EE 362 Electronic, Magnetic, & Optical Properties of Materials
Examination #2 (Spring 2026)

Name __KEY__

Instructions: Closed book. Put answers in indicated spaces & show all work (including graphs) for full credit. Insert equation sheet in exam. Answers should have **5-6 significant figures** (use more for constants).

1) A GaN semiconductor has a band gap energy of 3.2 eV, effective electron mass of $0.13m_0$, and effective hole mass of $1.4m_0$ at 450 K. Calculate the effective density of states function for the conduction and valence bands (#/cm^3) as well as the intrinsic carrier concentration (#/cm^3). If it is doped with donor atoms to a concentration of 4×10^{16} #/cm^3, find the thermal equilibrium electron and hole concentrations (#/cm^3) as well as the Fermi energy level with respect to the intrinsic Fermi energy level (eV).

Per (4.10), $N_c = 2\left(\dfrac{2\pi m_n^* k_B T}{h^2}\right)^{3/2} = 2\left(\dfrac{2\pi(0.13)9.109384\times10^{-31}(1.380649\times10^{-23})450}{(6.62607015\times10^{-34})^2}\right)^{3/2}$

$\Rightarrow$ **$N_c = 2.160847 \times 10^{24}$ #/m^3 = 2.160847×10^{18} #/cm^3**.

Per (4.18), $N_v = 2\left(\dfrac{2\pi m_p^* k_B T}{h^2}\right)^{3/2} = 2\left(\dfrac{2\pi(1.4)9.109384\times10^{-31}(1.380649\times10^{-23})450}{(6.62607015\times10^{-34})^2}\right)^{3/2}$

$\Rightarrow$ **$N_v = 7.636616 \times 10^{25}$ #/m^3 = 7.636616×10^{19} #/cm^3**.

Per (4.23), $n_i^2 = N_c N_v\, e^{-E_g/k_BT} = 2.160847\times10^{24}(7.636616\times10^{25})e^{-3.2/[(8.617333\times10^{-5})\,450]}$

$\Rightarrow$ $n_i^2 = 2.393873 \times 10^{14}$ #/m^6 $\Rightarrow$ **$n_i = 1.547215 \times 10^7$ #/m^3 = 15.47215 #/cm^3**.

Since $N_d = 4 \times 10^{16}$ #/cm^3 >> n_i = 15.47215 #/cm^3, $N_d = n_0$ $\Rightarrow$ **$n_0 = 4 \times 10^{16}$ #/cm^3**.

Per (4.43), $p_0 = n_i^2/n_0 = 15.47215^2/4\times10^{16}$ $\Rightarrow$ **$p_0 = 5.984683 \times 10^{-15}$ #/cm^3**.

Per (4.39), $n_0 = n_i\, e^{(E_F - E_{F,i})/k_BT}$. Therefore,

$E_F - E_{F,i} = k_BT \ln\left(\dfrac{n_0}{n_i}\right) = 8.617333\times10^{-5}(450)\ln\left(\dfrac{4\times10^{16}}{15.4721}\right)$ $\Rightarrow$ **$E_F - E_{F,i} = 1.37618$ eV**.

N_c = **2.16085×10^{18} #/cm^3** N_v = **7.63662×10^{19} #/cm^3** n_i = **15.47215 #/cm^3**

n_0 = **4×10^{16} #/cm^3** p_0 = **5.98468×10^{-15} #/cm^3** $|E_F - E_{F,i}|$ = **1.37618 eV**

2) At 300 K, a Germanium sample is uniformly doped with 8×10^{13} #/cm^3 acceptor atoms. First, find the thermal equilibrium electron and hole concentrations (#/cm^3). Next, determine the electron and hole mobilities (cm^2/V-s) and diffusion coefficients (cm^2/s). If 4×10^{12} #/cm^3 excess carriers are uniformly introduced, find the ambipolar mobility (cm^2/V-s).

From Table B.4, $n_i = 2.4 \times 10^{13}$ #/cm^3 at 300 K for Ge. Assume $N_d = 0$.

Since $N_a = 8 \times 10^{13}$ #/cm^3 is on the same order as n_i, use (4.62)

$$p_0 = \frac{(N_a - N_d)}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2} = \frac{(8\times10^{13} - 0)}{2} + \sqrt{\left(\frac{8\times10^{13} - 0}{2}\right)^2 + (2.4\times10^{13})^2}$$

$\Rightarrow$ **$p_0 = 8.6647615 \times 10^{13}$ #/cm^3**.

