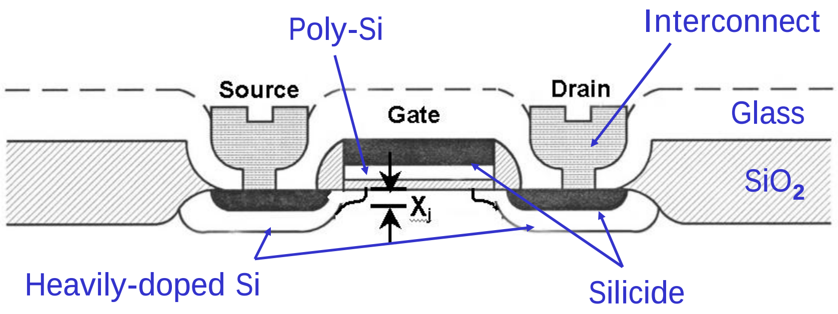
An Interdisciplinary Laboratory Course for Microelectronics Fabrication

MOSFET Schematic



Poly-Si

Interconnect

Glass

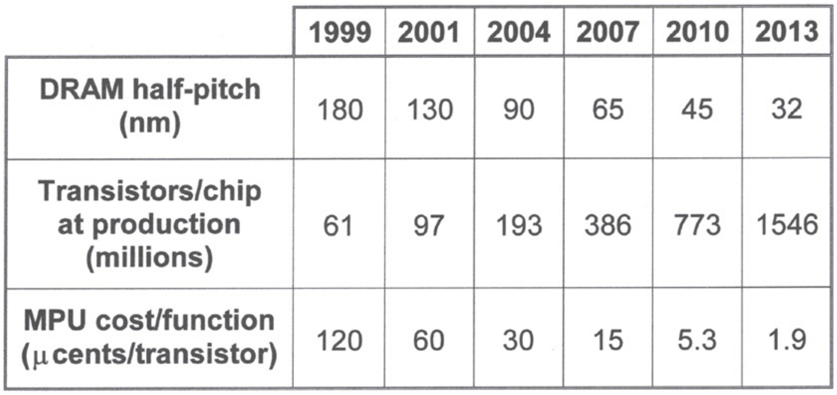
SiO_2

Heavily-doped Si

Silicide

- Hundreds of process steps
- Many materials
- Some components are nanoscale: finite-size effects

International Technology Roadmap for Semiconductors



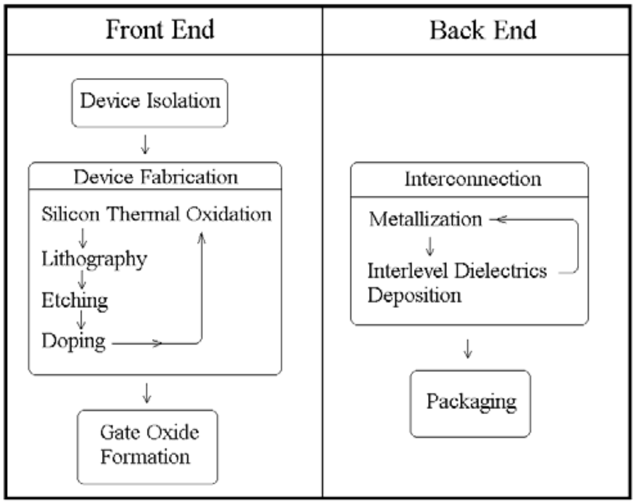
	1999	2001	2004	2007	2010	2013
DRAM half-pitch (nm)	180	130	90	65	45	32
Transistors/chip at production (millions)	61	97	193	386	773	1546
MPU cost/function (μcents/transistor)	120	60	30	15	5.3	1.9

- Rapid scaling requires skilled workforce for processing
  - Interdisciplinary, flexible

Employment Patterns

- Typical US fab employs:
  - 25-30% chemical engineering
  - 25-30% electrical engineering
  - Remainder: materials science, mechanical eng, physics…
- Distribution of training differs outside US
- Fast-moving but high capitalization
  - Profit margins squeezed, patterns shifting
  - Market cycles
  - Time-to-market critical
- Technical staff must have working knowledge beyond their formal disciplinary training

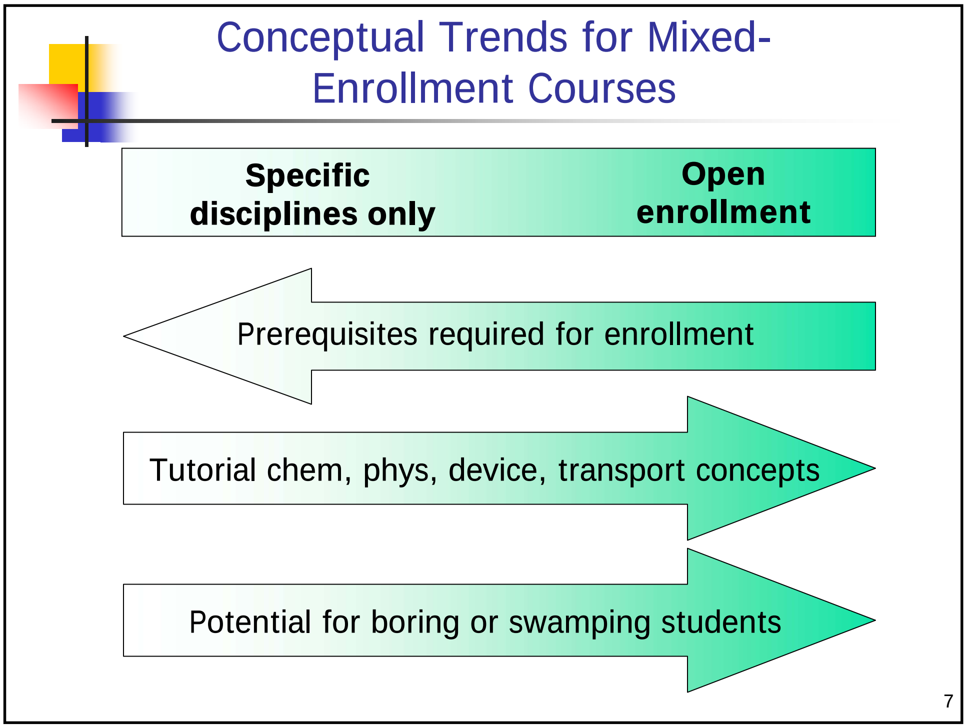
Process Flow Schematic



- Hundreds of steps
- Unit-ops concepts:
  - Lithography
  - Doping
  - Deposition
  - Etching
  - Cleaning/polishing
- Much chemistry, transport

