UNIVERSITY OF CALIFORNIA, BERKELEY
College of Engineering
Department of Electrical Engineering and Computer Sciences

EE 130: IC Devices Spring 2003

FINAL EXAMINATION

NAME: ______________ ____________________ _______________
Last First Signature

STUDENT ID#: ______________ E-MAIL: __________________________

INSTRUCTIONS:
1. Use the values of physical constant provided below.
2. SHOW YOUR WORK. (Make your methods clear to the grader!)
3. Clearly mark (underline or box) numeric answers. Specify the units on answers whenever appropriate.

Physical Constants

Description	Symbol	Value
electronic charge	q	1.6×10^{-19} C
electron rest mass	m_o	9.1×10^{-31} kg
thermal voltage at 300K	kT/q	0.026 V
Boltzmann constant	k	8.62×10^{-5} eV/K

$(kT/q)\ \ln(10) = 0.060$ V at $T = 300$K

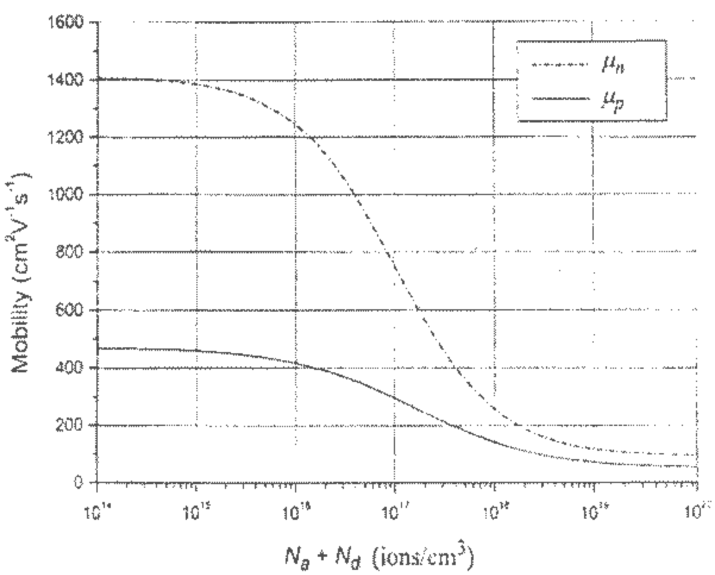
Properties of SiO_2 at 300K

Description	Symbol	Value
band gap	E_g	9 eV
permittivity	ε_{SiO2}	3.45×10^{-13} F/cm
electron affinity	χ_{SiO2}	0.95 V

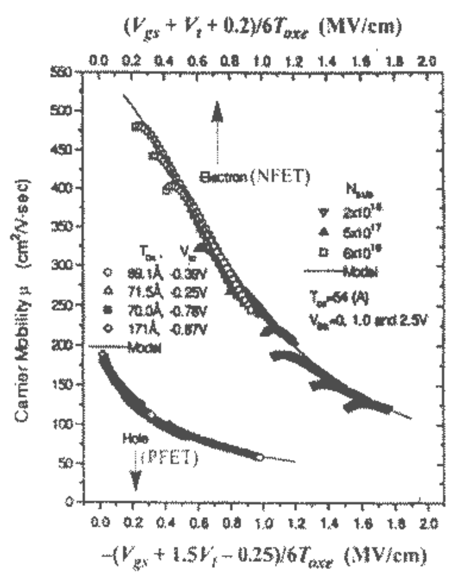
Properties of Silicon at 300K

Description	Symbol	Value
band gap	E_g	1.12 eV
intrinsic carrier density	n_i	10^{10} cm^{-3}
permittivity	ε_{Si}	1.0×10^{-12} F/cm
electron affinity	χ_{Si}	4.03 V

Electron and Hole Mobilities in Silicon at 300K

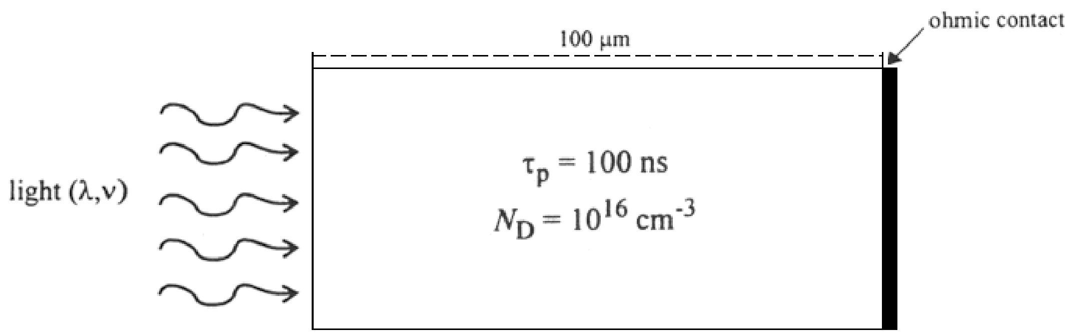


Field-Effect Mobilities in Si at 300K



1 ______________ / 30
2 ______________ / 30
3 ______________ / 40
4 ______________ / 30
5 ______________ / 30
6 ______________ / 40
Total: ___________ / 200

Problem 1: **Semiconductor Fundamentals [30 points]**
Consider the following uniformly doped n-type Si sample of length 100 μm, maintained at T = 300K:



Light incident on the surface is absorbed at x = 0, resulting in $\Delta p_{n0} = 10^8/\text{cm}^3$ excess holes at x = 0. (The generation rate for x > 0 is zero.)

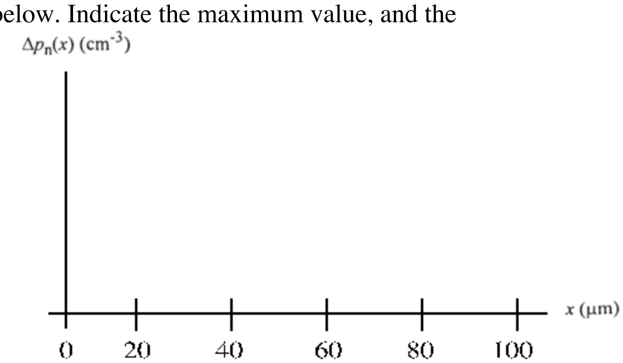
a) Describe the carrier actions (drift, diffusion, recombination-generation) in this sample. **[5 pts]**

b) i) Write a differential equation (simplest form possible) for the excess hole concentration Δp_n, for x > 0. **[5 pts]**

ii) What is the general solution for this differential equation? **[2 pts]**

iii) What boundary conditions must $\Delta p_n(x)$ satisfy? **[2 pts]**

iv) Solve for $\Delta p_n(x)$ and sketch it accurately on the axes provided below. Indicate the maximum value, and the point at which $\Delta p_n(x)$ falls to 1/e of the maximum value. **[3 pts]**



c) Draw the high-band diagram for this sample, indicating the positions of the quasi-Fermi levels for electrons and holes (F_N and F_P, respectively) relative to the intrinsic Fermi Level E_i. **[5 pts]**

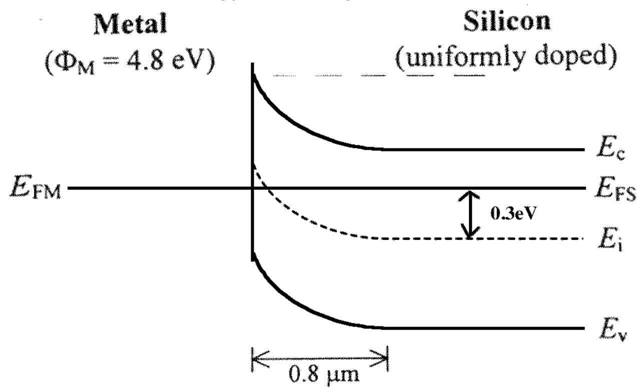
d) Do low-level injection conditions prevail throughout this sample? Justify your answer. **[2 pts]**

e) Do equilibrium conditions prevail throughout this sample? Justify your answer. **[2 pts]**

f) Estimate the resistivity of this sample. **[4 pts]**

Problem 2: Metal-Semiconductor Contact [30 points]

