7

72

# EE 121B Quiz 1

You have 1 hour to finish the quiz. There are four problems and each is 25% of the total grade. For problem 3, pick one from A ,B and C.

Use T=300K unless specified otherwise. Make appropriate assumptions when necessary.

## Constants for room temperature Si

1.5 10

$n_i = 10^{15} cm^{-3}$ $\quad E_g = 1.14eV$ $\quad \epsilon_{Si} = 1.04 * 10^{-12} F/cm$ $\quad q = 1.6 * 10^{-19} C$

$h = 6.63 * 10^{-34} m^2 kg/s = 2\pi\hbar$ $\quad k_B = 1.38 * 10^{-23} m^2 kg s^{-2} K^{-1} = 8.617 * 10^{-5} eV K^{-1}$

$$\mathrm{p} = \hbar k, \mathrm{E} = \frac{\hbar^2 k^2}{2m}, m_{\mathrm{eff}} = \hbar^2 / (\frac{\partial^2 E}{\partial k^2}) \qquad f_F(E) = \frac{1}{1 + \exp(\frac{E - E_F}{kT})}$$

$$n_0 p_0 = n_i^2 = N_c N_v \exp(-\frac{E_g}{kT}) \qquad g_c(E) = \frac{4\pi(2m_n^*)^{\frac{3}{2}}}{h^3}\sqrt{E - E_C},\ g_v(E) = \frac{4\pi(2m_p^*)^{\frac{3}{2}}}{h^3}\sqrt{E_v - E}$$

$$n_0 = N_c \exp\left[-\frac{(E_F - E_c)}{kT}\right] = n_i \exp[\frac{E_F - E_{Fi}}{kT}] \qquad p_0 = N_v \exp[-\frac{E_v - E_F}{kT}] = n_i \exp[\frac{E_{Fi} - E_F}{kT}]$$

$$n_0 + N_a - p_a = p_0 + N_d - n_d \qquad n_d = \frac{N_d}{1 + \frac{1}{2}\exp(\frac{E_d - E_F}{kT})},\ p_a = \frac{N_a}{1 + \frac{1}{4}\exp(\frac{E_F - E_a}{kT})}$$

$$|v| = \mu|E|, \qquad \frac{1}{\mu} = \frac{1}{\mu_{lattice}} = \frac{1}{\mu_{impurity}}$$

$$n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

$$J_{n,drift} = q\mu_n n E, J_{p,drift} = q\mu_p p E \qquad J_{n,diffusion} = qD_n\frac{dn}{dx}, J_{p,diffusion} = -qD_p\frac{dp}{dx}$$

$$\sigma = q\mu_n n + q\mu_p p,\ \rho = 1/\sigma,\ \tau_d = \frac{\epsilon}{\rho} \qquad \frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q}$$

$$L_p^2 = D_p\tau_{po},\ L_n^2 = D_n\tau_{no}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + g_p - \frac{p}{\tau_{pt}}, \quad \frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + g_n - \frac{n}{\tau_{pt}}$$

$$D_p\frac{\partial^2(\delta p_n)}{\partial x^2} - \mu_p E\frac{\partial(\delta p_n)}{\partial x} + g' - \frac{\delta p_n}{\tau_{po}} = \frac{\partial(\delta p_n)}{\partial t}$$

$$D' = \frac{\mu_n n D_p + \mu_p p D_n}{\mu_n n + \mu_p p}, \quad \mu' = \frac{\mu_n \mu_p (p - n)}{\mu_n n + \mu_p p}$$

$$D_n\frac{\partial^2(\delta n_p)}{\partial x^2} - \mu_n E\frac{\partial(\delta n_p)}{\partial x} + g' - \frac{\delta n_p}{\tau_{no}} = \frac{\partial(\delta n_p)}{\partial t}$$

