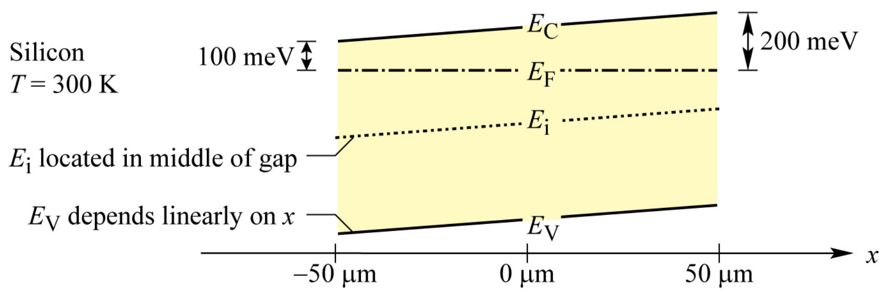
Spring 2008 – Quiz I

Note: (*i*) Put your name on top of each page
(*ii*) Show your work and always show units
(*iii*) This is an open book exam
(*iv*) For materials constants and physical constants, please refer to the tables on the course web site

1. Consider the band diagram of silicon, shown below, under thermal equilibrium conditions at room temperature.



(a) What is the electron and hole equilibrium carrier concentration, n and p, at $x = -50$ µm?
(b) What is the electron and hole equilibrium carrier concentration, n and p, at $x = 0$ µm?
(c) What is the electric field $\mathcal{E}$ in the semiconductor?
(d) What is the electron drift velocity at $x = 0$ µm (if electron / hole mobilities are needed, take them from the table entitled "Materials properties of Si, Ge, and GaAs")?
(e) What is the direction of the electron drift and the electron-drift current at $x = 0$ µm?
(f) What is the magnitude of the electron drift current density at $x = 0$ µm?
(g) What is the direction of the hole drift and the hole-drift current at $x = 0$ µm?
(h) What is the total electrical current in the semiconductor at $x = 0$ µm?
(i) Is there an electron diffusion current density at $x = 0$ µm?
(j) If there a electron diffusion current density at $x = 0$ µm, what is its magnitude?

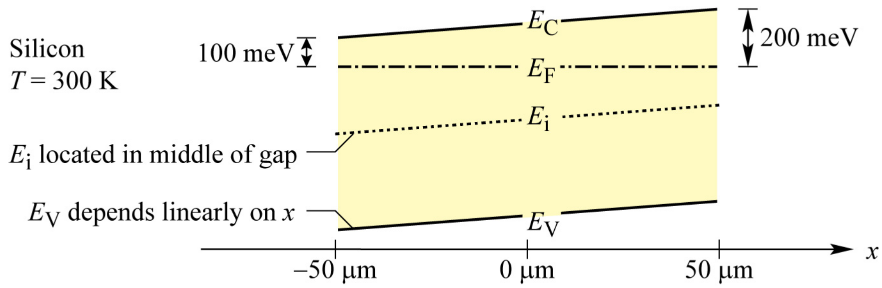
2. Circle correct answer (T = true; F = false; U = uncertain, i.e., cannot be decided based on given information):

A.	The electric field points from a positive charge to the negative charge	T F U
B.	Under thermal equilibrium conditions, all quantities, such electrical currents, recombination rates, etc., are invariant with time	T F U
C.	In n-type semiconductors, the Fermi energy is close to or inside the conduction band.	T F U
D.	Electric fields make carriers drift	T F U
E.	For low-level excitation, the excess carrier concentration is smaller than the majority carrier concentration	T F U
F.	For low-level excitation, the minority carrier concentration is approximately equal to the majority carrier concentration	T F U
G.	An electric field pulls majority and minority carriers in the same direction	T F U
H.	An electron diffusion current is caused by an electric field	T F U
I.	Under steady state conditions, the decay of the minority hole concentration can be described by $\Delta p = \Delta p_0 \exp(-t/\tau_p)$	T F U
J.	Amorphous materials have more favorable properties, e.g. a higher mechanical strength or electrical conductivity, than crystalline materials	T F U
K.	Under thermal equilibrium conditions, a drift current cannot occur	T F U

3. An n-type Si sample at T = 300 K is in thermal equilibrium and has an electron mobility of 500 cm^2/(Vs). The sample has a length of 1000 μm with the left and right end of the sample being located at x = 0 μm and x = 1000 μm, respectively. The doping concentration at the left end (x = 0 μm) is 1.0×10^{16} cm^{-3}. A diffusion current of 50 mA/cm^2 flows from right to left.
   (a) What is the diffusion constant of electrons?
   (b) Calculate the doping concentration at the right end of the sample.
   (c) What is the magnitude and direction of the drift current density at x = 0 μm?
   (d) Calculate the magnitude of the internal field causing the drift current at x = 0 μm.
   (e) What is the hole concentration at x = 0 μm and x = 1000 μm?