Student Enrollment

- Advantages of mixed course enrollment
  - Gives tast of work environment in fab
  - Broadens student base to justify large investment
- Two dimensions to mixed enrollment:
  - Multiple disciplines
    - Electrical/microelectronics engineering
    - Chemical engineering
    - Materials science
    - Chemistry
    - Physics
  - Multiple degree levels
    - MS, PhD
    - Upper-level undergraduate



Conceptual Trends for Mixed-Enrollment Courses

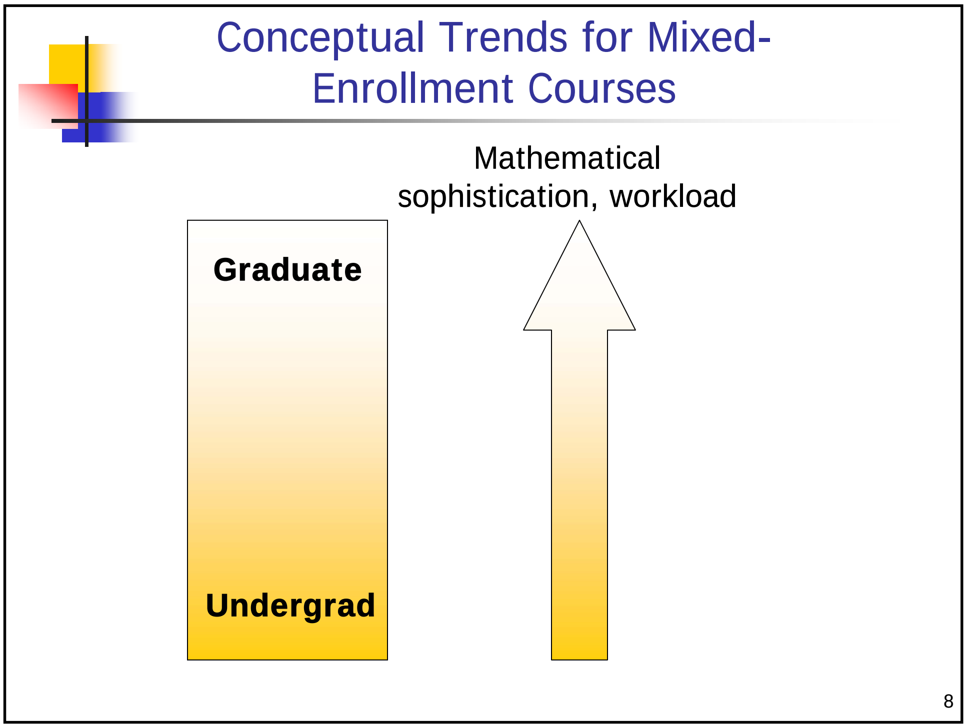
Specific disciplines only

Open enrollment

Prerequisites required for enrollment

Tutorial chem, phys, device, transport concepts

Potential for boring or swamping students



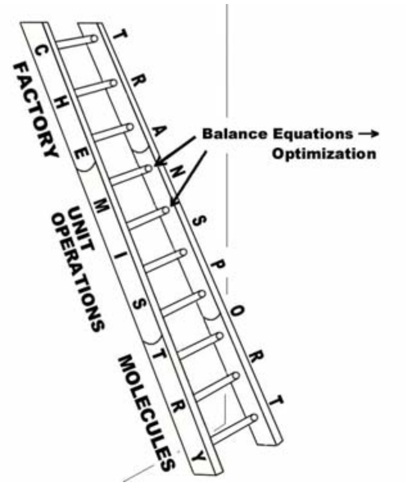
Conceptual Trends for Mixed-Enrollment Courses

Mathematical sophistication, workload

Graduate

Undergrad

Purposes of Laboratory Courses



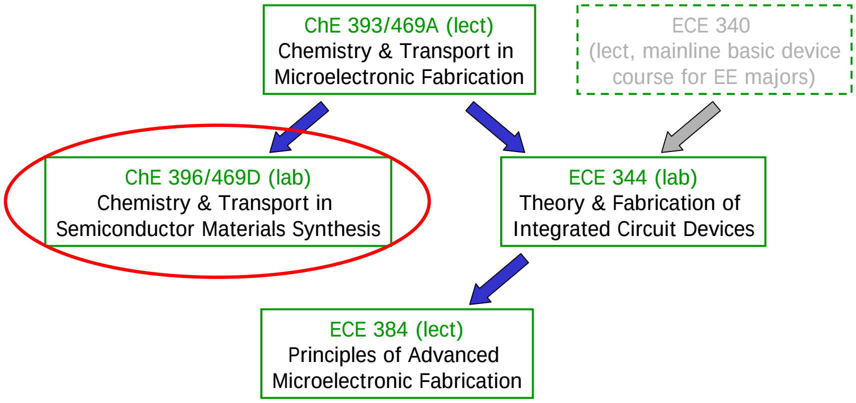
- Transfer specific facts
  - Technology details
  - Mathematical methods
- Offer an ordered framework for facts: knowledge
  - Unit operations ↔ process flow
  - Unity of form for balance eqns in mass, energy, momentum
- Offer experience in applying knowledge: wisdom
  - Necessarily experiential
  - Best done in lab course

UIUC: "Chemistry & Transport in Semiconductor Materials Synthesis"

- Lab course, up to 24 students per offering
  - Eight groups of 3 (mixed-discipline mandatory)
- Broad audience
  - ChE, EE, Chemistry, Materials Sci
  - Grad & Undergrad
- Limited number of in-depth experiments
  - Closely coupled to computational modeling
- Funded by Intel, Applied Materials, Illinois Board of Higher Education, 4 campus units

Informal Option in Processing at UIUC

- Up to 4 elective courses in chem eng, electrical eng
- Prerequisites kept minimal



Experiments

- Si oxidation kinetics
- Dry etching of SiO_2
- Photoresist spin coating
- Dry etching of photoresist
- Principles of vacuum technology
- Principles of surface chemistry
- Atomic layer deposition of TiO_2
- Planned:
  - Chemical mechanical polishing
  - PECVD of amorphous Si
  - Cu electrodeposition

“Process flow” (Si oxidation kinetics; Dry etching of SiO_2)

“Process flow” (Photoresist spin coating; Dry etching of photoresist)

