This homework is due on November 8.

**Problem 1** An optical power density of 1 W/cm² is incident on a GaAs sample. The photon energy is 2.0 eV and there is no reflection from the surface. Calculate the excess electron-hole carrier densities at the surface and 0.5 μm from the surface. The $\epsilon$-$\hbar$ recombination time is $10^{-8}$ s.

**Problem 2** Consider a long Si $p$-$n$ junction with a reverse bias of 1 V at 300 K. The diode has the following parameters:

- Diode area, $A = 1 \text{ cm}^2$
- $p$-side doping, $N_a = 3 \times 10^{17} \text{ cm}^{-3}$
- $n$-side doping, $N_d = 10^{17} \text{ cm}^{-3}$
- Electron diffusion coefficient, $D_n = 12 \text{ cm}^2/\text{s}$
- Hole diffusion coefficient, $D_p = 8 \text{ cm}^2/\text{s}$
- Electron minority carrier lifetime, $\tau_n = 10^{-7} \text{ s}$
- Hole minority carrier lifetime, $\tau_p = 10^{-7} \text{ s}$
- Optical absorption coefficient, $\alpha = 10^3 \text{ cm}^{-1}$
- Optical power density, $P_{op} = 10 \text{ W/cm}^2$
- Photon energy, $\hbar \omega = 1.7 \text{ eV}$

Calculate the photocurrent in the diode.

**Problem 3** Consider a long Si $p$-$n$ junction solar cell with an area of 4 cm² at 300 K. The solar cell has the following parameters:

- $n$-type doping, $N_d = 10^{18} \text{ cm}^{-3}$
- $p$-type doping, $N_a = 3 \times 10^{17} \text{ cm}^{-3}$
- Electron diffusion coefficient, $D_n = 15 \text{ cm}^2/\text{s}$
- Hole diffusion coefficient, $D_p = 7.5 \text{ cm}^2/\text{s}$
- Electron minority carrier lifetime, $\tau_n = 10^{-7} \text{ s}$
- Hole minority carrier lifetime, $\tau_p = 10^{-7} \text{ s}$
- Photocurrent, $I_L = 1.0 \text{ A}$
- Diode ideality factor, $m = 1.25$

Calculate the open circuit voltage of the diode. If the fill factor is 0.75, calculate the maximum power output.
Problem 4 Consider a GaAs $p-n^+$ junction LED with the following parameters at 300 K:

- Electron diffusion coefficient, $D_n = 25 \text{ cm}^2/\text{s}$
- Hole diffusion coefficient, $D_p = 12 \text{ cm}^2/\text{s}$
- $n$-side doping, $N_d = 5 \times 10^{17} \text{ cm}^{-3}$
- $p$-side doping, $N_a = 10^{16} \text{ cm}^{-3}$
- Electron minority carrier lifetime, $\tau_n = 10 \text{ ns}$
- Hole minority carrier lifetime, $\tau_p = 10 \text{ ns}$

Calculate the injection efficiency of the LED assuming no trap-related recombination.

Problem 5 The diode in Problem 4 is to be used to generate an optical power of 1 mW. The diode area is 1 mm$^2$ and the external radiative efficiency is 20%. Calculate the forward bias voltage required.

SOME IMPORTANT ISSUES DISCUSSED

- The Metal-Semiconductor Junction: The metal-semiconductor junction is an extremely important component of the semiconductor technology. In some devices such as the Schottky barrier diodes, this junction forms the entire device. In others such as field effect transistors, this junction forms the gate contact. And it is important to note that the metal-semiconductor junction is also the basis of the ohmic contact. In an ohmic contact the resistance of the junction is extremely small. This allows one to pass current through a semiconductor device with minimal potential drop at the junction.

  In general, when a metal is placed on a semiconductor, there is a potential barrier that develops between the metal Fermi level and the conduction or valence bandedge of the semiconductor at the junction. Under ideal conditions (no bandgap states), this barrier called the Schottky barrier, $\phi_b$ would simply be given by the work function difference between the metal and the semiconductor. However, in real junctions, there are always a lot of bandgap states at the interface and the value of $\phi_b$ is more or less fixed, regardless of the metal that is used.

