5.1 Introduction:

It has been already mentioned in the Chapter 2 that faithful interception of the signal at the receiving end of an optical communication system requires a photodetector with large bandwidth, high quantum efficiency and low noise [1-8]. In optical communication system, the ultimate limit to the detectability of weak signals is set by noise, the unwanted signal that obscures the desired signal. Photodetector being at the front-end of a photoreceiver, controls the noise performance of the whole system significantly [9, 10]. The noise in photoreceiver can be mainly of three types- Thermal noise (or Johnson noise), Shot noise and Flicker noise. Thermal noise (or Johnson noise) has its origin in the thermal agitation of the electrons inside an electrical conductor at equilibrium, which happens regardless of any applied voltage. The photodetector, the amplifier and the load resistor all contribute to thermal noise. Thermal noise is a white noise and, so, is present uniformly at all frequencies. Shot noise is caused by current fluctuations due to the randomness in the generation of current in the device. Dark current and quantum noises are two types of noise that manifest themselves as shot noise [11, 12]. Dark current noise is due to the current that continues to flow through the bias circuit in the absence of the light [12-15]. Quantum noise results from the random generation of electrons by the incident optical radiation. In the mid-frequency range noise is dominated by shot noise [9 - 11]. The spectrum distribution of shot noise is, in general, frequency independent, and is proportional to the average current of the devices. Flicker noise is usually inversely proportional to the frequency, and so sometimes called as \(1/f\) noise. As the present discussion is on optical
communication system, where operating frequency is very high, the flicker noise can be neglected. It may also be noted that at very high frequency thermal noise control the noise performance. The spectra of these three noise components are illustrated in Fig. 5.1 schematically.

It may be noted here that because of the band discontinuity at the Si/Ge interface, carriers get confined there and, hence, it may affect the noise arising out of the transit of carriers in the device. In this chapter, the noise performance like noise currents, signal to noise ratio and minimum detectable optical power of the resonant cavity enhanced Ge-on-Si Schottky photodetector is analyzed.

5.2 Calculation of Noise Currents:

In this section, the mean square noise currents due to thermal noise ($\langle i^2 \rangle$) and shot noise ($\langle i_s^2 \rangle$) are calculated for the Ge-based Schottky photodetector. The total r.m.s. noise current is then obtained using the relation

$$\sqrt{\langle i^2 \rangle} = \sqrt{\langle i_{th}^2 \rangle + \langle i_s^2 \rangle}$$

5.2.1 Thermal Noise

Thermal noise is approximately Gaussian in nature (white noise) and is independent of signal current. The mean square thermal noise current can be expressed as [1]

$$\langle i_{th}^2 \rangle = \frac{4k_BT}{R_{eq}}$$

where $k_B$ is the Boltzmann constant, $T$ is temperature (K), $B$ is noise equivalent bandwidth and $R_{eq}$ is the equivalent resistance seen from the output [Fig. 5.2],

$$R_{eq} = \left[1/(R_D + R_s) + 1/R_L \right]^{-1},$$
Fig. 5.1 Schematic of spectra of Thermal noise, Shot noise, and Flicker noise.

Fig. 5.2 Noise equivalent circuit of RCE Ge-on-Si Schottky photodiode.
where $R_d (R_s)$ is the shunt (series) resistance of the photodiode and $R_l$ is the load resistance. The noise equivalent bandwidth ($B$) is given by

$$B = \frac{1}{I_p^2} \int_0^\infty |I_p(\omega)|^2 d\omega,$$  \hspace{1cm} (5.4)

where $I_p(\omega)$ is the photocurrent at frequency $\omega$. The calculation of photocurrent is mentioned in the next subsection.

### 5.2.2 Shot Noise

The shot noise due to the statistical nature of the production and collection of photoelectrons in a photodetector is known as quantum noise. Besides photocurrent, there is current due to the thermally generated carriers in the reverse biased diode in the absence of light. This dark current ($I_D$) also contributes to the shot noise in a photodetector. The mean square shot noise current is then given by

$$\langle i_s^2 \rangle = 2q(I_p + I_D)B,$$  \hspace{1cm} (5.5)

where $q$ is the electronic charge.

