SIMULATION AND OPTIMIZATION OF EMITTER DEPTH AND DOPING FOR SILICON SOLAR CELLS UNDER CONCENTRATED SUNLIGHT

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1. Abstract

Higher concentration of sun light increases the amount of current and lower sheet resistance is needed to decrease the loss of current flow. Two ways can be considered for having lower sheet resistance: increasing the doping concentration and the depth of emitter region, but both of them may decrease the efficiency in some values. If we consider both methods simultaneously, the optimum values for doping concentration and emitter depth will change. Another suggestion for improving the efficiency is placing n^+-layer under the contacts. In this work, we simulate a common structure of silicon solar cell in different sunlight concentrations. Sunlight concentration causes different behaviors in different emitter doping concentrations and depths. These behaviors are studied by examining some physical phenomena occur during the cell operation. Thus, the optimum value for doping concentrations and depths and qualitative reasons for the changes can be determined. In addition, we compare the results with analytical description in some cases. Additionally, we simulate the n^+-layer under the contacts and compare the efficiency of that with previous condition, its influence is more considerable in higher sheet resistances.

2. Introduction

Silicon solar cells have currently the biggest portion of the market for photovoltaic systems in the world. In recent years, silicon solar cells using concentrated sun light radiation have gained great importance. Higher sunlight concentration brings two advantages for solar cells. Firstly, the required area can be reduced which results in less cost. Therefore, expensive technologies can be used for greater efficiency. Furthermore, by using this technique, open circuit voltage, as well as short circuit current of the cell increases. But other loss mechanisms affect the rising efficiency trend and especial considerations are needed to design new structure for these cells (Luque, 1989; Araki and Yamaguchi, 2000; Morvillo et al., 2007). Higher concentration of sun light generates more carriers in solar cells, thus, the amount of current will increase and lower sheet resistance is needed to decrease the loss of current flow. One way to decrease the sheet resistance is increasing the doping concentration in the emitter region. But this results in increasing the recombination rate in that region, lower carrier concentration near the contacts and accordingly, reduces the currents. Another way for having lower sheet resistance is increasing the depth of emitter region, but in this case the distance between p-n junction and the cell surface is increased and carriers have longer paths to reach the contacts, therefore, the collection probability is reduced. Both solutions have optimum values in certain condition, but if we consider both methods simultaneously, these values will change. A good suggestion for improving the efficiency may be the placing a heavily doped n^+-layer under the contacts. This would minimize the contact resistance to silicon and keeps minority carrier away from the contacts.

The analytic modeling of these phenomena is not simple because it necessarily involves two- and three-dimensional approaches (Antonini et al., 2003; Araki and Yamaguchi, 2003; Daliento and Lancellotti, 2010). Therefore, simulation of the cells can help to understand limiting factors and influences of all parameters more accurately.

In this work, we simulate the structure of a silicon solar cell that is shown in Fig.1, in different sunlight concentration. Sunlight concentration defines the point which the influence of sheet resistance overcomes the effect of high recombination rate. In fixed emitter depth, for higher illuminations, efficiency may decrease by changing the doping concentration. All of the simulations are performed in 2-dimensions and lateral effects in the emitter region are taken into account. For different emitter doping concentrations and depths, sheet resistance, recombination rate, band gap, short circuit current, open circuit voltage and efficiency are examined. In addition, we compare the results with analytical description for bandgap narrowing, recombination rate and sheet resistance. As the equations for photo generation and absorption cannot take simple forms and depend on depth and band gap non-linearly, simulation helps to accurately define the depth and doping of emitter region. Additionally, we simulated the n^+-layer under the contacts and compare the efficiency of that with previous condition with different emitter depths, emitter doping and sunlight concentrations, its influence is more considerable in higher sheet resistances.

3. Solar Cell Structure and TCAD Simulator

A TCAD device simulator is exploited to analyze the influences of doping concentration and emitter depth changing under different sunlight concentrations. The structure of simulated cell, defined according to previous works (Daliento and Lancellotti, 2010) is shown in Fig.1. It is made up by n-type emitter diffused into a 300µm p-type substrate. The metal grid has a multifinger pattern made up of ideal metal. The spacing between the fingers (center to center) is 200µm, the width of the fingers is 10µm and the height of them is 10µm. The emitter doping profile was assumed to have a uniform shape with different junction depths. It is also assumed that two layer of antireflection material (ZnS and SiO2) are coated on surface of the cell.

