Multiphysics Modeling for Equipment Performance Analysis and Control Design

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Overview

- **History of Modeling at SC (and before)**
  - Background 1980 - 2018

- **Purpose of Modeling**
  - Equipment Design
  - Real-time Feedback Control

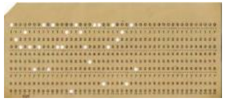
- **Examples**
  - Semiconductor Equipment
  - Advanced Materials
  - Miscellaneous

- **Summary**

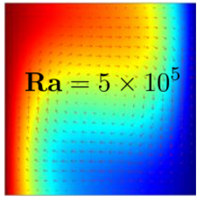
History

1980's

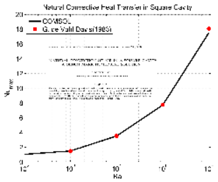
- In early 80's, modeling was mostly FORTRAN codes
  - *To be a "modeler", you also needed to be a programmer (of sorts)*
  - *Model development took months or years.*



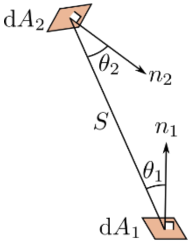
- Convective heat transfer
  - *Natural convection (an 80x80 grid was big).*
  - *Boundary layer theory (Stan5).*
  - *By late 80's increase computer power leads to big advances.*



de Vahl Davis (1983)

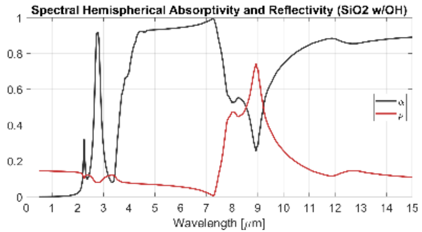


- Radiation heat transfer
  - *Tables of view factor formula*
  - *Ray Tracing (slow, but capable of complex geometry).*
  - *Direct Simulation Monte Carlo (DSMC) solves PVD problems.*



$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi S^2} dA_i dA_j$$

- Radiative properties
  - *Improving methods of measurement (FTIR, spectrometers, …)*
  - *Mie Scattering by small particles used better measurements and better codes*



History

- **1990's** **(SC's Control Division – 1996)**
  - **Significant increases in computing power**

Sun

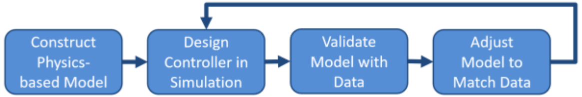
  - **Development of SC's ray trace and modeling capabilities**
    - *Driven by Consulting in Semiconductor industry.*
    - *New ray trace codes allowed very fast models of conduction/radiation dominated problems.*
    - *Models are now C-code, which makes them platform agnostic.*
    - *Resulting models run faster than real-time*

Kona ™

  - **Transition to matrix-friendly tools (Matlab, Matrix$_x$), the problem got much more user friendly.**
    - *Resulting models were further improved to make them even faster.*

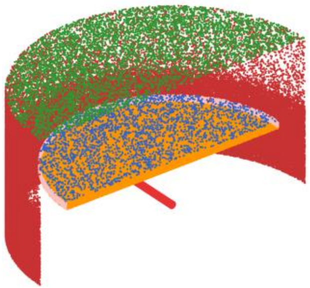
MATLAB PARTNER

  - **With models faster than real-time, the feedback control problem is changed – Model-based Control design.**
    - *Model-based control enables more complicated control strategies.*
    - *Use models to do virtual sensing, model-based estimators, etc.*



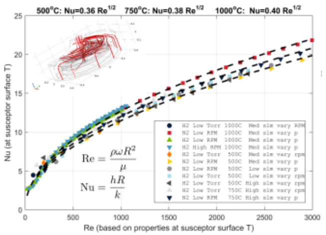
History

- 2000's +
  - The models we build are good for high temperature conduction/radiation dominated problems.
    - *Convection handled as a boundary condition. Accurate directional radiative properties and semitransparent media.*
  - Chemical Vapor Deposition, Thermal Stress, Convection, … our approach had serious limits. FEM is required.
  - 2006 – SC found COMSOL!
    - *Equation-based approach appealing.*
    - *My first model: natural convection : 1983 – 1 year, 2006 – 1hr.*
    - *More complex "modeling for design" is major advantage.*
    - *The recent addition of* ***surface-to-surface radiation*** *– very good (accurate).*
  - COMSOL is a powerful tool for equipment design and evaluation.
  - For fast models (100+ times faster than real-time), we use COMSOL to develop *old-fashioned* correlations.



COMSOL

certified consultant



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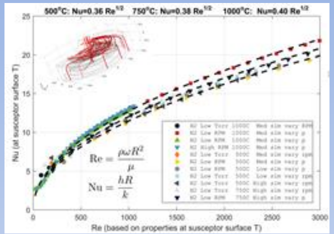
Purpose of Modeling

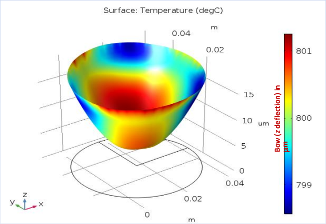
Using COMSOL for "Fast Model" inputs

Convective heat transfer



Complex geometry

Wafer Bow/Stress



Detail models for Design (COMSOL)

- Performance
- Flow
- Deposition
- Geometry
- Stress
- Cooling
- …

Fast models for Control (SC)

- Model-based control
- Virtual sensing
- Feed-forward control
- Optimal fast ramps
- …

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Semiconductor Processing:

Rapid Thermal Processing

Generic RTP System

An Axisymmetric model with 5 lamps and 5 temperature sensors

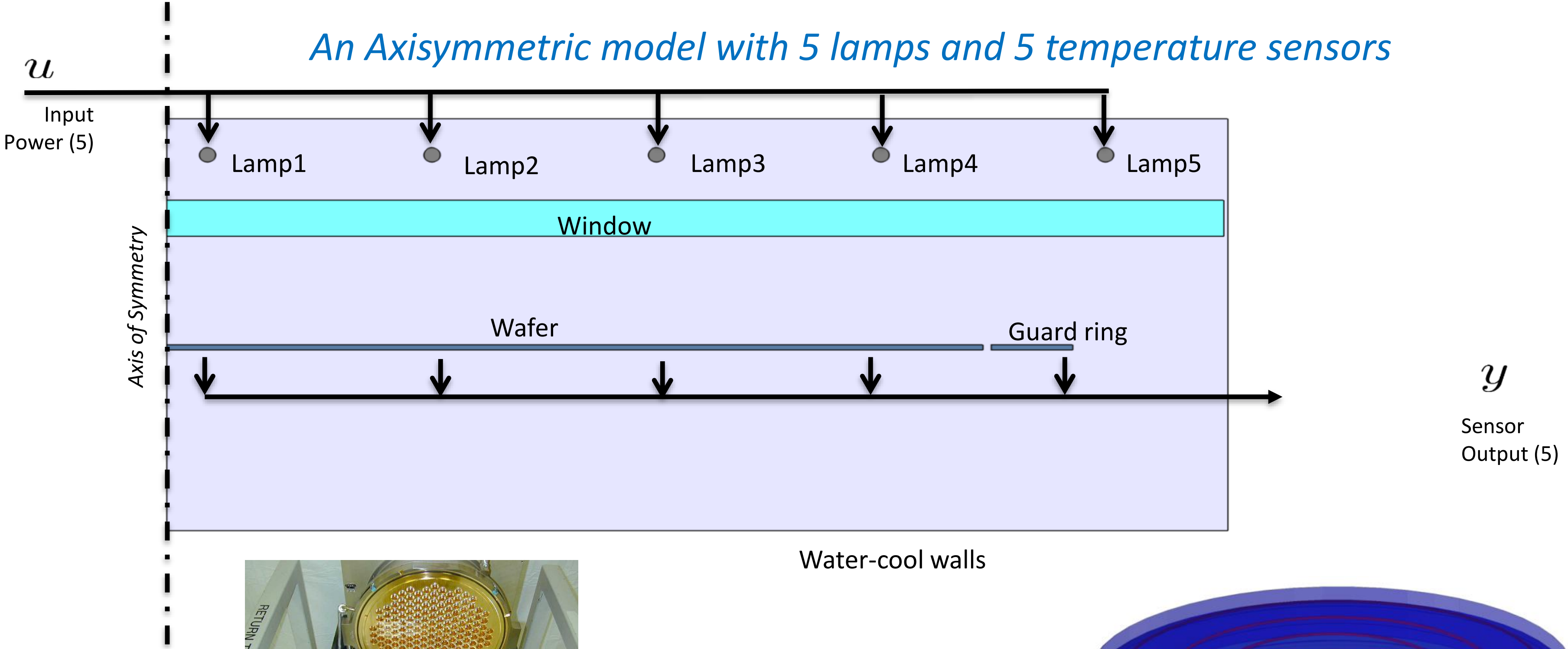
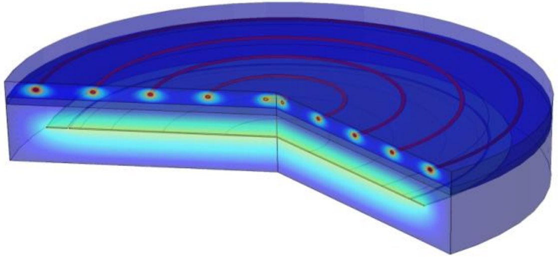
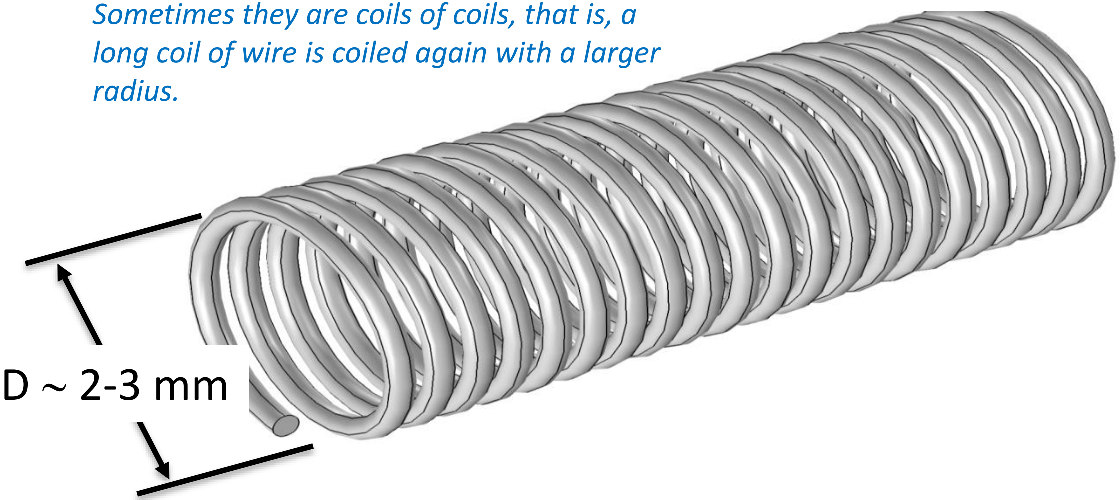


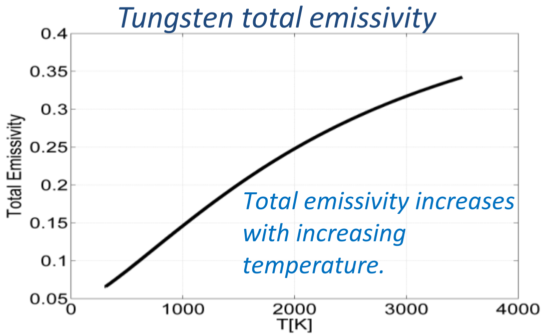
Image of actual RTP system.
There are a few designs



