EE506 Semiconductor Physics

Units: 4
Spring 2024, Mon, Wed: Time 9:00 am – 10:50 am

Location: THH 115 (Taper Hall)

Instructor: Tony Levi
Office: KAP 132
Office Hours: Mon, Wed, KAP132, 11:00 am – 12:00 am or by appointment
Contact Info: alevi@usc.edu, (213) 740-7318. Emails will be returned within 48 hours.

Teaching Assistant: TBD
Office: TBD
Office Hours: TBD
Contact Info: TBD

Course Description

This course will explore the physics that underpins the behavior and properties of semiconductors and their device applications. It aims to provide a framework and understanding that can be used to develop a methodology for creation of new combinations of materials, device geometries, and device functionality.

Prerequisite: Understanding to approximately the level of either MS/EE 501 Solid State Physics or EE 539 Quantum Mechanics

Suggested background reading: Essential Electron Transport for Device Physics, A.F.J. Levi, AIP, ISBN: 978-0-7354-2158-5.

Grading:	Homework	20%
	Midterm Exam	30%
	Final Exam	50%

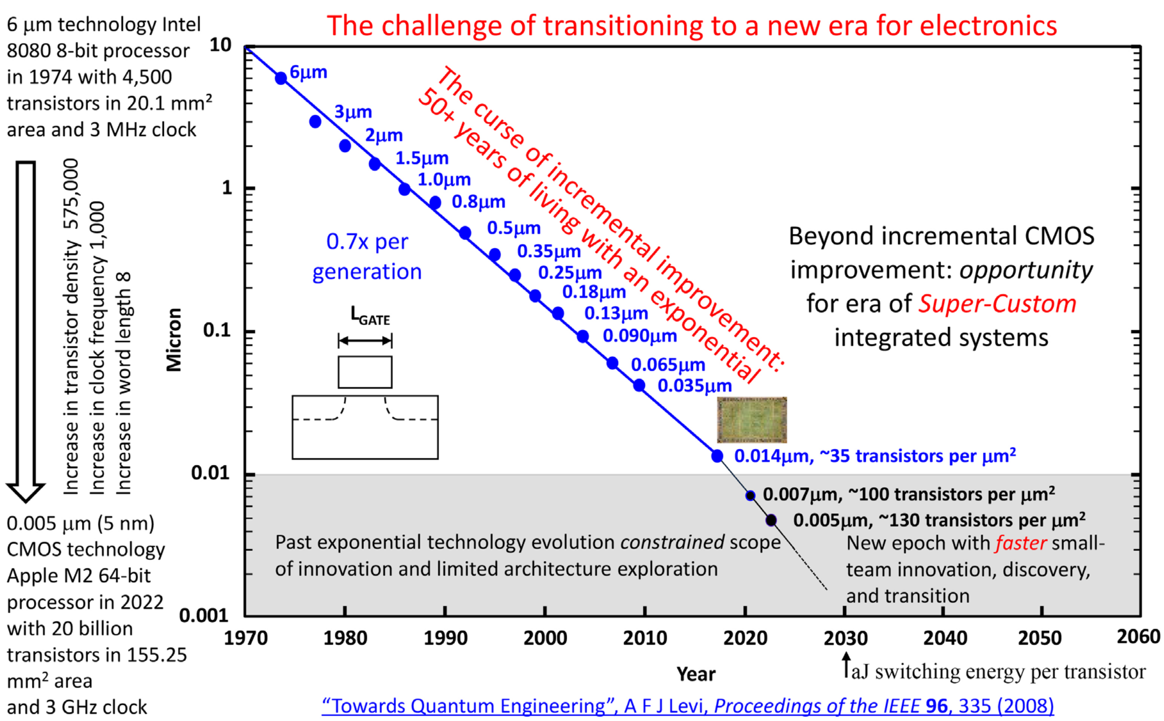
Prerequisite(s): none
Co-Requisite(s): none
Concurrent Enrollment: none

Recommended Preparation: an interest in semiconductor physics, devices, and technology. electrical and computer engineering

