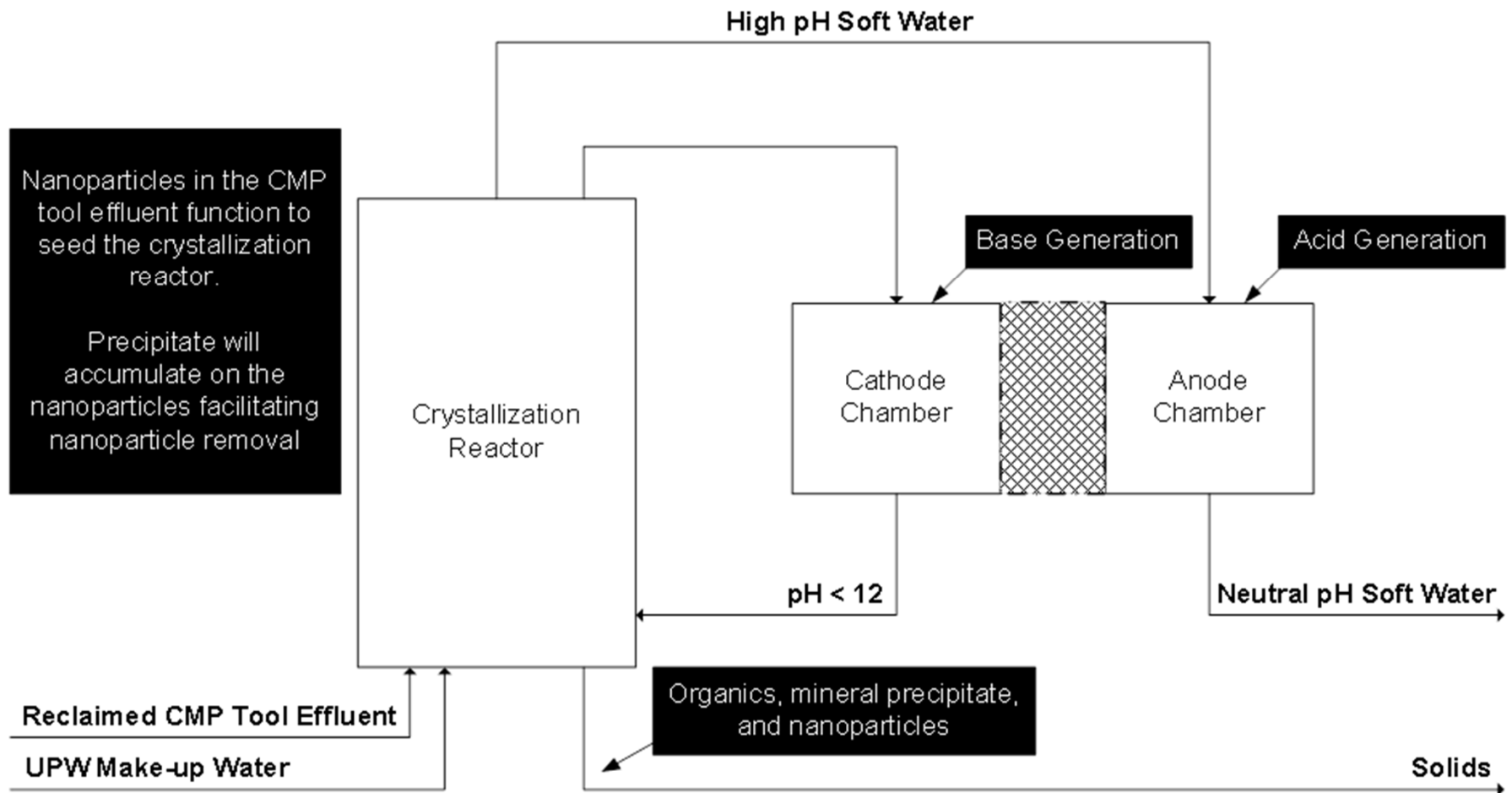
- **Reduces** sewer and fresh water costs
- **Reclaim** copper – \$8.40 in power recovers \$240 in copper
- **Reduce** acid/base purchase, storage, and distribution costs – electrochemical pH manipulation

# Rapid Electrochemical Crystallization Softening



- Nanoparticle removal – not discharged to the environment/sewer
- Reclamation of CMP tool wastewater
- No ion exchange brines are produced
- Other contaminants (i.e. metals, organics, silica) are removed
- Simple design – low maintenance
- Salt-free – no chemical addition that increases TDS

# Rapid Electrochemical Crystallization Softening



Crystallization reactor can be operated in slurry or fluidized bed configurations



