Theoretical Investigation of Base Doping and Illumination Level Effects on a Bifacial Silicon Solar Cell

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Authors' contributions

This work was carried out in collaboration between all authors. Author FIB designed the study, performed the simulation and wrote the first draft of the manuscript. Authors MS and BZ managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

In this paper, we are investigating theoretically the behavior of a bifacial silicon solar cell in steady state with different illumination conditions. The bifaciality coefficient and the conversion efficiency are calculated for various rear side illumination conditions (traduced here by the illumination level) and back surface recombination velocity, taking into account the base doping density. The main purpose of the work is to show that bifacial illumination can improve significantly the conversion efficiency of the solar cell and to exhibit the role of the back surface recombination velocity, the base doping density and the rear side illumination conditions in the performance of the bifacial silicon solar cell.

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1. INTRODUCTION

Solar cells are semiconductor devices that are able of direct conversion of light into electricity. Space research and the oil crisis in 1972 have induced the rapid growth of the production and use of solar cells. Many technologies have been developed like crystalline silicon solar cells, thin films, organic solar cells, nanowire solar cells and so on. In the field of crystalline silicon solar cells a particular type has been developed: the bifacial silicon solar cell.

Bifacial solar cells are solar cells that can be illuminated on both sides and produce current. The objective of using bifacial instead of classical monofacial solar cells is the generation of additional energy due to conversion of the radiation collected by the rear side of the solar cell. Since their introduction [1] these devices continue to be improved to minimize both optical and electrical losses so that their conversion efficiency increased significantly [2-4]. In order to continue these improvements it is of great importance to know exactly what are the major parameters influencing the bifacial cell and what are their importance in that conversion efficiency.

In bifacial illumination, that is, simultaneous front and rear illumination, the improvement in conversion efficiency is directly related firstly to the rear surface illumination condition (background surface reflection) that dictate rear illumination level and secondly to the quality of the rear side of the cell through back surface recombination velocity with or without back surface field (BSF). But back surface recombination velocity and internal recombination depend on base doping density. The dependence of performance parameters on illumination level can also get affected if the values of the cell parameters like R_{sh} (shunt resistance), R_s (series resistance), n (diode ideality factor) and I_o (reverse saturation current of the cell) themselves change with illumination intensity.

The main purpose of this work is to show how bifacial illumination can improve the conversion efficiency and how rear illumination level, back surface recombination velocity and base doping could influence that conversion efficiency.

2. MATHEMATICAL FORMULATION

A schematic diagram of the bifacial silicon solar cell is given in Fig. 1.

Carrier generation, recombination and drift/diffusion are the three major phenomena that occur inside a solar cell under illumination. We consider here only the base region of the cell, neglecting the emitter since its contribution is very low in comparison to that of the base. We also assume a quasi-neutral p-type base (QNB), low injection condition and no lateral effect; then, the principal transport mechanism remain a one-dimension diffusion of minority carriers (electrons).

In steady state we have:

$$\frac{\partial^2 \delta_\alpha(x)}{\partial x^2} - \frac{\delta_\alpha(x)}{L^2} = -\frac{G_\alpha(x)}{D} \tag{1}$$

δ_α is the excess minority carrier density, L is their diffusion length and D their diffusion coefficient. The diffusion coefficient is written as [5]:

$$D(Nb) = \frac{1350 \cdot Vt}{\sqrt{1 + \frac{81 \cdot Nb}{(Nb + 3{,}2 \cdot 10^{18})}}} \tag{2}$$

Where Nb is the base doping density.

The corresponding excess minority carrier lifetime τ is given by [5]:

$$\tau(Nb) = \frac{12}{1 + \frac{Nb}{5 \cdot 10^{16}}} \qquad \text{(in µs)} \tag{3}$$

The diffusion length can then be deduced as:

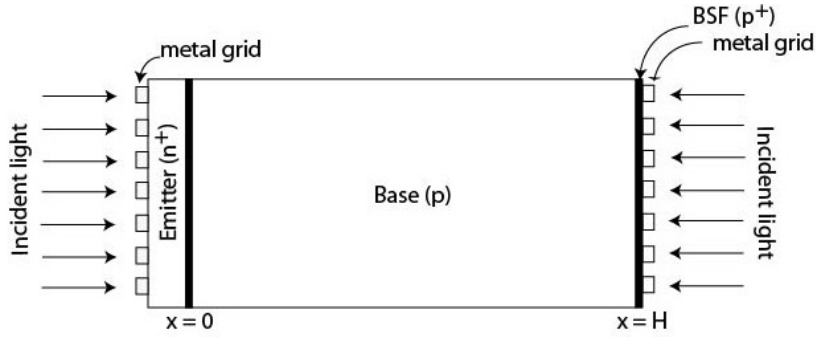$$L(Nb) = \sqrt{D(Nb) \cdot \tau(Nb)} \tag{4}$$

Fig. 1. Schematic diagram of a bifacial silicon solar cell

Carrier generation rate $G_\alpha(x)$ at the depth x in the base is written in the form [6,7]:

$$G_{front}(x) = n_{front} \sum_{m=1}^{3} a_m \cdot \exp(-b_m \cdot x) \tag{5.a}$$

$$G_{rear}(x) = n_{rear} \sum_{m=1}^{3} a_m \cdot \exp[-b_m \cdot (H-x)] \tag{5.b}$$

$$G_{bifacial}(x) = \sum_{m=1}^{3} a_m \cdot \left[n_{front} \cdot \exp(-b_m \cdot x) + n_{rear} \exp\{-b_m \cdot (H-x)\} \right] \tag{5.c}$$

n_{front}, n_{rear} indicate illumination levels for front and rear illumination respectively. Illumination level is taken to be the ratio between incident power and AM1.5 reference power (100 mW.cm^{-2}). Coefficients a_m and b_m are tabulated values obtained from solar irradiance and the dependence of the absorption coefficient on the illumination wavelength [6,8].

