In Situ and Real-Time Metrology during Cleaning, Rinsing, and Drying of Micro- and Nano-Structures

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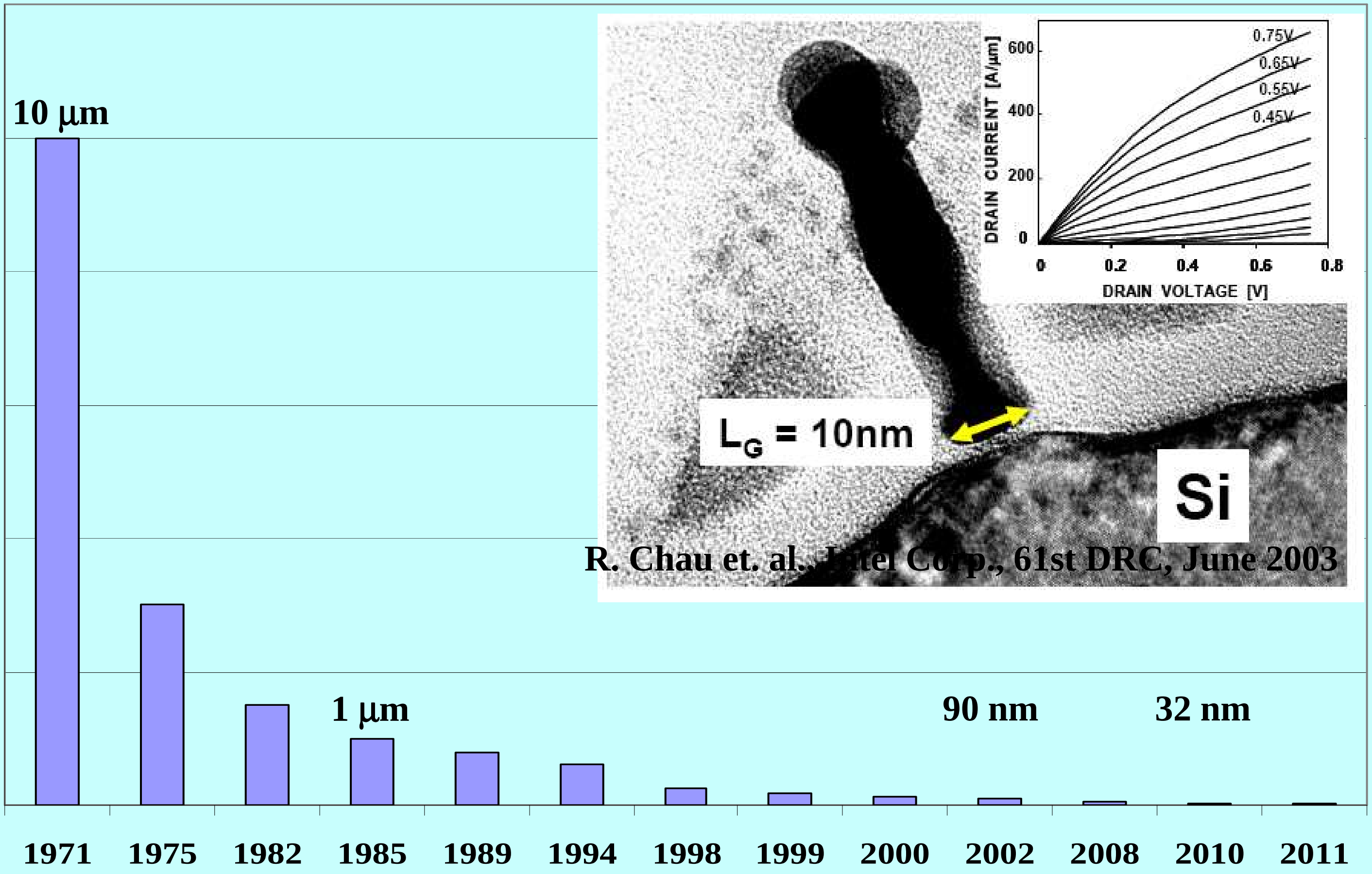
Outline

- Background
- Objective and Approach
- Electro-Chemical Residue Sensor (ECRS)
- Applications to the batch tools
- Applications to the single wafer tools

Semiconductor Manufacturing Technology Nodes

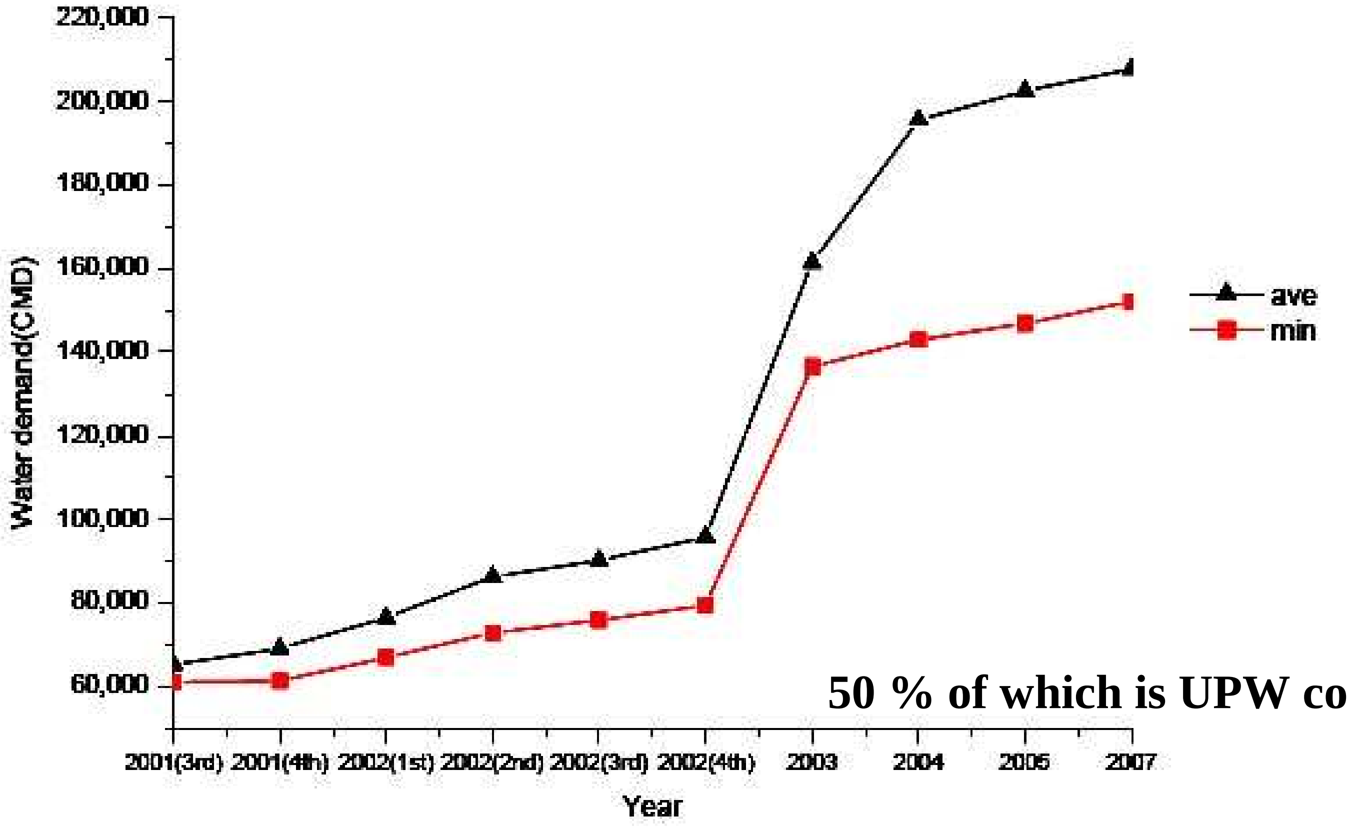


R. Chau et. al., Intel Corp., 61st DRC, June 2003

Can we use current surface preparation technologies for future nano features?

Data from http://en.wikipedia.org/wiki/Semiconductor_manufacturing

Fast Increase of Water Usage

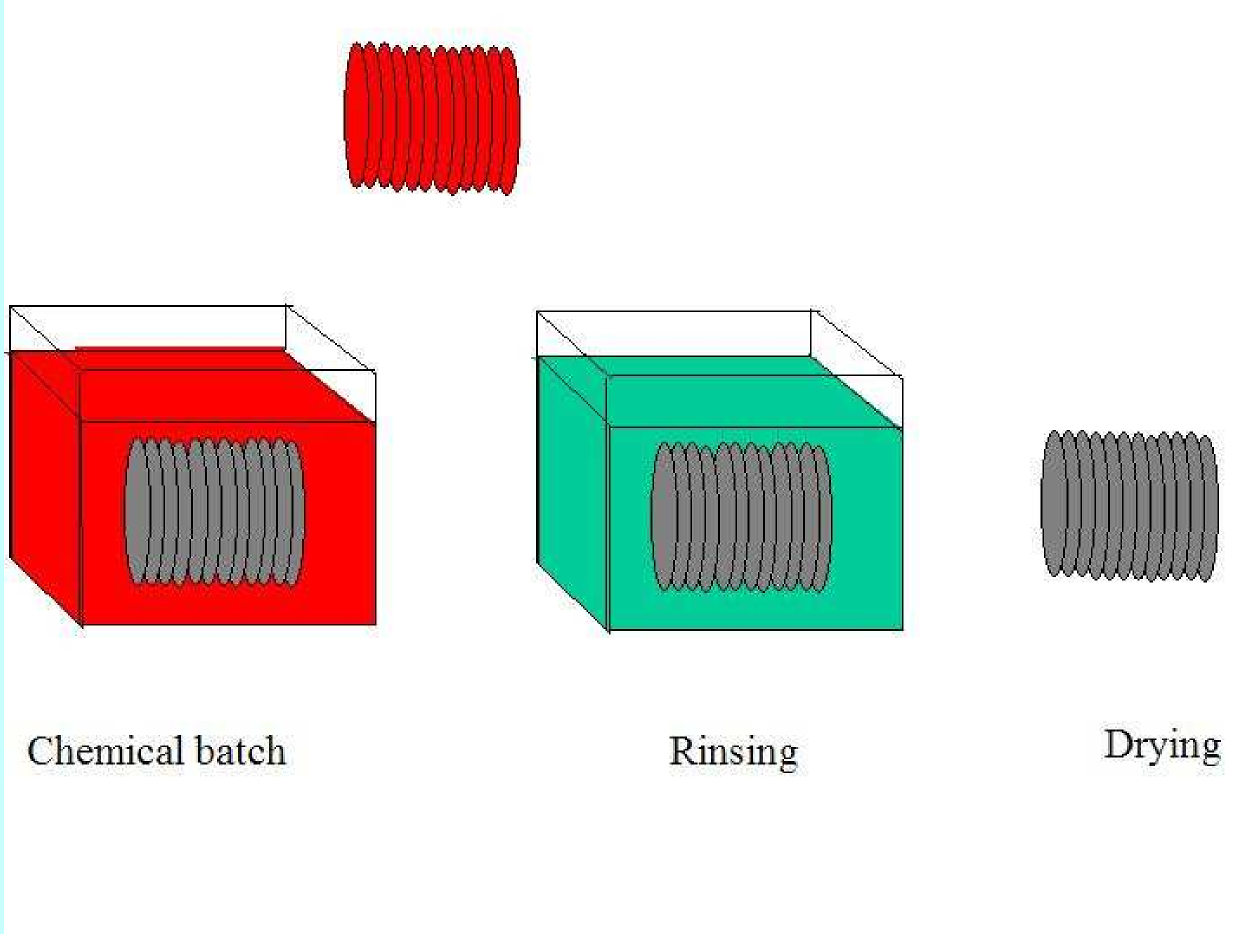


50 % of which is UPW consumption

Past and Future Water Demand for IC Industry in Taiwan (Taiwan (ROC) Ministry of Economic Affairs, Bureau of Industrial Development, 2003)

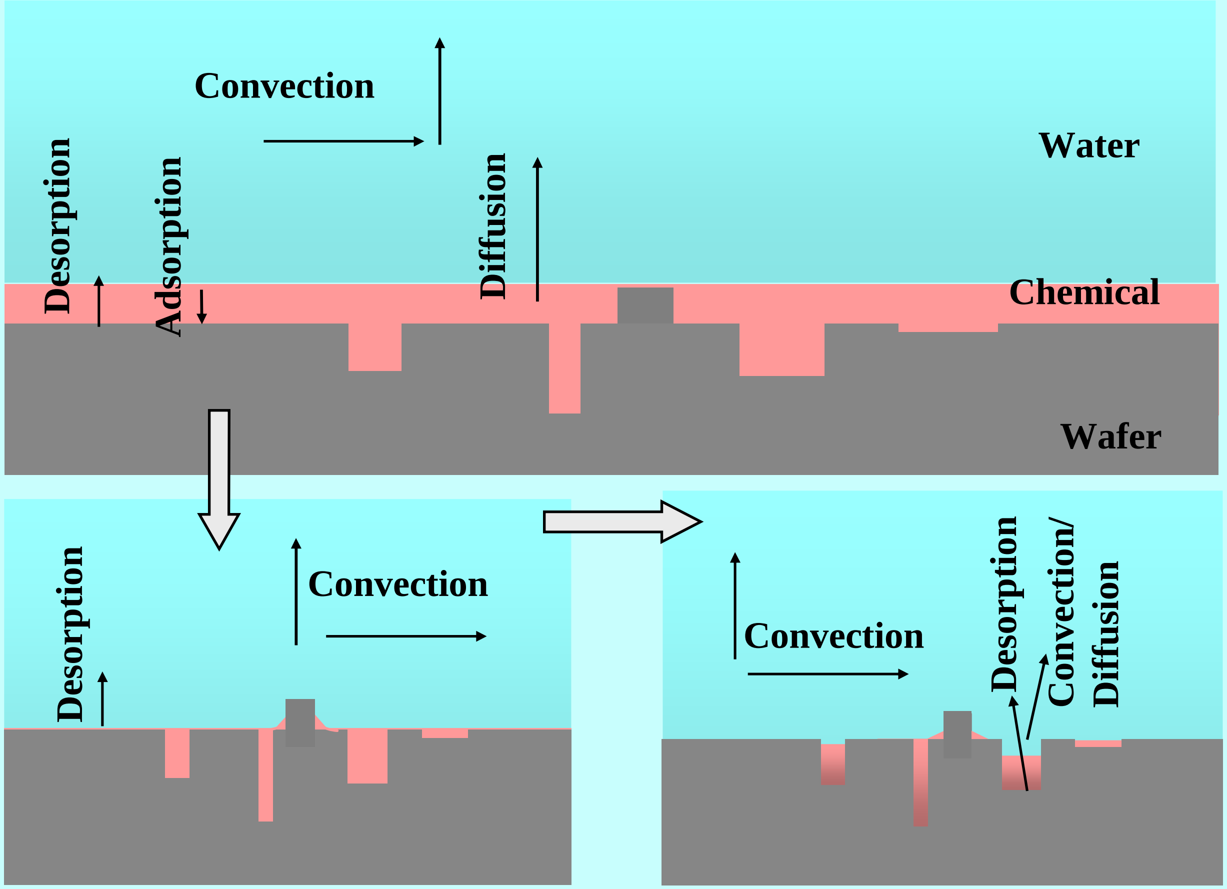
Can we decrease water usage per unit wafer area?

