Tutorial 6 Semiconductor in Non-Equilibrium

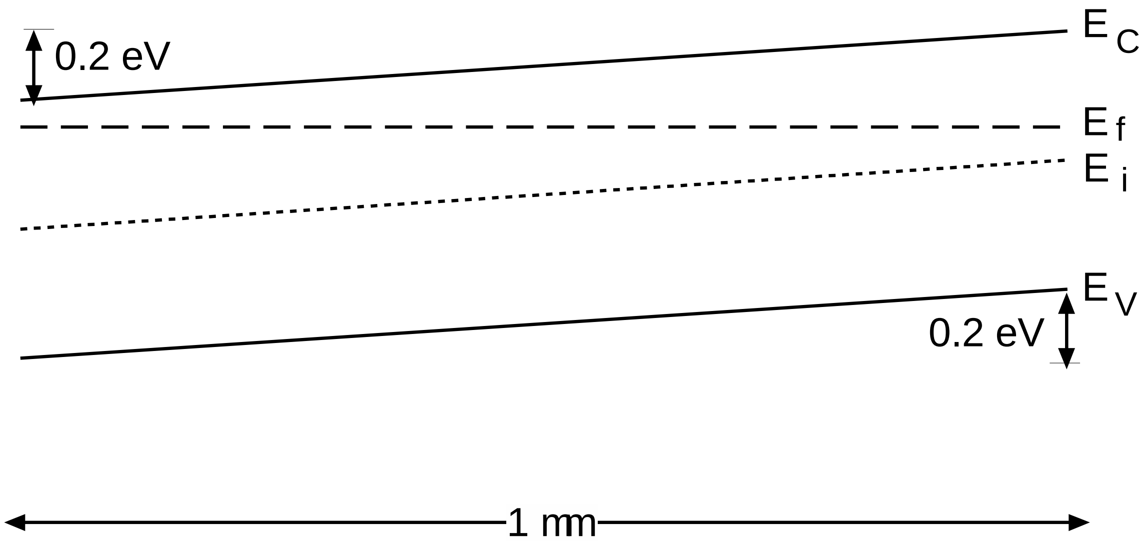
Question 1

The energy band diagram of a semiconductor is shown in the figure below.

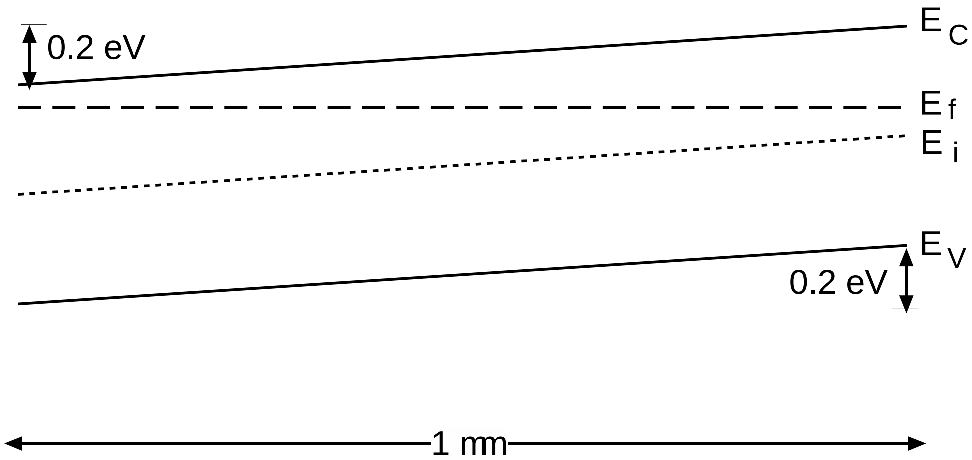
a) What is the effective electric field for electrons?

b) What is the direction of the electron diffusion current?

c) What is the direction of the electron drift current?



Q1



(a) Effective electric field for electrons:

$$\xi_e = \frac{1}{q}\frac{dE_C}{dx} = \frac{1}{1.6\times10^{-19}C}\left(\frac{0.2\ eV\times1.6\times10^{-19}J/eV}{10^{-4}\text{cm}}\right) = 2\ kV/\text{cm}$$

Positive value means pointing to x direction

(b) Direction of the electron diffusion current: Toward the negative x-direction

Electron concentration at the left is higher than that at the right. Electrons diffuse from left to right; diffusion current is from right to left.

