Given below some sample assignment problems on Semiconductor Device Modeling (EE5132). Please note that one should solve more problems available in any text book to master the subject.

1. What is the fraction of electron states occupied by electron at an energy of $E=E_F+0.0455eV$ at T=300K? What is the fraction of these states occupied by holes? What are the electron and hole occupancy fraction if Boltzmann approximation is made?

2. Explain why a completely filled band does not contribute in current flow?

3. A Si sample is uniformly doped with 10^{15} As atoms/cm^3 at T=300K. If intrinsic carrier concentration follows the formulation $n_i^2=1.5x10^{33}T^3exp(-1.21eV/kT)$ (with k as Boltzmann constant given in eV/K), where is the Fermi-level (E_F) located relative to intrinsic Fermi level (E_I) at (a) T=300K and (b) T=1200K?

4. For an indirect band-gap semiconductor with energy-gap, E_G=0.711eV, and lattice spacing, a=5A^o, wavelength of emitted photon due to radiative recombination is found to be λ=2µm. Assume that (i) the released energy due to a recombination is equal to the energy gap and is taken away partly by a photon and partly by phonons, (ii) change in electron momentum is equal to the photon momentum plus number of generated phonons times each phonon momentum. (a) Find out the number of phonons (each having energy of 30meV) generated during each radiative recombination. (b) If the change of electron wave number (k) due to the recombination process is of the order of $2\pi/a$, what is the wavelength of each emitted phonon?

5. In the following cases, show the position of the Fermi level at T=0K in energy band diagram and give reason for your answer. Mark E_C, E_V, E_F, E_I, E_A, E_D. for: a) N type, N_A=0, b) P type, N_D=0.

6. A 1cm^3 of a metal has a density of states as $D(E)=6.82\times10^{21}\sqrt{E}$, where E is the energy of interest. If the number of electrons in a small energy interval between E_1=4.6eV and E_2=4.601eV at 300K is 2.07×10^{15}, Determine (a) the fraction of the energy states between E_1 and E_2 occupied by electrons and position of the Fermi level, (b) the number of electrons between E_1 and E_2 at T=0K.

7. Prove that, within a material or in a junction of two materials in intimate contact (such that electrons can move between the two), there can be no discontinuity or gradient in the equilibrium Fermi level E_F.

8. Consider a Silicon sample in equilibrium whose $n_i=1.5x10^{10}/cm^3$ and $\mu_n=1350cm^2/V$-s, $\mu_p=480cm^2/V$-s, find (a) the electron concentration when its conductivity will be minimum and (b) the minimum conductivity.

9. Sketch the energy band diagram (E versus x) including Fermi level of an intrinsic semiconductor under uniform electric field in x-direction.

10. Sketch the energy band diagram of a moderately and uniformly doped n-type silicon, clearly showing the location of the phosphorus impurity level, Fermi-level and Intrinsic level at room temperature. On the diagram, mark the Energy differences ($E_c - E_v$) and ($E_f - E_i$) for a doping level of 10^{15}cm^{-3}, assuming the intrinsic concentration as $1.5\text{x}10^{10}$ cm^{-3} at room temperature.

11. A silicon sample is doped with 10^{18} donor atoms per cm^3. The position of the Fermi level for this sample is $E_F=E_i+0.45$eV at 300K. What fraction of the donors is ionized in this semiconductor?

12. Which statement(s) is (are) correct? When the temperature is increased, the position of the Fermi level in an n-type semiconductor (A) moves towards the conduction band edge (B) moves towards the valence band edge (C) moves towards the middle of the band gap (D) remains unchanged.

13. Which statement(s) is (are) correct? As the temperature is increased from 0K, the mobility of a moderately doped semiconductor shows (A) a decrease followed by an increase (B) an increase followed by decrease (C) a monotonic increase (D) a monotonic decrease.

14. A silicon sample A is doped with 10^{17} phosphorus atoms/cm^3 and sample B is doped with 10^{17} boron atoms/cm^3. Which of the two samples has a higher resistivity?

15. A phosphorus doped (10^{17} atoms/cm^3) Si sample has resistivity of 0.1Ω-cm. Calculate the doping concentration of boron atoms if it is additionally used to reduce the resistivity of this doped sample by 50%. Assume that due to this additional boron doping electron mobility is not reduced further and in the final sample it is three times of the hole mobility.