Typical Wet Process



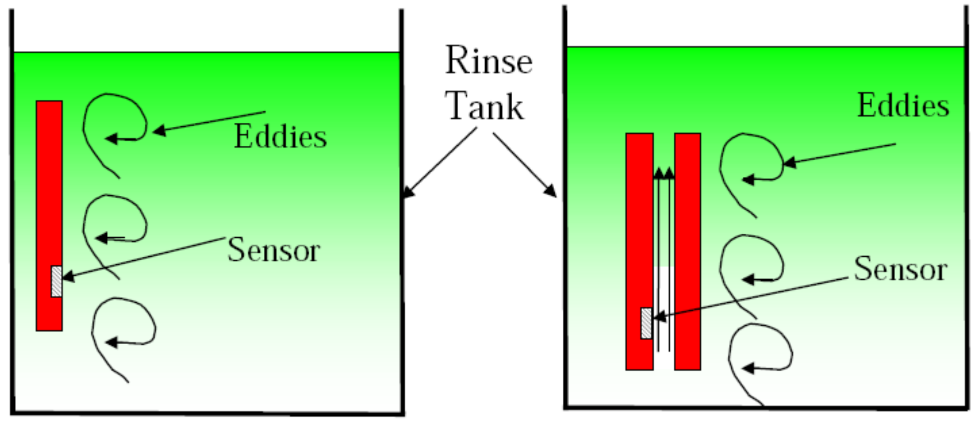
The rinse process consumes the 80-85% of the ultra pure water.
Over rinse is common practice.

Metrology Requirement

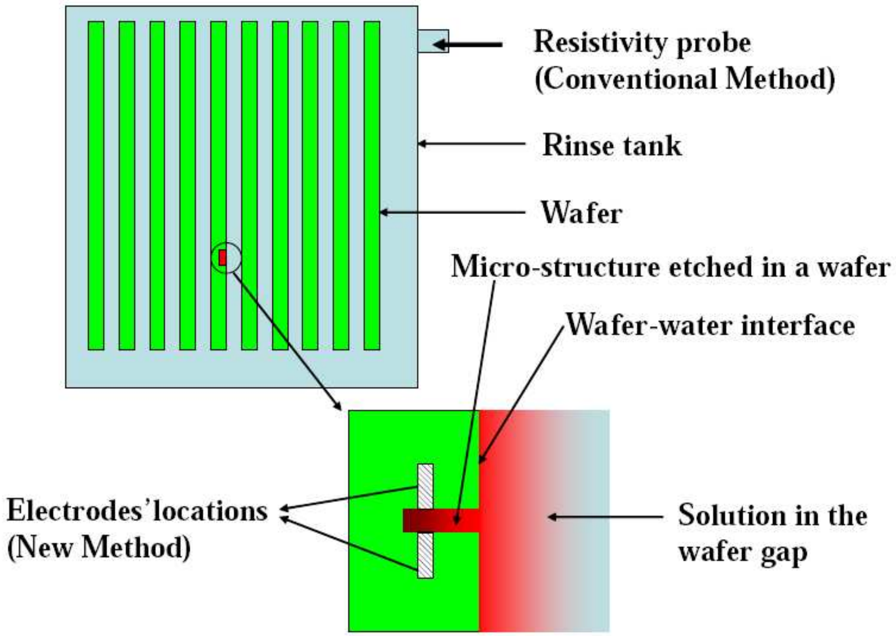


- **Fundamentals of rinsing patterned wafers are poorly understood**
- **Key to efficient rinse is on-line metrology; technology not available presently**

Resistivity Measurement



The poor mixing makes detection of contamination difficult in multi-wafer rinse tanks



Surface Analysis (TXRF and SIMS)

Pros:

- **High sensitivity (10^8-10^{12}atoms/cm^2)**
- **Low operation cost**

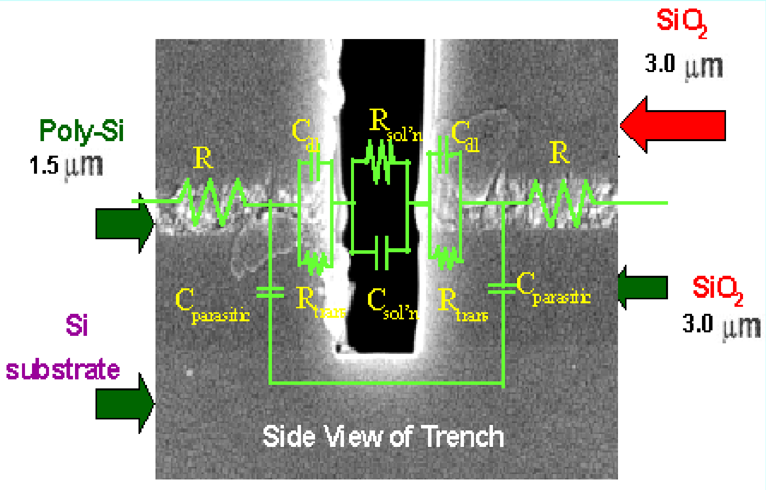
Cons :

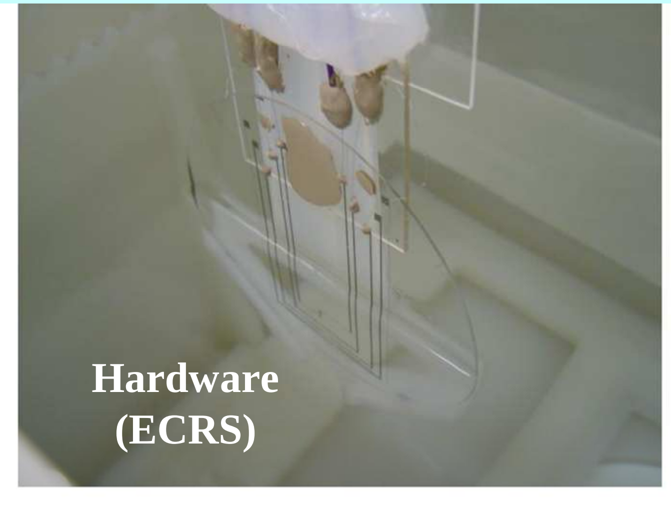
- **High equipment cost**
- **Time consuming**
- **Low portability**
- **Not sensitive for low atomic number elements (TXRF)**
- **Flat surface required(TXRF)**
- **Sensitivity decrease with probe diameter (SIMS)**

Objective and Approach

- Investigate the fundamentals of the cleaning, rinsing, and drying of micro- and nano-structures
- Develop a novel metrology method for in-situ and real-time monitoring of the dynamics of impurity transport inside micro- and nano-structures.
- Apply the metrology method together with process modeling to discover operational strategies for lowering resource usage in the cleaning, rinsing, and drying of small structures.

Novel Hardware: Electro-Chemical Residue Sensor (ECRS)

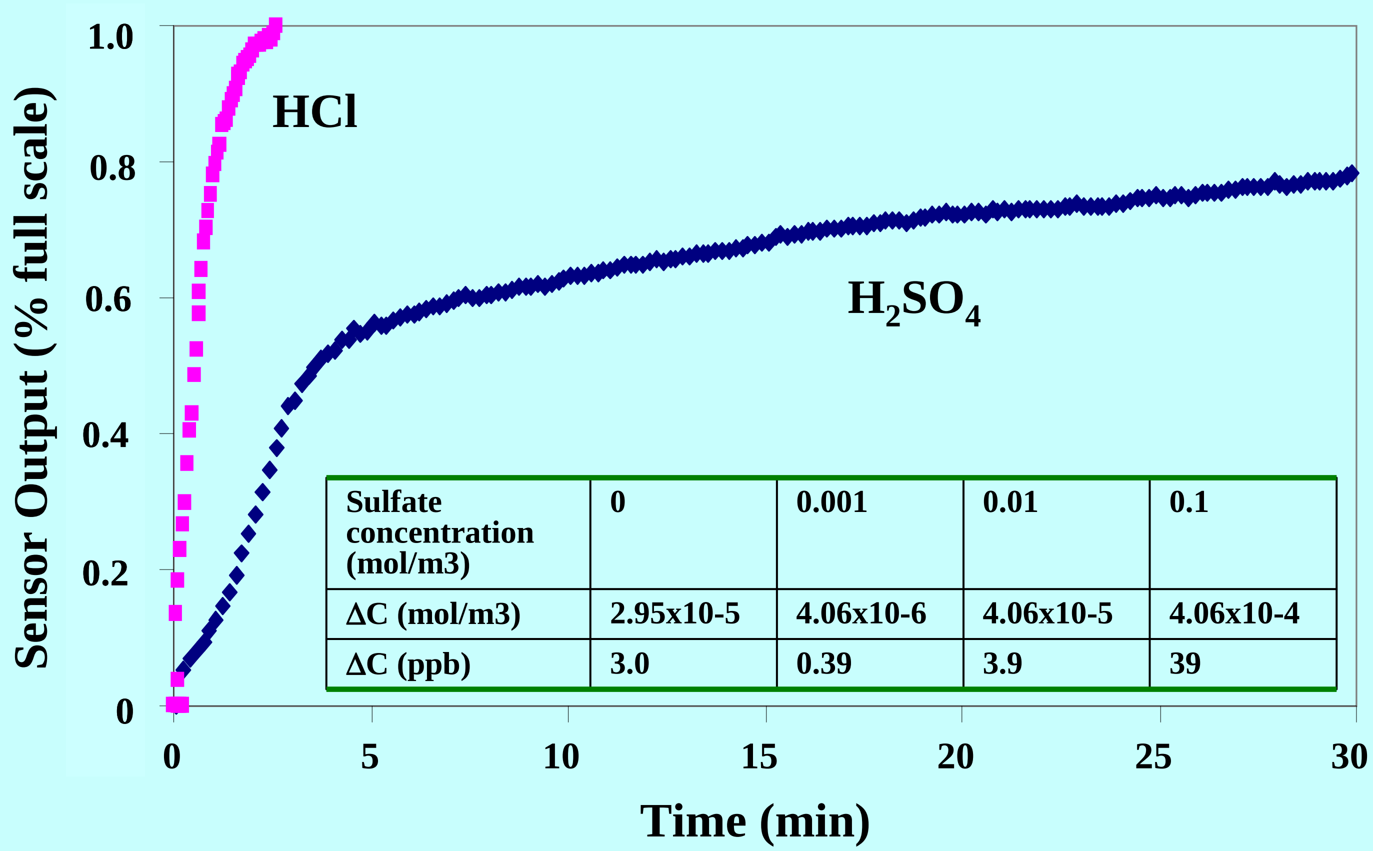




Key Features

- **Real Time**
- **In-situ**
- **Online**
- **High Sensitivity**
- **Non-destructive**
- **Quick Response**

Clean Chemistry Dependence of Rinse



Sulfate concentration (mol/m3)	0	0.001	0.01	0.1
ΔC (mol/m3)	2.95x10-5	4.06x10-6	4.06x10-5	4.06x10-4
ΔC (ppb)	3.0	0.39	3.9	39

Sensor shows different rinse dynamics for different chemicals

Software: Comprehensive Simulation of Rinse Process

Multi-component species transport equations :

$$\frac{\partial C_i}{\partial t} = \nabla \cdot (D_i \nabla C_i + z_i F \mu_i C_i \nabla \varphi)$$

Change in tank concentration :

$$V \frac{\partial C_b}{\partial t} = Q(C_{in} - C_b) + A \cdot Flux$$

Surface adsorption and desorption:

$$\frac{\partial C_{S2}}{\partial t} = k_{a2} C_2 (S_{02} - C_{S2}) - k_{d2} C_{S2}$$

Poisson equation: $$\nabla^2 \varphi = -\frac{\rho}{\varepsilon}$$

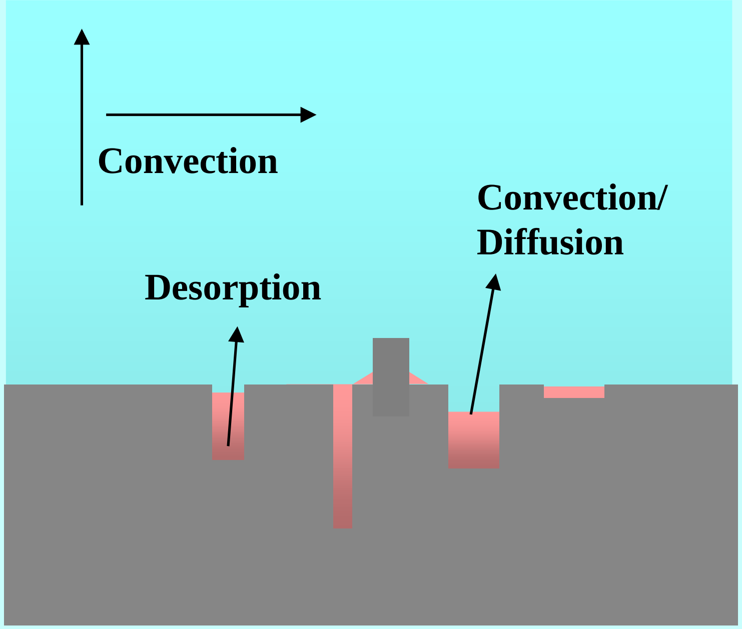
where charge density: $$\rho = F \sum_i z_i C_i$$