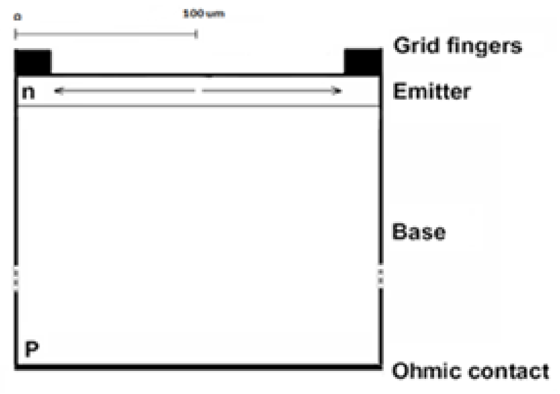

Fig. 1: Simulated silicon solar cell structure

Numerical solutions are obtained by discretizing the cell structure in grid points whose spacing has to be short enough to follow microscopic variations of geometrical and electrical parameters. Once the geometries of the cell have been defined, material electrical properties, in particular minority carriers recombination and surface recombination velocity, need to be defined too. In this cell, base doping concentration is set to $6\times10^{16}cm^{-3}$, bulk lifetime and surface recombination velocities are set to 75µs and 1000m/s respectively for both electron and hole.

4. Simulation Results and Discussion

4.1. Efficiency, Short Circuit Current and Open Circuit Voltage

We simulate the cell with different doping concentration and depth of emitter under several concentration of sunlight. In the first step, we consider the efficiency of the cell and discuss about the phenomena and their effects on efficiency qualitatively. Fig.2. shows the efficiency of the cell in different doping concentration and depths of emitter under 1sun and 50suns.

Increasing the doping concentration reduces the sheet resistance of emitter, and hence the power loss in this region. Higher doping concentrations causes higher recombination rate and narrower bandgap, therefore it can be seen that efficiency decreases considerably, especially in deeper emitters.

Decreasing the depth of emitter reduces the paths that carriers should go to reach the contacts in regions that more generation occurs and consequently collection probability increases. This results in higher efficiency in lower depths of emitter because the current rises, but decreasing the depth increases the sheet resistance and power loss which may degrade the efficiency.

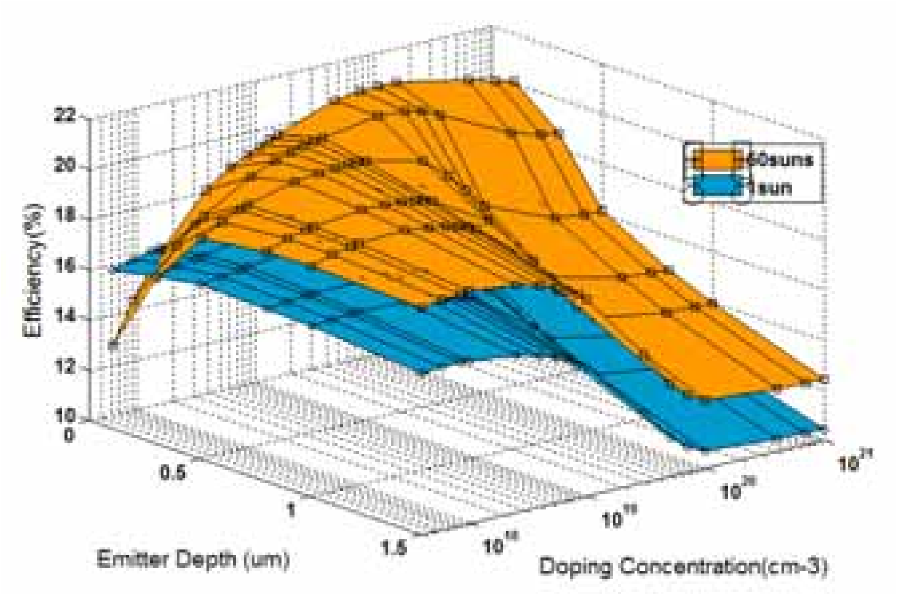

Fig. 2: The efficiency of the cell in different doping concentration and depths of emitter under 1sun and 50suns

If both effects are taken into consideration simultaneously, different results are gained. In shallower emitter, efficiencies have greater values but because of higher sheet resistance higher levels of doping are needed to reduce the power loss, therefore we see that maximum efficiency in shallower emitter occurs in higher doping concentration. Under concentrated sunlight, cell current and voltage increase, but the efficiency strongly depends on fill factor of the cell. In high illuminations more carriers are generated, thus high sheet resistance causes more loss due to lower fill factor. Reducing doping levels and depth of emitter at the same time results in very high sheet resistances and degraded fill factor. Their effects on efficiency are very considerable in 50suns. Fig.3. shows the efficiency of the cell in two doping concentration and five depths of emitter versus sunlight concentration. The optimum concentration of sunlight is different for each emitter depth in lower doping concentrations because the influence of increasing the voltage and the current overcomes the effect of low fill factor in different concentrations. In higher doping levels or emitter depths, efficiencies rise by increasing the concentration of sunlight.

