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ANALYSIS OF NON-UNIFORM DOPING IN SILICON SOLAR CELL AND OPTIMIZATION USING PC1D

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Silicon solar cells with non-uniform and heavily doped emitter region have been investigated. The results show that non-uniform doped solar cells have significantly higher conversion efficiency as compared to the uniformly-doped Si-solar cells. These results were obtained from simulation with the PC1D software. By introducing non-uniform doping profile in the emitter region of a Si solar cell, better performance parameters like improved current-voltage characteristics and higher quantum efficiency was achieved. However, a number of non-ideal effects have been also observed as the doping level increased from certain level. This results into dead layer formation at the front surface of emitter region. The recombinations become significant in which Auger recombination especially reduce lifetime, carrier mobility and tend to decrease the efficiency of solar cell. From the simulations results optimum surface doping level of 10^{19}cm^{-3} and 10^{17} cm^{-3} have been achieved for emitter and base regions, respectively.

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1. Introduction

Emitter formation plays an important role in the conversion efficiency of Si solar cell. A good emitter reduces recombination losses (at the surfaces and also in the diffused region) and resistive losses (lateral and contact) [1]. Thus, improvement in performance of solar cells can be attained by optimizing the emitter region without altering the design of solar cell [2]. For this purpose doping level should be optimized and minimize the power losses using concentrated sunlight [3].

Normally the solar cell performance deals with the measurements of electrical characteristics. These may include spectral response (SR) and current voltage (*I*-*V*) measurements. The SR as a function of wavelength is usually demonstrated by quantum efficiency (QE) [4, 5]. It gives more detailed insight about the response of cell to the incoming photon fluxes related to different regions of device. The *I-V* curve gives information about the fundamental parameters of the solar cell like open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), efficiency (η) and fill factor (FF) [6]. To obtain high conversion efficiency and higher FF of a solar cell, its *I-V* characteristics need to be improved. These improvements can be made by introducing heavy and non-uniform doping levels in the emitter-base regions. Consequently, peak doping levels for Si solar cell need to be higher to attain higher conversion efficiency [7]. However, non-uniform and heavy doping may introduce non-ideal effects like energy band gap narrowing and enhancement of Auger recombination processes. These effects reduce the output of Si solar cell and need to be addressed [8].

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In solar cell processing, emitter formation is lengthy and costly process [9]. Various computer aided tools can be used to simulate and to understand the behaviour of semiconducting devices (Sepeai *et al.*, 2013). It allows analysing the impact of certain parameters (junction depth, base thickness and doping levels) on the characteristics of solar cells [10]. Thus, computer modeling is an important tool for the analysis and design of solar cells [11]. The internal operation of crystalline solar cells is generally modelled by using PC1D simulator [12]. The objective of the present work was to investigate the effects of non-uniformly doped emitter region. For this purpose a model was developed with heavy and non-uniformly doped emitter regions and compared with uniform doped solar cells.

2. Materials and methods

Modelling of solar cell has been performed by using simulating tool PC1D. Number of simulations was accomplished in order to determine the effect of various parameters on the efficiency of solar cell. Region one and two were selected for emitter (n-type) and base (p-type) sides of solar cell, respectively. Solar cell area was 100 cm^2 with emitter and base thickness of 3μm and 300μm, respectively. The ratio of emitter to base region was so optimized that maximum charge carriers can leave the cell and take part in conduction process. Texturing and Anti-reflection coating (ARC) was also introduced so that minimum light can reflect back and maximum numbers of photons are captured. For non-uniform doping of emitter region, concentration of n-type was non-uniform and applied both at the surface (x=0) and at the junction (x=W). N-type background doping was selected as 1×10^{17} cm^{-3} and peak concentration was $1x10^{19}$ cm^{-3} for non-uniform emitter. The efficiency was observed under one-sun, AM1.5 solar radiation and constant intensity of 1000W/m^2. Front and rear surface recombination velocities (SRVs) were set to 1000 and 100 cm/s, respectively. Bulk recombination value was optimized according to the thickness of the base region. Resulting parameters of solar cells were measured at 25 $^{\circ}$C. Different peak concentrations of 10^{18}, 10^{19}, 10^{20}, 10^{21} cm^{-3} were taken with same background doping (10^{17} cm^{-3}) of emitter, whereas uniform doping was introduced into base region.

3. Results and discussion

Different electrical parameters of Si solar cell were obtained using simulation. It was observed that current and voltage values change with doping type or concentration. Doping type (uniform or non-uniform) and changing values of doping concentration were applied to obtain optimized results. The *I-V* results of both types of doping are shown in Table 1.

Table 1. Electrical parameters of silicon solar cell having uniform doping of emitter with background doping concentration of emitter is $1x10^{17}$ cm^{-3} and base is $1x10^{15}$ cm^{-3}.

