Interactions of Chemical Mechanical Planarization Nanoparticles with Model Cell Membranes: Implications for Nanoparticle Toxicity (425.041)

PI:

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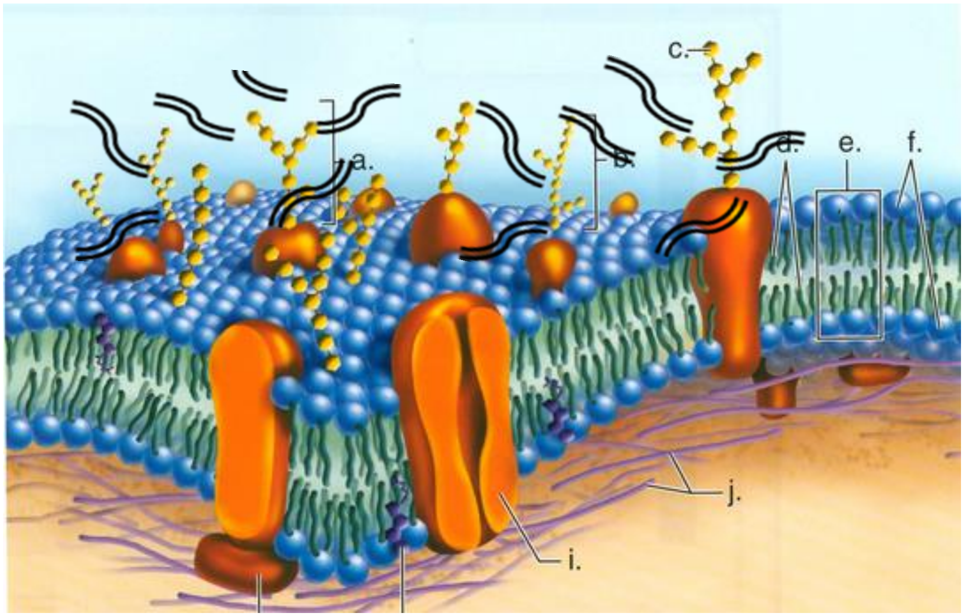
Graduate Students:

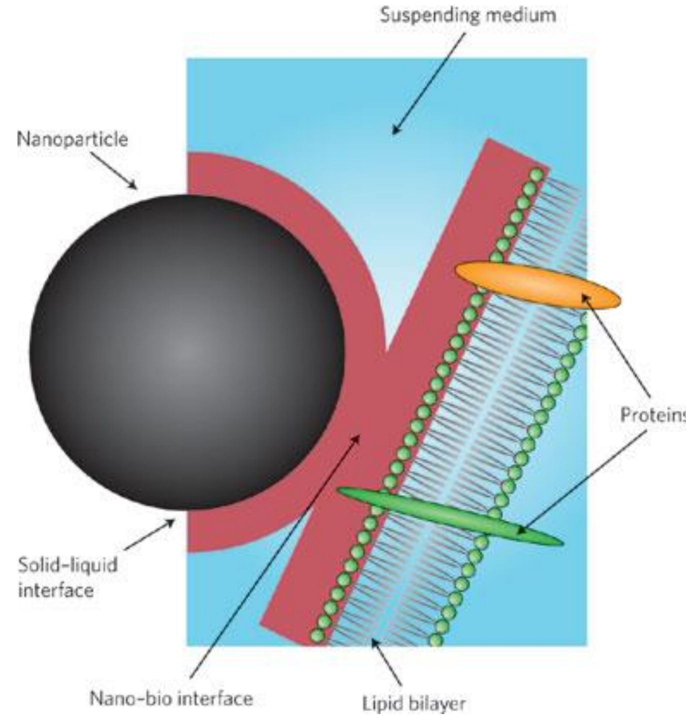
- **Peng Yi, PhD candidate, Geography and Environmental Engineering, Johns Hopkins University**
- **Wenyu Gu, MSE student, Geography and Environmental Engineering, Johns Hopkins University**

Cost Share (other than core ERC funding):

- **$101,472 from Johns Hopkins University in the form of 80% of Peng Yi's tuition for 3 years**

Objectives





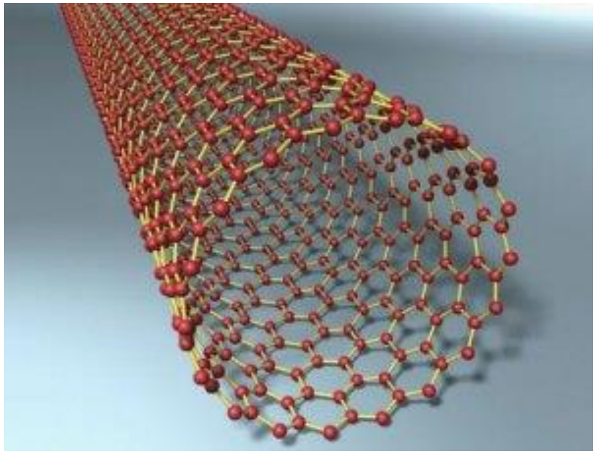
- **To investigate the influence of solution chemistry on the propensity of ceria oxide nanoparticles (CeO_2 NPs) and carbon nanotubes (CNTs) to attach to model biological membranes**
- **To develop a rapid assay to assess the propensity of nanomaterials to absorb on biological membranes**

Sylvia S. Mader, *Biology,* 9th ed., 2007, McGraw-Hill. Nel et al., *Nature Materials* 2009, 8, 543–557.

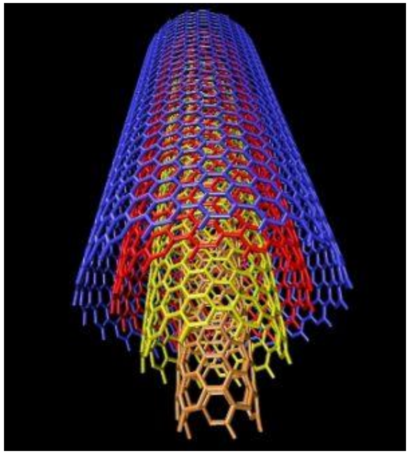
ESH Metrics and Impact

1. **Reduction in the use of toxic CMP particles and CNTs**
   - **CMP particles and CNTs will be tested with binding assay before being employed in semiconductor fabrication plants**
2. **Reduction in emission of toxic CMP particles and CNTs to environment**
   - **Potentially toxic nanomaterials will be replaced with nanomaterials that do not strongly interact with biological membranes**
3. **Safer work environment in fabrication plants as the exposure of workers to toxic nanomaterials is reduced**

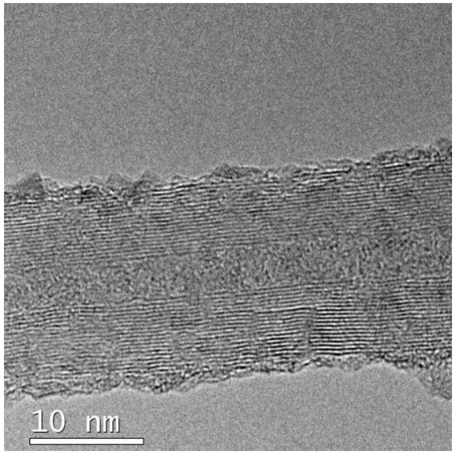
Carbon Nanotubes (CNTs)



mrbarlow.wordpress.com



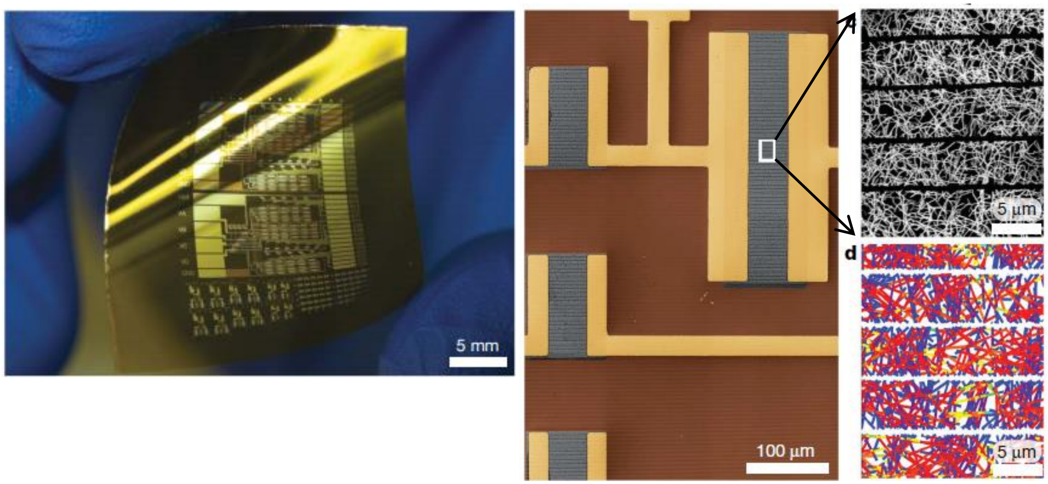
www.basesciences.com



Single-walled carbon nanotubes (SWNTs)

