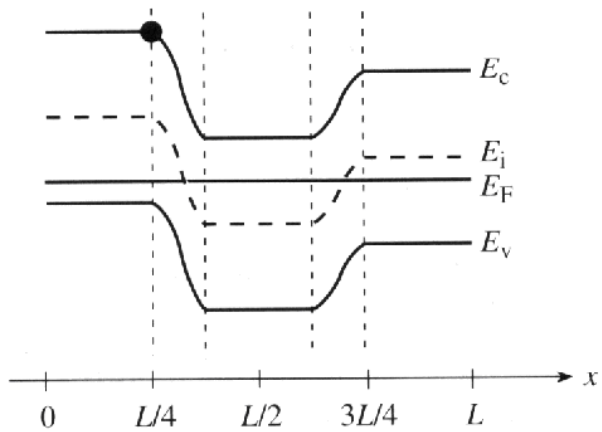
Note that OH has been moved to W 2-3 and F 1-2 in Moore Room per professor's request.

1. A silicon sample maintained at *T*=300K is characterized by the energy band-diagram below:



a) Do equilibrium conditions prevail? How do you know?

Since the Fermi level (E_F) is constant with position, equilibrium conditions prevail.

b) Sketch the electrostatic potential V(x) inside the semiconductor as a function of x.

The electrostatic potential can be drawn by flipping vertically either of E_c, E_i or E_v since

$$V = \frac{-1}{q}(E_c - E_{ref})$$

The reference voltage (E_{ref}) is taken to be such that $V = 0$ at $x = 0$.

c) Sketch the electric field E(x) inside the semiconductor as a function of x.

$\mathcal{E}(x) = \frac{-dV(x)}{dx}$ therefore $\mathcal{E}(x)$ can be determined by plotting the negative slope of $V(x)$.

Alternatively, $\mathcal{E}(x) = \frac{1}{q}\frac{dE_c}{dx}$ so that $\mathcal{E}(x)$ can be determined from the slope of E_c (or E_i or E_v) as a function of position.

d) Suppose the electron pictured in the diagram moves back and forth between x = 0 and x = L without changing its total energy. Sketch the kinetic energy and potential energy of the carrier as a function of x.

Let's take the reference energy level to be E_F: In this case, an electron in the conduction band has potential energy P.E. = $E_c - E_F$. The extra energy of the electron over E_c is its kinetic energy: K.E. = $E - E_c$.

e) Roughly sketch n and p versus x

Under equilibrium conditions, to find n and p, we can use the equations

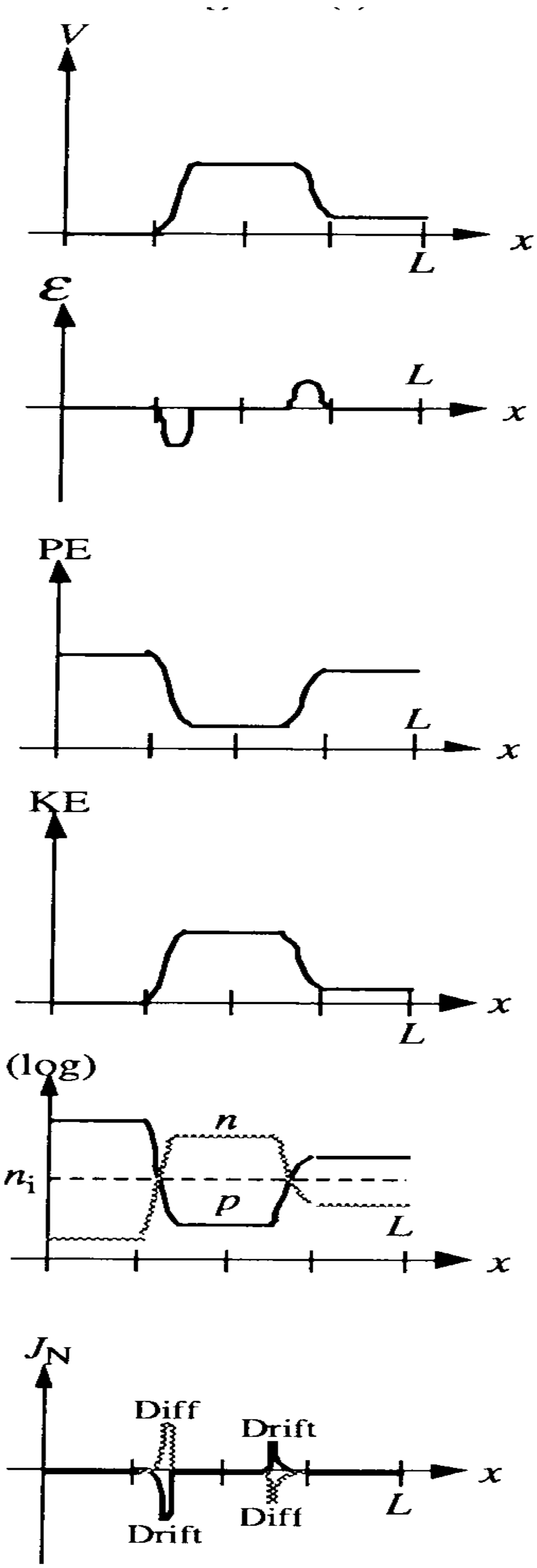
$$n = n_i \exp(E_F - E_i)/kT$$

$$p = n_i \exp(E_i - E_F)/kT$$

For a rough sketch, it is better to keep track of where the material is n-type and where it is p-type so that sketching the carrier concentration profiles becomes easy.

f) On the same set of coordinates, make a rough sketch of the electron drift-current density and the electron diffusion-current density as a function of position. Briefly explain how you arrived at your sketch.