Science-to-technology (Principles of surface chemistry; Atomic layer deposition of TiO_2)

Scope of Presentation

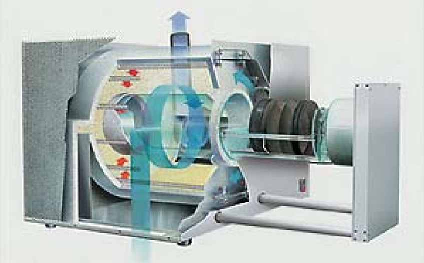
- Most equipment is custom-built
  - Often reduces expense
  - Tailored to specific goals
  - Details vary according to local circumstance
- For each experiment, outline:
  - Possible conceptual goals
  - Apparatus setup
  - Approach to data collection
  - Data analysis
- Offer suggestions for logistics of course setup

Silicon Oxidation Kinetics: Possible Goals

- Model a diffusion-reaction system with appropriate kinetics
- Show that different steps can be rate limiting depending upon conditions
  - Vary oxide thickness
- Determine an activation energy experimentally
- Observe spatial nonuniformity effects
  - Use observed kinetics to estimate nonuniformity in T
- Compare kinetics for different oxidants
- Provide material oxide for plasma etching experiment

Silicon Oxidation Kinetics: Apparatus

- Programmable furnace: ATV PEO-601



- Use wafer pieces to reduce costs
- Temperature in furnace is not uniform

Primary Metrology:
Optical Thickness Measurements

Sentech
Model CER SE 500

- Two instrument capabilities
  - Single-wavelength ellipsometry (632.8 nm)
  - White light reflectometry
- Spatial resolution: 1 x 3 mm^2
- *This instrument used for other experiments as well*

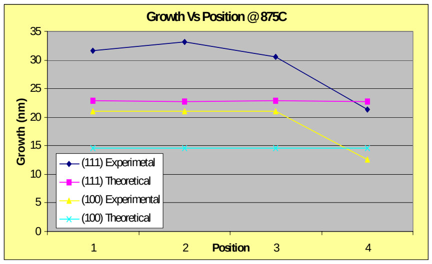
Optical Thickness Measurements

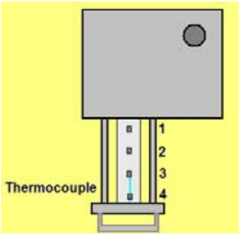
- Robust, multi-use instrument
  - Stands up to student mistakes
  - Combined ellipsometry, reflectometry needed for broad range of expts

- Ellipsometry
  - Advantages
    - High sensitivity (<10 nm)
    - Good for multifilm stacks
  - Disadvantages
    - Limited to transparent films (e.g., SiO_2)
    - Slow data acquisition
- Reflectometry
  - Advantages
    - Fast data acquisition
    - Good for transparent & translucent films (e.g., photoresist)
  - Disadvantages
    - Lower thickness sensitivity
    - Poorer for multifilm stacks

Silicon Oxidation Kinetics: Data Collection

- Experimental parameters
  - Temperature
  - Oxidant partial pressure
  - Crystallographic orientation
  - Position in furnace
- Two possible oxidants
  - Dry: $Si(s) + O_2(g) \rightarrow SiO_2(s)$
  - Wet: $Si(s) + 2H_2O(g) \rightarrow SiO_2(s) + 2H_2(g)$
    - Gives exposure to bubbler behavior (thermodynamics)





Silicon Oxidation Kinetics: Data Analysis

- Use simplified Deal-Grove model

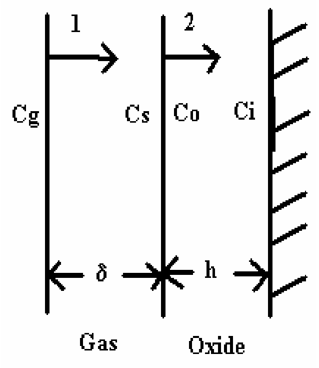
$$h = \frac{A}{2}\left[\sqrt{1 + \frac{4B(t+\tau)}{A^2}} - 1\right]$$

- Two regimes
  - Linear: rxn *and* diffusion matter

$$h \to 0 \Rightarrow h \approx \frac{B}{A}(t+\tau)$$

  - Parabolic: diffusion dominates

$$h \to \infty \Rightarrow h \approx \sqrt{B(t+\tau)}$$



- Aggregated results from different groups yield better data set

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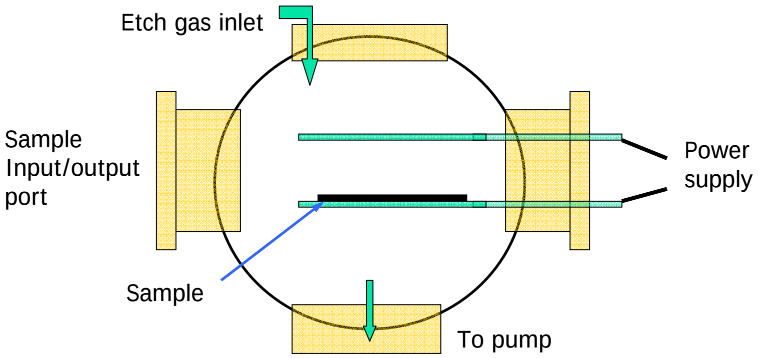
Dry Etching of SiO_2: Possible Goals

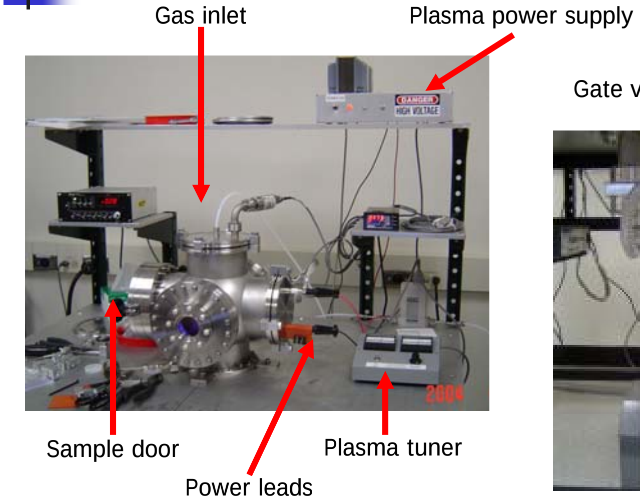
- Gain familiarity with concepts of dry etching
  - *Capacitatively* coupled plasma, sheath, plasma power…
  - Coupling between thermal, nonthermal chemistry
  - Spatial uniformity issues on wafer
- Gain exposure to spectroscopic diagnotics
  - Basic spectroscopy principles (emission)
  - Spatial uniformity in gas phase
- Use material from SiO_2 oxidation experiment
  - Process flow, integration

