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

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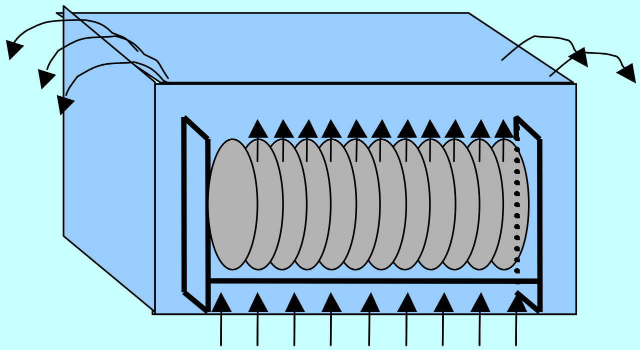
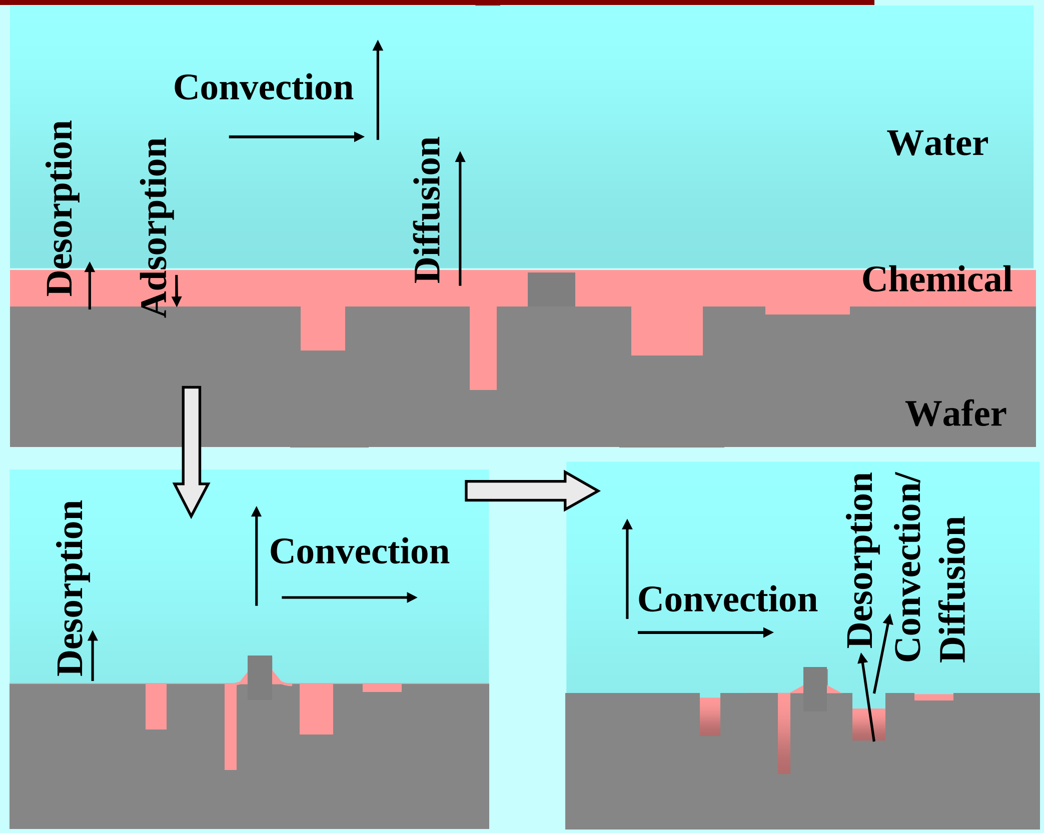
Objective and Approach

- 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.

Low-Water Rinse Requirement

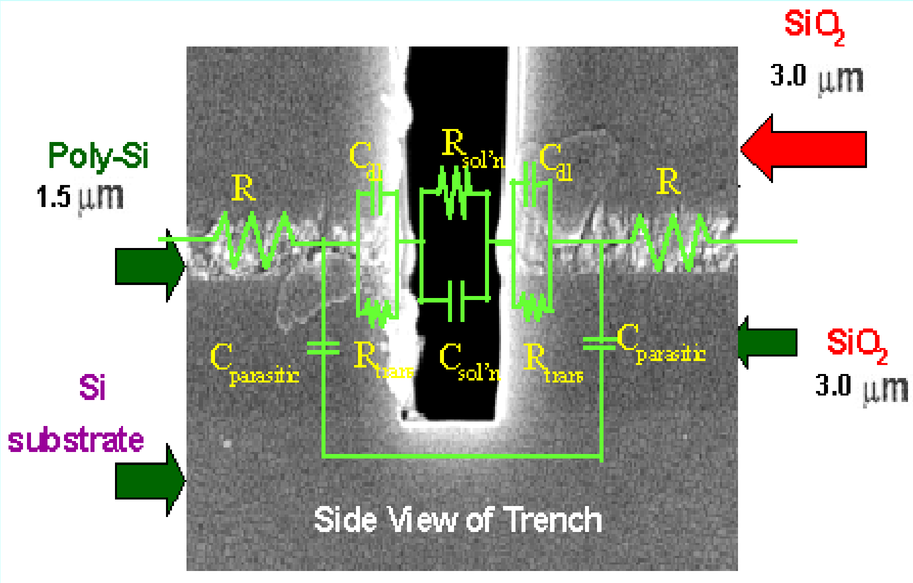


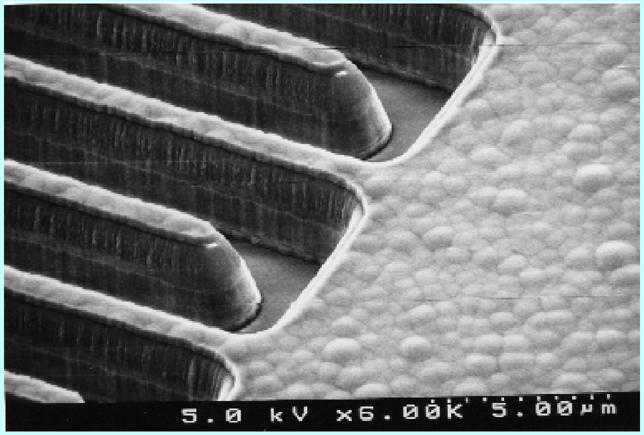
Over-Flow Rinse Process

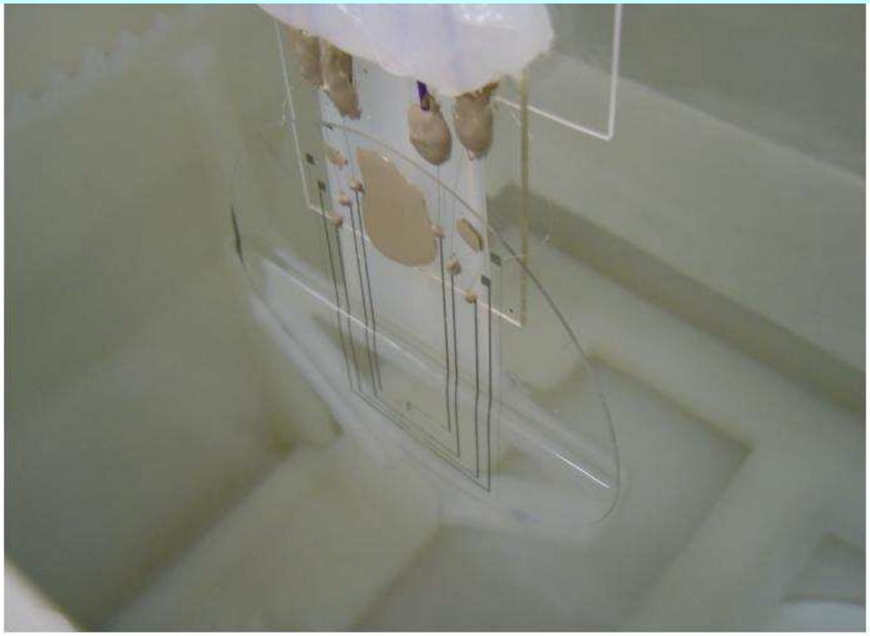


- Rinse progress is monitored by bulk or bath outlet resistivity measurements
- Fundamentals of rinsing patterned wafers are poorly understood
- Key to low-water rinse is on-line metrology; technology not available presently

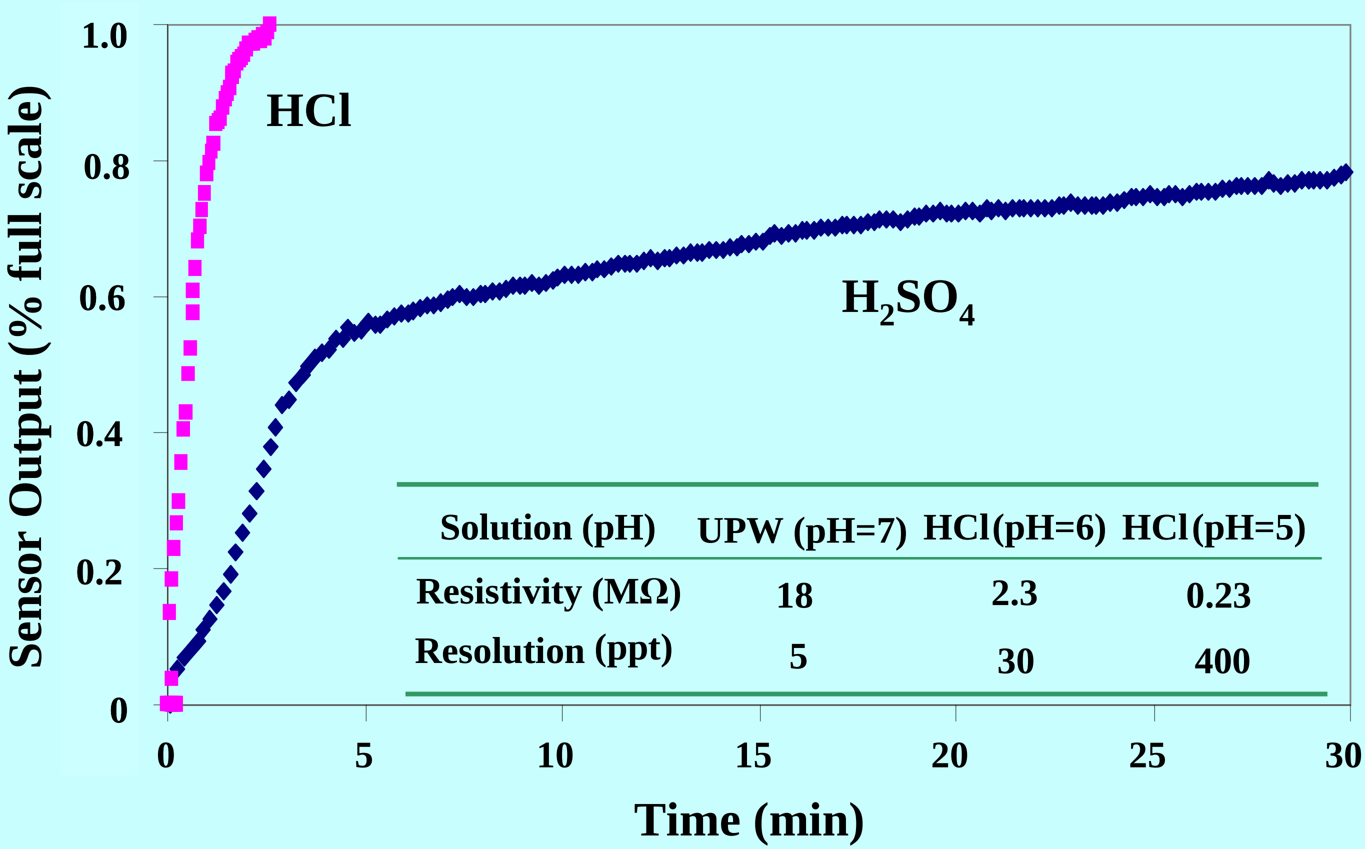
Novel Hardware: Electro-Chemical Residue Sensor (ECRS)