16. Estimate the room temperature hole concentration and resistivity in a silicon sample with 10^{15} cm^{-3} phosphorus atoms, taking hole mobility = 400 cm^2 / V-s, electron mobility =1000 cm^2 / V-s and intrinsic concentration = $1.5 \text{ x } 10^{10}$ cm^{-3}.

17. A silicon sample is doped with 10^{16} phosphorus atoms/cm^3. Assuming complete ionization, find out the resistivity of the sample at 300K considering the electron mobility in silicon to be 1350 cm^2/V-sec and the hole mobility 450cm^2/V-sec.

18. A current of 1 mA flows through a bar of uniformly doped n-type silicon with a cross sectional area of 2mm x 2mm and a length of 1cm when it is connected to a 3V battery at 300K. Calculate the electron and hole concentrations in the bar.

19. The equilibrium intrinsic Fermi potential (derived from intrinsic Fermi energy level) variation in an n-type Si slice of thickness L is found to be given by $V_I(x)=V_0+(V_L-V_0)(x/L)$. If $n(x=0)=10^{16}/cm^3$, (a) what are the equilibrium concentrations of electrons and holes as a function of x? (b) Obtain the expressions of the drift current density as a function of x. (c) If $V_0=0.8V$, $V_L=0.4V$, and $L=10\mu m$, obtain the numerical values of concentrations of electrons and holes, and drift current density at $x=5\mu m$. Use $n_i = 1.5x10^{10}\ cm^{-3}$, $\mu_n=1400cm^2/V\text{-}s$, and $\mu_p=478cm^2/V\text{-}s$ at 300K.

20. A current of 1A is forced through a homogenous n-type 1Ω-cm Si bar with a cross-sectional area of $1mm^2$. What are the quasi-Fermi electric field of electrons and quasi-Fermi electric field of holes in the Si bar? What is the electron (or hole) quasi-Fermi potential difference between the two ends of the bar of 1cm? What is the applied voltage across 1cm bar?

21. An intrinsic Si sample is doped with donors from one side such that $N_D=N_0exp(-ax)$. (a) Find an expression for the field $\varepsilon(x)$ at equilibrium over the range for which $N_D >> n_i$. (b) Evaluate $\varepsilon(x)$ when $a=1/\mu m$. (c) Sketch a band diagram indicating the direction of field. (d) If light is shone at one side of the sample yielding the generation of excess electrons and holes, sketch the resulting quasi-Fermi levels of electrons and holes onto the band diagram. Show the equilibrium Fermi level for reference.

22. Construct a time-dependent carrier concentration (semi-logarithmic) plot for Si doped with $2x10^{15}$ donors/cm^3 and having $4x10^{14}$ EHP/cm^3 created uniformly at t=0. Assume $\tau_n=\tau_p=5\mu s$. Calculate the recombination co-efficient α_r for this low level excitations. Assume that this value of α_r applies when the GaAs sample is uniformly exposed to a steady-state optical generation rate $g_{op}=10^{19}$ EHP/cm^3-s. Find the steady state excess carrier concentrations where the light is exposed.

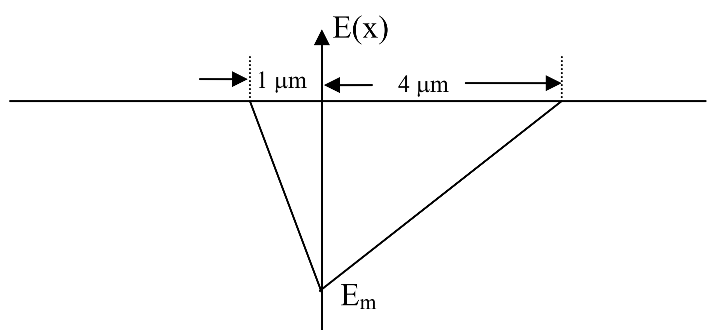
23. Assume an n-type semiconductor bar is illuminated over a narrow region of its length generating steady-state equal number of excess holes and electrons in the illuminated zone, and the excess carriers diffuse away and recombine in both directions along the bar. Assuming $\delta n=\delta p$, sketch the excess carrier distribution and, on a band diagram, sketch the quasi-Fermi levels of electrons and holes over several diffusion lengths from the illuminated zone.