(c) Direction of the electron drift current: Toward the positive-x direction

Because ξ_e points to positive direction, electrons are drifted against field. Hence the drift current flows to positive direction.

Question2

A *p*-type silicon sample has an acceptor doping concentration of 1×10^{16} cm^{-3}. It is uniformly irradiated with light of an appropriate wavelength resulting in the generation of electron-hole pairs (EHPs) at a rate of $G_L = 1 \times 10^{17}$ cm^{-3}s^{-1}. Assume a minority carrier lifetime $\tau_n = 10\mu s$.

a) Is the low-level injection condition valid? Justify your answer.

b) What is the maximum EHP generation rate that would ensure that the low-level injection condition remains valid?

Take $n_i = 1.5 \times 10^{10}$ cm^{-3}.

[1×10^{17} cm^{-3}; 1×10^{20} cm^{-3}.s^{-1}]

2a) Justify low level injection

For a p-type semiconductor

$$G_L = \frac{\Delta n}{\tau_n} \text{ @steady state}$$

$$\Delta n_{ss} = \Delta p_{ss} = 10^{17}\ \text{cm}^{-3}\text{s}^{-1} \times 10 \times 10^{-6}\ \text{s} = 10^{12}\ \text{cm}^{-3}$$

$$\text{Since } \Delta n_{ss} = 10^{12}\ \text{cm}^{-3} < 0.1 p_0 \left(= 10^{15}\ \text{cm}^{-3}\right)$$

low-level injection is valid

b) Maximum EHP generation rate, ensuring the validity of low-level injection:

$$\Delta n_{ss} = 0.1\, p_o = 0.1 \times 10^{16}\ \text{cm}^{-3} = 10^{15}\ \text{cm}^{-3}$$

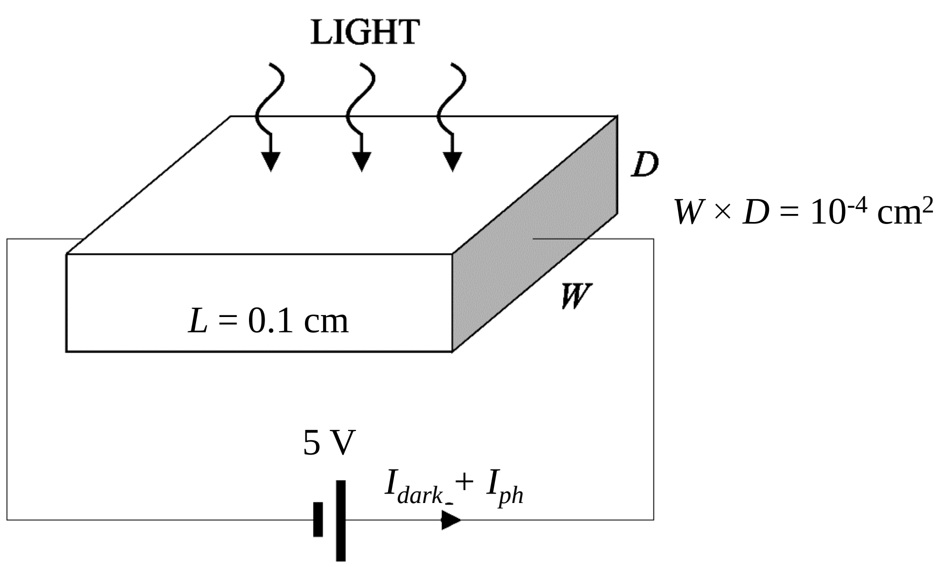
$$\max G_L = \frac{\Delta n_{ss}}{\tau_n} = \frac{10^{15}\ \text{cm}^{-3}}{10 \times 10^{-6}\ \text{s}} = 10^{20}\ \text{cm}^{-3}\text{s}^{-1}$$

Question 3

A silicon sample at 300 K is *n*-type with $N_d = 5 \times 10^{16}$ cm^{-3} and $N_a = 0$. The sample has a length of 0.1 cm and a cross-sectional area of 10^{-4} cm^2. A voltage of 5 V is applied between the ends of the sample.

