Tutorial problems for "Solar Energy" lecture (23745), WS 2021/2022

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Tutorial Questions #2: Drift and diffusion current densities; Doping; Charge recombination; Steady-state illumination

1. **Diffusion current density**
   The diffusion coefficient of electrons in silicon is $D_n = 36\ cm^2s^{-1}$. In a silicon layer, the electron density drops linearly from $n = 2.7 \times 10^{16}\ cm^{-3}$ down to $n = 10^{15}\ cm^{-3}$ over a distance of 2 µm. What is the electron diffusion current density $J_{n,diff}$ induced by such a density gradient?

2. **Electron drift flux**
   From the data of exercise 1, what electric field over the gradient zone of 2 µm would be required to compensate the electron diffusion flux with an electron drift flux? The electron mobility in silicon is $\mu_n = 1350\ cm^2V^{-1}s^{-1}$ and the direction of drift to compensate diffusion flux is directed from lower density to higher density.

3. **Doped silicon**
   Consider a slab of silicon crystal 10cm by 10cm by 10cm at room temperature, in the dark. Exactly 1.5×10^{19} phosphorus atoms were added to the crystal when it was still molten, during its growth. The effective conduction band density of states of c-Si can be described as: $N_C \approx 6.2\times 10^{15} \times T^{3/2}\ cm^{-3}$. The effective valance band density of states of c-Si can be described as: $N_V \approx 3.5 \times 10^{15} \times T^{3/2}\ cm^{-3}$. Assume room temperature conditions and that the density of atoms in c-Si is approximately $5 \times 10^{22}\ cm^{-3}$.
   a) Calculate the density of phosphorus atoms in the c-Si slab (cm^{-3}). Calculate the number of phosphorus atoms per million silicon atoms. i.e. ppm.
   b) Calculate the concentration of electrons (n), holes (p) and the intrinsic concentration of charge carriers (n_i). Assume the bandgap is equal to 1.1eV and that all the P atoms are ionized.
   c) Calculate the position of the Fermi level (E_F) in respect to the conduction band edge (E_C).
   d) What 'type' is our c-Si and what are the majority carriers?
   e) Answer question (b) to (d) for the silicon slab after it has been heated to a high temperature (727°C).
   f) Why is silicon a different 'type' at room temperature compared to the higher temperature? Where do the extra holes/electrons come from at high temperature compared to the room temperature?
   g) Draw an energy band diagram and include the position of the Fermi level as a dashed line for both cases. Comment on the position level at room temperature compared to at the high temperature.
   h) A drift current density of $J_{drift} = 110 A/cm^2$ is required in p-type c-Si (hole mobility $\mu_p \approx 470 cm^2V^{-1}s^{-1}$) with an applied electric field of 25V/cm. What doping concentration is required to achieve this current?

4. **Charge recombination process**

   Which of the charge carrier recombination mechanisms below, occurs due to the electron-hole recombination via a defect state in the bandgap?

   a) Radiative recombination
   b) Auger recombination
   c) Shockley-Read-Hall (SRH) recombination
   d) All of the above

5. **Diffusion length**

   The diffusion length is the average length that a carrier moves between generation and recombination. Calculate the minority diffusion length of a minority carrier having a lifetime of $\tau = 10$ µs and minority carrier diffusivity of $D = 25.6$ cm^2/s.

6. **Carrier lifetime**

   The minority carrier lifetime of a material is the average time which a carrier can spend in an excited state after electron-hole generation before it recombines. Calculate the minority carrier lifetime for a single crystalline solar cell having diffusion length of $L =$ 200 µm and minority carrier diffusivity of $D = 27$ cm^2/s.

7. **Steady-state illumination of silicon with no current**

   Consider a 100 µm thick p-doped crystalline silicon wafer illuminated with a monochromatic light at a wavelength of 650 nm as illustrated in Figure 1.
   The optical complex refractive index ($\tilde{n} = n - ik$) of the c-Si at 650 nm is $\tilde{n} = 3.84 - 0.015i$.
   The incident irradiance is 1,000 W/m^2. The
   absorption coefficient α is given by $\alpha = 4\pi k/\lambda$. The diffusion length of minority carriers is $L_n = 60$ µm and the diffusion coefficient of the minority carriers is 29 cm^2s^{-1}.
   Calculate:
   (a) The absorption coefficient at 650 nm.
   (b) The reflectance at interface air/Si (assume $\tilde{n}_{air} = 1$).
   (c) The photon flux after reflection at x = 0 and x = 50 µm.
   (d) The generation rate G_L at x = 50 µm.
   (e) The excess of minority carriers, Δn at x = 50 µm in the p-doped wafer.
   Assume the following steady-state conditions: sample is uniformly illuminated along y direction as shown in Figure 1; dominant thermal recombination and generation process and condition of low injection level and finally there is no current flowing through the wafer, which means:

$$\left.\frac{\partial n}{\partial t}\right|_{\text{diff}} = \left.\frac{\partial p}{\partial t}\right|_{\text{drift}} = 0.$$

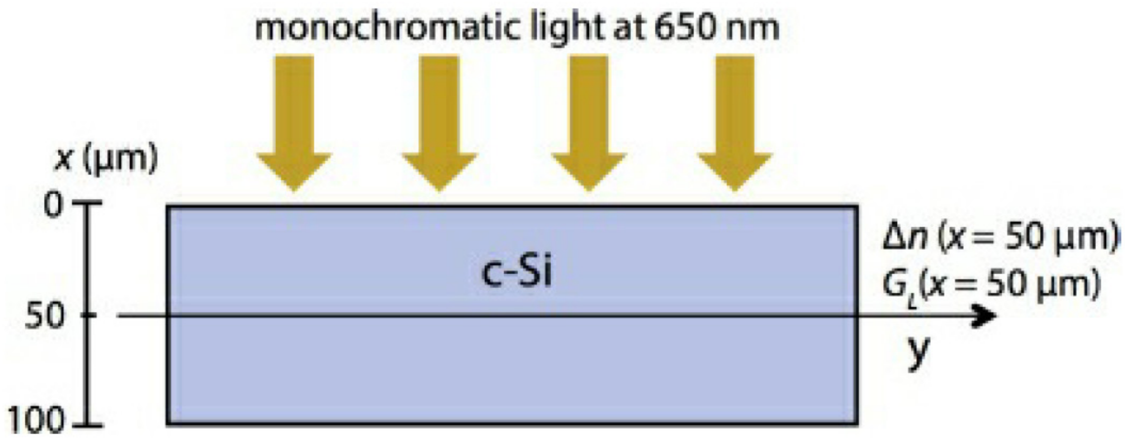

Figure 1: c-Si wafer illuminated with a monochromatic light.