Spring 2008 – Quiz I – Solution

1. Consider the band diagram of silicon, shown below, under thermal equilibrium conditions at room temperature.



(a) What is the electron and hole equilibrium carrier concentration, n and p, at $x = –50$ µm?
(b) What is the electron and hole equilibrium carrier concentration, n and p, at $x = 0$ µm?
(c) What is the electric field $\mathcal{E}$ in the semiconductor?
(d) What is the electron drift velocity at $x = 0$ µm (if electron / hole mobilities are needed, take them from the table entitled "Materials properties of Si, Ge, and GaAs")?
(e) What is the direction of the electron drift and the electron-drift current at $x = 0$ µm?
(f) What is the magnitude of the electron drift current density at $x = 0$ µm?
(g) What is the direction of the hole drift and the hole-drift current at $x = 0$ µm?
(h) What is the total electrical current in the semiconductor at $x = 0$ µm?
(i) Is there an electron diffusion current density at $x = 0$ µm?
(j) If there an electron diffusion current density at $x = 0$ µm, what is its magnitude?

Solution (***Note***: In this solution, we use $kT = 25.0$ meV; if you use a different value, the calculated numerical results obtained will be somewhat different)

(a) The energy gap of Si is $E_g = 1.12$ eV and the intrinsic carrier concentration is $n_i = 10^{10}$ cm^{-3}. At $x = –50$ µm, it is:
$E_F – E_i = E_g/2 – 100$ meV $= 560$ meV $– 100$ meV $= 460$ meV
$n = n_i \exp [(E_F – E_i) / kT] = 9.79 \times 10^{17}$ cm^{-3}
$p = n_i^2 / n = 1.02 \times 10^2$ cm^{-3}

(b) At $x = 0$ µm, it is:
$E_F – E_i = E_g/2 – 150$ meV $= 560$ meV $– 150$ meV $= 410$ meV
$n = n_i \exp [(E_F – E_i) / kT] = 1.33 \times 10^{17}$ cm^{-3}
$p = n_i^2 / n = 7.52 \times 10^2$ cm^{-3}

(c) The electric field is:
$\mathcal{E} = (1/q) [E_C(50\ \mu m) – E_C(–50\ \mu m)] / 100\ \mu m = (1/e)\ 0.100\ eV / 10^{-2}\ cm = 10\ V/cm$

(d) The electron mobility is $\mu_n = 1500$ cm^2/(Vs). The electron drift velocity is:
$v_d = \mu_n \mathcal{E} = 1500\ cm^2/(Vs) \times 10\ V/cm = 15 \times 10^3\ cm/s$

(e) The direction of electron drift is towards the left-hand side.
The direction of electron drift current is towards the right-hand side.

(f) Magnitude of electron drift current density:
$J_n = q\ n\ \mu_n\ \mathcal{E} = q\ n\ v_d = 1.6 \times 10^{-19}\ C \times 1.33 \times 10^{17}\ cm^{-3} \times 15 \times 10^3\ cm/s = 3.19 \times 10^2\ A/cm^2$

(g) The direction of hole drift is towards the right-hand side.
The direction of hole drift current is towards the right-hand side.

(h) The total electrical current is zero, because thermal equilibrium conditions have been assumed.

(i) Yes, there must be an electron diffusion current that exactly compensates the electron drift current.

