**ECEG287: OPTICAL DETECTION** **14 April 2004**

## Take–Home Final Exam

### General Instructions

**Offsite students may use the courier on the due date, submit good electronic copy as an e–mail attachment, or submit by mail or courier service with a postmark by the due date.**

Do not collaborate with other students or seek help from outside experts. However, you may use any reference book, journal articles, or other readily available resources. Please cite references if you do so.

If you have any questions, no matter how simple, please contact us rather than discussing anything with another student or an outside source. For example, if you are confused about the wording of a question, or if you don't understand what is expected from you, or if you simply do not understand the definition of a word, contact us.

We will not, of course, give out answers, but will clarify the wording of the problems, or correct an error in the questions if someone should find one. If someone finds an error or something which is unclear, we will post the question and answer on the web for all to see.

**You must sign and submit the cover page which is the last page of this document, as the first page of your submission.**

You will want to use a computer for some of the problems. You may use any language you like, but make sure that the equations and graphs are presented in such a way that we don't need to look at your code. When we ask for a plot, we are looking for a correctly labelled one, with correct numerical values. A sketch is not sufficient.

Present your work as clearly as possible. We can give partial credit if we can figure out that you know what you are doing. We do not give credit for putting down everything you know and hoping we will find something correct in it.

**To simplify the grading process, please staple each problem together and submit your cover sheet and the four solutions, bound together, either with a clip or in an envelope.**

# Problem 1. Thermal Imaging.

Consider an infrared imager with pixels which are 20 microns square, and an acquisition time of 1/30 second, and a cooled pupil limiting the solid angle to $\pi$ steradians. Assume that there is a cooled filter in the camera, which has a passband from 8 to 12 micrometers.

a. Plot the spectral radiant exitance of an object at 300K.

b. Write an equation for the radiant exitance of this object, in the detector's passband. Do this by calculating the spectral radiant exitance at 10 micrometers and multiplying by $\Delta\lambda$. In view of your plot in Part a, does this seem reasonable? Evaluate for these parameters.

c. Write an equation for $dN/dT$, the derivative of the number of photons with respect to the object's temperature.

d. Write an equation for the number of photons incident on a pixel from this object. Evaluate for these parameters.

e. Now, from Part c, we have a relationship between signal photons (and thus, detected charge) and temperature. The most optimistic situation is that the noise is limited by quantum fluctuation of the photon count. Write an equation for the noise–equivalent temperature change, which is the temperature change that produces a signal change equal to the noise. Evaluate for the parameters of the problem. Comment on the ways in which the result depends on detector area, optical passband, and electrical bandwidth.

# Problem 2. DOT System.

In diffuse optical tomography, a modulated laser is introduced *via* an optical fiber, to a tissue sample. Light passes through the tissue with much scattering and eventually is either absorbed or finds its way out of the tissue. A reasonable way to characterize a particular tissue sample, with a particular input location, is to define a reflectance as the output radiance, divided by the input power. This reflectance, therefore, has units of $cm^{-2}sr^{-1}$. It will, of course, be a function of the modulation frequency, as well as the wavelength of the laser light, the location of the collecting fiber, and the optical properties of the tissue.

Now, suppose that I have a 50–mW source, and a collecting fiber with an acceptance angle of 20 degrees and a core diameter of 200 micrometers.

The detector is an avalanche photodiode package, with a built–in amplifier and power supply, Hammamatsu model C5331–03. The detector has an active area of 1 mm diameter, bandwidth from 4kHz to 100 MHz, and NEP of $0.3pW/Hz^{1/2}$. The overall sensitivity is given as $-6.75 \times 10^4 V/W$. The sensitivity of the detector itself is given as $0.5A/W$ at 800 nm, assuming a gain of one.

a. For a particular combination of source and receiver locations, the reflectivity as defined above is $3 \times 10^{-5} cm^{-2}sr^{-1}$ at 70 MHz modulation frequency, and $1 \times 10^{-3}$ at DC. Assume that the laser modulation depth is 10%. That is, the power is

$$P = P_{DC} \left(1 + 0.1\, cos\, \omega t\right).$$

What are the DC and AC power levels at the detector? What are the DC and AC voltage levels at the output? Be careful of the trick question here.

