5.3 Ge Photodiode Consider a commercial Ge *pn* junction photodiode which has the responsivity shown in Figure 5Q3. Its photosensitive area is 0.008 mm^2. It is used under a reverse bias of 10V when the dark current is 0.3 mA and the junction capacitance is 4 pF. The rise time of the photodiode is 0.5ns.

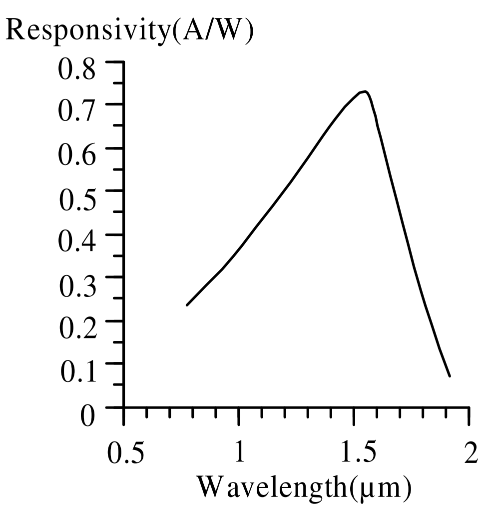
a Calculate its quantum efficiency at 850, 1300 and 1550nm.

b What is the light intensity at 1.55 mm that gives a photocurrent equal to the dark current?

c What would be the effect of lowering the temperature on the responsivity curve?

d Given that the dark current is in the range of microamperes, what would be the advantage in reducing the temperature?

e Suppose that the photodiode is used with a 100 W resistance to sample the photocurrent. What limits the speed of response?



The responsivity of a commercial Ge *pn* junction photodiode

Figure 5Q3

Solution

a At *l* = 850´10^{-9} m, from the responsivity vs. wavelength curve we have *R* = 0.25 A/W. From the definitions of quantum efficiency (QE) *h* and responsivity we have,

$$\eta = \frac{hcR}{e\lambda} = \frac{(6.626\times10^{-34}\,\text{Js})\times(3\times10^{8}\,\text{ms}^{-1})\times(0.25\text{A/W})}{(1.60218\times10^{-19}\,\text{C})\times(850\times10^{-9}\,\text{m})} = 36.5\%$$

Similarly, we can calculate quantum efficiency at other wavelengths. The results are summarized in Table 5Q3.

Table 5Q3

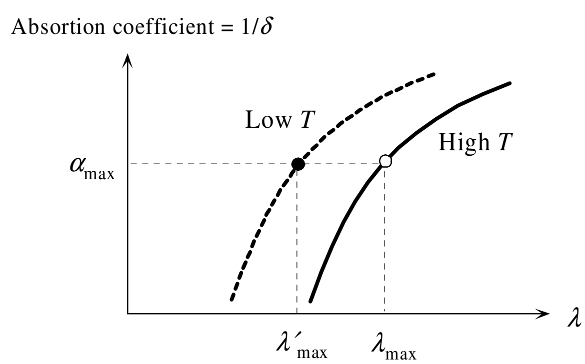
Wavelength, (nm)	850	1300	1550
Responsivity *R*, (A/W)	0.25	0.57	0.73
Quantum efficiency η, (%)	36.5	54.3	58.4

b Given, photocurrent $I_{ph} = I_d = 0.3$ μA = 0.3×10^{-6} A and area, $A = 8\times10^{-9}$ m^2, the incident optical power,

$$P_o = I_{ph}/R = (0.3´10^{-6}\text{ A})/(0.73\text{ A W}^{-1}) = 4.1096\ ´\ 10^{-7}\text{ W}$$

Light intensity, $I_o = P_0/A = (4.1096\ ´10^{-7}\text{ W})/(8\times10^{-9}\text{ m}^2) =$ **51.4 W m^{-2}** or **5.14 mW cm^{-2}**.

c From semiconductor data under *Selected Semiconductors,* for most semiconductors dE_g/dT is negative, E_g increases with decreasing temperature. Stated differently, *a* vs *l* curve shifts towards shorter *l* with decreasing *T*. The change in *a* with *T* means that the amount of optical power absorbed in the depletion region and hence the quantum efficiency will change with temperature. The peak responsivity will shift to lower wavelengths with decreasing temperature. If maximum photogeneration requires a certain absorption depth and hence a certain $a_{\max}$, then the same $a_{\max}$ will occur at a lower wavelength at lower temperatures. In Figure 5Q3, maximum responsivity corresponds to $a_{\max}$ which occurs at $l_{\max}$ at high *T* and at $l¢_{\max}$ at lower *T*.