Multiwalled carbon nanotubes (MWNTs)

Applications of Carbon Nanotubes



Cao et al., *Nature*, 2008, 495-500

- **Electronic properties: semiconducting or metallic**

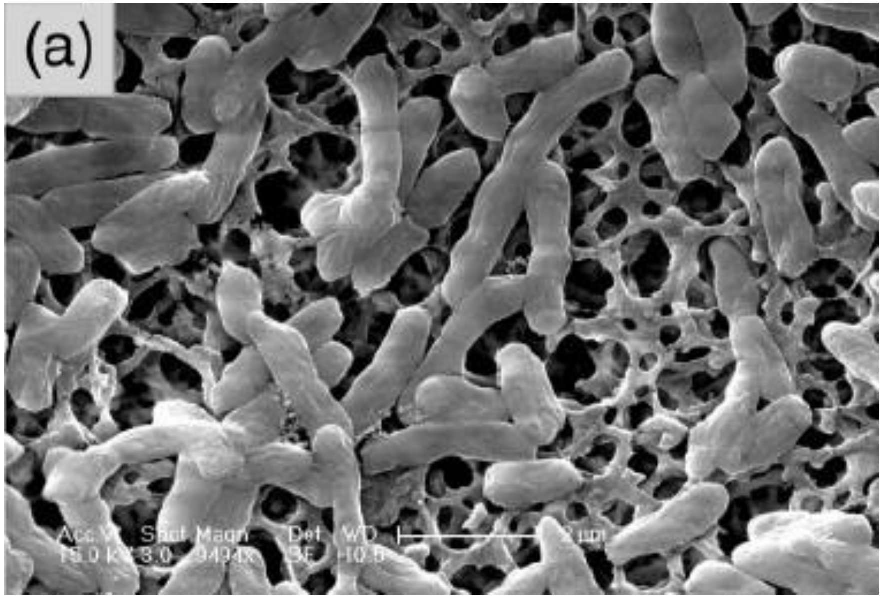
www.bayerus.com

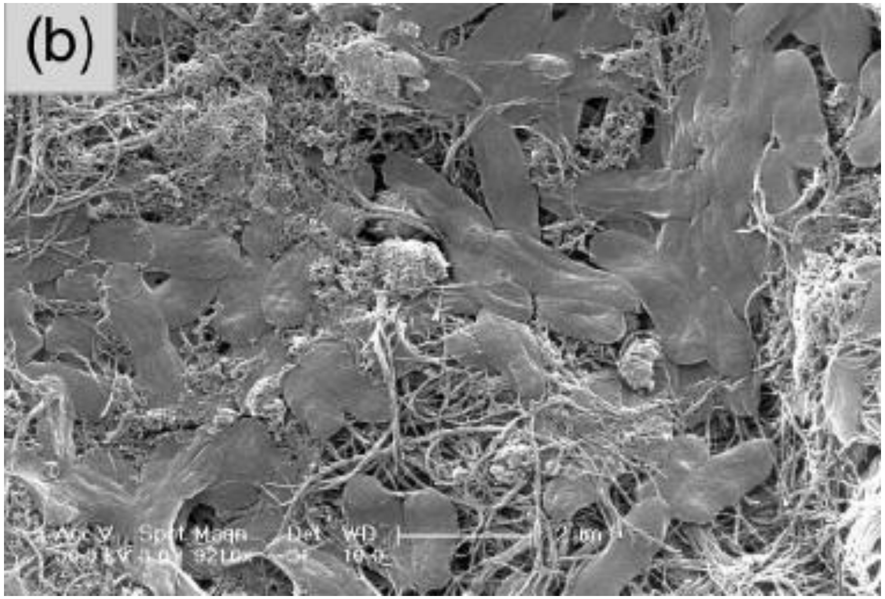
phys.org

- **Mechanical properties: high strength; light weight**

Toxicity of Carbon Nanotubes

- **Damage bacterial membrane and inhibit bacterial growth**

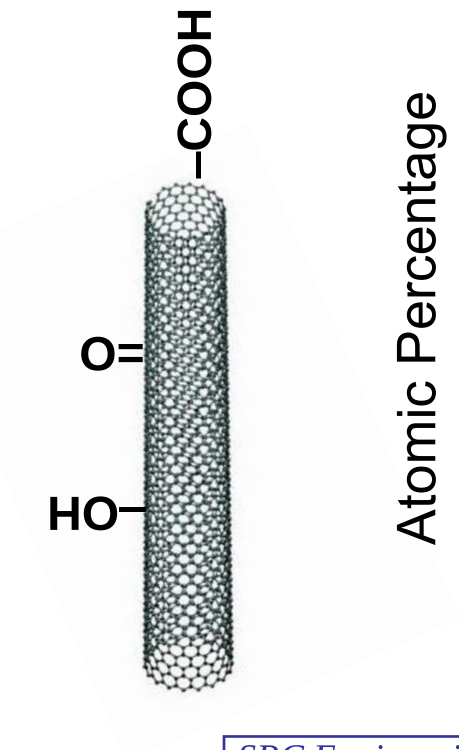


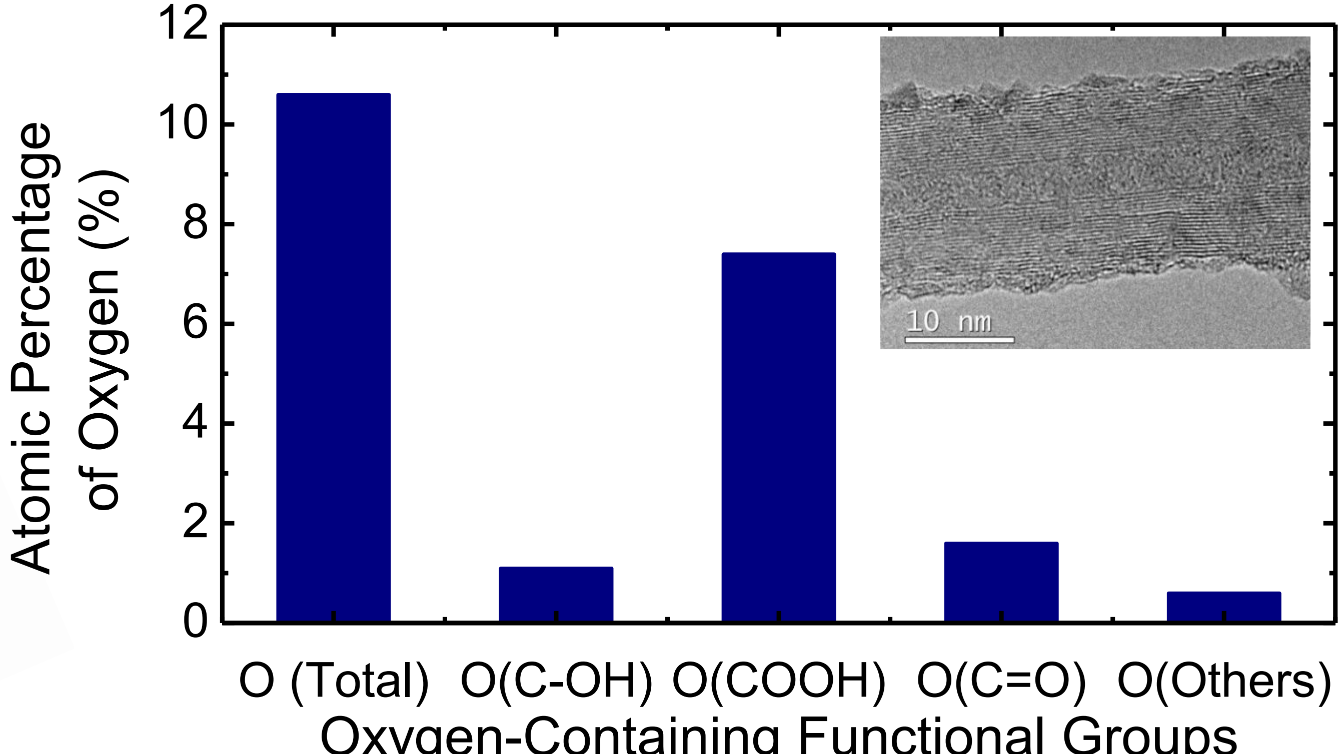


Kang et al., *Langmuir* 2007, 23, 8670-8673

Characterization of MWNTs

- Expose pristine multiwalled CNTs (MWNTs) to a 3:1 acid mixture of 98% H_2SO_4 and 69% HNO_3
- The distribution of oxygen-containing functional groups was quantified by X-ray photoelectron spectroscopy (XPS) in conjunction with vapor phase chemical derivatization