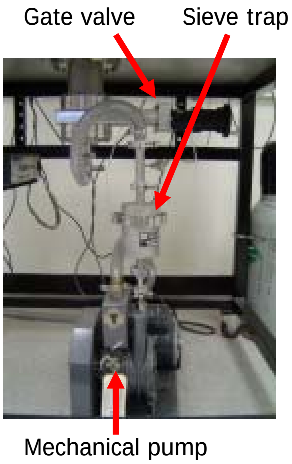
SiO_2 Dry Etching: Apparatus



- Capacitatively coupled
  - Improved spatial uniformity
  - Chamber can also be used for PECVD

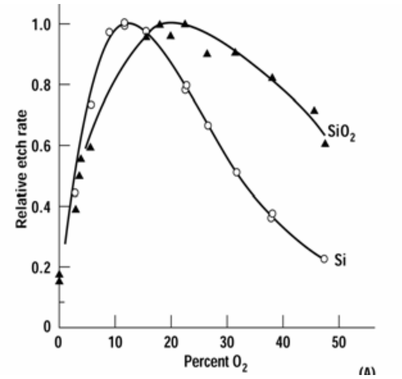
SiO_2 Dry Etching: Apparatus





SiO_2 Dry Etching: Data Collection

- Use CF_4 as etchant with added H_2 or O_2
- P ~ 500 mTorr, V ~ 100V
- Selectivity of depends on additive concentration
  - CF_4/H_2 increases C/F ratio, attacks SiO_2
  - CF_4/O_2 decreases C/F ratio, attacks Si



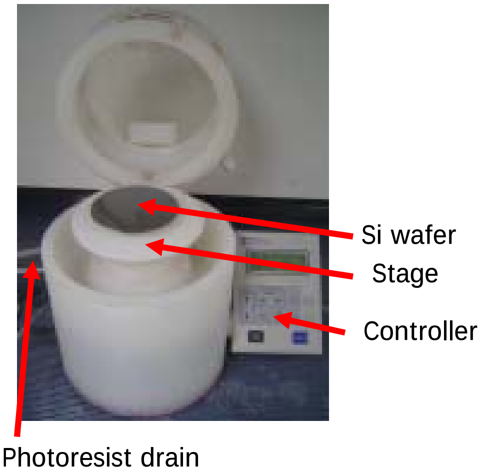
Mogab et al., *J. Appl. Phys.* 49: 3796 (1978)

Photoresist Spin Coating: Possible Goals

- Gain familiarity with concepts of spin-on techniques
  - Liquid application, spin effects
  - Soft bake, hard bake
  - Harmful effects of particulates
- Gain exposure to quantitative fluid mechanics
  - Coupled differential mass and momentum balances
  - Neglect of key terms
- Gain qualitative exposure to complex transport coupling
  - Solvent evaporation → skin formation, bubbling during bake
  - Surface tension → edge bead
- Create material for photoresist etching experiment
  - Process flow, integration

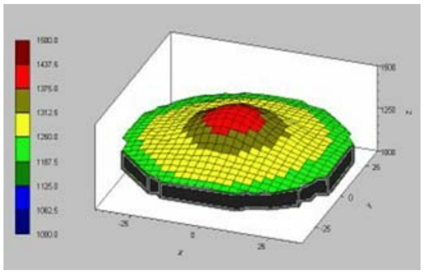
Photoresist Spin Coating: Apparatus

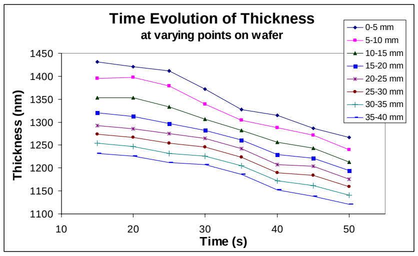
- Small commercial unit
- Resist injected through hole in top using syringe
  - SPR3612
    - Positive resist for bump-plating
    - Low viscosity
    - Thickness 1-2 μm
  - BPR 100
    - Negative resist for i-line, g-line implantation
    - High viscosity
    - Thickness 150 μm
- Bake on hot plate



Photoresist Spin Coating: Data Collection

- Experimental variables:
  - Spin rate ~ 0.0-5 krpm
  - Spin time ~ 15-60 s
  - Soft bake T ~ 70°C
  - Soft bake time ~ 3 min
  - Edge bead removal
  - Hard bake T ~ 70-120°C
  - Hard bake T ~ 3-10 min
  - Degree of dust removal
- Film thickness by reflectometry
- Examine thickness uniformity

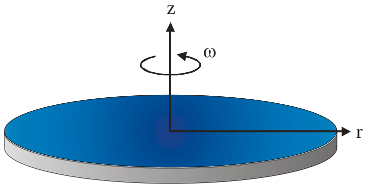




Photoresist Spin Coating: Data Analysis

- Height, velocity relation:

$$\frac{\partial h}{\partial t} = -\frac{\rho\omega^2}{3\eta}\frac{1}{r}\frac{\partial}{\partial r}\left(r^3 h^3\right)$$



- For h independent of r:

$$h = \frac{h_0}{\left[1 + \frac{4\omega^2 h_0^{\,2} t}{3\nu}\right]^{1/2}}$$

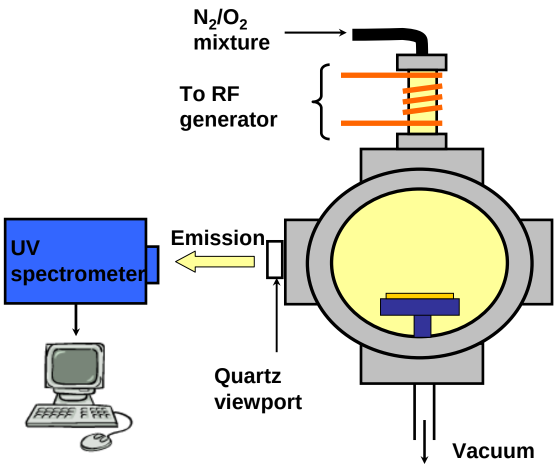
- Look at uniformity from ellipsometer measurements
- Compare results for different conditions to theory