Doping Type	I_{sc} **(mA/cm²)**	V_{oc} **(mV)**	I_m **(mA/cm²)**	V_m **(mV)**	P_{max} **(mW/cm²)**	***FF***	η **(%)**
Uniform	32	653	31.6	532	16.83	0.79	16.8
Non-uniform	32.9	682	29.8	596	17.78	0.79	17.8

The current versus voltage (*I-V*) curve of exhibits different combinations of its voltage and current outputs. The maximum power point (MPP) is the point in the *I-V* curve where current and voltage has the highest value. The maximum power point mostly exists near the curve. The values of short circuit current (I_{sc}), open circuit voltage (V_{oc}) were also obtained from this curve. Fig. 1 shows an improvement in short circuit current and open-circuit voltage for non-uniformly doped emitter region.

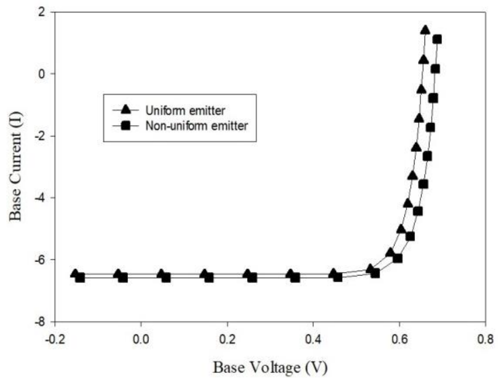

Fig. 1. Current-Voltage characteristics of Si solar cell with uniform and non-uniform doping.

Fig. 2 shows recombination of charges as a function of distance from the front surface. Recombination comparison of uniform and non-uniform doped emitter is also an evidence that non-uniformly doped emitter possess low recombination rate.

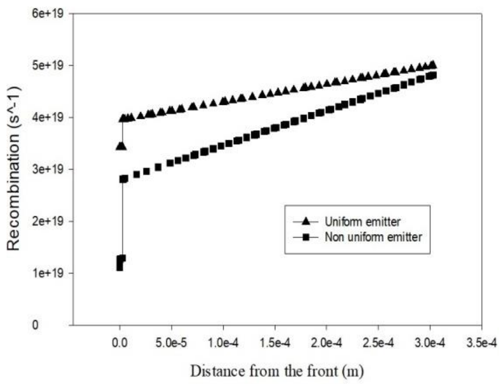

Fig. 2. Characteristic curve of recombination rate.

Quantum Efficiency (QE) is the most important parameter of a solar cell. Increase QE is an indication of improved carriers' collection. The QE parameter exhibits that how photons of various wavelengths can contribute to the I_{sc}. Fig. 3 shows the comparison of external quantum efficiency (EQE) of uniform and non-uniform doped solar cells with equal values of base concentrations. Increase in EQE can be achieved in short wavelength range by replacing the uniformly doped emitter region with non-uniformly doped emitter region in Si solar cell [13]. Another parameter to characterize the quality of solar cells is the internal quantum efficiency (IQE) in the short wavelength range of 300-500 nm. Most of the light with this wavelength range absorb in emitter and solar cell should have higher IQE and ultimately I_{sc} in this range. Fig. 4 shows IQEs of solar cells for uniform and non-uniform doped emitter regions. The IQE of the solar cell for non-uniformly doped emitter region exhibits an enhancement in the short wavelength range. Increase in short circuit current is attributed towards enhancement in IQE.

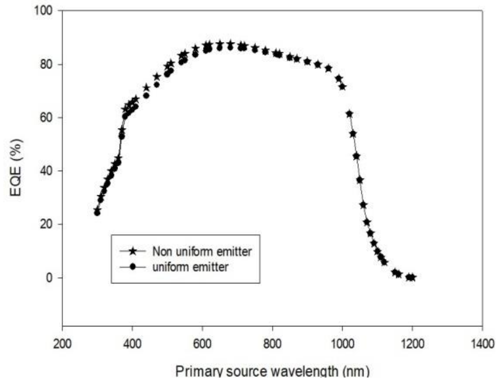

Fig. 3. External quantum efficiency of uniform and non-uniform doped Si solar cells.

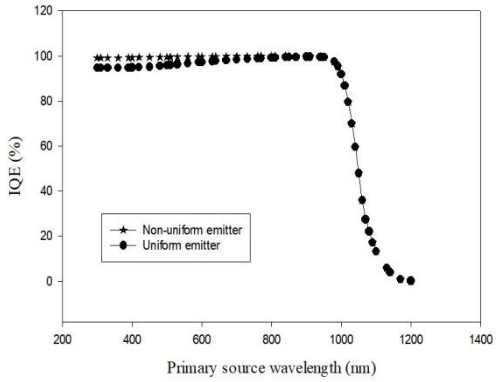

Fig. 4. Internal quantum efficiency of uniform and non-uniform doped Si solar cells.

Electrical characteristics of non-uniform doped regions were also evaluated for different values of peak concentrations. Table 3 exhibits optimized values of peak doping concentrations. It was observed that solar cell efficiency starts to decrease after increasing doping concentration greater than 10^{19} cm^{-3}. This effect is attributed towards dead layer formation at the surface of the emitter region [14]. This is also evident from Fig. 5, where maximum current-voltage values are obtained at concentration values of 10^{19} cm^{-3}. Further, the conversion efficiency is also greater at this value of peak doping concentration of emitter region. Simulation results at various doping concentration are shown in Table 2.

