Modeling Minority Carrier's Recombination Lifetime of p-Si Solar Cell

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Abstract- This paper presents the qualitative analysis of the variation of effective lifetime of minority carriers in p-type Si solar cell due to different recombination mechanisms associated with it. There is a direct relation between the minority carrier lifetime and the solar cell efficiency. The higher lifetime of minority carrier results in increased conversion efficiency of silicon solar cell. As silicon wafers are endowed with different crystal defects and grain boundaries, a reduced minority carrier lifetime is observed for both bulk and surface recombination processes that occur through these defects. A detailed knowledge of the role of recombination processes on carrier lifetime will facilitate the design of high efficiency solar cell.

Keywords- recombination; lifetime; solar cell.

1. Introduction

The concepts of carrier lifetime in semiconductor materials and average life expectancy in demography are similar. Like common mortals, electrons (and holes) die after some time and the average of this time is called the minority carrier life time. The rate at which they disappear or recombine, is given, in p-type material by $\Delta n/\tau$, , where is the electron lifetime, and is the excess electron concentration, which is essentially equal to the total electron population in most practical cases. In a steady-state situation the generation and recombination rates are perfectly balanced. When a typical 300 μm thick silicon wafer is illuminated by strong sunlight of irradiance 1000 mW/cm², electrons and holes are generated at a rate of GL= $9 \times 10^{18} cm^{-3} s^{-1}$ [1]:

$$G_L = \frac{\Delta n}{\tau} \qquad (1)$$

In a solar cell it is important to determine the electron population. Because the voltage of a solar cell is directly related to it and is given by [2]:

$$V_{OC} = \frac{kT}{q}\left(\frac{\Delta n (N_A + \Delta p)}{n_i^2} + 1 \right) \qquad .(2)$$

In addition, cell's output current is also related to the life time. This is because electrons take some time to travel across the silicon wafer and they reach the pn junction only if their life expectancy is long enough to complete the journey.

The lifetime indicates the quality of silicon material. This quality depends, primarily, on the growth process like FZ or CZ grown. Besides, lifetime can change when wafers are processed at high temperature or subjected to certain treatments. It is, therefore, essential to model the carrier lifetime before going for rigorous experiments or to be ascertained about correctness of experimental results.

In this venture, our aim was to get a solid understanding of the variation in minority carrier lifetime and their impacts on the conversion efficiency of c-Si solar cells due to different recombination mechanisms associated with c-Si.

2. Concept of Minority Carrier Recombination Lifetime

Generation in semiconductors refers to the process by which electron-hole pairs are created. The energy required for the excitation of an electron from valence band to conduction band can come from thermal process or through the absorption of photons. Recombination refers to the inverse processes by which the electron-hole pairs are lost due to the spontaneous transition of an excited electron from conduction band to an unoccupied state in valence band. The

excess energy and the change in the momentum are either released as photons or phonons or transferred to other carriers, which ensure energy and momentum conservation for the individual processes of electron hole recombination.

In thermal equilibrium, generation rate, G_0 is counterbalanced by recombination rate R_0, leading to constant electron-hole product, $n_0 p_0 = n_i^2$. If the system is passed through an external optical excitation, both the new generation rate, G and recombination rate, R will be greater than the thermal generation and recombination rate which will lead to increased non equilibrium electron-hole densities n and p with $np \rangle n_i^2$. As thermal equilibrium can't be reached instantaneously after switching off the external generation source, the excess carrier densities, $\Delta n = n - n_0$ and $\Delta p = p - p_0$ decay successively with net recombination rate, $U = R - R_0$, which is a characteristic of the individual recombination mechanism and vanishes in thermal equilibrium. Assuming charge neutrality, i.e, $\Delta n = \Delta p$, the time dependent decay of the excess carrier density is defined by the following rate equation [3].

$$\frac{\partial \Delta n(t)}{\partial t} = -U(\Delta n(t), n_0, p_0) \qquad (3)$$