Dry Etching of Photoresist: Possible Goals

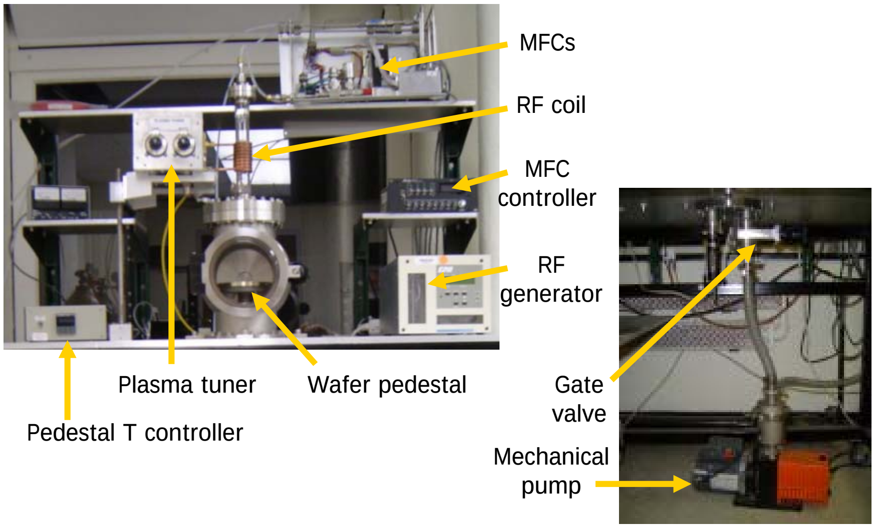
- Gain familiarity with concepts of dry etching
  - *Inductively* coupled plasma, sheath, plasma power…
  - Coupling between thermal, nonthermal chemistry
  - Spatial uniformity issues on wafer
- Gain exposure to spectroscopic diagnotics
  - Basic spectroscopy principles (emission)
  - Spatial uniformity in gas phase
- Use material from photoresist spinning experiment
  - Process flow, integration
- Couple experiments to simulations
  - Permits rapid testing/evaluation of different designs

Photoresist Dry Etching: Apparatus

- Oxygen plasma (N added to prevent recombination)
- Spectrometer monitors plasma composition
- Rate data correlated to gas composition

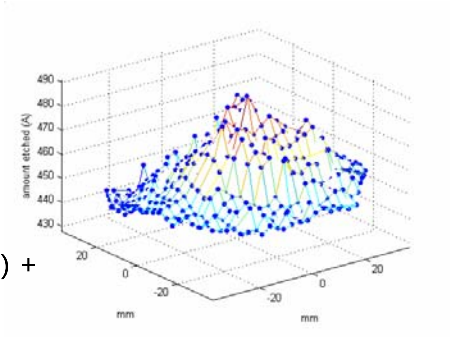


Photoresist Dry Etching: Apparatus



Photoresist Dry Etching: Data Collection

- Experimental parameters
  - Temperature
  - Oxidant partial pressure
  - Position in furnace
- Two possible oxidants
  - Dry: $Si(s) + O_2(g) \rightarrow SiO_2(s)$
  - Wet: $Si(s) + 2H_2O(g) \rightarrow SiO_2(s) + 2H_2(g)$
- Use ellipsometry for film thickness

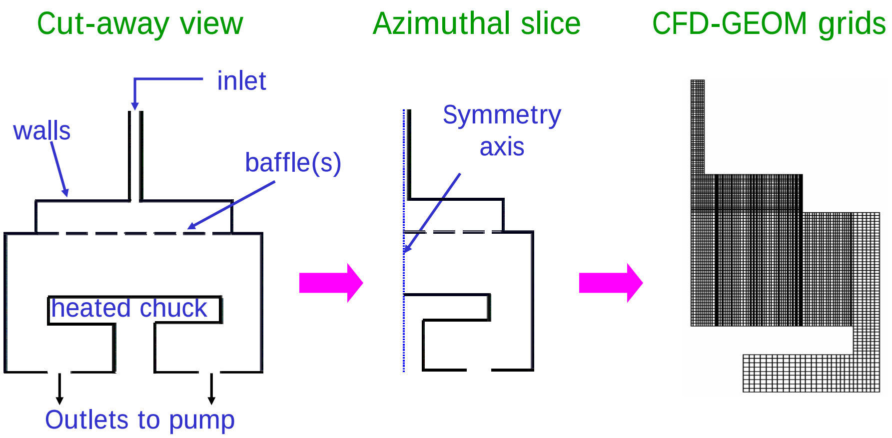


Photoresist Dry Etching: Data Analysis

- Model with CFD-ACE+
- Three main modules:
  - CFD-GEOM – computational grid generator
    - 2-D or 3-D objects rendered using CAD-oriented user-interface
  - CFD-ACE – solver
    - User defines problem type (flow, heat transfer, chemistry) and boundary/initial conditions
  - CFD-VIEW – graphical solution viewer