Per (4.43), $n_0 p_0 = n_i^2 \Rightarrow n_0 = n_i^2 / p_0 = (2.4\times10^{13})^2 / 8.6647615 \times 10^{13}$

$\Rightarrow$ **$n_0 = 6.6476152 \times 10^{12}$ #/cm^3**.

Since n_0 and p_0 are below 10^{14} #/cm^3, we can't use Fig. 5.3, but can use the Table 5.1 mobility values of **$\mu_n = 3900$ cm^2/V-s** and **$\mu_p = 1900$ cm^2/V-s**.

The diffusion coefficients are found using the Einstein relation (5.47)

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{k_B T}{e} = \frac{8.617333\times10^{-5}\,\text{eV/K}(300\text{K})}{e} = 0.025852\text{ V as}$$

$D_n = 0.025852\mu_n = 0.025852(3900)$ $\Rightarrow$ **$D_n = 100.8228$ cm^2/s**, and

$D_p = 0.025852\mu_p = 0.025852(1900)$ $\Rightarrow$ **$D_p = 49.1188$ cm^2/s**.

The ambipolar mobility (6.41) is

$$\mu' = \frac{\mu_n\mu_p(p-n)}{\mu_n n + \mu_p p} = \frac{\mu_n\mu_p[(p_0+\partial p)-(n_0+\partial n)]}{\mu_n(n_0+\partial n)+\mu_p(p_0+\partial p)}$$

$$= \frac{3900(1900)[(8.6647615\times10^{13}+4\times10^{12})-(6.6476152\times10^{12}+4\times10^{12})]}{3900(6.6476152\times10^{12}+4\times10^{12})+1900(8.6647615\times10^{13}+4\times10^{12})}$$

$\Rightarrow$ **$\mu' = 2773.2533$ cm^2/V-s**.

$n_0 =$ **6.6476152×10^{12} #/cm^3** $p_0 =$ **8.6647615×10^{13} #/cm^3** $\mu_n =$ **3900 cm^2/V-s**

$\mu_p =$ **1900 cm^2/V-s** $D_n =$ **100.823 cm^2/s** $D_p =$ **49.119 cm^2/s** $\mu' =$ **2773.2533 cm^2/V-s**

3) In the QC lab at a semiconductor fab, you are anticipating testing a *p*-type silicon sample using the Hall effect where L = 0.2 mm, W = 0.1 mm, and d = 16 μm. The sample is supposed to have an acceptor concentration of 3×10^{16} #/cm^3. Find the anticipated Hall voltage and electric field (V/cm) when a current I_x = 5 mA and magnetic flux density B_z = 48 mT are applied. What applied current $I_{x,2.5\mathrm{mV}}$ would be required to achieve a Hall voltage of 2.5 mV?

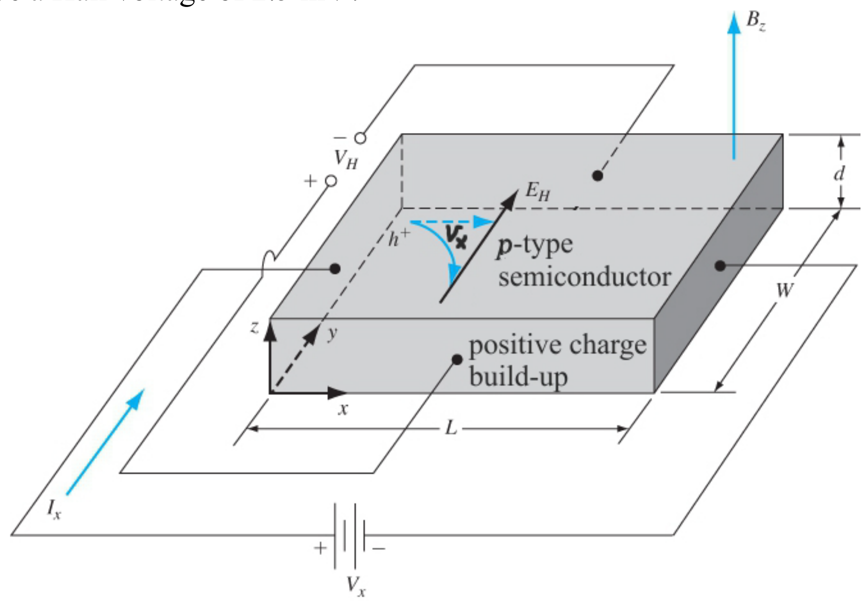

Figure 5.13 | Geometry for measuring the Hall effect.

