EEE337/348: Tutorial 3

1) Consider a Si pin photodiode with an absorption region of 10 μm.
   i) What is the photocurrent density produced when a GaAs laser with an optical power of 1 W/cm^2 is focused on the Si photodiode? The absorption coefficient of Si at this energy is ~$700cm^{-1}$ (slide 10 in Photodetectors notes) and you may assume no reflection loss.

   The photon energy from a GaAs laser is 1.42 eV. The absorption coefficient of Si at this energy is ~$700cm^{-1}$ (slide 10 in Photodetectors notes). Assuming no reflection loss the quantum efficiency is

   $$\eta = 1 - \exp(-\alpha W) = 1 - \exp(-700 \times 10 \times 10^{-4})$$

   The photocurrent produced is

   $I_{ph} = \dfrac{\eta \lambda P_{opt}}{1.24}$ and the current density is

   $$J_{ph} = \frac{I_{ph}}{A} = \frac{\eta \lambda (P_{opt}/A)}{1.24} = \frac{\{1-\exp(-0.7)\} \times 1W/cm^2}{1.42} = 0.35A/cm^2.$$

   Note that the wavelength from a GaAs laser is $\lambda = \dfrac{1.24}{\hbar\omega(eV)}$.

   ii) Estimate the transit time limited bandwidth if the electron and hole are assumed to travel at a saturated velocity of $7\text{x}10^4$ ms^{-1}.

   $$f_{3dB\_tr} = \frac{0.4}{t_r} = \frac{0.4 v_s}{W} = \frac{0.4 \times 7 \times 10^4}{10 \times 10^{-6}} = 2.8GHz$$

2) An extremely fast photodiode can be designed to achieve bandwidth approaching THz. Recommend a possible design to achieve a bandwidth 100 GHz. Discuss the design trade-off in your design.

   To answer this question, we need the value of the saturated velocity. For such a high speed application, normally a material such as InGaAs which has a high saturated velocity is used. We will assume a saturated velocity of 10^5 ms^{-1} (a more precise value will depend on conditions such as diode temperature and doping concentration). To ensure that the transit time does not limit the bandwidth the depletion width should be

   $$W = \frac{0.4 v_s}{f_{3dB\_tr}} = \frac{0.4 \times 10^5}{100 \times 10^9} = 0.4\mu m.$$

   This suggests that the depletion width should be no more than 0.4 μm. For high speed application (diffusion current from carriers generated outside the depletion region should be avoided, as carrier diffusion is a slower process) and to maximise the quantum efficiency, light should be absorbed within the depletion region (to minimise recombination of photogenerated carriers). To achieve these, a PIN diode with wide bandgap p and n layers and an i-layer of width W, will be a suitable design. For most practical applications, W should be at least 1/α to achieve satisfactory quantum efficiency

