CHAPTER TWO : BASIC PRINCIPLES IN SEMICONDUCTOR

2.0 Introduction

The understanding of surface recombination velocity and its relationship between effective lifetime are essential in this work. The effective lifetime depends on the bulk lifetime and surface recombination velocity. Hence, this chapter will begin with discussion on the recombination velocity which is determined by the surface localized energy density of states and surface potential. The later sections will study the effective lifetime and its relationship to the surface recombination velocity. Finally, we will propose a simple model to simulate the change of effective lifetime under UV irradiation.

2.1 Surface Recombination Velocity, S_r

The equilibrium concentration of electrons and holes in semiconductor can be changed by a photo-generation of electron-hole pairs, if photons with energies greater than the bandgap are absorbed by electrons in the crystal, the electrons may be excited from the valence band to the conduction band. This process produces excess carriers which persists as long as the light source continues. When the light source is removed, the excess carrier concentration will decay to the equilibrium value by means of recombinations. A recombination may occur either directly by a band-to-band transition or indirectly through localized state in the energy gap as illustrated in Figure 2.1.
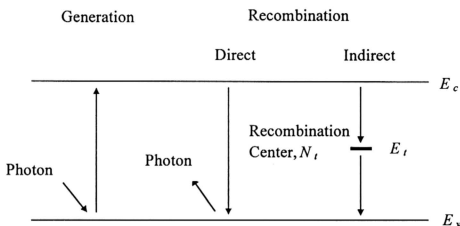
Figure 2.1 : Photo-generation and recombination of minority carriers

With the presence of localized energy state, there are four possible processes in the photo-generation and recombination of excess carriers as proposed by Shóckley, Read and Hall[8], namely:-

(i) Capture of an electron from the conduction band by a localized energy state.

(ii) Emission of an electron from the localized energy state into the conduction band.

(iii) Capture of a hole from the valence band by a localized energy state.

(iv) Emission of a hole from a localized energy state into the valence band.

The above processes can occur both in the bulk and surface regions of the semiconductor. The recombination process proceeds mainly through localized energy state in the energy gap. Using a model that assumed the presence of localized energy state, Shockley and Read[8] analyzed the statistics of recombination in the semiconductor bulk. They have shown that the localized energy states which are located near to the Fermi level may act as a effective recombination centers in the

recombination processes. A similar treatment was also carried out by A. Many[77] in a steady-state but non-equilibrium situation. In this situation, the semiconductor is exposed to a uniform and steady excitation source. The excess carriers are generated by the light source which will then flow to the surface and recombine via surface localized state. The surface recombination is determined by the surface recombination velocity, S_r which is defined as the ratio of the rate of electrons or holes flow into a unit surface area to the excess carrier density in the bulk just below the surface. It can be expressed as :

$$S_r = \frac{\sqrt{K_n K_p} N_t (n_b + p_b)}{2 n_i \{ cosh[\frac{(E_t - E_i)}{kT} - u_o] + cosh[u_s - u_o] \}} \tag{2.1}$$

and
$$u_o = \ln \sqrt{\frac{K_p}{K_n}}$$

where K_p and K_n are the capture probabilities for holes and electrons; E_t and E_i are the surface localized and the Fermi energy levels; u_s is the surface potential; N_t is the surface localized energy state density which may act as a effective recombination center; T is the absolute temperature and k is the Boltzmann's constant.

Since the recombination can occur both at the surface and in the bulk of the semiconductor, the effective minority carrier recombination lifetime, τ_{eff} is given by

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{1}{\tau_s} \tag{2.2}$$

where τ_b and τ_s are the bulk and surface recombination lifetimes respectively.

2.2 Minority Carries Under Continuous Pulsed Optical Excitation

Consider a p-type sample, as shown in Figure 2.2, that is illuminated with light and so

Sample thickness, L

N_o

Laser pulse, λ
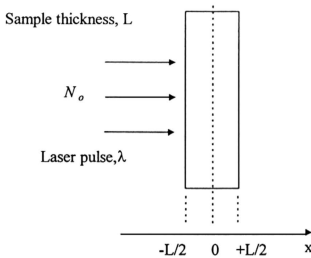
-L/2   0   +L/2   x

Figure 2.2 : Semiconductor sample under laser pulse illumination.

excess carriers are injected from one side of the semiconductor (by photons that create electron-hole pairs at the surface only). The light source is a pulsed laser of wavelength, λ. If the thickness, L of the sample is large as compared to the diffusion length, D_n and $\alpha_\lambda L \gg 1$, the excess minority carriers generated by the laser pulse at time t = 0 is given by[78] of

$$n(x, 0) = g_o \, exp[-\alpha_\lambda (x + \frac{L}{2})] \qquad (2.3)$$

where
$$g_o = N_o \alpha_\lambda (1 - R)$$

and N_o is the number of photons per cm^2 and R is the reflection coefficient of the semiconductor at wavelength λ.

After each pulse, G is zero and the excess minority carriers start to recombine while diffuse throughout the sample. The boundary conditions are assumed such that recombination occurs at the surface at a rate which may be represented by a recombination current, $i_r = n\, S_r$ for a p-type semiconductor. Therefore, the loss of excess minority carriers to the two surfaces at $x = \pm \dfrac{L}{2}$ are

$$D_n\,\frac{\partial n}{\partial x}\bigg|_{x=-\frac{L}{2}} = S_r\, n\left(-\frac{L}{2}, t\right), \text{ and}$$

$$D_n\,\frac{\partial n}{\partial x}\bigg|_{x=+\frac{L}{2}} = S_r\, n\left(+\frac{L}{2}, t\right) \qquad (2.4)$$

and the carrier transport equation for electron is given by

$$\frac{\partial n}{\partial t} = \frac{1}{q}\,\nabla \cdot J_n - U_{nt} \qquad (2.5)$$

where J_n is the electron current density; U_{nt} is the net rate of recombination and q is the electronic charge.