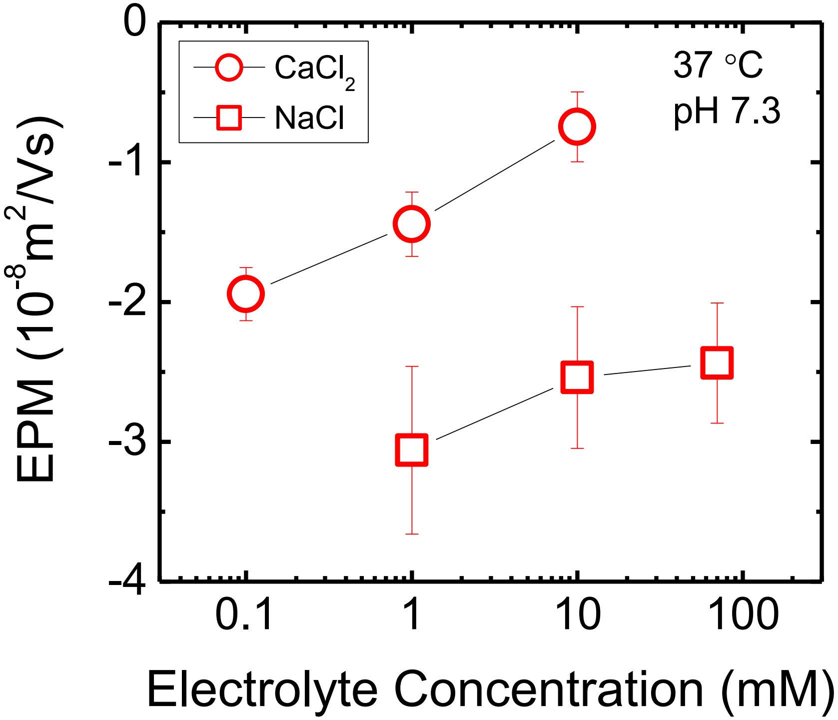




Yi and Chen, *Langmuir* 2011, 27, 3588–3599.

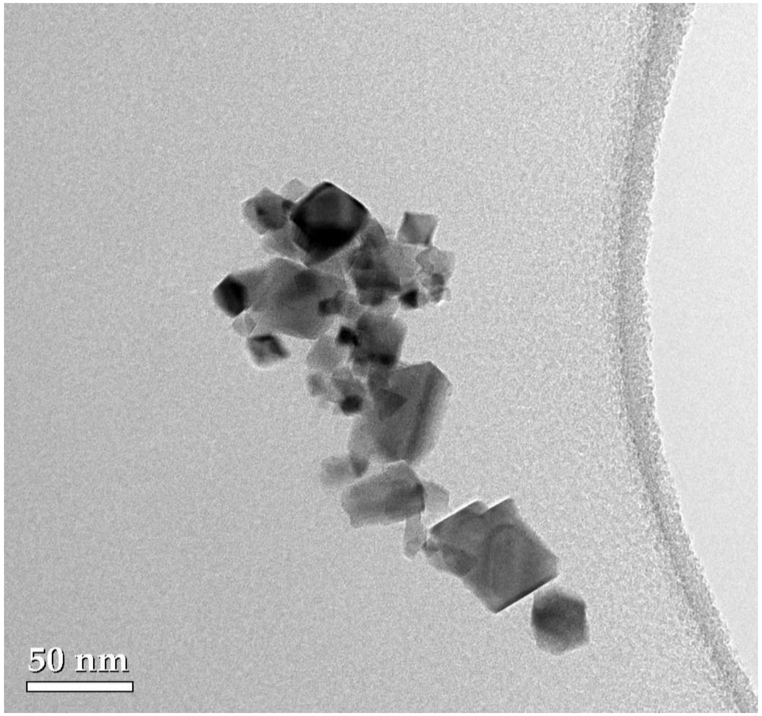
Electrokinetic Properties of MWNTs in NaCl and $CaCl_2$ Solutions

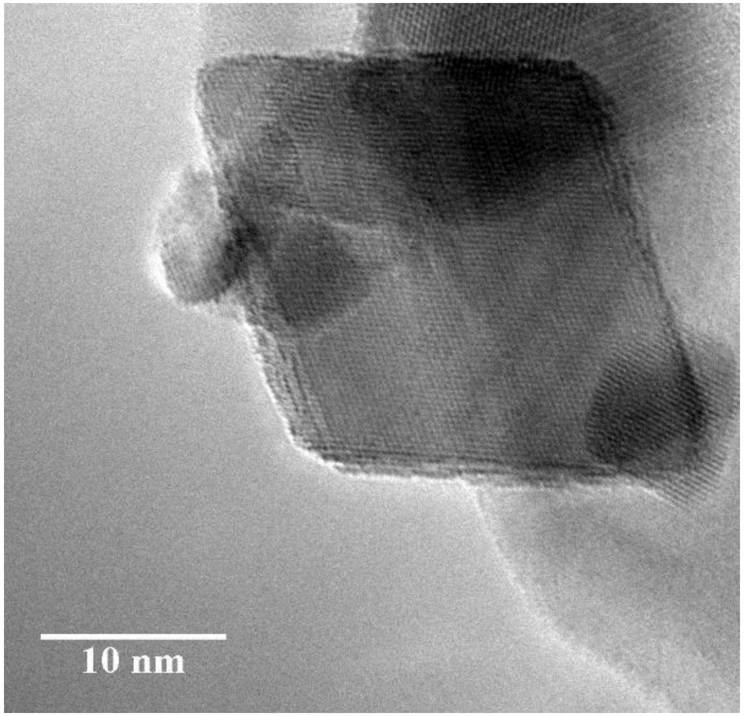
MWNT Stock Suspension



- **Electrophoretic mobility (EPM)**
- **Brookhaven ZetaPALS**
- **At pH 7.3, most carboxyl groups are expected to be deprotonated**