Clean Chemistry Dependence of Rinse

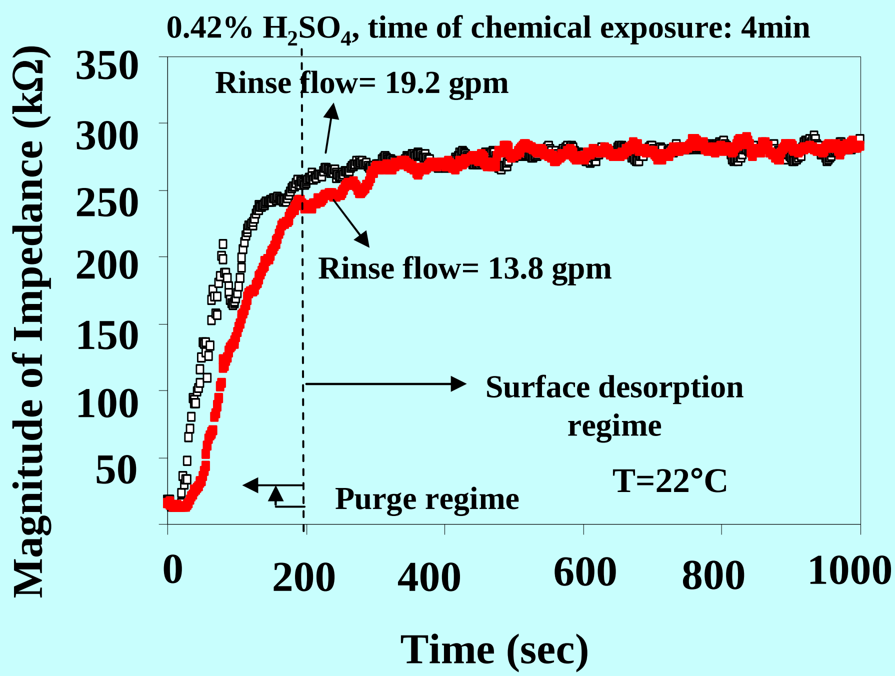


Solution (pH)	UPW (pH=7)	HCl(pH=6)	HCl(pH=5)
Resistivity (MΩ)	18	2.3	0.23
Resolution (ppt)	5	30	400

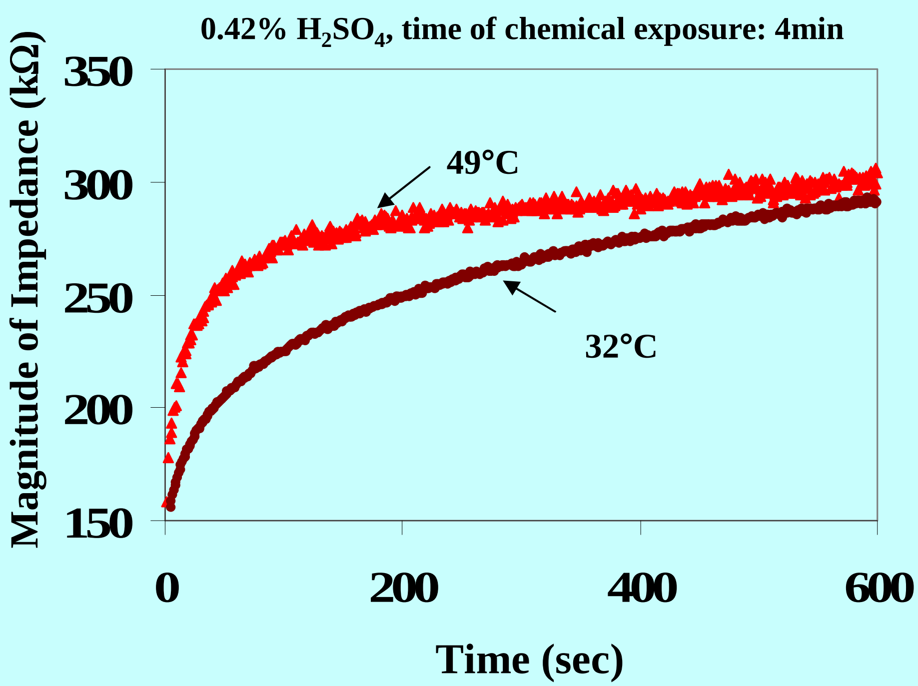
Sensor shows different rinse dynamics for different chemicals

Parametric Dependence of Rinse

Flow rate effect



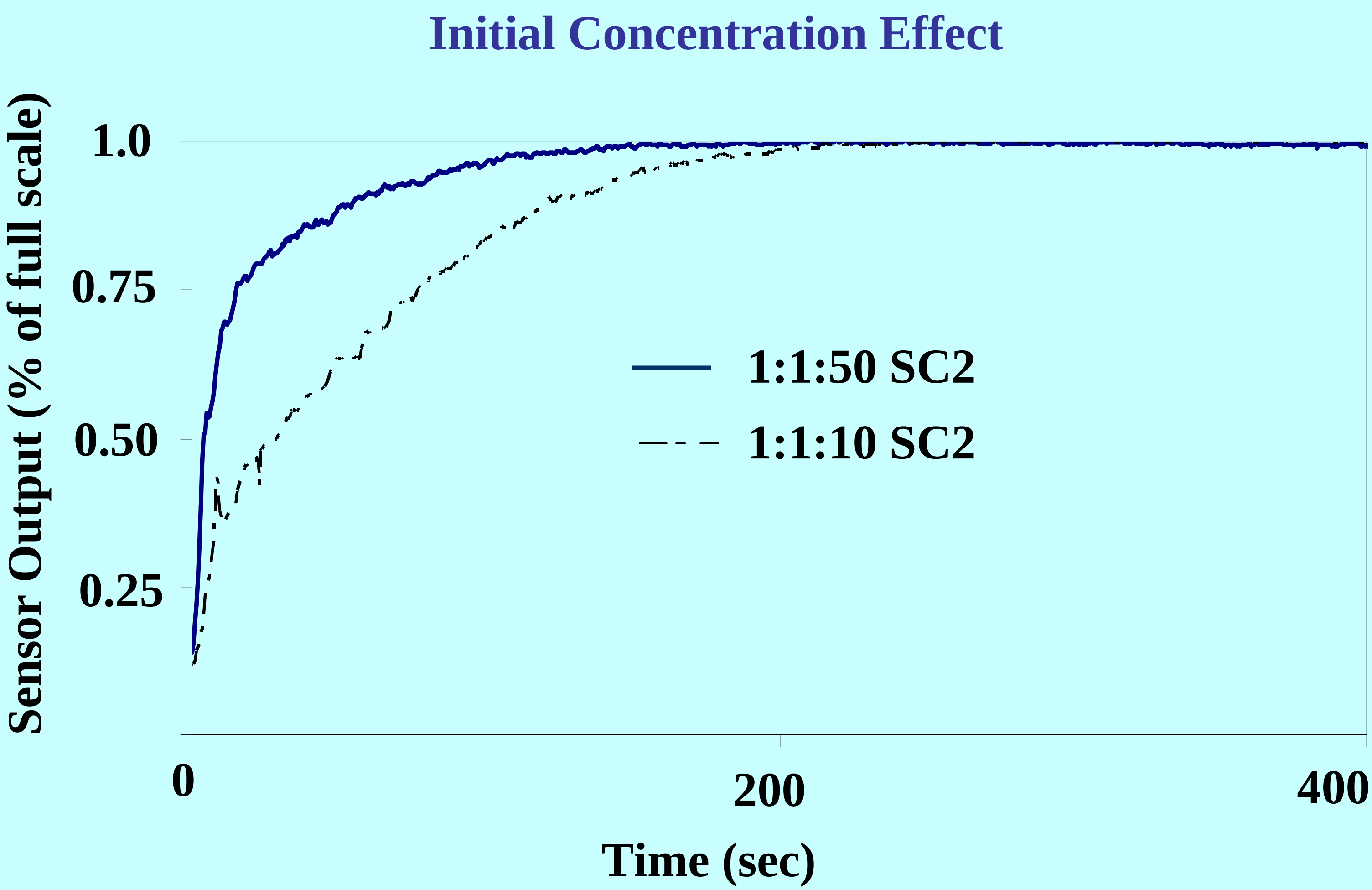
Temperature effect



Sensor shows the effects of various process parameters

Parametric Dependence of Rinse

SC2 Rinsing



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

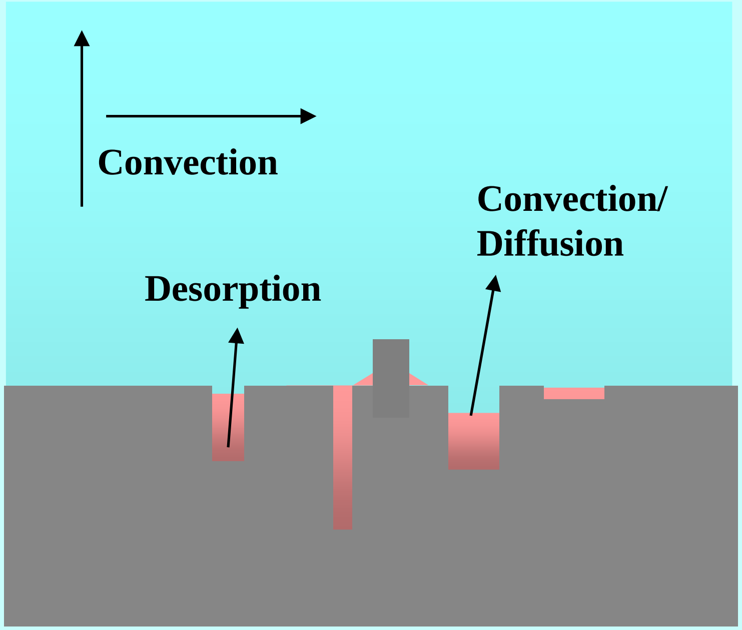
where charge density: $\rho = F \sum_i z_i C_i$

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

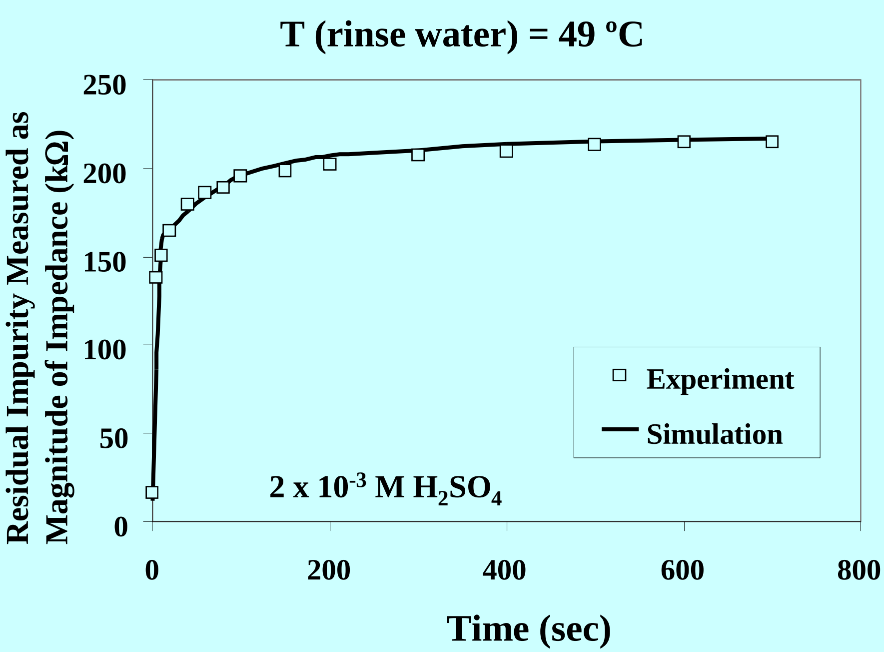
where electrical conductivity:

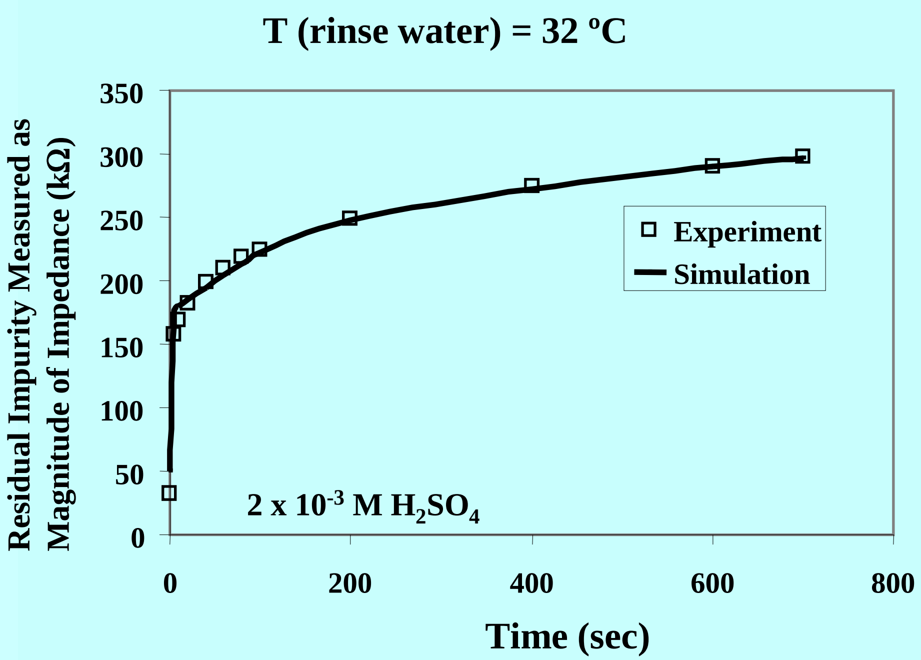
$$\sigma = \sum_i \lambda_i C_i$$

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



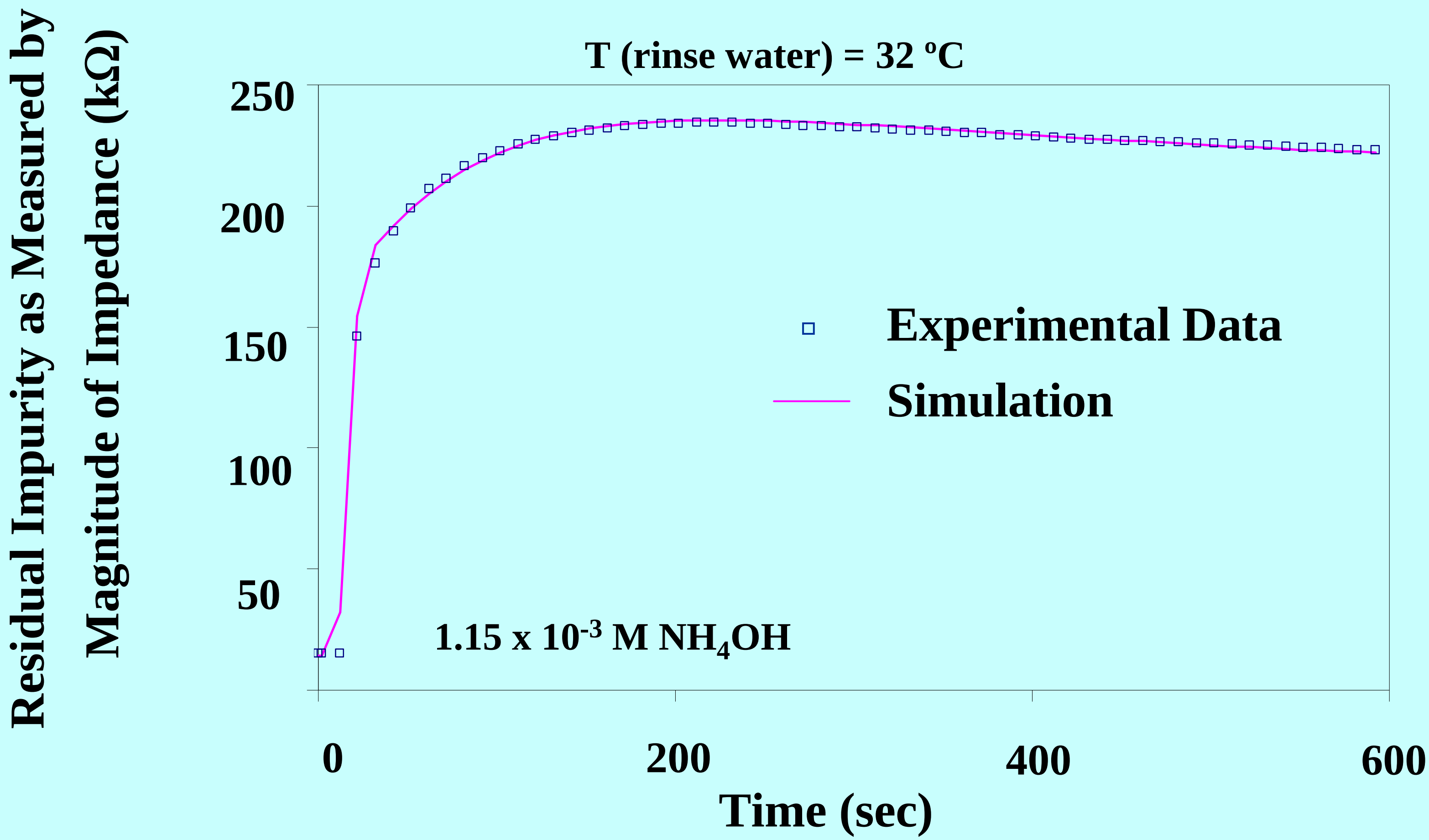
Comparison of Experimental Data with Model Prediction: H_2SO_4





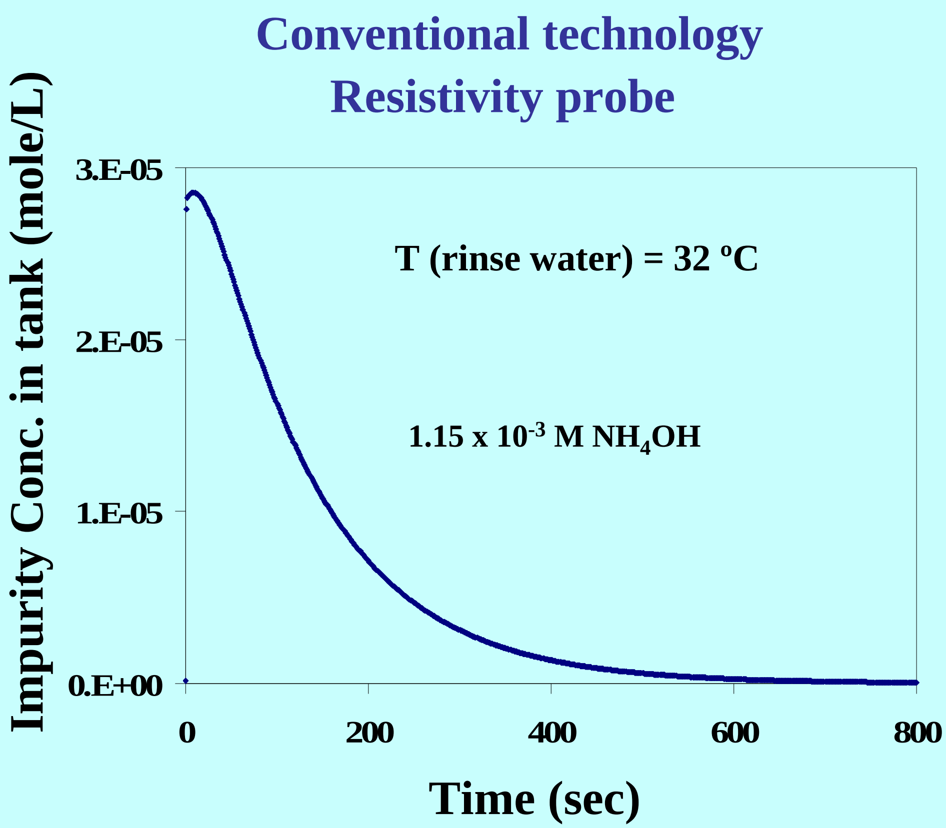
- **Accurate modeling of the surface cleanup during rinse is possible**
- **Surface cleanup model can be combined with a tank model to obtain a comprehensive rinse model**

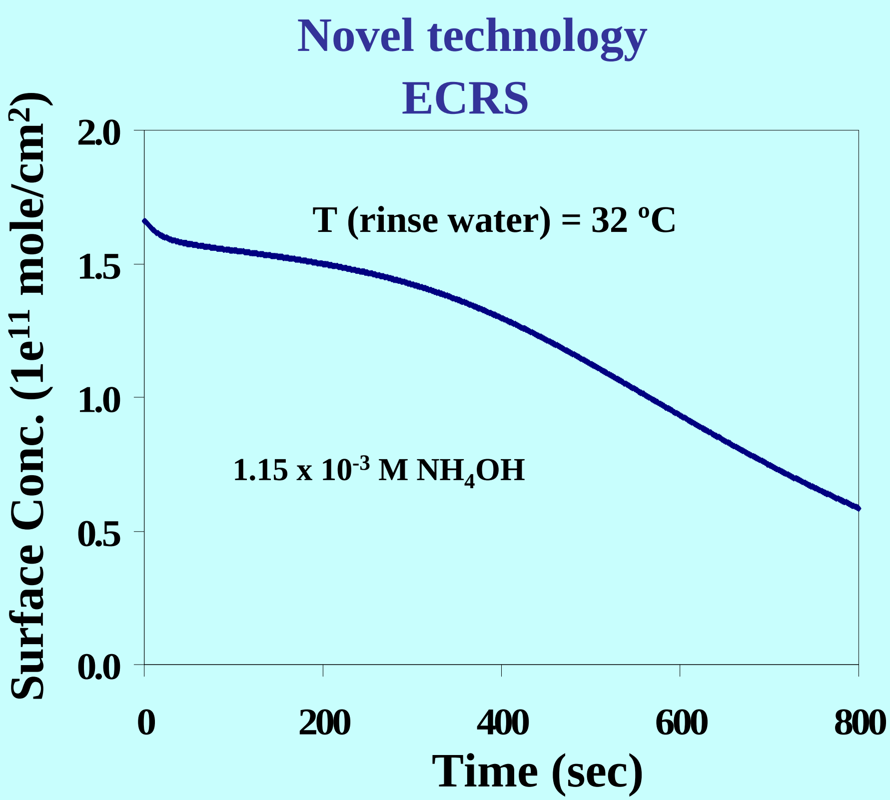
Comparison of Experimental Data with Model Prediction: NH4OH