Since $J_{N\,drift} = q\mu_n n\mathcal{E}$, we can plot $J_N(x)$ by forming the product of $\mathcal{E}(x)$ and $n(x)$ sketched earlier. For plotting the electron diffusion current, use the fact that under equilibrium the net current is 0 so that $J_{Ndiff}(x) = -J_{Ndrift}(x)$.


V
x
L
ε
L
x
PE
L
x
KE
x
L
(log)
n
n_i
p
L
x
J_N
Diff
Drift
x
L
Drift
Diff

2. Light of hv = 1.5eV (this is near infrared, at lambda = 826nm) at a power level of 10 mW/cm^2 shines on an intrinsic sample of GaAs of area 1cm^2. Let the electron lifetime be 10ps.

(a) What is the number of photons arriving at the semiconductor surface per second? (Recall W = Pt)

One photon has energy of 1.5 eV, so to produce a power of 10 mW, we require
10mW = N(photons) × 1.5eV / photon × (1.6 ×10−19 J/ eV) / 1s
N = 4.2 × 10^16 photons/s

(b) Verify that photons of this energy can be absorbed.

For the photons to be absorbed, the energy of a photon must be greater than the bandgap. The energy gap of GaAs is 1.43 eV, so these photons can be absorbed.

(c) Assuming every photon is absorbed and creates an electron-hole pair, and assuming the GaAs sample is 1mm thick, what is the optical generation rate? (NOTE: Assume the light is absorbed evenly across the whole volume of the sample for the entire problem.)

There are N=4.2×10^16 photons/sec arriving on an area 1 cm2, and absorbed in a volume 1 cm^2 x 0.1cm=0.1 cm^3. Since each photon produces and electron and a hole, the average optical generation rate is G = N / thickness= 4.2*10^16 photons/s/cm^2 / 0.1cm = 4.2x10^17 e-h pairs/sec/cm3

(d) What are the equilibrium electron and hole densities (in the dark)?

Since the GaAs is intrinsic, n_0=p_0=n_i=2.2×10^6 cm-3.

(e) What are the excess carrier concentrations when the light is on?

Since this is steady state, dn/dt=0. From Equation (3.63) we have

$$\frac{\partial n}{\partial t}=\frac{1}{q}\left(\frac{\partial J_n}{\partial x}\right)+\left(G-\frac{\Delta x}{\tau_n}\right)=0$$

If the photons are uniformly absorbed, there is no diffusion current, and
Δn = Gτ_n =4.2x10^17 cm^-3*s^-1 (10x10^-12 s) = 4.2x10^6 cm^-3.

(f) What are the recombination rates for electrons and for holes when the light is off? When the light is on?

$$R=\frac{n_0}{\tau_n}+\frac{\Delta_n}{\tau_n}$$

When the light is off, n_0=n_i (since this is intrinsic GaAs), or n_0=2.2×10^6 cm-3 and Δn=0.
Roff = n_0/Δn = 2.2×10^6 cm^-3 / 10×10^-12 s = 2.2×10^17 cm^-3*s^-1

When the light is on,
Ron = n_0/τ_n + $\Delta n/\tau_n$ = 2.2×10^17+4.2×10^6 cm^-3 / 10×10^-12 = 2.2×10^17 + 4.2×10^17 = 6.4×10^17 cm^-3 * s^-1.

(g) What are the steady-state carrier densities n and p? (when the light is on)

For electrons we have
$n=n_0+\Delta n=2.2\times10^6$ cm-3 + 4.2×10^6 cm-3$=6.4\times10^6$ cm-3
Since the material is intrinsic, $n_0=p_0=n_i$, and since the excess electrons and holes are created in pairs, $\Delta n=\Delta p$, so
$p=p_0+\Delta p=n_0+\Delta n=n=6.4\times10^6$ cm-3 .

(h) How much does the conductivity of this sample change compared with its dark value?

We know that
$\sigma = q(\mu_n n+\mu_p p) = q(\mu_n n0 + \mu_p p_0) + q(\mu_n \Delta n+\mu_p \Delta p)$
The mobilities for intrinsic GaAs are, from Figure 3.7, μ_n=8000 cm2/V-s and μ_p=400 cm2/V-s.
In the dark, the conductivity is
$\sigma = q(\mu_n n0+\mu_p p_0)$
=1.6x10^-19 C * [8000cm^2/(V*s) * 2.2x10^6 cm^-3 + 400cm^2/(V*s) * 2.2x10^6 cm^-3
= 3.0x10^-9 (Ohms - cm)^-1
When the light is on, the result is
$\sigma = q(\mu_n n+\mu_p p)$
=1.6x10^-19 C * [8000cm^2/(V*s) * 6.4x10^6 cm^-3 + 400cm^2/(V*s) * 6.4x10^6 cm^-3
= 8.6x10^-9 (Ohms–cm)^-1

showing that the conductivity nearly triples when the light is on in this case.

(i) Suppose the power level is kept the same, but the wavelength of light is shifted further into the infrared, at E = hv = 1eV. (lambda = 1240nm). What is the generation rate now?

It is zero. These photons have energy smaller than the band gap and cannot be absorbed.