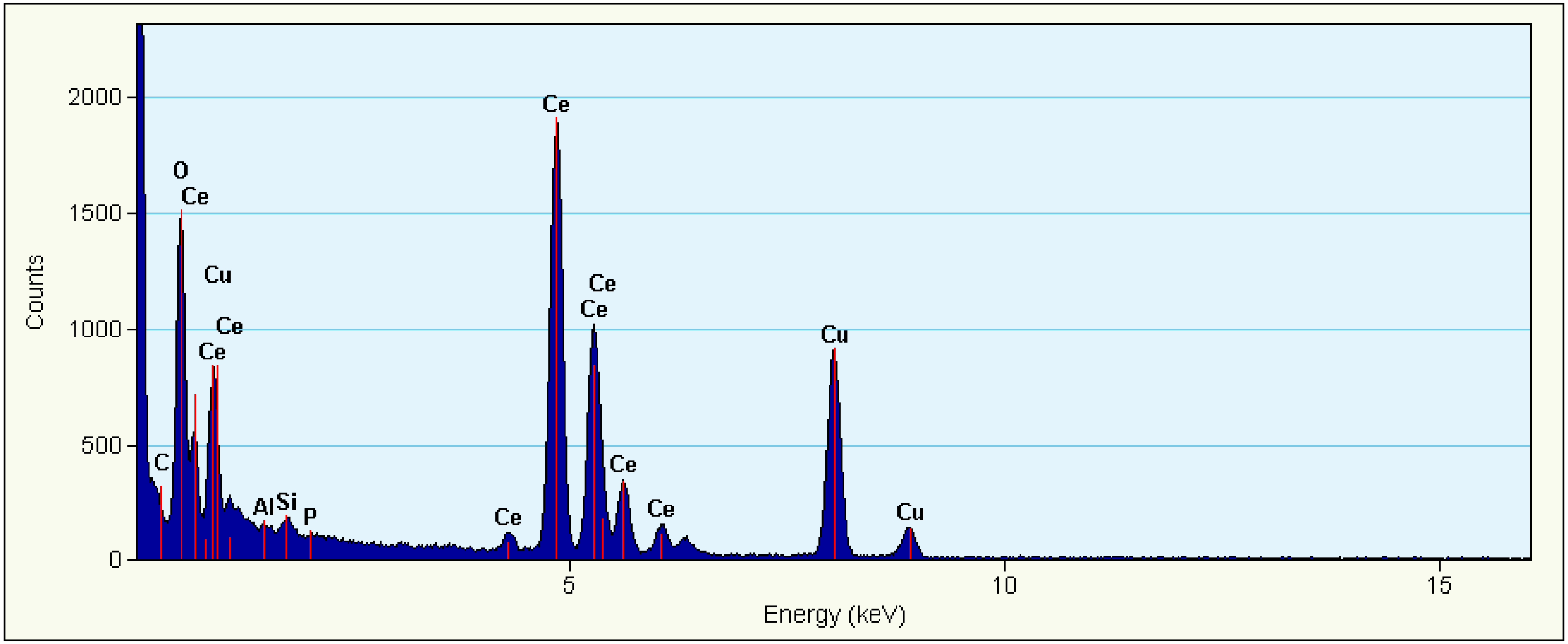
Characterization of CeO_2 NPs





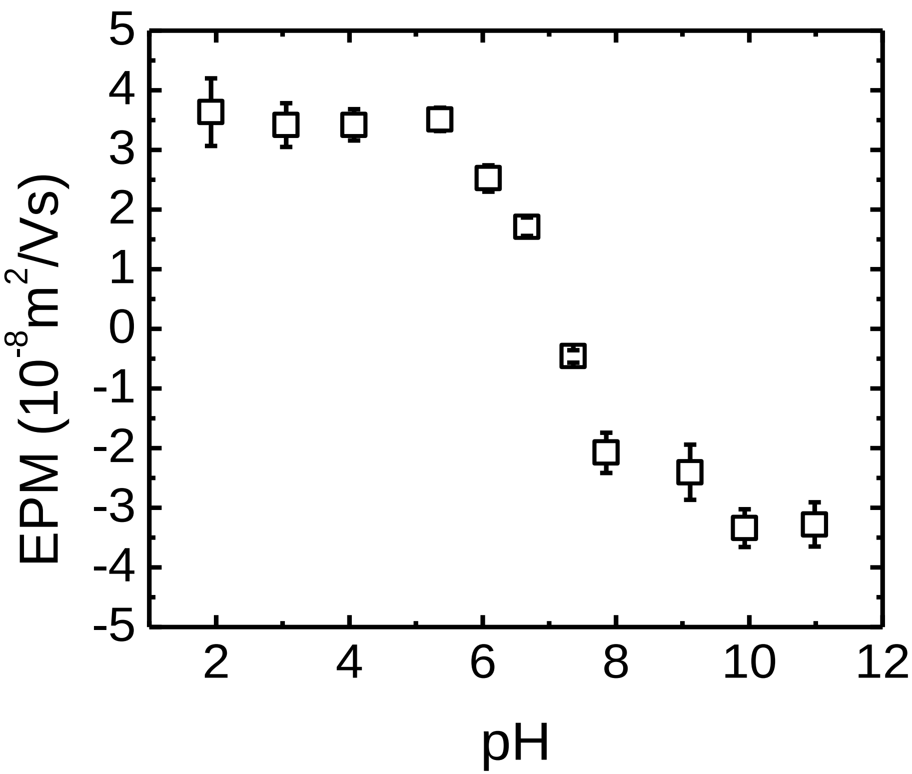
- **CeO_2 NPs were received from Professor Reyes Sierra's group at the University of Arizona**
- **NPs were examined under TEM**
- **NPs are mostly octahedral**

Elemental Composition of CeO_2 NPs



- The elemental composition of the NPs were determined through energy dispersive X-ray spectroscopy (EDS)
- The NPs are largely composed of ceria and oxygen
- Trace amount of aluminum, silicon, and phosphate is present

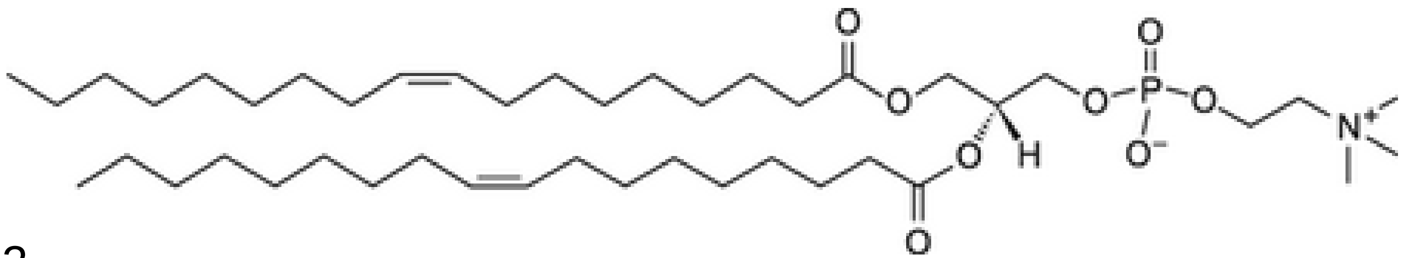
Electrokinetic Properties of CeO_2 NPs as a Function of Solution pH

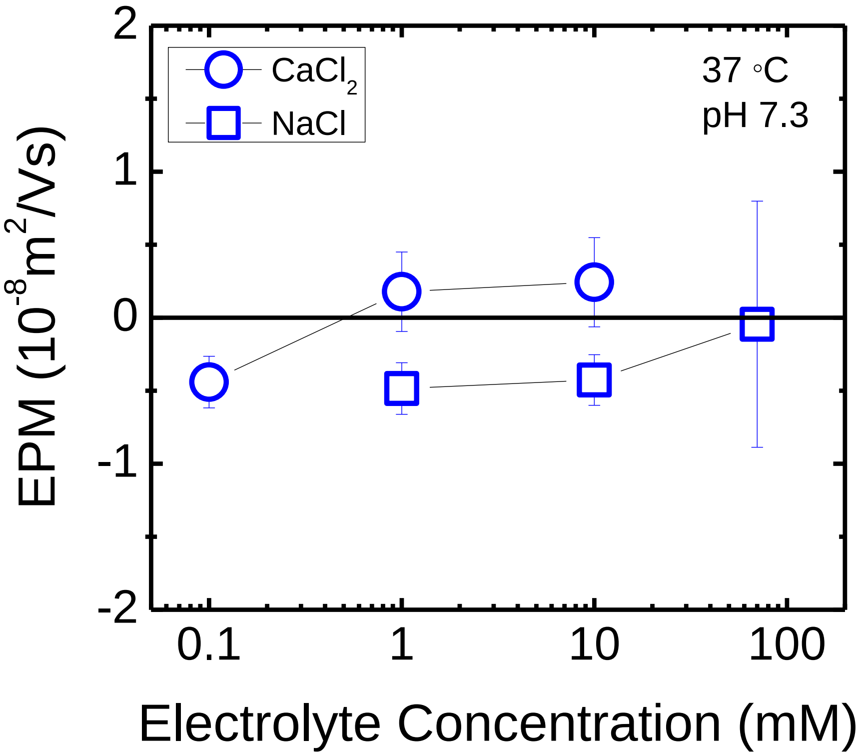


- **The pH of zero point of charge (pH_{ZPC}) of CeO_2 NPs is about 7**

DOPC Supported Lipid Bilayers (SLBs) as Model Cell Membranes

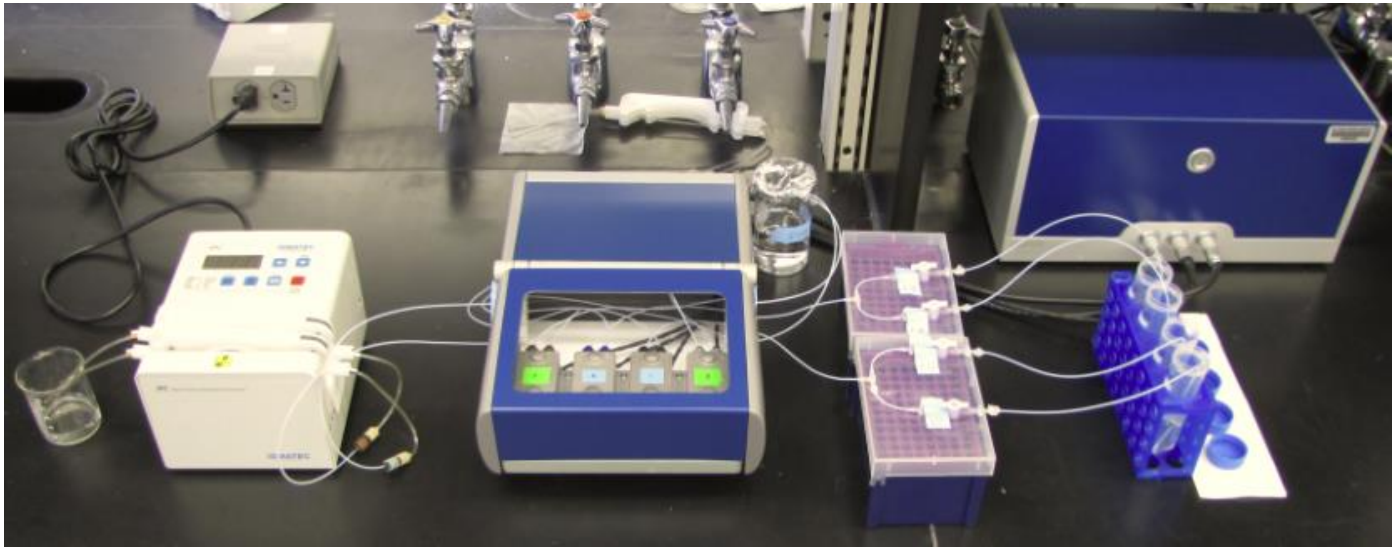
DOPC (1,2-dioleoyl-*sn*-glycero-3-phosphocholine)

