An Interdisciplinary Model for Education in Microelectronic Fabrication

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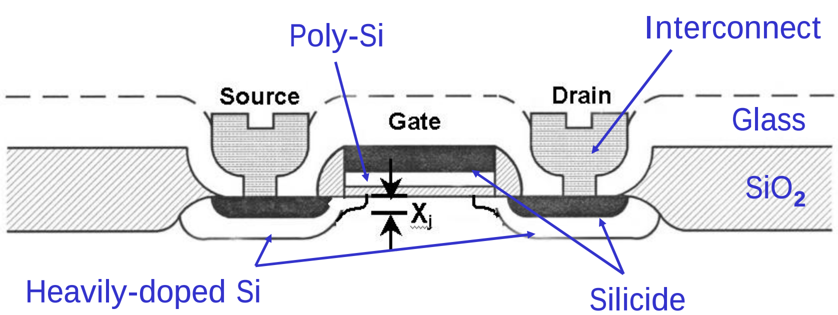
MOSFET Schematic



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

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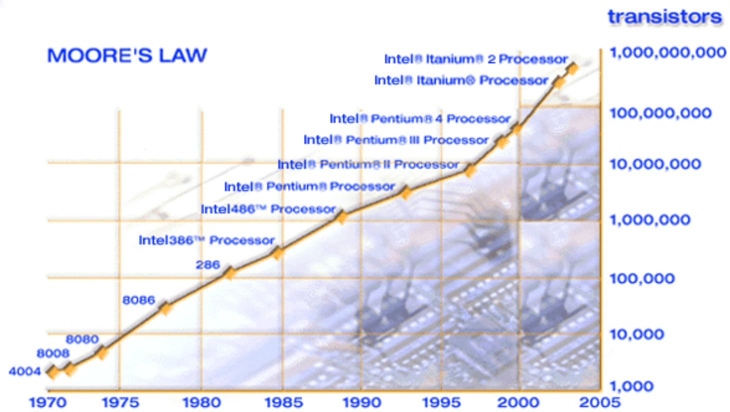
Transistor Scaling



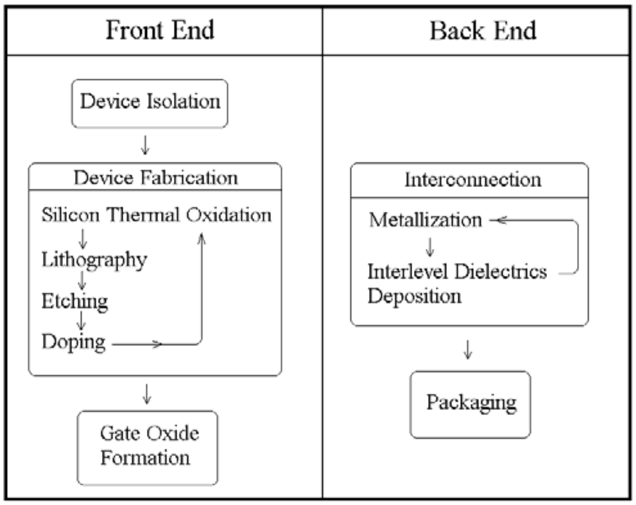
Symbiosis with software industry: **Better hardware** ⇄ **Frillier software**

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

Process Flow Schematic



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

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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 industry 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

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Clarifying the Placement of Microelectronic Processing Education

- Western universities evolved toward a departmental system during the 1500s
- Natural sciences and trades/crafts lie at opposite ends of a continuum

Science	Engineering	Trades/crafts
• Very general • Physics • Chemistry • Biology	• Considerable application focus • Mathematics • “Systems”	• Very application-specific • Practical “arts”

Disciplinary Orientations

- Engineering education now mixes basic science and practical “arts”
- Engineering departments vary in the breadth of science, amount of “art” they incorporate
  - Broad science incorporation
    - Materials engineering (condensed matter physics)
    - Electrical engineering (electronic-charge physics)
    - Chemical engineering (chemistry)
    - Bioengineering (biology)
  - Focused science incorporation
    - Nuclear engineering (nuclear physics)
    - Aeronautical engineering (gas-flow physics)

Disciplinary Definitions Help Make the Needed Distinctions

- Good definitions comprise a genus & differentia

Person = thinking animal

Differentia (thinking) — Genus (animal)

- Definitions are not enumerations!
- Example definition: Chemical Engineering

"The **study** and **practice** of transforming substances at large scales for the tangible improvement of the human condition."

