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Bulk Recombination Lifetime of Minority Carrier in Compensated p-Si Solar Cell

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Abstract-A numerical study has been carried out to extract bulk recombination lifetime of minority carrier in Fe contaminated p-type compensated silicon solar cell. In this paper it has demonstrated that the compensation will lead to a substantial increase in both intrinsic and Shockley-Read-Hall (SRH) lifetime for minority carrier in p-Si. The utmost importance of this result is the control of compensation level that will facilitate strong improvements in silicon solar cell efficiencies.

Keywords-Compensation, SoG, Recombination lifetime, Solar cell.

1. Introduction

Fast diffusion of solar PV requires the cost level cut down to acceptable minimum so that it can meet the grid parity of conventional electricity. Among several approaches to reach this goal, using inexpensive low-grade silicon, such as solar grade silicon (SoG), is a way to minimize the cost of solar cells production. This low-cost SoG material often contain high concentration of unwanted dopant species such as B, P and Al. These doping species introduce energy levels in the Si bandgap in the vicinity of the conduction band (E_C) for donor atoms (i.e. P) or in the vicinity of the valence band (E_V) for acceptor atoms (i.e. B).These energy levels enhance the trapping of the free carriers and responsible for low minority carrier lifetime due to Shockley-Read-Hall (SRH) recombination [1]. Previous works have determined the maximum concentrations of dopants that can be tolerated in the SoG feedstock without an excessive loss in the efficiency of the resulting solar cells, and have demonstrated the solar cell performance on compensated material that might be comparable with noncompensated solar cells [2,3]. This works focused on the Electronic effects of compensation in SoG silicon via modeling both the intrinsic recombinations (i.eradiative and Auger recombination) and recombination through defects (SRH recombination) to extract the minority carrier lifetime in p-Si solar cell. The compensation in p-Si was done with phosphorus (P) for PV applications and it was assumed that cell is intentionally contaminated by interstitial iron, Fe_i. [Fe_i] equals to defect density $N_t$which acts as trap/recombination centre for SRH recombination. Here it is shown that compensation in certain cases will lead an increase in carrier lifetime.

2. Theory of Recombination Lifetime

In thermal equilibrium, electron-hole product ($n_0 p_0 = n_i^2$) in a semiconductor is constant, hence the generation rate G_0 counterbalance the recombination rate R_0. If this equilibrium is perturbed by means of optical or thermal excitation, excess carriers ($\Delta n = n - n_0$ or $\Delta p = p - p_0$) are generated. As thermal equilibrium can’t be reached instantaneously after switching off the external generation source, the excess carrier densities decay successively with net recombination rate, $U = R - R_0$, which is a characteristic of the individual recombination mechanism and vanishes in thermal equilibrium. 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 by the following equation [4].

$$\tau(\Delta n, n_0, p_0) = \frac{\Delta n}{U(\Delta n(t), n_0, p_0)} \qquad (1)$$

Crystalline silicon is endowed with both intrinsic recombination and recombination through defects/surface states [5-7]. Intrinsic recombination comprised of radiative and Auger recombination. Radiative recombination is simply the direct annihilation of an electron-hole pair. It involves a conduction band electron falling from an allowed conduction band state into a vacant valence band state (a hole) as shown in the uppermost sketch of the fig.1. 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 as shown in the middle sketch of the fig.1. The charge carriers involved are assumed to be non-interacting quasi-free particles. Based on the experimental results, Kerr and Cuevas [8] developed a general expression for intrinsic recombination lifetime describing the combined effect of Auger and radiative recombination:

$$\tau_{\text{int}\,rinsic} = \frac{1}{(p_0 + n_0 + \Delta n)(1.8\times10^{-24} n_0^{0.65} + 6\times10^{-25} p_0^{0.65} + 3\times10^{-27}\Delta n^{0.8} + 9.5\times10^{-15})} \quad (2)$$

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 as shown in the bottom sketch of the fig.1. The dynamics of this recombination process was first analysed by Shockley and Read and Hall [9,10], with the recombination rate, U_{SRH}, for a single defect level given by [4]:

$$U_{SRH} = \frac{np - n_i^2}{\tau_{p0}(n + n_1) + \tau_{n0}(p + p_1)}, \quad (3)$$

where τ_{p0} and τ_{n0} are the fundamental capture time constants, n_1 and p_1 equal the equilibrium electron and hole densities when the Fermi energy E_F coincides with the energy level E_t of the recombination centre. Plugging equation (3) into equation (1), SRH lifetime can be resolved as:

$$\tau_{SRH} = \frac{\tau_{no}(p_0 + p_1 + \Delta n) + \tau_{p0}(n_0 + n_1 + \Delta n)}{n_0 + p_0 + \Delta n} \quad (4)$$