$$\frac{\rho(x)}{\epsilon_s} = \frac{dE(x)}{dx} = \frac{-d^2\phi}{dx^2} \qquad V_{bi} = \frac{kT}{q}\ln(\frac{N_a N_d}{n_i^2}), \quad V_B \approx \frac{\epsilon_s E_{crit}^2}{2qN_B}$$

$$x_n = \left\{\frac{2\epsilon_s V_{bi}}{q}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2}, x_p = \left\{\frac{2\epsilon_s V_{bi}}{q}\left[\frac{N_d}{N_a}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2}$$

$$J_{ideal} = (\frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{po}}{L_n})\left(\exp\left(\frac{qV_a}{kT}\right) - 1\right)$$

$$n_p = n_{po}\exp(\frac{qV_a}{kT}), \quad p_n = p_{no}\exp(\frac{qV_a}{kT})$$

$$C' = \frac{dQ'}{dV_R} = \left\{\frac{q\epsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)}\right\}^{1/2}$$

## Some solutions for the ambipolar transport equation

$$\delta p(t) = \delta p(0)e^{-t/\tau_{po}}$$
$$\delta p(t) = g'\tau_{p0}(1 - e^{-t/\tau_{p0}})$$

$$\delta p(x) = \delta p(0)e^{-|x|/L_p}$$
$$\delta p(x,t) = e^{-t/\tau_{po}} * (4\pi D_p t)^{-\frac{1}{2}} * \exp[-\frac{(x - \mu_p E_0 t)^2}{4D_p t}]$$

No generation!



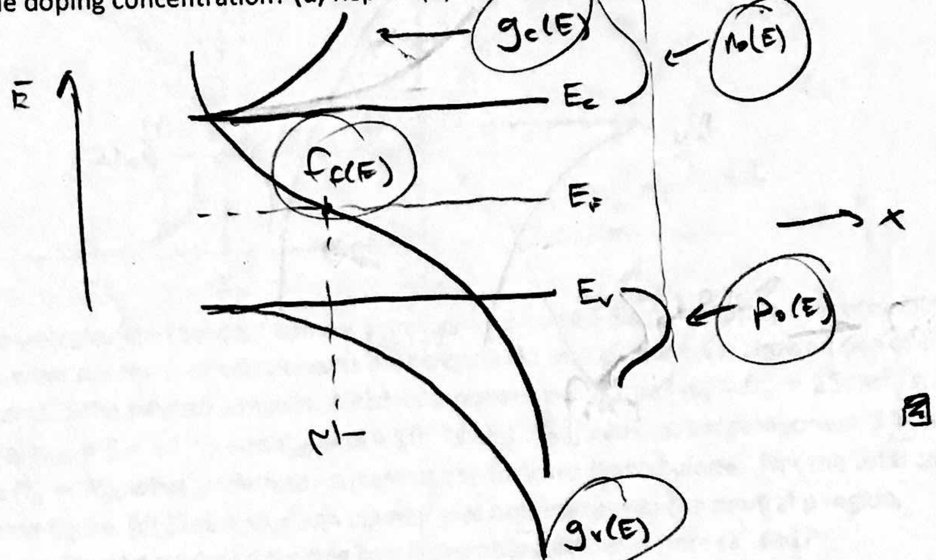
E, R, D >> 0 $\quad g = 0$

Name: UID:

1. **(a)** For intrinsic Si, use y-axis for energy and show the relative positions for the conduction band edge, valence band edge and the Fermi level. **(b)** In the figure from (a), sketch the Fermi-Dirac distribution, density of states functions for electrons and holes, carrier concentration for electrons and holes (total of 5 functions). **(c)** Now the Si is doped by a single dopant so that $E_F - E_{Fi} = 0.2eV$, What's the type of the dopant? What are the carrier concentrations now and what is the doping concentration? **(d)** Repeat (b) for the doped Si in (c).