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Where Does the Study of Microelectronics Fall?

- Product devices are clearly electronic
  - Device design — Electrical engineering
- Fabrication involves mostly chemistry, physics
  - Chemical reactions — Chemistry
  - Transport physics of mass, energy
  - Solid defect/diffusion physics
  - Optical physics

Solid defect/diffusion physics, Optical physics — Physics

Chemical reactions through Solid defect/diffusion physics — Chemical engineering

Fabrication requires *practice* of much chemical engineering, some chemistry & physics, *motivated* by electrical engineering

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Implications for Courses in Microelectronics Fabrication

- Courses lacking sufficient chem eng, chemistry & physics acquire a “practical arts” flavor
- “Practical arts” orientation is inadequate for technical staff in advanced fabs
  - Troubleshooting skills impaired
- Traditional departmental divisions can impair development of needed skill sets
  - Fabrication courses often offered in electrical engineering, microelectronics departments

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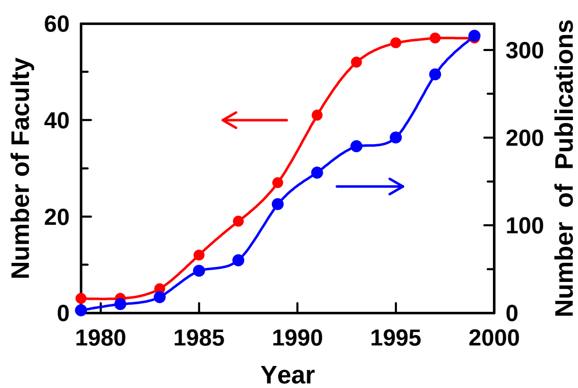
Additional Pressure in US: Stable or Decreasing Processing Faculty

- Example: chemical engineering
  - Microelectronics faculty level at ~55
  - 3-4% annual turnover
  - Leveraging courses outside discipline crucial



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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

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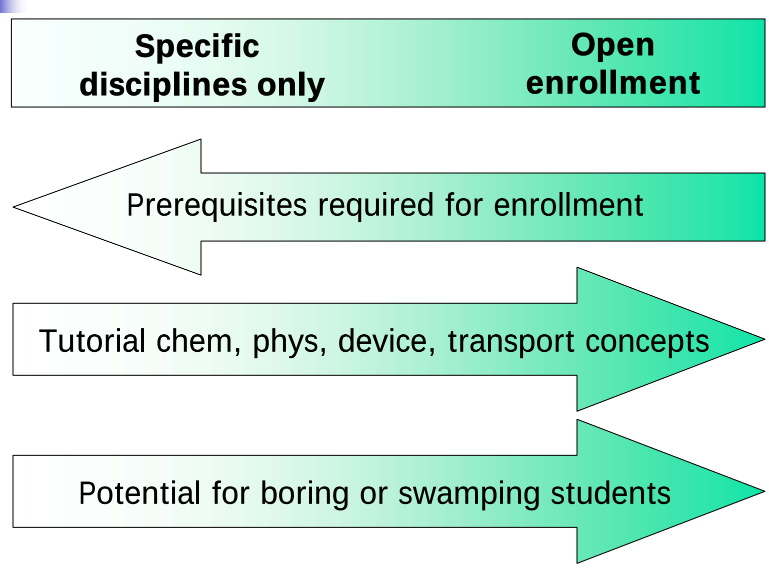
Conceptual Trends for Mixed-Enrollment Courses