Tungsten Halogen Lamps

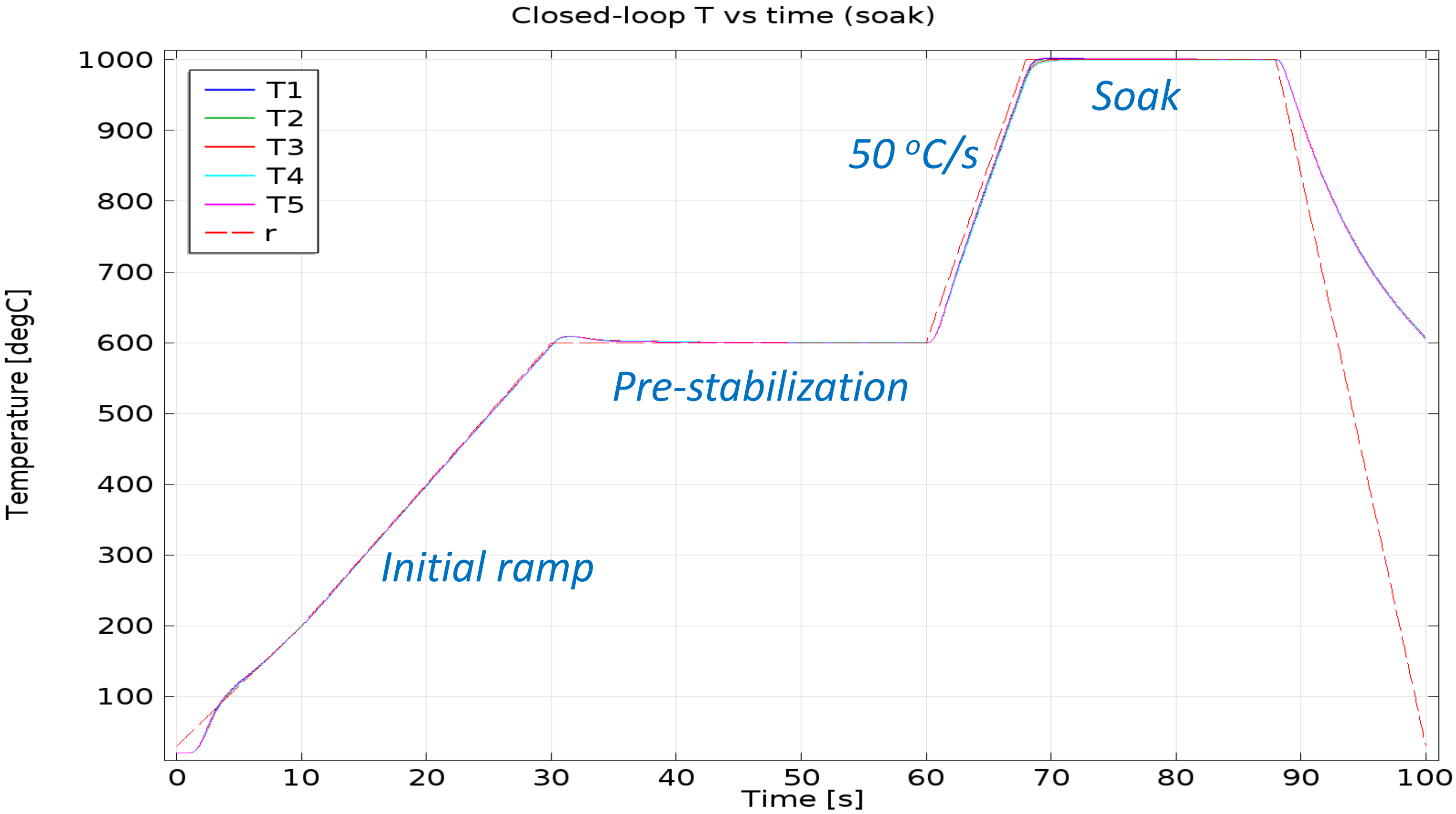
The lamp filaments are usually coils (helix). Sometimes they are coils of coils, that is, a long coil of wire is coiled again with a larger radius.





Geometric effects can cause the "effective" emissivity to be larger than the emissivity of the metal surface itself.

Closed-loop control within COMSOL



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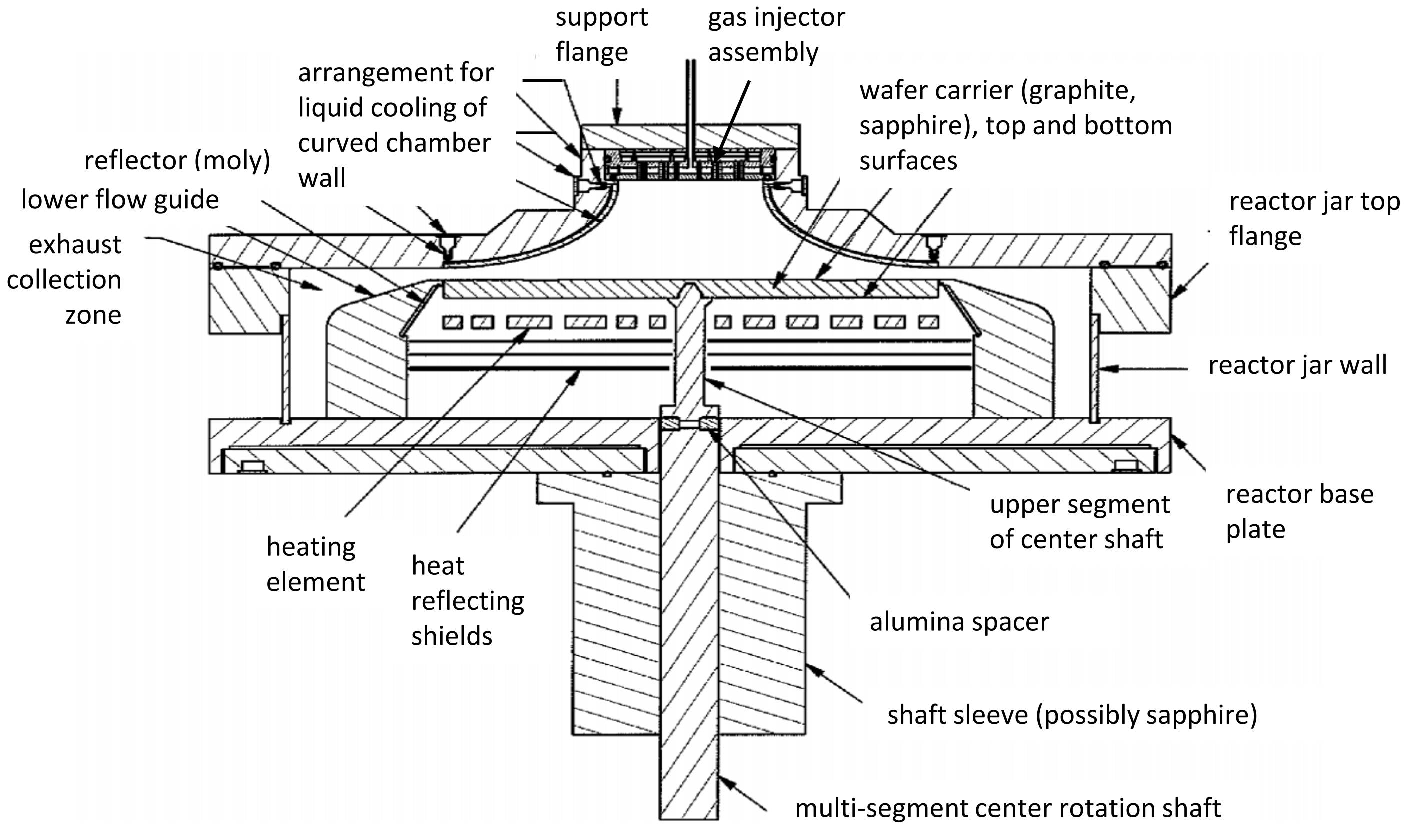
Advanced Materials:

Metal Organic Chemical Vapor Deposition (MOCVD) for production of LED’s

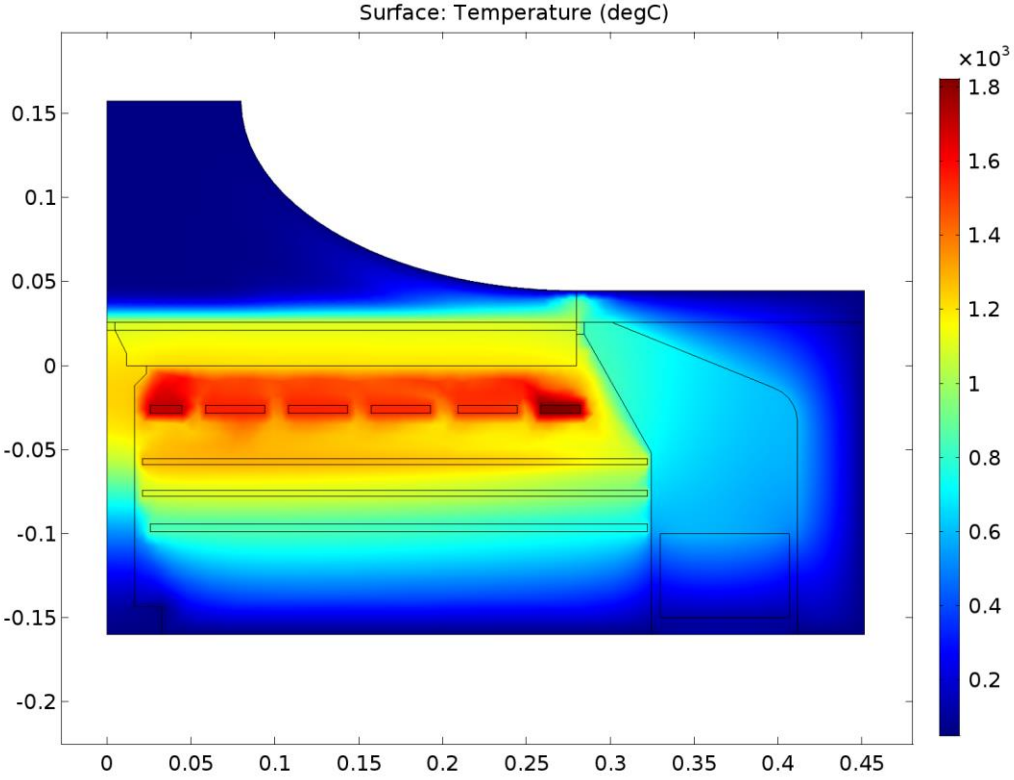
Model of Valence Equipment's MOCVD Chamber

- Chamber geometry details obtained from U.S. Patent 8778079.
- Materials, if specified in patent, are indicated in figure.