24. The steady-state excess hole concentration at x=0 is $\delta p(x=0)=10^{16}/cm^3$. The semi-infinite Si bar has a cross-section $A=10^{-3}cm^2$. The hole diffusion length L_p is given as 10^{-3}cm, and the hole life time is 10^{-6}s. What is the steady state stored charge Q_p in the exponential excess hole distribution? The hole current required to feed the hole injection at x=0 is obtained as $I_p(x=0)=(qAD_p/L_p)\delta p(x=0)$. Show that this current can be calculated by dividing Q_p by the average hole life time, τ_p. Explain why this approach gves $I_p(x=0)$. What is the slope of the steady state hole hole distribution at x=0?

25. Draw the energy band diagrams of an abrupt p-n junction diode when the diode is (a) in thermal equilibrium, (b) forward biased by V_f and (c) reverse biased by V_r. In each figure, show the position of the Fermi level or quasi Fermi levels along with their energy difference, whichever is applicable. Also show the difference in the energies of the conduction band edges of the p-region and n-region in all the cases (the built-in potential is V_{bi}).

26. A p-n junction under a forward bias of 0.4V has a depletion width of W = 0.1μm. Calculate the peak electric field E_{peak} in V/cm. Given the built in potential $V_0 = 0.8$V.

27. The figure below shows the electric field profile for a reverse biased p-n junction. (a) If the doping concentration on the p-side is $10^{17}/cm^3$, what is the doping concentration on the n-side? (b) If the built-in potential of the p-n junction is 0.75 V and the applied reverse bias is 5.25 V, what is magnitude of the maximum electric field (E_m)?



28. A p^+/n junction is doped with $N_{DD}=10^{16}/cm^3$ on the n-side where $D_p=10cm^2/s$ and lifetime $\tau_p=0.1\mu s$. The junction area is $10^{-4}cm^2$. Calculate (a) the reverse saturation current, (b) forward current at room temperature when applied bias is 0.6V, (c) the junction capacitance C_j with a reverse bias of 10V, and (d) the charge storage or diffusion capacitance C_s with a forward bias of 0.6V.

29. Assume a linearly graded junction with a doping distribution described by $N_{DD}-N_{AA}=Gx$, where G is a grade constant giving the slope of the net impurity distribution. The doping is symmetrical, so that $x_{p0}=x_{n0}=W/2$. (a) Show that space dependent electric field, space-charge layer width and junction capacitance are given by

$$E(x)=\frac{qG}{2\varepsilon}\left[x^2-(W/2)^2\right],\ W=\left[\frac{12\varepsilon(V_0-V)}{qG}\right]^{1/3},\ \text{and}\ C_j=A\left[\frac{qG\varepsilon^2}{12(V_0-V)}\right]^{1/3}.$$

30. The built-in potential of a p-n junction is 0.8 V. The depletion capacitances of the junction at a forward bias of 0.7 V and a reverse bias of 0.8 V are $C_{0.7f}$ and $C_{0.8r}$ respectively. Find out the ratio $C_{0.7f}/C_{0.8r}$.

31. Reverse saturation current, non-ideality factor, and room-temperature thermal voltage of a long p^+-n junction diode are 1.12pA, 1, and 0.025V, respectively. (a) Find out the room-temperature a.c. resistance of the diode at a forward current of 0.1mA. (b) If at room-temperature, diffusion capacitance at a forward current of 0.1mA is found to be 10pF, find out hole lifetime (τ_p) within the n-region.

32. Draw the forward and reverse I-V characteristics of a 7 V zener diode *approximately to scale*, showing whether the voltage axis is in nV, μV, mV or V, and the current axis is in nA, μA, mA or A.

33. In a p-n junction diode, the diffusion length of holes in the n-side is 30μm. If x = 0 is at the edge of the depletion region on the n-side and $x = W_n$ is at the n-contact, show the nature of hole concentration profile p(x) from x = 0 to $x = W_n$ when the diode is forward biased if (a) W_n = 2 μm and (b) W_n = 400 μm.

34. Two p-n junction diodes D1 and D2 are identical in all respects except that D1 is made of a wider bandgap material than D2. Which statement(s) is (are) correct? The reverse saturation current will be maximum for (A) D1 operating at 100°C, (B) D2 operating at 100°C, (C) D1 operating at 30°C, (D) D2 operating at 30°C.