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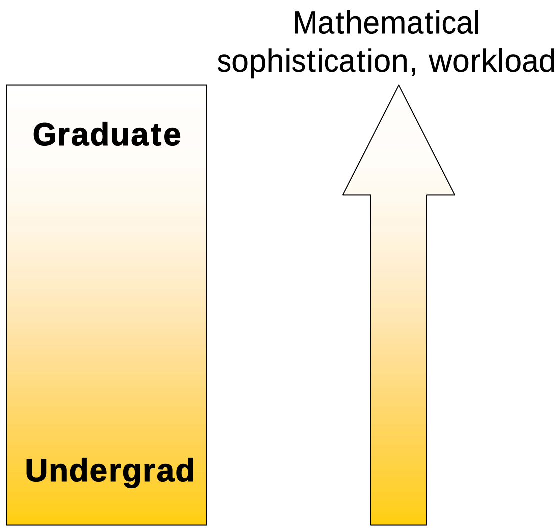
Conceptual Trends for Mixed-Enrollment Courses



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Role of Modeling

- Simple, unsophisticated
  - Simple analytical
    - Rate selectivity
    - Deal-Grove model of oxidation
  - Easy-to-use software packages
  - For undergraduate, graduate students
- Sophisticated
  - Complex analytical
    - Transient enhanced diffusion
    - Spin coating
    - CVD with viscous flow
    - Dry etching with flow
  - For graduate students only

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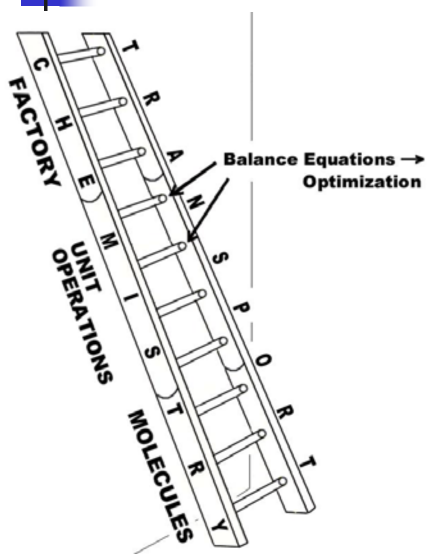
Metaphor for Thinking about Processing Education



- Three-segment extension ladder
  - Represent length scales
- Chemistry, transport linked by balance eqns
- Movement on ladder not algorithmic
  - Facts
  - Knowledge
  - Wisdom

Rev Chem Eng, **18** (2001) 1.

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Possibilities for Education in Fabrication – Undergraduate

- Stand-alone course
  - Lecture or lab
- Informal sequence of courses
  - Does not appear on transcript
  - Can leverage courses in other departments
- Formal option
  - Appears on transcript
  - Leverage courses in other departments

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Relative Merits of Differing Approaches

- Stand-alone course
  - Least effort, $$ to set up
  - Least comprehensive training
  - May lack interdisciplinary focus
- Informal sequence of courses
  - Greater flexibility for students
  - Effort, $$ can be minimized with careful cross-dept cooperation
- Formal option
  - Most effort, $$ to set up
  - Visible imprimatur for employers

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Examples of Formal Programs

- **Florida**
  - "Area of specialization" – Electronic Materials
  - Flexible curriculum, exit interview
- **NCSU**
  - "Concentration" – Electronic Materials
  - 6 replaced courses – 5 required, 1 elective
- **Oregon State**
  - "Option" – Materials Engineering
  - ~ 5 replaced courses
- **San Jose State**
  - "Concentration" – Microelectronics Process Engineering
  - Revised curriculum, internships, short courses
- **UCLA**
  - "Option" – Semiconductor Manufacturing
  - 6 replaced courses – 4 required, 2 elective
- **Univ. of Washington**
  - "Specialty" – Electronic Materials
  - 3 added courses as electives

