

Effect of surface recombination velocity (SRV) on the efficiency of silicon solar cell

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Surface recombination velocity is an important parameter which strongly impacts the overall performance of the solar cell. A high surface recombination velocity causes the creation of dead layer. The rate of photo generated carriers reduces due to higher surface recombination velocity (SRV). The impact of front and back surface recombination velocities on the important characteristics (namely short circuit current (I_{sc}), open circuit voltage (V_{oc}), conversion efficiency (η) and fill factor FF) of solar cell were investigated by Personal Computer One Dimension (PC1D) simulation software. Higher recombination rate of carriers due to high SRV provide a detrimental impact on the I_{sc} of solar cell. It was noticed that increase in surface recombination rate, the carrier starts to recombine at defected surface there by reducing the performance of the solar cell. The simulation results show that both internal and external quantum efficiency of solar cells reduces drastically with increasing the front and back SRV. The enhancement in efficiency because of the reduction in back SRV is prominent if the junction is shallower and cell thickness is smaller. There are limited advantages of the lower back SRV due to the recombination losses in the front region and front SRV value. The maximum efficiency is coming at FSRV of 100cm/s i.e. 16.33%.

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1. Introduction

A silicon solar cell is typically a p-n junction made in a few hundred-microns thick wafer of p-type silicon having almost 100 cm² area [1]. A heavily doped emitter region with a deep junction results in dead layer at the surface which causes a poor spectral response (SR) of the solar cells for short wavelength of light. On the other hand, if the emitter is doped too lightly or the junction is very shallow, it results in poor ohmic contact between Silver and n-type silicon. The resistive losses also arise as a consequence of lightly doped emitter [2]. Thus, the emitter design influences significantly the performance of the cell. A high surface recombination velocity (SRV) causes the creation of dead layer [3]. When surface recombination velocity increases, the carrier starts to recombine at the defect surfaces due to relatively low minority carrier's lifetime and diffusion length [4]. The carrier's lifetime is basically the average time in which photo generated electron-hole pair recombine. Surface recombination velocity is an important parameter which strongly impacts the overall performance of the device. The dead layer and surface recombination velocity also influences other parameters of the cell [5]. The presence of the dead layer results in poor spectral response of cell at shorter wavelength region and consequently short-circuit current density (J_{sc}) is decreased. Surface recombination mainly affect the short circuit current (I_{sc}) [6]. With increasing surface recombination, the short circuit

current decreases. When surface recombination velocity increases, the carrier starts to recombine at the defect surfaces which reduces the cell performance. Effect of surface recombination velocity (SRV) at the back surface is very low because the generation rate at the back surface is very small. Increase in the surface recombination decreases the value of V_{oc} . Therefore, surface recombination velocity is considered as an essential parameter that strongly affects the solar cell's performance [7, 8]. Numerical simulations were accomplished to determine critical parameters of IBC-SHJ (Interdigitated back contact silicon heterojunction) solar cell. To get high efficiency with that type of realistic structure, the key parameter is very low surface recombination velocity particularly at front surface [9]. The minimum surface-recombination velocity reported was only 0.25 cm/sec on Si (111). The surface seems to be shielded by Si-H covalent bonds, due to which surface dangling bonds do not appear to behave as recombination centers which have consequences for the maximum efficiency of solar cells [10].

The modelling of PV devices relies strongly on the several extrinsic and intrinsic properties of the material. The minority-carriers lifetime and SRV are the intrinsic parameters whereas, the doping level of the front surface is an extrinsic parameter (Abderrezek *et al.*, 2013). Computer based modelling is highly used now a days because it provides a deep understanding of the physical operation of PV cells [11]. By altering the optical model through the cell

