Semiconductor Processing and Characterization Techniques

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(Cleland, UCSB)
Semiconductors and micro- and nanofabrication are at the heart of essentially all modern technologies
Basics questions we address in this course:

(1) How are semiconductors made?
(2) How do we control their physical properties?
(3) How do we shape them and wire them to create circuit elements and eventually complex devices such as microprocessors?
Planar Processing with Semiconductors (Silicon)
A gallery of engineered complex micro and nanoscale architectures fabricated by planar processes
Evolution of Devices

Yesterday’s Transistor (1947)  Today’s Transistor (2006)
Transistor Design – Intel’s 22 nm 3D Platform

IBM now has 7 nm technology
1-meter spiral with red-laser alignment

S-Bend pure-silica-core waveguide

(John, 2011)
Photonics: Resonators

Racetrack ring resonator

Vahala, 2003

John, 2011

(Vahala, 2003)

[John, 2011]
Photonics: More Resonators and "Crystals"
\[ \psi_{right} = \exp\left(\frac{i\pi x}{a}\right) \]

\[ \psi_{left} = \exp\left(\frac{-i\pi x}{a}\right) \]

\[ \psi(+) = \exp\left(\frac{i\pi x}{a}\right) + \exp\left(\frac{-i\pi x}{a}\right) = 2 \cos\left(\frac{\pi x}{a}\right) \]

\[ \psi(-) = \exp\left(\frac{i\pi x}{a}\right) - \exp\left(\frac{-i\pi x}{a}\right) = 2i \sin\left(\frac{\pi x}{a}\right) \]

\[ |\psi(+)|^2 \propto \cos^2\left(\frac{\pi x}{a}\right) \]

\[ |\psi(-)|^2 \propto \sin^2\left(\frac{\pi x}{a}\right) \]

\[ |\psi_{travelling}|^2 = 1 \]
Photonics: Origin of the Gap in Semiconductors v1.0
Photonics: More Resonators and “Crystals”

2D photonic crystal with cavity

3D photonic crystal

(Sandia)
Microfluidic Devices
Electromechanical Devices

- Gear Speed Reduction Unit
  (Sandia)

- Movable Mirror
  (Clark)

- Turbine Engine
  (Sandia)

- Biosensor
  (Roukes)
Electromechanical Devices: SiC

(Alemán)
Nanoelectromechanical Devices: Carbon Nanotubes

(Alemán)
Integrated Devices: Electronics and Fluidics

(Cleland)
Integrated Devices: Optoelectromechanics

MEMS-tunable Vertical Cavity Surface Emitting Lasers (VCSELs)

(Praevium, Thorlabs)
Integrated Devices: Quantum Optoelectromechanics

(Cleland)
What are the advantages of miniaturization?

Yesterday’s Transistor (1947)  

Today’s Transistor (2006)
Why make electromechanical systems smaller?

• Smaller footprint
• Lower fabrication cost
• Lower power (lower operational cost)
• Improved efficiency
• More computational power per square
• Enhanced sensitivity to mass, charge, force
• Facilitate observation of quantum phenomena

\[
\omega_0 = \sqrt{\frac{k}{m + \Delta m}}
\]

\[\Delta m_{\text{min}} \propto m\]

(O’Connell, 2010)

(Arlett, 2006)

(Steele, 2009)
Challenges with traditional electronics as they are made smaller

- Thermal Management
- Fabrication
- Quantum Mechanics

Images: Public Domain
Emergence of carbon-based electronics
Carbon-based spintronics

Images: Public Domain
Abandoning perfection and embracing disorder
A special defect in diamond is a quantum spin

- Boron (B)
- Nitrogen (N)
- Vacancy
Quantum vs. Classical: Angular momentum and spin

Quantum

Classical

$\psi_{slow}$  $\psi_{fast}$

Discrete  Continuous
Spinning electrons in a diamond

Nitrogen-vacancy (NV) center:

- Spin 1 system in spin-free environment with ground state degeneracy lifted by strain
- Single photon emitter
- Two upper levels are not bright
- Temperature range 0 – 700 K
- Energy levels shift with magnetic field, temperature, and electric field
- Atomic scale size means high spatial resolution

\[ m_s = \pm 1 \]

\[ m_s = 0 \]
Spinning electrons in a nanosized diamond bottle

Computational task
Electric field
Magnetic field
Temperature

Nanoscale Diamond
Nanodiamonds are produced in high-yield
Nanodiamonds release easily and are single crystal

(Alemán)
Optical properties confirm presence of single NV centers

(Alemán)
The power of classical computation is linear

Power = $2^N$

32 bit to 64 bit
The power of quantum computation is *exponential*.