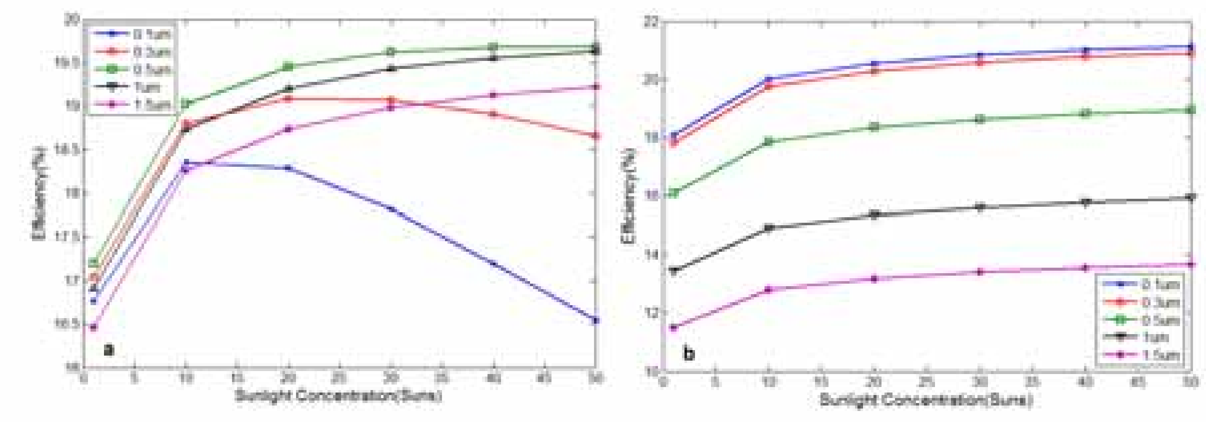

Fig. 3: The efficiency of the cell in Doping concentrations of a)1×10^{18}cm^{-3} b) 5×10^{19}cm^{-3} and five depths of emitter versus sunlight concentration for emitter depth of 0.1µm, 0.3µm, 0.5µm, 1µm, 1.5µm

Fig.4.a shows the short circuit current of the cell in two depths of emitter versus doping concentration under three

concentrations of sunlight. For lower depth the currents are higher because of shorter distances for carriers to reach the contacts. Short circuit current decreases by increasing the doping concentration because the life time of carriers reduces. The drop in higher levels is due to high recombination rate especially Auger recombination. Fig.4.b shows the open circuit voltage of the cell in two doping concentrations versus emitter depth under three concentrations of sunlight. For these two doping concentrations different behaviors can be seen by changing the emitter depth. According to eq.1 open circuit voltage depends on short circuit current and saturation current of the cell (Green, 1992). Deeper junction reduces both the saturation current and short circuit current, but short circuit current in higher level of doping, as it is shown in Fig.4.a has more considerable reduction, therefore decreasing the saturation current that increases the open circuit voltage can overcome the reduction of short circuit current in lower levels of doping but it cannot in higher levels. Consequently, in lower doping concentration open circuit voltage increases by increasing the depth but in higher levels of doping it decreases.

$$Voc = \frac{nKT}{e} \ln\left(1 + \frac{I_{sc}}{I_0}\right) \quad \text{(eq. 1)}$$

