EE 529 Homework #4 (due on 5/19/2016)

1. (20%) An InGaAs photodetector for \( \lambda = 1.3 \, \mu m \) has a responsivity of \( R = 0.8 \) (A/W), a specific detectivity \( D^* = 7 \times 10^{10} \, \text{cm} \cdot \text{Hz}^{1/2} \cdot \text{W}^{-1} \), a bandwidth of \( B = 2.5 \, \text{GHz} \), and a dynamic range \( DR = 60 \, \text{dB} \). It has a circular active area of 80 \( \mu m \) in diameter. The total resistance including the load is \( R = 50 \, \Omega \). The dark current and the background radiation current of the detector are not known.
(a) What is the NEP of this photodetector? What is the photocurrent at this power level?
(b) What is the saturation optical signal power for this photodetector? What is the photocurrent at this power level?
(c) What is the SNR at the saturation power level of this photodetector? Does the photodetector operate in the quantum or thermal regime at this power level?
(d) What is the risetime of the detector response to an impulse signal?

2. (5%) Continue to work on the problem about solution-processed quantum dot photoconductors discussed in Slide 4 of “Photodetectors and Solar Cells.” Please express NEP in units of fW and noise current rms(\( i_n \)) in units of pA.

3. (20%) (a) Show that the space-charge effect can appear if the length of the photoconductor considered in the exercise on Slide 8 of “Photodetectors and Solar Cells” is reduced to \( l = 10 \, \mu m \) while all other parameters remain unchanged. The photoconductor is biased at 2V. Find the optical signal power range for which the device is free of the space charge effect. (b) Find the gain and the responsivity of the photoconductor for the optical signal powers in both cases: photoconductor free of the space charge effect and photoconductor limited by the space charge effect. For the latter case, use the dark conductivity to calculate the dielectric relaxation time.

4. (20%) In this problem, we compare the performance of Si and GaAs p-i-n photodiodes that have the same physical structures for optical detection at 850 nm wavelength. Both have the same i-region thickness \( d_i = 3 \, \mu m \) and the same active-area diameter \( 2r = 40 \, \mu m \). Both are reverse-biased at 3V. Take \( R_L + R_j = 50 \, \Omega \) and \( C_p = 0 \) for both devices.
(a) At 300K and under 3V reverse bias, Si has the following parameters: \( \alpha = 7 \times 10^4 \, \text{m}^{-1} \), \( v_e = 8 \times 10^4 \, \text{m/s} \), \( v_h = 3.2 \times 10^4 \, \text{m/s} \), and \( \varepsilon = 11.8\varepsilon_0 \). Find the 3-dB cutoff frequency, \( f_{3dB} \), and the internal bandwidth-efficiency product, \( f_{3dB} \eta_l \), for the Si p-i-n photodiode.
(b) At 300K and under 3V reverse bias, GaAs has the following parameters: \( \alpha = 1 \times 10^6 \, \text{m}^{-1} \), \( v_e = 1.2 \times 10^5 \, \text{m/s} \), \( v_h = 1.7 \times 10^4 \, \text{m/s} \), and \( \varepsilon = 13.18\varepsilon_0 \). Find the 3-dB cutoff frequency, \( f_{3dB} \), and the internal bandwidth-efficiency product, \( f_{3dB} \eta_l \), for the GaAs p-i-n photodiode.
(c) Compare the performance of these two devices. Which one has higher \( f_{3dB} \eta_l \)? Why?
(Note: In this problem, the bias is not high enough to achieve saturation velocities, and the hole velocity in GaAs is slower which limits its bandwidth. In general, high-speed p-i-n photodiodes are operated with saturation velocities for both electrons and holes. GaAs has higher saturation velocities, and GaAs p-i-n photodiodes are typically faster than Si p-i-n photodiodes.)
5. (15%) Under illumination, a GaAs solar cell with a dark saturation current \( I_s = 0.5 \text{ nA} \) produces a short-circuit current \( I_{SC} = 100 \text{ mA} \). Estimate the value of the maximum voltage \( V_m \) and maximum current \( I_m \).

6. (20%) (a) The intensity of light arriving at a point on earth, where the solar latitude is \( \alpha \), can be approximated by the Meinel and Meinel equation

\[
I \approx 1.353(0.7)^{\alpha}\sin(\alpha)^{-0.74} \quad \text{(kW m}^{-2} \text{)}
\]

The solar latitude \( \alpha \) is the angle between the sun rays and the horizon as shown in the figure. Around March 22\textsuperscript{nd} and September 23\textsuperscript{rd}, the sun rays arrive parallel to the plane of the equator. Plot intensity \( I \) vs. \( \alpha \). What is the maximum power available for a solar panel of area 1 m\(^2\) if its power conversion efficiency is 20%? (b) Manufacturer’s characterization tests on a particular Si p-n junction solar cell at 300K specifies \( V_{OC} = 0.45 \text{ V} \) and \( I_{SC} = 400 \text{ mA} \) when illuminated directly with light of intensity 1 kW m\(^{-2}\). The fill factor of the solar cell is 0.73. This solar cell is to be used in a portable equipment application near Eskimo Point (Nunavut, Canada) at a latitude (\( \phi \)) of 63\(^\circ\). Calculate \( V_{OC} \) and the maximum available power when the solar cell is used at noon on September 23\textsuperscript{rd}, when the temperature is around -10\(^\circ\)C. What is the maximum power this solar cell can generate? (Note: Assume the dependence of the dark current \( I_s \) on temperature is only through the exponential dependence on temperature for \( n_{p0} \) and \( p_{n0} \), the bandgap energy \( E_g \) (= 1.1 eV) and the fill factor remain the same when reducing the temperature from 300K to -10\(^\circ\)C, the temperature dependence of the effective density of states at the band edge is negligible compared to the exponential dependence.)