Surface cleanup during rinse is chemistry-dependent

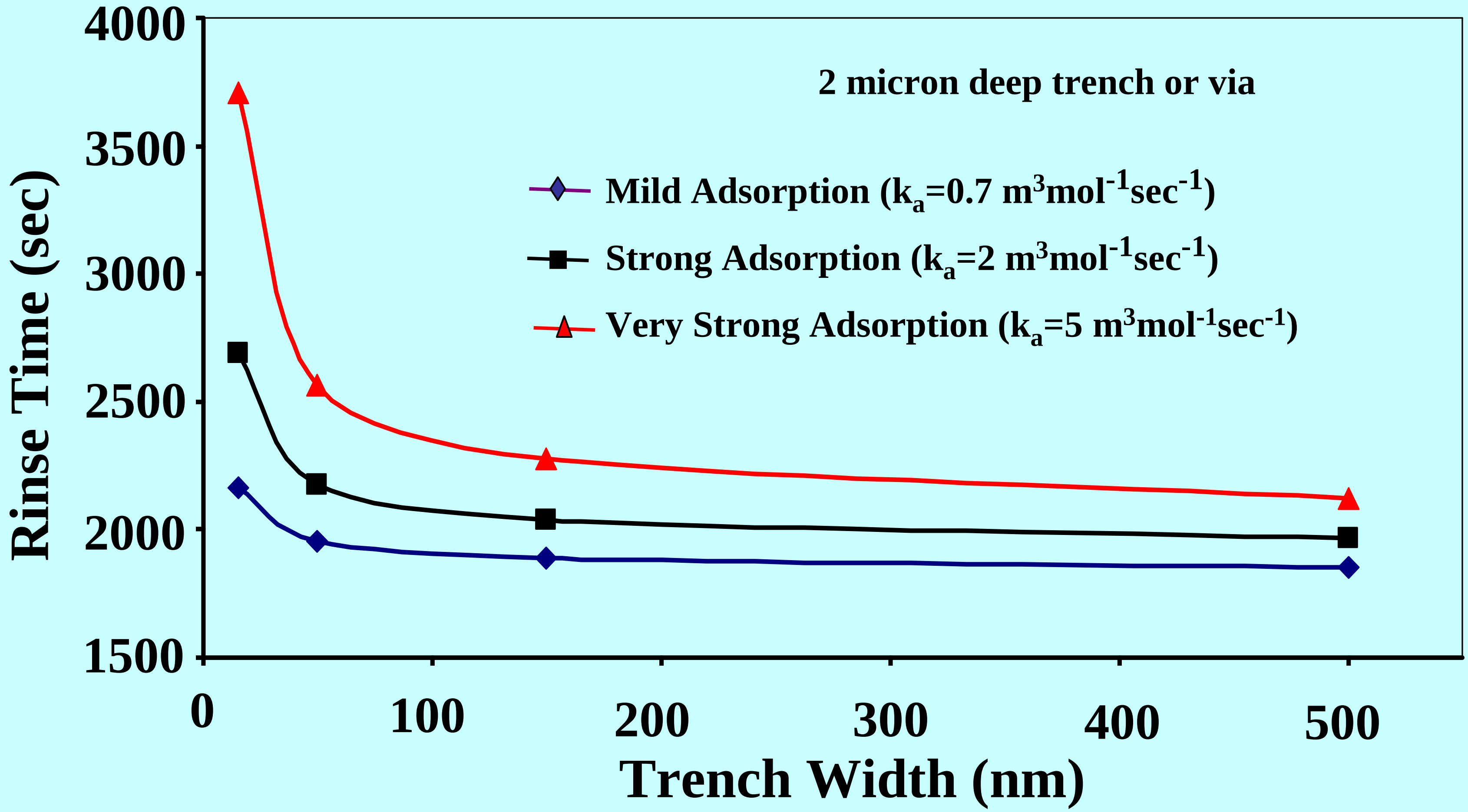
Surface Concentration Profile





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

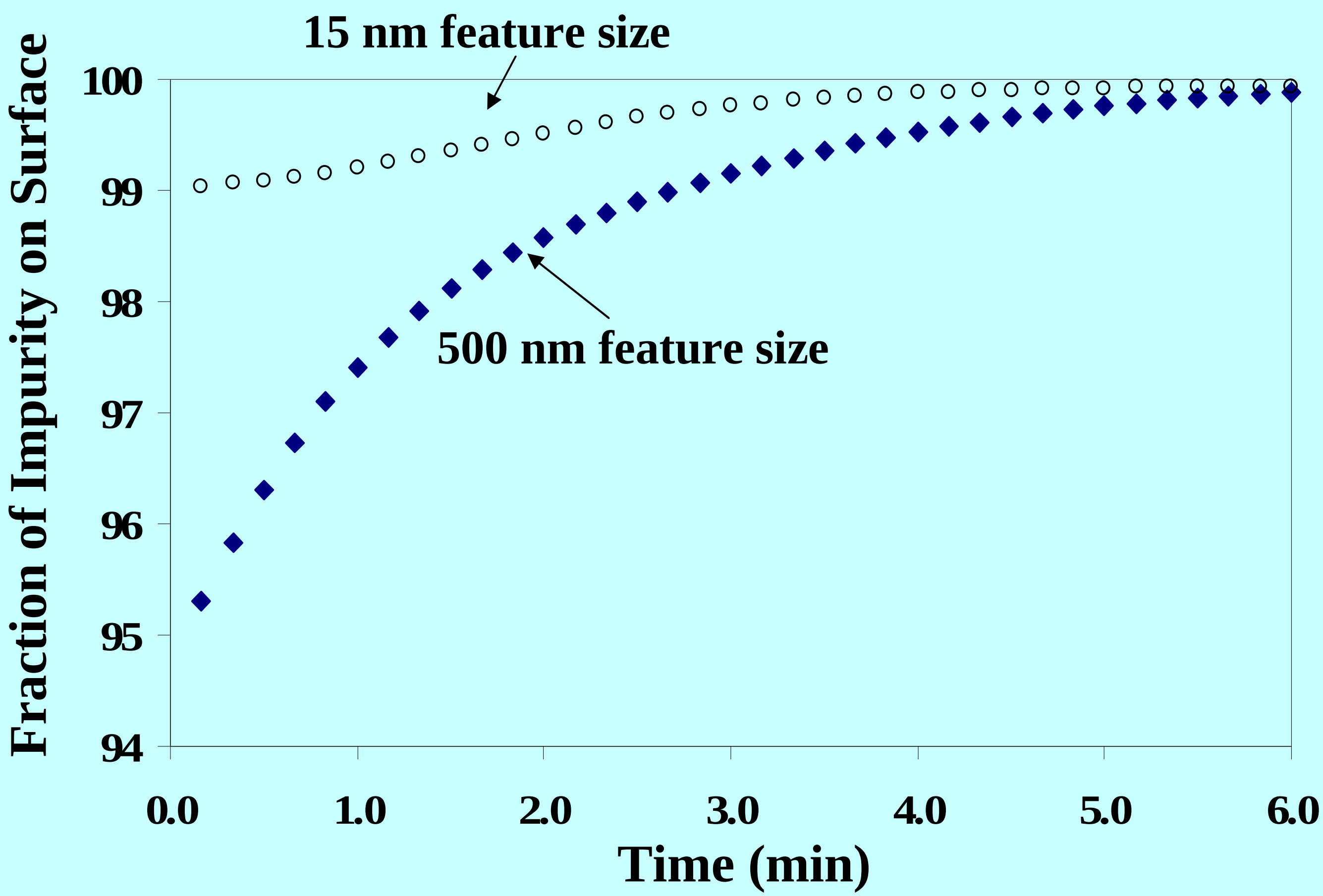
Effect of Micro-Feature Size on Rinse Time and Water Usage



