EE119 Homework 8: Photodiodes, Solar Cells, and CCDs

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Due Friday, April 3, 2009

1. Draw a diagram of a p-n junction. Label the p-type material and the n-type material. Draw an arrow in the direction of the built-in E-field and explain why p-n junctions have an e-field. If a photon was absorbed by the p-n junction, In which directions would the electron and hole travel after they have been separated by the photon energy? Clearly label these directions on your diagram.

   Solution:

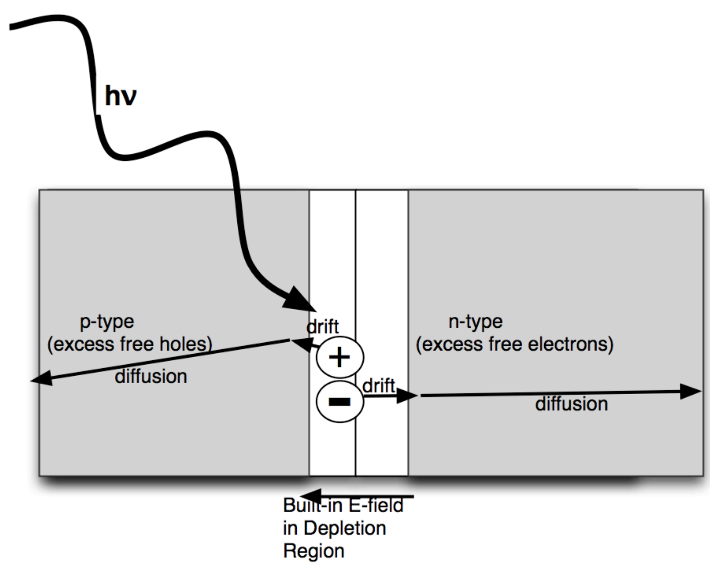

Figure 1: a p-n junction working as a solar cell. The hole travels through the p-type material to an electrode, and the elecron travels through the n-type materials. The built-in E-field is due to diffusion of holes and electrons accross the junction, giving rise to a slightly positive charge on the n-type material and a slightly negative charge on the p-type. The depletion is so-called because there are no free carriers in it–all the carrier have recombined with the ones that diffused from the other side of the junction.

2. In order to detect light from a Nd:YAG laser at 1064 nm wavelength, what is the maximum energy gap of the detector material?

   Solution:

$$\frac{1240}{1064} = 1.16\text{eV}$$

3. Semiconductor Photodiodes

   For a particular PIN photodiode, a pulse of light containing 5×10^{12} incident photons at wavelength of 1.55 μm gives rise to, on average, 1.5 x 10^{12} electrons collected at the terminals of the device.

   (a) What is the energy incident to the photodiode? What is the quantum efficiency of the photodiode?

   Solution:

   The energy in each photon is 1240 eV$\times$nm/1550 nm=0.8 eV. The incident energy of the pulse is 0.8 eV/photon $\times 5 \times 10^{12}$ photons=4×10^{12}eV= 6.4×10^{-7} Joules. The quantum efficiency is the fraction of photons that contribute to the current, so it is just equal to 1.5/5=0.3.

   (b) The diffusion length of a charge carrier is the distance that it will travel, on average, before it recombines with another oppositely charged carrier and stops carrying any current. The diffusion length of charge carriers is 0.5 μm in this detector. The detector is roughly a circle with a 0.5 μm radius. (Making the detector any larger would mean that you lose a lot of carriers before they reach electrodes). If the electron diffusion velocity is 7 $\times10^6$ cm/s, estimate the response time of the detector (do not take drift into account).

   Solution:

   A charge carrier (hole or electron) must travel 0.5μm at the diffusion velocity to reach an electrode, and this will take 0.5×10^{-6} m/7×10^4 m/s $\approx 0.07 \times 10^{-10}$s=7ps.

   (c) The thickness of the intrinsic layer in the photodiode is typically about 2.5 μm. If the drift velocity of the electrons in this region is 10^7 cm/s, estimate the response time of the detector (do not take diffusion into account).

   Solution:

   The electrons have to drift through 2.5×10^{-6}m at a speed of 10^5m/s, and the time this would take is 1.5×10^{-11}s=25 ps.