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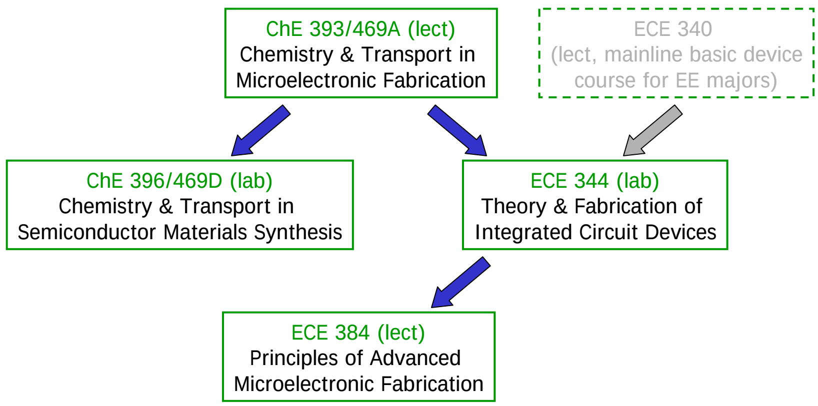
Examples of Informal Options

- Univ of Illinois at Urbana-Champaign
  - Up to 4 elective courses in chem eng, electrical eng
  - Prerequisites kept minimal



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Possibilities for Education in Fabrication – Graduate

- MS-level
  - Stand-alone lecture courses common
  - Few additional lab courses
  - In US, comprehensive dedicated programs driven by local industry needs
  - Coursework-only, 1 yr
  - NCSU, UCLA, Washington,…
- PhD-level
  - No formal programs
  - Education requires presence of research faculty

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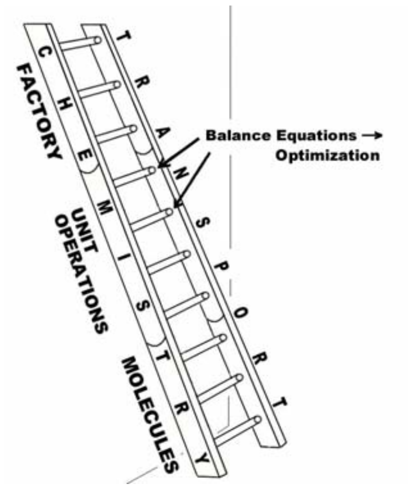
Purposes of Lecture Courses



- 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

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UIUC: “Chemistry & Transport in Microelectronic Processing”

- Lecture course, 70+ students per offering
- Broad audience
  - ChE, EE, Chemistry, Materials Sci
  - Grad & Undergrad
- 2-week intro to semiconductor physics, devices
- Subjects ordered by increasing sophistication of mathematical governing equations

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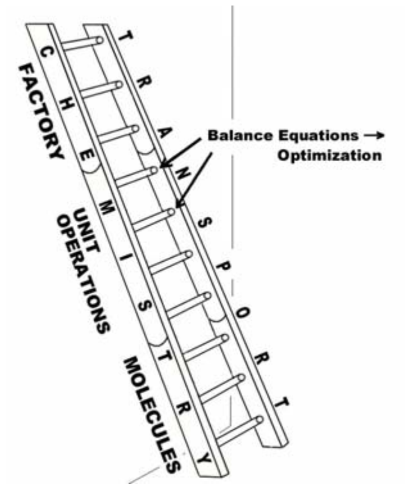
Purposes of Laboratory Courses



- 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

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UIUC: “Chemistry & Transport in Semiconductor Materials Synthesis”

- Lab course, Up to 24 students per offering
  - Eight groups of 3 (mixed-discipline)
- 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

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Experiments

- Si oxidation kinetics
- Dry etching of SiO_2

"Process flow"

- Photoresist spin coating
- Dry etching of photoresist

"Process flow"

- Principles of vacuum technology
- Principles of surface chemistry
- Atomic layer deposition of TiO_2

Science-to-technology

- Cu electrodeposition
- Chemical mechanical polishing

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Laboratory Course Challenges

- Initial investment of time (several years)

- Initial investment of $$$
- Ongoing expenses $$$
- Experienced staffing

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Summary

- Interdisciplinary nature makes education in microelectronic fabrication
  - No department easily claims ownership for teaching
  - Student enrollment should be mixed
    - Between disciplines, grad + undergrad
- Suites of courses need lab courses
  - Expensive, time-consuming to set up & operate