Chapter-4
Quantum Efficiency
of Ge-on-Si Schottky
Photodetector

4.1 Introduction:

Electron-hole pairs created by incident optical pulse give rise to current in the external circuit of a photodetector. Quantum efficiency, another figure of merit of a photodetector with no internal gain, is the ratio of the number of photogenerated electron-hole pairs to the number of incident photons. Responsivity is also sometimes used to characterize a photodetector, and is directly proportional to the quantum efficiency. It also gives a measure of the sensitivity of the detector [1-3].

The quantum efficiency of a conventional photodiode is given by, 
\[ \eta = (1 - e^{-\alpha d}) \]
where \( \alpha \) is the absorption coefficient, \( d \) is the active layer thickness of photodetector [4-6]. For semiconductors with low absorption coefficients, a thick absorption region is required to achieve high quantum efficiency. But, thick active layer thickness reduces the transit-time controlled bandwidth, \( f_{3dB} \), which is approximately given by \( 0.45\nu / d \), where \( \nu \) is the saturation velocity of the photogenerated carrier [7, 8]. So, a very thin active layer of the photodetector is required to decrease the transit-time and, hence, to increase the transit-time limited bandwidth of the detector. The thin layer, on the other hand, reduces quantum efficiency. Thus, there is a tradeoff between bandwidth and quantum efficiency. One of the techniques to remove this tradeoff is to encapsulate the photodetector in a Fabry-Perot resonant cavity, so that the light undergoes multiple reflections to effectively increase the absorption thickness. This results in increased quantum efficiency which may even approach a value close to unity [9-14]. The resonant cavity also provides wavelength selectivity of detection. Therefore, RCE detectors can be viewed as
high sensitivity detectors at selected wavelengths and may function as channel
discriminators in wavelength division multiplexing system [15, 16]. This
advanced structure provides both high quantum efficiency and bandwidth at the
same time without sacrificing the much preferred vertical illumination facility
[17]. An alternate approach to overcome the bandwidth–quantum efficiency
trade-off is to use a waveguide structure of the photodetector, but the coupling
and design issues are critical in this type of structure [18, 19]. On the other hand,
coupling is easier with resonant cavity encapsulated structure. In this chapter,
detailed study of the quantum efficiency of a resonant cavity enhanced Ge-on-Si
Schottky photodetector is given.

4.2 Calculating the Quantum Efficiency:

Photogenerated electrons and holes in the reverse biased photodetector move
in opposite directions to give photocurrent. An expression for quantum
efficiency of a resonant cavity enhanced structure considering the reflectivity
and phase shift of end mirrors, have been calculated by earlier researchers[5].
But, that relation does not include the important carrier confinement effect. In
our model, we have considered the carrier confinement effect to calculate
quantum efficiency [20]. As mentioned earlier, for the Schottky photodetector
structure in our consideration, only holes are confined at the hetero-interface.
Due to this interface confinement, holes take long time to reach the contacts, and
during this period of time some of the confined holes get recombined. Hence,
the number of photogenerated carriers that are ultimately collected decreases,
thus, reducing the quantum efficiency of the photodetector. The continuity
equation and rate equation can be written in a similar manner described in
Chapter 3. Let us consider a schematic resonant cavity enhanced structure
shown in Fig. 3.2(a) with the reflectors on both side of the cavity indicated. For
the wavelength of the incident light (hv), absorption occur in the i-region. For
illumination using light impulse \((\alpha P; \delta(t))/(A.E_p)\) and following the procedures
for calculating fields, the generation rate can be written as
\[ g(x) = \frac{P_c e^{(1 - R_f) x}}{A E_p \left( 1 - 2 \sqrt{R_f R_b e^{-ad} \cos(2 \beta L + \phi_f + \phi_b) + R_f R_b e^{-2ad}} \right)} \left[ e^{\alpha r} + R_b e^{-\alpha r} \right] \quad (4.1) \]

where \( L = d + L_1 \) is the length of the cavity.