The absorption coefficient depends on the temperature

Figure 5Q3

d Dark current (∝ exp($-E_g/kT$)) will be drastically reduced if we decrease the temperature. Reduction of dark current improves SNR.

e The *RC* time constant $= 100 \times (4\times10^{-12}) = 0.4$ ns. The *RC* time constant is comparable to the rise time, 0.5 ns. Therefore, the speed of response depends on both the rise time and *RC* time constant. (It is not simply 0.4 ns + 0.5 ns.)

5.7 Si *pin* photodiode speed Consider Si *pin* photodiodes which has a p^+ layer of thickness 0.75 mm, *i*-Si layer of width 10 mm. It is reverse biased with a voltage of 20 V.

a What is the speed of response due to bulk absorption? What wavelengths would lead to this type of speed of response?

b What is the speed of response due to absorption near the surface? What wavelengths would lead to this type of speed of response?

Solution

a Given, reverse biased voltage, V_r = 20 V and the width of *i*-Si layer is 10μm. The electric field,

$$E \approx \frac{V_r}{W} = \frac{20\,\text{V}}{10\times10^{-6}\,\text{m}} = 2\times10^{6}\ \text{Vm}^{-1}$$

At this electric field, drift velocities of electrons and holes are 9×10^4 ms^{-1} and 4.5×10^4 ms^{-1} respectively. Holes are slightly slower than the electrons. The transit time t_h of holes across the *i*-Si layer is

$t_h = W/v_h = (10\times10^{-6}\text{m})/(4.5\times10^4\ \text{ms}^{-1}) = 2.22\times10^{-10}$ s or **0.22 ns**

Therefore, the speed of response is 0.22 ns as determined by the slowest charge carrier (hole).

This type of speed of response occurs when the absorption and hence photogeneration occurs over the entire width *W* of the *i*-Si layer. So, the absorption depth must be greater than the width *W* of the *i*-Si layer. Thus,

$1/\alpha > W$

or, $\alpha < 1/W = 1/(10^{-5}\text{m}) = 10^5\ \text{m}^{-1}$.

$\alpha = 10^5$ m^{-c}orresponds to wavelength of about 0.81 μm wavelength. The light of *l* > 0.81 μm, leads to this type of speed of response.

b There is no electric field in the p^+ side outside the depletion region as shown in Figure 5.8 (in the textbook). The photogenerated electrons have to make it across to the n^+ side to give rise to a photocurrent.

In the p^+ side, the electrons move by diffusion. The diffusion coefficient (D_e) of electrons in the heavily doped p^+ is approximately 3×10^{-4} m^2s^{-1}. The diffusion time,

$$t_{diff} = \ell^2/(2D_e) = (0.75\times10^{-6}\ m)^2/[2(3\times10^{-4}\ m^2\ s^{-1})] = 9.375\times10^{-10}\ s\ \text{or}\ 0.94\ ns.$$

Once the electron reaches the depletion region, it becomes drifted across the width W of the *i*-Si layer. Thus, the response time of the *pin* to a pulse of short wavelength radiation that is absorbed near the surface is very roughly given by

$$\text{Response time} \approx t_{drift} + t_{diff} = 0.94\ ns + (10\times10^{-6}m)/(9´10^4\ ms^{-1})$$