Ohm's law: $$\vec{J} = \sigma \vec{E} \qquad \nabla \times \vec{E} = 0$$

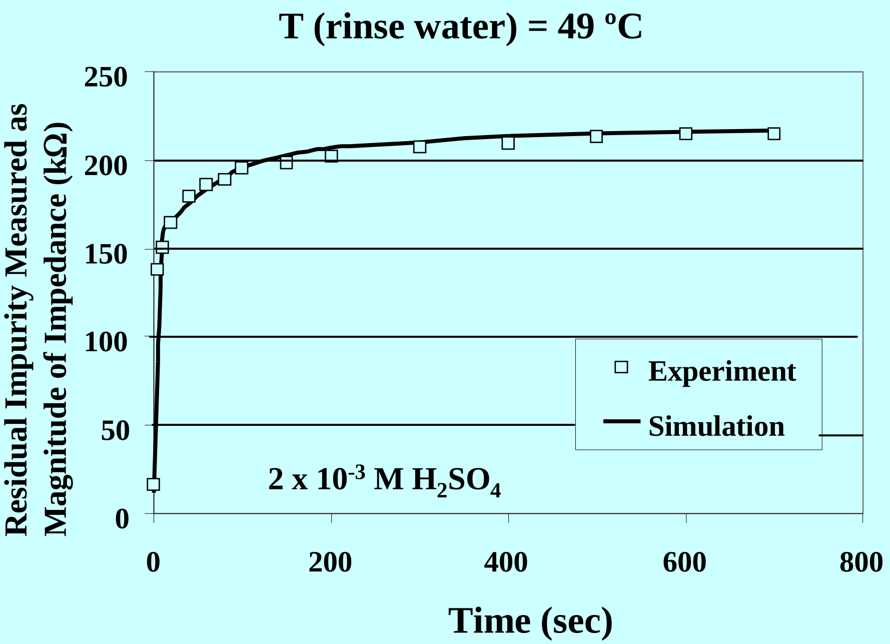
where electrical conductivity:

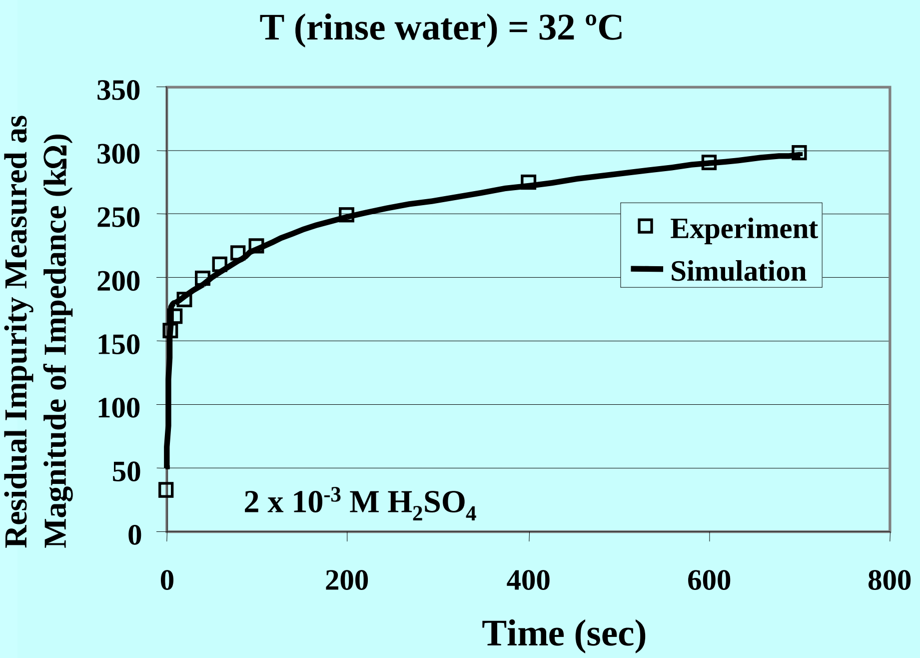
$$\sigma = \sum_i \lambda_i C_i$$

- **Surface Charge**
- **Diffusion**
- **Surface reaction**
- **Ionic transport**



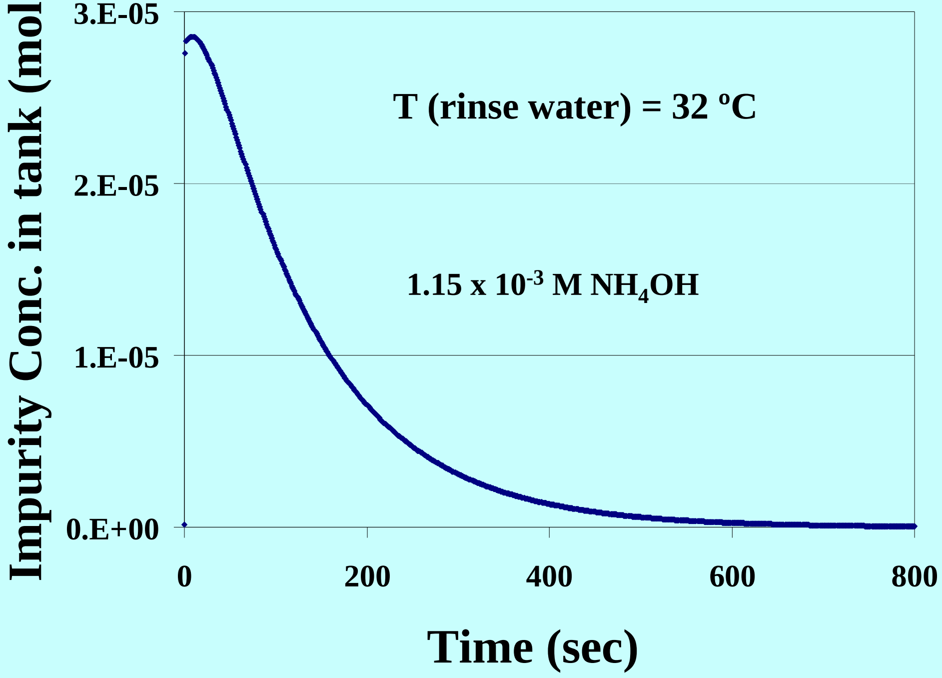
Comparison of Experimental Data with Model Prediction: H_2SO_4

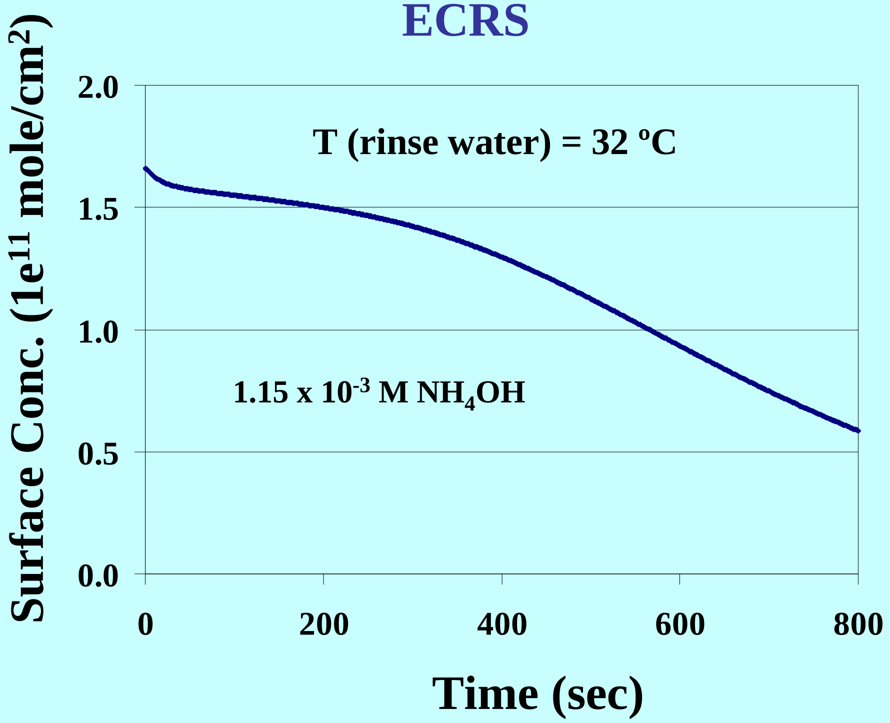

T (rinse water) = 49 °C


T (rinse water) = 32 °C

Accurate modeling of the surface cleanup during rinse is possible

Surface Concentration Profile


Conventional technology
Resistivity probe


Novel technology
ECRS

- Conventional technology might provide misleading information
- ECRS provides in situ and real-time contamination profile

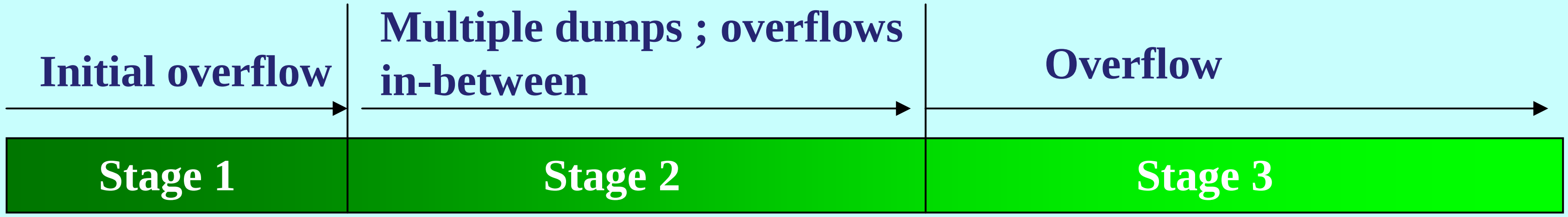
ECRS Application in Over-Flow and Quick- Dump Rinse Tools

Joint work with Freescale and EMC* on development of new low-water rinse processes using ECRS and process modeling.

Co-Investigators and Liaisons: Hsi-An Kwong, Marie Burnham, Tom Roche, Amy Belger, Stuart Searing, Georges Robert, and Andrew Hebda

**** EMC is a Engineering Research Center spin-off company that is formed for tech transfer and commercialization of ECRS technology***

Sample Results: Optimization of Rinse Recipe in OFR/QDR Combination



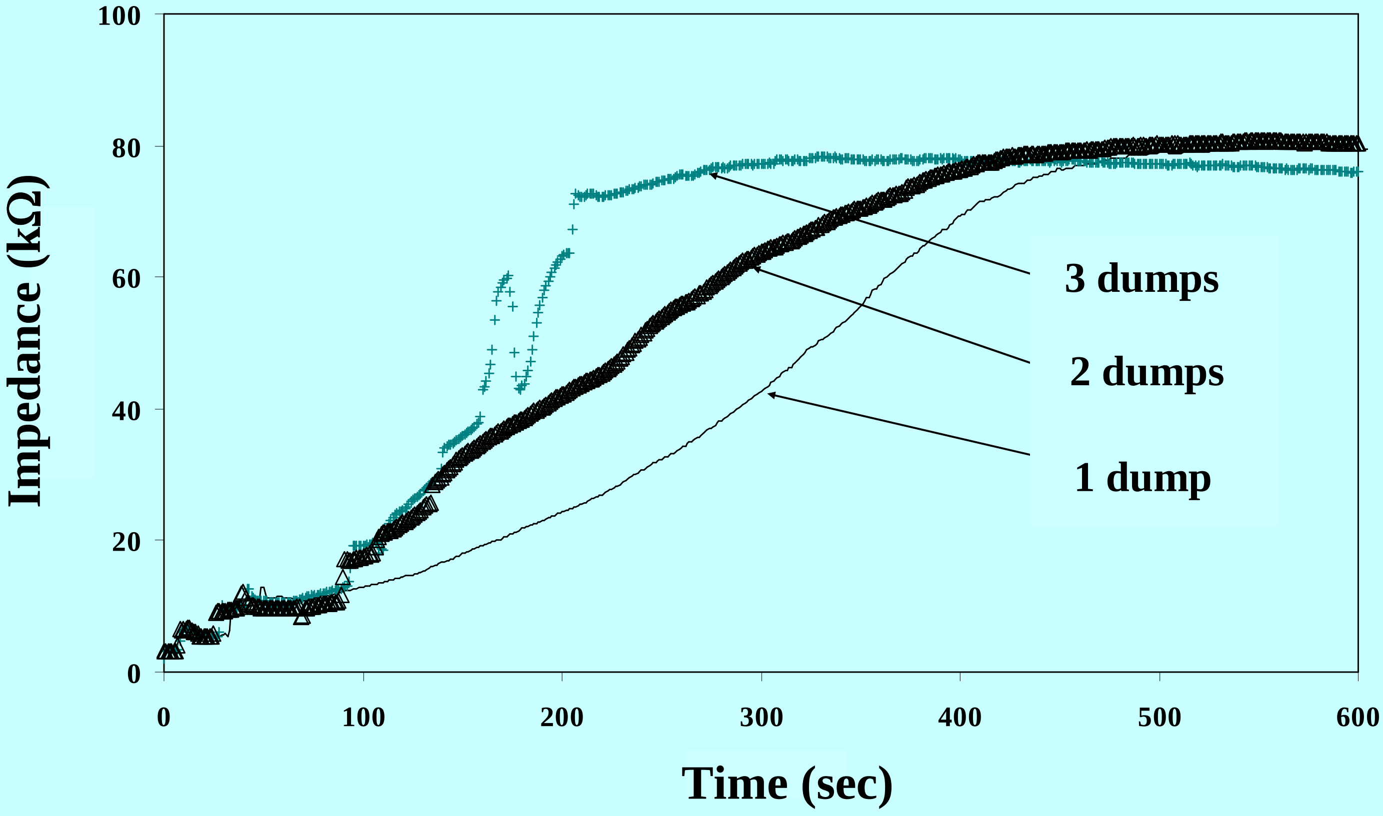
Process Parameters

- Flow rates at different stages
- Time for every session of overflow rinse
- Number of quick dumps
- Water temperature at every session