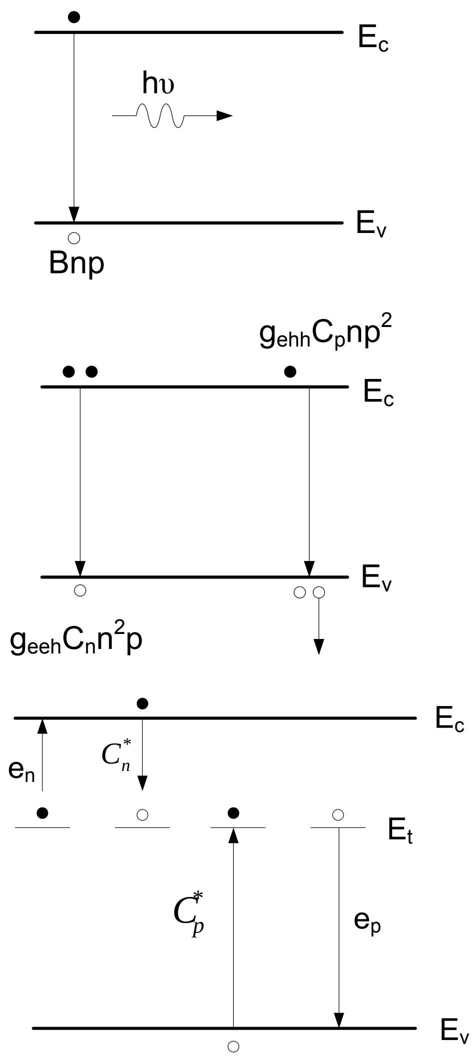

Fig. 1 Radiative, Auger and SRH recombination process, respectively.

Fig.2 shows the injection dependent bulk recombination lifetime of minority carrier in noncompensated p-Si solar cell.

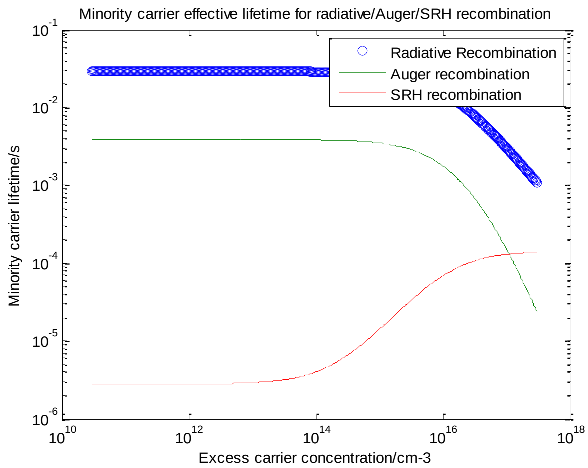

Fig.2. Bulk recombinationslifetime (SRH recombination, radiative recombination and free particle Auger recombination.)fornoncompensated p-Si solar cell [11].

3. Results and Discussion

For the case of compensated p-type silicon ($N_A \succ N_D$), p_0 and n_0 in the equations (2) and (4) have to be calculated by following equations:

$$p_0 = \frac{N_A - N_D}{2} + \sqrt{\frac{(N_A - N_D)^2}{4} + n_i^2} \qquad (5)$$

$$n_0 = \frac{n_i^2}{p_0} = \frac{n_i^2}{N_A - N_D} \qquad (6)$$

The compensation level, C_l is defined as N_D/N_A-N_D, N_A and N_D being the total concentrations of acceptor and donor species, respectively.

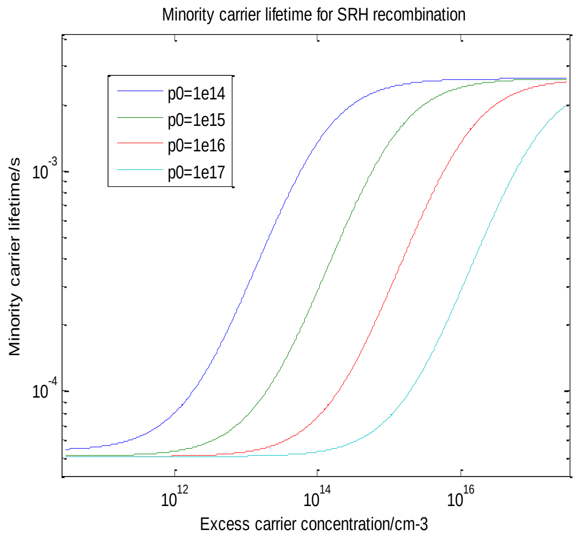

Fig.3. Injection dependent SRH lifetime for four different values of p0 for compensated p-Si solar cell.