For $t < 0$, the sample has been illuminated with light, producing an excess-carrier generation rate of 5×10^{21} cm^{-3}s^{-1} uniformly throughout the entire silicon. The minority carrier lifetime is 0.3 µs. At $t = 0$, the light is turned off.

Derive the expression for the current in the sample as a function of time $t \geq 0$. Take $\mu_n = 1350$ cm^2(Vs)$^{-1}$, $\mu_p = 480$ cm^2(Vs)$^{-1}$ and $n_i = 1.5\times10^{10}$/cm^3



[54 + 2.2 exp($-t/\tau_p$) mA]

3) **Derive current *I* versus time *t*.**

I=JA=σξA. Need to find σ(t) and ξ first. $\sigma = q(\mu_n n + \mu_p p)$

For $t < 0$, the excess carriers:

$$\Delta p\,(t=0) = G_L\ \tau_p$$

$$= 5\times10^{21}\ \text{cm}^{-3}\text{s}^{-1}\times0.3\times10^{-6}\ \text{s}^{-1} = 1.5\times10^{15}\ \text{cm}^{-3}$$

For $t > 0$, the excess carriers:

$$\Delta p\,(t) = \Delta p\,(t=0)\exp\left(-\frac{t}{\tau_p}\right) = 1.5\times10^{15}\exp\left(-\frac{t}{\tau_p}\right)$$

$$\text{Conductivity, } \sigma = q\left(\mu_n n + \mu_p p\right)$$

$$= q\mu_n\left(n_0 + \Delta n\right) + q\mu_p\left(p_0 + \Delta p\right)$$

$$\text{Since } \Delta n = \Delta p \quad \text{and} \quad n_0 >> p_0$$

$$\therefore \sigma \approx q\mu_n n_0 + q\left(\mu_n + \mu_p\right)\Delta p$$

$$\sigma \approx q\mu_n n_0 + q\left(\mu_n + \mu_p\right)\Delta p$$

$$\approx 1.6\times10^{-19}(1350)(5\times10^{16}) + 1.6\times10^{-19}(1350+480)(1.5\times10^{15})e^{-t/\tau_p}$$

$$\approx 10.8 + 0.439e^{-t/\tau_p}\,\mathrm{C.cm^2/Vscm^{-3}}$$

$$\approx 10.8 + 0.439e^{-t/\tau_p}\,\Omega^{-1}\mathrm{cm}^{-1}$$

$$I = JA = \sigma\ \xi\ A$$

$$= \left(10.8 + 0.439\,e^{-t/\tau_p}\right)\left(\frac{5}{0.1}\times10^{-4}\right)\ \Omega^{-1}\mathrm{cm}^{-1}\ \mathrm{Vcm}^{-1}\ \mathrm{cm}^2$$