transmittance and internal quantum energy (IQE), an improved efficiency solar cell was fabricated [12]. The nano structures of CdS with specific morphology can be produced by changing polyethylene glycol (PEG) concentration with sulphur powder, cadmium acetate and ethylenediamine (EDA) in the reaction system [13]. Assembly of 2D graphene oxide dispersed liquid crystalline materials with CdS nanowires have received extensive unprecedented consideration due to their extraordinary electrical, mechanical and thermal properties [14]. Due to electric field, from LC (liquid crystal) molecules a charge transfers to the nanomaterial, finally that turns into a trap for the ionic charges [15]. Efficiency enhancement of cadmium sulphide nanowire (CdS NW) is most important due to its promising capability of investigation the size and dimensionality [16]. CePO₄ and LaPO₄ nanowires have synthesized with certain aspect ratios by using hydrothermal microemulsion technique under trifling conditions. The aspect ratios of 1D nanostructures could be fine-tuned with simply varying the molar ratios [17]. Demonstrated by computer simulation that n^+pn^+ EWT (emitter-wrap-through) cell is mainly appropriate for thin substrates and low bulk lifetimes. However, to design high-efficiency EWT cell, a lifetime of about 45 ms will be necessary enough [18]. PC1D is a computer-based program and mostly used for the simulation of semiconductor devices. The essential characteristics (I-V and QE) of Si solar cell are attained via simulation by adjusting various key parameters that include thickness of p-type layer, the device area, front and back surface recombination, thickness of n-type layer, front and back surface recombination, doping level of n-type and p-type material, bulk recombination etc [19]. Simulation through PC1D program allows observing the impacts of varying FSRV on the characteristics of solar cell PC1D is a computer-based program and mostly used for the simulation of semiconductor devices. It was developed in 1984 by Paul A. Basauri in order to model semiconductors containing photovoltaic components [20]. By applying different values of FSRV on solar cell in the presence of the dead layer and the outcome of the device was studied. The electrical parameters of the cell and how they influenced by various front surface recombination velocities (FSRV) were also studied.

2. Theoretical modelling

In current work simulation of Si solar cell was performed by changing the SRV of the solar cell. Before simulating solar cell device, the materials which are used to develop the structure must be described briefly. The device area was chosen to be 100cm². The "SI.mat" was selected for all the material properties such as 'dielectric constant', 'carrier mobilities', 'bandgap' etc. Surface texturing of solar cell helps to increase the carrier's absorption rate. The starting material of solar cell is p-type Si wafer doped with the n-type semiconductor to form emitter layer. The thickness and doping level of n and p-type region is adjusted on 3µm, 300µm, 1x10¹⁹cm⁻³ and 1x10¹⁸cm⁻³, respectively.

The optimum doping level of n-type region is 1x10¹⁸cm⁻³, after that point the dead layer (highly doped region) starts to begin near the front surface. The n-type bulk recombination value is kept on 58.78µs and p-type bulk recombination is 1000µs. Different simulation had been performed by varying the FSRV from 100 to 10⁵ cm/s and BSRV from 10 to 10⁴cm/s. In order to simulate Si solar cell after setting all basic parameters, the "Run" command was selected. Both the current-voltage characteristics and quantum efficiency (QE) of solar cell has been obtained through PC1D program. The 'ONE-SUN.EXC' excitation file has been selected to determine the I-V characteristics of Si solar cell. After several simulations, the different values of I_{sc}, V_{oc}, and the P_m (maximum power) determined from I-V curve of solar cell. The 'SCAN-QE.exc' file was chosen to find out the QE of solar cell. The impact of varying FSRV and BSRV values on the cell efficiency and I-V characteristics has been observed from PC1D simulated graphs of solar cell.

3. Results and discussion

The simulation of Si solar cell has been carried out by using PC1D simulation program. Several simulations have been performed to see the impact of FSRV and BSRV on the I-V characteristics and quantum efficiency (QE) of solar cell. The Fig. 1 indicates the simulation results of carriers recombination rate at different SRV. After optimum value the heavily doped region start to begin and consequently the minority carrier lifetime and diffusion length decreases. If the diffusion length increases the lifetime of minority carrier also increases which enhance the cell performance [21]. With increasing the SRV the minority carrier lifetime decreases and hence the efficiency of solar cell reduced. The simulation results of the carriers recombination rate at different SRV has been explained.