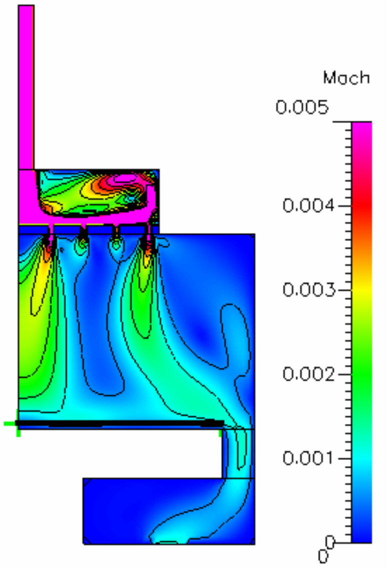
Example Grid Setup

- Reduce 3D geometry to 2D axisymmetric problem

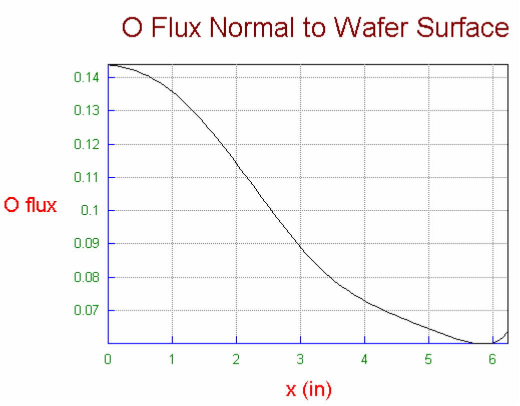


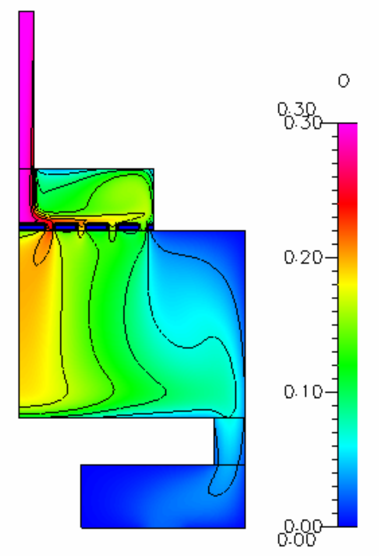
Example Results: Laminar Flow Field

- Recirculation problem above showerhead
  - Decrease height between chamber top and baffle
- Primary flow through 1st, 4th set of holes
  - Decrease area of 1st set of holes, widen 2nd & 3rd set



Reactive Species Profile


O Flux Normal to Wafer Surface



- Higher uniformity of O flux desired
  - Solution: redesign showerhead

Uses for Computational Module

- Explore various showerhead designs to:
  - Reduce flow recirculation
  - Improve spatial uniformity of reactive species flux
- Reconfigure chamber to reduce nonessential volume
- Test selected cases experimentally

Principles of Vacuum Technology: Possible Goals

- Gain familiarity with vacuum equipment, measurement
  - Pumps, gauges, flanges, gaskets, feedthroughs, valves…
- Learn key vacuum concepts
  - Pumping speed, conductance
  - Molecular vs. viscous flow
  - Measure & compare conductance of various tubes
  - Compare results with theory
- Learn simple mass balance equations
  - Compare steady-state, transient experimental results for mass flow

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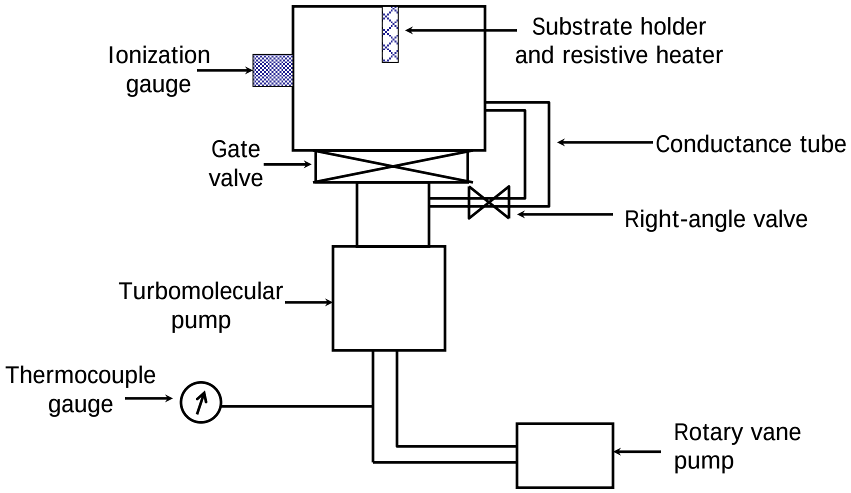
Vacuum Technology: Apparatus Schematic

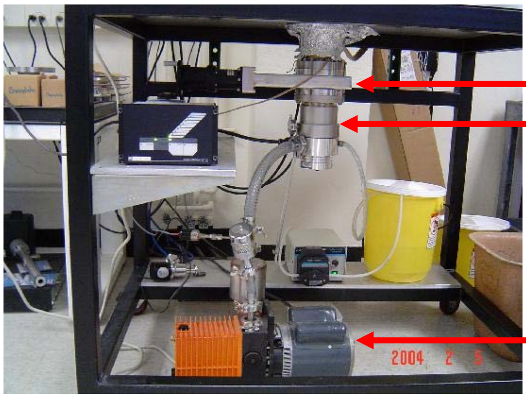


Vacuum System: Upper Portion

Ion gauge

Base pressure ≈ 1 x 10^{-8} Torr

Vacuum System: Lower Portion

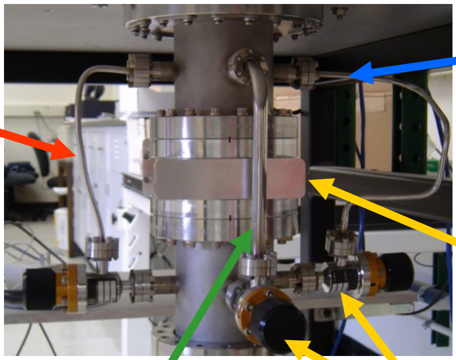


Gate valve

Turbomolecular pump

Mechanical backing pump

Accessories for Conductance Experiments



Tube 1:
Diameter- ¼”
Length- 8.5”

Tube 3:
Diameter- ¼”
Length- 16”

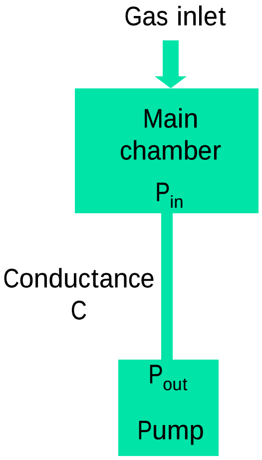
Gate valve

Tube 2:
Diameter- ½”
Length- 8”

Right-angle valves

Vacuum Technology: Data Collection

- Admit air through leak valve, ~ 10^{-5} Torr
- Pump chamber through one of several long thin tubes
  - Diameter, length varies
  - Independent valving
- Measure pressures P_{in} and P_{out}
- Snap leak valve shut, measure time constant for pressure decay



Vacuum Technology: Data Analysis

- Use transient mass balance to determine effective system pumping speed:

$$V\frac{dP}{dt} = -S_{eff}P$$

- Use pump specs to obtain tube conductance:

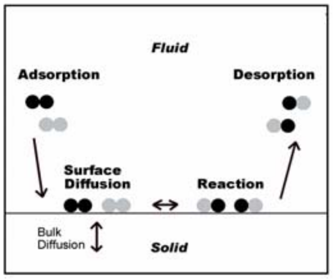
$$\frac{1}{S_{eff}} = \frac{1}{S_{pump}} + \frac{1}{C}$$

- Verify conductance relationship:

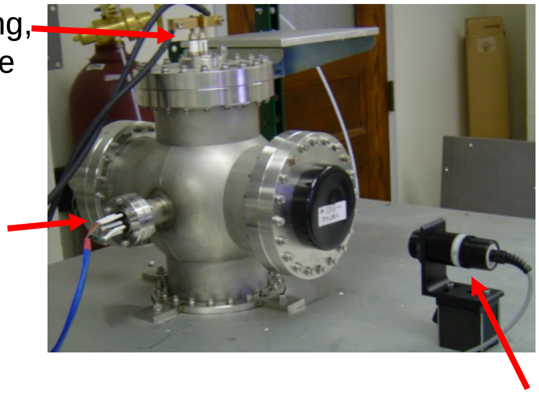
$$C_{tot} = C_1 + C_2 + \ldots C_n$$

Principles of Surface Chemistry: Possible Goals

- Gain familiarity of surface kinetics
  - Adsorption, desorption
  - Concepts generalize to CVD, ALD
  - Results feed into ALD experiments
- Manipulate transient mass balances
  - Vacuum chamber
  - Surface
- Learn concepts of linear-ramp kinetics from temperature programmed desorption
  - Concepts generalize to RTP



Surface Chemistry: Apparatus



Feedthrough for resistive heating, thermocouple

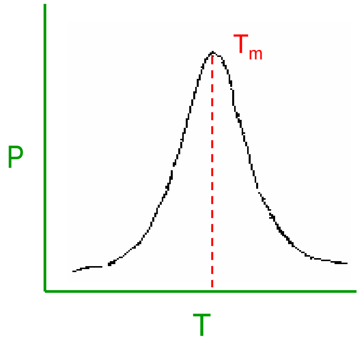
Ion gauge

Optical pyrometer

Base pressure ≈ 1 x 10^{-8} Torr

Surface Chemistry: Data Collection

- Perform temperature programmed desorption experiments with $TiCl_4$ or H_2O
  - Expose surface to gas for fixed t, P
  - Apply linear temperature ramp ~10K/s
  - Measure ΔP vs t in ion gauge
    - ΔP ∝ desorption rate
- Vary exposure, heating rate β
  - Peak area ∝ initial coverage
  - T_m increases with β



Surface Chemistry: Data Analysis

- Mass balance on chamber shows P ∝ desorption rate

$$-A\frac{d\Theta}{dt}=\frac{V}{k_BT}\left(\cancelto{0}{\frac{dP}{dt}}+\frac{S}{V}P\right)\approx\frac{S}{k_BT}P$$

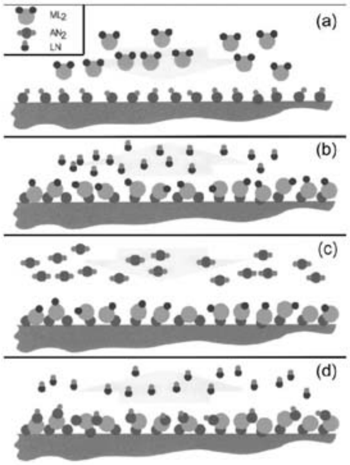
thus $P\propto-\frac{d\Theta}{dt}=\frac{k_n^0\Theta^n}{\beta}\exp(-E_{des}/k_BT)$

- Line shape analysis gives all kinetic parameters
- Peak temperature T_m varies with heating rate

$$\frac{k_1^0}{\beta}\exp\left(-\frac{E_{des}}{k_BT_m}\right)=\frac{E_{des}}{k_BT_m^2}$$

Atomic Layer Deposition of TiO_2: Possible Goals

- See gas-solid interaction kinetics used in practice
  - Use concepts, data from surface chemistry experiment
  - Learn connection between CVD, ALD
- Manipulate transient mass balances
  - On surface
  - In deposition reactor (gas transport greatly simplified)



Seidel et al., *Thin Sol.* Films 402: 248 (2002)

Safety Problems in Deposition Experiments

- Toxicity, flammability of “interesting” source gases, products
  - SiH_4, Si_2H_6 (pyrophoric)
  - SiH_2Cl_2
  - H_2
  - Dopants

- Alternative: deposition of TiO_2 from $TiCl_4$, H_2O
  - HCl product no worse than standard chem lab

Aspects of $TiCl_4$, H_2O Chemistry

- Advantages
  - Low substrate T (~200°C)
    - Less strain on equipment (heaters, o-rings, etc.)
  - High rate (easier to measure)
  - Low P (less source gas used)
  - Good for both CVD, ALD
- Disadvantages
  - Not a conventional semiconductor material

ALD From $TiCl_4$, H_2O

- Operating Conditions:
  - $P_{TiCl4} \approx 0.2$ Torr
  - $P_{H2O} \approx 2$ Torr
  - $T \approx 250$ ˚C
- Half Reactions (* indicates surface species):

$$(-\mathrm{OH})_n^* + \mathrm{TiCl}_4 \rightarrow n\mathrm{HCl} + (-\mathrm{O}-)_n\,\mathrm{TiCl}_{4-n}^*$$

$$(-\mathrm{O}-)_n\,\mathrm{TiCl}_{4-n}^* + (4-n)\mathrm{H_2O} \rightarrow (-\mathrm{O}-)_n\,\mathrm{Ti(OH)}_{4-n}^* + (4-n)\mathrm{HCl}$$

Atomic Layer Deposition of TiO_2: Data Collection

- Experimental parameters
  - Temperature
  - Source gas partial pressure
  - Number of cycles
  - Length of cycles
  - Length of purge time
    - Observe switch to CVD if purge too short
- 300 cycles, estimated depth ~45 nm
- Thickness from ellipsometry
- Possible supplementary experiment: standard low-pressure CVD

Atomic Layer Deposition of TiO_2: Data Analysis

- Use film thickness, number of cycles to compute thickness/cycle
- Compare for various conditions and cycle times
- Model growth using adsorption, desorption parameters from surface chemistry experiment
  - Compare with experimental results

Chemical Mechanical Polishing: Possible Goals

- Gain familiarity with concepts of CMP
  - Relative angular velocity, down-pressure, slurries
  - Physics-based governing equations used phenomenologically
- Gain familiarity with quantifying spatial nonuniformity effects