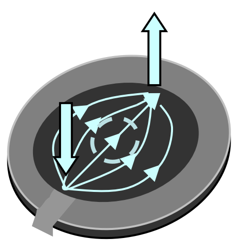




- **DOPC vesicles prepared by extrusion with 50-nm membranes**
- **EPM of DOPC vesicles approaches zero at 70 mM NaCl**
- **Surface charge of vesicles is reversed when $CaCl_2$ concentration >0.5 mM**

Quartz Crystal Microbalance with Dissipation Monitoring (QCM-D)



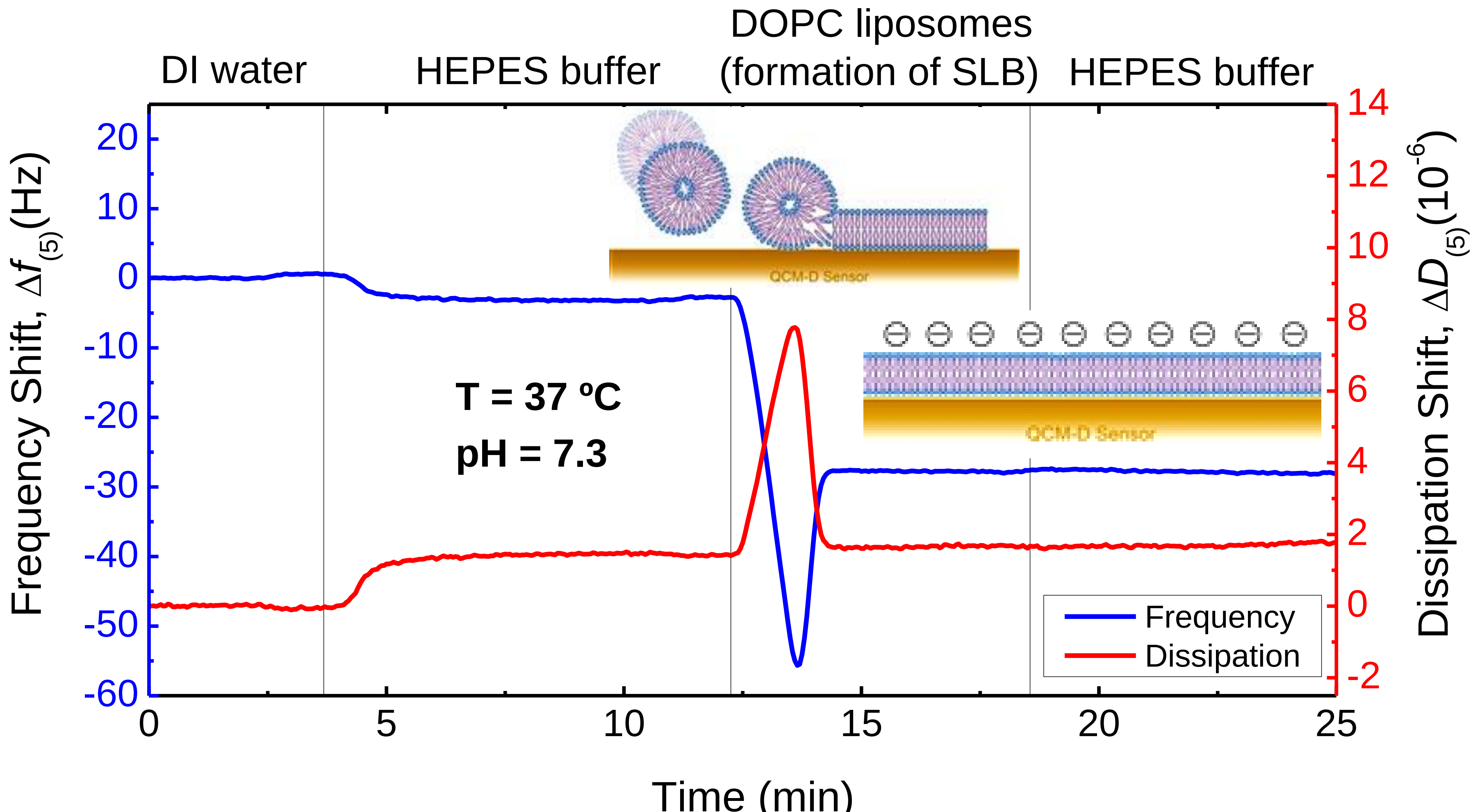


- **Sensitivity of ca. 10 ng/cm^2**
- **Frequency, Δf, and dissipation, ΔD, monitored**
- **Laminar flow at 0.1 or 0.6 mL/min**
- **T = 25 or 37°C, pH = 2–8**

Picture of crystal is from qsense http://www.qsense.com/

Formation of Supported Lipid Bilayers on Silica-Coated QCM-D Crystals

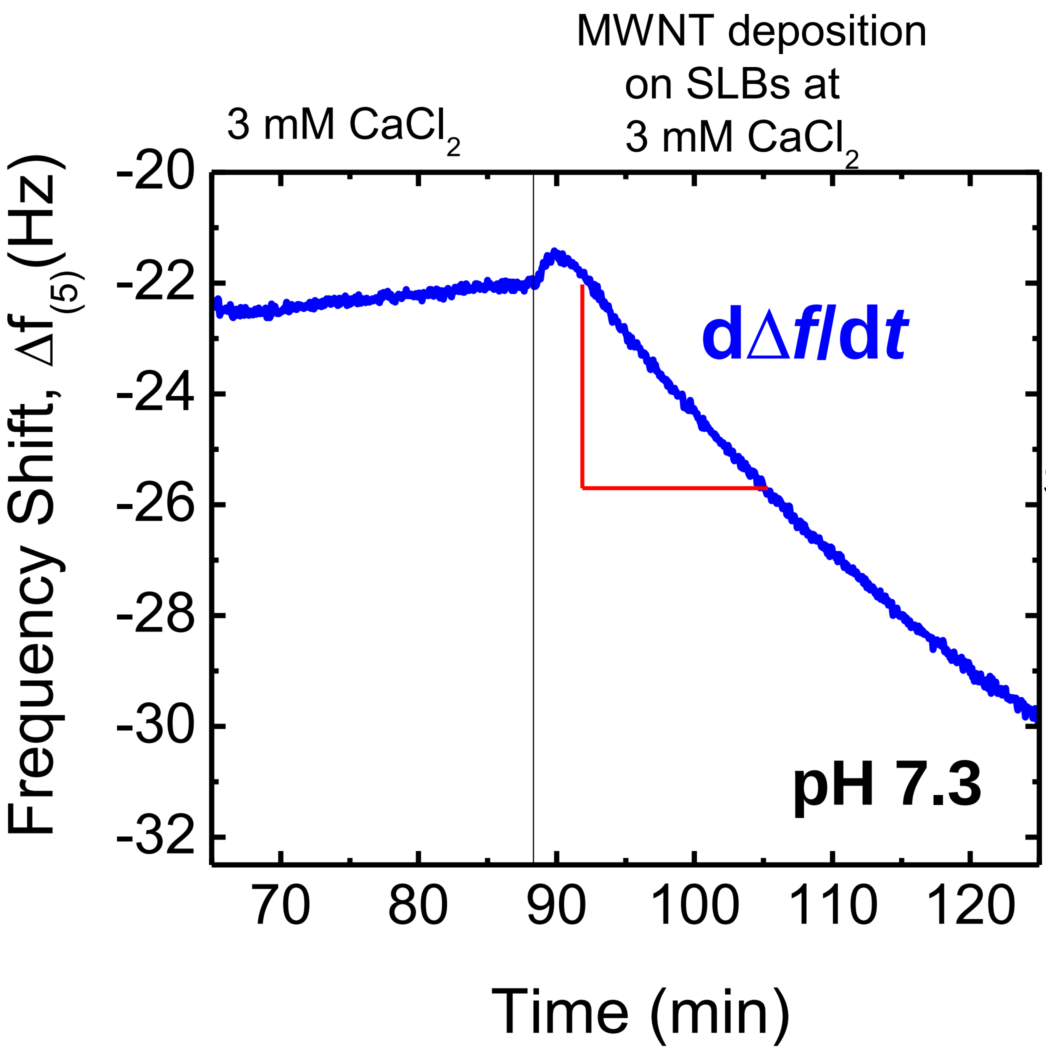
- **Approach of Keller and Kasemo, 1998**