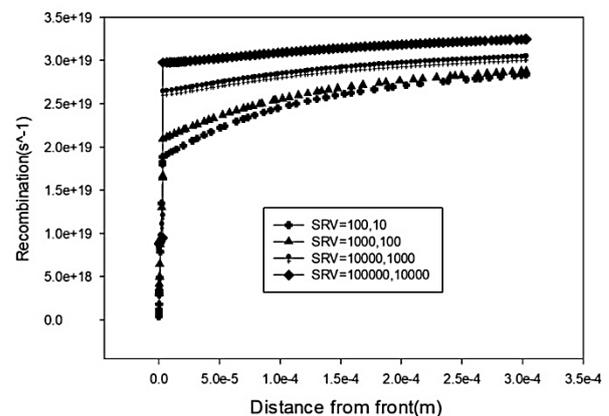


Fig. 1. Characteristic curve of recombination rate at the different front and back surface recombination velocity(S) values of solar cell

From results, it can be seen that carrier's recombination rate increases gradually with increasing SRV of both regions. The high SRV significantly reduces minority carrier lifetime and diffusion length.

The carriers start to recombine quickly as the diffusion length and minority carrier lifetime is relatively low, which cause a notable reduction in the cell efficiency. High recombination rate of carriers due to high SRV clearly indicates the presence of dead layer near the front surface of Si solar cell. Variation in the V_{oc} and I_{sc} values is strongly depend upon the SRV of both n and p -type regions. Higher recombination rate at the both surfaces provides a detrimental effect on the I_{sc} of Si solar cell. The impact of recombination velocity on the V_{oc} and short circuit current has been analysed by varying the front and back SRV of solar cell [22]. The Fig. 2 shows the I-V characteristic curves at different recombination velocities.

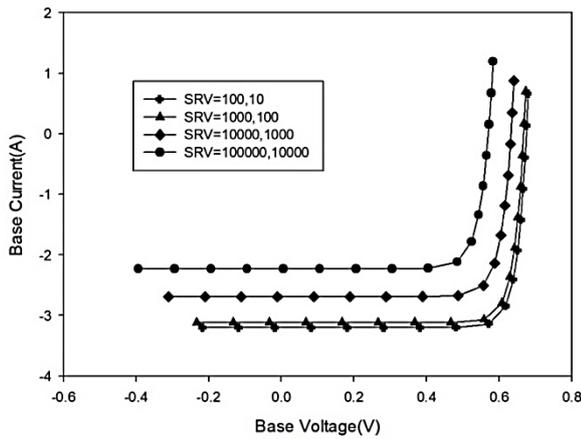


Fig. 2. I-V curve at the different front and back surface recombination velocity (S) values of Si solar cell

Table 1. Output parameters of Si solar cell at different front and back surface recombination velocity (S) values

S_{FSV} (cm/s)	S_{BSV} (cm/s)	V_{oc} (mV)	I_{sc} (mA/c m ²)	V_m (mV)	I_m (mA/c m ²)	P_{max} (mW/c m ²)	FF	η (%)
100	10	674.7	29.11	571.5	28.57	16.33	0.83	16.33
1000	100	667.3	28.36	558.0	27.90	15.57	0.82	15.57
10000	1000	632.4	24.45	556.3	22.90	12.69	0.82	12.69
100000	10000	570.2	20.27	484.4	22.81	9.31	0.80	9.31

The conversion efficiency is the most generally used parameter in order to compare the performance of the solar cells with one another. The simulation results show that the conversion efficiency (η) of Si solar cell is strongly influenced by SRV of both regions. The η decreases as the S values increases due to higher recombination rate of minority carriers near the front surface of solar cell. A notable reduction in the V_{oc} and I_{sc} has also been observed. The rapid decrease in the cell parameters due to higher surface recombination rate is the strong evidence of the presence of 'dead layer' near the front surface of Si solar cell.