Here assuming that the entire Ge layer is depleted at the applied bias. Considering the case of holes, the continuity equation can be written in a simplified form as

\[ \frac{V_h}{\tau_h} \frac{\partial p(x)}{\partial x} + \frac{p}{\tau_h} = k_i [e^{\alpha x} + R_b e^{-\alpha x}] \quad (4.2) \]

where \( k_i = \frac{P_c e^{(1 - R_f) x}}{A E_p \left( 1 - 2 \sqrt{R_f R_b e^{-ad} \cos(2 \beta L + \phi_f + \phi_b) + R_f R_b e^{-2ad}} \right)} \) \quad (4.3)

To solve the above differential equation (4.2), both sides are divided by \( v_h \) and multiplied by the integrating factor \( e^{\frac{\alpha x}{v_h}} \). Solving the equation we get

\[ p(x) e^{\frac{\alpha x}{v_h}} = \frac{k_i}{v_h} \left[ \frac{e^{\left( \frac{1}{v_h \tau_h} + R_b \right)}}{1 + \alpha} \right] + C \quad (4.4) \]

where \( C \) is integration constant and its value can be obtained by applying the boundary condition (at \( x=0, p(x)=0 \)) as follows,

\[ C = \frac{k_i}{v_h} \left[ \frac{1}{1 + \alpha} + \frac{R_b}{v_h \tau_h - \alpha} \right] \quad (4.5) \]

Putting the value of \( C \) in Eq.4.4 and simplifying it

\[ p(x) = \frac{k_i}{v_h} \left[ \frac{e^{\alpha x} - e^{\frac{x}{v_h \tau_h}}}{1 + \alpha} \right] + \frac{R_b}{v_h \tau_h - \alpha} \quad (4.6) \]

Similarly, we can derive the expression for electron density \( n(x) \). In this case, the continuity equation is
\[ \frac{\partial n(x)}{\partial x} - \frac{n}{\tau_e} = k_i [e^{ax} + R_h e^{-ax}] \]  
\hspace{1cm} \text{...(4.7)}

Using the procedure mentioned above this differential equation can be solved along with boundary condition (at \( x=d, n(x)=0 \)), we obtain

\[ n(x) = \frac{k_i}{v_e} e^{\frac{x}{v_e}} \left[ e^{ax} - e^{-ax} \right] \left[ \frac{-1}{v_e \tau_e} \right]^d + \frac{R_h}{\alpha + \frac{1}{v_e \tau_e}} \left[ e^{ax} - e^{-ax} \right] \left( \frac{x}{v_e \tau_e} \right)^d \]  
\hspace{1cm} \text{...(4.8)}

The total current density is given by the relation

\[ J = \frac{q}{d} \int \left[ \frac{\partial n(x) v_e}{v_e} + \xi \phi(x) v_h \right] dx \]  
\hspace{1cm} \text{...(4.9)}

where

\[ \xi = \frac{e_{ho}}{e_{ho} + \frac{1}{\tau_h}} \]  
\hspace{1cm} \text{...(4.10)}

The total conduction current density in the resonant cavity enhanced Schottky photodetector is the summation of electron and hole densities. Assuming confinement of holes only and no confinement of electrons at the hetero-interfaces, the expression for current density can be obtained as

\[ J = \frac{q k_i}{d} \left\{ e^{ax} - e^{-ax} \right\} \left[ \frac{-1}{v_e \tau_e} \right]^d \frac{e^{ax} - 1}{\alpha + \frac{1}{v_e \tau_e}} + \frac{R_h}{\alpha + \frac{1}{v_e \tau_e}} \left[ e^{ax} - e^{-ax} \right] \left( \frac{x}{v_e \tau_e} \right)^d \]  
\hspace{1cm} \text{...(4.11)}

The expression of quantum efficiency in terms of the current density can be written as
\[ \eta = \left( \frac{J_A}{q} \right) \left/ \left( \frac{P_i}{h \nu} \right) \right. \] \hspace{1cm} \text{(4.12)}

where, \( A \) is effective area of the detector, \( P_i \) is incident optical power.