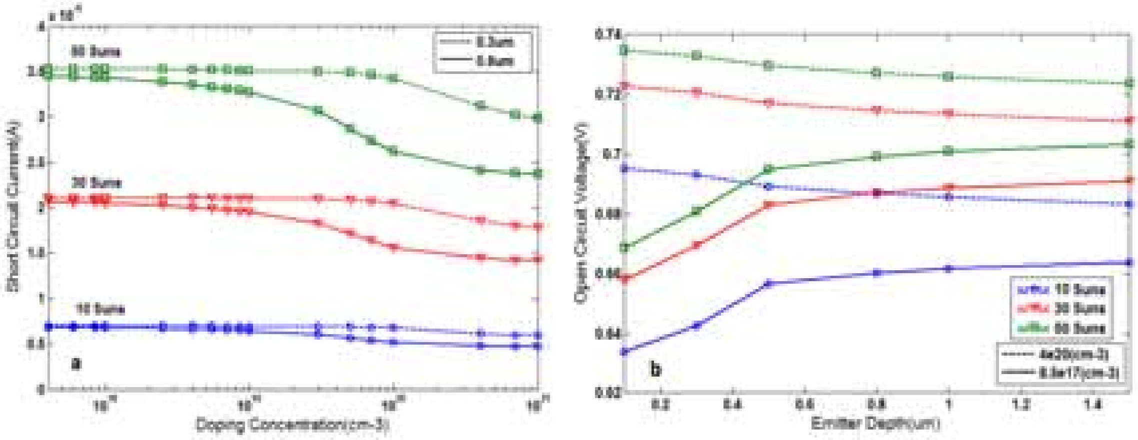

Fig. 4: a)The short circuit current of the cell in depths of 0.3µm and 0.8µm for emitter versus doping concentration b)The open circuit voltage of the cell in doping concentrations of 4×10^{20}cm^{-3} and 8.5×10^{17}cm^{-3} versus emitter depth, both under 10,30 and 50 suns

4.2. Bandgap Narrowing, Recombination Rate and Sheet Resistance

In this section, the simulation results for effects of bandgap narrowing, recombination rate and sheet resistances are studied and compared with analytic descriptions.

In the presence of heavy doping, greater than 10^{18}cm^{-3}, experimental work has shown that the p-n product in silicon becomes doping dependent (Slotboom, 1977). As the doping level increases, a decrease in the bandgap separation occurs, where the conduction band is lowered by approximately the same amount as the valence band is raised. By considering this effect new intrinsic concentration is described with following equation.

$$n_{ie}^2 = n_i^2 \exp\left(\frac{\Delta E_g}{kT}\right) \quad \text{(eq. 2)}$$

Which n_{ie} is the new intrinsic concentration.

Bandgap narrowing is calculated from the expression by Slotboom and de Graaf (Slotboom and De Graaf,, 1976).

$$\Delta \mathrm{Eg} = \mathrm{E}_1 \left[\ln\left(\frac{N}{N_0}\right) + \sqrt{\ln\left(\frac{N}{N_0}\right)^2 + \mathrm{C}} \right] \quad \text{(eq. 3)}$$

Which E1, N0 and C are constant values.

The bandgap reduces logarithmically by increasing the doping concentration. Bandgap narrowing versus doping concentration is shown in Fig.5. In this figure simulation results are compared with analytic results from eq.3.

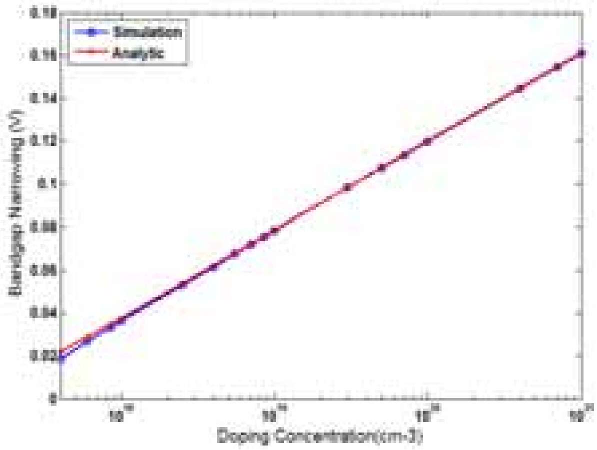

Fig. 5: Bandgap narrowing versus doping concentration (comparing simulation results and analytic results from eq.2)

Fig.6.a shows recombination rate, SRH recombination and Auger recombination for doping concentration of 3×10^{19}cm^{-3} versus the position in lateral direction. The analytic equations for SRH (Shockley,and Read, 1952; Hall, 1952) and Auger (Kerr and Cuevas, 2002) recombination are brought in advance. Recombination rate is mainly determined by two different mechanisms: SRH recombination for lower concentrations and Auger for higher ones.

$$R_{SRH} = \frac{pn - n_i^2}{\tau_p\left(p + n_i\, e^{-Et/kT}\right) + \tau_n\left(n + n_i\, e^{Et/kT}\right)} \qquad \text{(eq. 4)}$$

$$R_{Aug} = (C_n n + C_p p)(np - n_i^2) \qquad \text{(eq. 5)}$$

Near the contacts, recombination rate has higher values because the concentration of carrier is very high near the contacts. Because of this reason - increasing the carrier concentration - also by increasing the illumination, recombination rate becomes higher. Recombination rate in several concentrations of sunlight are seen in Fig.6.b.