$$= 0.94\ ns + 0.11\ ns = \mathbf{1.05\ ns}$$

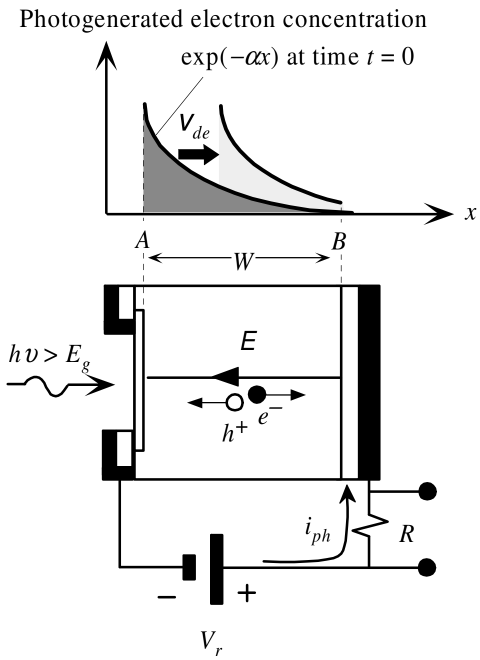
This type of speed of response occurs when the absorption depth,

$$\delta << l$$

or, $$\alpha >> 1/l = 1/(0.75\times10^{-6}m) = 1.33\times10^6\ m^{-1}.$$

$\alpha = 1.33\times10^6$ m^{-c}orresponds to wavelength of about 0.49 μm wavelength. The light of $l <$ 0.49 μm, lead to this type of speed of response.

NOTE: Carriers are not all simply generated at a depth d but rather they are generated exponentially from the surface. Further, diffusion is a statistical process and not all carriers diffuse to the depletion layer exactly in time t_{iff}.



An infinitesimally short light pulse is absorbed throughout the depletion layer and creates an EHP concentration that decays exponentially

Figure 5Q8-1

5.11 The NEP and Ge and InGaAs photodiodes

a Show that the noise equivalent power of a photodiode is given by

$$NEP = \frac{P_1}{B^{1/2}} = \frac{hc}{\eta e\lambda}\left[2e\left(I_d + I_{ph}\right)\right]^{1/2}$$

How would you improve the *NEP* of a photodiode? What is *NEP* for an ideal PD at operating at *l* = 1.55 mm?

b Given the dark current I_d of a PD, show that for SNR = 1, the photocurrent is

$$I_{ph} = eB\left[1 + \left(1 + \frac{2I_d}{eB}\right)^{1/2}\right]$$

What is the corresponding optical power P_1?

Table 5Q11-1 Ge *pn* junction and InGaAs *pin* PDs. Photosensitive area has a diameter of 1 mm.

Photodiode	R at 1.55 mm ($A W^{-1}$)	I_d (nA)	I_{ph} for SNR = 1 at B = 1 MHz. (nA)	Optical power for SNR = 1 at B = 1 MHz (nW)	NEP W. $Hz^{-1/2}$	Comment
Ge at 25 °C	0.8	400				
Ge at -20 °C	0.8	5				Thermoelectric cooling
InGaAs *pin*	0.95	3				

c Consider a fast Ge *pn* junction PD which has a photosensitive area of diameter 0.3 mm. It is reverse biased for photodetection and has a dark current of 0.5 mA. Its peak responsivity is 0.7 A/W at 1.55 mm (see Figure 5Q3). The bandwidth of the photodetector and the amplifier circuit together is 100 MHz. Calculate its *NEP* at the peak wavelength and find the minimum optical power and hence minimum light intensity that gives a SNR of 1. How would you improve the minimum detectable optical power?

d Table 5Q11-1 shows the characteristics of typical Ge *pn* junction and InGaAs pin photodiodes in terms responsivity and the current. Fill in the remainder of the columns in the table assuming that there is an ideal, noiseless, preamplifier to detect the photocurrent from the photodiode. Assume a working bandwidth, B, of 1 MHz. What is your conclusion?

Solution

a The responsivity, $$R = \eta \frac{e\lambda}{hc} \quad (1)$$

The noise equivalent power, $$NEP = \frac{P_1}{B^{1/2}} = \frac{1}{R}\left[2e\left(I_d + I_{ph}\right)\right]^{1/2} \quad (2)$$

Substituting Eq. (1) in (2), we get

$$NEP = \frac{hc}{\eta e\lambda}\left[2e\left(I_d + I_{ph}\right)\right]^{1/2}$$

We can improve NEP by increasing quantum efficiency η and decreasing dark current I_d.