Therefore the quantum efficiency of the Ge-on-Si RCE Schottky photodetector has been calculated as,

\[
\eta = \frac{k_\text{e} e^{\text{ad}}}{P_d \alpha} \left[ \left( \frac{d - 1 - e^{-\text{ad}}}{\alpha} \right) - \frac{R_b}{\alpha} \left\{ \frac{e^{-\text{ad}} - 1 + de^{-\text{ad}}}{\alpha} \right\} + \right. \\
\left. \xi \left\{ \frac{e^{-\text{ad}} - 1}{\alpha} - \frac{d}{\nu\tau_h} \left( 1 - e^{-\frac{d}{\nu\tau_h}} \right) \right\} \left/ \left( \alpha + \frac{1}{\nu\tau_h} \right) \right] + \right. \\
\left. \xi R_b \left( \frac{1 - e^{-\text{ad}}}{\alpha} - \frac{d}{\nu\tau_h} \left( 1 - e^{-\frac{d}{\nu\tau_h}} \right) \right) \left/ \left( \frac{1}{\nu\tau_h} - \alpha \right) \right] \right.
\hspace{1cm} \text{(4.13)}

When the effect of carrier confinement is negligibly small, and so, the recombination time is larger than the transit time (\( \tau_b \gg d/v_h \)), it can be seen that the quantum efficiency reduces to the following

\[
\eta = \frac{1 + R_e e^{-\text{ad}}(1 - R_f)(1 - e^{-\text{ad}})}{1 + R_f R_e e^{-2\text{ad}} - 2 \sqrt{R_f R_e e^{-\text{ad}}} \cos(2\beta L + \Phi_f + \Phi_e)} \hspace{1cm} \text{(4.14)}
\]

which is the same as that given in [6]

The responsivity \( \Re \) of a photodetector is defined as the ratio of the photocurrent and incident optical power. It depends on the quantum efficiency \( \eta \) of the photodetector and is given by

\[
\Re = \eta \times \frac{q}{h \nu} \hspace{1cm} \text{(4.15)}
\]
4.3 Results and Discussions:

In Fig. 4.1, the quantum efficiency has been plotted as a function of wavelength to verify our model with the experimental data (at zero bias and 0.5 V) given in [9] and reasonably good agreement has been found. The main parameters taken for the analysis are, active layer thickness of 1450 nm, absorption coefficient of Ge of $3.4 \times 10^3$ at 1550 nm, photodetector diameter ranging from 10μm to 78μm, bottom mirror reflectivity of 55% and assuming top mirror reflectivity of 90%. Simulated data taken from [9] are also plotted in this figure. It has been seen from the figure that the experimental data show closer agreement with our model than with the simulated data of [9]. Present model considers the effect of carrier confinement, which has possibly not been considered in the simulation given in [9] resulting in overestimation of the quantum efficiency at zero bias, as at low bias the effect of carrier confinement is significant. Throughout the study, the cavity parameters are chosen in such a way that the quantum efficiency always becomes maximum due to resonance in the cavity. In the present analysis, variation of this maximum quantum efficiency with different parameters has been studied.

Plot of quantum efficiency with respect to active layer thickness for conventional and resonant cavity enhanced Schottky photodetector is shown in Fig. 4.2. The quantum efficiency of the resonant cavity enhanced Schottky photodetector is oscillatory in nature due to the interference of incident and reflected rays of gradually varying phase with thickness. For some values of active layer thickness, the quantum efficiency maxima occur due to constructive interference of waves confined between the mirrors. Similarly, quantum efficiency minima occur for some values of the active layer thickness, due to destructive interference of waves. It is noticeable that for some values of active layer thickness, the quantum efficiency of the RCE Schottky photodetector becomes much larger than the quantum efficiency of the conventional Schottky photodetector. So, if resonant cavity enhanced photodetector is fabricated with
Fig. 4.1 Plot of quantum efficiency as a function of wavelength, $\lambda$, for the reverse bias of 0V for model verification. Experimental data are taken from [9].

