EE 362 Electronic, Magnetic, & Optical Properties of Materials
Examination #2 (Spring 2024)

Name Key A

Instructions: Closed book. Put answers in indicated spaces, use notation as given in class & show all work for credit. Insert equation sheet in exam. Answers should have 4-5 significant figures (use more for constants).

1) At thermal equilibrium @ 300 K, a germanium semiconductor is doped with phosphorous atoms to a concentration of 4×10^{14} (#/cm^3) and aluminum atoms to a concentration of 9×10^{14} (#/cm^3). Will the phosphorous act as a donor or acceptor? Will the aluminum act as a donor or acceptor? Is the doped germanium an *n*-type or *p*-type semiconductor? Find the equilibrium electron and hole concentrations.

Looking @ periodic table (p. 5)

Al is to left by 1 column of Ge $\Rightarrow$ acceptor $N_a = 9\times10^{14}\ \#/cm^3$

P is to right by 1 column of Ge $\Rightarrow$ donor $N_d = 4\times10^{14}\ \#/cm^3$

$N_a >> N_d >> n_i = 2.4\times10^{13}\ \#/cm^3 \Rightarrow$ p-type Ge

$$(4.62)\quad p_o = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a-N_d}{2}\right)^2 + n_i^2}$$

$$= \frac{(9-4)\times10^{14}}{2} + \sqrt{\left(\frac{(9-4)\times10^{14}}{2}\right)^2 + (2.4\times10^{13})^2}$$

$$= \underline{5.0114936\times10^{14}\ \#/cm^3 \quad \text{holes}}$$

$$(4.43)\quad n_o p_o = n_i^2 \Rightarrow n_o = \frac{(2.4\times10^{13})^2}{5.0115\times10^{14}}$$

$$= \underline{1.149358\times10^{12}\ \#/cm^3}$$

phosphorous a [✓ donor] or acceptor? (circle correct) aluminum a donor or [✓ acceptor?] (circle correct)

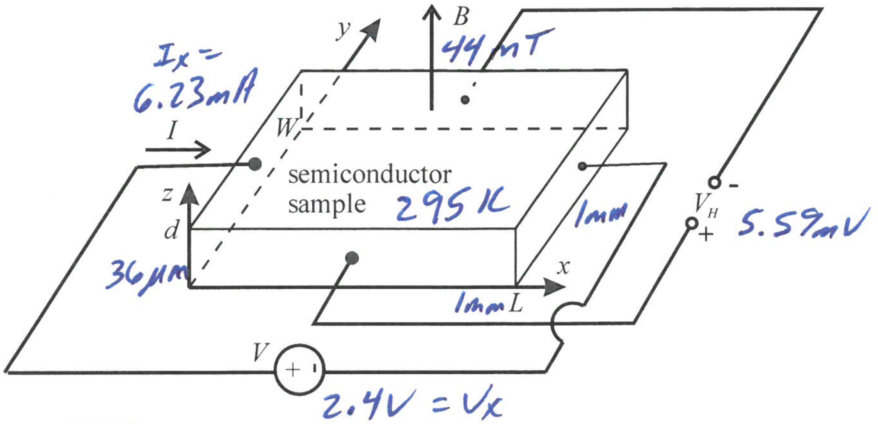
Doped germanium *n*-type or [✓ *p*-type] semiconductor? (circle correct)

equilibrium electron conc. = $1.1494\times10^{12}\ \#/cm^3$ equilibrium hole conc. = $5.0115\times10^{14}\ \#/cm^3$

2) A sample of silicon (see below) is being tested at 295 K. The dimensions of the sample, $L \times W \times d$, are 1 mm × 1 mm × 36 μm. When a voltage of 2.4 V and a uniform magnetic flux density of 44 mT are applied, a current of 6.23 mA and voltage of 5.59 mV are measured. Find the majority charge carrier type, concentration (#/cm^3), mobility (cm^2/V-s), and diffusion coefficient (cm^2/s). Finally, calculate the conductivity (S/cm), resistivity (Ω-cm), and resistance (Ω) of the sample.