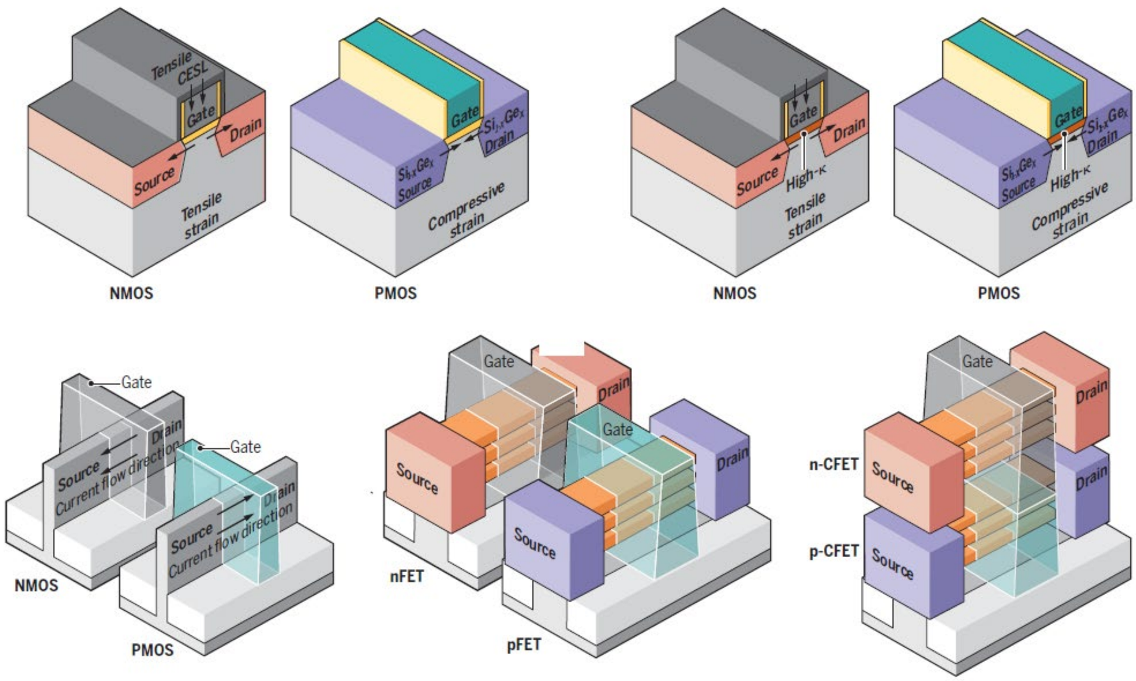
Grading Timeline
Assignments will be graded and feedback provided within one week of submission.

Course Schedule: Lectures

Lecture 1: Motivation. Semiconductors and electronics. Evolution of materials and geometries used in creation of transistors:



"Towards Quantum Engineering", A F J Levi, *Proceedings of the IEEE* **96**, 335 (2008)



Lecture 2: Atom "shape" in solid materials determines crystal structure. The critical role of quantized electron orbitals. The hydrogen atom. The Pauli exclusion principle and the periodic table of elements. Hybridization.

Lecture 3: Bonds. The hydrogen molecule ion. The hydrogen molecule covalent bond using valence bond and molecular orbital description. The ionic bond.

Lecture 4: Crystal structure. Crystal systems in three-dimensions. The reciprocal lattice. Nonequilibrium materials and disordered materials. Isotropic materials with linear local response. Bloch's theorem. Localized Wannier functions. Crystal momentum and electron effective mass.

Lecture 5: The generalized Kronig-Penney model and complex band structure.

Lecture 6: Introduction to the tight-binding method. A single s-band in a one-dimensional lattice. Density of electron states. A one-dimensional lattice with a two-atom basis, the example of trans-polyacetylene. Complex band structure in the tight-binding approximation. Single electron wave packet tunneling and complex band structure.

Lecture 7: Graphene lattice. Carbon sp^2 hybridization and bonding. Graphene band structure calculated using the tight-binding method. Electron transport in graphene.

Lecture 8: Band structure: Tight-binding method in three dimensions based on the paper by Vogl et al., (1983). The band structure of III-V and group-IV semiconductors.

Lecture 9: Band structure: Kane's **k.p** method. Hartree self-consistent solution to Schrodinger and Poisson equation, Hartree-Fock, and density functional theory.

Lecture 10: Doping electrons and holes. The semiconductor heterostructure. The gap state model. Substitutional doping of electrons and holes. Metallic behavior and rs. Density of electron states at band extremum. Fermi particle statistics, few-electron fermi-particle statistics, the Fermi-Dirac distribution. The Bose-Einstein distribution. The chemical potential. The electron propagation matrix. Current-voltage characteristic of a semiconductor heterostructure tunnel diode. Calculation of the semiconductor heterostructure tunnel diode current in the depletion approximation.

Lecture 11: Electron transmission in the presence of inelastic scattering. Inelastic electron tunneling spectroscopy.

Lecture 12: Lattice vibrations. The damped driven oscillator. Noise, fluctuation-dissipation theorem, and diffusion. Einstein relation.

Lecture 13: Optimal semiconductor device design. Cost function, distance measure, noise in data, regression. The heterostructure tunnel diode forward model. The adjoint method.