(j) The magnitude of the electron diffusion current density is $J_{n,diffusion} = J_{n,\ drift} = 3.19 \times 10^2$ A/cm^2

2. Circle correct answer (T = true; F = false; U = uncertain, i.e., cannot be decided based on given information):

A. The electric field points from a positive charge to the negative charge	True
B. Under thermal equilibrium conditions, all quantities, such electrical currents, recombination rates, etc., are invariant with time	True
C. In n-type semiconductors, the Fermi energy is close to or inside the conduction band.	True
D. Electric fields make carriers drift	True
E. For low-level excitation, the excess carrier concentration is smaller than the majority carrier concentration	True
F. For low-level excitation, the minority carrier concentration is approximately equal to the majority carrier concentration	False
G. An electric field pulls majority and minority carriers in the same direction	False
H. An electron diffusion current is caused by an electric field	False
I. Under steady state conditions, the decay of the minority hole concentration can be described by $\Delta p = \Delta p_0 \exp(-t/\tau_p)$	False
J. Amorphous materials have more favorable properties, e.g. a higher mechanical strength or electrical conductivity, than crystalline materials	False
K. Under thermal equilibrium conditions, a drift current cannot occur	False

3. An n-type Si sample at T = 300 K is in thermal equilibrium and has an electron mobility of 500 cm^2/(Vs). The sample has a length of 1000 μm with the left and right end of the sample being located at x = 0 μm and x = 1000 μm, respectively. The doping concentration at the left end (x = 0 μm) is 1.0×10^{16} cm^{-3}. A diffusion current of 50 mA/cm^2 flows from right to left.

(a) What is the diffusion constant of electrons?

(b) Calculate the doping concentration at the right end of the sample.

(c) What is the magnitude and direction of the drift current density at x = 0 μm?

(d) Calculate the magnitude of the internal field causing the drift current at x = 0 μm.

(e) What is the hole concentration at x = 0 μm and x = 1000 μm?

Solution (***Note***: In this solution, we use kT = 25.0 meV; if you use a different value, the calculated numerical results obtained will be somewhat different)

(a) The diffusion constant can be derived from the Einstein relation:

$D_n = (kT/q)\,\mu_n = (25 \text{ meV}/e)\ 500 \text{ cm}^2/(\text{Vs}) = 12500 \times 10^{-3} \text{ cm}^2/\text{s} = 12.5 \text{ cm}^2/\text{s}$

(b) The electron diffusion current density is given by

$J_{n,diffusion} = q\,D_n\,(dn/dx)$

Solving this equation for the concentration gradient gives

$(dn/dx) = J_{n,diffusion} / (q\,D_n) = 50 \text{ (mA/cm}^2) / (1.6 \times 10^{-19} \text{ C} \times 12.5 \text{ cm}^2/\text{s}) = 50 \times 10^{-3} \text{ C s}^{-1} \text{ cm}^{-2} / (1.6 \times 10^{-19} \text{ C} \times 12.5 \text{ cm}^2/\text{s}) = 2.5 \times 10^{16} \text{ cm}^{-3} / \text{cm}$

Thus the concentration at the right-hand side of the sample is given by:

$n_{\text{right-hand side}} = 1.0 \times 10^{16}\ \text{cm}^{-3} - (dn/dx) \times 1000\ \mu\text{m} = 1.0 \times 10^{16}\ \text{cm}^{-3} - 2.5 \times 10^{15}\ \text{cm}^{-3} = 7.5 \times 10^{15}\ \text{cm}^{-3}$

(c) At $x = 0\ \mu\text{m}$ (and at any other location) the overall current must be zero because the sample is under thermal equilibrium conditions. Thus the magnitude of the drift current is 50 mA/cm^2 and the direction is from left to right.

(d) Consider the relationship between electric field and current density:

$J_{n,\text{drift}} = q\ n\ v_{\text{drift}} = q\ n\ \mu_n\ \mathcal{E}$

Solving the equation for $\mathcal{E}$ yields:

$\mathcal{E} = J_{n,\text{drift}} / (q\ n\ \mu_n) = 50\ (\text{mA/cm}^2) / [\ 1.6 \times 10^{-19}\ \text{C} \times 1.0 \times 10^{16}\ \text{cm}^{-3} \times 500\ \text{cm}^2/(\text{Vs})\ ] = 0.0625\ \text{V/cm}$

(e) The hole concentration can be calculated from the equation: $n\ p = n_i^2$, which is valid under thermal equilibrium conditions. Using $n_i = 1.0 \times 10^{10}\ \text{cm}^{-3}$ (valid for Si), the hole concentration given by:

$x = 0\ \mu\text{m}$ $\quad n = 1.0 \times 10^{16}\ \text{cm}^{-3}$ $\quad p = n_i^2 / n = 1.00 \times 10^{4}\ \text{cm}^{-3}$

$x = 1000\ \mu\text{m}$ $\quad n = 7.5 \times 10^{15}\ \text{cm}^{-3}$ $\quad p = n_i^2 / n = 1.33 \times 10^{4}\ \text{cm}^{-3}$