$V_H = 5.59 mV > 0$

$\Rightarrow$ p-type



$$(5.54)\quad p = \frac{I_x B_z}{e d V_H}$$

$$p = \frac{6.23\times10^{-3}(44\times10^{-3})}{1.6022\times10^{-19}(36\times10^{-6})5.59\times10^{-3}}$$

$$\underline{p = 8.5019\times10^{21}\ \#/m^3 = 8.5019\times10^{15}\ \#/cm^3}$$

$$(5.59)\quad \mu_p = \frac{I_x L}{e p V_x W d} = \frac{6.23\times10^{-3}(1\times10^{-3})}{1.6022\times10^{-19}(8.5019\times10^{21})2.4(10^{-3})36\times10^{-6}}$$

$$\underline{\mu_p = 0.052936\ \frac{m^2}{V\text{-}S} = 529.356\ \frac{cm^2}{V\text{-}S}}$$

$$(5.47)\quad \frac{D_p}{\mu_p} = \frac{k_B T}{e} \Rightarrow D_p = 529.356\ \frac{1.380649\times10^{-23}(295)}{1.6022\times10^{-19}} = \underline{13.4568\ \frac{cm^2}{s}}$$

n_i silicon is $\sim 1.5\times10^{16}\ \#/m^3$ @ 300K $p \gg n_i$

$$(5.23)\quad \sigma = e\mu_p p = 1.6022\times10^{-19}(0.052936)8.5019\times10^{21} = 72.10648\ S/m$$
$$= \underline{0.721065\ S/cm}$$

$$(5.24)\quad \rho = 1/\sigma = \frac{1}{0.7211} = \underline{1.38684\ \Omega\cdot cm}$$

$$(5.22b)\quad R = \frac{L}{\sigma A} = \frac{10^{-3}}{72.10648(10^{-3})36\times10^{-6}} = 385.2327\ \Omega$$

or Ohm's Law $= V/I = 2.4/6.23\times10^{-3} \longrightarrow$

maj. charge carrier type = p-type/holes maj. charge carrier conc. = $8.5019\times10^{15}\ \#/cm^3$

maj. charge carrier mobility = $529.356\ \frac{cm^2}{V\text{-}S}$ maj. charge carrier diffusion coeff. = $13.457\ cm^2/S$

conductivity = $0.721065\ S/cm$ resistivity = $1.3868\ \Omega\cdot cm$ R_{sample} = $385.23\ \Omega$

3) A semiconductor has a bandgap energy of 0.36 eV at 290 K. The electrons have an effective mass of $0.8m_0$ while holes have an effective mass of $0.4m_0$. The Fermi energy is centered on the bandgap.

a) Find the total number of energy states (#/cm^3) between the bottom of the conduction band E_c and $E_c + 0.3k_BT$.

$$(3.72)\quad g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E-E_c}$$

$$N = \int_{E_c}^{E_c+0.3k_BT} g_c(E)\,dE = \frac{4\pi(2m_n^*)^{3/2}}{h^3}(2/3)\left[E-E_c\right]^{3/2}\Big|_{E_c}^{E_c+0.3k_BT}$$

$$= \frac{4\pi\left(2(0.8)9.1093837\times10^{-31}\right)^{3/2}}{(6.62607015\times10^{-34})^3}(2/3)\left[0.3(1.380649\times10^{-23}(290))\right]^{3/2}$$

$$= 5.06715\times10^{55}\left[4.163\times10^{-3}\right]$$

$$= 2.10944\times10^{24}\ \#/m^3 = \underline{2.10944\times10^{18}\ \#/cm^3}$$

total number of energy states = 2.10944×10^{18} #/cm^3

b) Find the probability (unitless) that an energy state is occupied by an electron at E_c and $E_c + 0.3k_BT$.

$$(3.79)\quad f_F(E) = \frac{1}{1+e^{\frac{E-E_F}{k_BT}}}$$

@ $E = E_c$, $E_c - E_{mid} = E_g/2 = 0.18\text{eV}$

@ $E = E_c + 0.3k_BT = E_g/2 + 0.3k_BT$

$$k_BT = 8.617333\times10^{-5}(290) = 0.02499\ \text{eV}$$

$$f_F(E_c) = \frac{1}{1+e^{0.18/0.0249903}} = \underline{0.000743941}$$

$$f_F(E_c+0.3k_BT) = \frac{1}{1+e^{\frac{0.18+0.3(0.02499)}{0.0249903}}} = \underline{5.51231\times10^{-4}}$$

Prob. energy state occupied: @ E_c = 7.4394×10^{-4} @ $E_c + 0.3k_BT$ = 5.5123×10^{-4}

b) Find the probability (unitless) that an energy state is empty at $E_v - 0.1k_BT$.

Example 3.7 prob empty = $1 - f_F(E)$

@ $E_v - 0.1k_BT$, $E - E_F = E_v - 0.1k_BT - E_{mid} = -E_g/2 - 0.1k_BT$

$$\text{prob. empty} = 1 - \frac{1}{1+e^{\frac{-0.18-0.1(0.02499)}{0.0249903}}} = \underline{6.73193\times10^{-4}}$$

probability an energy state is empty at $E_v - 0.1k_BT$ = 6.7319×10^{-4}

4) At thermal equilibrium @ 300 K, a compensated germanium semiconductor is doped with acceptor atoms to a concentration of 5×10^{17} (#/cm^3) and donor atoms to a concentration of 2×10^{17} (#/cm^3). Determine the electron and hole concentrations (#/cm^3). Then, find the majority carrier mobility (cm^2/V-s). If the germanium semiconductor carries a current density of 200 A/cm^2, calculate the drift velocity (cm/s) of the majority carriers.