Lecture 14: Machine generated, non-intuitive, optimal semiconductor heterostructure tunnel diode device design for user specified current-voltage characteristics.

Lecture 15: Review.

Lecture 16: Current. Charge transport in semiconductor devices. Electron transport in semiconductors. Electron wave packet dynamics at a tunnel barrier.

Lecture 17: Bloch oscillations. Material parameters contributing to current. Velocity field characteristics and electron transfer to subsidiary minima. The Gunn diode oscillator. Ballistic transport.

Lecture 18: The Boltzmann transport equation. Evolution of the distribution function with time. The scattering term. Relaxation time approximation. Conductivity. The diffusion term.

Lecture 19: Mean free path and scattering time from mobility. Mean free path and scattering time in 2DEG. Electron optics in the 2DEG. Diffusion in devices. Diffusion and recombination of minority carriers. The metal-semiconductor Schottky barrier. Depletion width. Thermionic emission. Capacitance as a function of voltage bias. Single-crystal nickel-silicide silicon Schottky diode and metal-induced gap states.

Lecture 20-21: Electron scattering in semiconductors. The electron-phonon interaction. The Frohlich interaction. The longitudinal polar-optic phonon scattering rate. The LO phonon scattering rate in the conduction band of GaAs. Energy and momentum conservation. Electron scattering rate from linear dielectric response. Scattering rates and fluctuation dissipation.

Lecture 22-23: Elastic scattering from ionized impurities. The screened coulomb potential. Elastic scattering of electron from ionized impurities in GaAs. Correlation effects due to spatial position of dopant atoms. estimating mean free path and mobility. Calculating the screened potential and dielectric function in wave vector space. Comparison between Thomas-Fermi screening and RPA.

Lecture 24-25: RPA and inelastic scattering of majority carriers in n-type semiconductors. Inelastic scattering of minority carriers in p-type semiconductors.

Lecture 26-27: Review

Web sites:

https://alevi.usc.edu/teaching/ee506/

https://alevi.usc.edu

https://classes.usc.edu/term-20241/classes/ee

Class schedule, study days and and final exam

First day of classes Monday January 8, 2024

Last day of classes Wednesday April 24, 2024

Study Days: Saturday, April 27 – Tuesday, April 30, 2024

Final Exam: TTH 115, Friday, May 3, 2024, 8.00am – 10.00am

Statement on Academic Conduct and Support Systems

Academic Conduct:

Plagiarism – presenting someone else's ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in SCampus in Part B, Section 11, "Behavior Violating University Standards" policy.usc.edu/scampus-part-b. Other forms of academic dishonesty are equally unacceptable. See additional information in SCampus and university policies on scientific misconduct, policy.usc.edu/scientific-misconduct.

Support Systems:

Counseling and Mental Health - (213) 740-9355 – 24/7 on call
studenthealth.usc.edu/counseling
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

National Suicide Prevention Lifeline - 1 (800) 273-8255 – 24/7 on call
suicidepreventionlifeline.org
Free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week.

Relationship and Sexual Violence Prevention Services (RSVP) - (213) 740-9355(WELL), press "0" after hours – 24/7 on call
studenthealth.usc.edu/sexual-assault
Free and confidential therapy services, workshops, and training for situations related to gender-based harm.

Office of Equity and Diversity (OED) - (213) 740-5086 | Title IX – (213) 821-8298
equity.usc.edu, titleix.usc.edu
Information about how to get help or help someone affected by harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants.

Reporting Incidents of Bias or Harassment - (213) 740-5086 or (213) 821-8298
usc-advocate.symplicity.com/care_report
Avenue to report incidents of bias, hate crimes, and microaggressions to the Office of Equity and Diversity |Title IX for appropriate investigation, supportive measures, and response.

The Office of Disability Services and Programs - (213) 740-0776
dsp.usc.edu
Support and accommodations for students with disabilities. Services include assistance in providing readers/notetakers/interpreters, special accommodations for test taking needs, assistance with architectural barriers, assistive technology, and support for individual needs.

USC Campus Support and Intervention - (213) 821-4710
campussupport.usc.edu
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity at USC - (213) 740-2101
diversity.usc.edu
Information on events, programs and training, the Provost's Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency - UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call
dps.usc.edu, emergency.usc.edu
Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety - UPC: (213) 740-6000, HSC: (323) 442-120 – 24/7 on call
dps.usc.edu
Non-emergency assistance or information.

Office of the Ombuds - (213) 821-9556 (UPC) / (323-442-0382 (HSC)
ombuds.usc.edu
A safe and confidential place to share your USC-related issues with a University Ombuds who will work with you to explore options or paths to manage your concern.