Fig. 3 shows the injection level dependent SRH lifetime for compensated p-Si solar cell. It can be seen that SRH lifetime shifts left for low values of p0. As compensation is done by adding donor impurity, hole concentration decreases and results in higher SRH lifetime. A linear increase is found in SRH lifetime with compensation level change as shown in fig. 4. Such injection level effects only occur for deep levels impurity, for example Fe_i in silicon, with a much larger capture cross section for minority carriers than for majority carriers. The larger capture cross section for electrons results in a strong injection dependence in p-Si, and causing an increase in lifetime as the degree of compensation is increased.

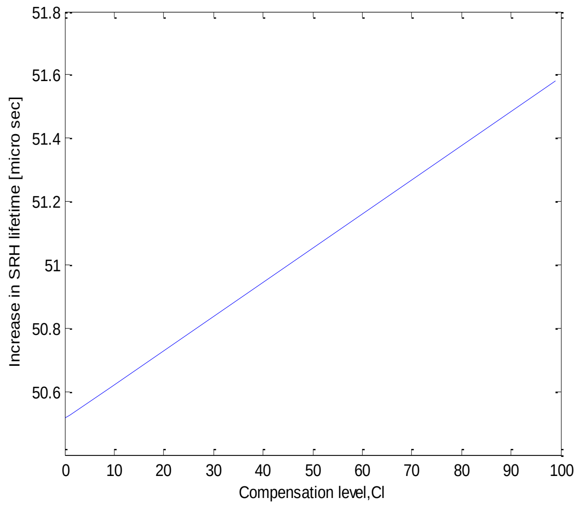

Fig.4. Change in SRH lifetime due to change in compensation level.

In p-Si, it is considered fixed [B] equal to 3×10^{17} cm^{-3} and injection level equal to 10^{12} cm^{-3} while calculating intrinsic carrier lifetime. The simulated results are shown in fig.4. Although the intrinsic recombination lifetime in noncompensated silicon solar cell is almost negligible, from the simulated results, it has found a strong increase in intrinsic lifetime with C_l. Indeed, an absolute gain of 0.02 second is observed (shown in fig.5) for every decade change in C_l which is a huge for p-Si solar cell. This is due to a considerable reduction of the recombination strength of B. This predicted result could lead to strong improvements in the conversion efficiency of highly B doped solar cells. When [B] increases, the Fermi level gets closer to the acceptor energy level and enhances its ability for the capture of minority carriers. When compensation is done by adding donor atoms, a reduction in free carrier concentration in p-Si is normally observed which shifts the Fermi level toward the centre of gap, meaning that the attractivity of neutral B atoms for electron is reduced, and resulting in an increase in carrier lifetime [12, 13].

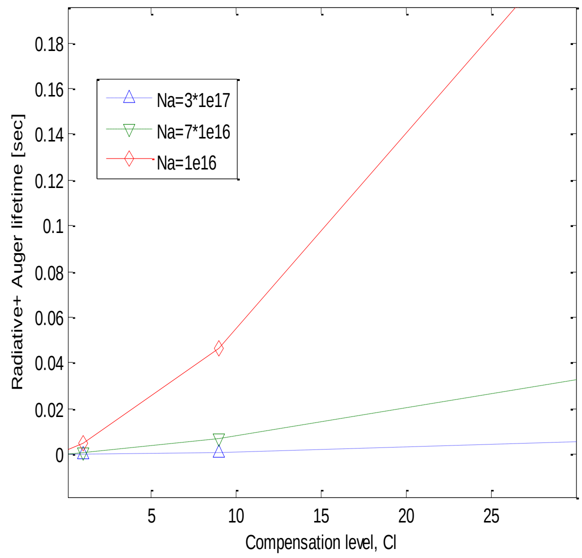

Fig.5. Intrinsic lifetime of compensated p-Si solar cell.

The combined effect of intrinsic and SRH lifetime produce effective lifetime as per Equation 7 which is shown in fig.6. A linear increase in effective lifetime is observed as a logical sequence of improved intrinsic and SRH lifetime for compensation effect.

$$(\tau_{effective})^{-1} = (\tau_{\text{int}rinsic})^{-1} + (\tau_{SRH})^{-1} \quad (7)$$

