EECS 2077
Semiconductor Devices

1 - Bands & Carrier Concentration   Name:___________________________

Ground Rules (Read Carefully!)

(1) In this course, you will do the homework in class in groups of ideally 3. You must change at least one group member EACH week to someone you have not had yet or for a long time.

(2) About 90% of the homeworks can be finished during class. So if you come in focused and ready to work, all you typically have to do before the next class is watch the lecture videos! What a deal! If you have never done a flipped class like this before, this will feel strange at first, but after a few sessions, you will 'get it'…

(3) You must upload your HW to blackboard as word or PDF file before the start of the next class. Most students just take a photo of the whiteboard and insert the solutions as photos into this document. This is also good, as you will have an organized long-term copy of your work for later reference!

(4) Importantant! There are on-line solutions already available for most of the problems. You may access these ONLY if:

(a) you have completed the problem and want to check the solution.

(b) you are stuck, have asked me or another group for help, and I tell you to check out the solutions (the default is always to ask me, so I can teach and help you learn more than just looking at a solution!).

(5) When you are done, clean up! No food or drink other than water please.

Problems

1) Each group, begin drawing on the board the following:

(a) a drawing of the conduction band, valence band, and Fermi level for an intrinsic (undoped) semiconductor.

(b) now, assume 300K, and draw with arrows how electrons and holes are created.

(c) next, note that they are always moving around a bit (both electrons and holes) and show with arrows what happens when they line-up with each other (hint, if it were not for this, they would reach infinite concentration over time).

(d) further label your diagram in the right locations with: 'free space in between atoms', 'the valence orbits of the actual atoms', and 'energy gap between free space and valance'.

Now take a picture of the diagram and post it below in this document as your homework! Do this for each problem!

2) Si is doped with 10^{17} B atoms/cm^3. Assume 300K (as usual).

(a) What is the equilibrium hole concentration p_0? This is the majority carrier (it is the doped carrier). *Note, I posted some key tables at the end of this document. Keep them handy all semester.*

$$p_0 = p_{doped} + n_i = N_A + n_i \approx N_A \approx 10^{17} / cc$$

(b) What is the equilibrium electron concentration n_0? This is the minority carrier (less than the doped).

Instructor – Prof. Jason Heikenfeld

$$n_0 = \frac{n_i^2}{N_A} = \frac{2.25x10^{20}}{10^{17}} = 2.25x10^3 / cc$$

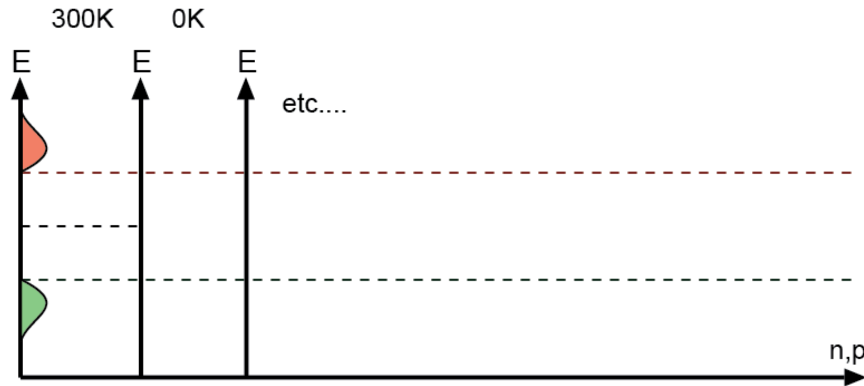
(c) Why is the electron concentration so much lower than that for un-doped Si? One sentence maximum.

Because you created more holes by doping, and therefore more holes in the valence band can diffuse around a bit, match up with an electron in the conduction band, recombine, and therefore remove (eliminate) electrons.

(d) Lastly, calculate how far the Fermi level (E_F) had to shift down compared to the intrinsic Fermi (E_i) level (intrinsic Si means un-doped Si). Use equation $3-25b: p_o = n_i e^{(E_i-E_F)/kT}$. In this course, at 300K, kT is 0.0259 eV (electron-volts which is a unit of energy), kT/q is 0.0259 V (volts, you divided by q, which is the charge of an electron or 'e').

$$Equation\ 3-25b: \quad p_o = n_i e^{(E_i-E_F)/kT} = 10^{17}/cc \quad \therefore E_i - E_F = 0.0259\ln(10^{17}/1.5\times10^{10}) = 0.41\,eV$$

3) Draw on the board, the carrier concentration plot below. Give yourself space, because we are going to re-draw the carrier concentrations for different cases (hence why there are multiple energy axis).