   (d) Estimate the response time of the detector taking drift and diffusion into account.

   Solution:

   The carriers have to drift through the active layer and then diffuse to an electrode once they reach the doped semiconductors, so the response time of the detector is the sum of the drift and diffusion response times, or approximately 7+25=32 ps.

4. You've developed a way to make really cheap solar cells that absorb the same fraction of the solar spectrum as silicon. However, the material you're using has a drawback, because it can only generate 0.8 eV of energy per photon absorbed (as opposed to 1.1 eV for silicon).

   (a) What is the maximum generation current for your solar cell material?

   Solution:

   The maximum generation current is the same as that for silicon, which is given in the notes on p. 65 to be 44 mA/cm^2. This is because the material absorbs the same number of photons.

   (b) What is the maximum amount of power per area you will get out of your cell?

   Solution:

The maximum amount of power will be the generation current times the voltage of each electron, so it would be 0.8V$\times$ 44 mA/cm^2=35.2 mW/cm^2.

(c) What fraction of the total intensity coming from the sun will your solar cell harness? The "standard" intensity of sunlight, according to p. 68 of our lecture notes, is 100 mW/cm^2. So your solar cell can capture $\sim$35% of the sun's intensity. Real solar cells do much worse than this because of all sorts of losses and inefficiencies.

5. We have a CCD camera with 242 pixels (vertical) by 350 pixels (horizontal), operating at a video frame rate of 30 frames per sec, and each pixel is made with a MOS structure. The size of the CCD is 4.8mm (V) by 6.4mm (H). The CCD is saturated when the incident power density is 0.05 μW/cm^2 at the wavelength of 630nm. The quantum efficiency at that wavelength is 56%. You can ignore the gap between each pixel.

(a) The potential well in a CCD pixel will continue to collect all available electronic charges until it is filled with electrons. When this potential well is completely filled with charges, this is the saturation point of the detector and this is the maximum capacity of the potential well. Calculate the maximum well capacity of the CCD (in # of electrons).

Solution:

We want to calculate how many electrons can fill up in the CCD. Each pixel has an area (in square meters) of

$$A = \frac{4.8 \times 10^{-3}}{242}\frac{6.4 \times 10^{-3}}{350} = 3.6 \times 10^{-10}$$

which is equal to 3.6$\times$10^{-6} cm^2. So the total power hitting a single pixel is 0.05 μ W/cm^2 $\times$ 3.6 $\times$ 10^{-6} cm^2=0.18 μ W=0.18$\times$10^{-6} Joules/second$\cdot$ pixel. The CCD operates at a frame rate of 30 frames per second, so the light is collected for approximately 1/30 of a second (ignoring the time it takes to read out the charge from the CCD, during which the shutter would be closed).

This means that the amount of energy hitting a pixel is 0.18$\times$10^{-6} Joules/second $\times$ 1/30 seconds=0.006 $\times$10^{-6} Joules=6$\times$10^{-9}J. The energy in one photon is 1240 eV$\cdot$ nm/630 nm=1.97 eV=3.15 $\times$ 10^{-19}, so the number of photons striking the CCD in one frame interval is 6$\times$10^{-9}/3.15 $\times$ 10^{-19} = 1.9 $\times$ 10^{10} photons.

The quantum efficiency is 56%, meaning that we get 0.56 electrons in the well photon in. This gives a maximum well capacity of 1.066$\times$10^4 electrons.

We know that the maximum number of photons that can be absorbed has an energy density

(b) Now, we want to use that CCD to detect radiation from a laser with wavelength of 193nm. The quantum efficiency at that wavelength is 3%, and the maximum well capacity is the same as what you calculated in part (a). What is the saturation power density for this application?

Solution:

We can still get 1.07$\times$10^4 electrons in a pixel, but now this represents only 0.03 of the total power, so we will need more power. We'll also need more power because 193 nm light has more energy per photon. We can just take the saturation power from the previous problem and apply a few conversions

$$P_{\text{sat}} = \frac{0.05\mu W}{cm^2}\frac{0.56}{0.03}\frac{630}{193} = \frac{3.046\mu\text{W}}{\text{cm}^2}$$