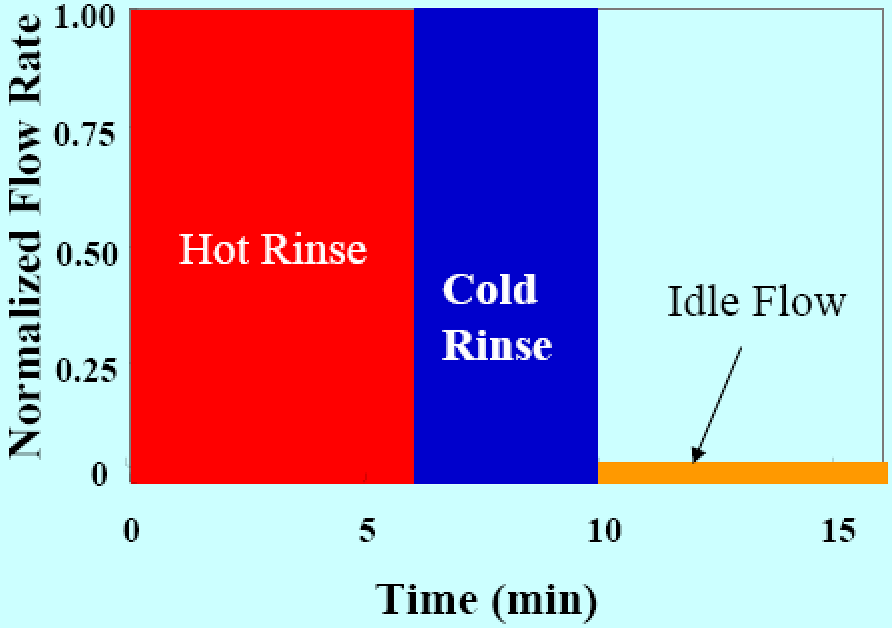
Collaboration with Freescale to optimize existing rinse recipes is ongoing.

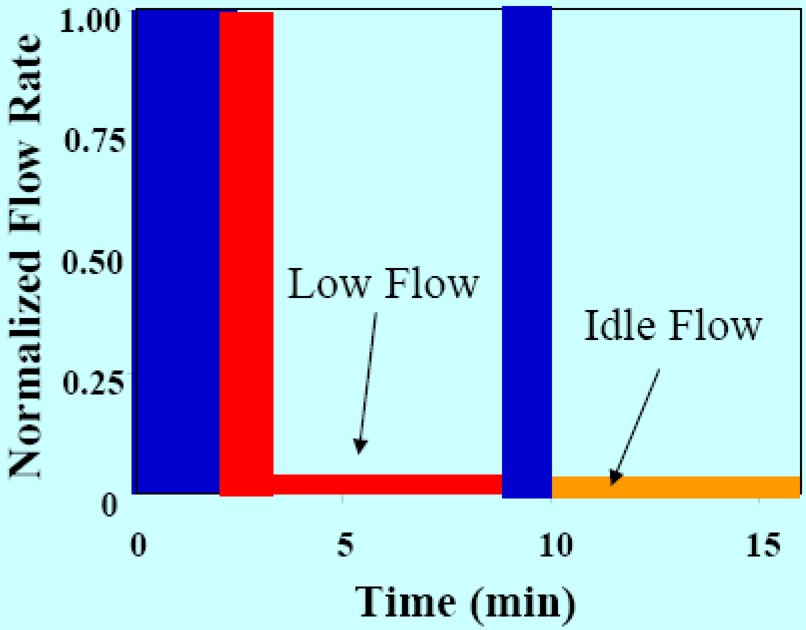
Effect of the Number of Dumps on the Post-APM Rinsing

Initial overflow for 5 sec; overflow in between for 5 sec; flow rates are high flow at all stages; 32 ºC



Example of a New Hot Rinse Schedule


Conventional Rinse


ECRS Enabled Rinse

- Use initial cold rinse to flush tank
- Use hot water to finish flush and heat wafers
- Cycle time is not increased
- Savings: ~ 25% cold water and ~ 80% hot water

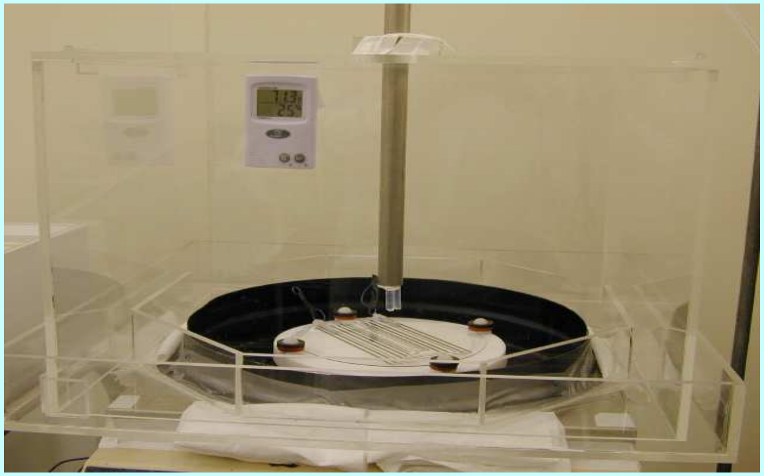
ECRS Application in Single-Wafer Spin Rinse

Joint work with Samsung and EMC* on analysis of the dynamic of spin rinse and development of new low-water rinse processes.

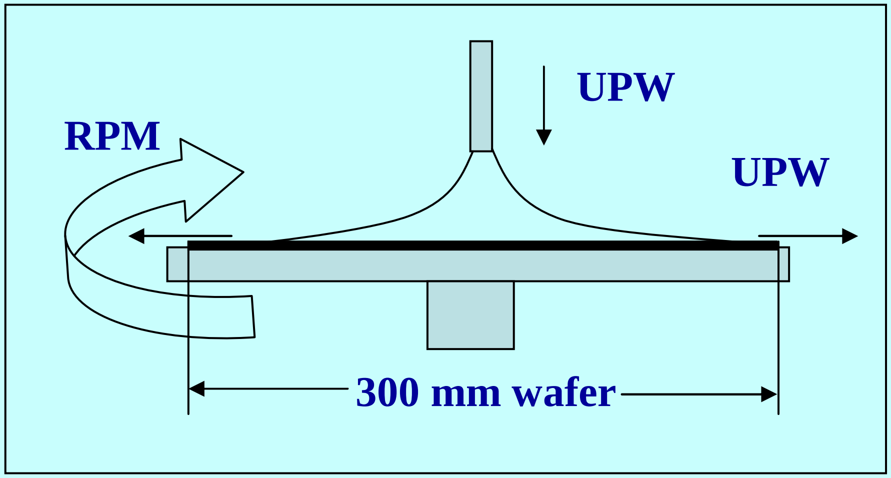
Samsung Co-Investigators and Liaisons: Jeongnam Han, Seung-Ki Chae, Pil-Kwon Jun

*** EMC is a Engineering Research Center spin-off company that is formed for tech transfer and commercialization of ECRS technology***

Application of ECRS to Single Wafer Rinsing and Drying



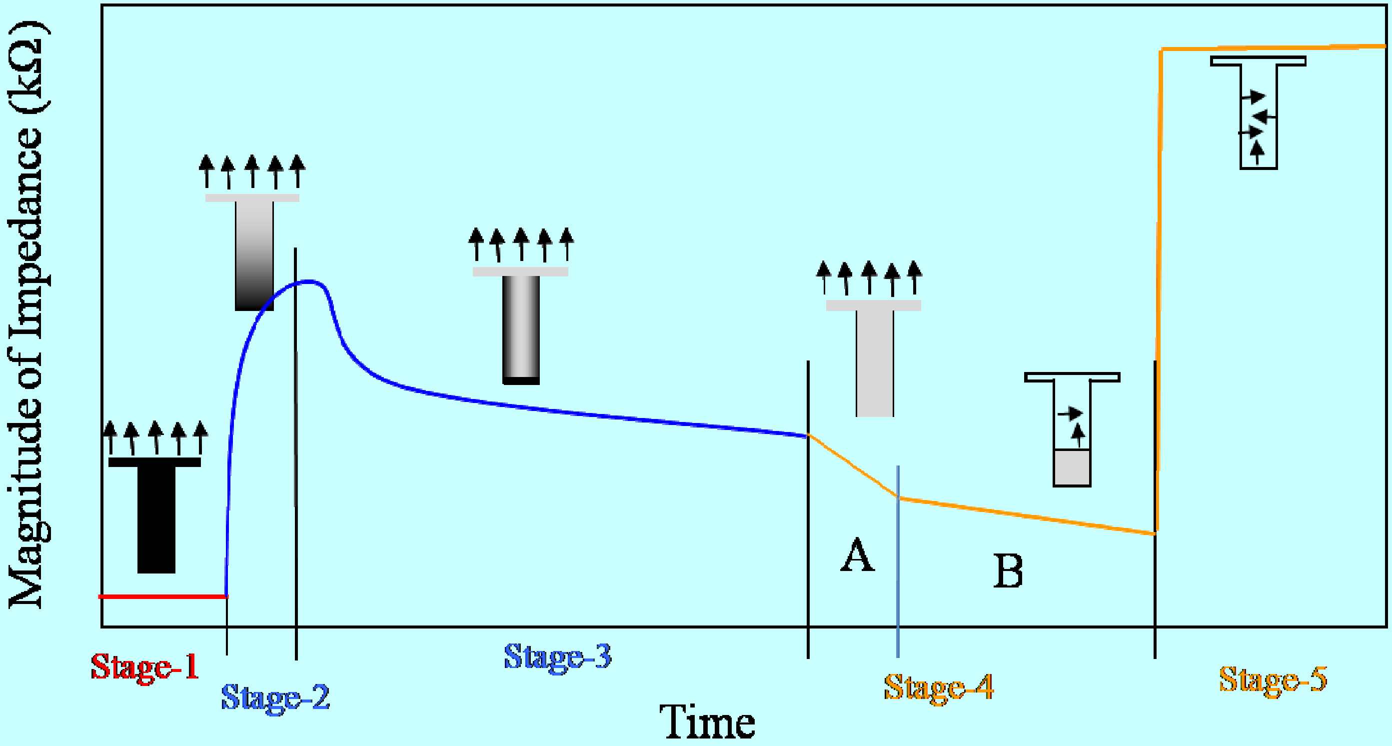
Experimental Setup



Process Model Schematic

- A single wafer tool equipped with ECRS is designed and set up.
- Combination of experiments and process model is used to study the effect of various process parameters.

Monitoring Capabilities of ECRS



Stage-1: Chemical Exposure

Stage-2: Rinsing -Purging of the Trench

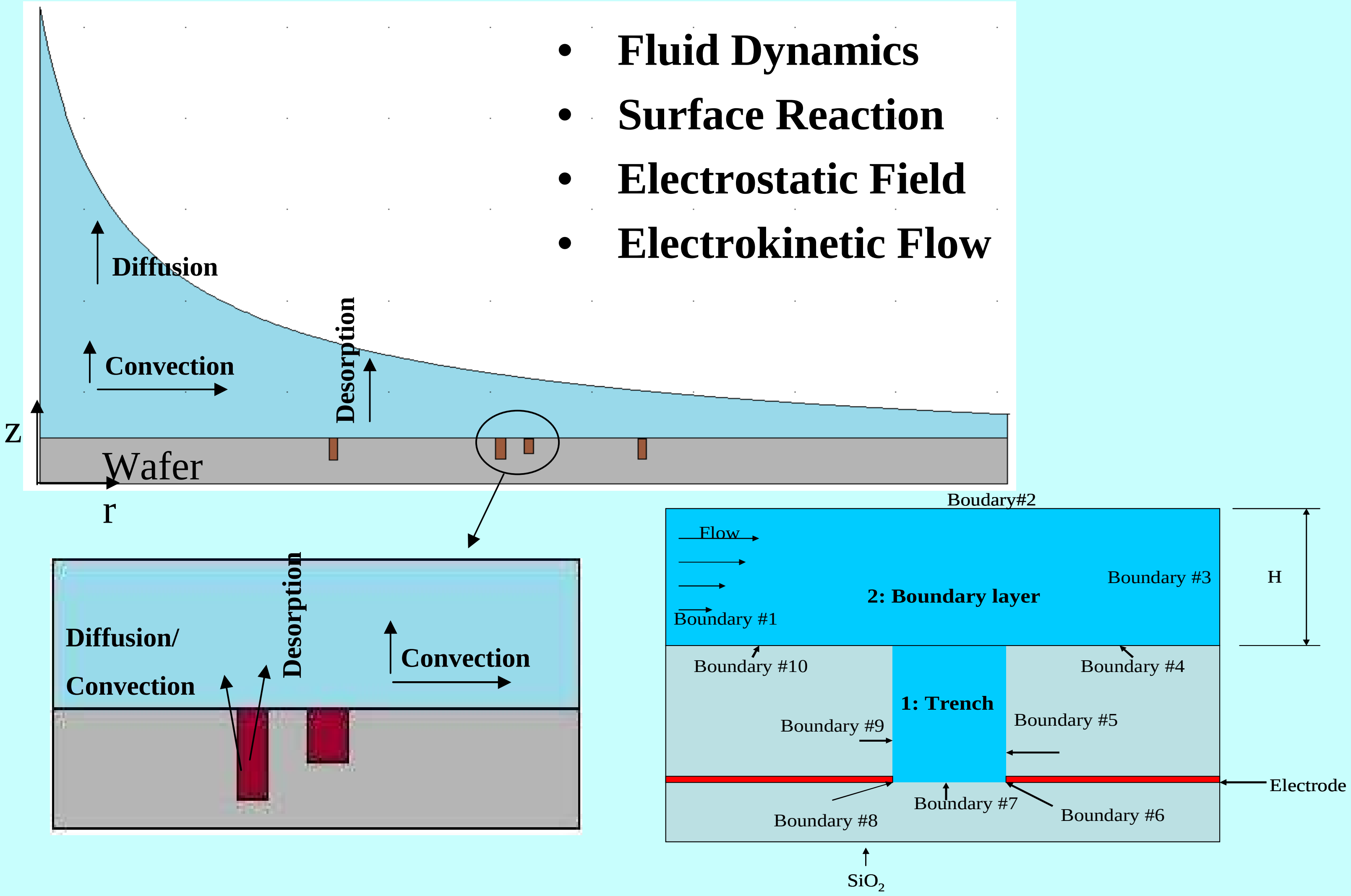
Stage 3: Rinsing: Surface Reaction

Stage-4: Bulk Drying

Stage-5: Surface Drying

Process Model for Spin Rinsing

- Fluid Dynamics
- Surface Reaction
- Electrostatic Field
- Electrokinetic Flow



Bulk's Fluid Dynamics

From the conditions that $\left(\frac{z}{r}\right) = \left(\frac{h}{R}\right) << 1$