The performance of Si solar cell is also characterized by QE measurement, the most important characterization tools for solar cells. Quantum efficiency is the ratio of no. of carrier pairs collected by a solar cell to the no. of photons of a specific energy incident onto the cell. QE either describe as function of energy or as wavelength. Two types

of Quantum Efficiencies are generally considered (i) internal quantum efficiency (IQE) (ii) external quantum efficiency (EQE). Variation in the IQE of Si solar cell due to SRV can be seen from PC1D IQE graph. IQE is generally the ratio of no. of carrier pairs generated to the no. of incident photons. However, the EQE basically the ratio of the no. of carrier pairs generated to the number of photons absorbed by the material. So, the varying FSRV and BSRV makes an extreme impact on the both IQE and EQE of Si solar cell. The carrier's recombination rate increases when the SRV increases. So, the lifetime of minority carriers of solar cell decreases. Higher the S value faster is the recombination of photogenerated carriers. That higher recombination rate due to high SRVs cause a notable reduction in IQE of Si solar cell as shown in Fig 3.

From I-V results it has been observed that, the V_{oc} and I_{sc} strongly affects by FSRV and BSRV of solar cell. The simulated current-voltage curve shows that both V_{oc} and I_{sc} decreases with increasing the SRVs. The reduction in I_{sc} and V_{oc} is observed only due to high recombination rate of carriers near the front surface which highly reduce the cell performance. The FF and efficiency of Si solar cell is also decreasing because both are strongly related to the I_{sc} and V_{oc} . The maximum power (P_m) point has also been observed from I-V curve of solar cell. P_m is the point on the current-voltage curve where I and V are maximum.

The simulated results of various S values on the V_{oc} , I_{sc} , I_m , V_m , P_m , FF and conversion efficiency of Si solar cell is shown in the table 1. Four different values of the SRVs is used in this work. The conversion efficiency is the most generally used parameter in order to compare the performance of the solar cells with one another. The simulation results show that the η of Si solar cell is strongly influenced by SRV of both regions. The η decreases as the S values increases due to higher recombination rate of minority carriers near the front surface of solar cell. A notable reduction in the V_{oc} and I_{sc} has also been observed. The rapid decrease in the cell parameters due to higher surface recombination rate is the strong evidence of the presence of 'dead layer' near the front surface of Si solar cell [23].

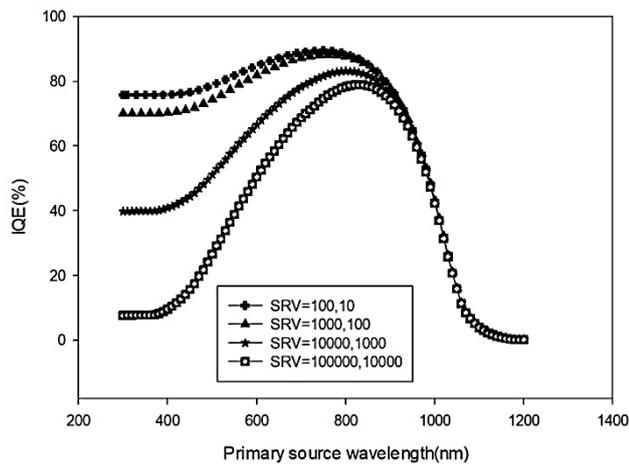


Fig. 3. Variation in IQE at the different front and back surface recombination velocity (S) values of solar cell

EQE is define as the ratio of the no. of carrier pairs generated to the number of photons absorbed by the material. So, the SRV of both regions had a deep impact on the EQE of Si solar cell. Variation in EQE with the varying SRV is shown in Fig. 4. The EQE is strongly related to the reflectance and absorption and of incident photons from the surface of Si solar cell. Higher the reflection of incident photons from the Si interface lower is the rate of photogenerated carriers. The EQE drastically reduces when the reflectance of Si solar cell increases. Moreover, higher S values leads to the higher recombination of charge carriers near the front surface of solar cell. The higher recombination rate causes a loss of carriers which highly reduce the both IQE and EQE. The worst response of solar cell is strong evidence of the presence of 'dead layer' near the front surface.