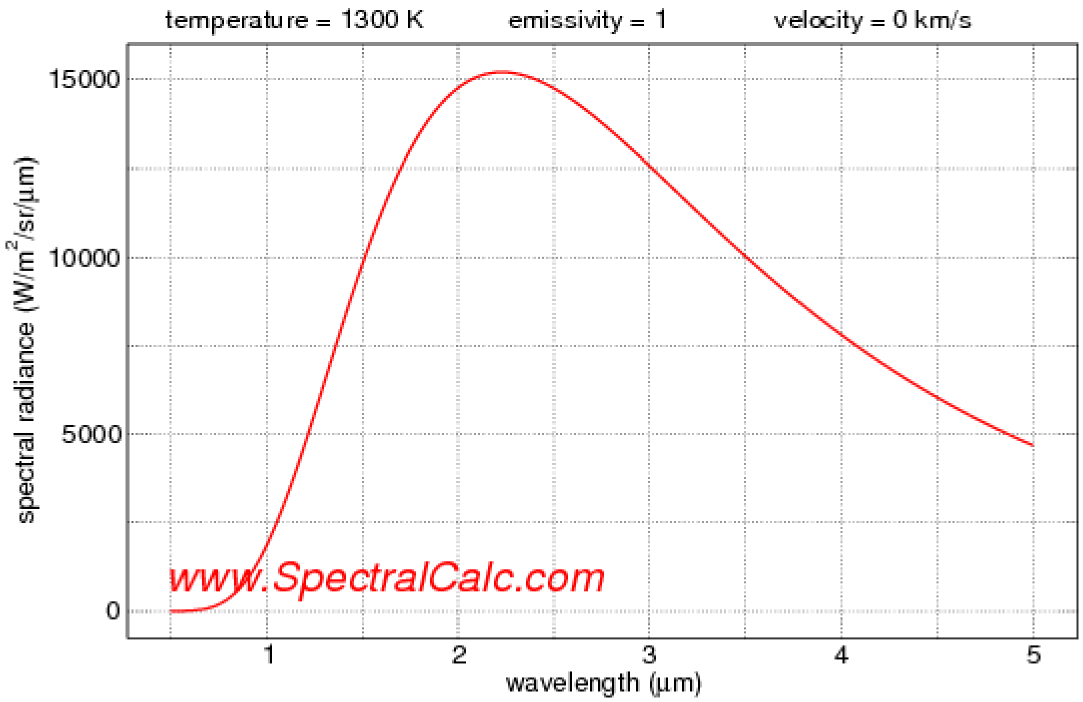
   $$\eta = (1-R)[1-\exp(-\alpha W)].$$

Since α is usually of values of 1000-10,000 cm^{-1} (see slide 10 in Photodetectors notes), W should be 10^{-4}-10^{-3} cm or 1-10 μm. Clearly there is a trade-off between bandwidth and quantum efficiency.
In addition to the transit time consideration, the RC time should also be considered.

$R_tC = R_t \dfrac{\varepsilon A}{W}$, where R_t is the resistance from the diode and measurement system. Clearly the area of the diode A should also be carefully scaled to minimise diode capacitance when W is small. If the diode area is too small for a vertically coupled fibre, waveguide photodetector configuration is used.

3) In metal manufacturing, the temperature measurement is an important approach to maintain the quality. This is typically done by detecting the infrared radiation from the hot metal. If the temperature of the iron is 1000 °C, suggest a suitable photodetector technology that can be used to monitor the temperature uniformity of a 30x30 cm^2 iron plate. Explain your choice. (Assume the iron plate is a perfect blackbody and you may use the Planck's Law to estimate its radiation). You may use a blackbody calculator (http://www.spectralcalc.com/blackbody_calculator/blackbody.php).

First, we need to find the radiation spectrum of the iron at 1000 °C



We can see that the peak wavelength is at 2.2 μm. In general we can either attempt to detect across the entire spectrum using a narrow bandgap detector or detect only a fraction of this spectrum. Since a narrow bandgap detector usually requires cooling to reduce dark current, an uncooled detector is preferred. A Si diode (covers up to 1.1μm) would be the obvious uncooled detector choice as it has very low leakage current and is low in cost. InGaAs (covers up to 1.7μm) can also be used if measurements at above 1.1 μm is desirable to avoid attenuation due to water absorption.

However it is more expensive than Si. Therefore one can use Si, which will detect a smaller fraction of the radiated energy and would require a larger amplifier gain than InGaAs. In practice heat monitoring of metal does not require high bandwidth amplifier. Therefore the lower signal produced by the Si photodetector can be easily magnified by a high gain amplifier.

4) Consider a Si avalanche photodiode (APD) with a breakdown voltage V_b = 150 V, a series resistance of 1 Ω and n_m = 2. When biased at 90% of its breakdown voltage the dark current is 10 nA.
   i) Calculate the gain produced by this APD when biased at 90% of its breakdown voltage.
   ii) The APD is expected to produce a photocurrent of 2 nA, under unity gain condition. If the incident optical power is 5 nW and the wavelength is 633 nm, what is the required quantum efficiency?