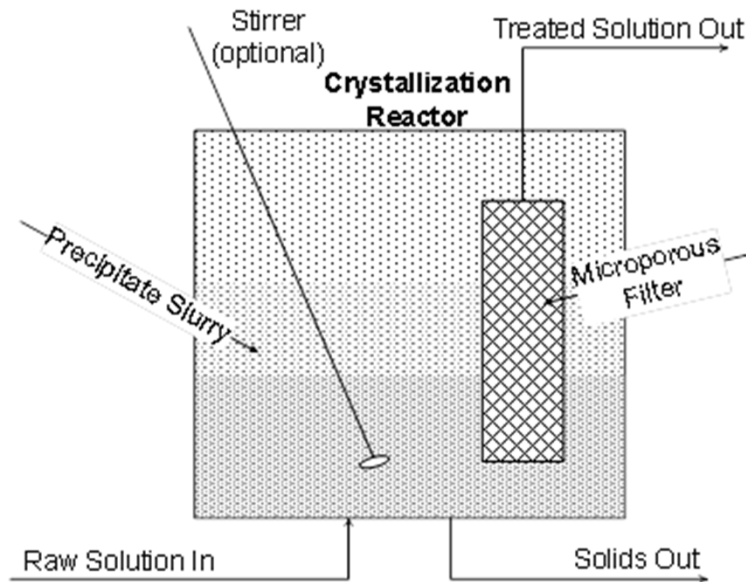
# Crystallization Softening in Amsterdam

68 mgd of potable water is softened from 250 to 150 ppm as  $\text{CaCO}_3$   
by Fluidized Bed Crystallization Softening



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# Crystallization Softening Output Characteristics



## Compact Accelerated Precipitation Softening (CAPS) Operation

A backwash was performed every 15 min for 2-4 s

The production rate was maintained at ~40 L/h  
(equivalent of 2000 L/m<sup>2</sup>-h)

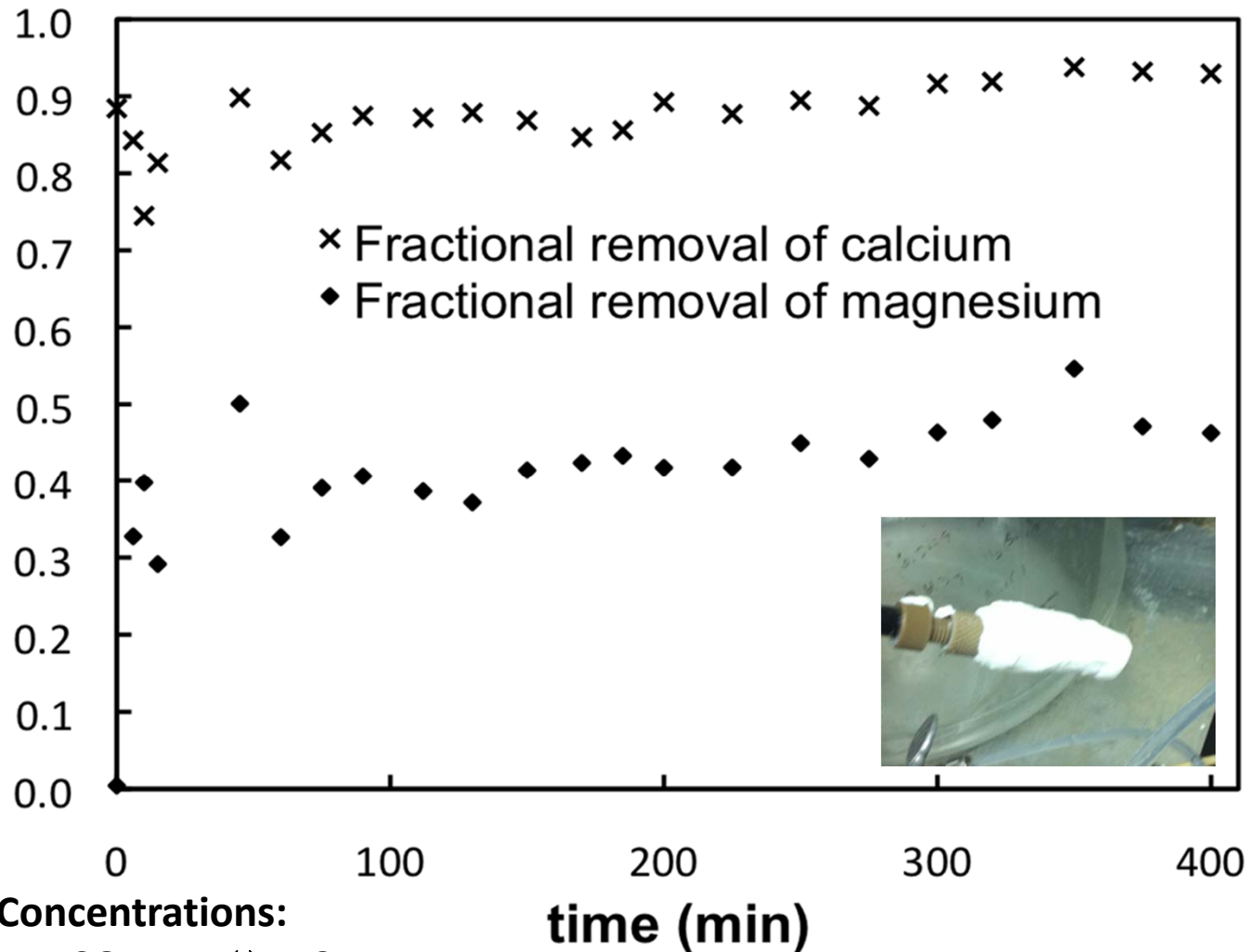
Caustic soda added to maintain the exit pH at ~9.0.