According to Eq. (3), the time dependent decay of Δn then follows an exponential law. The time constant of this exponential decay represents the recombination lifetime - often also referred to as the carrier lifetime or lifetime - which is thus generally defined via the following equation [3].

$$\tau(\Delta n, n_0, p_0) := \frac{\Delta n}{U(\Delta n(t), n_0, p_0)} \qquad (4)$$

The recombination lifetime is a property of the carriers within the semiconductor, rather than a property of the semiconductor itself. As such, it is a weighted average across all the carriers, whose individual behaviours may be influenced by different factors, including surfaces, bulk defects and the density of carriers, besides the fundamental properties of the semiconductor material. Interpreting the recombination lifetime can, therefore, be difficult as it represents a number of specific recombination mechanisms occurring simultaneously within the bulk and at the surfaces. For this reason, the recombination lifetime is often referred to as an effective lifetime.

3. Recombination Mechanisms and Carrier Lifetime

Once the electron-hole pairs are generated by absorption in the silicon, they are exposed to several recombination mechanisms. These processes occur in parallel and the recombination rate is the sum of those for individual processes. Different recombination mechanisms and the lifetime associated with them are discussed below. The theory is supported by simulation results too.

3.1. Radiative Recombination

Radiative recombination is simply the direct annihilation of an electron-hole pair. It is the inverse process to optical generation, the excess energy being released mainly as a photon with energy close to that of the bandgap. It involves a conduction band electron falling from an allowed conduction band state into a vacant valence band state (a hole). The radiative recombination rate, U_{rad}, therefore, depends on the concentration of free electrons, n, and free holes, p [3]:

$$U_{rad} = B(np - n_i^2) \qquad (5)$$

where B is the coefficient of radiative recombination. The coefficient B directly reflects the quantum-mechanical probability of a radiative transition, which strongly depends on the band structure of the semiconductor.

Inserting the non-equilibrium concentration n = n0+Δn and p = p0+Δp in Eq. (5), which upon use in Eq. (3) and assuming charge neutrality (Δn=Δp), following general expression for radiative recombination lifetime, τ_{rad} yields [3]:

$$U_{rad} = B(n_0 + p_0)\Delta n + B\Delta n^2 \qquad (6)$$

$$\tau_{rad} = \frac{1}{B(n_0 + p_0) + B\Delta n} \qquad (7)$$

From Eq. (7), the common relationships for the radiative lifetime in n-type and p-type material under low injection (τ_{rad}, l_i) and high injection conditions (τ_{rad}, h_i) can be determined

$$\tau_{rad,li} = \frac{1}{BN_{dop}} \qquad and \qquad \tau_{rad.hi} = \frac{1}{B\Delta n} \qquad (8)$$

From Fig. 1, it can be seen that the radiative lifetime depends on the inverse of the carrier density. Therefore, τ_{rad} is constant at low injection, but then decreases and continues to decrease as the injection level increases.

While radiative recombination is typically the dominant recombination process in direct semiconductors, where it forms the basis for the operation of light-emitting diodes, it is considered to be small or even negligible compared to other recombination processes in indirect semiconductors such as silicon.
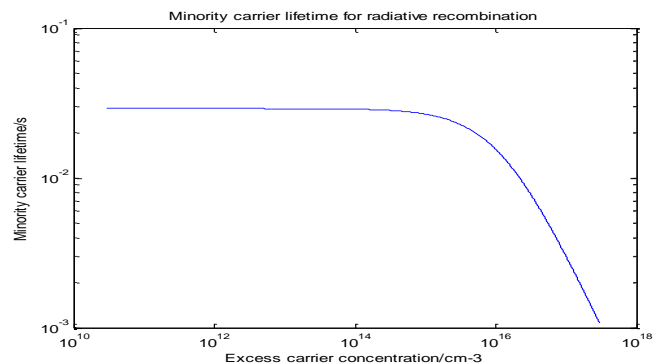