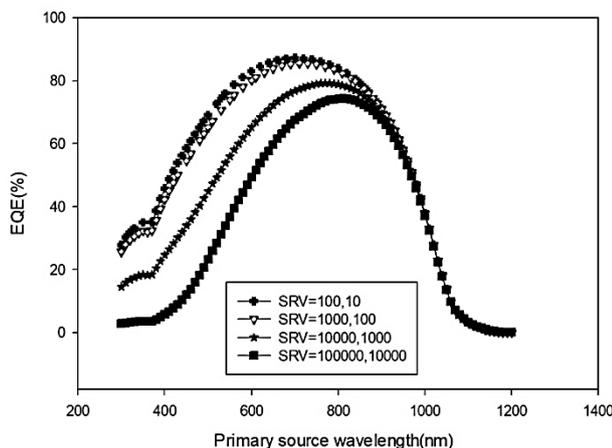


Fig.4. Variation in EQE at the different front and back surface recombination velocity (S) values of solar cell

The maximum efficiency of solar cell was obtained by passivating and texturing the front surface which significantly reduces the recombination velocity. The larger the surface area the better will be the output as the large numbers of light photons fall on the surface of cell.

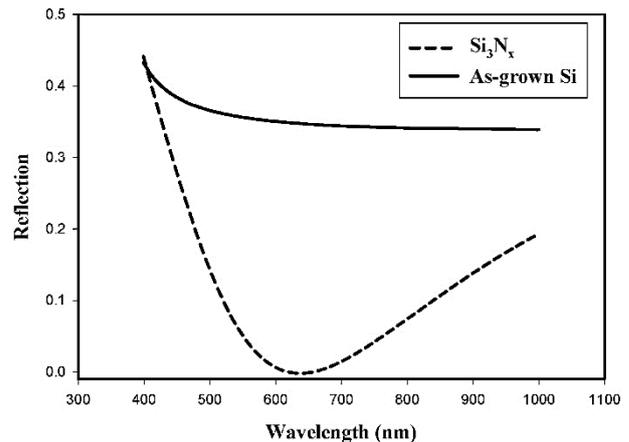


Fig. 5. Shows the reflectance data with Si_3N_x and as-grown Si solar cell

The incident photons strike the front surface and reflected because of high reflectivity of Si in the visible and UV region. As a result, a very small percentage of incident sunlight was absorbed at the top surface leading to lower efficiency [24, 25]. It became necessary to reduce the reflection and increase the carrier absorption. In order to improve the cell efficiency, the reflectance must be minimum. The reflection data of solar cell with and without antireflection coating is shown in Fig. 5. By applying antireflection layer, reflection was reduced to on average of 10% as compared to an average solar reflectance of about 35% on bare silicon [26].

4. Conclusion

The aim of this work was to investigate the impact of SRV on the performance of Si solar cell through PC1D simulation program. Simulation results indicate poor response of cell as the SRV of both (front and back) region increases. Higher SRV value makes the recombination rate of carrier faster which may create a dead layer near the front surface of solar cell. I-V characteristics and QE of solar cell mainly affected due to presence of dead layer. The results suggested that the front surface of Si solar cell should be textured and passivated in order to optimize the SRV. Maximum efficiency of solar cell was obtained by passivating both surfaces and consequently obtained lower values of SRV. It has been observed that the short circuit current changes with variation in surface recombination. Maximum efficiency of solar cell was obtained by minimizing the SRV value which highly reduces the recombination of carriers near the front surface. The enhancement in efficiency because of the reduction in back SRV is prominent if the junction is shallower and cell thickness is smaller. Optimization of FSRV value of solar cell design resulted into maximum efficiency of about 16.33%.

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