**Table 1. Typical Composition of Brackish Groundwater at Mashabe Sadeh in the Negev Region of Israel before and after CAPS Pretreatment**

species	concentration, mg/L	
	raw	CAPS
Ca <sup>2+</sup>	188–274	10–15
Mg <sup>2+</sup>	72–109	91
Fe <sup>3+</sup>	0.01–0.15	<0.01
Na <sup>+</sup>	610–710	630–755
K <sup>+</sup>	17.5–22	21
NH <sub>4</sub> <sup>+</sup>	0.3	
CO <sub>3</sub> <sup>2-</sup>	0.3–11	30
HCO <sub>3</sub> <sup>-</sup>	218–324	75
SO <sub>4</sub> <sup>2-</sup>	420–520	480–520
Cl <sup>-</sup>	1030–1140	1062
SiO <sub>2</sub>	8.7–17.5	9
TOC	2–10	<2
General Properties		
pH	7.8–8.0	9–9.5
temp, °C	25	25
TDS, mg/L	2712	
conductivity, mS/cm	4.71	4.01
LSI	0.79	
% saturation (CaSO <sub>4</sub> )	11	



# RECS Experiments



Initial Concentrations:

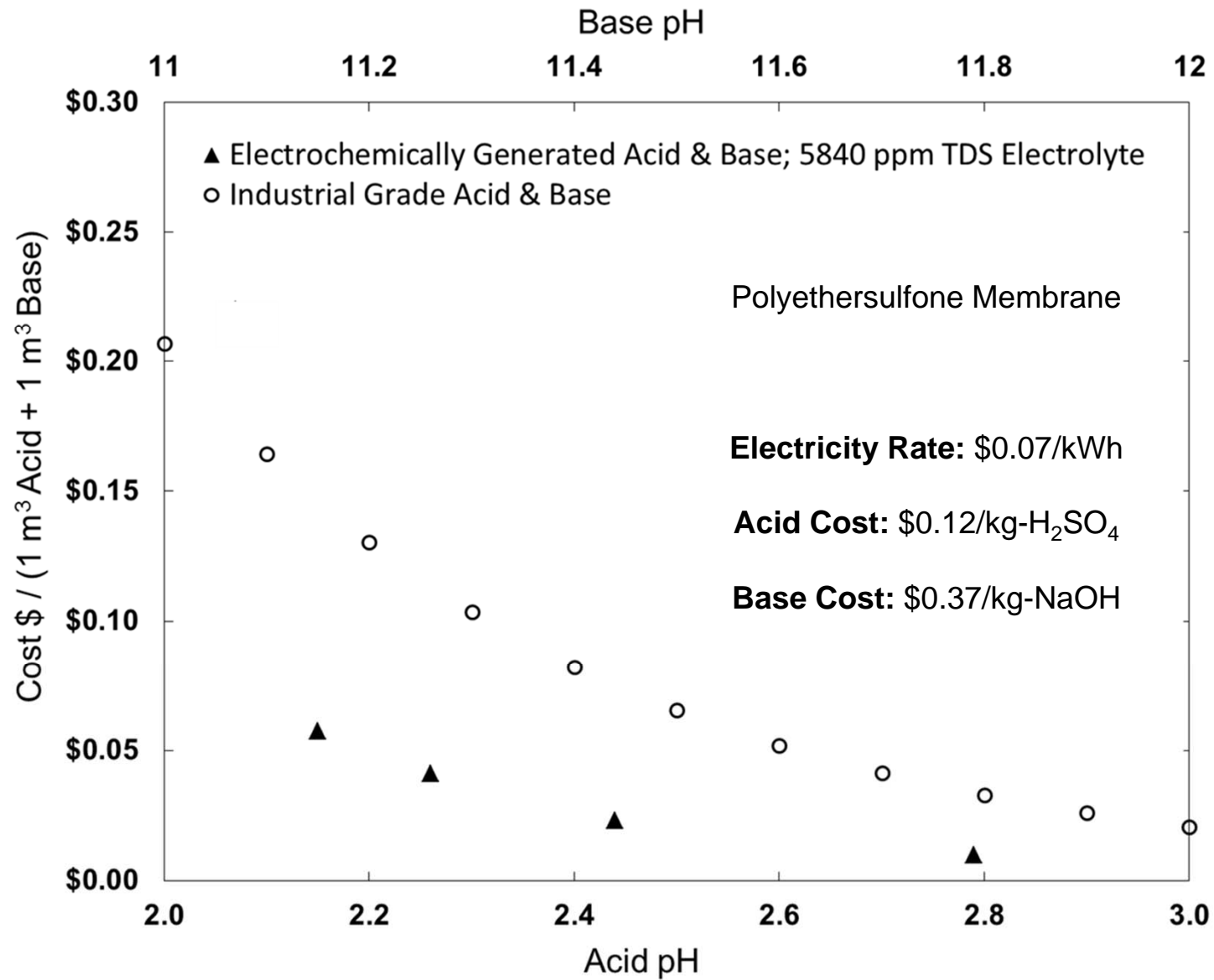
$[\text{Ca}]_0 = 51.06 \text{ ppm} \Leftrightarrow 1.27 \text{ mM}$

