Syllabus - EE 601
Semiconductor device physics. 4-unit course.
Spring. TTh
A. F. J. Levi.

Outline and course content
This is an advanced course in the operation and behavior of nanoscale semiconductor devices. The course is designed for graduate students with an interest in the fundamentals and limitations of our understanding of operation of electronic and photonic components used as the building blocks for more complex circuitry. The course emphasizes the actual calculation of useful parameters relevant to the design and operation of practical and research devices such as scaled transistors and scaled lasers.

Beyond the Moore's Law era, novel combinations of materials and heterogeneous components will likely evolve, changing the design paradigm and requiring knowledge and insight that this course aims to provide. In addition to fundamental aspects of device physics, connection to typical SPICE model descriptions will be made and conditions when such models fail will be established.

The course also includes a project involving presentation in class of a selected research paper, analysis, critique, and suggest potential research directions that might emerge from the work described. There is also a discussion section.

Knowledge to the level of EE506 and EE539 is helpful, but not a prerequisite for this course. Recommended text books are "Applied Quantum Mechanics" by A.F.J. Levi, Cambridge University Press; 2 edition (June 26, 2006), ISBN-10: 0521860962, "Optimal Device Design" edited by A.F.J. Levi and S. Haas, Cambridge University Press; (January 29, 2010), ISBN-10: 0521116600, and "Essential Classical Mechanics for Device Physics" by A.F.J. Levi, IoP, Morgan & Claypool Publishers, 2016 (print ISBN: 978-1-6817-4412-4).

Some material covered by this course does not appear in any textbook.

Course content:

Lectures 1-2: Review of Maxwell equations. Charge conservation. Polarization, capacitance, and inductance. Classical electromagnetism and numerical solution of Maxwell equations. Radiation and wave-guides.

Lectures 3-6: Review of materials and atomic potentials. Quantum mechanics. Statistics of identical indistinguishable particles. Bonding, Bloch theorem and band structure. Complex band structure. Tight binding model. Impurities and doping. Crystal momentum and effective electron mass.

Lectures 7-8: Concepts from classical mechanics. Conservative and non-conservative systems. The harmonic oscillator. Lattice vibrations. The damped driven oscillator. Methods of control.

Lecture 9: Origin of noise, fluctuation-dissipation theorem, and diffusion. Einstein relation.

Lecture 10-11: Lorentz model of light-matter interaction. The Kramers-Kronig relations. Propagation of electromagnetic waves in a dielectric medium. Complex dispersion relation and complex refractive index. The loss function.

Lecture 12: Introduction to electron transport. The Drude model. DC and AC conductivity. Kinetic inductance.

Lecture 13: Permittivity of metal. The loss function of copper. Physical origin of plasma frequency. Local response in the Drude model. An electromagnetic field interacting with a metal. Drude dispersion of electromagnetic radiation. Changing the properties of a metal. Metal and electromagnetic fields in integrated circuits. Doping in semiconductors, metal-insulator transition and r_s^*.

Lecture 14: Bloch oscillations. Material parameters contributing to current. Velocity-field characteristics and electron transfer to subsidiary minima. The Gunn diode oscillator. Ballistic transport.

Lecture 15: The Boltzmann transport equation including conductivity and diffusion in the relaxation-time approximation. Evolution of the distribution function with time. The scattering term. Relaxation time approximation. The diffusion term.

Lecture 16: 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 Schottky barrier. Depletion width. Thermionic emission. Capacitance as a function of voltage bias.

Lecture 17-18: 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. Coupled plasmon-phonon scattering. Scattering rates and fluctuation dissipation.

Lecture 19: The Field Effect Transistor. Device modeling. Physical performance limitations. Tunnel-FET concept and lessons learned. CNT and graphene FET device design, performance metrics, and SPICE models.

Lectures 20-21: Introduction to Coulomb scattering from ionized impurities. 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 potetnial and dielectric function in wave vector space. Comparison between Thomas-Fermi screening and RPA.

Lectures 22-23: Lindhard dielectric function. Application to metals and semiconductors. Single particle excitations and coupled plasmon–phonon collective excitation spectrum. Analysis of semiconductor dielectric function and use of MATLAB example code.

Lectures 24-25: Calculation of electron lifetime and device design. Calculation of electron lifetime in unipolar transistors. Temperature dependence of non-equilibrium electron scattering rates. Non-equilibrium electron spectroscopy.

Lecture 26: Numerical determination of non-equilibrium electron scattering rates. MATLAB code example. The truncated parabola of integration. Phase-space and its influence on scattering rate. Evaluation and interpretation of temperature dependence.

Lectures 27-28: Non-equilibrium electron transport in bipolar transistors. Theory of minority carriers in conduction band interacting with majority carriers in valence band. Collective and single-particle excitation spectral function in three-band model. Calculation of scattering rates. Parabola of integration. Phase-space and device scaling. Experimental evidence that non-equilibrium electron transport dominates the static and dynamic performance of scaled HBTs.

Lecture 29: The semiconductor laser. Influence of electron and photon quantization on static and dynamic behavior of scaled laser diodes and photon statistics. Failure of the non-equilibrium phase-transition description of laser light emission in scaled devices.

Lecture 30: Scaled semiconductor laser. Meso-scale lasers. The single quantum dot laser. Cavity QED and non-classical light. MATLAB models of laser behavior.

Presentation of research papers. Class discussion and student presentation in class of selected research papers. Specifically, each participant is expected to describe the contents of a selected research paper, analyze the results, provide a critique, and suggest potential research directions that might emerge from the work described.

Examinations:
There are two written examinations, each of which will contribute 20% to the final grade. Presentation of a research paper contributes 50% of the final grade. The remaining 10% is for written solutions to written homework problems.

Statement for Students with Disabilities

Any student requesting academic accommodations based on a disability is required to register with Disability Services and Programs (DSP) each semester. A letter of verification for approved accommodations can be obtained from DSP. Please be sure the letter is delivered to me (or to TA) as early in the semester as possible. DSP is located in STU 301 and is open 8:30 a.m.–5:00 p.m., Monday through Friday. The phone number for DSP is (213) 740-0776.

Statement on Academic Integrity

USC seeks to maintain an optimal learning environment. General principles of academic honesty include the concept of respect for the intellectual property of others, the expectation that individual work will be submitted unless otherwise allowed by an instructor, and the obligations both to protect one's own academic work from misuse by others as well as to avoid using another's work as one's own. All students are expected to understand and abide by these principles. Scampus, the Student Guidebook, contains the Student Conduct Code in Section 11.00, while the recommended sanctions are located in Appendix A: http://www.usc.edu/dept/publications/SCAMPUS/gov/. Students will be referred to the Office of Student Judicial Affairs and Community Standards for further review, should there be any suspicion of academic dishonesty. The Review process can be found at: http://www.usc.edu/student-affairs/SJACS/.