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

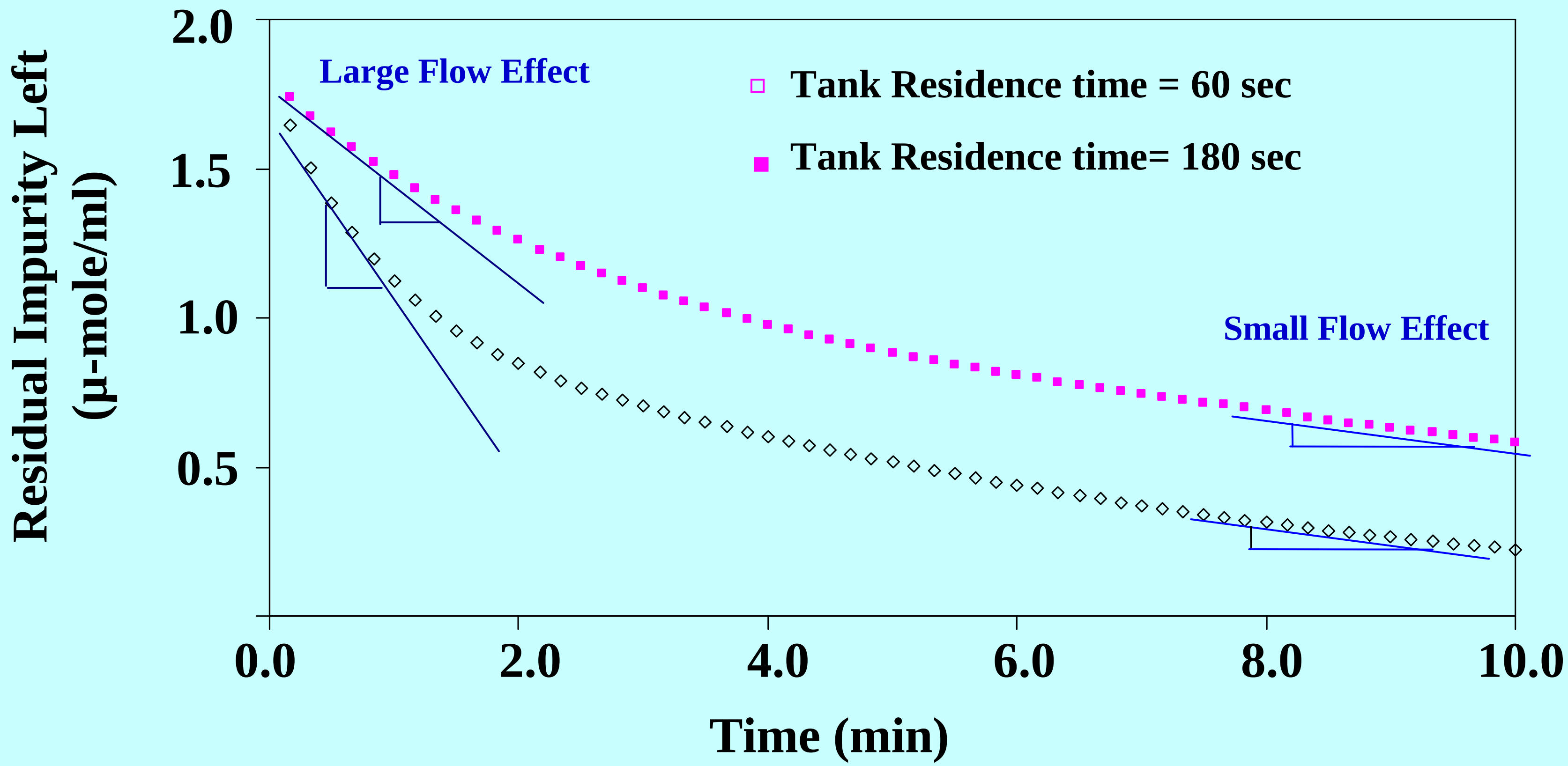
Rinse Mechanism and Dynamics

2 micron deep trench or via, mild adsorption



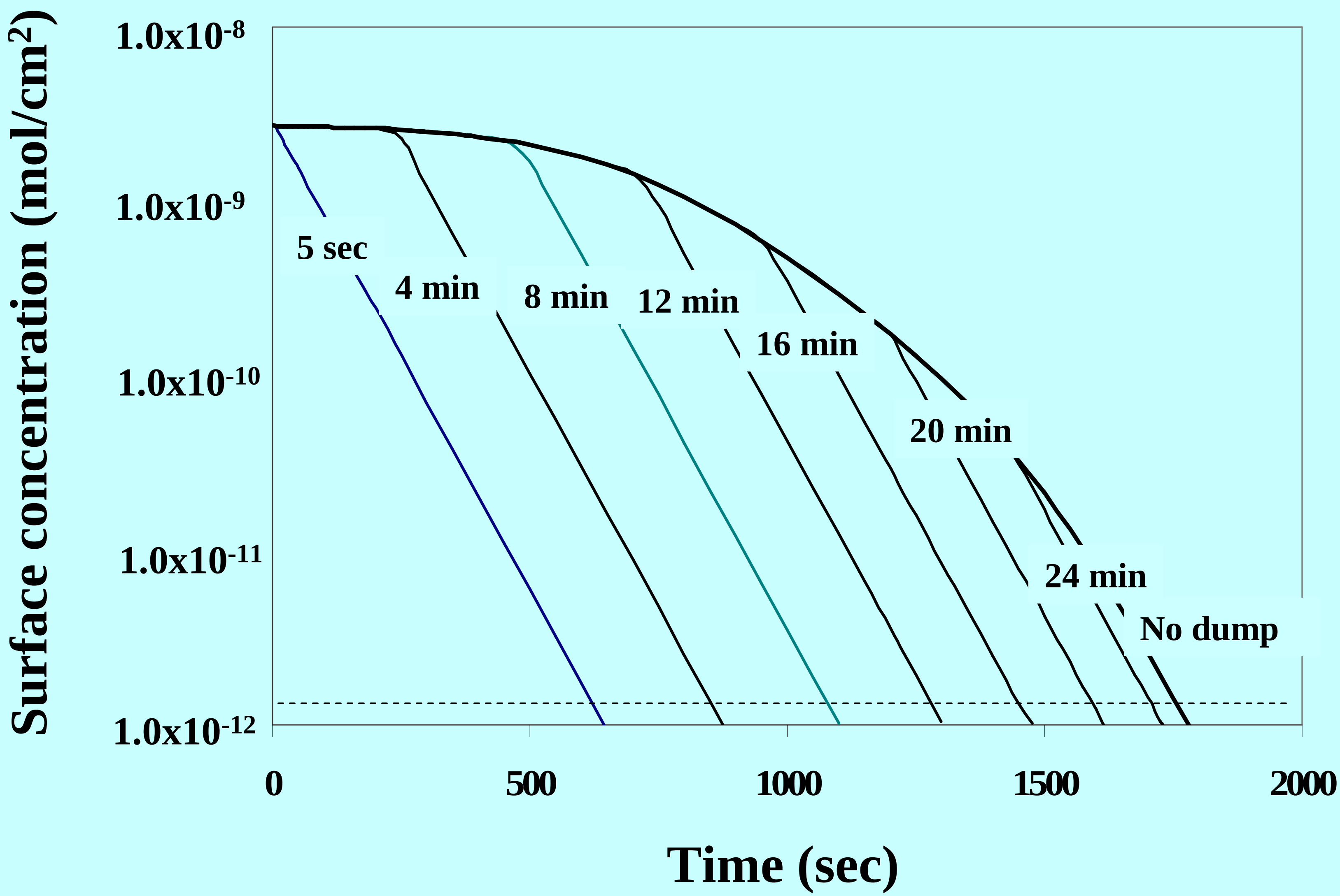
Effect of Flow on Rinse Dynamics

width- 500 nm, mild adsorption



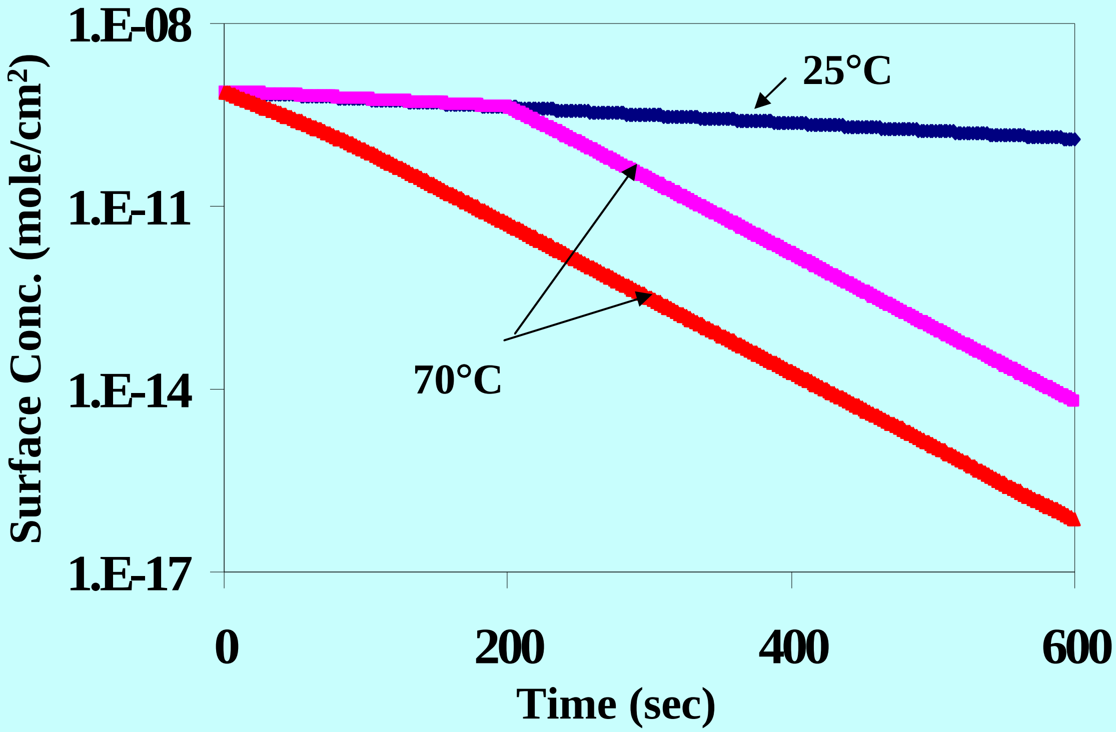
Large savings and water use reduction are possible with staged flow rate based on the proposed metrology.

Dump Rinse Dynamics



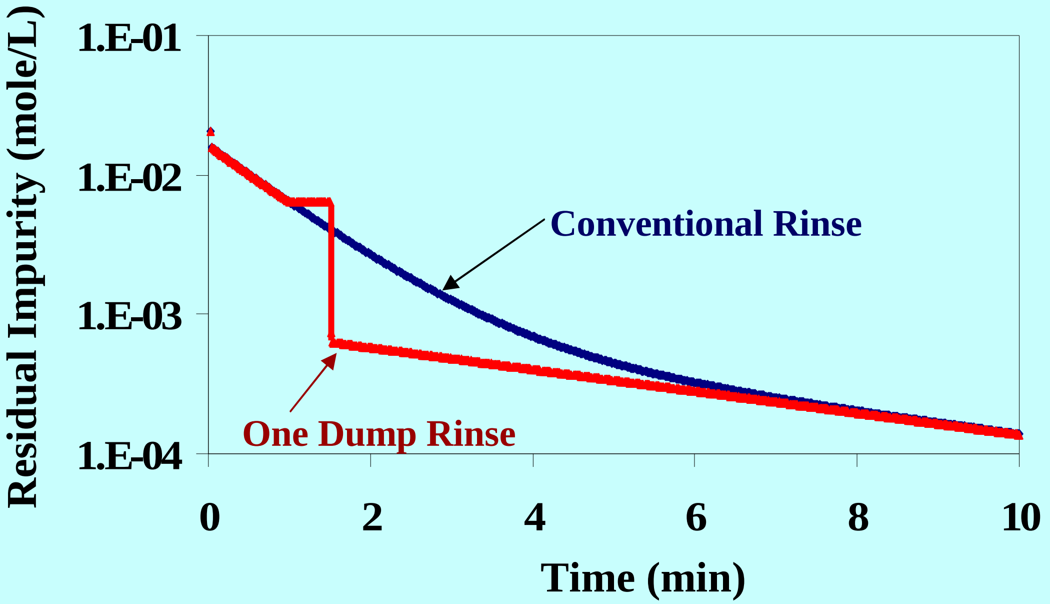
Rinsing Dynamics Enabled by the Model

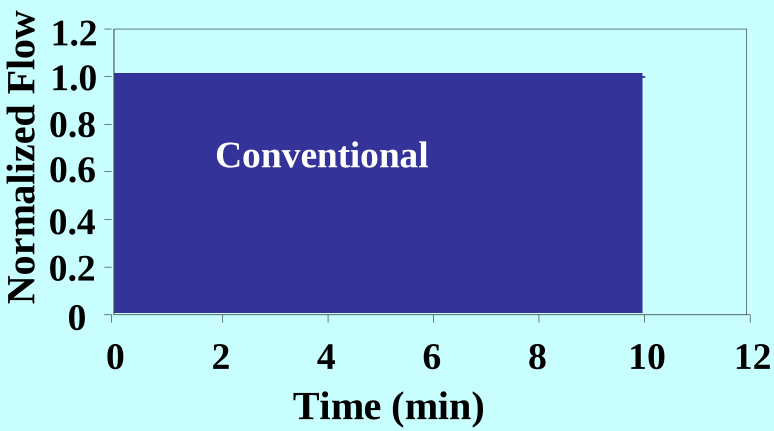
Temperature effect

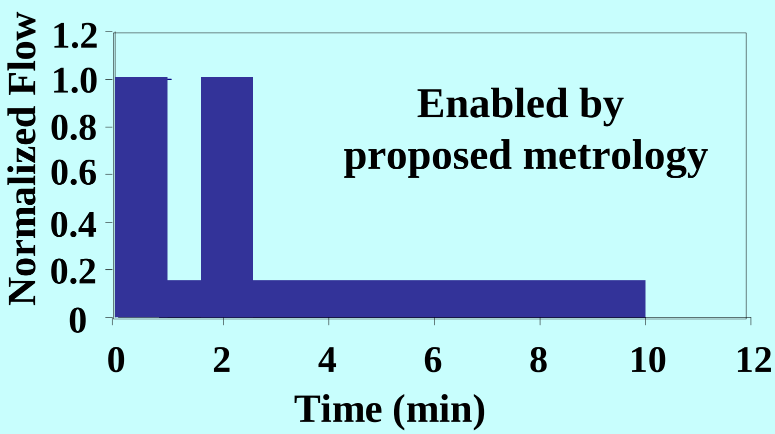


The process model associated with the ECRS provides the capability for theoretical parametric study

ECRS Rinsing Application







New rinse recipe enabled by ECRS can save up to 72% water

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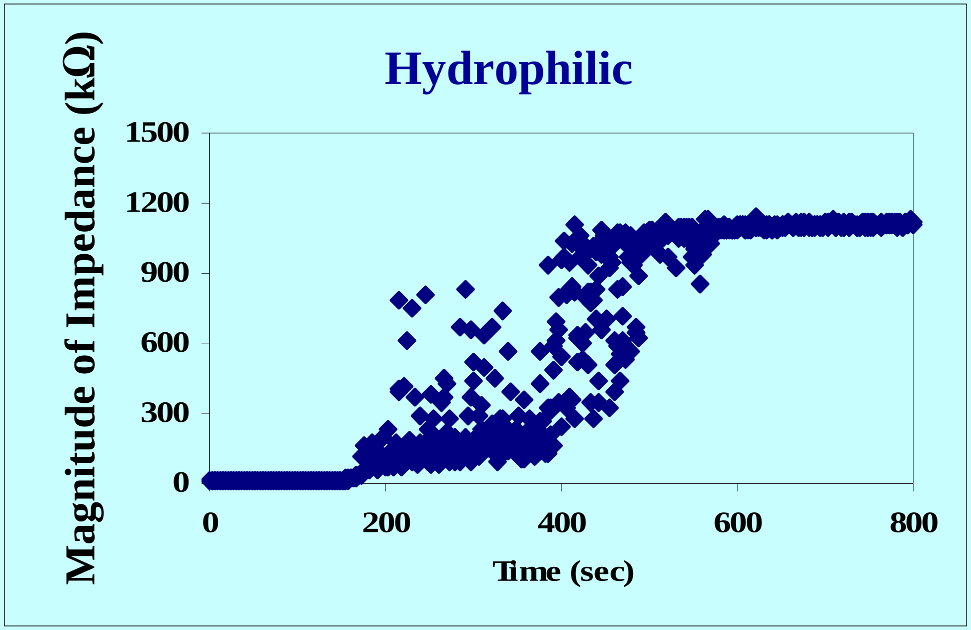
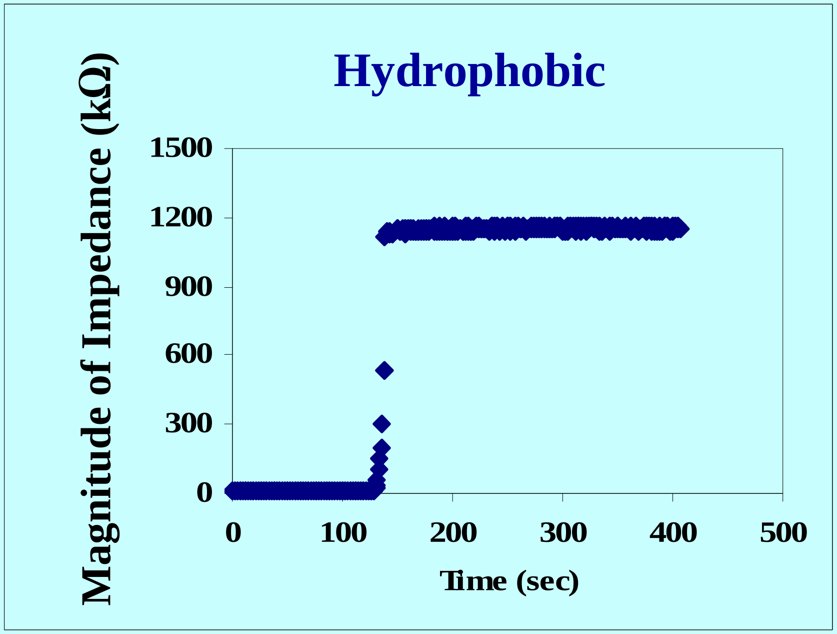
Part -2