$$= \ 54 + 2.2\,e^{-t/\tau_p}\ \ \mathrm{mA}$$

Question 4

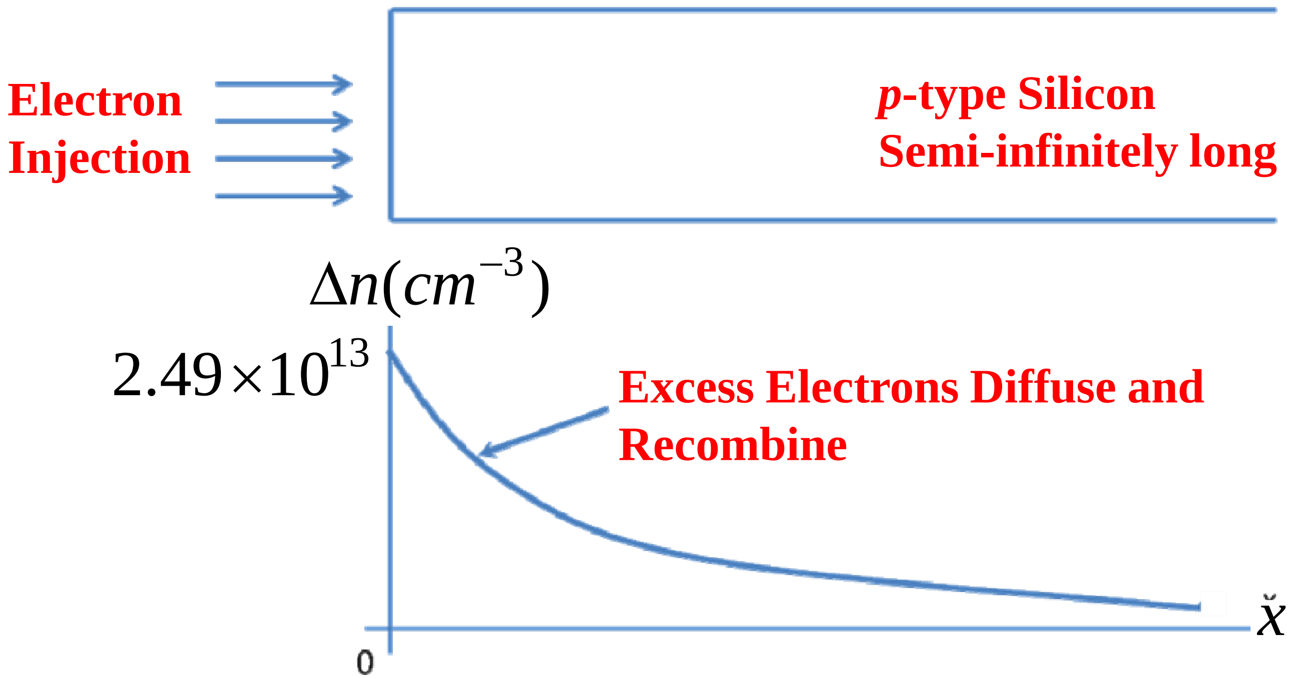
Consider a semi-infinite p-type Si bar doped homogeneously to a value of 1.39×10^{16} cm^{-3}. The applied electric field is zero. A minority carrier concentration is electrically injected at one end of the sample (x = 0) such that the excess minority carrier concentration at x = 0 is 2.49×10^{13} cm^{-3}. The electron lifetime is 1×10^{-6} s.

(a) Write down the expression for the steady state excess electron concentration as function of x.

(b) Calculate the electron diffusion current density at x = 0 and x = 10 μm.

[24.4 mA cm^{-2}; 20.7 mA cm^{-2}]

4) Expression for the steady state excess electron concentration as function of x.



$$\therefore \Delta n(x) = \Delta n(x=0)\exp\left(-\frac{x}{L_n}\right)\text{cm}^{-3}$$

Minority electron carrier diffusion length L_n,

$$L_n = \sqrt{D_n \tau_n} = \sqrt{\frac{k_B T}{q}\mu_n \tau_n} = 6.13\times 10^{-3}\,cm$$

$$\therefore \Delta n(x) = 2.49\times 10^{13}\exp\left(-\frac{x}{61.4\times 10^{-4}}\right)\text{cm}^{-3}$$

(b) Calculate the electron diffusion current density at x = 0 and x = 10 μm.

The minority diffusion current density:

$$J_{n\,diff} = qD_n \frac{dn}{dx} = qD_n \frac{d\left(n_0 + \Delta n\right)}{dx} = k_B T \mu_n \frac{d\Delta n}{dx}$$

$$= -\frac{1.38\times 10^{-23}}{61.4\times 10^{-4}} \times 300 \times 1450 \times 2.49 \times 10^{13} \exp\left(-\frac{x}{61.4\times 10^{-4}}\right) \text{A/cm}^2$$

$$= -2.44\times 10^{-2} \exp\left(-\frac{x}{61.4\times 10^{-4}}\right) \text{A/cm}^2$$

At $x = 0$, $\left|J_{n\ \mathrm{diff}}\right| = 2.44\times 10^{-2}\ \text{A/cm}^2 = 24.4\ \text{mA/cm}^2$

At $x = 10\ \mu\text{m}$, $\left|J_{n\ \mathrm{diff}}\right| = 2.07\times 10^{-2}\ \text{A/cm}^2 = 20.7\ \text{mA/cm}^2$