35. Two p^+n diodes D3 and D4 having short n-regions are identical in all respects except that the width of the n-region in D3 is double that in D4. If the current in D3 is 1 mA at a forward bias of 0.6 V, what will be the current in D4 at the same bias?

36. Which statement(s) is (are) correct? In their normal mode of operation, (A) a LED is forward biased and a Zener diode is reverse biased, (B) a LED is reverse biased and a Zener diode is forward biased, (C) both LED and Zener diode are forward biased, (D) both LED and Zener diode are reverse biased.

37. Find the expression for zero bias depletion capacitance in a p/n junction. Also find the expression for bias dependent depletion charge in terms of zero bias depletion capacitance. What is the substrate dopant concentration needed to make a p^{++}/n junction capacitor to tune over the frequency range of the 17MHz to 28MHz radio band with a variable voltage of 1.75-18 Volt? The diode is to have a diameter of 250μm and the inductance of the tuned LC circuit is 100μH. (A tuned parallel L-C circuit has a resonance or peak impedance frequency of $f_r=1/2\pi\sqrt{LC}$.)

38. In this problem we wish to derive the high-injection diode equation. Assume space charge neutrality in n- and p-regions, $\Delta n_p=\Delta p_p$ and $\Delta p_n=\Delta n_n$. (a) Find Δp_n and Δn_p in terms of equilibrium quantities and the applied voltage. (b) Derive the diode current equation under high injection level.

39. A p^+/n diode is switched from zero bias (I=0) to a forward current I=100mA at t=0. (a) Find the expression for the excess hole charge $Q_p(t)$ during the turn on transient and sketch its time dependence. (b) Assuming exponential decay of excess hole concentration inside n-region, find the junction voltage v(t) at t=0.1μs. Given thermal voltage V_T=0.0259V, $n_i=1.5\times10^{10}/\text{cm}^3$, uniform diode area as $A=10^{-4}\text{cm}^2$, hole life time, diffusivity, and donor concentration in the n-side as, τ_p=1μs, $D_p=10\text{cm}^2/\text{s}$, and $N_D=10^{16}/\text{cm}^3$, respectively.

40. A p^+/n diode has an area of $1\mu\text{m}^2$, donor concentration at n-side $N_{DD}=10^{16}/\text{cm}^3$ and minority hole life time τ_p=100nS. Total band bending at the equilibrium appears to be 0.68eV. It provides 1mA current at a forward bias of V=0.7V, find the small-signal diode admittance at V=0.65V and f=1GHz. If the current through this diode is changed from 1mA to 3mA at t=0, what is the junction voltage at t=1μS? Assuming that the critical peak electric field for breakdown is 10^6V/cm, calculate the breakdown voltage (V_{Br}) for this p^+/n diode. If ionization collision probability is given as $\int_{-x_p}^{x_n} \alpha(x)dx = \left(\frac{V_r}{V_{Br}}\right)^3$, find out the multiplication factor at a reverse bias of V_r=150V.

41. A Schottky barrier is formed between a metal having work function 4.5eV and p-type Si (electron affinity = 4eV). The acceptor doping is $N_A=10^{18}/\text{cm}^3$. (a) Draw the equilibrium band diagram showing a numerical value for barrier height qV_0. (b) Draw the band diagram with 0.4V forward bias and (c) 2V reverse bias. If the Schottky barrier is formed between the metal and n-type Si (with $N_D=10^{16}/\text{cm}^3$), draw the equilibrium energy band diagram to scale.

42. Will two diodes connected back-to-back behave as a transistor? Justify your answer.

43. Obtain the expression and plot the excess hole distribution $\delta p(x)$ in the base $[0,W_b]$ of a pnp transistor, assuming W_b/L_p=1 and 0.1. Sketch the minority carrier distribution in the base of a BJT biased in the (a) forward active and (b) saturation regions.

44. A n^+pn Si transistor has a uniform area of $2\times10^{-4}\text{cm}^2$ and base width W_b of 1μm. The emitter doping is $10^{18}/\text{cm}^3$ and base doping is $10^{16}/\text{cm}^3$. The electron lifetime and transit time in the base are 1μs and 0.01μs, respectively. Mobility values available in text book can be used. Using first order approximation calculate I_B and I_C, with V_{BE}=0.6V, and negligible Δn_C.