Q: volumetric flow rate, m^3/s

υ: kinematic viscosity, m^2/s

r: radius of the wafer, m

ω: angular velocity, rad/s

$$h = 0.782 \cdot \left(\frac{Q.\nu}{r \cdot \omega}\right)^{0.33}$$

$$u_r = \frac{\rho\omega^2 r h^2 (1 - (1 - \frac{z}{h})^2)}{2\mu}$$

I. Lesgev, G. Peev, "Film flow on horizontal rotating disk", Chemical Engineering and Processing, vol. 42, 2003, pp. 925-929.

Surface Reaction

Surface adsorption and desorption

$$\frac{dC_S}{dt} = k_a C_{SO_4^{-2}}(S_0 - C_S) - k_d C_S$$

Cs: surface concentration

K_a: adsorption constant

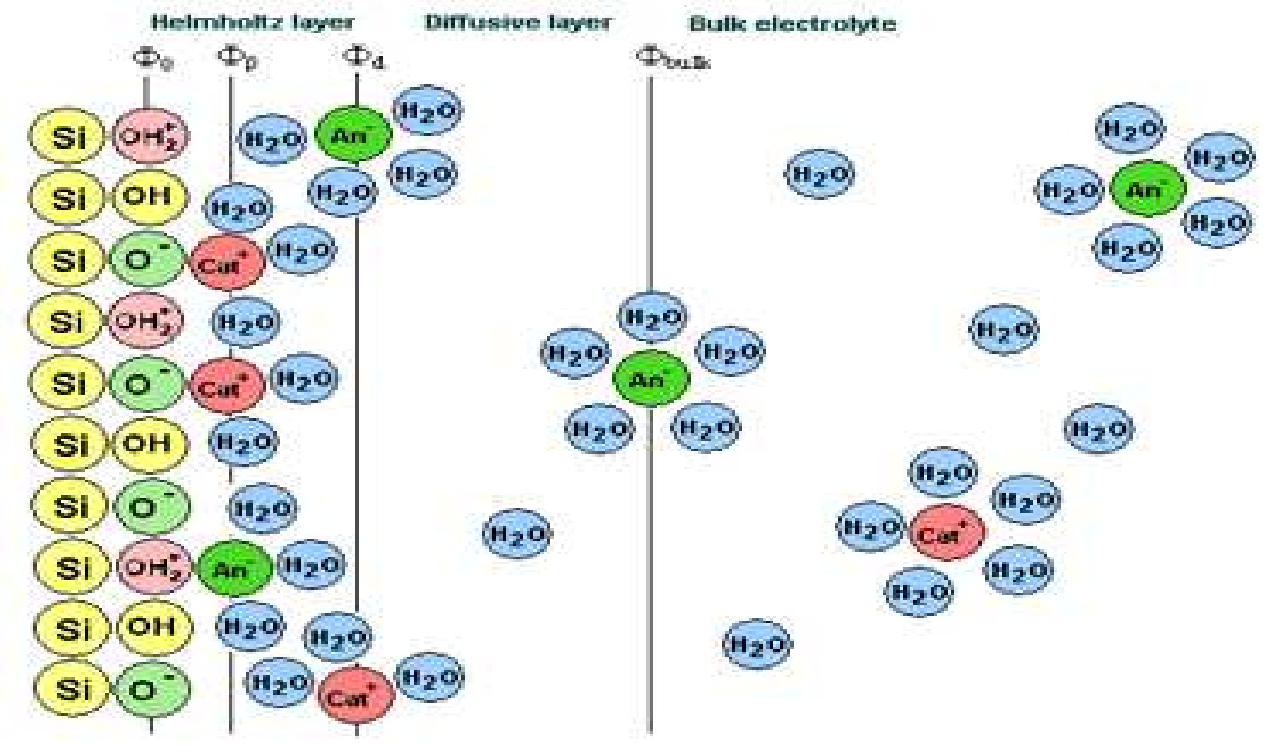
K_d: desorption constant

S_0: maximum number of sites available for adsorption

Electrostatic Filed

Dissociation of silanol group

$$\mathrm{SiOH} \xleftrightarrow{K_{\mathrm{SiOH}}} \mathrm{SiO}^{-} + \mathrm{H}^{+}$$



Poisson's Equation

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon}$$

where charge density:

$$\rho = F \sum_i z_i C_i$$

F: Faraday constant, 96485.339 C/mol

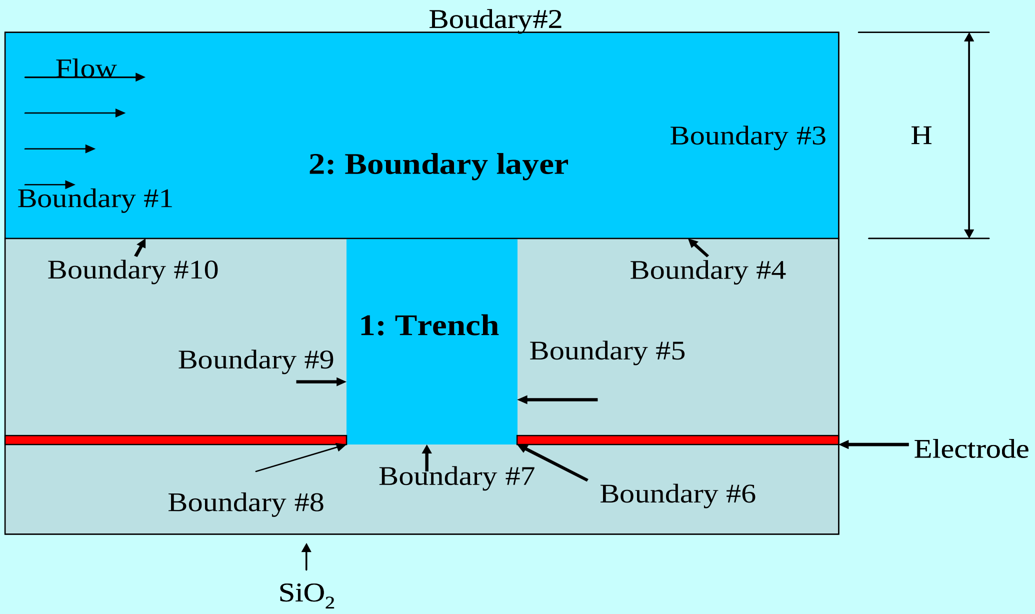
C_i : ions concentration

z_i: ions valence

Electrokinetic Flow and Ohm's Law

Multi-component species transport equations

$$\frac{\partial C_i}{\partial t} = \nabla \cdot (D_i \nabla C_i + z_i F \mu_i C_i \nabla \varphi) - u \nabla C_i$$



Ohm's law:

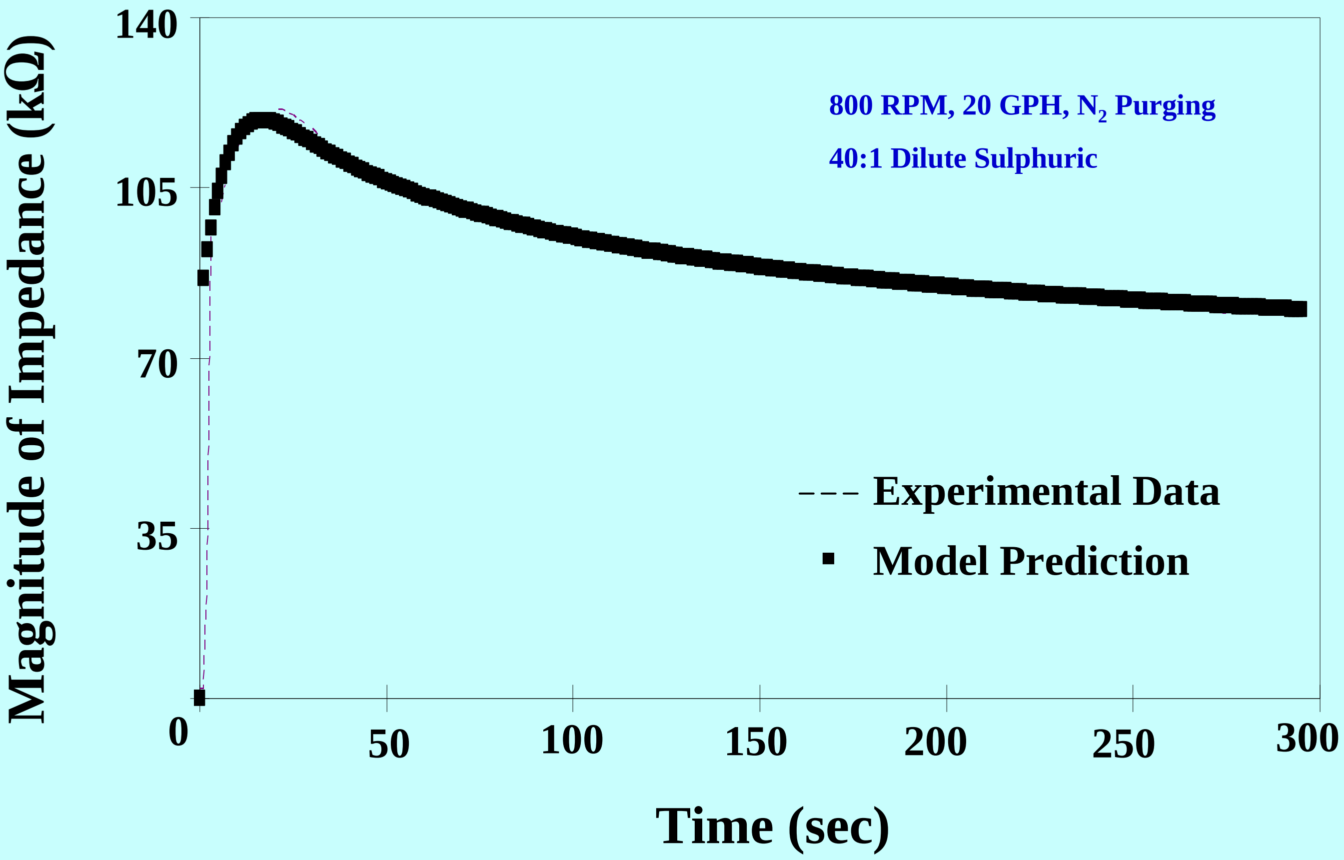
$$\vec{J} = \sigma \vec{E} \qquad \nabla \times \vec{E} = 0$$

where electrical conductivity:

$$\sigma = \sum_i \lambda_i C_i$$

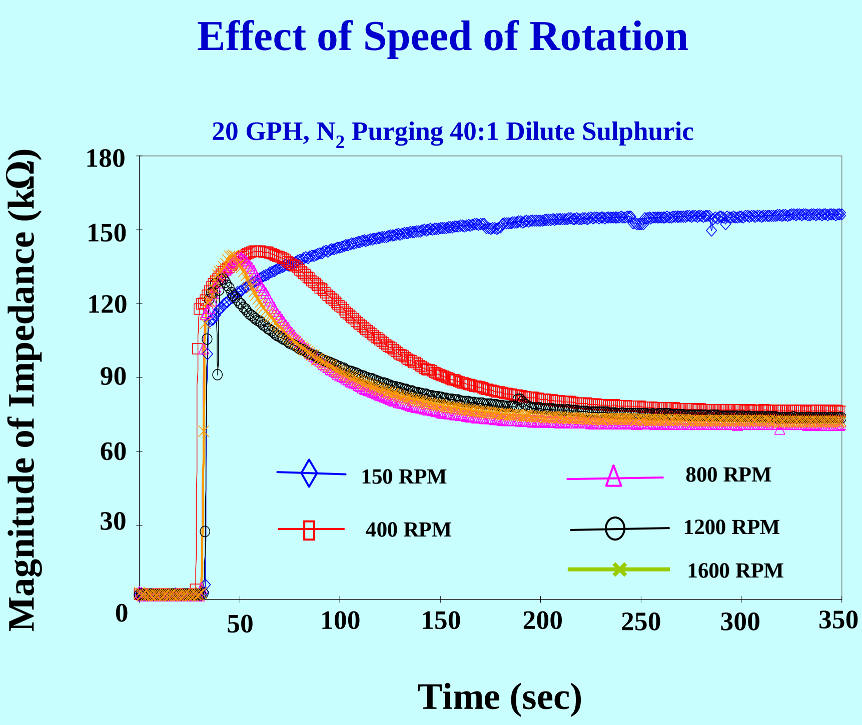
SRC/Sematech Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