(a)

(b)




(c) The dopant is electrons (donors), because the extrinsic Fermi energy increased

$$n_o = n_i e^{E_F - E_{Fi}/kT} = (10^{10}) e^{0.2eV/kT}$$

$$= 3.435 \times 10^{13} \text{ cm}^{-3}$$

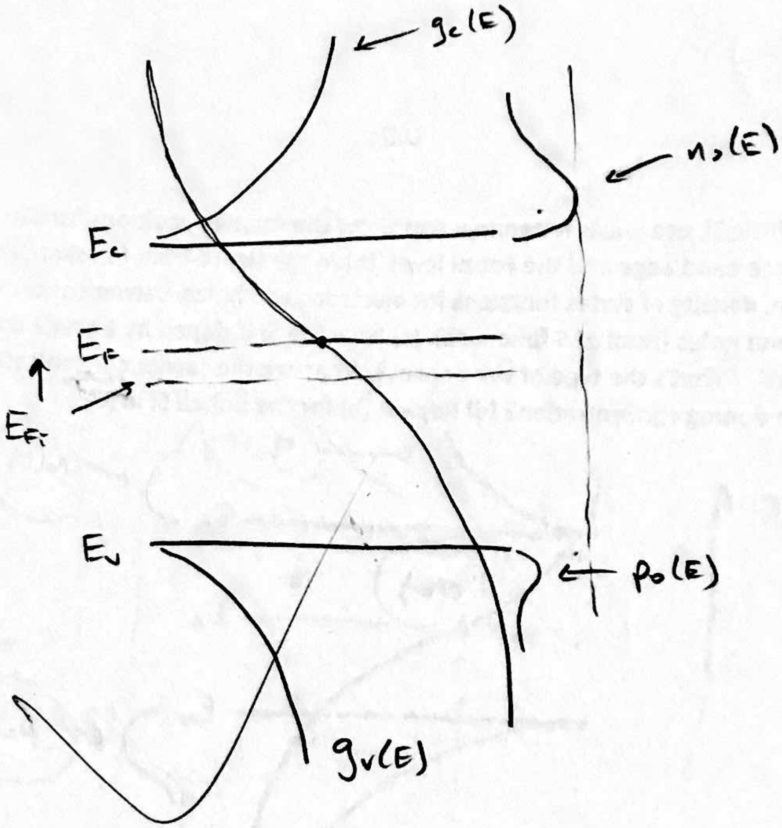
$$p_o = \frac{n_i^2}{n_o} = 6.55 \times 10^{6} \text{ cm}^{-3}$$

At $T = 300K$, complete ionization, so

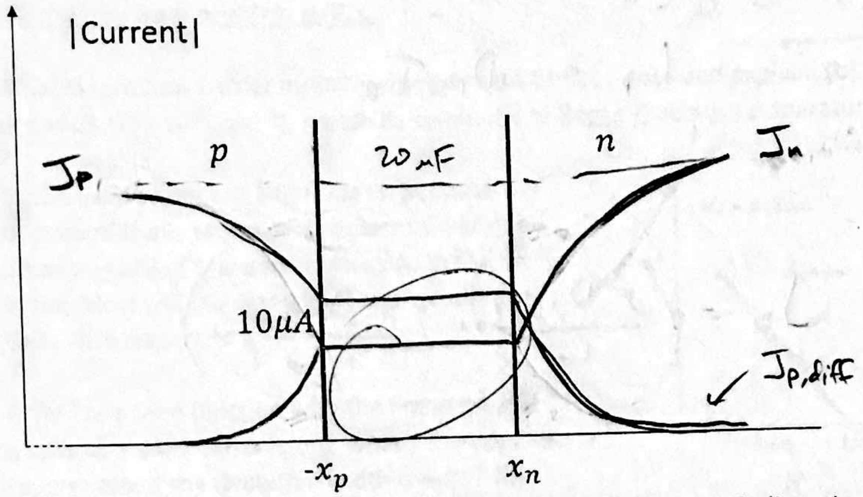
$N_d \approx n_o$. $N_a \propto p_o$.