Fig. 1. Radiative recombination lifetime

3.2. Auger Recombination

Traditionally, Auger recombination is viewed as a three-particle interaction where a conduction band electron and a valence band hole recombine, with the excess energy being transferred to a third free electron or hole. The charge carriers involved are assumed to be non-interacting quasi-free particles. The *eeh* process denotes when the excess energy is transferred to another electron, with the recombination rate given by $U_{eeh}=C_n n^2 p$. Similarly, the ehh process denotes when the excess energy is transferred to another hole, with recombination rate $U_{ehh}=C_p n^2 p$, where C_n and C_p are Auger coefficients. The total Auger recombination rate, U_{Auger} is then given by [4]:

$$U_{Auger} = C_n n^2 p + C_p np^2 \qquad (9)$$

from which the common relationships for the Auger lifetime in n-type and p-type material under low injection ($\tau_{Auger,li}$) and high injection conditions ($\tau_{Auger,hi}$) can be determined. For n-type silicon

$$\tau_{Auger,li} = \frac{1}{C_p N_D^2} \quad and$$
$$\tau_{Auger,hi} = \frac{1}{(C_n + C_p)\Delta p^2} \qquad (10)$$

$$\tau_{Auger,li} = \frac{1}{C_p N_A^2} \quad and$$
$$\tau_{Auger,hi} = \frac{1}{(C_n + C_p)\Delta n^2} \qquad (11)$$

for p-type silicon, where Ca=□Cn+Cp is the ambipolar Auger coefficient. The most commonly quoted values for the Auger coefficients appear to be those determined by Dziewior and Schmid (Cn=2.8x10-31cm6s-1 and Cp=0.99x10-31cm6s-1) for silicon with a doping concentration greater than 5x1018cm-3. The implied value for the ambipolar Auger coefficient is then Ca=3.79 x 10-31cm6s-1 [5].

From Eq. (10) and (11), it can be seen that the Auger lifetime ideally depends on the inverse of the carrier density squared and this can be better explained by the Fig. 2.
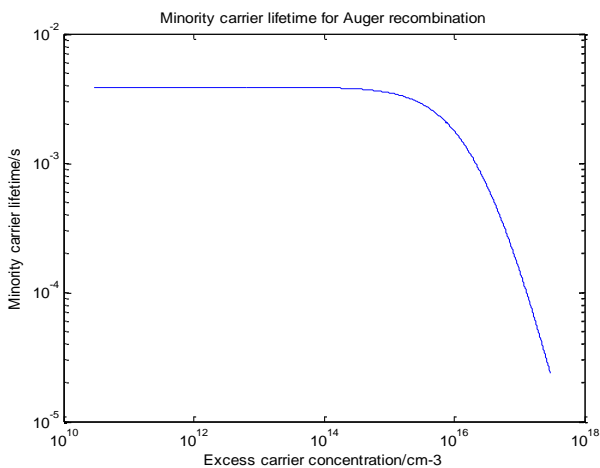

Fig. 2. Auger Recombination lifetime

It shows a stronger dependence with the injection level than τrad, and therefore, Auger recombination will become the dominant mode of recombination in silicon for high injection levels, as might occur in concentrator solar cells, or for high dopant densities, as occurs in heavily doped emitter regions of silicon solar cells.

3.3. Shockley-Read-Hall(SRH) Recombination

The presence of defects in a semiconductor crystal due to impurities or crystallographic imperfections such as dislocations produces discrete energy levels within the bandgap. These defect levels, also known as traps, greatly facilitate recombination through a two-step process where a free electron from the conduction band first relaxes to the defect level and then relaxes to the valence band where it annihilates a hole. The dynamics of this recombination process first analysed by Shockley and Read and Hall [8-9], with the recombination rate, USRH, for a single defect level given by [3]:

$$U_{SRH} = \frac{np - n_i^2}{\tau_{p0}(n + n_1) + \tau_{n0}(p + p_1)} \qquad (12)$$

where τ_{n0} and τ_{p0} are the fundamental hole and electron lifetimes which are related to the thermal velocity of charge carriers, ,the density of recombination defects, N_t, and the capture cross-sections, σ_n and σ_p , for the specific defect [3]:

$$\tau_{p0} = \frac{1}{\sigma_p v_{th} N_t} \quad and$$
$$\tau_{n0} = \frac{1}{\sigma_n v_{th} N_t} \qquad (13)$$

n_1 and p_1 are statistical factors defined as [6]:

$$n_1 \equiv N_C \exp\left(\frac{E_t - E_C}{kT}\right) \quad and$$
$$p_1 \equiv N_V \exp\left(\frac{E_C - E - E_t}{kT}\right) \qquad (14)$$

here N_C and N_V are the effective density of states at the conduction and valence band edges, E_C and E_G are the conduction band and bandgap energies and Et is the energy level of the defect.

It follows from Eq. (3) that the SRH lifetime, , can be expressed as:

$$\tau_{SRH} = \frac{\tau_{no}(p_0 + p_1 + \Delta n) + \tau_{p0}(n_0 + n_1 + \Delta n)}{n_0 + p_0 + \Delta n} \qquad (15)$$

From simulated results in Fig.3, and Fig. 4, it can be seen that the SRH lifetime is constant for low level injection densities where it increases quadratically for high injection level. The effective lifetime in multicrystalline silicon is mostly predominated by SRH recombination process at high

injection level of carrier densities (see Fig.6b). An important result follows from Eq. (15) is that the traps with energies close to the centre of the bandgap (deep defects) are the most effective recombination centres.
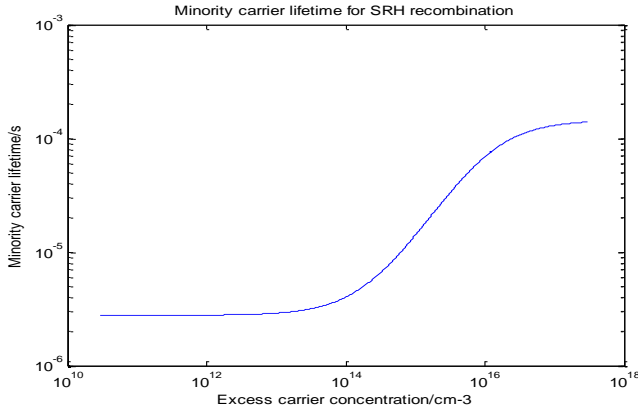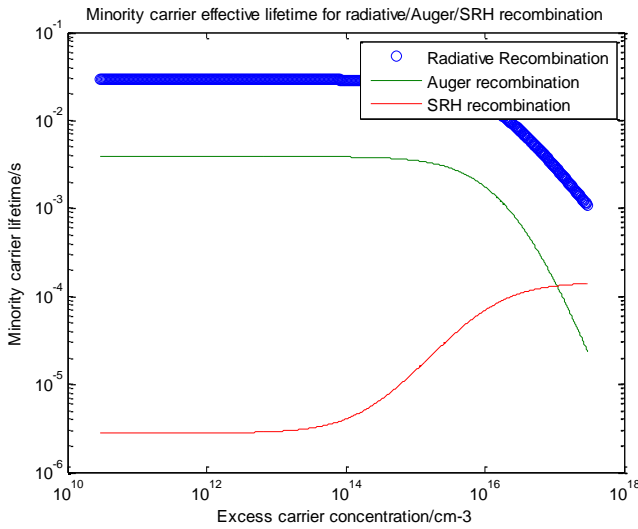

Fig. 3. SRH recombination lifetime

Fig. 4. Bulk recombination lifetime curves for SRH recombination, radiative recombination and free particle Auger recombination.

3.4. Surface Recombination

The surfaces or interfaces of a silicon substrate represent a severe discontinuity in its crystalline structure. The large numbers of partially bonded silicon atoms give rise to many dangling bonds, and therefore, a large density of defect levels are found within the bandgap near the semiconductor surface. Even if the silicon surface is not bare, say due to a native oxide, the presence of silicon-oxygen bonds can stress the crystal structure at the surface, which again introduces many defect states. The SRH analysis of section 3.3 again applies, although it has to be reformulated in terms of recombination events per unit surface area, rather than per unit volume.