Power = $2^N$

32 bit to 33 bit

Over 1 million times more powerful
Take-home messages

• Semiconductor processing enables new devices – faster and with new functions

• Advances in semiconductor processing are happening – the field is not static

• Field requires a multidisciplinary background: electronics, optics, mechanics, fluidics, quantum mechanics

• Our Approach: learn fundamental science behind basic processing skills/strategies and problem solving approaches to apply in diverse scenarios.
Planar Processing with Semiconductors (Silicon): Course Map

- Crystal growth (semiconductors)
- Wafer doping (in situ)
- Wafer characteristics
- SiO₂ growth*
- Defects and impurities

- SiO₂ growth*
- Lithography
- Masked diffusion doping
- Vacuum Systems
- Thin Films: CVD, MBE, PVD, ALD
- Implantation
- Wet and Dry Etching
- Integration
## Approximate Course Schedule

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<th>Day</th>
<th>Reading/Reference</th>
<th>Lecture Topics, Important Dates, etc.</th>
<th>Lab</th>
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<td><strong>Week 1</strong></td>
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| M | Wolf § 1, 2, Sze § 11 | Introduction to semiconductor processing, Crystal Growth | MOS Capacitor:  
- Optical Lithography  
- Oxide Growth  
- Metallization |
| Tu | Wolf § 8, Sze § 12.1 | Crystal Growth, SiO₂ Thermal Oxidation |
| W | Wolf § 9, Sze § 14 | Defects and Impurities, diffusion |
| Th | Wolf § 9, Sze § 14 | Diffusion |
| F | Wolf § 13, Sze § 13.1-13.2 | Lithography I—Optics  
Quiz I |
| **Week 2** |
| M | Wolf § 12 | Lithography II—Photoresist Materials |
| Tu | Wolf § 3 | Vacuum and Gas Technology and Physics |
| W | Wolf § 4, 11, Sze § 12.5 | Thin Films |
| Th | Wolf § 6, 7, Sze § 12.2-12.4 | Chemical vapor deposition (CVD), Metallorganic CVD (MOCVD), Atomic Layer Deposition (ALD), Molecular beam epitaxy (MBE) |
| F | Wolf § 6, Box-Hunter-Hunter § 5 | Grove’s Model for CVD, PVD; Factorial Design, Introduction to Virtual CVD project  
Quiz II |
| **Week 3** |
| M | Wolf § 7, 10 | Physical vapor deposition (PVD)—Sputtering and evaporation, Ion implantation  
Virtual CVD Design Strategy Presentations due at 8 AM during Process Meeting. |
| Tu | Wolf § 14, Sze § 13.3-13.4 | Wet and Dry Etching |
| W | Guest Lecture | Gary Stinson from Microchip |
| Th | Wolf § 15 | Integration, Catch-up, Review  
Virtual CVD Presentations due at 8 AM during Process Meeting; VCVD written reports due at 9 AM. |
| F | | Final Exam |
About you?
About Me
Benjamín J. Alemán

• Mathematics and Physics Degrees from the University of Oregon (2004)
  • Some good micro/nanofabrication experience (Caltech and UO)
  • Skateboarding, Snowboarding, Travelling, and Music!

• Travelling: Spain, Morocco

• Ph.D. from the University of California at Berkeley (2005—2011)
  • Graphene and Carbon Nanotube Nanoelectromechanical Systems
  • Lots of experience doing micro/nanofabrication
  • AFM, TEM, SEM
  • Music and Travel to Europe!

• University of California President’s Postdoctoral Fellow at UC Santa Barbara (2011—2013)
  • Quantum optics with spins in diamond
  • Microfluidics
  • More experience doing micro/nanofabrication
  • Surfing SoCal!

• Assistant Professor of Physics at the University of Oregon (2013—present)