(d) → Back

(d)



Name: UID:




(c)

2. (a) When we calculate the ideal current for a forward-biased diode (ignoring the recombination current), what are the four components of the current? In the figure, we showed one of the four components in the neutral p region. Which component is this one? (b) If $D_n = 25cm^2/s$, $D_p = 10cm^2/s$, $\tau_{n0} = 5 * 10^{-7}s$ and $\tau_{p0} = 5 * 10^{-6}s$ and the given current component is $10\mu A$ at $-x_p$ and $N_a = N_d$, what is the total current of the forward-biased diode? Plot the total current in the same figure. (c) Sketch electron current and hole current in the neutral p region, depletion region and neutral n regions based on the information from (a) and (b).

(a) Diffusion and drift for electrons & holes.

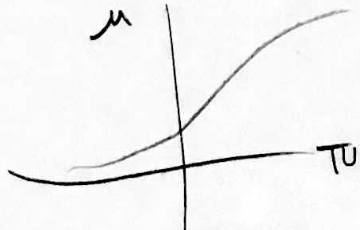
$\Sigma J = J_{p,diff} + J_{p,drift} + J_{n,diff} + J_{n,drift}$

The component shown in the graph is the diffusion of electron carriers. So $J_{n,diffusion}$.

(b) ~~Because the doping regions are the same concentration, the currents balance out.~~

~~Thus, $J_\Sigma = 2 \cdot 10\ \mu A = 20\ \mu A$.~~

-15




Name: TUID:

$\mu \propto T^{-3/2}$ (low temp)

$\mu \propto T^{3/2} / N_d^+ + N_a^+$ (high temp)

3. <u>Choose one from problem A, B, C</u>

A: **(a)** Sketch how carrier mobility changes with temperature and explain. **(b)** For a moderately doped Si ($N_d \sim 10^{15} cm^{-3}$), sketch its conductivity ($\log(\sigma)$) versus temperature ($1/T$).

B: Si is used as dopant ($N_I$) in GaAs. Suppose a fraction of the Si atoms, α% replaces Ga and the other 1 − α% of Si atoms replaces As in the lattice. How will the Fermi level change in the GaAs with respect to α?

C: **(a)** For a p-i-n junction with the linear dopant profile as shown in the figure, what's the applied reverse bias if the depletion width is 4μm? **(b)** Repeat (a) if the i-region is now replaced by metal ($\sigma = \infty$).

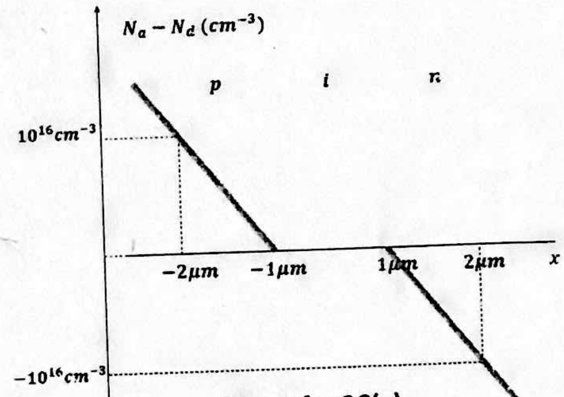



**Figure for 3C(a)**

(b) We can analyze a change in Fermi level by the built in voltage $\Delta V_{bi} = |\Phi_{Fp}| + |\Phi_{Fn}| = \frac{E_{Fn} - E_{Fp}}{e}$

$\phi_{Fp} = \frac{kT}{e} \ln \left| \frac{N_a}{n_i} \right| \qquad \phi_{Fn} = \frac{kT}{e} \ln \left| \frac{N_d}{n_i} \right|$

$n_0 = n_i e^{eV_{bi}/kT}$

Suppose $N_I$ : Si dopant, w/

$E_F$

$p_0 = n_i e^{eV_{bi}/kT}$

Ga : acceptor

As : donor

I think

$N_I \cdot \alpha/_{100} = -\Delta N_a \rightarrow$ Ga

$N_I (1-\alpha)/_{100} = -\Delta N_d \rightarrow$ As

$\Phi_{Fp} = \frac{kT}{e} \ln \left| \frac{N_a - N_I \alpha/_{100}}{n_i} \right|$

