Recitation 1 -- Wednesday, Sept. 5: Introductory materials. Diagnostic exam: 1st. order diff. eqs; 1-d electrostatics; LECs and linear ckt analysis. Semiconductors and why they are of interest. PS #1 out (n_o, p_o, given N_A, N_D; drift and conductivity, electrostatics for devices).

Lecture 1 -- Thursday, Sept. 6: Introduction. Intrinsic semiconductors, bond structure, holes and electrons; n(T). Dopants -- donors and acceptors. n_o and p_o in extrinsic (doped) Si: thermal equilibrium, detailed balance, n_o p_o product; n_o and p_o given N_A and N_D. Uniform e-field, drift, mobility.

Recitation 2 -- Friday, Sept. 7: Calculations of n_o, p_o in variously doped examples to review "n_o and p_o given N_A and N_D" from lecture. Drift, basic concepts: net velocity vs. field, mobility; conductivity, resistivity; typical values. Concept of n-type and p-type.

Tutorial 1 -- Monday, Sept. 10: Review of electrostatics (8.02) and Poisson's equation; \( \rho, E, \phi \); parallel plate capacitors. Doping and carrier type issues as needed.


Recitation 3 -- Wednesday, Sept. 12: Review minority carrier lifetime; typical values. Extended discussion of Fick's laws and diffusion fluxes and currents. PS #1 due; PS #2 out (population transients, photoconductivity, the 5 equations, electrostatic potential, \( \phi_b \)).

Lecture 3 -- Thursday, Sept. 13: Continuity/conservation. The five basic equations. Non-uniformly doped material in thermal equilibrium. Electrostatic potential (using Einstein relation); Poisson equation. \( n_o(x), p_o(x), \phi(x) \) when doping varies slowly; quasi-neutral approximation; mention of extrinsic Debye length, \( L_D \).

Recitation 4 -- Friday, Sept. 14: Review concepts in Lecture 3. Discussion of electrostatic potential energy, \( q\phi \). Typical values of \( \phi_b, \phi_o \); emphasize weak dependence on \( n_o, p_o \); 60 mV/decade rule.


Lecture 4 -- Tuesday, Sept. 18: Abrupt p-n junction in thermal equilibrium; the depletion approximation. Expressions for \( W, x_o, x_p, E_p, \phi_b \). Extension of model to biased junctions: argue can replace \( \phi_b \) by \( (\phi_b - v_A) \) if charge due to currents can be neglected and all \( v_A \) appears across junction.

Recitation 5 -- Wednesday, Sept. 19: Review depletion approximation model for junction and the effect of bias; comment on \( \phi(x) \) around a circuit through contacts Charge store associated with SCL and depletion capacitance. PS #2 due; PS #3 out (p-n junction depletion approximation, diffusion and simple minority carrier flow situations).

Lecture 5 -- Thursday, Sept. 20: Linearization and decoupling of 5 basic equations in flow problem regime: quasineutrality, Debye length, \( L_{Dx} \), and dielectric relaxation time, \( \tau_D \); minority carrier flow by diffusion. Diffusion equation(s) for \( n' \): general solutions; basic boundary conditions; procedure to find \( n, p, J_n, J_p, E_x \) having \( n' \).

Tutorial 3 -- Monday, Sept. 24: Discussion carrier flow, boundary conditions, special cases and solutions (example excess carrier profiles, currents, electric field; targeted a prep for p-n diode).


Recitation 6 -- Wednesday, Sept. 26: Review carrier population profiles through forward and reverse biased short base p-n diodes (emphasize injection is into lightly doped side; discuss design
possibilities). Charge storage associated with minority carrier injection; diffusion capacitance. \( PS \#3 \) due; \( PS \#4 \) out (current flow in p-n diodes, diffusion capacitance, BJT operation and modeling).

**Lecture 7** -- Thursday, Sept. 27: Introduce BJT structure as two coupled diodes, and bipolar junction transistor (BJT) operating principles; derive currents for npn BJT in forward active region; introduce base and emitter defects.

**Recitation 7** -- Friday, Sept. 28: Large signal BJT characteristics and models: review of BJT focusing on reverse biased CB diode and impact of carrier injection toward it. Two equivalent views: \( i_C \) controlled either by \( v_{BE} \) or \( i_B \). Approximate circuit models valid in forward active region: diode model, \( \beta \)-model. Limitations of simple models and extremes of operation; non-ideal elements.

**Tutorial 4** -- Monday, Oct. 1: Examples of various junction profiles (p-i-n, p-n-n+, etc.) to reinforce understanding of the depletion approximation and the electrostatics of p-n junctions. Estimation of recombination under profile obtained assuming infinite lifetime. \( PS \#4 \) due.

**Lecture 8** -- Tuesday, Oct. 2: Other junction devices (a disguised quiz review): LEDs, illuminated p-n diodes; superposition; solar cells and photodiodes.