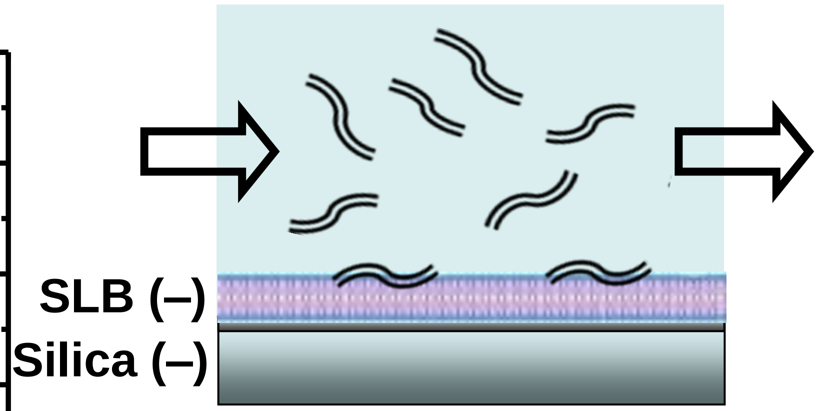


SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

Cartoons are from qsense http://www.qsense.com/

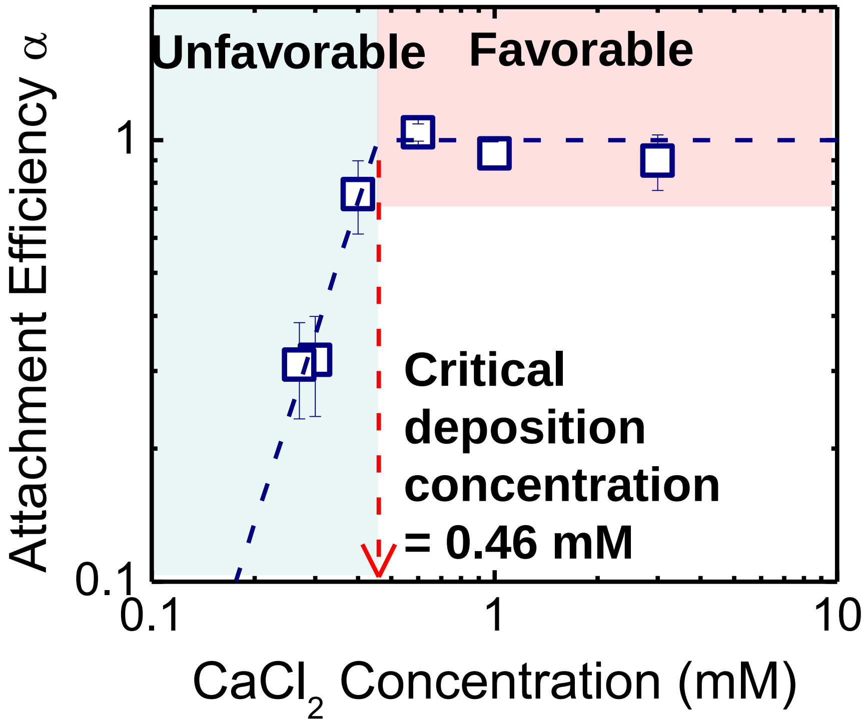
Deposition of MWNTs on SLBs





- **dΔ*f*/d*t* is proportional to rate of nanoparticle deposition**

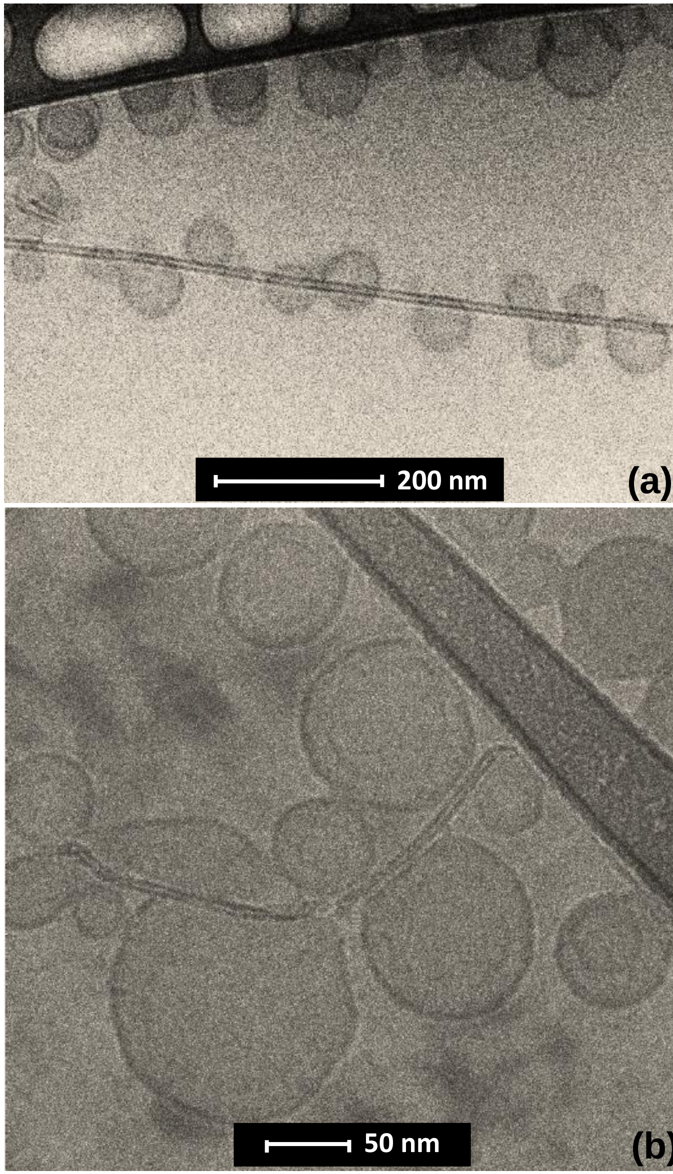
Deposition Kinetics of MWNTs on SLBs in $CaCl_2$ at pH 7.3



- Deposition behavior on SLBs in $CaCl_2$ is in qualitative agreement with classical DLVO theory
- Favorable deposition takes place at >0.5 mM $CaCl_2$ where SLBs undergo charge reversal

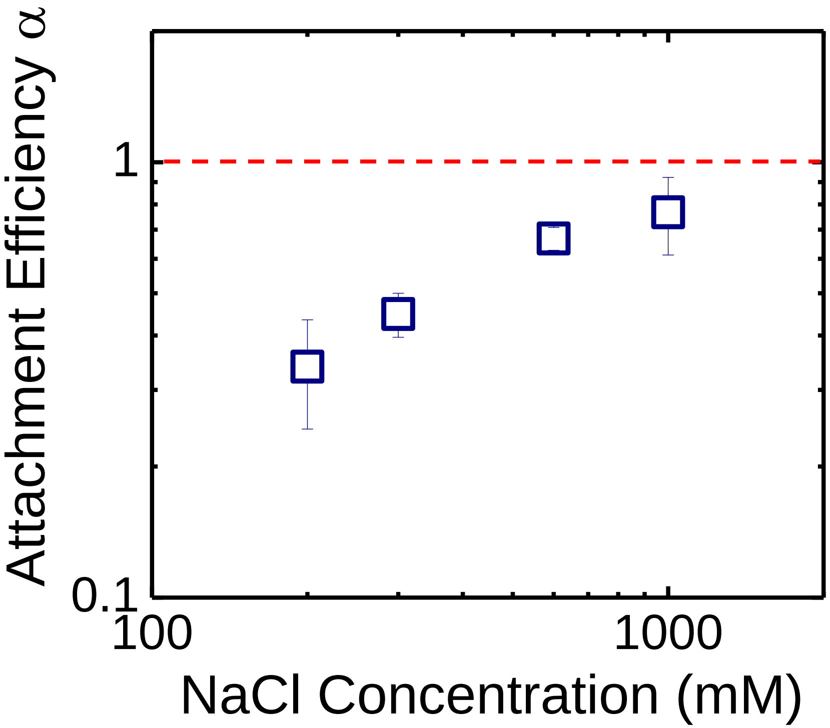
Attachment Efficiency, $\alpha = \dfrac{d\Delta f / dt}{(d\Delta f / dt)_{favorable}}$

Cryogenic TEM Imaging of MWNT-Vesicle Suspensions



- **MWNTs had aggregated with DOPC vesicles in a 1 mM $CaCl_2$ and pH 7.3 solution for ca. 20 min before cryo-TEM images were taken**
- **Interactions between MWNTs and DOPC vesicles seem to be favorable, consistent with QCM-D results**