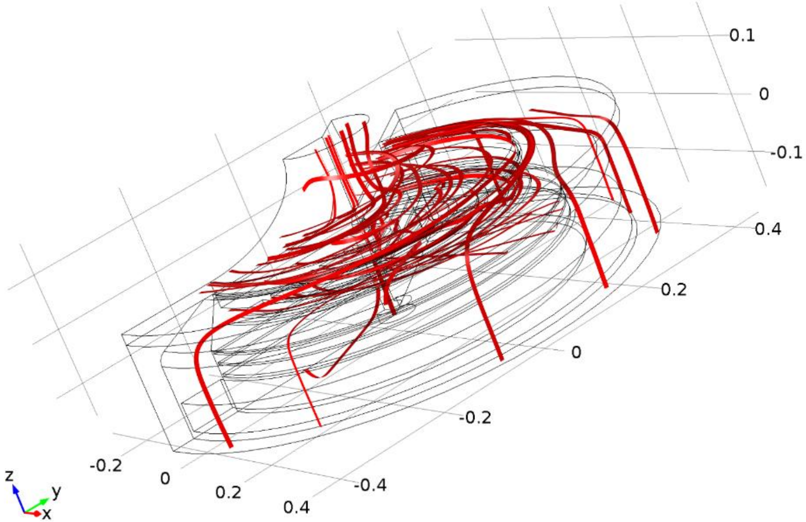


Temperature Distributions

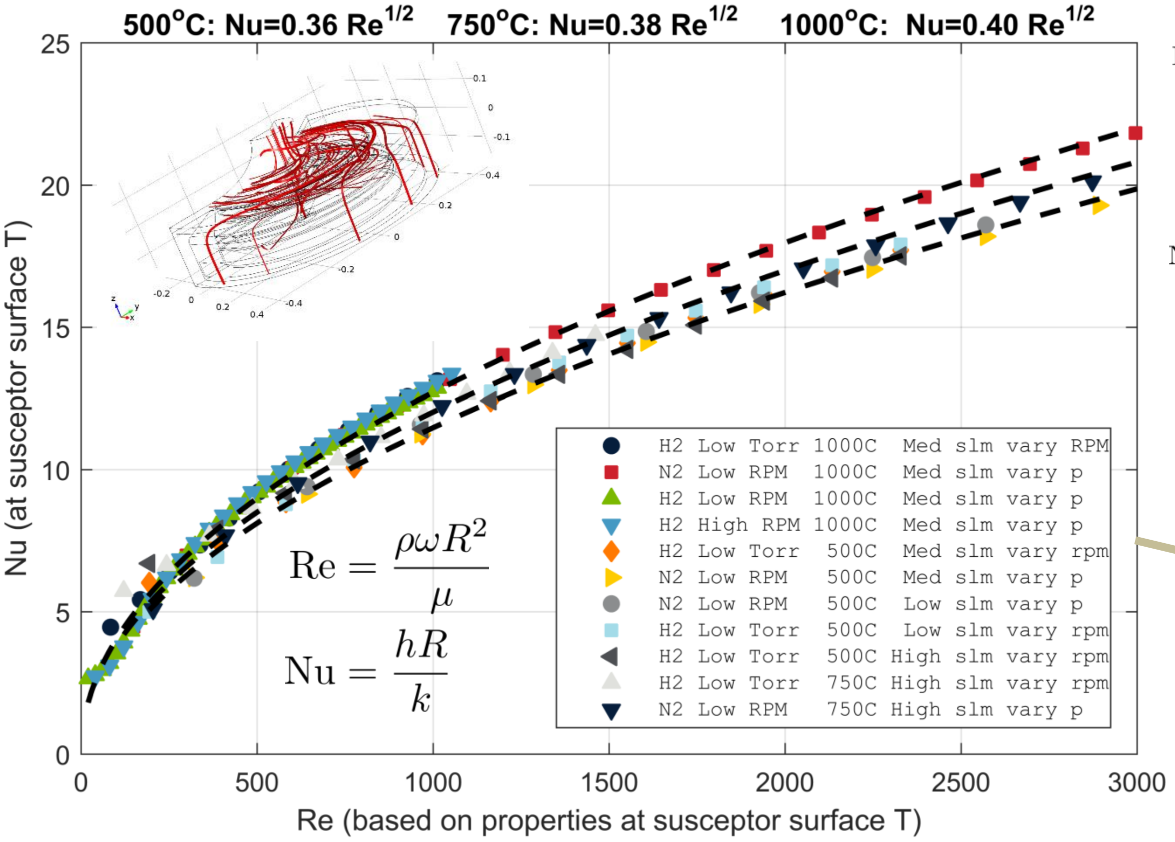
Wafer carrier heated by tungsten filaments primarily by radiative heat transfer.



- ❑ Conduction heat transfer
- ❑ Surface-to-surface radiation
- ❑ Convection with "swirl" flow
- ❑ Temperature-dependent properties



Heat Transfer Coefficient Correlation Derived from Simulations



Re = Reynolds Number

ρ = gas density

ω = rotation rate, rad/s

R = susceptor radius

μ = gas viscosity, Pa s

Nu = Nusselt Number

h = heat transfer coefficient, $W/m^2/K$

k = gas thermal conductivity

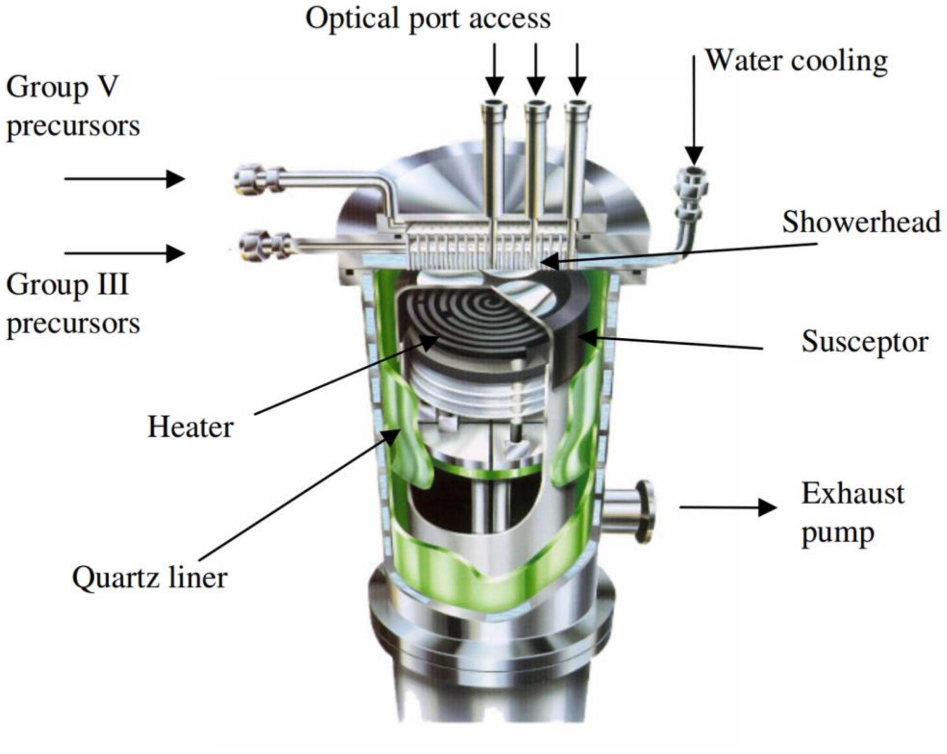
all properties evaluated at susceptor temperature

This COMSOL result can be used for **fast** model-based control models

Advanced Materials:

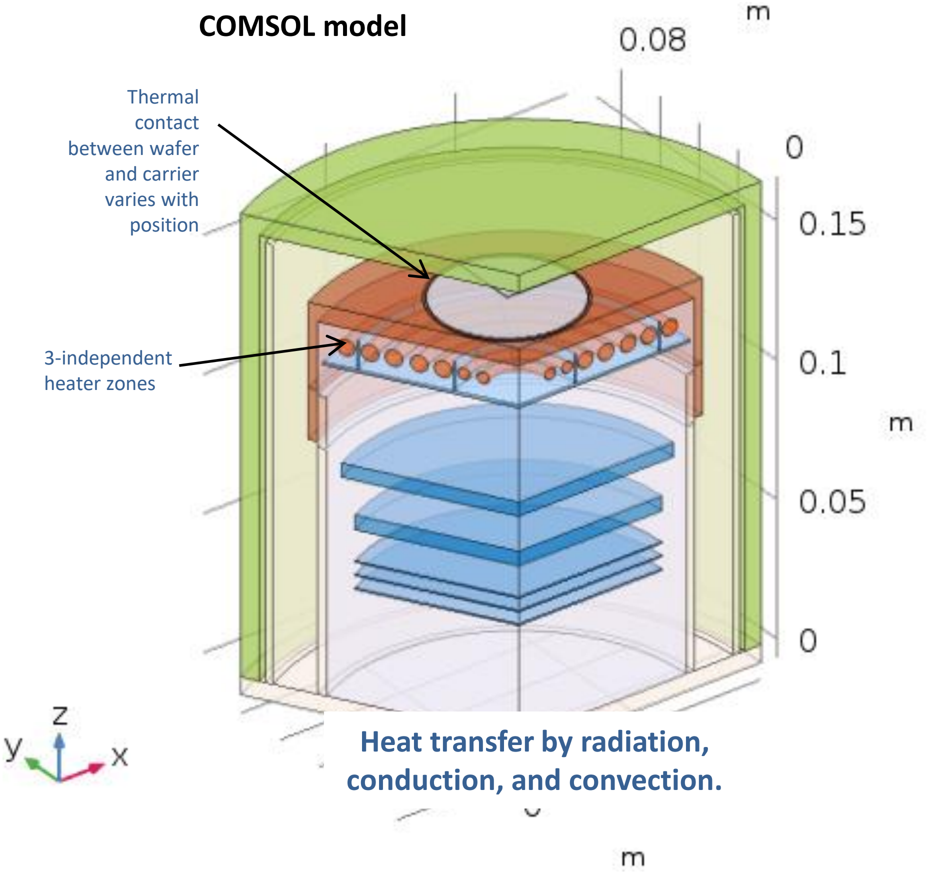
Another MOCVD System (one we can show data)

Commercial MOCVD 3 x 2” Reactor (three wafers of 2” diameter)



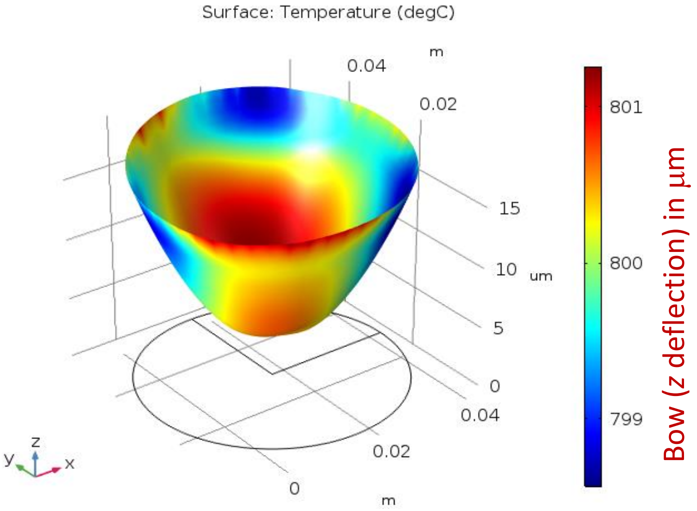
S. Boeykens, Development of Gan/Sic Components for Power Applications, Ph. D. Dissertation, Catholic University of Leuven, p. 28, 2006.

COMSOL model



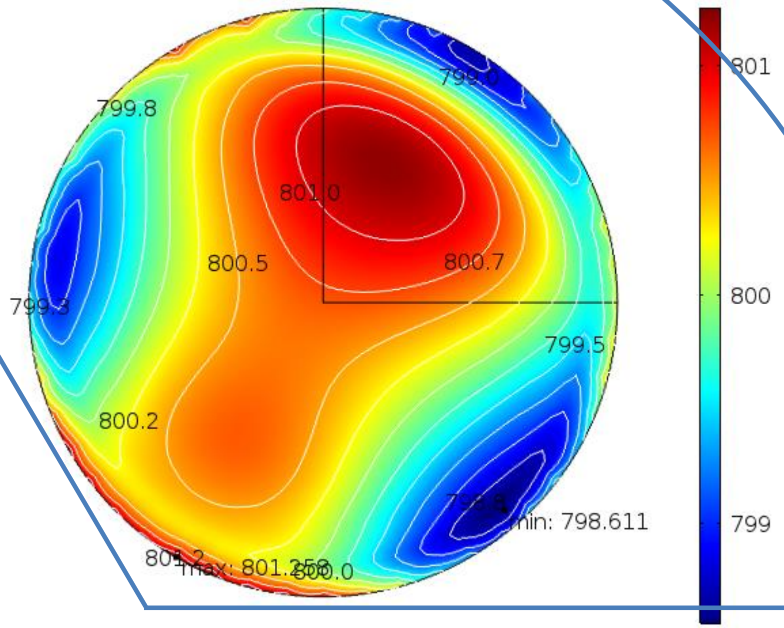
Heat transfer by radiation, conduction, and convection.

- Nominal temperature on top surface of the wafer (~800 °C).
- Bottom surface is ~4 C hotter than top surface.
- Gradient through thickness of wafer causes bow.



800°C nominal temperature.

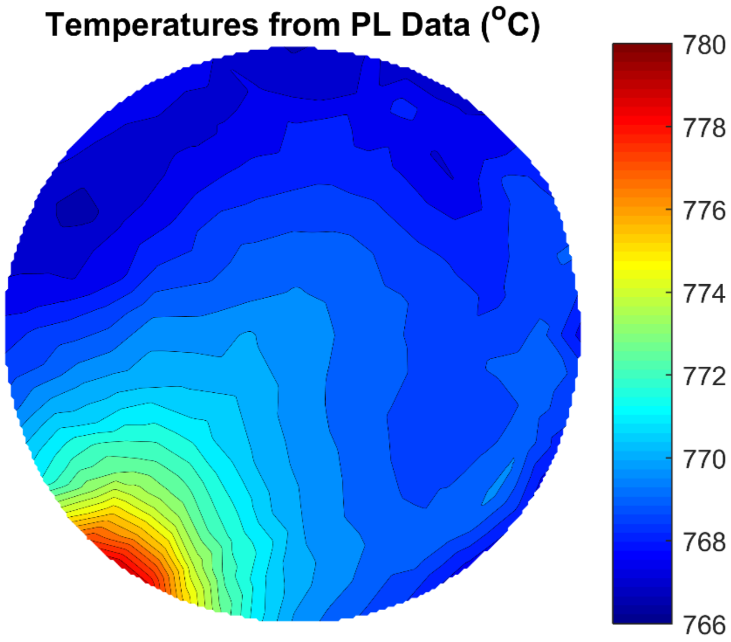
Range = 2.65°C, isotherm ΔT = 0.25°C.