Per (5.53) using all MKS units, the Hall voltage for p-type is

$$V_H = \frac{I_x B_z}{e\,p\,d} = \frac{5\times10^{-3}(48\times10^{-3})}{1.602176634\times10^{-19}(3\times10^{22})16\times10^{-6}}$$

$\Rightarrow$ **V_H = 0.003121 V = 3.120755 mV**.

Per (5.50), the Hall electric field is

$E_H = V_H / W = 0.002120755 / 10^{-4}$ $\Rightarrow$ **E_H = 31.207545 V/m = 0.31207545 V/cm**.

To get the applied current for 2.5 mV, note that V_H is linearly related to I_x and scale the result-

$I_{x,new} = I_x\,(2.5\ \mathrm{mV} / V_H) = 5\ \mathrm{mA}\,(2.5\ \mathrm{mV} / 3.120755\ \mathrm{mV})$ $\Rightarrow$ **$I_{x,new}$ = 4.00544 mA**.

V_H = **3.1208 mV** E_H = **0.31208 V/cm** $I_{x,2.5\mathrm{mV}}$ = **4.0054 mA**

4) A GaAs semiconductor sample has been doped with donor atoms to a concentration of 4×10^{16} #/cm^3 at 300 K. Find the thermal equilibrium electron and hole concentrations (#/cm^3). Next, determine the majority carrier mobility (cm^2/V-s) and diffusion coefficient (cm^2/s). Last, calculate the conductivity (S/cm) and resistivity (Ω-cm). Extra credit: Find the resistance of the sample if it is 2 mm long, 1 mm wide, and 36 μm thick.

From Table B.4, $n_i = 1.8 \times 10^6$ #/cm^3 and $E_g = 1.42$ eV at 300 K for Ge. Assume $N_d = 0$.

Since $N_d = 4 \times 10^{16}$ #/cm^3 >> n_i, ***n*-type** semiconductor $\Rightarrow$ **$n_0 = N_d = 4 \times 10^{16}$ #/cm^3**.

Per (4.43) $n_0 p_0 = n_i^2$, we get $p_0 = n_i^2 / n_0 = (1.8\times10^6)^2 / 4\times10^{16}$ $\Rightarrow$ **$p_0 = 8.1 \times 10^{-5}$ #/cm^3**.

On the bottom graph of Figure 5.3, draw a vertical line up from $N_I = N_d = 4 \times 10^{16}$ #/cm^3 and read the majority carrier (electrons for n-type) mobility as **$\mu_n = 5000$ cm^2/V-s**.

The majority carrier diffusion coefficient is found using the Einstein relation (5.47)

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{k_B T}{e} = \frac{8.617333\times10^{-5}\,\text{eV/K}(300\text{K})}{e} = 0.025852\ \text{V as}$$

$$D_n = 0.025852\mu_n = 0.025852(5000)$$ $\Rightarrow$ **$D_n = 129.26$ cm^2/s.**

Per (5.23) $\sigma = e(\mu_n n + \mu_p p)$. Since $n_0 >> p_0$, this becomes

$\sigma \approx e\,\mu_n n = 1.602176634\times10^{-19}$ C (5000 cm^2/V-s) 4×10^{16} #/cm^3 $\Rightarrow$ **$\sigma = 32.043533$ S/cm**.

Per (5.20) $\rho = 1/\sigma = 1 / 32.043533$ S/cm $\Rightarrow$ **$\rho = 0.0312075$ Ω-cm**.

Extra Credit

Per (5.22b), $R = L/\sigma A = 2\times10^{-3} / [32.043533$ S/cm*100 cm/m $(1\times10^{-3})\, 36\times10^{-6}]$

$\Rightarrow$ **$R = 17.33753$ Ω**.