Substituting the Equations (2.4) into Equation (2.5) to satisfy the boundary conditions.

By using the Fourier transform analysis, the solution for excess minority carriers as a

function of x and t is

$$n(x,t) = exp[-\frac{t}{\tau_b}] \sum_j \{A_j \ exp[-\alpha_j^2 D_n t] cos[\alpha_j x]\}$$

where $\qquad c \ ot \ \delta_j \ = \ [\frac{2D_n}{S_r L}] \ \delta_j \qquad , \qquad \delta_j = \frac{\alpha_j L}{2}$ $\qquad$ (2.6)

and A_j is a Fourier coefficient. The bulk recombination appears explicitly in the

exponent term, $exp[-\frac{t}{\tau_b}]$ while the surface recombination appears implicitly in the

term, $\alpha_j^2 D_n$. Taking a Gaussian laser pulse and averaging the density of the excess

carriers from $-\frac{L}{2}$ to $+\frac{L}{2}$, the change of minority carriers as a function of time is then

$$n(t) = [\frac{1}{L}] \sum_{j=1}^{\infty} \{\{[\frac{A_j}{\alpha_j}] \ sin[\frac{\alpha_j L}{2}] \ exp[-\frac{1}{2}[(\frac{1}{\tau_b} + \alpha_j^2 D_n)\sigma]^2]\}$$

$$\{erf[\frac{T_o}{\sqrt{2}}\sigma + \frac{\sigma}{\sqrt{2}}(\frac{1}{\tau_b} + \alpha_j^2 D_n)] - erf[-\frac{(t - T_o)}{\sqrt{2}}\sigma + \frac{\sigma}{\sqrt{2}}(\frac{1}{\tau_b} + \alpha_j^2 D_n)]\}$$

$$\{exp[-(\frac{1}{\tau_b} + \alpha_j^2 D_n)(t - T_O)]\}\ \}$$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (2.7)

where T_o is the center of the Gaussian pulse and 2σ is the Gaussian pulse width. The solution for the above Equation (2.7) consists of a sum of time-dependent decaying terms from $j=0$ to ∞ with the characteristic constants of

$$\lambda_j = (\frac{1}{\tau_b} + \alpha_j^2 D_n) \tag{2.8}$$

The first component in the Equation (2.8) is due to bulk recombination and the second component is due to the surface recombination which may be defined as $\dfrac{1}{\tau_{Sj}} = \alpha_j^2 D_n$, where τ_{Sj} is the surface recombination lifetime for the j-th time-dependent decaying term. However, the higher order time-dependent decaying terms (j $\rangle$ 1) are decaying faster than the first time-dependent decaying term ($j=1$) in Equation (2.7). Therefore, the first time-dependent decaying term predominates the Equation (2.7) when t $\geq \tau_{S1}$ which can be represented by the characteristic constant, that is

$$\frac{1}{\tau_o} = \lambda_1 = \frac{1}{\tau_b} + \alpha_1^2 D_n \tag{2.9}$$

where α_1 is the first root of Equation (2.6). τ_o is a measurable quantity and it may be defined as the effective minority carriers lifetime of the semiconductor ($\tau_{eff} = \tau_o$) :

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{1}{\tau_{S1}} \tag{2.10}$$

2.3 Relationship Between Effective Minority Carrier Lifetime and Surface Recombination Velocity

As have been described in the previous Section 2.2, the decay of the photo-generated carriers by a Gaussian laser pulse is predominated by a the first time-dependent decaying term if $t \geq \tau_{S1}$. The effective minority carrier lifetime given in the Equation (2.10) can be rewritten as

$$\tau_{eff}(t) = \frac{\tau_b}{1 + D_n \alpha_1^2 \tau_b} \qquad (2.11)$$

where

$$cot\ \frac{\alpha_1 L}{2} = \frac{D_n \alpha_1}{S_r(t)}$$

There are three special cases to determine the relationship between effective minority carrier lifetime, τ_{eff} and surface recombination velocity, S_r.

Case I : For $S_r L \ll 2 D_n$, $cot[\frac{\alpha_1 L}{2}] \approx \frac{2}{\alpha_1 L} = \frac{D_n \alpha_1}{S_r}$,

Thus the effective lifetime is $\qquad \tau_{eff}(t) = \dfrac{\tau_b}{1 + \dfrac{2\tau_b S_r(t)}{L}} \qquad (2.12)$

Case II : For $S_r L > 2 D_n$, $\quad \dfrac{\alpha_1 L}{2} \approx cot^{-1}[\dfrac{\alpha_1 D_n}{S_r}] \approx \dfrac{\pi}{2} - \dfrac{D_n \alpha_1}{2}$,

and thus the effective lifetime is $\qquad \tau_{eff}(t) = \dfrac{\tau_b}{1 + \dfrac{\pi^2 D_n \tau_b S_r^{2}(t)}{[S_r(t)L + 2 D_n]^2}}$ $\qquad (2.13)$

Case III : For $S_r L \gg 2 D_n$, $\dfrac{\pi}{2} = \dfrac{\alpha_1 L}{2}$,

the effective lifetime is therefore $\quad \tau_{eff}(t) = \dfrac{\tau_b}{1 + \dfrac{\pi^2 D_n \tau_b}{L^2}}$ $\qquad (2.14)$

For the extreme case III, due to the large surface recombination velocity, S_r, the surface act as an "infinite sinks" for the photo-generated carriers.