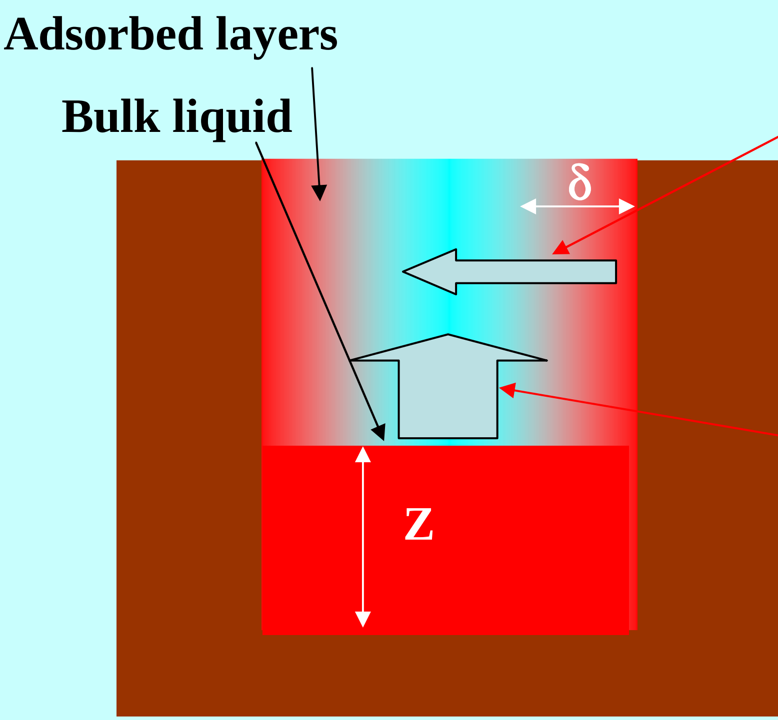
Typical Drying Data





- Time required for drying depends on the surface condition.
- ECRS detects complex mechanism for drying, particularly for hydrophilic surfaces.

Mechanism of Drying of Small Structures



Removal rate from adsorbed layer:

$$R_d = k_d C_s - k_a C_g$$

$$k_a = k_{aI} + (k_{aII} - k_{aI})\frac{\theta}{1+\theta}$$

$$k_d = k_{dI} + (k_{dII} - k_{dI})\frac{\theta}{1+\theta}$$

Removal rate from bulk liquid:

$$R_e = k(P_{sat} e^{-\frac{\alpha}{w}} - P_{bulk})$$

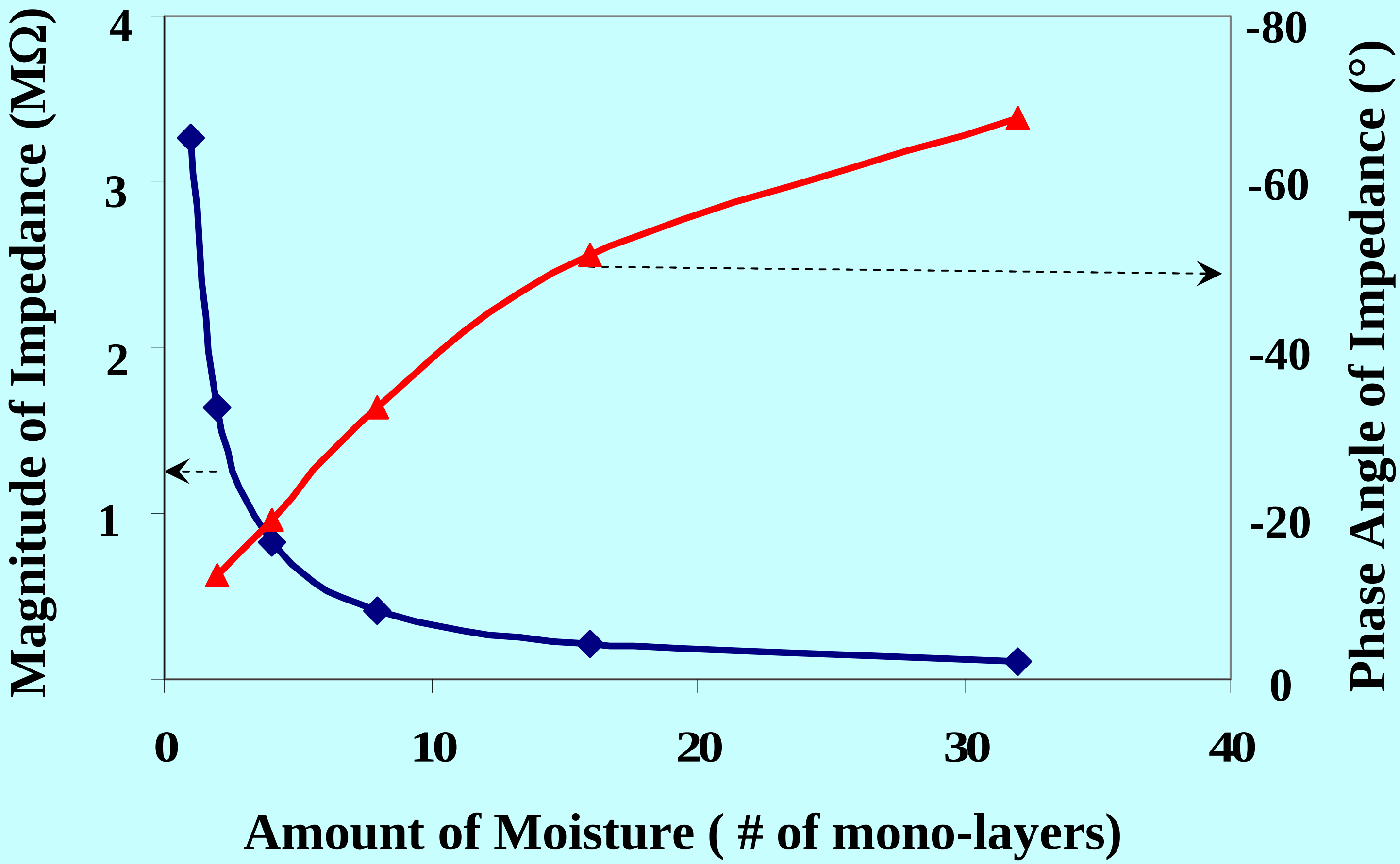
Total removal rate from pore:

$$R = R_e + R_d$$

Two simultaneous processes:

- **Conventional evaporation of liquid-like molecules (mild feature size effect)**
- **Adsorption and desorption in a multi-layer (both chemisorbed and physisorbed; strong feature size dependence)**