$n_0 =$ **4×10^{16} #/cm^3** $p_0 =$ **8.1×10^{-5} #/cm^3** $\mu_{\text{majority}} =$ **$\mu_n = 5000$ cm^2/V-s**

$D_{\text{majority}} =$ **$D_n = 129.26$ cm^2/s** $\sigma =$ **32.0435 S/cm** $\rho =$ **0.0312075 Ω-cm**

Extra Credit: $R_{\text{sample}} =$ **17.33753 Ω**

Table 5.1 | Typical mobility values at $T = 300$ K and low doping concentrations

	μ_n (cm²/V-s)	μ_p (cm²/V-s)
Silicon	1350	480
Gallium arsenide	8500	400
Germanium	3900	1900

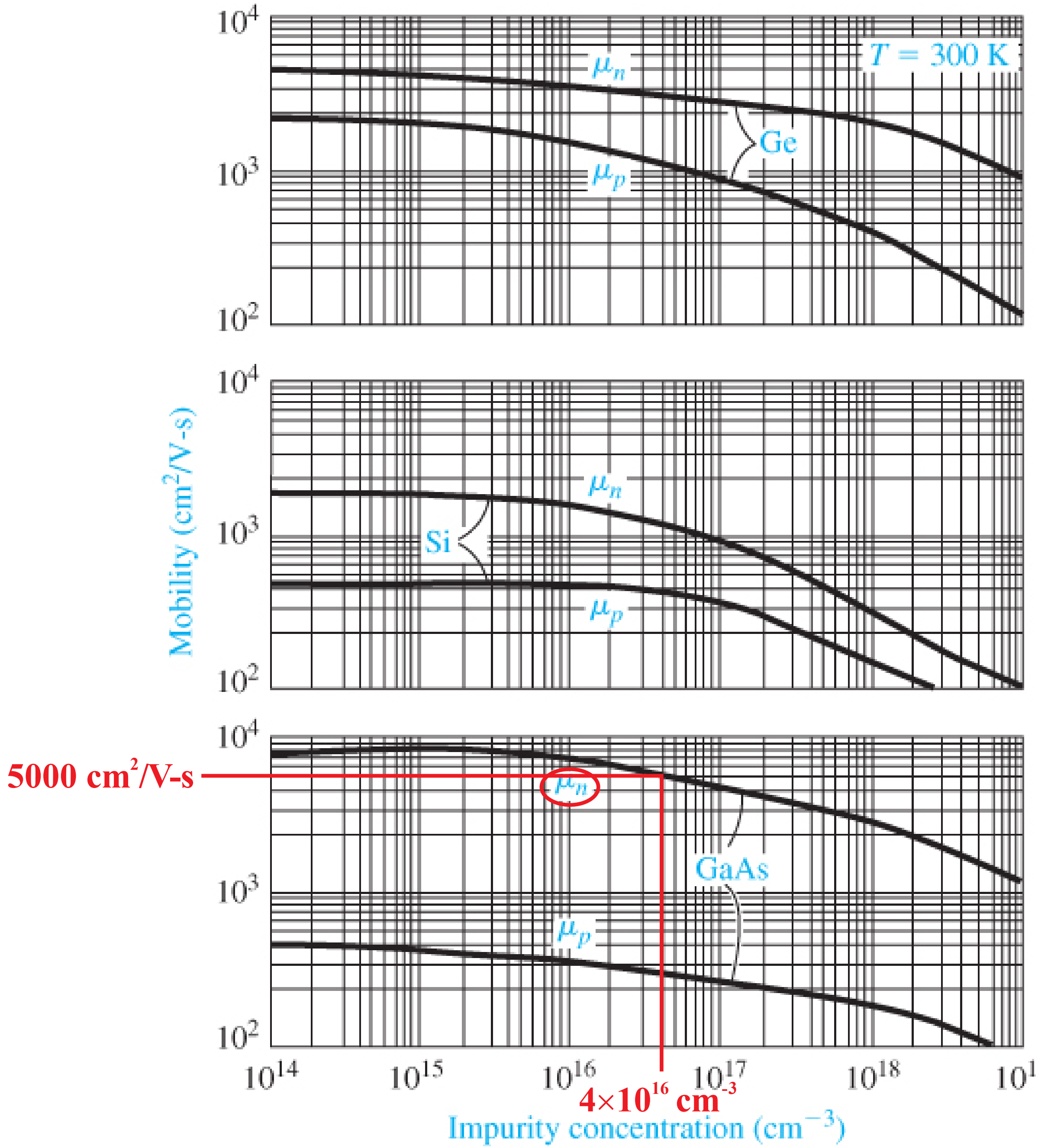

Figure 5.3 | Electron and hole mobilities versus impurity concentrations for germanium, silicon, and gallium arsenide at $T = 300$ K.
(From Sze [14].)