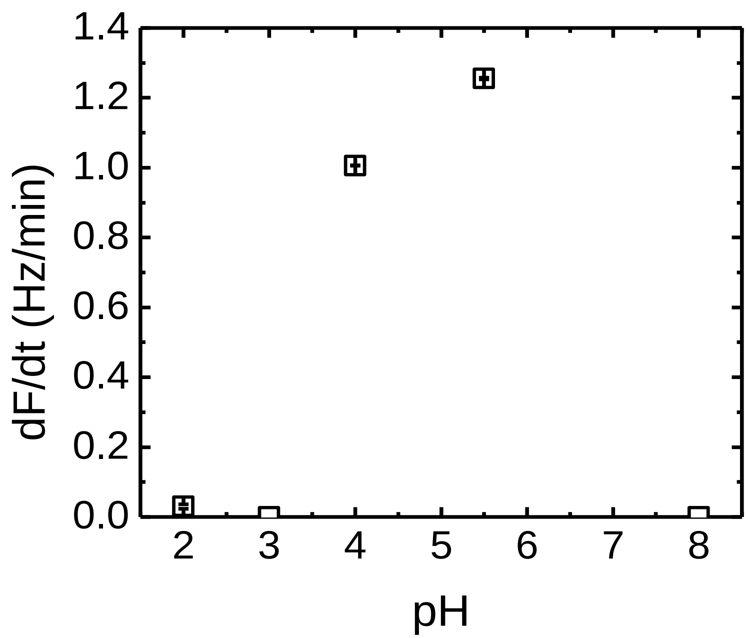
Deposition Kinetics of MWNTs on SLBs in NaCl at pH 7.3

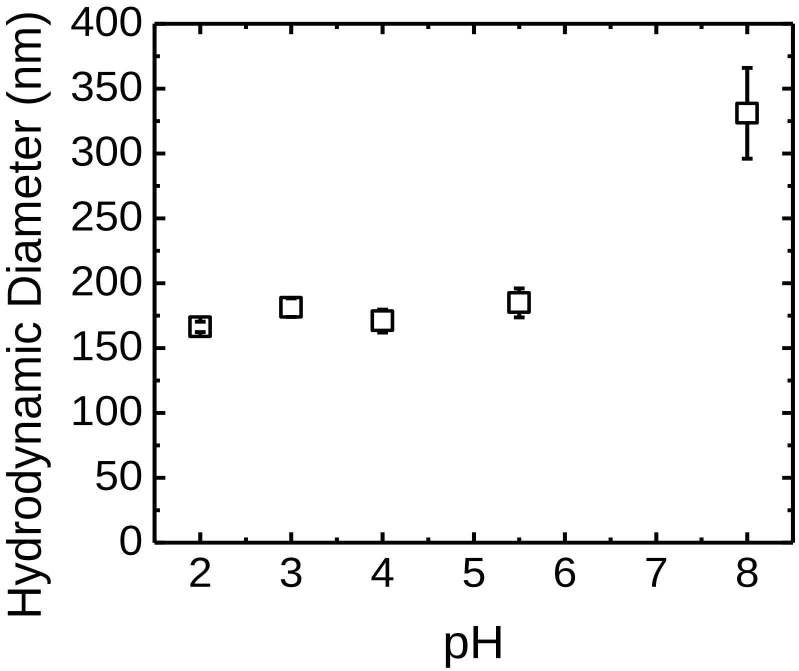


- **EPM of DOPC vesicles is close to zero at 70 mM NaCl**
- **Electrostatic repulsion is unlikely to dominate MWNT–SLB interactions**
- **Headgroups of DOPC lipids are highly hydrophilic**
- **Water can bind strongly to the exposed headgroups of SLBs and may result in repulsive hydration forces**

Influence of pH on CeO_2 NP Deposition Rates

Background solution: 1 mM NaCl





pH<4: both positively charged, unfavorable deposition

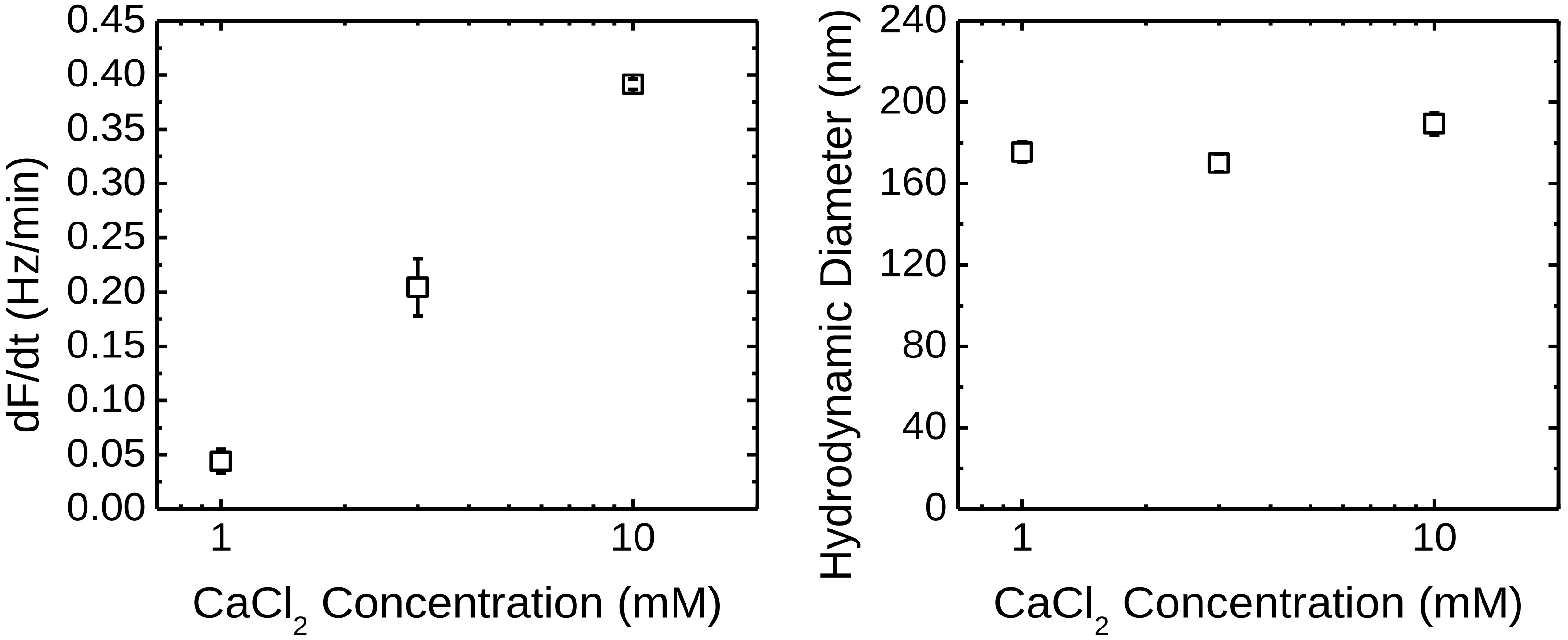
pH>7: both negatively charged, unfavorable deposition