$|\Phi_{Fp} - \Phi_{Fn}|$

$= |E_F - E_{Fi}|$

$\Phi_{Fn} = \frac{kT}{e} \ln \left| \frac{N_d - N_I \left(\frac{1-\alpha}{100}\right)}{n_i} \right|$

$\rightarrow \Delta E_F = \left| \frac{kT}{e} \ln \left| \frac{N_a - N_I \alpha/_{100}}{N_d - N_I\left(\frac{1-\alpha}{100}\right)} \right| \right|$ J

abs value

Name: UID:

$\delta_n \approx \delta_p$

4. Assume that a finite number of electron-hole pairs is generated instantaneously at $t = 0$ and $x = 0$ in an n-type semiconductor, assume the excess carrier generation rate is zero for $t > 0$. **(a)** Sketch excess carrier concentration with respect to $x$ for $t = t_1, t = t_2, t = t_3$ (3 curves) and $t_3 > t_2 > t_1 > 0$ for no external field ($E_0 = 0$). **(b)** Repeat (a) for $E_0 > 0$. **(c)** Inspired by the result from (b), a very famous experiment is set up to measure the minority carrier mobility, minority carrier diffusion coefficient and minority excess carrier lifetime. What's the name of the experiment and what's its significance? Draw the set up for the experiment. **(d)** Describe how you can use it to measure the underlined parameters (you might need hint from the equation sheet).

$g' = 0$

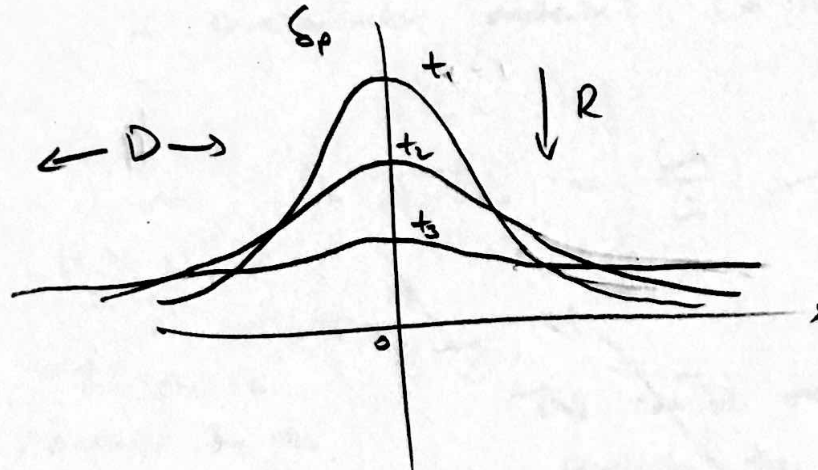
$t > 0$

Dielectric Relax.