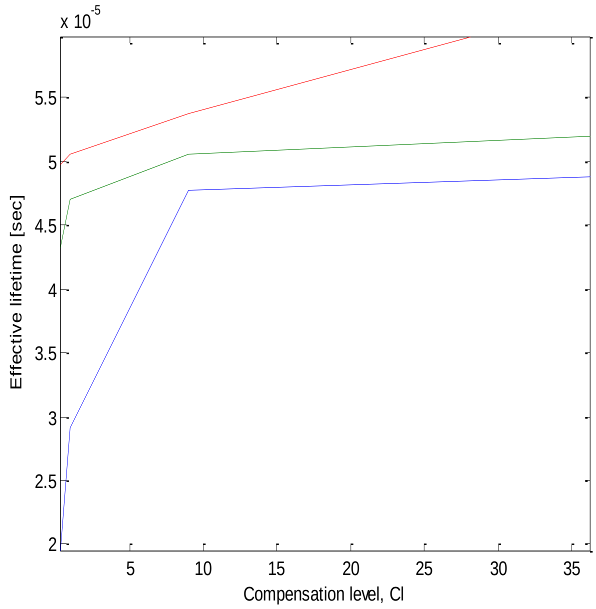

Fig.6. Effective lifetime of minority carrier in compensated p-Si solar cell.

Table 1. List of parameters used in this studies

Parameters used in this study	
Intrinsic carrier concentration, n_i [cm^{-3}]	1.0923×10^{10}
Density of States in E_C, N_C [cm^{-3}]	2.84×10^{19}
Density of States in E_V, N_V [cm^{-3}]	2.68×10^{19}
Energy gap, E_g [eV]	1.124
Thermal velocity, V_{th} [cm/s]	1.1×10^{7}
Donor state energy, E_t [eV]	0.38
electron capture cross section, σ_n [cm^2]	3.6×10^{-15}
Hole capture cross section, σ_p [cm^2]	6.8×10^{-17}
Density of defect states, N_t [cm^{-3}]	5×10^{11}

4. Conclusion

A strong correlation between increased compensation level and measured recombination lifetime in p-Si solar cell has shown in this study. It was found that compensation lead to increased lifetime both for intrinsic recombination and recombination through defect processes which in turns will results in higher cell efficiencies in-terms of better improvement in short circuit current and open circuit voltage of a given cell. A positive impact on solar cell device electrical characteristics is expected herewith. The compensation range between 1×10^{16} and 6×10^{17} has shown here to be the interesting range for PV application. It could infer that the deliberate compensation of low-cost SoG silicon will lead to enhance device performance without expensive additional purification steps indeed.

References

[1] D. Macdonald, "Recombination and Trapping in MulticrystallineSiliocn Solar Cell", PhD thesis. Australian National University, Australia, 2001.

[2] J. Libal et al.., "Effect of Compensation and Metallic Impurities on the Electrical Properties of Cz-grown Solar Grade Silicon," Journal of Applied Physics 104, 10450 (2008).

[3] S. Dubois et al., "Effects of the Compensation Level on the Carrier Lifetime of Crystalline Silicon," Journal of Applied Physics 93, 032114 (2008).

[4] S. Rein, "Lifetime Spectroscopy," Springer, Berlin, Germany, 2005.

[5] Mohammad Ziaur Rahman, Shahidul Islam Khan, "Advances in Surface Passivation of c-Si Solar Cells", *Materials for Renewable and Sustainable Energy, Springer verlag*, 1 (2012) 1-11. doi:10.1007/s40243-012-0001-y.

[6] Mohammad Ziaur Rahman, "Advances in surface passivation and emitter optimization techniques of crystalline silicon solar cell", Renewable and Sustainable Energy Reviews **30** (2014) 734-742, doi: 10.1016/j.rser.2013.11.025.

[7] M. Rahman, "Status of Selective Emitters for p-Type c-Si Solar Cells," *Optics and Photonics Journal*, Vol. 2 No. 2, 2012, pp. 129-134. doi: 10.4236/opj.2012.22018.

[8] M. J. Kerr, and A. Cuevas, "General Parameterization of Auger Recombination in Crystalline Silicon," Journal of Applied Physics, vol. 91(4), 2473 (2002).

[9] R. Hall, "Electron-hole recombination in germanium", Physics Review 87, 387 (1952).

[10] W. Shockley, and W. Read, "Statistics of the recombinations of holes and electrons", Physical Rev.87, 835-842 (1952).

[11] Mohammad ZiaurRahman, Modeling Minority Carrier Recombination Lifetime in Silicon Solar Cell", International Journal of Renewable Energy Research, Vol.2 (1), pp. 449- 454, March, 2012.

[12] Mohammad ZiaurRahman, Mohammad Jahangir Alam, "SRH Recombination Strength of Fe in Compensated Solar Grade Silicon", Photonics letters, Poland, VOL. **5**(3), 118-120 (2013) , doi: 10.4302/plp.2013.3.13

[13] Mohammad Jahangir Alam, Mohammad ZiaurRahman, "Correlation of Fe-rich Defect Centre and Minority Carrier Lifetime in p-Type Multicrystalline Silicon", Applied Mechanics and Materials, 440 (2014) 82-87. doi: 10.4028/www.scientific.net/AMM.440.82