For a single defect at the surface, the rate of surface recombination, U_S is given by [3]:

$$U_s = \frac{n_s p_s - n_i^2}{\dfrac{n_s + n_1}{S_{p0}} + \dfrac{p_s + p_1}{S_{n0}}} \qquad (16)$$

where n_s and p_s are the concentrations of electrons and holes at the surface, and S_{p0} and S_{n0} are related to the density of surface states per unit area, N_{ts}, and the capture cross-sections, σ_n and σ_p, for the specific defect [3]:

$$S_{n0} \equiv \sigma_n v_{th} N_{ts} \quad and$$
$$S_{p0} \equiv \sigma_p v_{th} N_{ts} \qquad (17)$$

In reality, defect levels are so numerous that they can be considered to be continuously distributed throughout the bandgap, and both their density and capture cross-sections will be dependent on their energy level.

Similar to the definition of the recombination lifetime in Eq. (3), the surface recombination velocity, S is defined as

$$U_s \equiv S\Delta n_s \qquad (18)$$

and so the surface recombination velocity can be related to the fundamental properties of the surface defects through Eq. (18). It is the surface recombination velocity, S, that is typically used for quantifying surface recombination processes. Surface recombination lifetime is given as [7]:

$$\tau_{surface} = \left(\frac{2S}{W} + \frac{1}{D_n} \left(\frac{W}{\pi} \right)^2 \right)^{-1} \qquad (19)$$

Fig. 5 shows the impact of wafer thickness and surface recombination velocity (SRV) on the variation of minority carrier lifetime. It is obvious that surface recombination velocity is the highest on the top of the surface of the wafer while it decreases sharply along the deeper into the wafer. As expected, a reciprocal relationship between the minority carrier lifetime and SRV or wafer thickness, respectively, is generally observed from the simulated results. Detailed knowledge of the surface properties of the Si wafers will help to choose the best or to explore the new passivation techniques to circumvent the minority carrier lifetime deterioration due to adverse effect of SRV and dangling bonds over the wafer's surfaces.
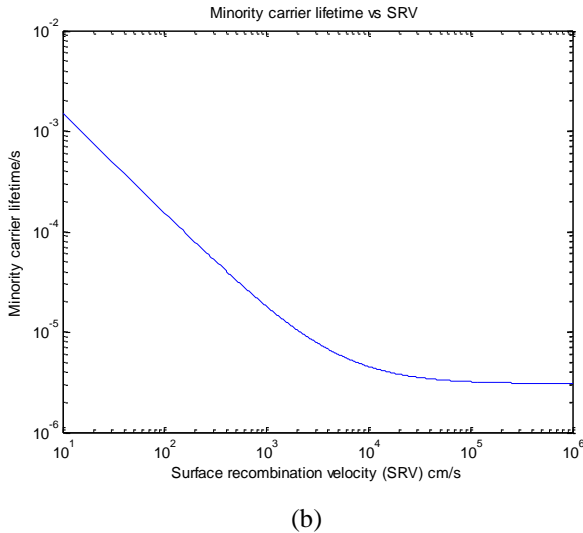

(a)

(b)

(b)
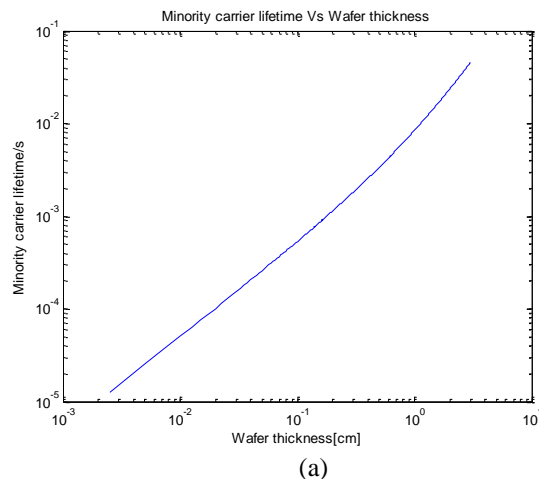
Fig. 5. Variation of minority carrier lifetime with respect to (a) wafer thickness, and (b) surface recombination velocity, respectively.