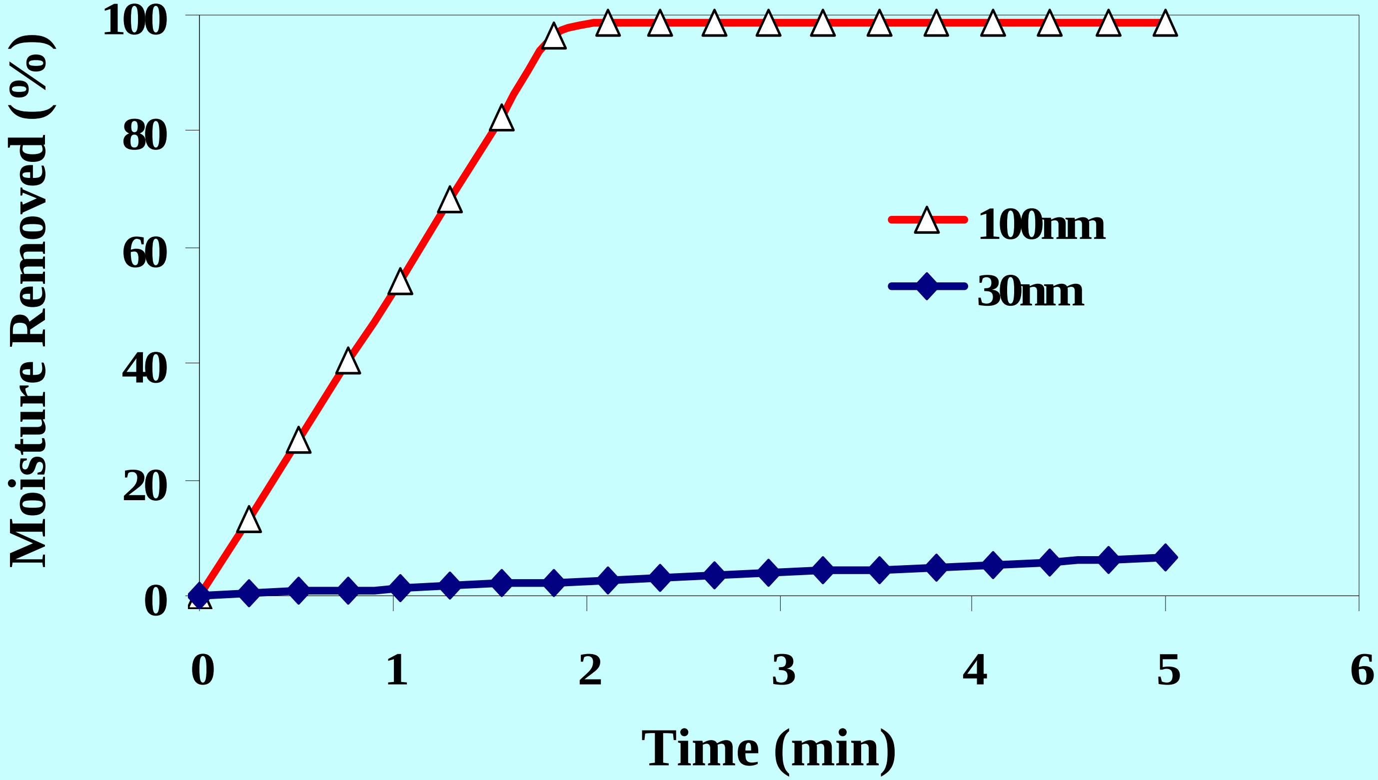
ECRS Calibration for Drying



*** Magnitude was collected at optimum frequencies; Phase angle was collected at 100Hz.**

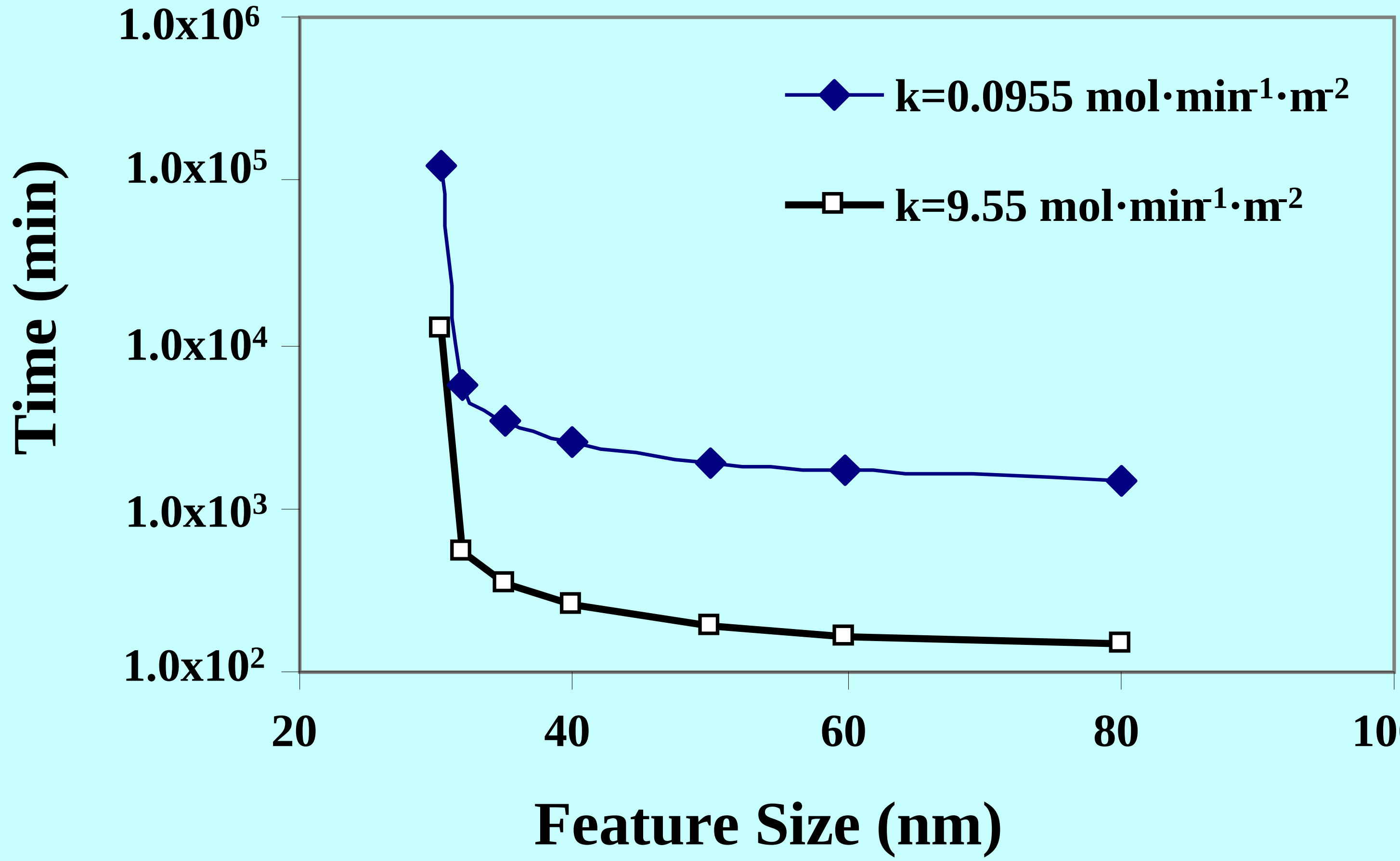
Dynamics of Drying of Nano-Structures

Feature Size Dependence



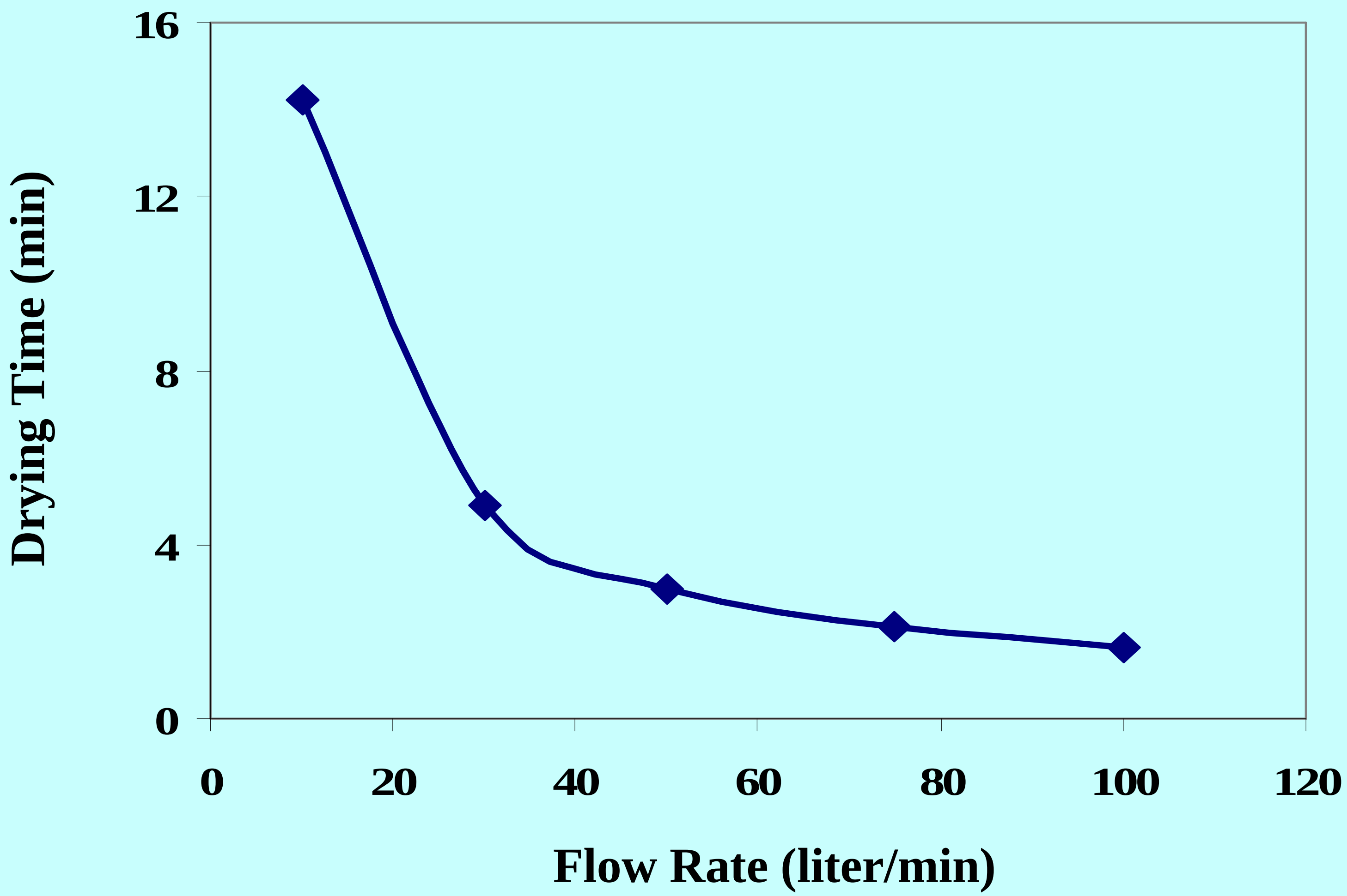
Dynamics of Drying of Nano-Structures

Feature Size Dependence



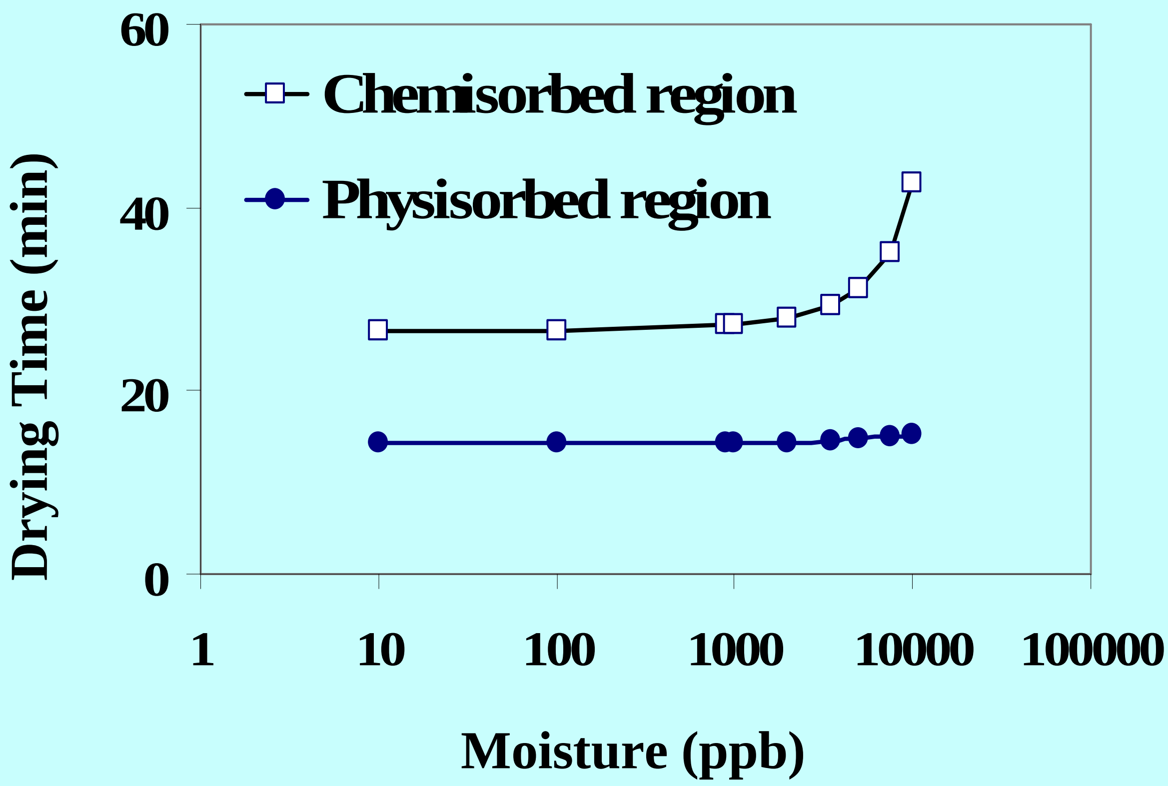
Drying of Nano-Structures

Effect of Purge Gas Flow Rate



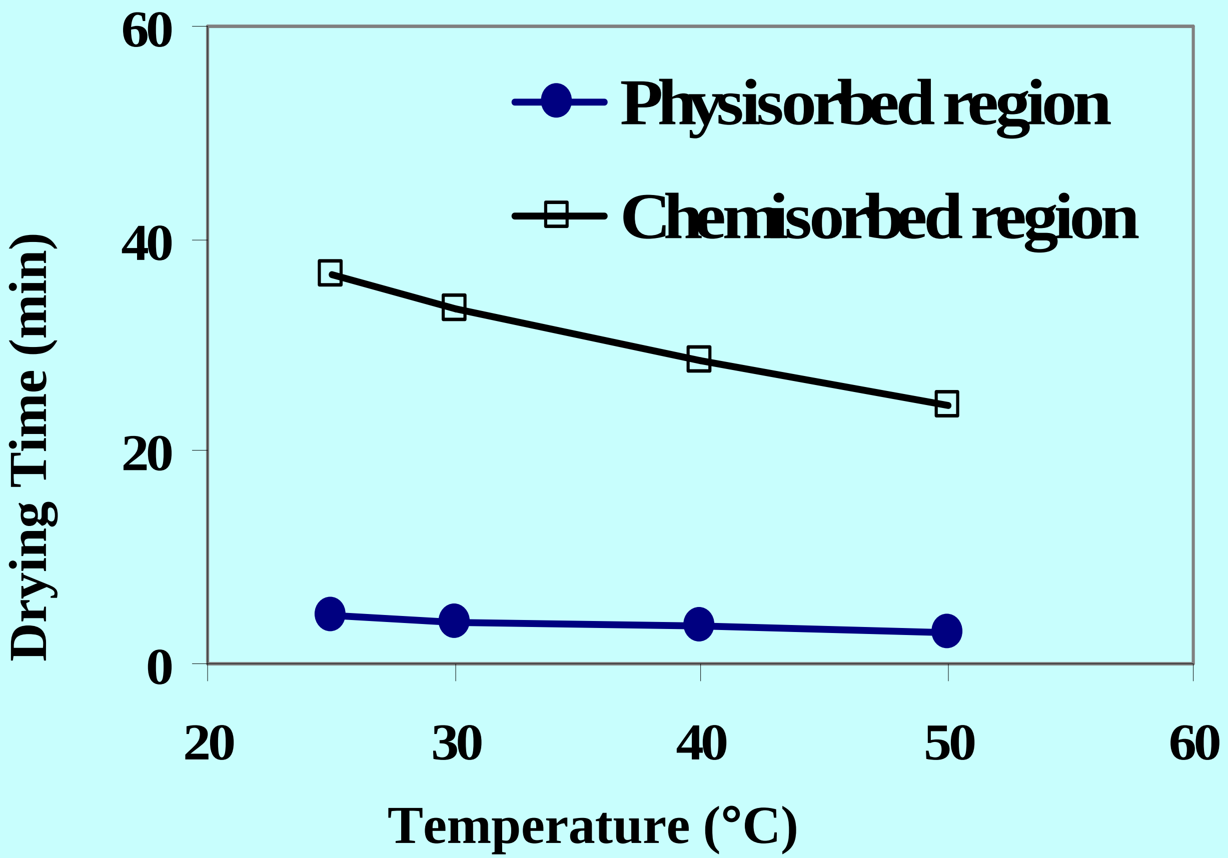
Drying of Nano-Structures

Effect of Purge Gas Purity

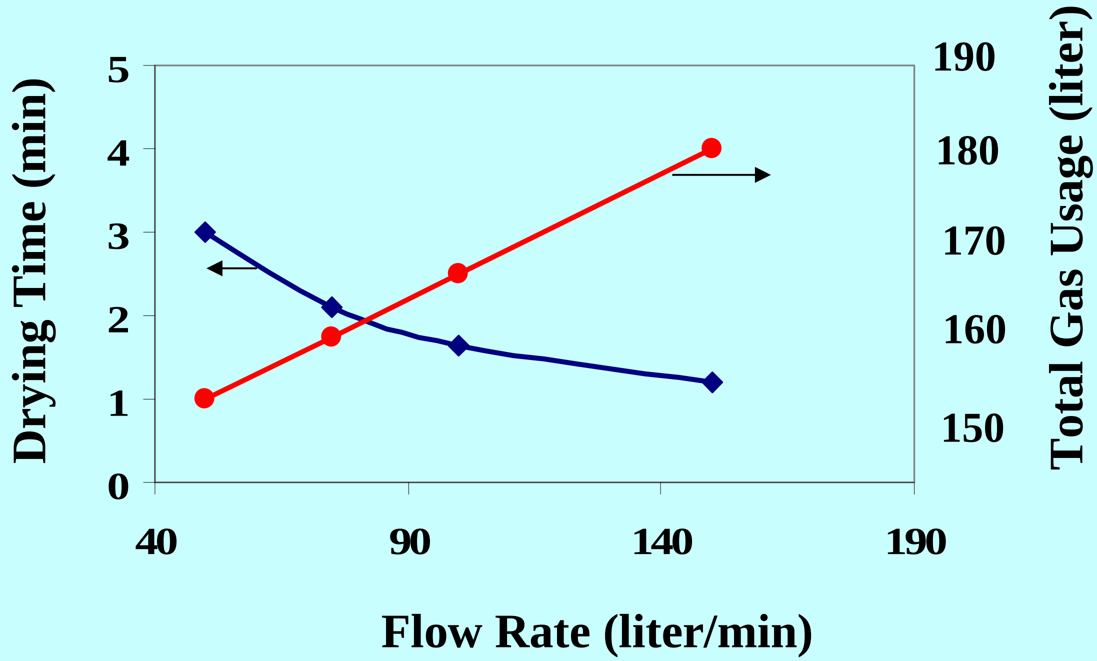


Drying of Nano-Structures

Effect of Purge Gas Temperature



ECRS Drying Application

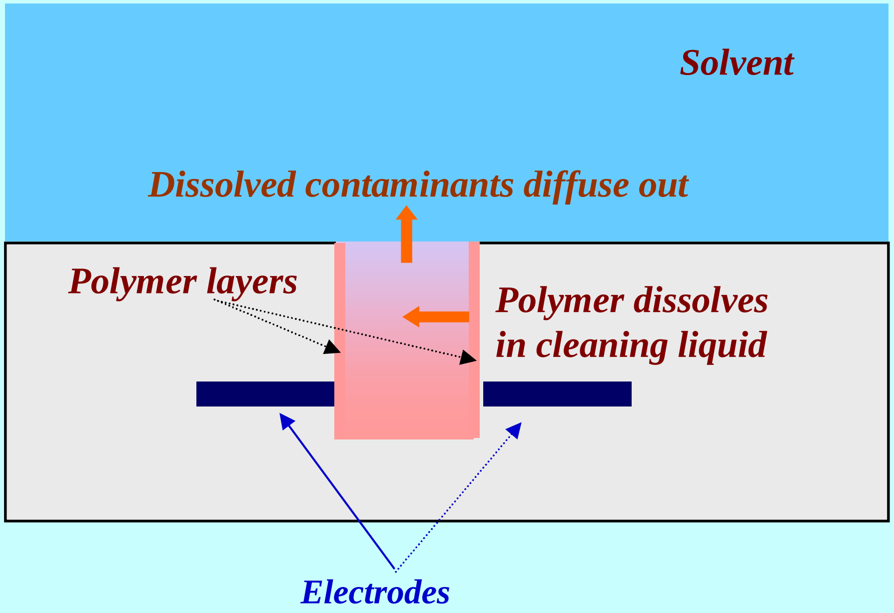