  When a metal-semiconductor junction is used as a Schottky barrier, the value of $\phi_b$ should be as large as possible. This is not always possible, and in such cases one cannot make high quality Schottky diodes. The reason we want the barrier to be as large as possible is to reduce the reverse current in the diode.
In an ideal Schottky diode the Schottky barrier height for an n-type and p-type diode can be made different by using different metals. However, in real diodes, since the Schottky barrier height is fixed by the position of the defect levels in the bandgap, the sum of the n-type and p-type heights is very close to the bandgap

$$\phi_d(n\text{-type}) + \phi_d(p\text{-type}) \sim E_g$$

**Operation of the Schottky Barrier Diode:** The operation of the Schottky Barrier Diode is very similar to that of the p-n diode except for some important differences. The similarities are:

i) Depletion width: The expression for the depletion width in presence (absence) of a bias is similar. *Note that the entire depletion width is on the semicon ductor side since the metal has an extremely high free electron density.*

ii) Capacitance-voltage relations: This relation is also similar for the junction capacitance.

The differences are:

i) The current is carrier by majority charge only. Thus in an n-type diode, the current is controlled by the electron flow from the semiconductor to the metal. There is essentially no hole current flow.

ii) Because there is no minority charge injection in any part of the semiconductor, the device speed is not controlled by minority carrier lifetime. The speed is controlled by the time taken by electrons or holes to move through the device. Thus the device can be extremely fast.

iii) The reverse saturation current in the Schottky diode is much larger than that in a p-n diode. This is primarily because the p-n diode built-in voltage can be quite large compared to the Schottky barrier height. Due to this the turn-on of the Schottky diode occurs at a smaller voltage than that of a p-n diode using the same semiconductor.

**Optoelectronic Devices**

This week we have examined several optoelectronic devices (discussed in Chapter 11 of the text). The key devices are: (i) devices that convert optical energy into an electronic signal (detectors, solar cells); (ii) devices that convert an electrical signal into an optical signal (light emitters).

**Detector:** When light shines on a semiconductor it creates electron-hole pairs if the light particle (photon) energy is larger than the bandgap of the semiconductors i.e

$$h\omega = \text{photon energy} \geq E_g$$

This gives a cutoff wavelength ,$$\lambda_c$$, above which there is no absorption of light

$$\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)} \mu m$$
Here $\hbar = \frac{\hbar}{2\pi}$ and $c$ is the velocity of light. For example, if the bandgap is 1.0 eV, the cutoff wavelength is 1.24 $\mu$m.

The rate at which electron-hole pairs are generated is given by

$$G_L = \frac{\alpha P_{op}}{\hbar \omega}$$

where $\alpha$ is the absorption coefficient for light of frequency $\omega$.

Detectors are p-n diodes that are reverse biased. Electron-hole pairs produced in the depletion region or within a diffusion length of the depletion region are swept by the electric field in the depletion region and produce a photocurrent. The photocurrent is given by

$$I_L = e G_L A (W + L_n + L_p)$$

where $A$ is the detector area, $W$ is the depletion width, and $L_n$, $L_p$ are the depletion lengths.

In a solar cell the optically generated current and voltage are used to create electrical power. The open circuit voltage in a solar cell is given by

$$V_{oc} = \frac{n k_B T}{e} \ln \left( 1 + \frac{I_L}{I_0} \right)$$

where $I_0$, $n$ are the diode current prefactor and ideality factor (in dark).

Solar cells can usually produce a power equal to

$$P \sim 0.7 \times V_{oc} \times I_L$$

**Light Emitters: LEDs and Laser Diodes**

In order to produce an optical signal a p-n diode is forward biased. This causes electrons from the n-side to diffuse into the p-side and holes from the p-side to diffuse into the n-side. These carriers then recombine with holes (electrons) and emit light with an energy

$$\hbar \omega \sim E_g$$

For a light emitter to work efficiently we must have the following considerations:

(i) Non-radiative recombination rate should be much smaller than the radiative recombination rate. This requires a high purity material and a direct bandgap material;

(ii) The emitted photons should be able to come out of the device and not be re-absorbed in the device. This can be accomplished by designing the diode so the emission is close to the surface.
In a laser diode one incorporates a high quality mirror which reflects the emitted photons back into the p-n diode. As a result photon intensity inside the device can become very high. A phenomena called stimulated emission then becomes very dominant. In stimulated emission the radiative recombination rate becomes very high for those photons which are built up in the cavity due to the presence of the mirror. Also the light that is emitted is very coherent i.e has a well defined frequency and wavelength.

Stimulated emission only starts after there is a sufficient build-up of photons in the laser cavity. Thus at low forward bias the laser is just like a LED. But above a threshold forward current the laser emission is highly coherent.