Fig. 6. (a) Effective lifetime of minority carrier (b) Dependence of effective lifetime on different recombination mechanisms.
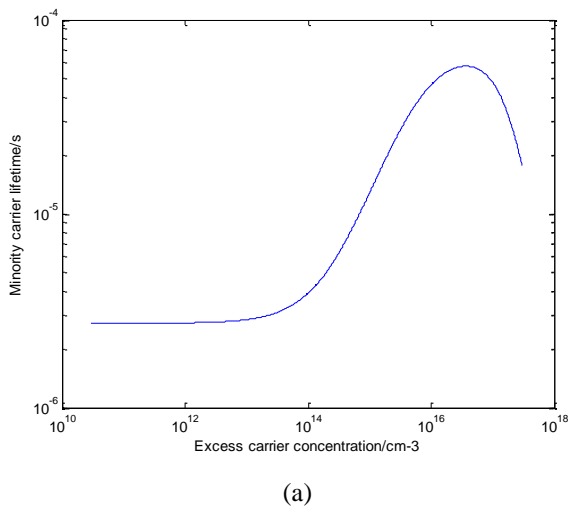
4. Effective Lifetime

The four recombination mechanisms discussed so far may occur simultaneously in a given sample. For an independent process the overall recombination rate is just sum of the individual recombination rates, resulting in an effective lifetime τ_{eff} given by [3]:

$$\frac{1}{\tau_{eff}} = \left(\frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{rad}} \right) + \frac{1}{\tau_{surface}}$$
$$= \frac{1}{\tau_{bulk}} + \frac{1}{\tau_{surface}}$$

(20)

The simulated results that shown in Fig.6 shows that the effective lifetime is dominated by bulk recombination process rather than intrinsic recombination mechanisms. The lifetime increases with injection level for SRH recombination through deep defects but decreases for intrinsic bulk recombination processes. The resulting effective lifetime is, therefore, dominated by SRH recombination at low injection and Auger recombination at high injection.
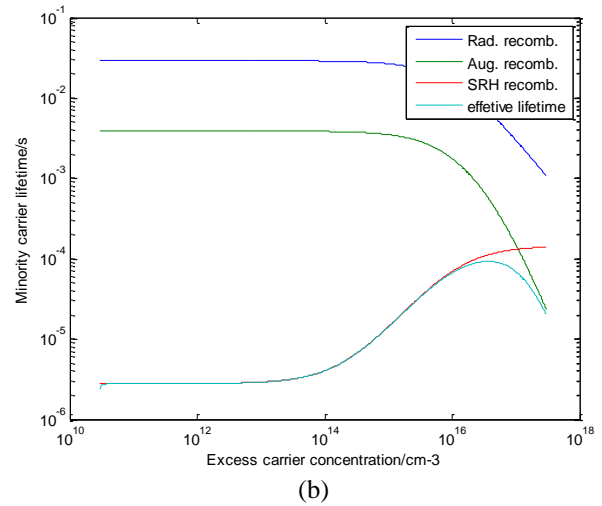
As mc-Si riches with numerous crystal defects that act as defect centres for SRH recombination, minority carrier lifetime in mc-Si solar cell is much lower than that of mono-crystalline silicon solar cell. This is one of the vital reasons why solar cells made from mono-Si wafers have higher energy conversion efficiency compare to mc-Si wafers.

5. Conclusion

To ensure an accurate interpretation of the recombination lifetime, the principle recombination mechanisms in silicon have been studied analytically. The parameters for modeling are taken from the experimental data of published literatures. The simulated results showed a good agreement with those experimental data. It was shown that recombination greatly reduce the effective carrier lifetime, hence, therefore, reduces the performance of solar cells, particularly the cell voltage and efficiency. Indeed, it could be concluded that besides the avoidable losses in silicon solar cells, recombination losses are the most significant for both high efficiency laboratory cells and commercial multicrystalline cells.

(a)

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