Columbia University
Department of Electrical Engineering
Solid State Devices and Materials
ELEN E3106/4106
Homework #6

Due: Saturday, October 25th by 11:59pm
Goal: Practice solving practical problems in optoelectronic devices based on photoconductive semiconductors and p-n junctions. Device applications include solar cells, photodetectors, and semiconductor lasers. Test basic understanding of key device fabrication processes.
Instructions: Show your work and include units in answers for full credit. Unless stated otherwise, make the assumptions we have been taking in class (the sample is at 300 K) and anti-reflective coating has 100% efficiency (the reflection from the surface of the semiconductor is neglected).
Circle or box your final answer.
Points: 110 pts for 3106. 130 pts for 4106.

- **Problem 1 (20 pts)** Plotting solar cell $I\text{–}V$ characteristics.

Remember to label axes, including units.

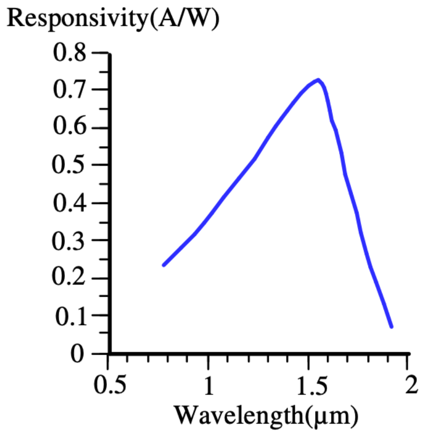
(a) A Si solar cell with a dark saturation current I_{th} of 5 nA is illuminated such that the short-circuit current is 200 mA. Plot the $I\text{–}V$ curve for the cell as in Fig. 8–6 in your textbook. (Remember that I is negative, but is plotted positive as I_r.)
(b) A major problem with solar cells is internal resistance, generally in the thin region at the surface, which must be only partially contacted, as in Fig. 8–5. Assume that the cell of (a) has a series resistance of 1 Ω, so that the cell voltage is reduced by the IR drop. Replot the $I\text{–}V$ curve for this case.
(c) How does the cell in (b) compare with the cell in part (a)?
(d) Solar cells are severely degraded by unwanted series resistance. For the cell described in (b), include a series resistance R, which reduces the cell voltage by the amount IR. Calculate and plot the fill factor for a series resistance R from 0 to 5 Ω.
(e) Comment on the effect of R on cell efficiency.

- **Problem 2 (30 pts)** Band gap and photodetection.

(a) Determine the maximum value of the energy gap (bandgap) which a semiconductor, used as a photodetector, can have if it is to be sensitive to yellow light (600 nm).
(b) A photodetector whose area is 6×10^{-2} cm² is irradiated with yellow light whose intensity is 3 mW cm^{-2}. Assuming that each photon generates one electron-hole pair (EHP), calculate the number of EHPs generated per second. (Hint: # of incident photons per second is equal to the optical power divided by the energy of a photon. 1 W = 1 J/s)
(c) From the known energy gap of the semiconductor GaAs (Eg = 1.42 eV), calculate the primary wavelength of photons emitted from this crystal as a result of electron-hole recombination.
(d) Is this wavelength in the visible?
(e) Will a silicon photodetector be sensitive to the radiation from a GaAs laser? Why?

- **Problem 3 (20 pts)** Photodetector properties.

Consider a commercial Ge p-n junction photodiode which has the responsivity shown in the figure below. Its photosensitive area is 0.008 mm². It is used under a reverse bias of 10 V when the dark current is 0.3 μA and the junction capacitance is 4 pF. The rise time of the photodiode is 0.5 ns.



(a) Calculate its responsivity and quantum efficiency at 850, 1300 and 1550 nm. Fill in the table below.

Wavelength (nm)	**850**	**1300**	**1550**
Responsivity (A/W)			
η_{QE} **(%)**			

(b) What is the intensity (optical power/unit area) of light at 1.55 μm that gives a photocurrent equal to the dark current?

(c) If the temperature is lowered, will the peak of the responsivity curve shift to the left or to the right? Why? (Hint: what happens to the bandgap?)

(d) Suppose that the photodiode is used with a 120 Ω resistance to sample the photocurrent. What is the RC time constant? How does this compare to the rise time (e.g. which will limit the speed of response)?

- **Problem 4 (20 pts)** Photodetector properties.

(a) In a compound $Al_xGa_{1-x}As$ material, calculate the energy band gap for the Al concentration of 0.45 using linear interpolation method (Vegard's law) at 300 K temperature. Bandgaps can be found in Appendix III of your textbook.

(b) Calculate the minimum carrier concentration n = p for population inversion in the AlGaAs at 300 K if the intrinsic carrier concentration is $2.1 \times 10^3\ cm^{-3}$.

- **Problem 5 (10 pts)** Multiple choice questions on device fabrication.

5.1 Which one of the following parameters is **not** associated with photolithography?

(a) Resolution

(b) Accuracy
(c) Etch rate
(d) Exposure Field

5.2 Which one of the following methods is used for doping semiconductors?
(a) Atomic layer deposition
(b) Electron beam evaporation
(c) Thermal oxidation
(d) Ion implantation

5.3 What do we call the end product that we pull out of the melt in the Czochralski growth method?
(a) Ingot
(b) Wafer
(c) Thin film
(d) Dielectric

5.4 To create a metal junction on a semiconductor, which technique would be use?
(a) Thermal oxidation
(b) Sputtering
(c) Metal organic chemical vapor deposition
(d) Reactive ion etching

- **Problem 6 (Required for 4106 students ONLY, 20 pts)** Optoelectronics diodes.
  (a) When a light-emitting diode (LED) is turned on (*i.e.* forward biased), minority carriers are injected into the quasi-neutral regions, where they subsequently recombine with majority carriers. Because the LED is made using a direct band-gap semiconductor material, a photon is emitted whenever an electron and hole recombine. Recall the wavelength of the emitted photon is dependent on the band-gap energy E_G (in eV):

$$\lambda \cong \frac{1.24}{E_G}$$

  In words: the larger the energy band gap, the larger the energy of the emitted photon and hence the shorter the wavelength of the emitted light. Recall that the visible spectrum spans the wavelength range from ~400 nm (violet) to ~700 nm (red). How would you expect the LED bias voltage for a given forward current (e.g. 1 mA) to change with the LED color? Does a red or blue LED require a lower bias voltage? Explain briefly.

  (b) In order to maximize the amount of power that can be generated by a pn-junction solar cell, would you design the quasi-neutral regions to be "long" or "short"? Should the quasi-neutral regions be lightly doped, or heavily doped? Provide physical explanations for your answers (without using any equations or formulas).