$N_a = 5\times10^{17}\ \#/\text{cm}^3 = 5\times10^{23}\ \#/\text{m}^3$

$N_d = 2\times10^{17}\ \#/\text{cm}^3 = 2\times10^{23}\ \#/\text{m}^3$

Table B.4

$n_i = 2.4\times10^{13}\ \#/\text{cm}^3$

$= 2.4\times10^{19}\ \#/\text{m}^3$

$N_a > N_d \Rightarrow \underline{p\text{-type}}$ $\quad N_a - N_d = 3\times10^{17}\ \#/\text{cm}^3$

(4.62) $p_0 = \frac{N_a-N_d}{2} + \sqrt{\left(\frac{N_a-N_d}{2}\right)^2 + n_i^2}$

$= \frac{3\times10^{17}}{2} + \sqrt{\left(\frac{3\times10^{17}}{2}\right)^2 + (2.4\times10^{13})^2} = \underline{3\times10^{17}\ \#/\text{cm}^3}$

(4.43) $n_0 p_0 = n_i^2 \Rightarrow n_0 = \frac{(2.4\times10^{13})^2}{3\times10^{17}} = \underline{1.92\times10^{9}\ \#/\text{cm}^3}$

using graph w/ $N_i = N_a + N_d = 7\times10^{17}\ \#/\text{cm}^3$, read

$\underline{\mu_p = 400\ \frac{\text{cm}^2}{\text{V}\cdot\text{s}}}$

(5.5) $J_{p|drf} = e\,p\,v_{dp}$

$200\ \text{A/cm}^2 = (1.602176634\times10^{-19})(3\times10^{17}\ \#/\text{cm}^3)\,v_{dp}$

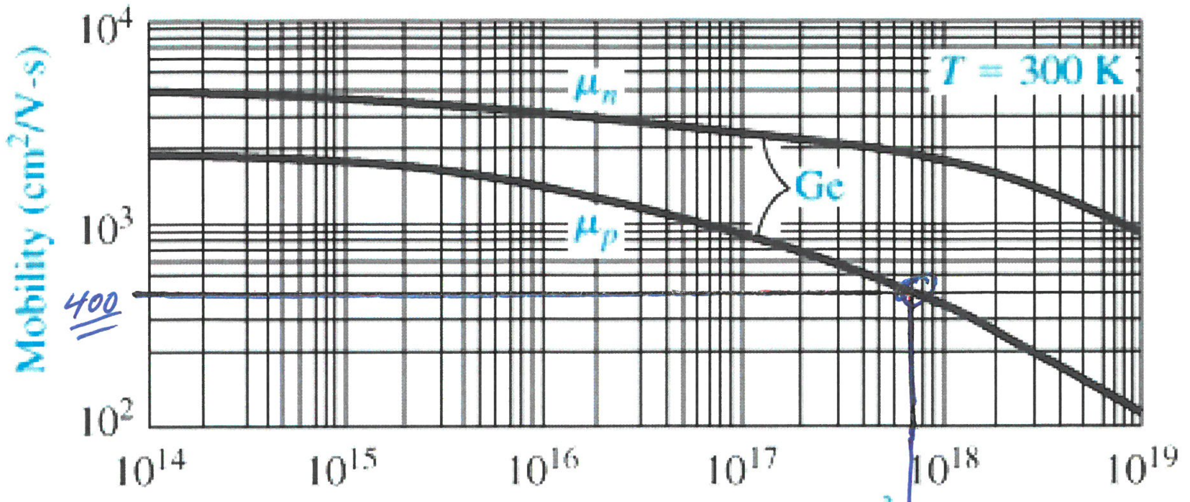
$v_{dp} = \frac{200}{1.6022\times10^{-19}(3\times10^{17})} = \underline{4161.006\ \text{cm/s}}$

n_0 electron concentration = $1.92\times10^{9}\ \#/\text{cm}^3$

p_0 hole concentration = $3\times10^{17}\ \#/\text{cm}^3$

μ_p majority carrier mobility = $400\ \frac{\text{cm}^2}{\text{V-s}}$

v_{dp} majority drift velocity = $4161\ \text{cm/s}$



$7 \times 10^{17} = N_I = N_a + N_d$

1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

↑ acceptor ↑ donor