### A. Photocurrent

To calculate the photocurrent, the carrier continuity equations can be solved along with appropriate boundary conditions, given in Chapter 3. At the hetero-interface between P-Si and i-Ge, band-offset occurs in the valence band and holes are confined there. To include the effect of this confinement in the photocurrent calculation, we assume that the holes from confinement are emitted by slow thermionic emission over the potential barrier. So, it takes a long time for holes to reach the metal contacts and some of the holes are lost due to the recombination during confinement at the hetero-interface [16]. To consider the effect of this hole confinement, rate equation is to be solved applying the boundary conditions, to get the final expression for the photocurrent including the parasitic RC effect, as derived in Chapter 3.
B. Dark Current

To calculate the dark current we have considered contributions from diffusion current and generation-recombination current [17] due to thermally generated carriers within the device. The diffusion current due to these thermally generated minority carriers in the absence of light can be derived as

\[ I_{D, \text{diff}} = q \eta d \left[ \frac{\sqrt{D_n/\tau_e}}{N_a} + \frac{\sqrt{D_p/\tau_h}}{N_d} \right] \left[ 1 - \exp \left( -\frac{qV}{kT} \right) \right] \]  

...(5.6)

where \( n \), is the intrinsic carrier concentration, \( N_A \) (\( N_D \)) is the doping density in the p (n) region, \( \tau_e \) is the recombination time of electrons and \( V \) is the applied reverse bias. In Schottky diodes, there is thermal emission of electrons from the metal to the semiconductor across the Schottky barriers to contribute to the diffusion current of electrons [10]. As the photodiode is operated under the reverse bias, this emission current is negligible. In general, the contribution from the diffusion current has significance particularly for the undepleted regions or when the field is very low. In the depleted region with high field, the dark current is mainly dominated by the generation-recombination current due to thermally generated carriers. The generated holes during transit get confined at the hetero-interface due to potential barrier arising from the valence band discontinuity. Its contribution to the total current is affected due to their recombination during the confinement. The dark current due to generation-recombination of these thermal electron-hole pairs in the depletion region is given by

\[ I_{D, \text{rec}} = \frac{qnd}{4} \left[ 1 + \frac{e_{\text{ho}}}{e_{\text{ho}} + 1} \right] \left[ 1 - \exp \left( -\frac{qV}{kT} \right) \right] \]  

...(5.7)

The total dark current is given by

\[ I_D = I_{D, \text{diff}} + I_{D, \text{rec}} \]  

.....(5.8)

5.3 Minimum Detectable Power

The signal-to-noise ratio of the photodetector for a sinusoidally varying input signal with 100% modulation index is given by the expression
The weakest signal that can be detected by a photodetector in the presence of noise is usually given by the noise equivalent power of the system which corresponds to unit signal-to-noise ratio. This is also defined as the minimum detectable optical power in the presence of noise. With this definition, the minimum detectable power \( P_{\text{min}} \) is given by

\[
P_{\text{min}} = \frac{2h\nu}{\eta q} \sqrt{q(I_p + I_D) + \frac{k_B T}{R_{\text{eq}}}} B
\]

where \( \eta \) is the quantum efficiency. Quantum efficiency is calculated using the relation

\[
\eta = \frac{I_p(0)h\nu}{qP_{\text{inc}}},
\]

where \( I_p(0) \) is the dc photocurrent obtained putting \( \omega=0 \) in Eq.(3.9). This quantum efficiency is also affected by the carrier confinement at the hetero-interface.

5.4 Results & Discussions:

The dark current is computed by Eq. (5.8) to verify the model for dark current, a plot is shown in Fig. 5.3, as a function of bias. The experimental data for comparison are taken from literature [12] where the device is a Ge p-i-n photodetector with Ge as the intrinsic layer and Si as p and n layer. So the confinement effect for electrons has also been considered in this computation. However, the potential barrier for electrons being less than that of holes, the confinement effect of electrons is small. It is clear from the figure that the model results fit well with the experimental data. The dark current in the absence of the confinement effect is shown by the dotted line.

The photocurrent and dark current with respect to reverse bias voltage are plotted in Fig. 5.4(a) for an input power of 100\( \mu \)W. In all the results, the reflectivity of the top (bottom) mirror of the resonant cavity has been assumed to
be 80% (55%). The dark current is less than the photocurrent mainly because of the operation of the photodiode under reverse bias. Photocurrent can be increased by increasing the input optical power. When the bias voltage is very small the dark current is nearly zero and it increases with voltage to finally reach the saturation value (reverse saturation current). It has been seen that the main contribution to the dark current comes from the generation-recombination (thermal) current. The dotted line shows the current in the absence of carrier confinement. The effect of carrier confinement is significant near the knee of the curves. The graph shows that both photocurrent and dark currents are reduced due to confinement effect. In Fig. 5.4(b), dark current is plotted against applied reverse bias for different values of thicknesses. As the thickness increases, dark current increases.

The noise equivalent bandwidth has been plotted as a function of bias voltage for different values of thickness in Fig. 5.5(a). At low bias, noise equivalent bandwidth is low because the rate of emission of holes from the confinement occurs at a slow rate because of the large potential barrier. With increase in bias, the effective potential barrier for confinement is reduced, and so noise equivalent bandwidth increases to ultimately reach a constant value at a high bias. The above variation with bias is, however, not significant for small thickness \(d\), because now the noise equivalent bandwidth becomes RC effect limited, whereas the effect of confinement is apparent only through the transit time.