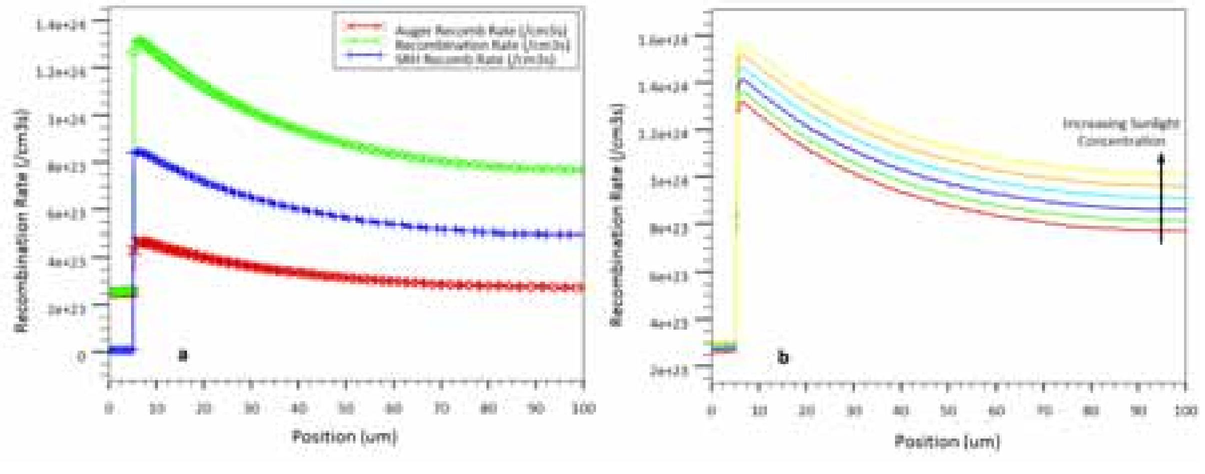

Fig. 6: a)Recombination rate, SRH recombination and Auger recombination b)Recombination rate for sunlight concentrations of 1, 10, 20, 30, 40 and 50 suns, both for doping concentration of 3×10^{19}cm^{-3} versus the position in lateral direction

Fig.7. shows the sheet resistance of the emitter region versus the doping concentration. By increasing the doping concentration sheet resistance decreased as it is expected from the eq.7 (Green 1992). In Fig.7. the results from simulation and analytic equation are compared. The difference between the diagrams is because of constant value for mobility in analytic equation, whereas changing mobility with doping concentration is accounted in simulations.

$$\rho_s = \frac{1}{q\,\mu_e\,N_d\,t} \quad (\Omega/\square) \qquad \text{(eq. 7)}$$

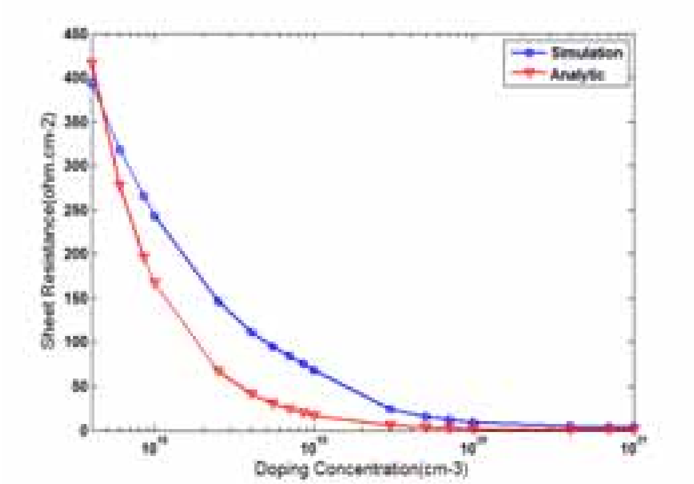

Fig. 7: The sheet resistance of the emitter region versus the doping concentration (comparing the simulation and analytic results)

4.3. Effect of placing n^+-layer under the contacts

Surface recombination has a major impact both on the short circuit current and on the open circuit voltage. High recombination rates at the top surface have a particularly detrimental influence on the short circuit current since top surface also corresponds to the highest generation region of carriers in the solar cell. Lowering the high top surface recombination is typically accomplished by reducing the number of dangling silicon bonds at the top surface by growing a passivating layer (usually silicon dioxide) on the top surface. This passivating layer is usually an insulator and any region which has an ohmic metal contact cannot be passivated. Instead, under the top contacts the effect of the surface recombination can be minimized by increasing the doping. While typically such a high doping severely degrades the diffusion length, the contact regions do not participate in carrier generation and hence the impact on carrier collection is unimportant. In addition, in cases where a high recombination surface is close to the junction, the lowest recombination option is to increase the doping as high as possible.