(a) with blue marker - qualitatively plot the mathematical function for density of states and for Fermi distribution for '300K'

(a) redraw the electron and hole concentrations, density of states, Fermi distribution, and Fermi level, for '0K'

(c) redraw the electron and hole concentrations, density of states, Fermi distribution, and Fermi level, for '300K & n-type'

(d) redraw the electron and hole concentrations, density of states, Fermi distribution, and Fermi level, for '300K & p-type'

(e) take a picture of the diagram and post it below and turn it in with your homework ★

4) Check below, how a thermally generated electron-hole pair allows electrical conduction.

__ (a) the hole is positive charge due to lack of an electron, and Si atoms can trade back and forth this lack of an electron.

__ (b) the electron is freed from the Si atoms and can freely move in between Si atoms.

__ (c) neither of the above.

_X_ (d) both of the above.

5) An insulator like SiO_2 or Al_2O_3 has no electrical conduction, why is this typically?

__ (a) it has no conduction band or valance band.

_X_ (b) it has a conduction and a valence band, but so far apart in energy that at 300K no electrons/holes are generated.

__ (c) neither of the above.

6) Most often Si is used with n or p-type doping, if we add As to Si, it will bond like other Si atoms and:

__ (a) it has one less electron than Si so it will create an electron (n-type).

_X_ (b) it has one more electron than Si so it will create an electron (n-type).

__ (c) it has one less electron than Si so it will create a hole (p-type).

__ (d) it has one more electron than Si so it will create a hole (p-type).

7) Explain in 1-2 sentences max, why the Fermi level is closer to the conduction band for n-type SI.

Fermi level is the energy level at which you have a 50% chance (probability) for finding an electron, right?! So, if you dope Si n-type and create a bunch of electrons in the conduction band, then your chances of finding an electron are greater in the conduction band, and therefore this location for a 50% chance of finding an electron better be closer to the conduction band!

8) The y-axis units in this class for energy band diagrams, will always be in 'eV' which is 'electron-Volt'. We use this because it is convenient and allows us 'whole numbers' to represent how much energy we have in device barriers, band-gaps, etc. For example, we say Si has a bandgap energy of ~1.1 eV. Also, our charges, holes and electrons, both have a magnitude of ~1.6×10^{-19} C which instead we can just call 'e', and our voltages are just a few V typically. That is more convenient that Joules, which leads us into the questions:

(a) calculate the energy in Joules for 1 eV (would you want to write this out each time on an energy axis?).

1.6E-19 C x 1 V = 1.6E-19 J

(b) if I accelerate 1 hole through 4V of voltage (electric field), how much energy in eV will the hole achieve?

Magnitude of the charge of a hole is same as an electron (just opposite polarity). So in eV is 1e and 4V for a total of 4eV energy gained by the hole.

9) Si is doped with B atoms, the B atoms have one less electron with Si, so when they bond with the Si they 'steal' and electron from the Si which creates a hole, and which cause B to have negative charge. Which is true:

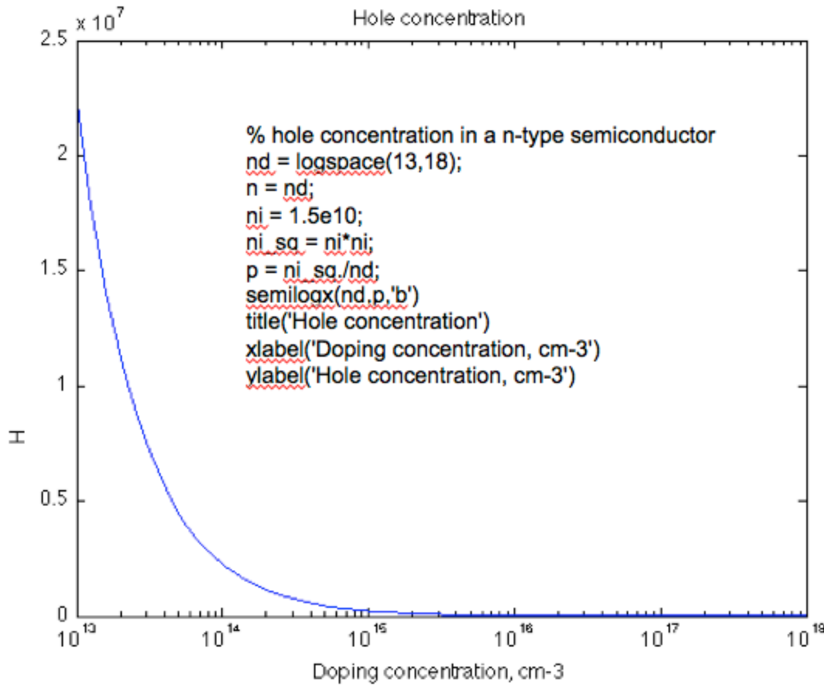
_X_ (a) the positively charged holes created by B atoms add to the total electrical conductivity of the Si.