From Example 5.10.1, for **ideal** photodiode (QE = 100% and $I_d = 0$), for SNR = 1,

$$P_1 = \frac{2hc}{\lambda} B$$

If we put B = 1 Hz, then *NEP* is numerically equal to P_1. Thus,

$NEP = 2hc/\lambda$.

Given, λ=1.55 μm,

$$NEP = \frac{2 \times (6.626 \times 10^{-34})(3 \times 10^{8})}{1.55 \times 10^{-6}} = 2.565 \times 10^{-19} \text{ W Hz}^{-1}$$

b For SNR = 1, the photocurrent is equal to the noise current when,

$$I_{ph} = \left[2e(I_d + I_{ph})B\right]^{1/2}$$

∴

$$I_{ph}^2 - 2eBI_{ph} - 2eBI_d = 0$$

∴

$$I_{ph} = \frac{2eB + \sqrt{(2eB)^2 + 8eBI_d}}{2} = eB\left[1 + \left(1 + \frac{2I_d}{eB}\right)^{1/2}\right]$$

If the corresponding optical power is P_1, then,

$$I_{ph} = RP_1 = eB\left[1 + \left(1 + \frac{2I_d}{eB}\right)^{1/2}\right]$$

and

$$P_1 = \frac{eB}{R}\left[1 + \left(1 + \frac{2I_d}{eB}\right)^{1/2}\right] = \frac{Bhc}{\eta\lambda}\left[1 + \left(1 + \frac{2I_d}{eB}\right)^{1/2}\right]$$

c The minimum optical power at l = 1.55´10^{-6} m, for SNR =1, B = 100 MHz, given I_d = 0.5´10^{-6}, and R= 0.7 at l = 1.55´10^{-6} m

$$P_1 = \frac{1.60218 \times 10^{-19} \times 100 \times 10^{6}}{0.7}\left[1 + \left(1 + \frac{2 \times 0.5 \times 10^{-6}}{1.60218 \times 10^{-19} \times 100 \times 10^{6}}\right)^{1/2}\right]$$

$$= 4.81 \times 10^{-9} \text{ W or } 4.81 \text{ nW}$$

The noise equivalent power,

$$NEP = \frac{P_1}{B^{1/2}} = \frac{4.81\times10^{-9}}{(100\times10^{6})^{1/2}} = 4.81\times10^{-13} \text{ W Hz}^{-1/2}$$

Given, D = 0.3 mm, Area, $A = \pi D^2/4$= 7.0686×10[2] mm[2]. The minimum light intensity,

$$I_o = P_1/A = (4.81\times10^{-9}\text{ W})/(7.0686\times10^{2}\text{ mm}^2) = 6.805\times10^{-12}\text{ W mm}^{-2}.$$

We can improve the minimum detectable power by decreasing the dark current and increasing quantum efficiency.

d Similar calculations to above using R, I_d as given in Table 5Q11-1, for Ge (at two temperatures) and InGaAs photodiodes are summarized in Table 5Q11-2. The following equations have been used with B = 1 MHz:

$$I_{ph} = RP_1 = eB\left[1+\left(1+\frac{2I_d}{eB}\right)^{1/2}\right];$$

$$P_1 = \frac{eB}{R}\left[1+\left(1+\frac{2I_d}{eB}\right)^{1/2}\right]; \qquad NEP = \frac{P_1}{B^{1/2}}$$

Table 5Q11-2 Ge *pn* junction and InGaAs *pin* PDs. Photosensitive area has a diameter of 1 mm.

Photodiode	R at 1.55 mm (A W^{-1})	I_d (nA)	I_{ph} for SNR = 1 at B = 1 MHz. (nA)	Optical power for SNR = 1 at B = 1 MHz (nW)	NEP W Hz$^{-1/2}$	Comment
Ge at 25 °C	0.8	400	0.358	0.4475	4.475×10^{-13}	NEP is very high due to high dark current which is undesirable.
Ge at -20 °C	0.8	5	0.042	0.0525	5.25×10^{-14}	Thermoelectric cooling
InGaAs *pin*	0.95	3	0.0312	0.0328	3.28×10^{-14}	Acceptable for practical purposes

5.12 The APD and excess avalanche noise APDs exhibit excess avalanche noise which contributes to the shot noise of the diode current. The total noise current in the APD is given by

$$i_{n\text{-APD}} = [\ 2e(I_{do} + I_{pho})M^2FB]^{1/2} \qquad (1)$$

where F is the excess noise factor which depends in a complicated way not only on M but also on the ionization probabilities of the carriers in the device. It is normally taken simply to be M^x where x in an index that depends on the semiconductor material and device structure.

a Table 5Q12 provides measurements of F vs. M on a Ge APD using photogeneration at 1.55 mm. Find x in $F = M^x$. How good is the fit?

b The above Ge APD has an unmultiplied dark current of 0.5 mA and an unmultiplied responsivity of 0.8 A W^{-1} at its peak response at 1.55 mm and is biased to operate at M = 6 in a receiver circuit with a bandwidth of 500MHz. What is the minimum photocurrent that will give a SNR = 1? If the photosensitive area is 0.3 mm in diameter what is the corresponding minimum optical power and light intensity?

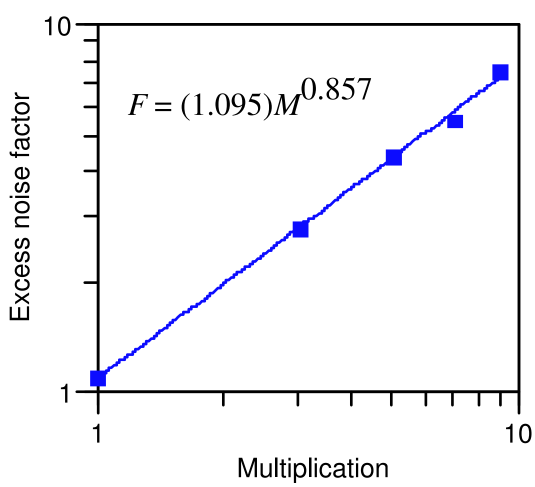
c What should be the photocurrent and incident optical power for SNR = 10?

Table 5Q12 Data for excess avalanche noise as F vs M for a Ge APD

(from D. Scansen and S.O. Kasap, Cnd. J. Physics. Vol. 70, pp. 1070-1075, 1992)

M	1	3	5	7	9
F	1.1	2.8	4.4	5.5	7.5

a We can find the value of x by plotting F vs. M on a log-log plot, which is shown in Figure 5Q12. From the plot, the index x = 0.857. The fit shows that, $F = 1.095M^{.8571}$ which agrees well with the equation, $F \approx M^x$.



Excess noise factor F vs. M for a GE APD; from Scansen and Kasap 1992.

Figure 5Q12

b Given, I_{do} = 0.5 μA, M = 6, B=500 MHz and x = 0.857. From Equation (12) §5.10, the SNR can be written as,

$$\text{SNR} = \frac{\text{Signal Power}}{\text{Noise Power}} = \frac{M^2 I_{pho}}{\left[2e\left(I_{do} + I_{pho}\right)M^{2+x}B\right]}$$

$$\therefore \quad M^2 I_{pho}^2 - \left[2eM^{2+x}B(\text{SNR})\right]I_{pho} - \left[2eM^{2+x}B(\text{SNR})I_{do}\right] = 0 \qquad (2)$$

Solving this quadratic Equation (2) with a SNR = 1 for I_{pho} we find,

I_{pho} = 1.9665×10^{-8} A or 19.665 nA

If P_o is the incident optical power, then by the definition of responsivity, $R = I_{pho}/P_o$,

$P_o = I_{pho}/R$ = (1.9665×10^{-8} A)/(0.8 A/W) = 2.458×10^{-8} W or 24.58 nW.

c Solving this quadratic Equation (2) with a SNR = 10 for I_{pho} we find,

I_{pho} = 6.4832×10^{-8} A or 64.665 nA

The incident optical power,

$P_o = I_{pho}/R$ = (6.4832×10^{-8} A)/(0.8 A/W) = 8.104×10^{-8} W or 81.04 nW.

Note: Although the SNR has gone up by a factor of 10, the required increase in the incident optical power is only a factor of 3.3.