Fig.8. shows the efficiency of the cell in both the case that no n+ layer exists and the case that n+ layer placed under the contacts versus doping concentration under three sunlight concentrations for emitter depths of 0.3µm and 0.5µm.

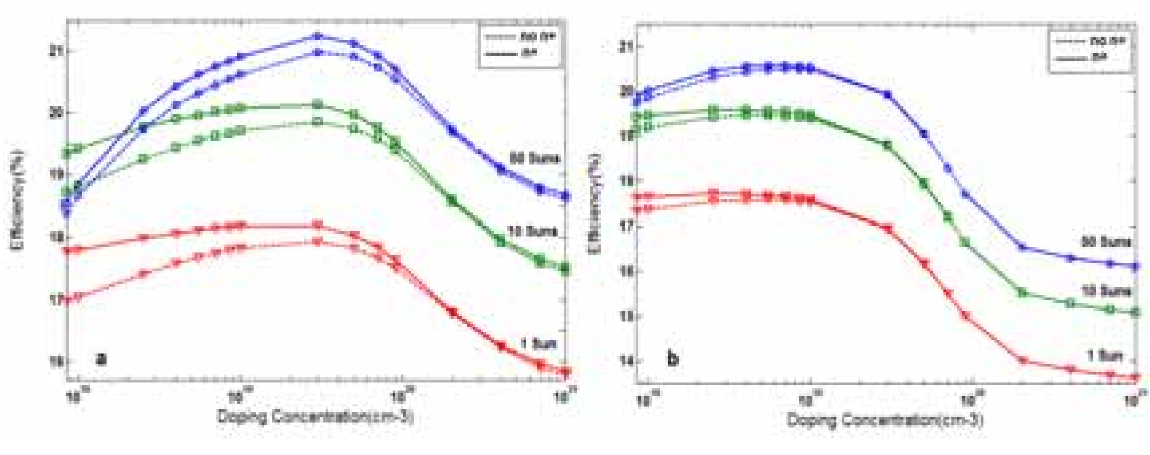

Fig. 8: The efficiency of the cell in the case that no n+ layer exists and the case that n+ layer placed under the contacts versus doping concentration under 1, 10 and 50 suns for emitter depths of a)0.3µm and b)0.5µm.

This figure shows that in lower doping concentrations n+ layer has more effective influence on efficiency of the cell because sheet resistance is higher and also more carriers recombine near the contacts, therefore high doped layer can reduce sheet resistance and recombination rate more considerably. This improving of the efficiency is about %0.5 for emitter depth of 0.5μm and %1.5 for 0.3μm under 1sun and doping concentration of 8.5×10^{17} cm^{-3}. The distance between the surface and junction and hence carrier recombination are higher in 0.5μm. Placing the n+ layer has greater influence in shallower emitters because it reduces the recombination rate more. In addition when the sheet resistance is higher this layer decrease the sheet resistance more which results in lower power loss. Increasing the sunlight concentration causes more recombination and more power loss especially in higher doping concentration and the efficiency improvement reduces.

5. Conclusion

In this paper we simulated a conventional structure of solar cell for working under concentrated sunlight. We aimed to study the important parameters of emitter region and their influence on efficiency in higher concentration of light. It is concluded that for shallower emitter, efficiency rises and has a peak value in higher doping concentration. This lower depth of emitter makes some problem in lower doping concentration especially in concentrated sunlight. We simulated the cell in different emitter depth and doping and several sunlight concentrations and examined all the behaviors and explained all the reasons by considering short circuit current, open circuit voltage, bandgap narrowing, recombination rate and sheet resistance. This helps the designers to consider all effects before production process. Finally the impact of n^{+}-layer was studied as a solution for reducing the sheet resistance and recombination of carriers near the contacts. This layer improves the efficiency specifically in lower levels of doping.

6. References

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