Fig. 4.2 Plot of quantum efficiency as a function of active layer thickness for both conventional and RCE Schottky photodetector. Reflector parameters are $R_f=0.55$, $R_s=0.80$, $\varphi_j=0$, $\varphi_h=0$. 
the submicron absorption layer thicknesses corresponding to these maxima positions (Fig. 4.2), it is possible to achieve large quantum efficiency.

In Fig. 4.3, the quantum efficiency at 1.55μm wavelength has been plotted as a function of active layer thickness \(d\) for different bias voltages using Eq. (4.13). It can be seen from the figure that the quantum efficiency initially increases with increase in \(d\), and then decreases after attaining peak. The particular value of \(d\) for which peak occurs depends on the applied bias. This is due to the fact that with increase in layer thickness, quantum efficiency increases mainly for enhanced absorption. However, some of the thermionically emitted holes are lost by recombination. Thus, overall number of holes, collected at the contacts and, hence, quantum efficiency reduces due to the carrier confinement effect. But, due to the usual predominant effect of \(d\) on quantum efficiency, quantum efficiency increases with increase in \(d\). The usual variation of quantum efficiency with \(d\) is that it starts to saturate as \(d\) increases. So, the decrease of the quantum efficiency at higher value of \(d\) is due to the predominant effect of the carrier confinement. The effect of confinement is again bias dependent. As the applied bias increases, the carrier confinement effect starts to dominate for larger \(d\) and so, the peak position shifts towards right with increase in bias. The effect of bias on the quantum efficiency can be seen more clearly from Fig. 4.4. It is clear from the figure that quantum efficiency initially increases and ultimately saturates as bias increases. This can be explained in the following way. With increase in bias, the carrier confinement effect at the Si/Ge hetero-interface gets reduced and finally vanishing at high biases. It has been seen from the figure that the saturated quantum efficiency increases with increase in active layer thickness \(d\) from 0.5μm to 1.0μm due to the predominant effect of \(d\) i.e. enhancement in total absorption. But, the saturation value decreases when \(d\) increases roughly beyond 1.0μm. This is due to the predominant carrier confinement effect at larger \(d\). It may further be mentioned here that for larger thickness \(d\), larger applied bias is required so that
Fig. 4.3 Plot of resonant quantum efficiency as a function of $d$ for different bias

Fig. 4.4 Plot of resonant quantum efficiency as a function of $d$ for different bias
Fig. 4.5 Responsivity and bandwidth product of the photodetector as a function of the active layer thickness for zero bias and 2V bias.
the carrier confinement effect at the hetero-interface vanishes. This is because
the field due to a constant applied bias is less for a larger thickness making the
voltage across the interface also less. This voltage across interface for
confinement effect to vanish is thus requires applied bias to be larger for larger
thickness.

Responsivity is proportional to quantum efficiency as shown in Eq. (4.15).
In Fig. 4.5 the product of responsivity with bandwidth are plotted in against
active layer thickness. It can be seen that the product of bandwidth and
responsivity passes through a maximum depending on the bias. In this plot the
responsivity is assumed to be independent of bias. Active layer thickness ($d$)
being small, standing wave effect (SWE) will be present. However, for the
thicknesses under consideration, the values of $\beta d$ (where $\beta=2\pi n/\lambda$, $n$ is the
refractive index) are such that the spatial variation of amplitude of the optical
field within the cavity is small. Besides, the active layer (Ge) covers almost the
entire region of the cavity, so any small variation will be averaged out. Thus,
SWE will not affect the responsivity significantly in the present case.
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