Columbia University
Department of Electrical Engineering
Solid State Devices and Materials
ELEN E3106/4106
Homework #5

Due: Friday, October 17th by 5pm
Goal: Gain familiarity with ohmic and Schottky M-S junction electrostatics in equilibrium and with external bias. Practice calculating/sketching energy band and electrostatic diagrams. Practice finding important parameters like the built-in potential, depletion width, capacitance, doping, current, and contact resistance.
Instructions: Show your work and include units in answers for full credit. Unless stated otherwise, make the assumptions we have been taking in class (the sample is at 300 K). Circle or box your final answer.
Points: 110 pts for 3106. 130 pts for 4106.

- **Problem 1 (10 pts)** M-S junction under equilibrium. (Streetman and Banerjee)

We deposit a metal with a work function of 4.6 eV on Si (electron affinity of 4 eV) and acceptor doping level of 3 x 10^{18} cm^{-3}.

(a) Find the work function of the semiconductor.
(b) Is this a Schottky or ohmic contact, and why?
(c) Draw the equilibrium band diagram **before the metal and semiconductor join** and mark off the Fermi level, the band edges, and the vacuum level.
(d) By how much should the metal work function be altered (in eV) to change the type of contact? Explain with reference to the band diagram.

- **Problem 2 (15 pts)**

In a metal-semiconductor contact, the metal has a work function of 5.15 eV, and the semiconductor is n-type Si (electron affinity of 4 eV) with uniform doping concentration of $2 \times 10^{17}\ cm^{-3}$. The junction is under 0.4 V applied forward bias.

(a) Find the numerical values for $q\Phi_B$, $q\Phi_s$ and $q(V_0 - V)$.
(b) Draw the energy band diagram for the M-S contact (including the vacuum level) under 0.4 V applied forward bias. Label clearly $q\Phi_m$, $q\Phi_B$, $q\left(V_0 - V\right)$), and χ on your sketch. Assume no surface states are present.
(c) Sketch "the big three": $E(x)$, $\rho(x)$, $V(x)$ for the device in (a). For each diagram, draw two curves: one for equilibrium case and one for V = 0.4 V. No numbers or calculations are required.

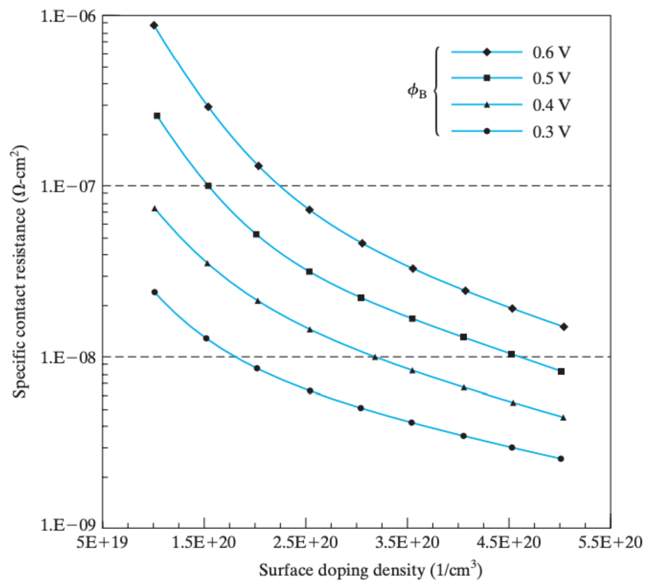
- **Problem 3 (16 pts)** Ohmic contact band diagrams and doping importance.

Qualitatively sketch the energy band diagram for (a) through (c).

(a) An ohmic contact between P+-type silicon and $TiSi_2$ at equilibrium.
(b) An ohmic contact between N+-type silicon and $TiSi_2$ at equilibrium.
(c) A rectifying contact between P-type silicon and $TiSi_2$ under 2 V reverse bias.
(d) Comment whether a very heavy doping is important, unimportant, or unacceptable for each of the three cases above.

- **Problem 4 (24 pts)** Properties of ohmic contacts to p-n diodes.

A p-n diode conducting 1 mA of current has an ohmic contact of area 0.1 μm^2 and surface doping density of 1×10^{20} cm^{-3}.



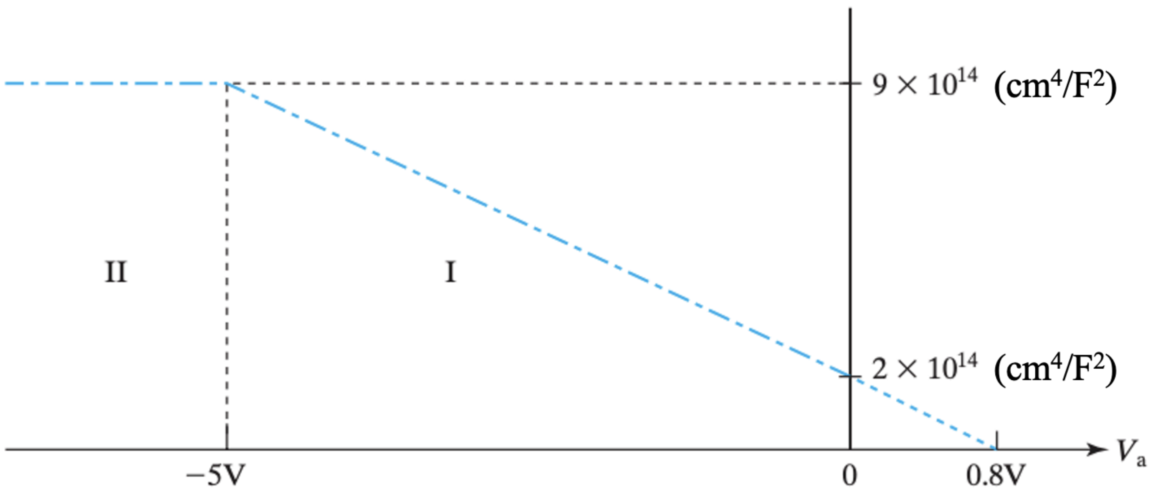
(a) What specific contact resistance can be allowed if the voltage drop at the ohmic contact is to be limited to 60 mV?

(b) Using the figure above (which is applicable to both n+ and p+ silicon) ,estimate Φ_B. Is that the maximum or minimum allowable Φ_B?

(c) Now assume the doping concentration is instead $4.5 \times 10^{20}\ cm^{-3}$. Using the figure above, estimate the R_C of NiSi contact on n+ and p+ silicon.

- **Problem 5 (20 pts)** Using $C - V$ data to find Schottky diode properties. (C. Hu)

A metal/n-type semiconductor Schottky diode has the $(Area/C^2) - V$ characteristic given below:



(a) What is the built-in voltage of the diode?
(b) Find the doping profile of the n-type semiconductor.

- **Problem 6 (10 pts)** Checking your answers in NanoHub.

Launch the PNToy (a.k.a. the p-n Junction Lab) in NanoHUB. This is available at https://nanohub.org/tools/pntoy/. Set the length of each side to be 1 micron and set the doping levels below:

p-side	n-side
$N_a = 1\times 10^{16}\, cm^{-3}$	$N_d = 1 \times 10^{18}\, cm^{-3}$

(a) Build this diode; plot the "big 3" (charge density, electrostatic potential, and electric field), the energy band diagram, and the I-V curve in equilibrium in NanoHUB, grab the figures, and include them in your report. Note that the simulator makes the "DA" depletion approximation (which is what we are using in the class - this is the approximation that the edges are square and charge is zero in the channel). The system also has a simulator for a more realistic version which is also shown on the plots, don't worry about that for now - use the depletion approximation. Make the available intrinsic center region zero width for this problem.
(b) What built-in potential does the system predict? Annotate this on your relevant plot(s).
(c) What values does the simulator give for x_p, x_n, and W? Annotate this on your relevant plot(s).
(d) What maximum electric field does the system predict? Annotate this on your relevant plot(s).
(e) What is the forward voltage? Annotate this on your relevant plot(s).

- **Problem 7 (20 pts) (Required for 4106 students ONLY)** Determining M-S junction properties.

You are given a metal semiconductor at room temperature in which the workfunction of the metal equals the electron affinity of the semiconductor plus 3kT (i.e. $\Phi_M = \chi + 3kT$) and the Fermi level in the semiconductor is 3kT below E_C . The semiconductor has a bandgap of 1 eV.

(a) Is the semiconductor n-type, p-type, or intrinsic? Justify your answer.
(b) What is the numerical value of the built-in potential, V_0?
(c) Is the metal contact to the semiconductor ohmic or rectifying? Justify your answer.