We can ignore the effect of series resistance since IR << V.

$$M = \frac{1}{1-\left(\frac{V-IR}{V_b}\right)^{n_m}} = \frac{1}{1-\left(\frac{V}{V_b}\right)^{n_m}} = \frac{1}{1-\left(\frac{0.9V_b}{V_b}\right)^{2}} = 5.26\,.$$

$I_{ph} = \frac{\eta \lambda P_{opt}}{1.24}$, rearranging we have $\eta = I_{ph}\frac{1.24}{\lambda P_{opt}} = \frac{2\times10^{-9}\times1.24}{0.633\times5\times10^{-9}} = 0.78$

5) In a high speed optical communication, it is a common practice to amplify the signal from an APD with a low noise amplifier. Consider an example, where the APD in question 4(ii) is connected to a low noise transimpedance amplifier with a bandwidth of 1 GHz and a noise current of 4 pA/$Hz^{1/2}$.
   i) Calculate the minimum gain required so that the APD can raise the signal above the noise floor of the amplifier.
   ii) What is the bias voltage required?

The noise signal at the output of the amplifier is given by

$v_{noise} = 4\times10^{-12}\times\sqrt{1\times10^{9}}\times G_{amp}$ where G_{amp} is the amplifier gain factor.

The photocurrent signal is $v_{photo} = 2\times10^{-9}\times M\times G_{amp}$. Therefore to overcome the amplifier noise

$M > \frac{4\times10^{-12}\times\sqrt{1\times10^{9}}\times G_{amp}}{2\times10^{-9}\times G_{amp}} = 63.2$. Using the equation $M = \frac{1}{1-\left(\frac{V-IR}{V_b}\right)^{n_m}}$, we have

$63.2 = \frac{1}{1-\left(\frac{V}{150}\right)^{2}}$. Therefore V = 148.8 V.

6) Conventional APDs used in high speed optical communication have InGaAs absorption region and an InP avalanche region. Explain the advantages offered by this combination over an InGaAs pin diode.

In the APD, the InGaAs absorption layer is designed to achieve the same quantum efficiency as the pin diode. However in InGaAs/InP APD, holes generated by the light absorption can produce more carriers in the InP avalanche region. Therefore, on average, a large number of electron-hole pairs can be produced for each absorbed photon, leading to much higher output current compare to the InGaAs pin diode. The much higher output current leads to much better signal to noise ratio of the detector-amplifier combination, provided the excess noise from the APD does not increase the APD noise above the amplifier noise.

7) Due to increasing internet traffic, very high speed photodetectors are required. Recommend the best option at 2.5 Gb/s and at 100 Gb/s. Provide supporting statements for your recommendations.

For optical communication the detector is usually combined with a low noise amplifier. In general designing an amplifier such as a transimpedance amplifier that has high gain, high bandwidth and low noise is difficult. Slide 24 in the Photodetectors notes show that InGaAs/InP APDs have gain bandwidth products below 200 GHz.
At 2.5 Gb/s, InGaAs/InP APD is the best option as it has sufficient bandwidth and can provide significant improvement over InGaAs pin. However at 100 Gb/s, the APD does not provide sufficient bandwidth. If a bandwidth of 50-100 GHz is required, the gain provide by the APD is limited to 2-4. While a small avalanche gain is useful, the higher cost of APD makes an InGaAs pin diode a more attractive option.

8) Discuss how the gain-bandwidth of an APD can be increased. What are the constraints that limit the gain-bandwidth products in conventional telecom APDs.

Based on slide 24 in the Photodetectors notes. The gain-bandwidth can be increased either by using a very thin multiplication region (or avalanche region) OR by using a semiconductor with k = 0 (i.e only one type of carrier can impact ionise).

Consider an avalanche region of a pin structure. In this case the avalanche region is defined by the i-region width, *w*. At a given applied bias, V, the electric field is $E=(V+V_{bi})/w$, where V_{bi} is the built-in potential. Clearly the smaller w the higher E. In practice, at a very high E, all semiconductors experience band to band tunnelling, where electron can be transferred from valence to conduction band via tunnelling effect. Therefore the lower limit of scaling w is determined by the onset of band to band tunnelling which rapidly increases the leakage current in the APD.

For telecom APD, the avalanche region is InP. Unfortunately in InP both holes and electrons can impact ionise. Therefore the only option to improve the gain-bandwidth product in InGaAs/InP telecom APD is to reduce the avalanche region. As mentioned above the lower limit is set by tunnelling.