The following is the equilibrium (T = 300K) energy-band diagram for an ideal metal-semiconductor contact:



a) Label the Schottky barrier height (ϕ_B) and built-in voltage (V_{bi}) on the band diagram above. Calculate the values of ϕ_B and V_{bi}. **[6 pts]**

b) Is this a rectifying or ohmic contact? Explain why. **[3 pts]**

c) What does qV_{bi} represent? (Why is there a built-in voltage?) **[2 pts]**

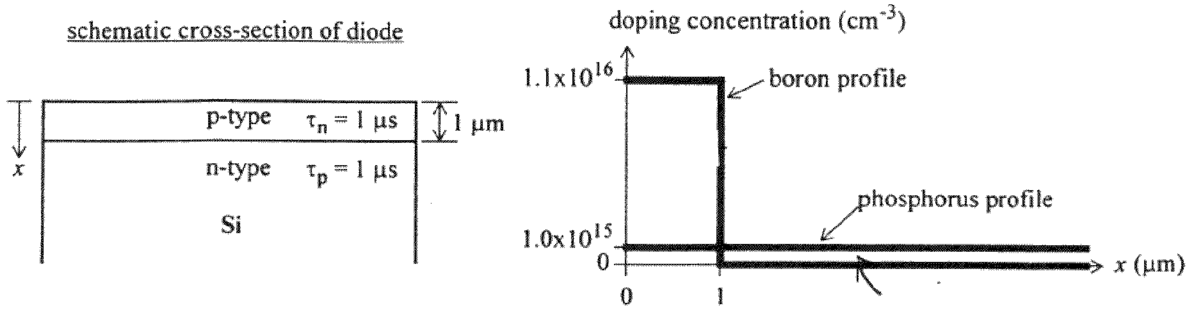
d) Sketch the energy-band diagram for this M-S contact with 0.3 V forward bias applied (V_A = 0.3 V). Indicate qV_A on your diagram. **[5 pts]**

e) Explain how the doping concentration in the silicon can be determined from capacitance measurements. **[8 pts]**

f) Sketch the equilibrium energy-band diagram for a metal ($\phi_M = 4.8$ eV) contact of degenerately doped n-type silicon. Why is this practically an ohmic contact? **[6 pts]**

<u>Problem 3:</u> pn Junction Diode [40 points]

A pn diode is formed by introducing boron into the surface region of a Si sample uniformly doped with phosphorus:



a) Draw the equilibrium (T = 300K) energy-band diagram for this diode. Indicate the position of E_F relative to E_i in the quasi-neutral regions. (Numerical values are required.) Label the depletion width W and built-in potential V_{bi}, and calculate their values. **[15 pts]**

b) Sketch the energy-band diagram for this diode with a large reverse bias applied. Use this diagram to explain how reverse-bias breakdown occurs. **[5 pts]**

c) Suppose a forward bias of 0.6 V is applied to this diode: (Note that $[\exp(qV_A/kT)] = 10^{10}$)

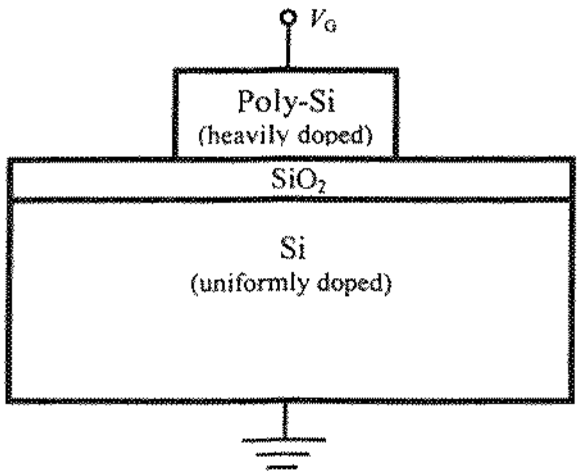
i) Sketch the excess minority carrier profiles in the quasi-neutral regions. Indicate their values at the edges of the depletion region. **[6 pts]**