45. If the base of a Si n^+pn transistor is doped with 10^{16} acceptors/cm^3, and the collector with 10^{15} donors/cm^3, find the width of the depletion region on the base side of the base-collector junction for V_{BC}=-4V at T=300K. Assuming no change in neutral base boundary at base-emitter junction what is the percentage reduction of base width, compared to its equilibrium value of 1μm?

46. Assume that the transit time of electrons across the base of an npn transistor is 100ps, and electrons cross the 1μm depletion region of the collector region at their scattering limited velocity. The emitter-base junction charging time is 30ps and collector capacitance and resistance are 0.1pF and 10Ω respectively. Find the cut-off frequency f_T.

47. In normal active mode an n-p-n bipolar transistor is assumed to have emitter injection efficiency γ=1 and negligible holes entering from collector into base. If the transit time and life time of electrons in the base region are found to be 10 ns and 0.99 μs, respectively, find out on an average how many electrons will recombine inside the base for every 1000 electrons injected from emitter.

48. Which statement(s) is (are) correct? To increase the β of a bipolar transistor (A) the base width or doping concentration in the base should be increased, (B) the base width or doping concentration in the base should be reduced, (C) the base width should be reduced and doping concentration in the base should be increased, (D) the base width should be increased and doping concentration in the base should be reduced.

49. The β of an npn transistor is estimated to be 150 considering only the effect of emitter efficiency (γ) and assuming base transport factor (α_T) =1. On the other hand, considering only the effect of α_T and assuming γ =1, the β of the same transistor is found to be 120. What is the actual β of the transistor if both α_T and γ are taken into account?

50. The β of an npn BJT is 78. If it is biased in the normal active mode in the common emitter configuration, what is its transconductance (g_m) at 300K when base current (I_B) = 10μA?

51. Draw the large-signal and small-signal equivalent circuit of an npn transistor and write down the expressions for input (y_{11}) and trans-admittance (y_{21}) parameters.

52. An Al-gate p-channel MOS capacitor is made on an n-type Si substrate with N_D=5x10^{17}/cm^3. The SiO_2 thickness is 100A^o in the gate region, and effective interface charge Q_i is 5x10^{10}qC/cm^2. Given metal-semiconductor work-function potential difference Φ_{MS}=-0.18V. Draw the band diagram under equilibrium, flat-band condition, and under strong inversion. Find the maximum depletion width, flat band potential, and threshold voltage. Sketch the capacitance versus voltage curve for this device marking important points.

53. The flat band voltage is shifted to -2V for an Al-SiO_2-Si capacitor with substrate acceptor doping of N_A=10^{16}/cm^3, SiO_2 thickness of 100A^o, relative dielectric constant of Si as 11.8 and that of SiO_2 as 3.9. Draw the capacitance versus voltage curve and find the oxide interface charge Q_i required to cause this shift in V_{FB}, with work function difference (in terms of potential) given in Fig.1.