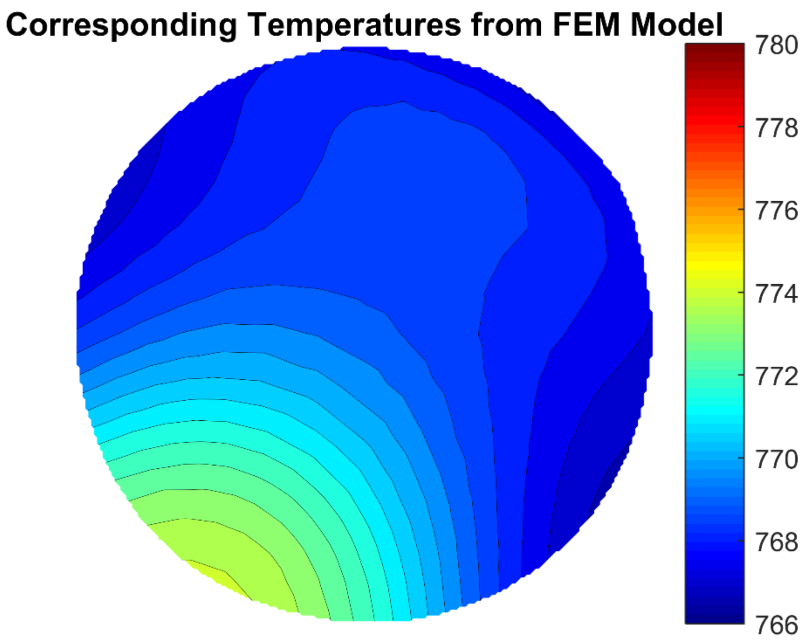


Model Validation with Photoluminescence (PL) Data

Temperature distribution on wafer obtained from PL-temperature correlation in the literature.

COMSOL model simulated with actual heater inputs for the processed wafer with PL data.

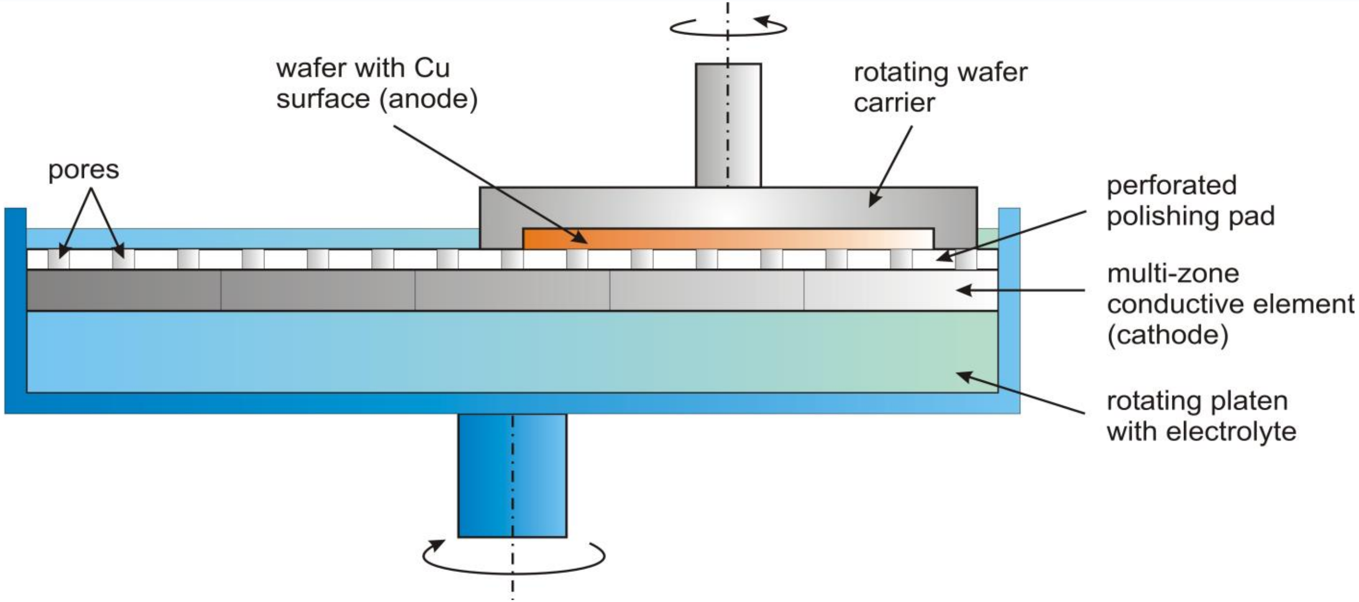


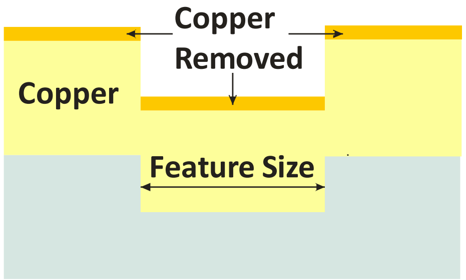


Miscellaneous:

Modeling of Electro-Chemical-Mechanical Polishing (ECMP) Process

ECMP Modeling (Electrochemistry)