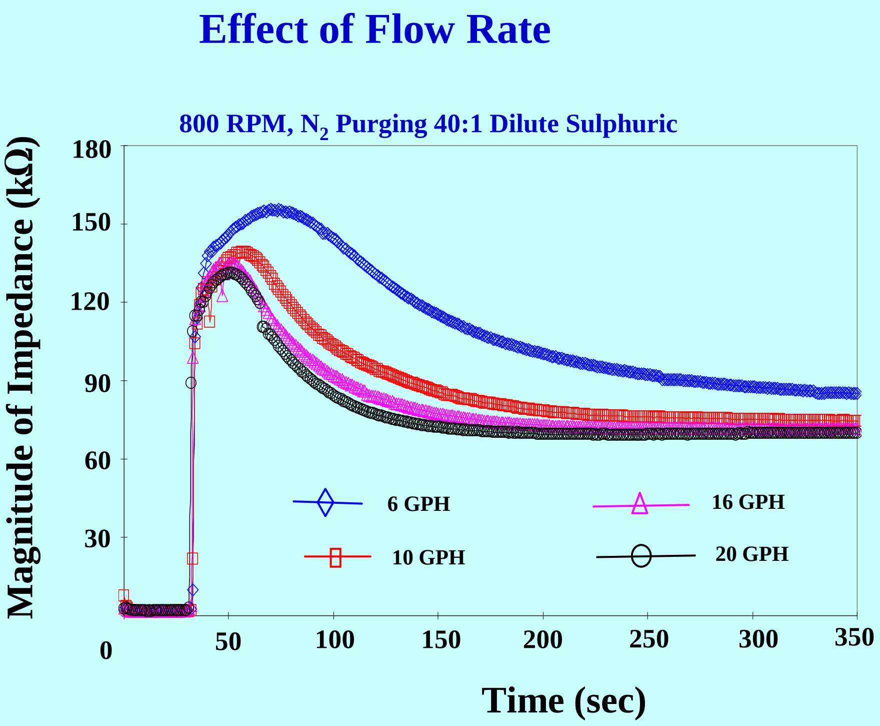
Validation of Process Simulation



Simulation results are in good agreement with the experimental data

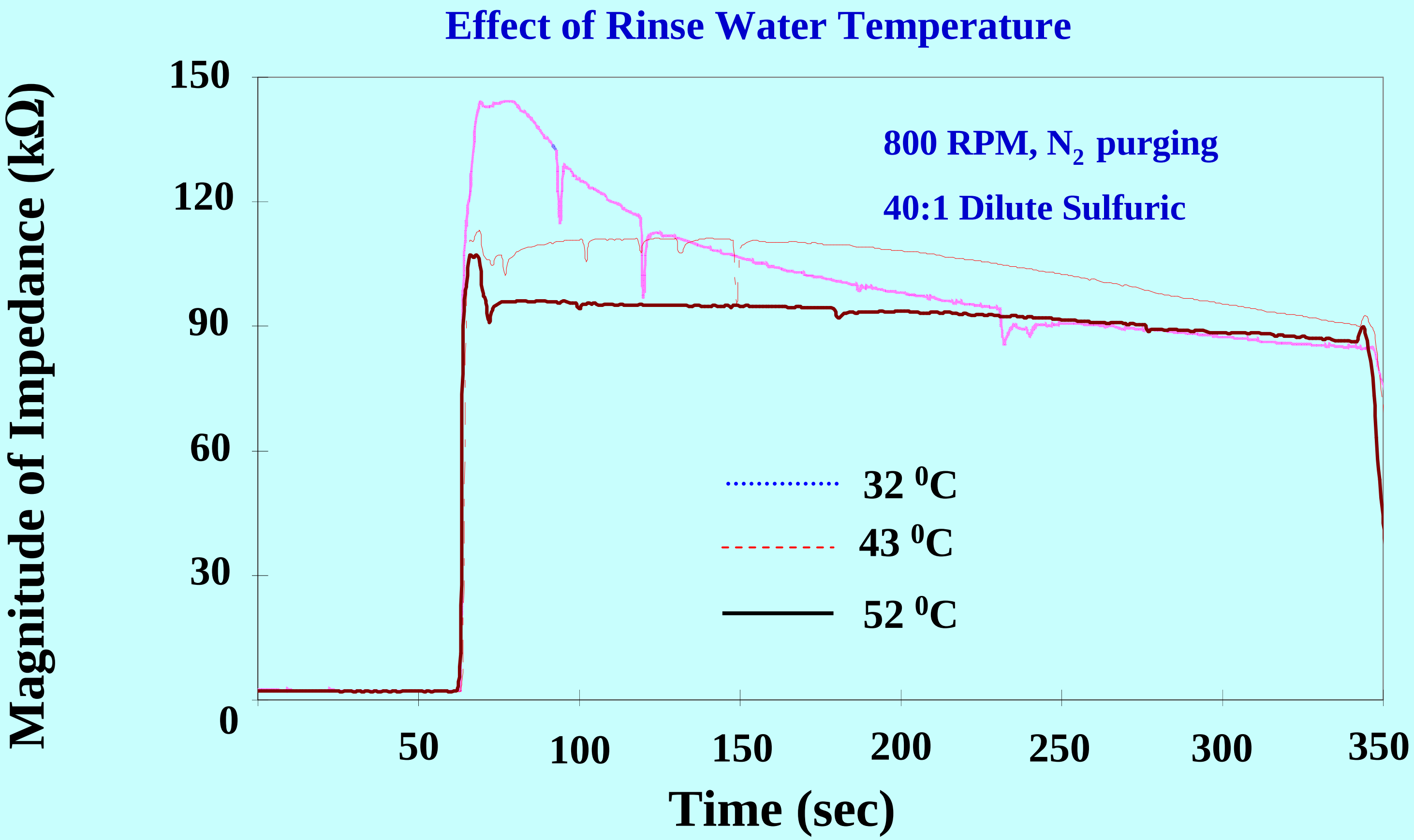
Effect of Process Parameters





- **Gain in rinse efficiency diminishes as we reach an optimum speed of rotation and rinse-water flow rate.**
- **Speed of rotation and water flow rate can be optimized to reduce rinse time and increase throughput.**

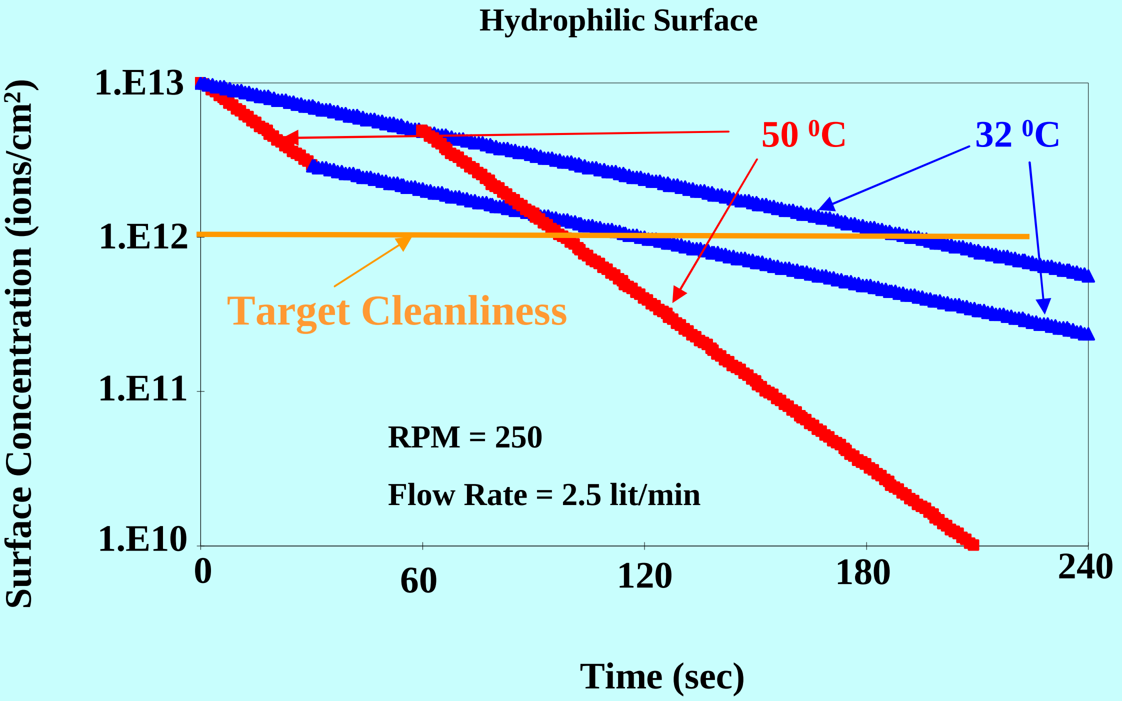
Effect of Process Parameters

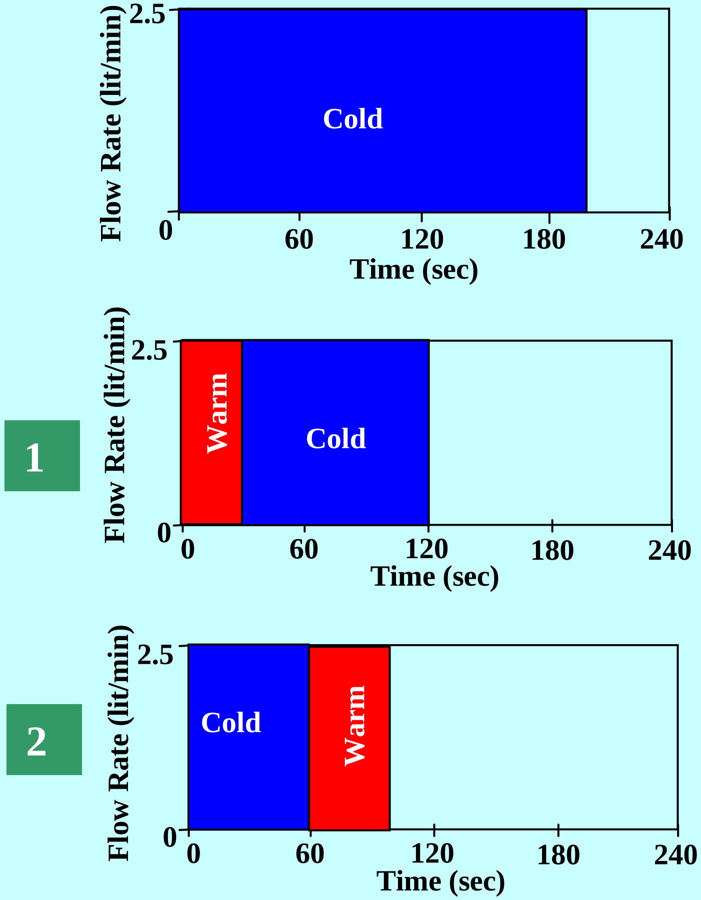


Temperature has significant effect on enhancing both the early stage and the final stage of the rinse process.