**Review 1** -- Wednesday, Oct. 3: No formal recitation sessions. Instructors will be available to answer questions and review issues for the quiz.

**First Hour Exam** -- Wednesday, Oct. 3, 7:30 to 9:30 pm, Rm 54-100. Closed book. Covering material through 9/28/12 and Problem Set \#4 (i.e., through BJTs).

**Lecture 9** -- Thursday, Oct. 4: MOS structures. Discussion of accumulation, depletion, inversion. Application of depletion approximation to MOS capacitor to relate channel charges to gate voltage. Flat band and threshold voltages. Bias on adjacent n+ region (i.e. \( v_{BC} \neq 0 \)). \( PS \#5 \) out (MOS caps).

**Recitation 8** -- Friday, Oct. 5: Review accumulation, depletion, and inversion in MOS, and model relating channel charge to gate voltage in excess of threshold. Look at charge on gate, and discuss C-V relationship for MOS structures.

**Recitation 9** -- Wednesday, Oct. 10: Further discussion of MOS capacitors. Review calculation of threshold voltage. Plot \( C_{GS} vs V_{GS} \). Introduce three terminal MOS structure; discuss impact on threshold. \( PS \#5 \) due; \( PS \#6 \) out (3-terminal MOS capacitors; MOSFET modeling).

**Lecture 10** -- Thursday, Oct. 11: Weak inversion electron charge. Impact of including it; justification for neglecting it. Gradual channel approximation for MOSFET i-v characteristics; quadratic approx. if \( V_T \) constant under gate. Saturation. Regions of operation.

**Recitation 10** -- Friday, Oct. 12: Review of gradual channel model. Features of characteristics. Possible MOSFET device types: n- and p-channel, enhancement and depletion mode.

**Tutorial 5** -- Monday, Oct. 15: MOSFET models for n- and p-channel devices, enhancement and depletion mode.

**Lecture 11** -- Tuesday, Oct. 16: MOSFET i-v linearizing \( V_T \) dependance on \( v_{BC} \); \( \alpha \) factor. MOSFET saturation region: Discussion of pinch-off. Channel length modulation, velocity saturation. Begin discussion of operating near threshold and in the sub-threshold region.

**Recitation 11** -- Wednesday, Oct. 17: Complete discussion of MOSFET modeling. Use large signal model to calculate transfer characteristics of common-source inverter with resistor pull-up. \( PS \#6 \) due; \( PS \#7 \) out (MOSFET large signal characteristics; iLab exercise – MOSFET; sub-\( V_T \) region).

**Lecture 12** -- Thursday, Oct. 18: Modeling sub-threshold operation of MOSFETs. BJT nature of device. Transition to strong inversion region (GCA) model.

**Recitation 12** -- Friday, Oct. 19: Review sub-threshold model and fit to earlier model. Discuss large signal circuit model. Review and compare BJT, MOSFET (strong inv), and MOSFET (sub-\( V_T \)).

Lecture 13 -- Tuesday, Oct. 23: Rev. large signal models. Small signal linear equivalent circuit models for BJT (hybrid-π) and MOSFET (both strong inv and sub-V_T). npn vs. pnp; n-channel vs. p-channel; g_m Early voltage; capacitive charge stores. Importance of a stable bias point.

Recitation 13 -- Wednesday, Oct. 24: Review LECs with focus on bias point dependences of values and the importance of a stable bias point. Compare and contrast the three transistor choices. PS #7 due; PS #8 out (small signal transistor models; inverter transfer characteristics - hand calculation; i-Lab exercises - Diode and BJT).

Lecture 14 -- Thursday, Oct. 25: Basic inverters as building blocks for digital logic, memory; performance criteria. Begin MOS logic; inverter options; why CMOS. Sketch transfer characteristic.

Recitation 14 -- Friday, Oct. 26: Discuss calculating transfer characteristic of MOSFET inverter focusing on CMOS. Derive characteristics; discuss design; introduce A_v approximation (optional).

Tutorial 7 -- Monday, Oct. 29: Calculating inverter transfer characteristics for stages other than CMOS. Problems involving LECs; determining bias point and finding LEC parameter values.

Lecture 15 -- Tuesday, Oct. 30: CMOS performance: Transfer characteristic estimation including Early effect. Switching transients and minimum gate delay. Dependences on device dimensions, parameters. Power dissipation and power density at maximum data rate.

Recitation 15 -- Wednesday, Oct. 31: Final review of minimum gate delay model and dynamic power dissipation model; also power dissipation at maximum data rate and power density calculations. Output buffer design; leaving the minimum-dimension world.

Lecture 16 -- Thursday, Nov. 1: Moore’s law and the modern semiconductor industry: Toward smaller and smaller devices. Scaling rules. Examples of scaling: Intel families through the ages. (disguised, albeit early, quiz review)

Recitation 16 -- Friday, Nov. 2: Discussion of features and aspects of modern Si IC technology preparatory to showing Silicon Run video; Silicon Run video. PS #8 due; PS #9 out (CMOS gate delays, output stages; HSPICE exercise - inverter transfer characteristics).