$[\text{Mg}]_0 = 0.71 \text{ ppm} \Leftrightarrow 0.03 \text{ mM}$

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# RECS Experiments



# **Industrial Interactions and** **Technology Transfer**

- **Don Hooper, Intel Corporation**
- **Dan Hodges, Intel Corporation**
- **Allen Boyce, Intel Corporation**
- **Avi Fuerst, Intel Corporation**
  
- **Sharon Megdal, Water Resources Research Center, UA**
- **Christine Mackay, Economic Development Director, Chandler, AZ**

# Future Plans

## Next Year Plans

- Funding ended 4/1/10

## Long-Term Plans

Seek partners for proposal

# References

1. Masarwa, A.; Meyerstein, D.; Daltrophe, N.; Kedem, O. Compact accelerated precipitation softening (CAPS) as pretreatment for membrane desalination. II Lime softening with concomitant removal of silica and heavy metals. *Desalination* 1997, 113, 73-84.
2. Kweon, J.H.; Lawler, D.F. Evaluating precipitative softening as a pretreatment for ultrafiltration of a natural water. *Environ. Eng. Sci.* 2002, 19 (6), 531-544
3. Van der Veen, C.; Graveland, A. Central Softening by crystallization in a fluidized bed process, *J. AM. Water Works Ass.* 1988, 80 (6), 51-58.
4. Oren et al. Compact accelerated precipitation softening (CAPS) with submerged filtration: Role of the  $\text{CaCO}_3$  “cake” and the slurry. *Ind. Eng. Chem. Res* 2002, 41 (21), 5308-5315.

# **Publications, Presentations, and Recognitions/Awards**

- David Hubler: Triffet Prize and GEP Smith Fellowship
- Francis Dakubo: Department of Mining Engineering Fellowship
- Kyle Kryger: Ella Philipossian Memorial Scholarship & Pillars of Excellence Award
- David Hubler: First Place Award, University of Arizona 2009 Student Showcase, B.P.A. Division, November 6-7, 2009, Tucson, AZ
- “Economic Benefit of Commercial and Industrial Water Uses in a Semi-arid Municipality,” presented at the Arizona Hydrological Society/American Institute of Hydrology 2009 Hydrological Symposium, August 30-September 2, 2009, Scottsdale, AZ
- “Electrochemical Methods for Water Reclaim in Semiconductor Manufacturing,” presented at the International Conference on Microelectronics Pure Water, November 11-12, 2008, Mesa, AZ
- “Electrochemical Water Treatment using Diamond Film Electrodes,” presented at the University of Illinois at Urbana-Champaign, November 7, 2008
- “Evaluating Economic Impacts of Semiconductor Manufacturing in Water-Limited Regions,” submitted to *Journal of the American Water Works Association*