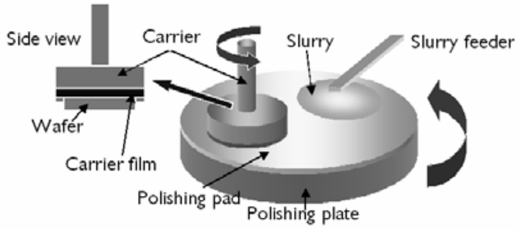
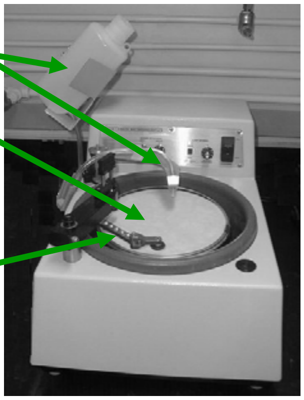


Illustration courtesy of Prof. David B. Graves

Chemical Mechanical Polishing

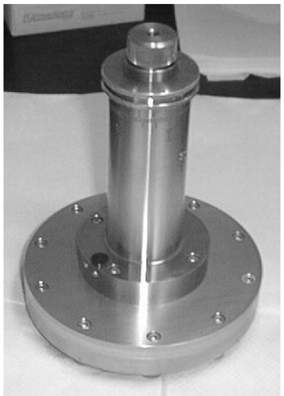
- Use conventional tabletop polishing tool



Slurry supply

Polishing plate

Wafer carrier stabilizer arm



Wafer carrier

Photos courtesy of Prof. David B. Graves

Chemical Mechanical Polishing: Data Collection

- Polish wafers with grown thermal oxide
- Experimental parameters
  - Spin rate
  - Pressure on wafer
  - Polishing time
- Thickness/uniformity from reflectometry
  - 9-point inspection pattern
  - Surface tension → edge bead
- Use material from photoresist etching experiment
  - Process flow, integration

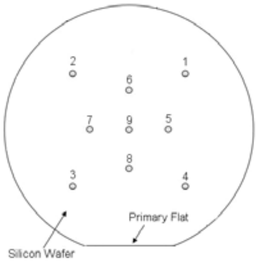


Illustration courtesy of Prof. David B. Graves

Chemical Mechanical Polishing: Data Analysis

- Quantify Planarization: With-In-Wafer-Non-Uniformity

$$\mathrm{WIWNU}(\%) = Max\left[\frac{\left|\text{oxide thickness}_{i+1} - \text{oxide thickness}_{i}\right|}{\text{mean of total oxide thicknesses}}\times 100\right]$$

- Examine Preston's wear equation:

$$\left.\frac{dh(x)}{dt}\right|_P = C\left.\frac{dL(x)}{dA}\frac{ds(x)}{dt}\right|_P$$

- Quantify Preston's coefficient C:

$$C = \Delta h\left(\frac{A}{L}\right)\left(\frac{1}{v_{avg}\Delta t}\right)$$

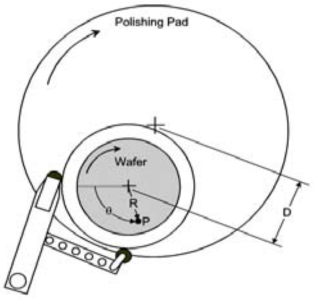


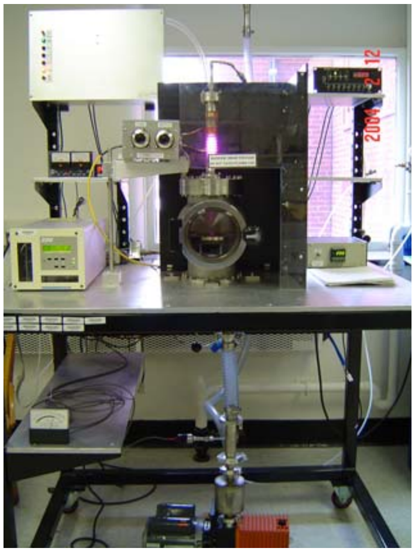
Illustration courtesy of Prof. David B. Graves

PECVD of Amorphous Si: Possible Goals

- Gain familiarity with concepts of plasma deposition
  - *Inductively* coupled plasma, sheath, plasma power…
  - Comparison to plasma etching
  - Spatial uniformity issues on wafer
- Potential for CFD modeling

Amorphous Si PECVD: Apparatus

- Inductively coupled plasma
  - Home-build tuner
  - Need to keep close to wafer surface
- Bottled SiH_4 diluted in Ar (<0.5% by volume) – below flammability limit



Amorphous Si PECVD: Data Collection

- Parameter space explored experimentally over semester with aggregate data from all groups
  - Process P (~500 mtorr)
  - Gas flow rate (~100 sccm SiH_4/Ar)
  - Wafer T (~200°C)
  - RF power (~4 W)
- Film thickness by ellipsometry
- SiH_4 plasma chemistry can be modeled

Copper Electrodeposition: Possible Goals

- Gain familiarity with concepts of electrochemistry
  - Redox potentials, buffers…
  - Electrochemical kinetics
  - Comparison to CVD
- Experiment still in planning stages

Laboratory Course Challenges

- Initial investment of time (several years)

- Initial investment of $$$
- Ongoing expenses $$$
- Experienced staffing
- Setting proper pace, depth
- Creating faculty, student constituency

Techniques to Mitigate Challenges (Faculty)

- Design experiments that dovetail to research
  - Permits equip exchange, leverages expertise of support staff
  - UIUC examples
    - CVD/ALD of TiO_2
    - Surface chemistry/vacuum technology (for equip exchange)
    - Thin film metrology tool
- Engage faculty from several disciplines
  - Adds depth to experiments
  - Offers access to additional financial resources
  - Expands pool of students likely to enroll
  - Aids in staffing

Techniques to Mitigate Challenges (Students)

- Add discussion section early in course development
  - Presentations given by students
    - 1 “primary” (25-min) presentation
    - Several “secondary” (5 min)
  - Provides future lecture material
  - Q&A teaches students how in interdisciplinary conversation
  - Presentations, Q&A calibrates what students understand
- Use enrolled students to help build, debug equip in pilot course offerings
  - Less support staff required
  - Design orientation benefits students
  - Expt robustness: typcial student mistakes emerge early

Summary

- Interdisciplinary lab course with nonstandard equipment
  - Focuses of processing fundamentals
  - Gives exposure to:
    - Elements of process flow, integration
    - Conversation in interdisciplinary groups
- Mixed enrollment simulates dynamics of industrial teams
- Challenges to setup are significant
  - Need multidisciplinary faculty constituency
    - Intellectual fertilization
    - Resource development