pH=4~7: favorable deposition

pH=8: CeO_2 NPs are lowly charged, not stable to aggregation

Influence of $CaCl_2$ on CeO_2 NP Deposition Rates

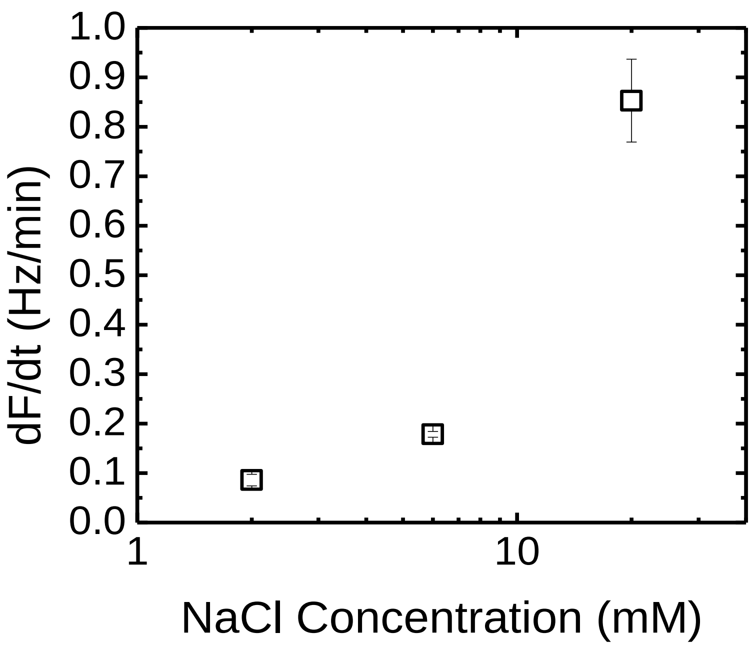
Background: pH 2

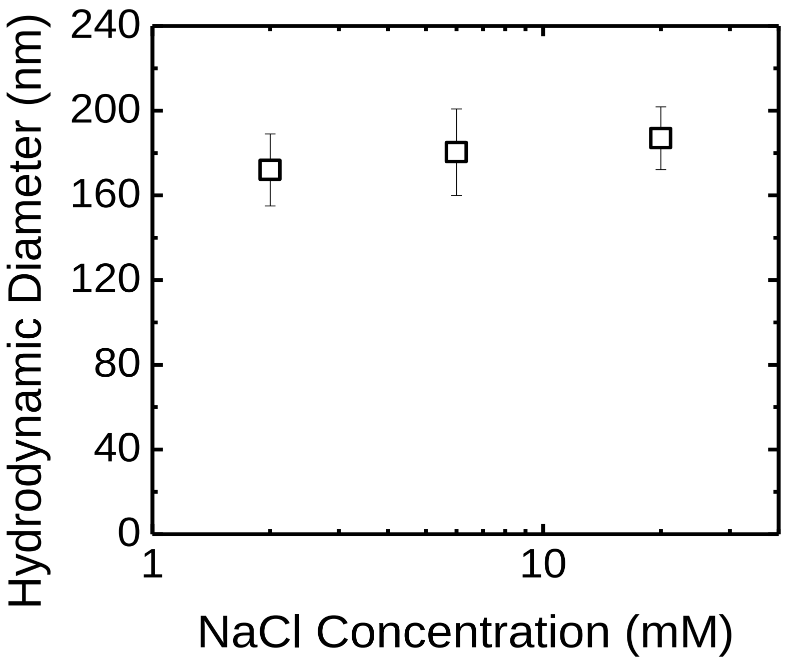


- **As $CaCl_2$ concentration increases, charge screening effect by Cl^- counterions increases**

Influence of NaCl on CeO_2 NP Deposition Rates

Background: pH 2





- **As NaCl concentration increases, charge screening effect by Cl^{-} counterions increases**

Summary of Current Findings

- **Solution chemistry, such as ionic strength, counterion valence, and pH, plays an important role in controlling the attachment of MWNTs and CeO_2 NPs on model biological membranes. Electric double layer interactions and hydration forces can vary as functions of solution chemistry.**
- **Attachment of NPs is affected by the chemistry of SLBs. Ca^{2+} can reverse the charge of DOPC SLBs.**
- **The QCM-D is sensitive enough to measure the attachment of MWNTs and CeO_2 NPs on model biological membranes. Thus, it has the potential to be used as an rapid or online assay for nanoparticle propensity to bind to membranes.**

Industrial Interactions and Technology Transfer

- **Dr. Chen, together with the other PIs from the SRC ERC for Environmentally Benign Semiconductor Manufacturing, will be obtaining representative CMP nanoparticles from SRC industrial members in order to investigate their propensity to attach to biological membranes**
- **SRC industrial members will be updated on the development of the QCM-D as a rapid and online binding assay for nanomaterials**
- **SRC industrial members will be informed of the types of CMP particles and CNTs that are potentially toxic based on the research findings in Dr. Chen's lab**

Future Plans

Next Year Plans

- Investigate the propensity of other CMP particles, specifically SiO_2 NPs and Al_2O_3 NPs, to attach to model biological membranes
- Investigate the influence of surface coatings and surface chemistry on the interactions between CMP particles/CNTs and model cell membranes

Long-Term Plans

- Examine the mechanisms for the penetration of model cell membranes by CMP particles/CNTs
- Develop a rapid assay using the QCM-D to evaluate the propensity of CMP particles/CNTs to disrupt biological membranes

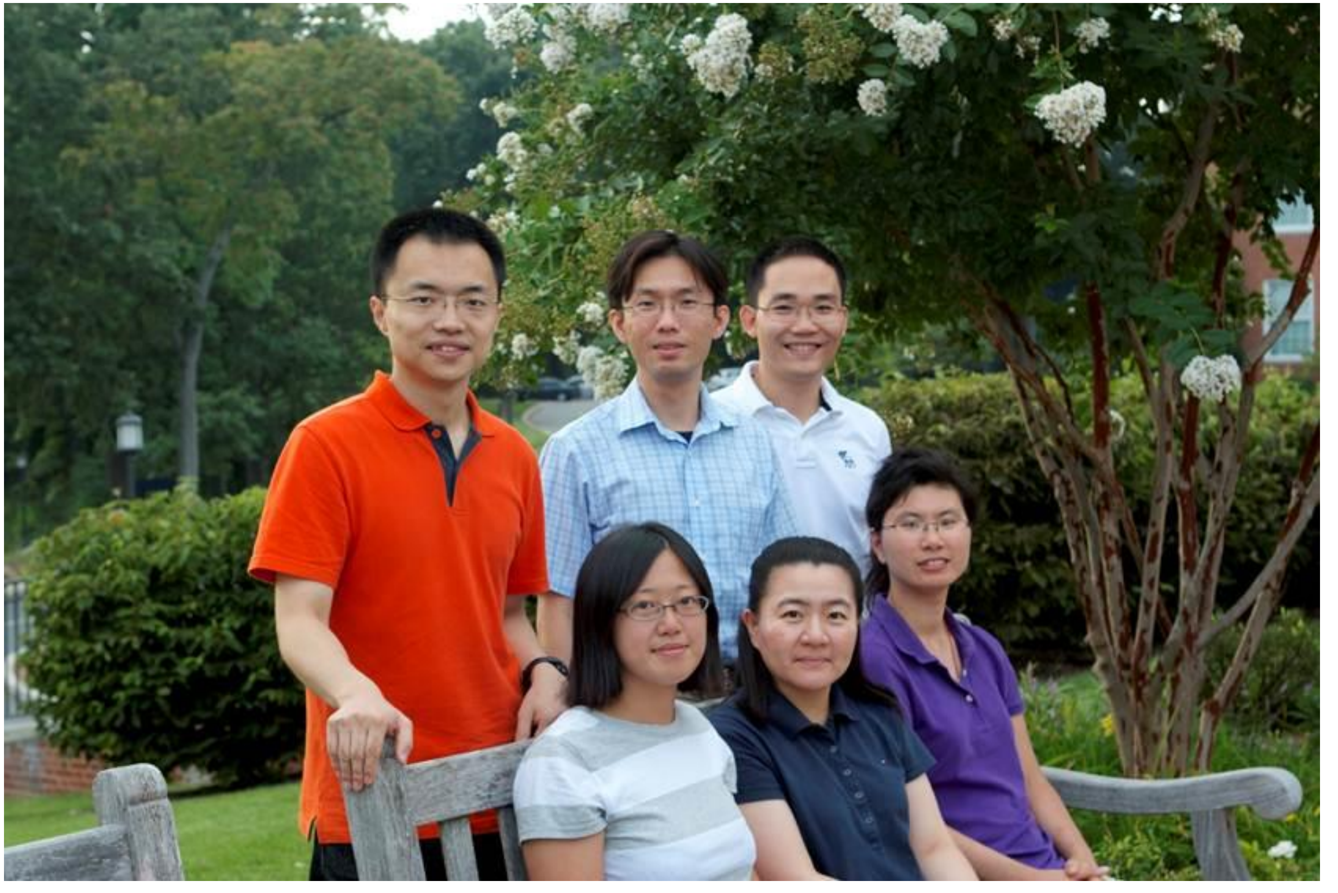
Publications, Presentations, and Recognitions/Awards

- **Publications**
  - **A manuscript has been submitted to *Environmental Science & Technology* and is currently in revision**
- **Presentations**
  - **Dr. Chen has been invited to give seminar talks at the University of Delaware, Washington University at St. Louis, Tsinghua University, and Peking University**
  - **3 oral presentations and 1 poster presentation :**
    - ✓ **American Chemical Society Fall Meeting, September 2013, Indianapolis, Indiana**
    - ✓ **Sustainable Nanotechnology Organization 1st Conference, November 4–6, 2012, Arlington, Virginia**
    - ✓ **86th American Chemical Society Colloid and Surface Science Symposium, June 10–13, 2012, Baltimore, Maryland**
    - ✓ **Gordon Research Conference 2012 – Environmental Sciences: Water, June 24–29, 2012, Holderness, New Hampshire**

Publications, Presentations, and Recognitions/Awards

- **Recognitions/Awards**
  - **Dr. Chen is invited to give a keynote talk at the International Water Association (IWA) Symposium on Environmental Nanotechnology in Nanjing, China**
  - **Dr. Chen is invited to chair a session on nanoparticle transport and transformation at the Gordon Research Conference on Environmental Nanotechnology in Vermont**
  - **Peng Yi received the prestigious 2013 C. Ellen Gonter Environmental Chemistry Award from the American Chemical Society Division of Environmental Chemistry**

Thank you!



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