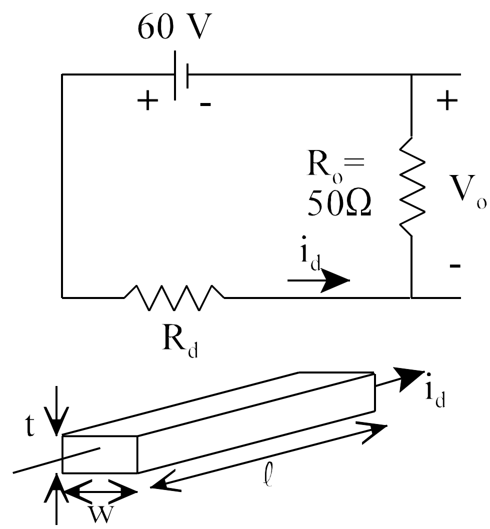
b. What is the quantum efficiency?

c. What is the photon noise voltage out of the package? Be careful how you think about this. Remember that the photon noise will be determined by the detected photoelectrons, and then will be amplified by the APD gain and the built–in amplifier.

d. Now, I will mix the detected signal with samples of the oscillator used to modulate the laser. I will do this mixing with both in–phase and quadrature samples, pass the results through a 100–Hz. low–pass filter, and deliver the results to a computer, where I will examine them to determine the magnitude and phase of the signal. To actually do this would require a lot of amplifiers, splitters, and mixers, to get the levels right. Let's ignore all that for this problem. What is the SNR for the AC signal, considering quantum noise? What is it, considering the stated NEP?

Problem 3. Semiconductor Detectors

A silicon photodetector is being designed for a 633nm laser system. Silicon has an energy gap of 1.11 eV, an electron mobility of $\mu_e$ = 1200 $cm^2$/V-s and a hole mobility of 400 $cm^2$/V-s. The dielectric constant is $11.8\epsilon_o$ Consider a photoconductive detector as shown below. The photodetector has length $\ell$=5 mm, width w = 2mm, and thickness t=10 μm. The n-type doping is $1x10^{15}$ $cm^{-3}$ and the electron recombination time, $\tau_n$, can be tuned by doping with deep impurities. Assume that the photocurrent is carried entirely by electrons (hole-trapping recombination).



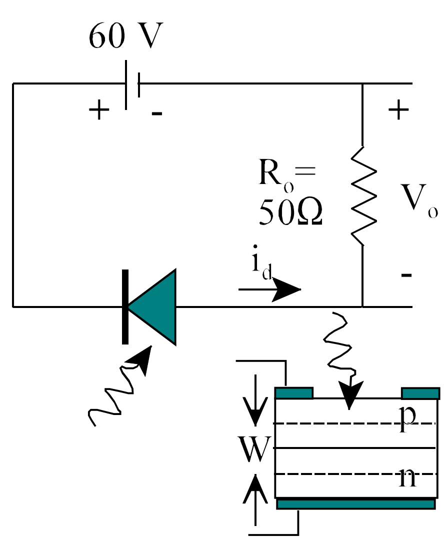

a) Calculate the dark current through the detector circuit.

b) Calculate the electron velocity in the photodetector and the transit time $\tau_t$ for an electron across the length of the detector. (Note that the electron velocity cannot exceed the saturation velocity, $v_s=1x10^7$ cm/s.)

c) Assume that $\tau_n$ is adjusted to equal the transit time of the detector (photoconductive gain G=1). Find the change in current if the electron-hole generation rate is $g_{op}=10^{20}$ e-h pairs/$cm^3$-s. Find the output voltage responsivity $\Re_v = \Delta V_o/\Delta\phi_e$ (units: V/W) assuming the quantum efficiency is 0.8. What is the bandwidth of the detector in Hz?