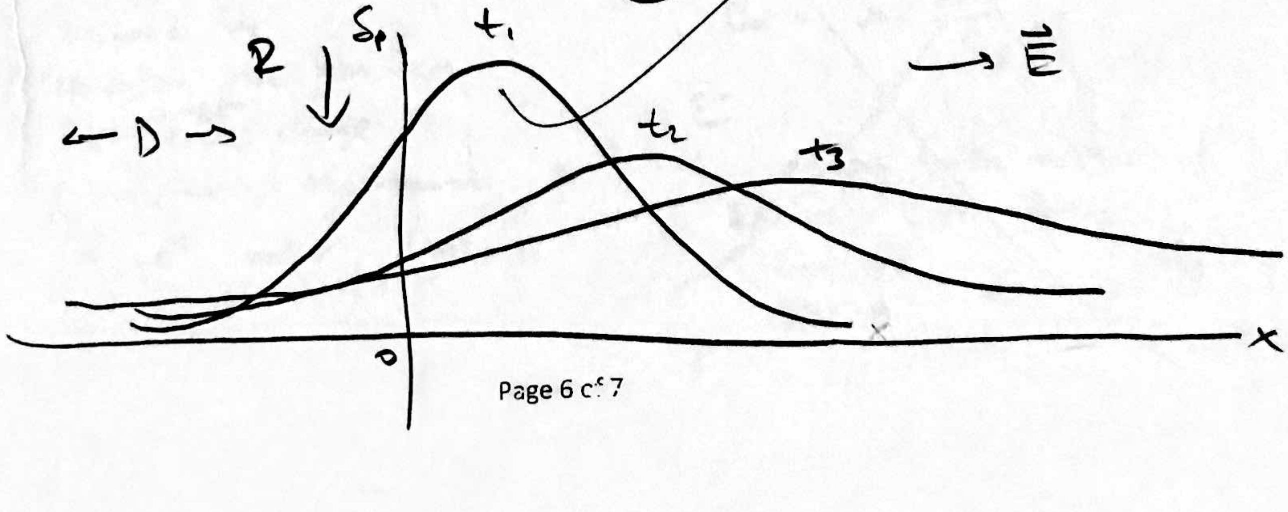
(a) $$\delta_p(x,t) = e^{-t/\tau_{p0}} \cdot (4\pi D_p t)^{-1/2} \cdot e^{-\frac{(x - \mu_p E_0 t)^2}{4 D_p t}}$$

This is the excess carrier concentration in a semiconductor under diffusion, recombination, and $E \neq 0$.

Suppose $E = 0$. Then:

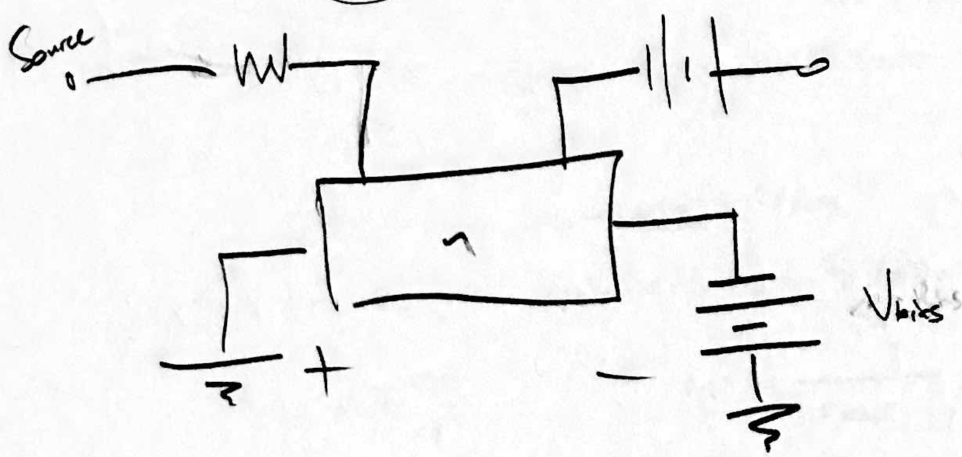



(b) With $E \neq 0$ in the $+x$ direction.



Name: Haynes - Shockley UID:

(c) ~~Schottsky - 2~~ Experiment




The experiment is set up to observe the diffusion and drift of excess carriers through a semiconductor material (n-type)

(d) $\mu_n$ $D_n$ $\tau_{n0} = \frac{L_n}{D_n}$ → Found after $D_n$ is found. ???

This can be measured by the drift velocity
$V_d = \mu E$
captured by controlling the generation of excess charge and timing the movement of $e^-$ under $V_{bias}$.

~~This can be measured by considering the measured mobility by Einstein's Relation.~~
~~$D_n = \mu_n \frac{kT}{e}$~~
~~or~~
~~the diffusion length relative to the width of the material.~~