Tutorial 8 -- Monday, Nov. 5: Review of large signal models, CMOS inverters, and LECs in preparation for second hour exam.

Lecture 17 -- Tuesday, Nov. 6: Review of small signal LEC models, including all capacitances. Importance of a stable bias point and circuit methodologies for setting it. Current source biasing, current source design. Discussion of input/output/ground options.

Second Hour Exam -- Wednesday, Nov. 7, 7:30 to 9:30 pm, Rm 54-100. Closed book. Covering material through 11/2/09 and Problem Set #8.

Lecture 18 -- Thursday, Nov. 8: Linear analysis of amplifiers. Concept of mid-band frequency range. Two-port view of amplifiers; key model parameters and amplifier metrics. Basic single transistor amplifier building block stages: analysis and features of the common-emitter/source.

Recitation 17 -- Friday, Nov. 9: Analysis of common gate/base and source/emitter follower stages. Discussion of features. Concept of cascading stages and issues of choosing and coupling. PS #9 due; PS #10 out.

Lecture 19 -- Tuesday, Nov. 13: Differential amplifiers: large signal analysis and transfer characteristics; incremental analysis and half-circuit analysis techniques. Example of their use to simplify the analysis of a complex multi-stage amplifier circuit (i.e., DP circuit); simplify, divide, conquer.

Recitation 18 -- Wednesday, Nov. 14: Discuss differential amplifier issues with focus on source-
coupled pair: full incremental analysis by decomposing inputs into difference and common mode inputs; doing half-circuit analysis, and recovering total outputs.

**Lecture 20** -- Thursday, Nov. 15: Multi-stage amplifier basics. Cascading differential stages; stage choices; calculating gain. Stage gain dependence on bias point; gain power trade-offs.

**Recitation 19** -- Friday, Nov. 16: Continue/complete single-transistor amplifier stage discussion. Comparison of stages, and when and where each might be used. *PS #10 due. Design problem out.*

**Tutorial 9** -- Monday, Nov. 19: Design problem discussion, issues, encouragement.

**Lecture 21** -- Tuesday, Nov. 20: Achieving maximum gain while staying in forward active region: resistor loads, non-linear loads, active loads (current mirror, Lee load, double- to single-ended output conversion). Selecting bias point for maximum gain. Examples from design problem circuit.

**Recitation 20** -- Wednesday, Nov. 21: Overview of design problem circuit. Understanding the performance specifications: gain stage analysis; output stages; biasing issues; common- and difference-mode voltage ranges. *Drop Date.*

**Tutorial 10** -- Monday, Nov. 26: Discussion of design problem issues. Getting back into it.

**Lecture 22** -- Tuesday, Nov. 27: Through the design problem from left to right. Emitter follower output stages. Discussion of specialized pair stages in design problem context and other ICs, including µA 741; use to discuss Darlington, Cascode, Push-pull, and adding capacitor for stability.

**Recitation 21** -- Wednesday, Nov. 28: Continued consideration of multi-stage differential amplifiers, design problem concerns. Input/output resistances, and voltage swings; power dissipation.

**Lecture 23** -- Thursday, Nov. 29: Gain of CS amplifiers at high frequencies. General Miller capacitance phenomenon. Intrinsic limits to high freq. performance of MOSFETs and BJTs: $\omega_c$, $\omega_v$, $\omega_t$. Limits of quasi-static approximation.

**Recitation 22** -- Friday, Nov. 30: Lack of Miller capacitance in common-gate/-base and followers. The value of the cascode for high frequency design. *PS #11 out (high freq perf; OCTCs).*


**Lecture 24** -- Tuesday, Dec. 4: Bounding mid-band; methods of open- and of short-circuit time constants in high frequency analysis of multi-stage amplifiers.

**Recitation 23** -- Wednesday, Dec. 5: High frequency analysis; review method of open-circuit time constants (OCTC) and Miller effect.

**Lecture 25** -- Thursday, Dec. 6: Sub-threshold amplifiers and inverters. Issues and trade-offs encountered working in this sphere; reviewing the world of low energy applications.. Fully depleted MOSFETs, including FinFETs for high sub-$V_T$ applications.

**Recitation 24** -- Friday, Dec. 7: Implications of sub-threshold operation for high frequency operation. Ask your recitation instructor about her area of research. *PS #11 due.*

**Tutorial 12** -- Monday, Dec. 10: Review of the early part of semester, i.e. remind me...what are p and n, and how do transistors work?

**Lecture 26** -- Tuesday, Dec. 11: CCDs, MOS imagers; pixels and more. Life after 6.012; what's next?

**Recitation 25** -- Wednesday, Dec. 12: Student-driven review of semester; last chance to ask your most troubling question.

**Final Exam** – Monday, Dec. 18, 9am to noon, Walker Gymnasium. Closed book. Covering all material in the subject.