Benefits of Staged Rinsing

Post SC-1 Rinsing

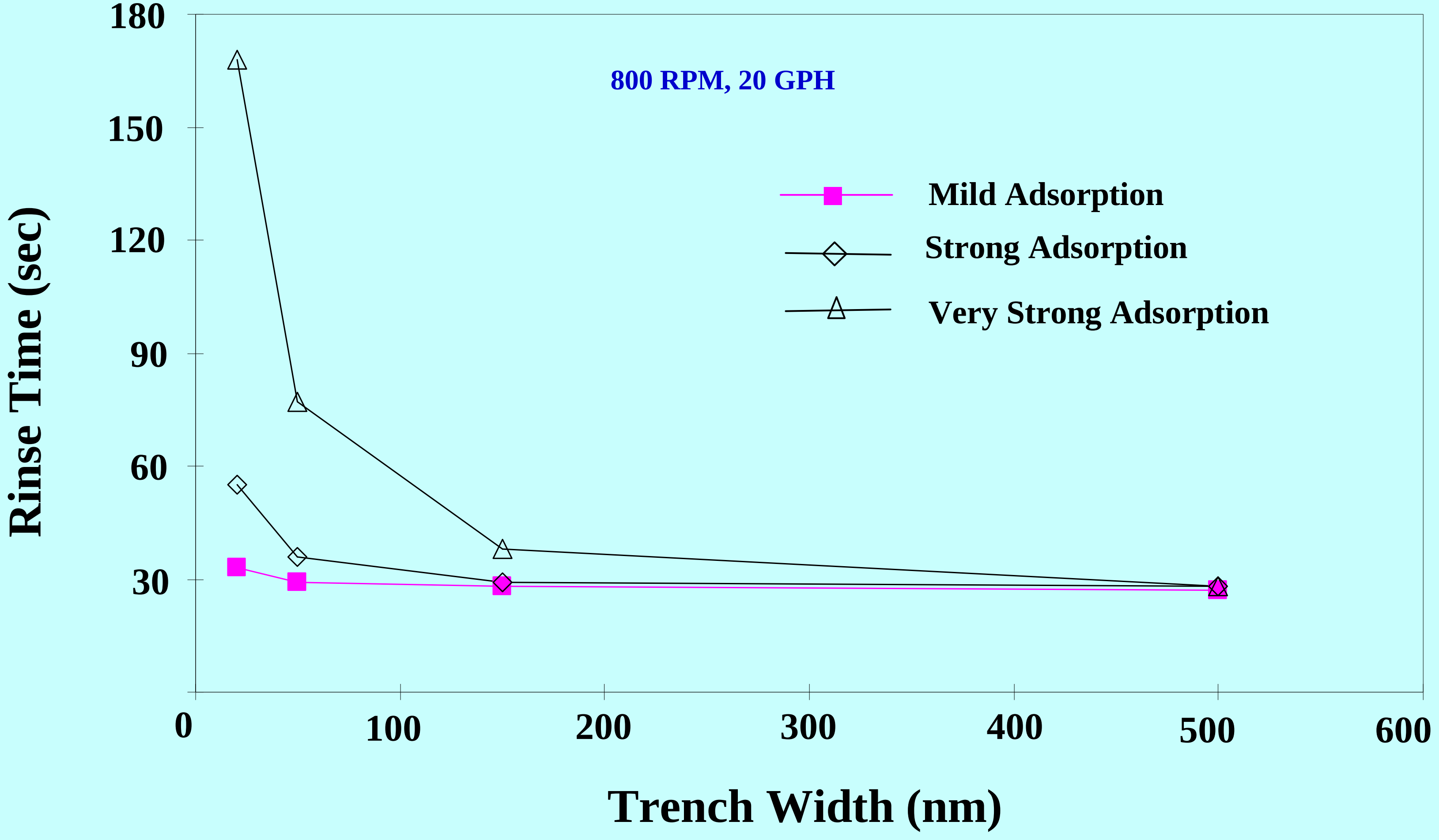




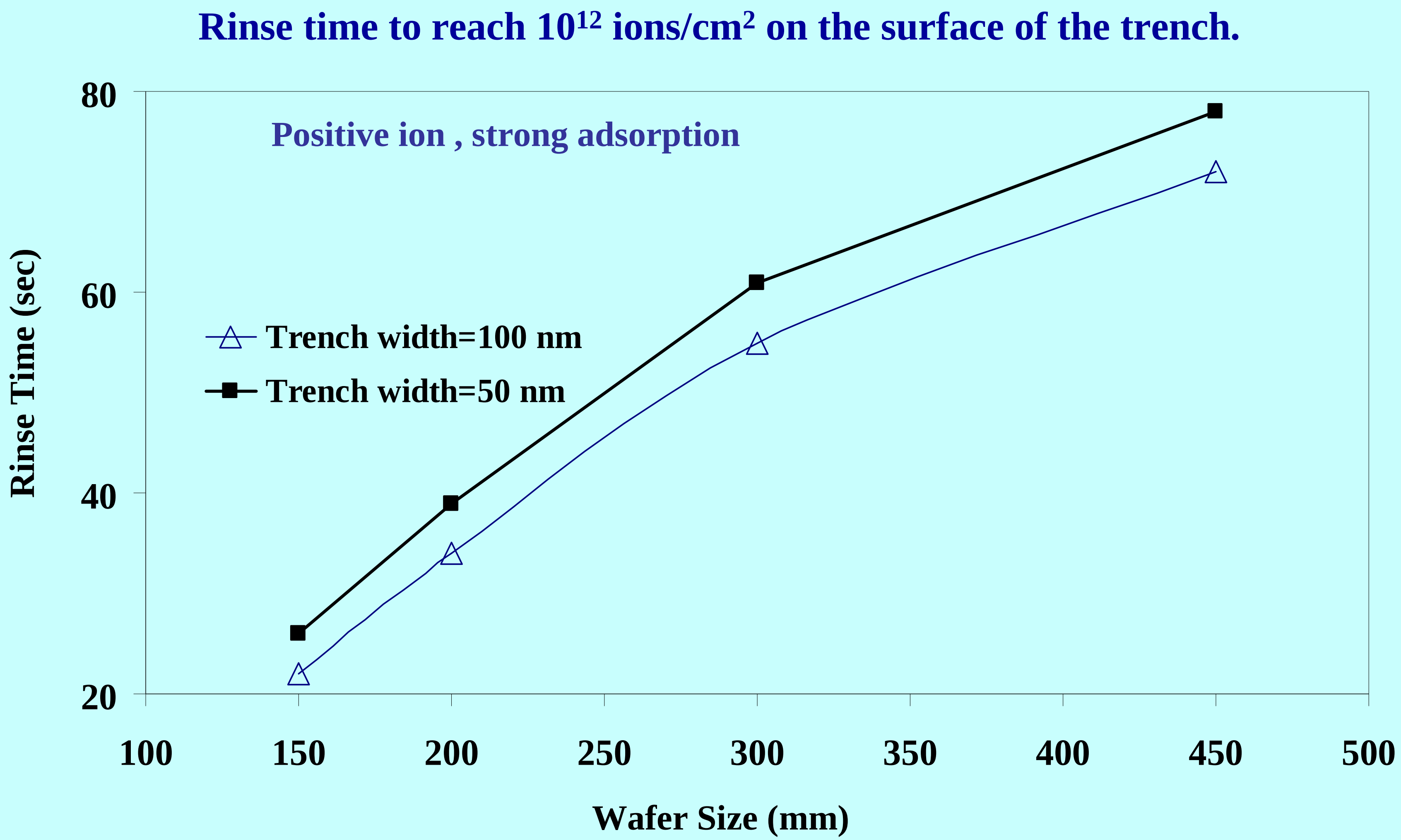
- **Staging temperature of UPW decreases rinse time without sacrificing cleanliness**
- **To reach 1.E12 ions/cm², staged rinsing leads to water savings of 40% for staged rinse “1” and 50% for staged rinse “2”.**

Effect of Feature Size

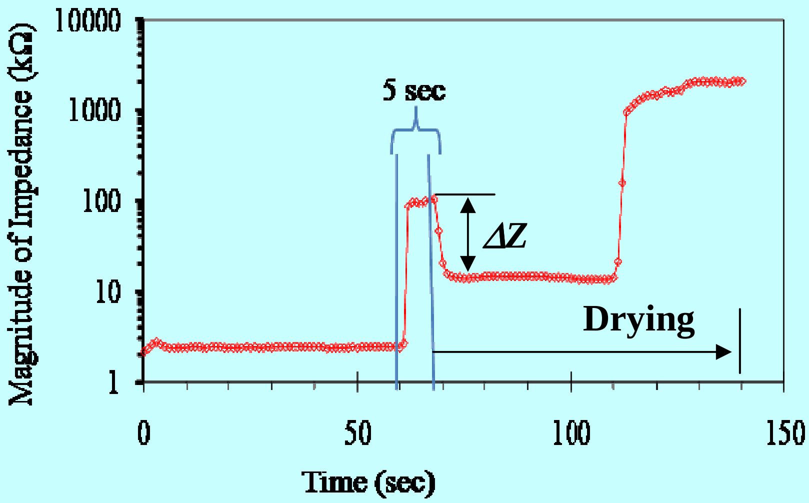
Rinse time to reach 10^{12} ions/cm^2 on the surface of the trench.



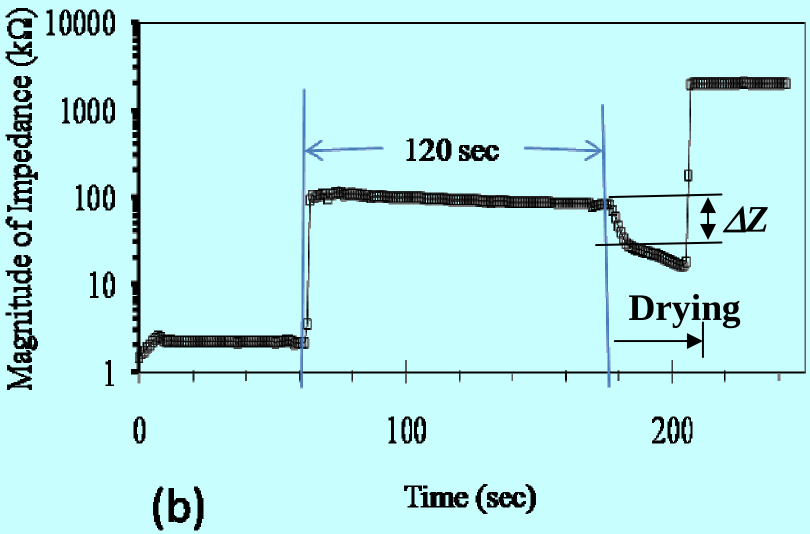
Effect of Wafer Size



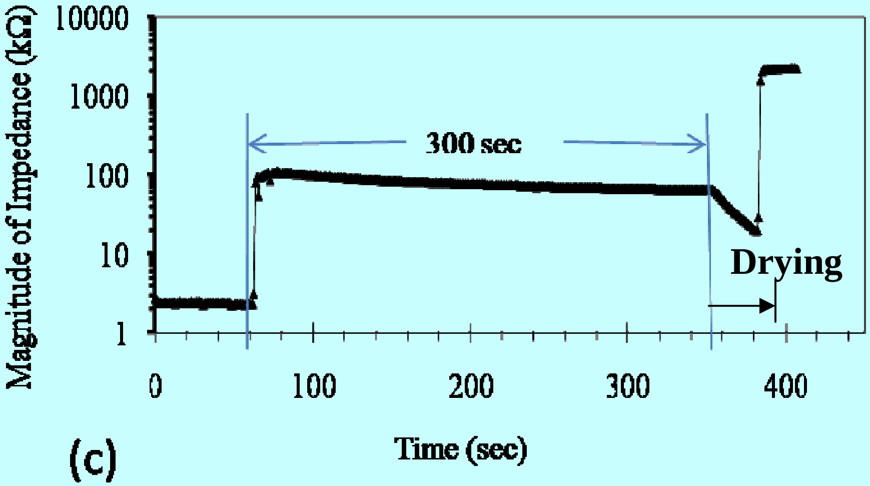
Sensor Responses During Drying



(a)

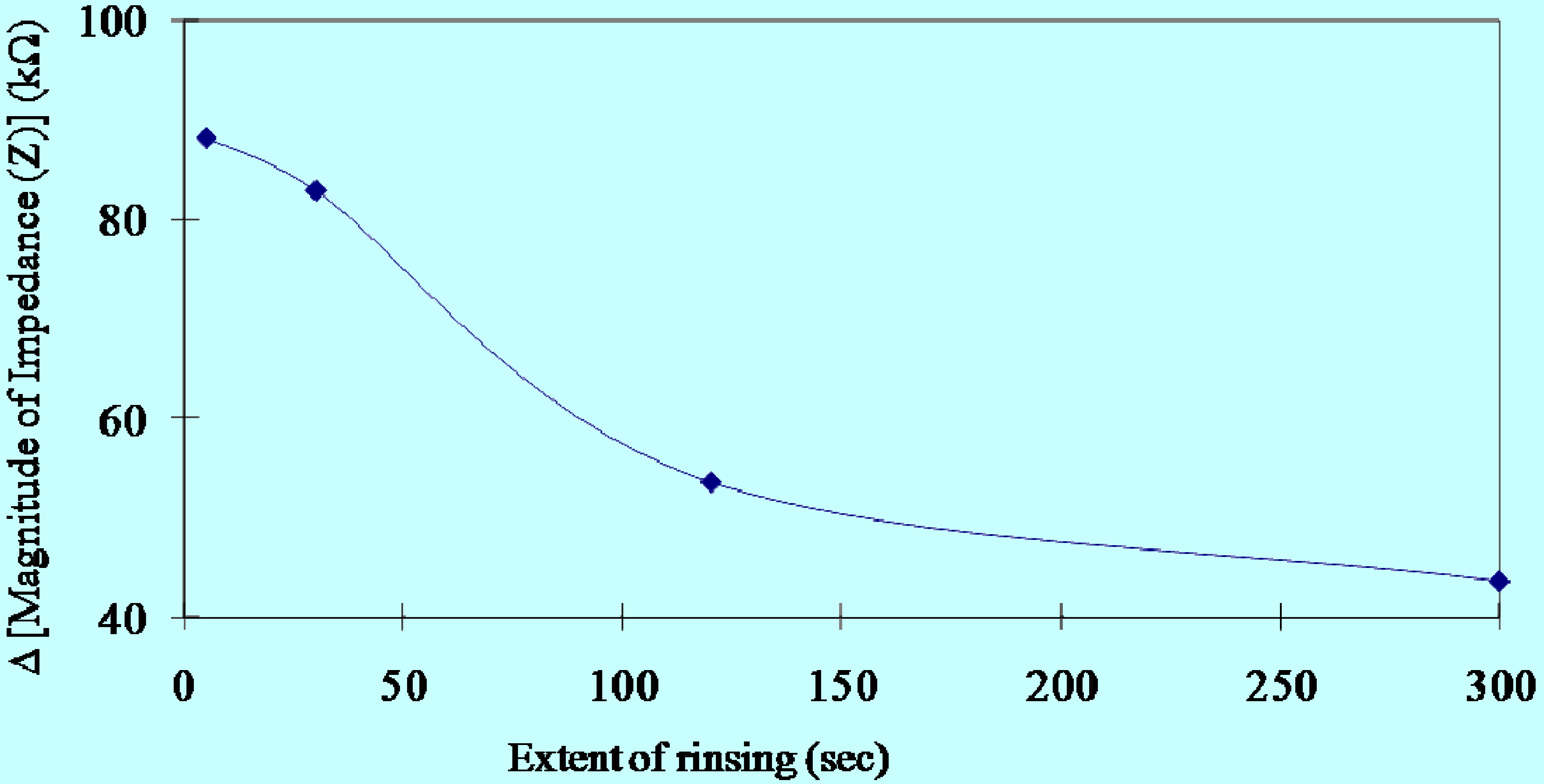


(b)