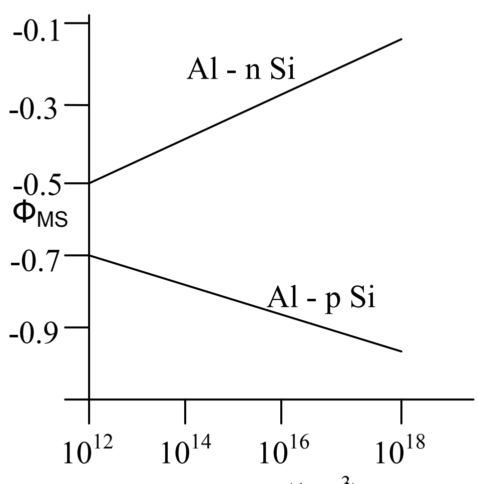


Fig. 1

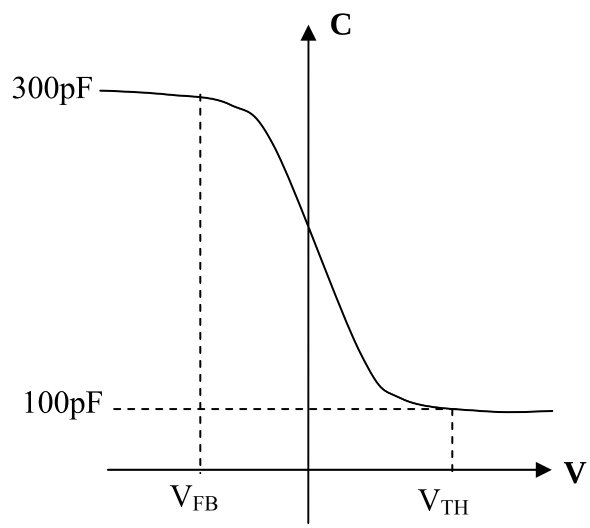


Fig. 2

54. Fig. 2 shows the C-V characteristics of a metal-oxide-silicon (MOS) capacitor. Pick the correct statement below: (A) The substrate is n-type and the measurement is done at low frequency. (B) The substrate is p-type and the measurement is done at low frequency. (C) The substrate is n-type and the measurement is done at high frequency. (D) The substrate is p-type and the measurement is done at high frequency. If the area of the MOS capacitor is 1.5mm^2. What are (a) the gate oxide thickness (t_{ox}) and (b) the maximum depletion layer width (W_{max}) in μm?

55. If the area of a MOS capacitor is 1 mm^2 and the gate oxide thickness (t_{ox}) is 100nm, (a) what is C_{max}? (b) if C_{min} = ½C_{max}, what is the maximum depletion layer width (W_{max})?

56. In a metal/SiO_2/p-Si MOS capacitor, the SiO_2 layer thickness is t_{ox} and the doping concentration of the p-type substrate is N_A. The threshold voltage of the MOS capacitor will definitely increase if (A) t_{ox} is decreased and N_A is increased, (B) t_{ox} is increased and N_A is decreased, (C) both t_{ox} and N_A are decreased, (D) both t_{ox} and N_A are increased.

57. Draw the drain current versus drain voltage characteristics of an n-type MOSFET for three different gate voltages. Clearly show the saturation and ohmic regions, and the relative spacing between the saturation segments of the curves assuming equal increments in gate voltage.

58. For a MOS transistor if Φ_{ms}=-0.95eV, $Q_i=5x10^{10}qC/cm^2$, t_{ox}=100A°, and $N_A=10^{16}/cm^3$, calculate the substrate bias required to achieve enhancement mode operation with V_{TH}=+0.5V for the n-channel device.

59. Plot I_D vs. V_D with several values of V_G for thin-oxide p-channel MOS transistor with $N_D=10^{16}/cm^3$, $Q_i=5x10^{10}qC/cm^2$, and t_{ox}=0.01μm. Use p-channel version of drain current equation, and assume that $I_{D,sat}$ remains constant beyond pinch off. Assume that $\bar{\mu}_p=200cm^2/Vs$, and Z=10L.

60. The threshold voltage (V_{TH}) of an n-channel MOSFET is 1V. If the drain current (I_D) is 10μA when drain-to-source voltage (V_{DS}) is 3V and gate-to-source voltage (V_{GS}) is 2V, find out the value of I_D in μA when $V_{DS} = V_{GS}$ = 4V.

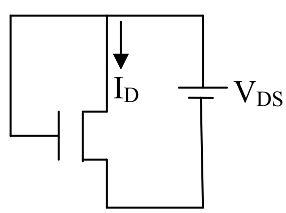


Fig. 3

61. An n-channel MOSFET with threshold voltage (V_{th}) of 1 V has its gate shorted to drain as shown in Fig. 3. If the drain current (I_D) = 2 mA when V_{DS} = 2 V, what is I_D when V_{DS} = 4V?

62. A MOSFET with threshold voltage (V_{Th}) of 1V has its gate and drain tied together and is used as a voltage variable resistor. A d.c resistance (R = I_D/V_{DS}) of 1KΩ is seen between source and drain when $V_{DS} = V_{GS}$ = 10V. What is the value of R when $V_{DS} = V_{GS}$ = 5V.

63. In an n-channel MOSFET having a threshold voltage (V_{th}) of 1V, the drain current (I_D) is 2mA when $V_{GS} = V_{DS}$ = 2V, where V_{GS} and V_{DS} are the gate-to-source voltage and drain-to-source voltage, respectively. What is I_D when V_{GS} = 4 V and V_{DS} = 2V?

64. Plot drain voltage dependent (a) transconductance and (b) output conductance of an n-channel MOSFET (with V_{TH}=1V) where drain voltage is swept from 0V to 5V at V_{GS}=3V. Mark important points in terms of the factor $\mu C_{ox}Z/L$. Assume that the substrate is shorted with source.