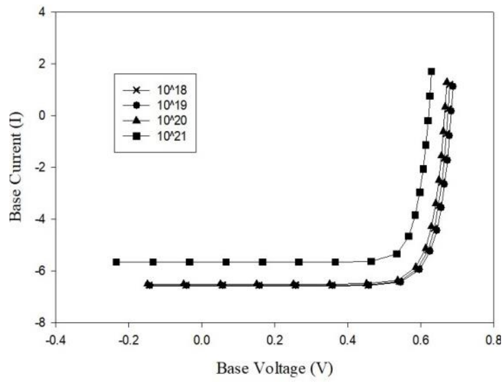

Fig. 5. I-V curve at various concentrations of surface doping.

Table 2. Electrical parameters of Si solar cells with various peak concentrations.

Doping Concentration (cm^{-3})	I_{sc} **(mA/cm^2)**	V_{oc} **(mV)**	I_m **(mA/cm^2)**	V_m **(mV)**	P_{max} **(mW/cm^2)**	***FF***	η **(%)**
$1x10^{18}$	32.8	673	29.6	592	17.52	0.79	17.5
$1x10^{19}$	32.9	682	29.8	596	17.78	0.79	17.8
$1x10^{20}$	32.5	665	29.3	586	17.19	0.79	17.2
$1x10^{21}$	28.3	620	26.7	534	14.26	0.81	14.2

Effect of different concentrations on recombination rate, in relation to the emitter distance from the surface is shown in Fig. 5. It is evident from the results that optimized value of concentration have low recombination rate in connection with emitter distance from the surface.

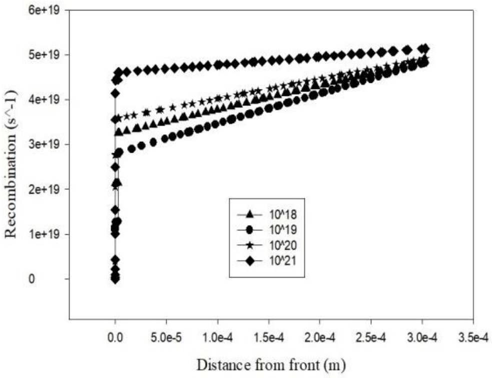

Fig. 6. Recombination rate and emitter distance from surface in connection with different concentrations.

Relation between conversation efficiency and peak doping concentration is shown in Fig. 7. At optimized doping concentration, maximum conversion efficiency of 17.8% was obtained. It is observed that conversion efficiency first increased with increasing value of doping concentration. However, it tends to decrease after a certain optimized value and then sharply decrease with further increase in doping concentration. This behavior is attributed towards different types of recombinations that may influence the conversion efficiency of solar cell [15]. Particularly, augur recombinations become active when heavy doping is present on the surface of solar cell. Auger recombination, further results into band gap narrowing, decrease in lifetime, carrier mobility and tend to decrease the efficiency of solar cell.

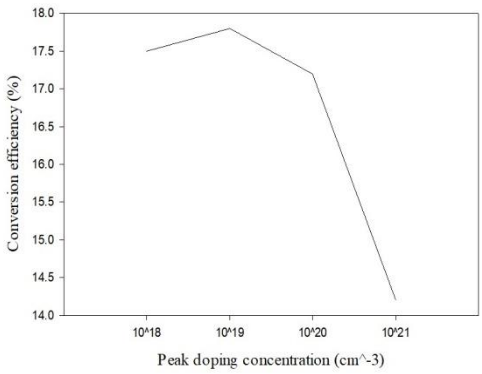

Fig. 7. Influence of peak doping concentration on conversion efficiency of a Si solar cell.

4. Conclusion

By introducing non-uniform doping in a silicon solar cell, better performance parameters like improved current-voltage characteristics and higher conversion and quantum efficiencies were achieved. Simulations were carried out for a silicon solar cell with non-uniformly doped emitter region along with uniformly doped base region. These simulations were accomplished by using PC1D simulation tool. Different peak concentrations of 10^{18}, 10^{19}, 10^{20}, 10^{21} cm^{-3} were taken with same background doping (10^{17} cm^{-3}) of emitter region to find out optimized value of doping concentration for maximum conversion efficiency of solar cell. Maximum conversion efficiency of 17.8% and fill factor of 0.79 was achieved for peak doping concentration of 10^{19} cm^{-3}. With increasing doping concentration at the surface, conversion efficiency was decreased. This is attributed towards non-ideal defects that become dominant with the heavy increase of doping concentration. These defects results into recombinations of minority charge carriers. It was observed that non-uniformly doped silicon solar cells have significantly higher conversion efficiency over the uniformly-doped Si-solar cells and have improved current-voltage characteristics.

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