__ (b) the now negatively charged B atoms add to the total electrical conductivity of the Si.

__ (c) both of the above.

__ (d) neither of the above.

10) Easy MATLAB warm-up! Plot electron conc. in p-type Si vs. Na from 10^{13} to 10^{14}. Hint, see end of lecture 1 power point slides…



As you can see above, a log-log plot would be more appropriate!

Here are some key tables that will be useful all semester (from the book).

Avogadro's number	$N_A = 6.02 \times 10^{23}$ molecules/mole
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K
	$= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$q = 1.60 \times 10^{-19}$ C
Electronic rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm
	$= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.63 \times 10^{-34}$ J-s
	$= 4.14 \times 10^{-15}$ eV-s
Room temperature value of kT	$kT = 0.0259$ eV
Speed of light	$c = 2.998 \times 10^{10}$ cm/s

	Prefixes:		
1 Å (angstrom) $= 10^{-8}$ cm	milli-,	m-	$= 10^{-3}$
1 μm (micron) $= 10^{-4}$ cm	micro-,	μ-	$= 10^{-6}$
1 nm = 10 Å $= 10^{-7}$ cm	nano-,	n-	$= 10^{-9}$
2.54 cm = 1 in.	pico-,	p-	$= 10^{-12}$
1 eV $= 1.6 \times 10^{-19}$ J	kilo-,	k-	$= 10^{3}$
	mega-,	M-	$= 10^{6}$
	giga-,	G-	$= 10^{9}$

A wavelength λ of 1 μm corresponds to a photon energy of 1.24 eV.

		E_g (eV)	μ_n (cm^2/V-s)	μ_p (cm^2/V-s)	m^*_n/m_o (m_l, m_t)	m^*_p/m_o (m_{lh}, m_{hh})	a (Å)	ϵ_r	Density (g/cm^3)	Melting point (°C)
Si	(*i/D*)	1.11	1350	480	0.98, 0.19	0.16, 0.49	5.43	11.8	2.33	1415
Ge	(*i/D*)	0.67	3900	1900	1.64, 0.082	0.04, 0.28	5.65	16	5.32	936
SiC (α)	(*i/W*)	2.86	500	—	0.6	1.0	3.08	10.2	3.21	2830
AlP	(*i/Z*)	2.45	80	—	—	0.2, 0.63	5.46	9.8	2.40	2000
AlAs	(*i/Z*)	2.16	1200	420	2.0	0.15, 0.76	5.66	10.9	3.60	1740
AlSb	(*i/Z*)	1.6	200	300	0.12	0.98	6.14	11	4.26	1080
GaP	(*i/Z*)	2.26	300	150	1.12, 0.22	0.14, 0.79	5.45	11.1	4.13	1467
GaAs	(*d/Z*)	1.43	8500	400	0.067	0.074, 0.50	5.65	13.2	5.31	1238
GaN	(*d/Z, W*)	3.4	380	—	0.19	0.60	4.5	12.2	6.1	2530
GaSb	(*d/Z*)	0.7	5000	1000	0.042	0.06, 0.23	6.09	15.7	5.61	712
InP	(*d/Z*)	1.35	4000	100	0.077	0.089, 0.85	5.87	12.4	4.79	1070
InAs	(*d/Z*)	0.36	22600	200	0.023	0.025, 0.41	6.06	14.6	5.67	943
InSb	(*d/Z*)	0.18	10^5	1700	0.014	0.015, 0.40	6.48	17.7	5.78	525
ZnS	(*d/Z, W*)	3.6	180	10	0.28	—	5.409	8.9	4.09	1650*
ZnSe	(*d/Z*)	2.7	600	28	0.14	0.60	5.671	9.2	5.65	1100*
ZnTe	(*d/Z*)	2.25	530	100	0.18	0.65	6.101	10.4	5.51	1238*
CdS	(*d/W, Z*)	2.42	250	15	0.21	0.80	4.137	8.9	4.82	1475
CdSe	(*d/W*)	1.73	800	—	0.13	0.45	4.30	10.2	5.81	1258
CdTe	(*d/Z*)	1.58	1050	100	0.10	0.37	6.482	10.2	6.20	1098
PbS	(*i/H*)	0.37	575	200	0.22	0.29	5.936	17.0	7.6	1119
PbSe	(*i/H*)	0.27	1500	1500	—	—	6.147	23.6	8.73	1081
PbTe	(*i/H*)	0.29	6000	4000	0.17	0.20	6.452	30	8.16	925

All values at 300 K.

*Vaporizes