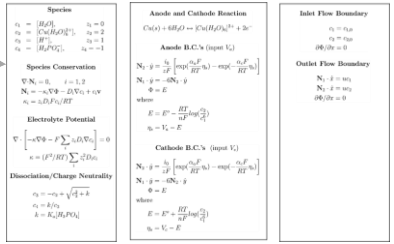




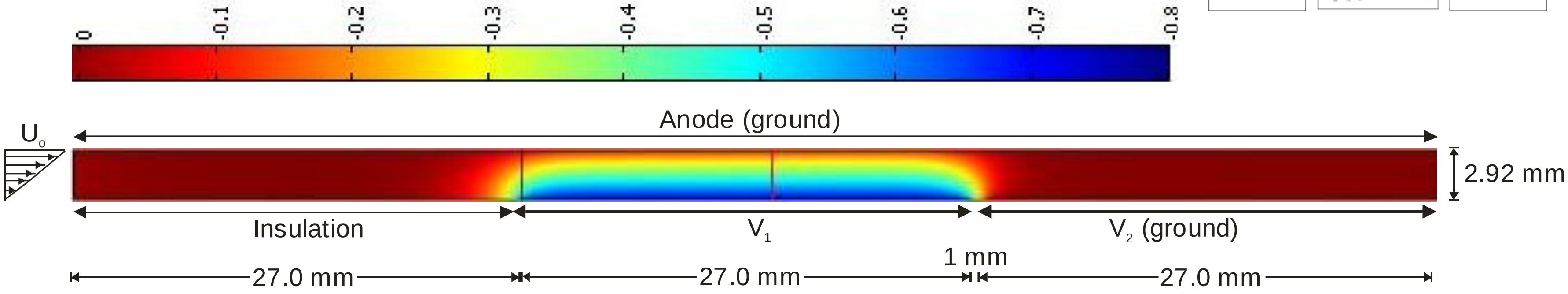
- Electro-Chemical Mechanical Planarization (ECMP) can be used in IC fabs for polishing semiconductor wafers.
- ECMP uses a combination of mechanical pressure, chemical reaction, and electrochemistry to remove the metallic (copper) layers between steps such as thin film deposition and etch.
- The copper layer acts as anode and the conductive layer on polishing pad acts as cathode with the thin layer of electrolyte flowing between the rotating pad and wafer.

ECMP Equations

- This model was implemented using COMSOL's PDE interface (before the electrochemistry package was available)

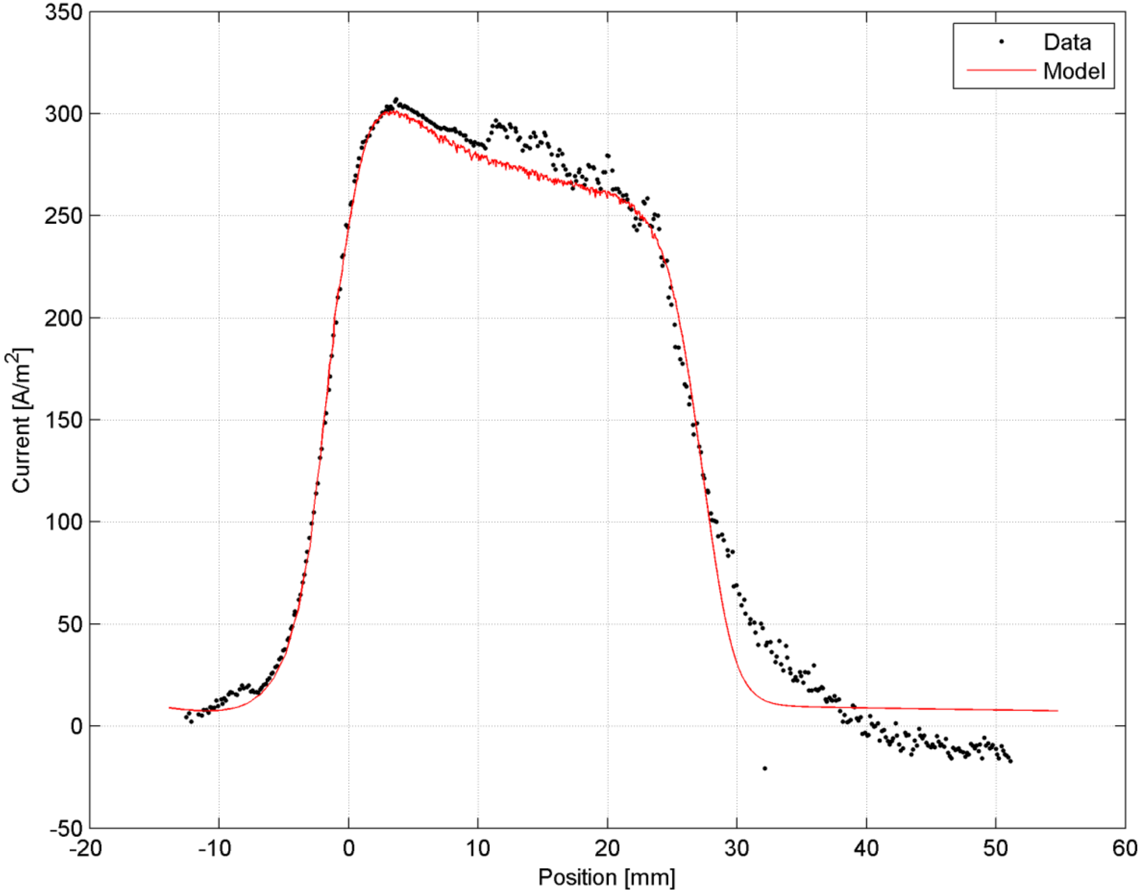


- Species transport modeled using COMSOL's Chemical Species Transport interface.



- A simple 2D geometry for ECMP allowed focus on electrochemistry.
  - Electrolyte enters from the left with linear velocity profile (U).
  - Polishing occurs at the copper anode (top "wall") which is moving at velocity U_0 with respect to the cathode on the pad (bottom "wall").

COMSOL Model Results (including Experimental Validation)



- Copper polish rates in Å/minute computed from the gradient of the copper complex flux at anode.
- Rate decreases in flow direction as water available for the reaction decreases.
- Very good agreement with our experimental results.

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- SC has used COMSOL for two main purposes
  - Design and analysis of equipment performance.
  - Augment SC's fast models for model-based control design.

- Our main areas include thermophysics and we've worked on many projects over the years.
  - Equipment: RTP, CMP, Etch, CVD, MOCVD, Epi, MBE, Sputtering, PVD, …
  - Physics: Heat transfer, Fluid flow, Species transport, Electrochemistry, Thermal stress,…

- Our business consists of two parts:
  - Real-time Model-based Control
  - Engineering Consulting

COMSOL certified consultant

Thank You