d) Find the $N_D$=number of electrons passing through the detector in 1 second with no light on the detector (dark current). Assuming that the thermal generation-recombination noise (in a 1 Hz bandwidth) is proportional to $N_D^{1/2}$, find the NEP related to thermal generation-recombination. Compare this with the NEP from Johnson noise at 300K across Ro and with the background-limited NEP at $\lambda$=633nm for a 300K background with 180° field of view and quantum efficiency $\eta$=1.

e) Compare the responsivity and bandwidth of the photoconductive detector above to the 3mm x 3mm photovoltaic detector that we considered in class with $N_a=N_d=1x10^{15}$ $cm^{-3}$. For the responsivity, assume $\eta$=0.8 and each electron-hole pair contributes to the current through $R_o$.



## Problem 4. Photomultiplier Tube

Consider a photomultiplier tube with n dynodes, each with a secondary emission coefficient as given by the Cu-BeO-Cs curve on the chart at right.

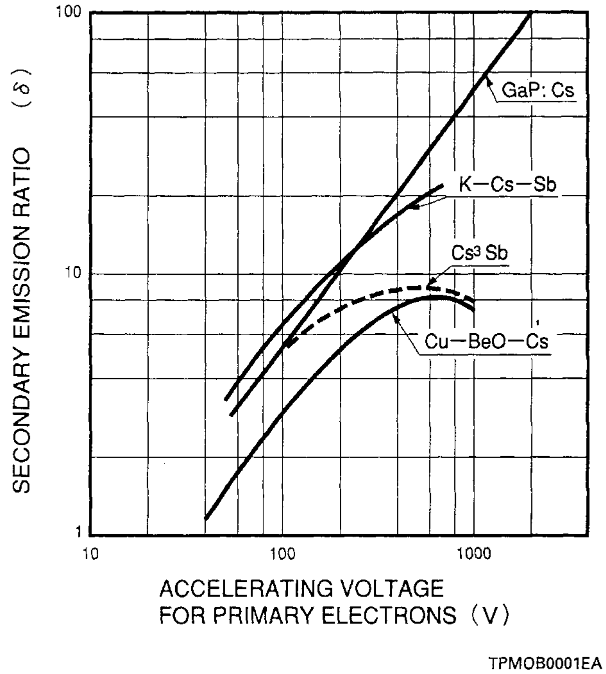


**Figure 2-7: Secondary emission ratio**

a. Assume that the dynode plates are parallel plates separated by a distance of 3mm and the secondary electrons are emitted off the surface with essentially zero velocity. Calculate the time for an emitted electron to travel from one dynode plate to the next assuming a potential difference of 100 V between the plates.

b. Assuming that the bandwidth is inversely proportional to the total transit time of the dynode chain, plot the gain and the bandwidth vs. the number of dynodes for n=1 to n=20 assuming the voltage between each dynode pair is 100V.

c. Plot the gain and bandwidth for PMT as a function of n=1 to n=20, assuming that the total voltage across the dynode chain is fixed at 1000 V.

d. For n=8, plot the gain and bandwidth of the PMT as the total voltage across the dynode chain is varied from 500 to 1500 V.

## Final Exam Coverpage

Name: ______________________________

The work I am submitting attached to this sheet is my own. I have consulted reference material as cited in the work, and have used the notes handed out in class, but I have not solicited any help from any other person.

Signature and date: ________________________________________

Problem 1: ____ /25 — a: ____ b: ____ c: ____ d: ____ e: ____

Problem 2: ______ /25 — a: ____ b: ____ c: ____ d: ____

Problem 3: ______ /25 — a: ____ b: ____ c: ____ d: ____ e: ____

Problem 4: ______ /25 — a: ____ b: ____ c: ____ d: ____

Total: ______ /100