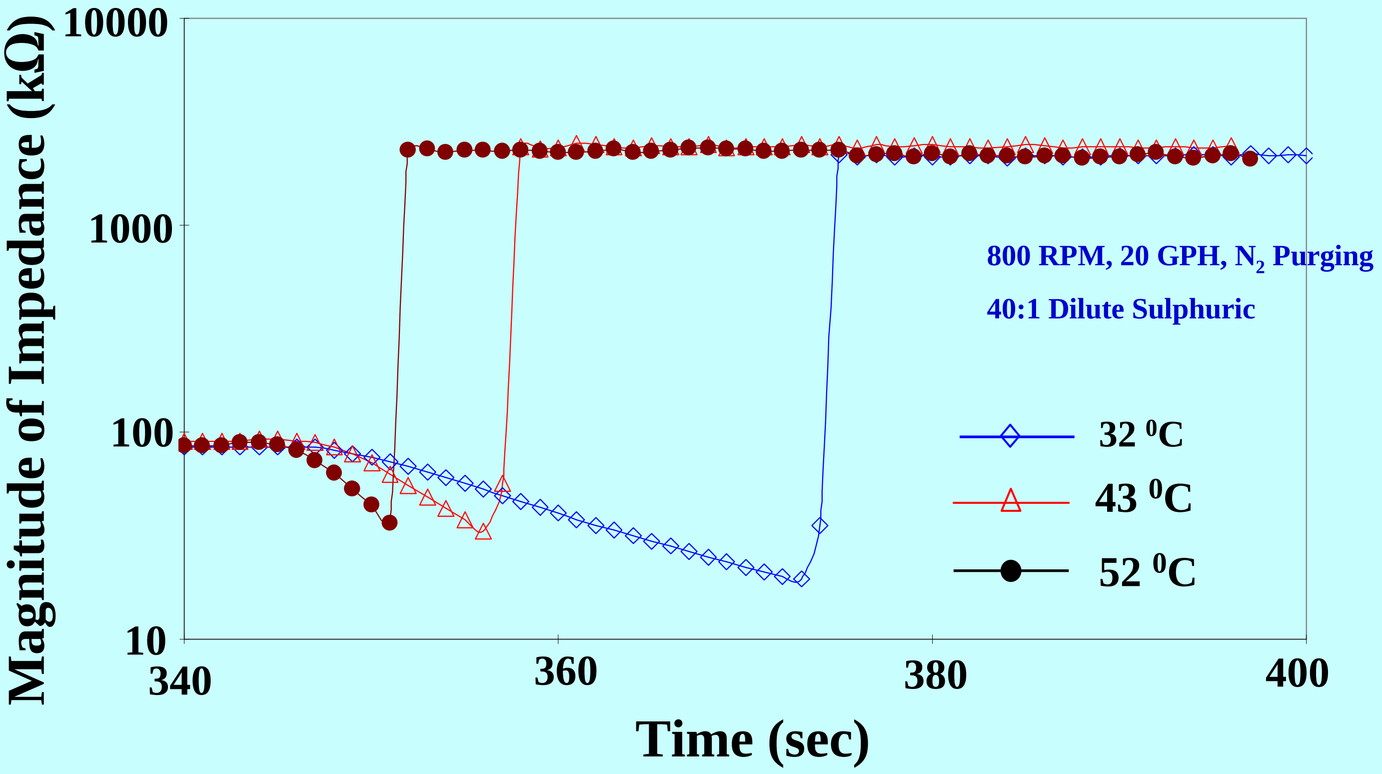


(c)

Indication of Drying Responses



Effect of Rinse Water Temperature on Drying

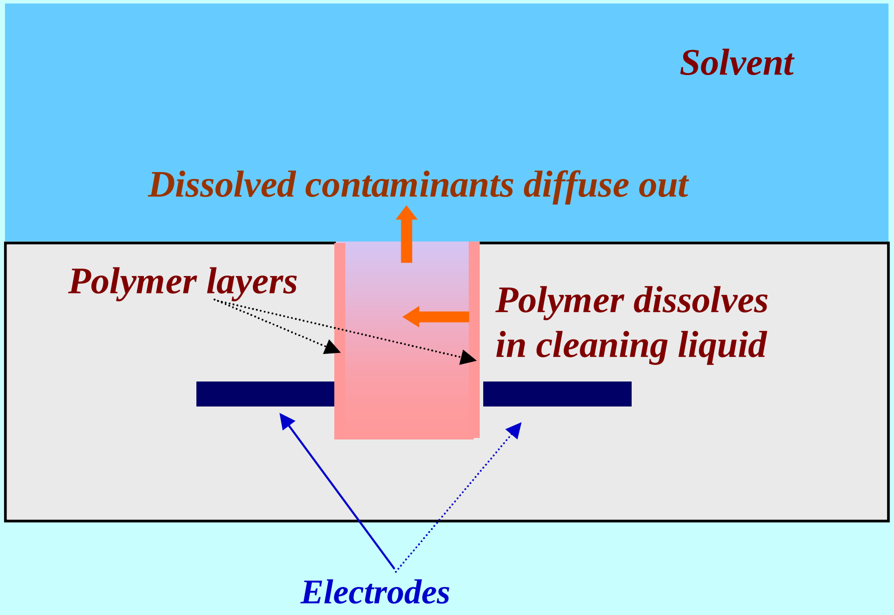


Higher rinse water temperature leads to higher wafer temperature and therefore, faster drying.

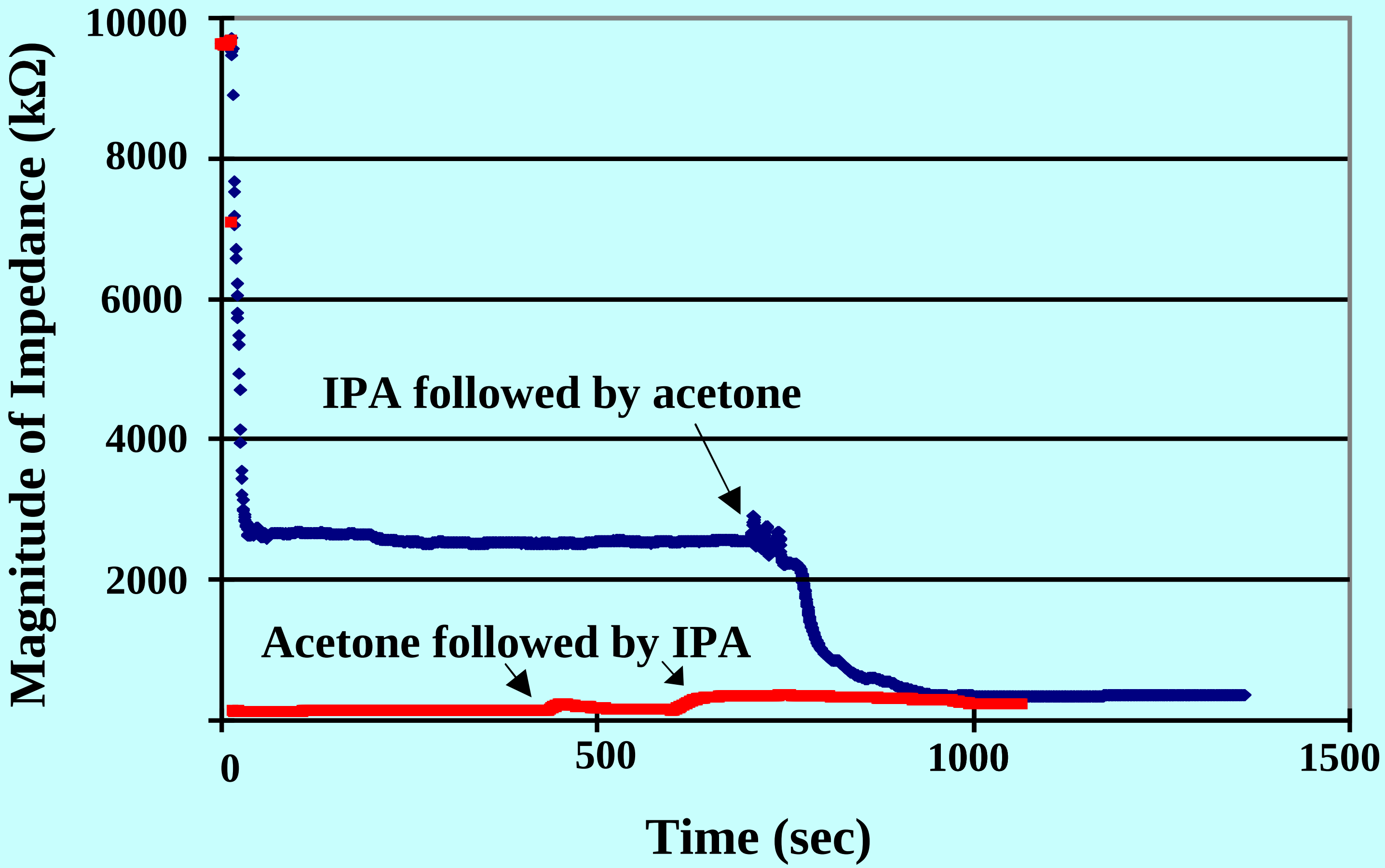
Development of Low-Impact Cleaning

Determining the Bottlenecks Using ECRS

- Etching creates residues on the sidewalls of the trenches and vias.
- Side wall cleaning becomes more complex, more difficult, and more resource intensive as we move further into manufacturing of high-aspect-ratio nano-features
- No in-situ sensor is available for on-line monitoring of residues; ECRS would result in significant reduction in use of cleaning chemicals.

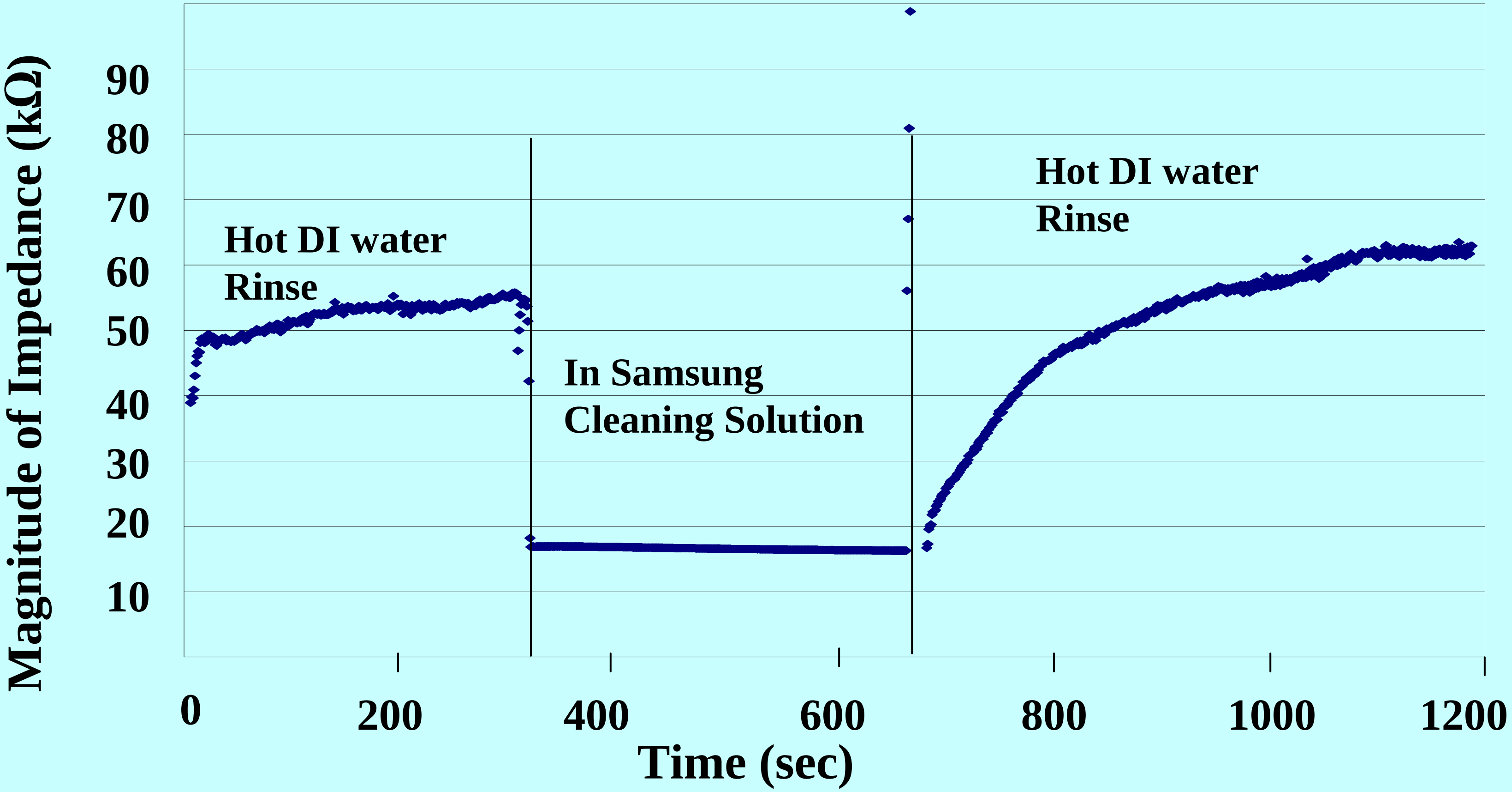


Post-etch Cleaning of Micro- and Nano-Structures



High sensitivity and a detection of the end point

Cleaning of Micro- and Nano-Structures



ECRS can monitor cleaning of the polymer residue inside trench

Summary

- ECRS hardware was developed and fabricated.
- Developed comprehensive process simulator and verified it for both batch overflow rinsing and single-wafer spin rinsing; the simulator is applicable to rinsing and cleaning of fine structures on patterned wafers.
- Developed a method for integrating ECRS with single-wafer tools.
- Applied ECRS to determine the effect of key process parameters such as flow rate, rinse water temperature, and speed of rotation. Rinse and dry recipes can be optimized by applying the real-time and in-situ metrology using ECRS and the associated process simulator.
- The impact of feature size and wafer size was studied by ECRS.

Industrial Interactions and Future Plans

- Continue work on application and tech transfer:
  - Joint work, co-sponsored by Freescale (Hsi-An Kwong, Marie Burnham, Tom Roche, Andrew Hebda); rinse process
  - Joint work, co-sponsored by Samsung (Seung-Ki Chae, Jeong-Nam Han, Pil-Kwon Jun); cleaning and rinse processes
  - EMC (Doug Goodman); commercialization
- Fundamental work on a novel wireless metrology version of ECRS
- Acknowledge to all the partners and co-workers