- Optimum purge is a balance between throughput and resources usage
- ECRS provides in situ and real-time profile of residual moisture
- ECRS helps developing purge recipes (flow rate, purity, and temperature) to enhance the two modes of drying discovered in this study.

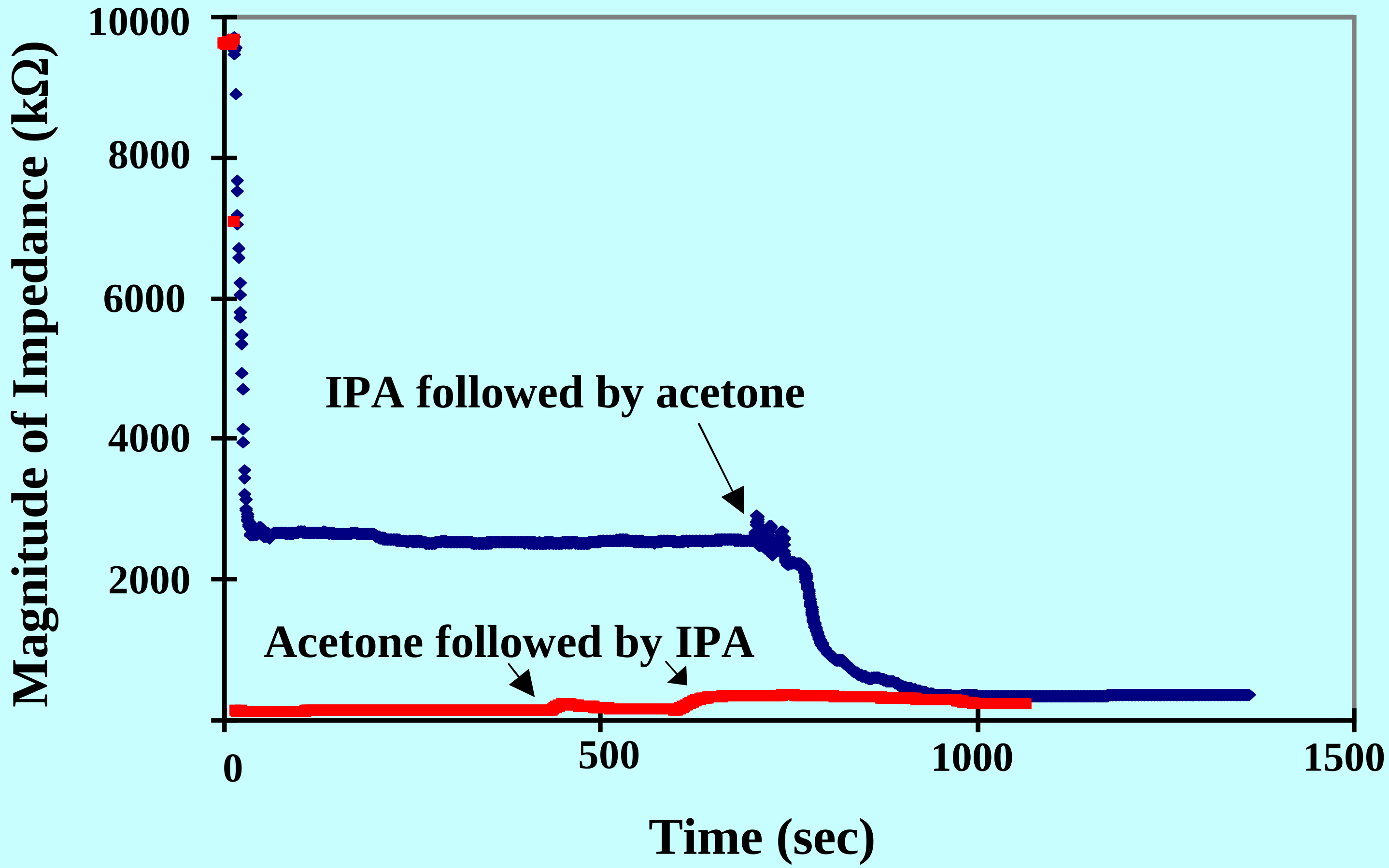
Development of Low-Impact Cleaning

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.**

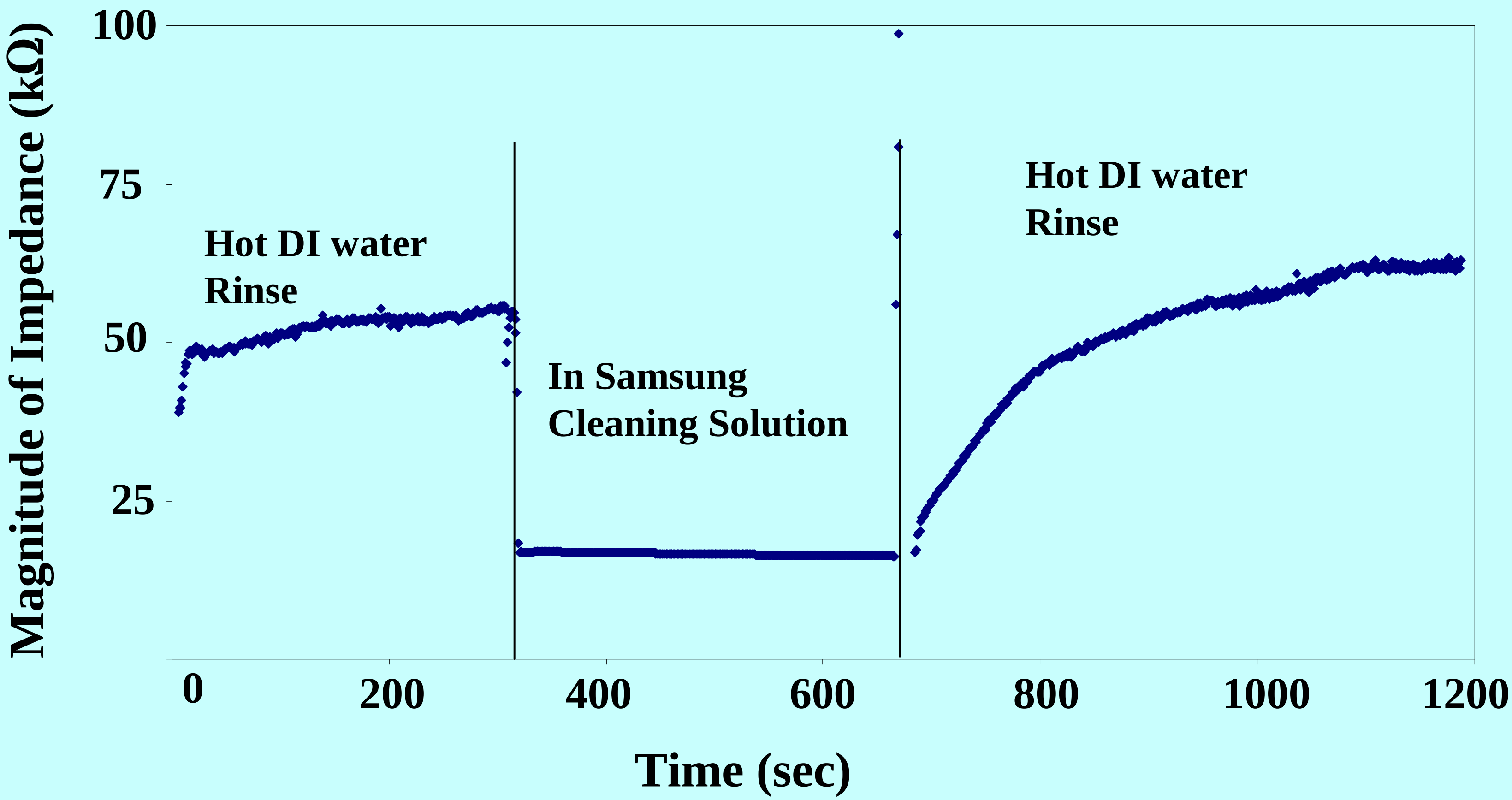


Post-etch Cleaning of Micro- and Nano-Structures



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

Industrial Interactions and Future Plans

- Continue work on application and tech transfer:
  - Joint work, co-sponsored by Freescale (Hsi-An Kwong, Marie Burnham); 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