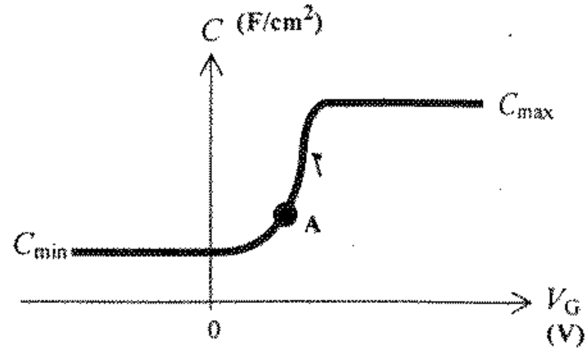
ii) Estimate the total amount of excess minority carrier charge (in units of C/cm^2) stored in the diode. **[4 pts]**

iii) Estimate the diode current density. **[5 pts]**

iv) Suppose the diode is suddenly shut off at $t = 0$ by disconnecting it from the circuit, so that no current flows for times $t > 0$. Show how the excess minority carrier charge on the n-side changes, for t > 0. Estimate the time required for the diode voltage to reach 0 V. **[5 pts]**

<u>Problem 5</u>: Metal-Oxide-Semiconductor Capacitor [30 pts]





a) Was this *C*-*V* characteristic measured using a high-frequency ac signal, or low-frequency ac signal? How do you know? **[3 pts]**

b) Is the Si substrate n-type, or p-type? Justify your answer. **[3 pts]**

c) Is the poly-Si gate doped heavily in n-type or p-type? Justify your answer. **[3 pts]**

d) Sketch the MOS energy-band diagram corresponding to the gate bias at point A on the *C*-*V* curve. **[6 pts]**

e) Describe how you would obtain the following parameters from the *C*-*V* data:

i) gate-oxide thickness (T_{ox}) **[3 pts]**

ii) substrate doping concentration (N_{sub}) **[4 pts]**

iii) flatband voltage (V_{FB}) **[4 pts]**

iv) fixed oxide charge density (Q_F) **[3 pts]**

<u>Problem 6</u>: MOS Field-Effect Transistor [40 points]

a) In a certain CMOS technology, the electrical oxide thickness it T_{oxe} = 3.45 nm, the body-effect factor is m = 1.2, and the absolute value of the threshold voltage of a long-channel MOSFET is $|V_T|$ = 0.4 V.

i) Sketch the I_D vs. V_{DS} characteristic for an n-channel MOSFET of channel width W = 1 μm, channel length L = 1 μm, and gate bias V_{GS} = 1.5 V. Indicate the values of V_{Dsat} and I_{Dsat}. **[10 pts]**

ii) For what channel lengths will the effect of velocity saturation be significant (*i.e.* resulting in a reduction in I_{Dsat} by more than a factor of 2)? $v_{sat} = 8 \times 10^6$ cm/s. **[5 pts]**

b) Short-Answer Questions

i) What does the factor *m* in the MOSFET drain current (I_{DS}) equation account for? (Why is it needed in order to accurately predict the drain current flowing in a MOSFET?) **[4 pts]**

ii) for a given process technology (*i.e*. fixed gate-oxide thickness, source/drain junction depth, and channel doping concentration), why does the magnitude of V_T decrease at very short channel lengths *L*? **[4 pts]**

iii) How does the leakage current of a MOSFET change with increasing temperature? Justify your answer. **[4 pts]**

c) Indicate in the table below (by checking the appropriate box for each line) the effect of **decreasing the gate** oxide **thickness (*T_{oxe}*)** on the performance parameters of an n-channel MOSFET. Provide brief justification for each of your answers. **[12 pts]**

MOSFET parameter	increases	decreases	remains the same	
Transconductance (g_m)				
Body effect parameter (γ)				
Subthreshold swing (S)				