The variation of noise equivalent bandwidth with active layer thickness \(d\) is shown in Fig. 5.5(b) for different diameters at zero bias. For small \(d\), RC effect dominates to reduce the noise equivalent bandwidth. As \(d\) increases, RC time constant decreases while transit-time increases to limit the noise equivalent bandwidth. Thus, noise equivalent bandwidth goes through a peak as \(d\) is increased. This peak of the noise equivalent bandwidth shifts to lower \(d\) with decrease in diameter as RC effect is reduced. A dotted line is shown for noise equivalent bandwidth of the photodetector of a particular diameter (50μm) in the
Fig. 5.3 Plot of dark current as a function of reverse bias. The symbols correspond to data extracted from the experimental results given in [12] and dotted line for dark current without considering carrier confinement effect.
absence of the carrier confinement effect. As the confinement effect alters the transit-time limited bandwidth, so its effect is present at large thickness. It may be seen from the figure that the effect of confinement is to reduce the noise equivalent bandwidth.

Both bandwidth and noise equivalent bandwidth (NEB) are nearly similar in nature with a little exception because of the way they are defined. While a peak in bandwidth is desired, the same in noise equivalent bandwidth is not desired. So, the noise equivalent bandwidth to bandwidth ratio may give some important information for noise performance with reference to high frequency performance. In Fig. 5.6(a), the ratio of noise equivalent bandwidth to photodetector bandwidth has been plotted as a function of active layer thickness for different diameters of the active area at a fixed bias. We see that the ratio is high for low $d$, and then decreases with increase in $d$. In some cases, the ratio may show a minimum, which means that there is an optimum choice for $d$, where noise performance can be improved without affecting its high frequency performance. In Fig. 5.6(b), the plot is shown for no bias. The nature of variation indicates the increased effect of confinement at zero bias.

Signal-to-noise (S/N) ratio has been plotted as a function of incident optical power in Fig. 5.7 for different $d$. The signal-to-noise ratio increases with increase in input optical power. At higher powers, however, the increment is at a lower rate due to the fact that the shot noise due to photocurrent becomes more significant. The results also show that with increase in thickness of the photodiode, signal-to-noise ratio is improved. It has been seen that with increase in $d$ the signal current increases while the noise current decreases thus improving the signal-to-noise ratio at higher active layer thickness. Dotted lines are shown for signal-to-noise ratio in the absence of confinement of holes at the Si/Ge hetero-interface. Due to confinement, both signal current and noise current are reduced. It has been observed that the percentage change is more for noise than for signal at $d = 1 \mu$m, so the confinement improves the S/N ratio. But
Fig. 5.4(a) Plot of photocurrent and dark current as a function of reverse bias.

(b) Plot of dark current for different active layer thicknesses.
Fig. 5.5 Plot of Noise equivalent bandwidth of the photodetector (a) as a function of reverse bias for different active layer thickness and constant diameter (50 μm), and (b) as a function of active layer thickness, d for different values of detector diameter at 0V.
it is the reverse for $d = 4\mu m$, so the hetero-interface confinement deteriorates the signal-to-noise ratio.

Minimum detectable optical power $P_{\text{min}}$ is plotted in Fig. 5.8. In Fig. 5.8(a), the variation is shown as a function of the reverse bias for different thicknesses. At low bias, the shot noise due to photocurrent is low, so the minimum detectable signal power (optical) is low. The effect of confinement is also shown by dotted lines. It may be seen that the hetero-interface confinement is effective at low bias and it may either improve or deteriorate $P_{\text{min}}$ depending on the dimension of the photodiode. The variation of $P_{\text{min}}$ with thickness is shown in Fig. 5.8(b) at 0V. With the increase of $d$, $P_{\text{min}}$ increases, the increment being more rapid for smaller thicknesses where the noise equivalent bandwidth is dominated by RC-effect. At larger $d$, the noise equivalent bandwidth is transit-time limited and so the effect of confinement also becomes relatively significant. It may be seen that the effect of confinement is to deteriorate the $P_{\text{min}}$ except for a smaller diameter (e.g. $25\mu m$) and a smaller thickness (around $1\mu m$) when the confinement improves the minimum detectable power.
Fig. 5.6 Plot of noise equivalent bandwidth and bandwidth ratio as a function of active layer thickness, $d$ for different values of detector diameter

(a) at Bias = 2V
(b) at No Bias
Fig 5.7 Plot of signal to noise ratio as a function of incident optical power for different active layer thickness and diameter keeping fixed at 25 μm.
Fig. 5.8 Plot of Minimum detectable power
(a) as a function of reverse bias for different active layer thicknesses and fixed diameter (25 µm)
(b) as a function of active layer thickness for different active area diameter at no bias.
References:


