

1. Explain why a transient current flows when you touch a piece of n -type semiconductor to a piece of p -type semiconductor. What is the direction of current flow? What stops the current after a while? Similar questions are in *Bloomfield*, p. 439.

Somewhat naively the picture is as follows. Start with germanium (Ge) atoms which have four valence electrons. Take the Ge ions (the nuclei plus the bound electrons) and construct a lattice. Then find the states associated with this structure and fill them up (obeying the Pauli exclusion principle and starting with the lowest energy). One should find that the energies of these states fall into bands separated by gaps. Furthermore, one should find that the last filled state completes a band (the valence band) and that the next available state is E_g higher in energy.

Now let us consider substituting a small percentage of As atoms for some of the Ge . Since As has five valence electrons, it would be rather similar to the above calculation except that we have some extra electrons which must be in the higher (conduction) band. This isn't quite right because the As ions are different from the Ge ions (they have more charge); however, it is true that the Ge doped with As has very similar energy levels as pure Ge and that there are filled states that are close in energy to the conduction band of pure Ge . This is called an n -type semiconductor.

If we substituted gallium Ga atoms (which have three valence electrons) instead, the energy levels would again be quite similar to those in pure Ge , but this time there would be some unfilled levels (holes) in the valence band. This is called a p -type semiconductor.

Now if we brought the As doped Ge (n -type semiconductor) into contact with the Ga doped Ge (p -type semiconductor), we would have electrons in the conduction band on the n -type side and holes in the valence band on the p -type side. We could lower the energy by moving some of the former into the latter. Since the electrons are negatively charged, the current would be from the p -type side to the n -type side. There is also a concentration gradient, i.e. more electrons on one side, more holes on the other, which would lead to a diffusion that from a region of high concentration to one of lower concentration. This effect pushes electrons in the same direction as the energy considerations. In fact, the two are related. The real quantity driving the migration of electrons is the chemical potential.

Before this electron migration started both sides were electrically neutral, but now negative charges are building up on the p side and positive on the

n side. It costs energy to separate charge. So when the gain in energy from moving electrons from conduction to valence bands balances the loss in energy from separating the charges, the current stops. (The current stops when the chemical potential is the same on both sides.)

This process creates a depletion region or depletion zone, and it is important in the operation of diodes.

2. Melissinos, exercise 1.1.

(a) Look up the atomic mass number A , and density ρ of Si and Ge and find the number of atoms per cm^3 .

(b) Assuming that the atoms are in a diamond structure (8 atoms/unit cell) find the lattice spacing.

(c) Find the resistivity of Ge at room temperature if it is doped with 10^{15} atoms/ cm^3 of Sb . Assume a mobility of the donor electrons of $\mu_e = 1200 \text{ Cm}^2/\text{V} \cdot \text{s}$.

(a) From the CRC Handbook we find the mass numbers A and densities ρ for Si and Ge

$$\begin{aligned} A_{Si} &= 28.09 & \rho_{Si} &= 2.33 \text{ g/cm}^3 \\ A_{Ge} &= 72.59 & \rho_{Ge} &= 5.32 \text{ g/cm}^3 \end{aligned} \quad (1)$$

Noting that there are N_A atoms in a mole where N_A is Avogadro's number, we can calculate the number density from the mass density and the atomic mass, as follows

$$\begin{aligned} Si : & \left(\frac{2.33 \text{ g}}{\text{cm}^3} \right) \left(\frac{6.022 \times 10^{23} \text{ atoms}}{28.09 \text{ g}} \right) = 5.00 \times 10^{22} \text{ atoms/cm}^3; \\ Ge : & \left(\frac{5.32 \text{ g}}{\text{cm}^3} \right) \left(\frac{6.022 \times 10^{23} \text{ atoms}}{72.59 \text{ g}} \right) = 4.41 \times 10^{22} \text{ atoms/cm}^3. \end{aligned} \quad (2)$$

(b) Next, from the number density we can calculate the volume of a unit cell which contains 8 atoms in this instance

$$\begin{aligned} V_{cell-Si} &= 8 \text{ atoms} \left(\frac{\text{cm}^3}{5.00 \times 10^{22} \text{ atoms}} \right) = 1.60 \times 10^{-22} \text{ cm}^3; \\ V_{cell-Ge} &= 8 \text{ atoms} \left(\frac{\text{cm}^3}{4.41 \times 10^{22} \text{ atoms}} \right) = 1.81 \times 10^{-22} \text{ cm}^3. \end{aligned} \quad (3)$$

Then from the volume of the unit cell we can calculate the lattice spacing

$$\begin{aligned} a_{Si} &= \left(1.60 \times 10^{-22} \text{ cm}^3\right)^{1/3} = 5.43 \times 10^{-8} \text{ cm} = 5.43 \text{ angstroms}; \\ a_{Ge} &= \left(1.81 \times 10^{-22} \text{ cm}^3\right)^{1/3} = 5.66 \times 10^{-8} \text{ cm} = 5.66 \text{ angstroms}. \end{aligned} \quad (4)$$

(c) First of all we can see by the position of Antimony (*Sb*) on the periodic table that it is a donor and that we are talking about an *n*-type (doped) semiconductor. The intrinsic carrier density n_i of *Ge* calculated at the end of Section 1.1 in *Melissinos* is $10^{13}/\text{cm}^3$; it is much less than donor density N_D given in the problem as $10^{15}/\text{cm}^3$. Therefore, the carrier density of negative charges n is essentially equal to N_D . The carrier density of positive charges is approximately n_i^2/N_D (see *Melissinos*, p. 11) which is very much smaller, and so we will neglect any contribution from positive carriers hereafter.

When only one carrier contributes the conductivity σ is given by

$$\sigma = qn\mu, \quad (5)$$

where q is the charge, n the carrier density, and μ the mobility (see *Melissinos*, p. 13). Thus

$$\sigma = \left(1.60 \times 10^{-19} \text{ C}\right) \left(10^{15} / \text{cm}^3\right) \left(1200 \text{ cm}^2/\text{V} \cdot \text{s}\right) = \frac{0.192 \text{ C}}{\text{V} \cdot \text{s} \cdot \text{cm}}. \quad (6)$$

Converting the cm to m and taking the reciprocal gives the resistivity $\rho = 5.21 \times 10^{-2} \text{ } \cdot \text{m}$.

3. *Melissinos*, exercise 1.3.

Consider germanium doped with $10^{14}/\text{cm}^3$ atoms of arsenic.

(a) Find the conductivity assuming a reasonable value of the mobility of the impurities.

(b) The energy gap of germanium is $E_g = 0.67 \text{ eV}$ and the density of states at the edge of the conduction band can be taken as $N_c = 10^{19}/\text{cm}^3$. Estimate the intrinsic carrier density for germanium at room temperature.

(c) Use the result of (b) to find the density of holes in the doped sample. (Note that part (a) is closely related to part (c) of exercise 1.1.)

(b) I think it is more sensible to answer part (b) first. The intrinsic carrier density n_i is related to the density of states at the edge of the conduction

band N_C through

$$n_i = N_C \exp\left(-\frac{E_g}{2kT}\right). \quad (7)$$

(See *Melissinos*, p. 8.) So

$$n_i = 10^{19}/\text{cm}^3 \times \exp\left(-\frac{0.67 \text{ eV}}{2(\text{eV}/40)}\right) \approx 1.5 \times 10^{13}/\text{cm}^3. \quad (8)$$

(a) Arsenic (*As*) is a donor. The density of donors $N_D = 10^{14}/\text{cm}^3$ is many times larger than the intrinsic carrier density, so the carrier density we need in the calculation of the conductivity ($\sigma = qn\mu$) is approximately the donor density ($n = N_D$). Next we must assume a reasonable value for the mobility of donor electrons in *Ge*. Let us take as an order-of-magnitude approximation $10^3 \text{ cm}^2/\text{V} \cdot \text{s}$. Then

$$\sigma = (1.60 \times 10^{-19} \text{ C}) (10^{14} /\text{cm}^3) (10^3 \text{ cm}^2/\text{V} \cdot \text{s}) = \frac{0.016 \text{ C}}{\text{V} \cdot \text{s} \cdot \text{cm}} = 1.6/ \cdot \text{m}. \quad (9)$$

Using a relationship between the hole and electron densities and the intrinsic carrier density ($np = n_i^2$) and the approximation $n \approx N_D$ led to eq. (1.12) in *Melissinos*, which yields in this particular case

$$p_n \approx \frac{n_i^2}{N_D} \approx 2.3 \times 10^{12}/\text{cm}^3. \quad (10)$$

4. *Melissinos* exercise 1.4.

Make a plot of the Fermi-Dirac distribution at $T = -78^\circ\text{C}$, room temperature, and a $T = 500^\circ\text{C}$ when $E_F = 1 \text{ eV}$.

(Accurate plots are expected. First plot for $0 < E < 2 \text{ eV}$ and then for $0.8 \text{ eV} < E < 1.2 \text{ eV}$.)

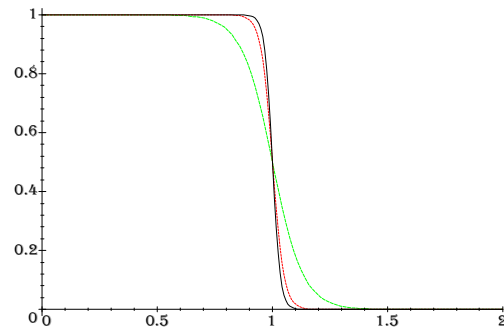
The Fermi-Dirac distribution is given by

$$f(E) = \frac{1}{\exp[(E - E_F)/kT] + 1}, \quad (11)$$

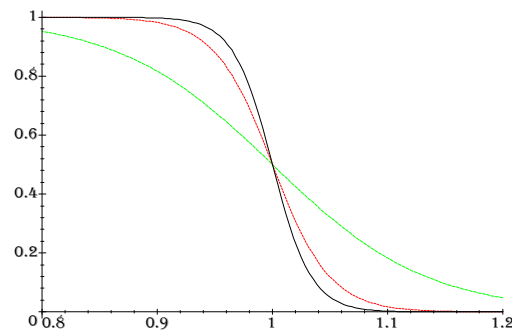
where E_F is the Fermi energy. Let us express kT for the various temperatures in *eV* s:

T (in C)	kT in eV s
-78° C	0.017 eV
17° C	0.025 eV
500° C	0.067 eV

Now let us plot the Fermi distribution for the range $0 < E < 2$
 $1/(\exp((E - 1.0)/0.017) + 1)$



and then in a smaller region surrounding the Fermi energy ($0.8 < E < 1.2$)



This function gives the average number of fermions filling a level with energy E . Because we are talking about fermions, $f(E)$ varies between zero and one. At $T = 0$, $f(E)$ is a step function — equal to one for $E < E_F$ and equal to zero for $E > E_F$.