Solution of equation (1) is:

$$\delta_{front}(x) = C1_{front} \cdot \exp\left(\frac{x}{L}\right) + C2_{front} \cdot \exp\left(-\frac{x}{L}\right) + \sum_{m=1}^{3} n_{front} \cdot K_m \cdot \exp(-b_m \cdot x) \tag{6.a}$$

$$\delta_{rear}(x) = C1_{rear} \cdot \exp\left(\frac{x}{L}\right) + C2_{rear} \cdot \exp\left(-\frac{x}{L}\right) + \sum_{m=1}^{3} n_{rear} \cdot K_m \cdot \exp[-b_m \cdot (H-x)] \tag{6.b}$$

$$\delta_{bifacial}(x) = C1_{bifacial} \cdot \exp\left(\frac{x}{L}\right) + C2_{bifacial} \cdot \exp\left(-\frac{x}{L}\right)$$
$$+ \sum_{m=1}^{3} K_m \cdot \left[n_{front} \cdot \exp(-b_m \cdot x) + n_{rear} \cdot \exp\{-b_m \cdot (H-x)\} \right] \tag{6.c}$$

Coefficients $C1_\alpha$ and $C2_\alpha$ (subscript α refer to the bifacial silicon solar cell illumination mode) can be evaluated if we consider the two following boundary conditions:

- at the junction (x= 0):

$$\frac{\partial \delta_\alpha(x)}{\partial x}\bigg|_{x=0} = \frac{Sf_\alpha}{D} \cdot \delta_\alpha(0) \tag{7}$$

- at the backside (x= H):

$$\frac{\partial \delta_\alpha(x)}{\partial x}\bigg|_{x=H} = -\frac{Sb_\alpha}{D} \cdot \delta_\alpha(H) \tag{8}$$

With Sb_α and Sf_α being respectively the back surface recombination velocity and the junction dynamic velocity [9,10].

Since the excess minority carrier density is known, we can derive both photocurrent density and photovoltage respectively as:

$$Jph_\alpha = q \cdot D \cdot \frac{\partial \delta_\alpha(x)}{\partial x}\bigg|_{x=0} \qquad (9)$$

q is the electronic charge

$$Vph_\alpha = V_T \cdot \ln\left(\frac{N_B \cdot \delta_\alpha(x=0)}{n_i^2} + 1\right) \qquad (10)$$

V_T the thermal voltage, N_B the base doping density and n_i the intrinsic concentration.

The performance of the bifacial cell can be well characterized by its bifaciality coefficient [11] and also its conversion efficiency [12,13].

The bifaciality coefficient is defined by the ratio of the short circuit current densities as:

$$\text{bifacialit } y = \frac{J_{sc\_rear}}{J_{sc\_front}} \qquad (11)$$

Where J_{sc_rear} and J_{sc_front} are the short circuit current densities respectively for rear illumination and front illumination.

For the conversion efficiency, we can write that:

$$\eta = \frac{P_{max}}{P_{inc}} \qquad (12)$$

With P_{max} the maximum power delivered by the solar cell and P_{inc} the incident power.

3. RESULTS AND DISCUSSION

Based on the above mathematical formulation, simulations were performed for front, rear and bifacial illumination for various base doping densities various illumination levels and various back surface recombination velocities.

3.1 Photocurrent Density

We present on Fig. 2 the photocurrent densities for the bifacial solar cell front illumination, rear illumination and then bifacial illumination.

This figure shows clearly that bifacial illumination is more interesting given that it provides the more photocurrent density while the base doping density is of the order of 10^{17} cm^{-3}. Above 10^{18} cm^{-3}, the benefit of bifacial illumination is lost given that $J_{bifacial}$ curve and J_{front} curve become identical.

These curves also show that there is a limit to base doping density as we can observe a very marked decrease of the photocurrent densities near and above 10^{17} cm^{-3}, but rear contribution (J_{rear}) is more sensitive to base doping density. Effectively for this illumination mode, carriers are generated in the neigh borough of the backside so that they are submitted to back surface recombination and other defects in the base since these carriers must also pass across the base to reach the junction. Given that recombination activities (centers) are directly related to base doping density, that is why rear contribution is more sensitive to base doping density.

The rear side illumination produce the lower current density since carrier path to junction is greater than that of front side illumination but this is also directly related to the back surface recombination velocity. Effectively for very low back surface recombination velocity, carrier are not lost at the rear side so that they can't reach the junction and participate to photocurrent that is, for a well passivated surface with the presence of a back surface field (BSF), the back surface recombination velocity will be very low and the presence of the BSF will improve significantly the rear illumination photocurrent as presented by Hübner A et al. [14] and Gonsui S et al. [15].

At this point, it is clear that for the same material quality, the more the base is thinner, the more the photocurrent density will be greater. It is then of great interest to improve the cell especially from the rear side and have in mind that thinner base will be better.

3.2 Bifaciality Coefficient

The idea of the bifaciality coefficient was first introduced by Ooshaksaraei P et al. [11] because of the need to compare the rear illumination photocurrent density and the front one for bifacial solar cell. This concept was then largely used by many authors to analyze the performance of their bifacial cells.

In Fig. 3, we plotted the bifaciality coefficient versus base doping density for various illumination conditions of the back side. These illumination conditions are traduced here by the illumination level of the back side compared to that of the front side.

As noted on Fig. 2, the photocurrent density decrease as the base doping density increase, especially above 10^{17} cm^{-3}. Given that the rear illumination short circuit photocurrent density
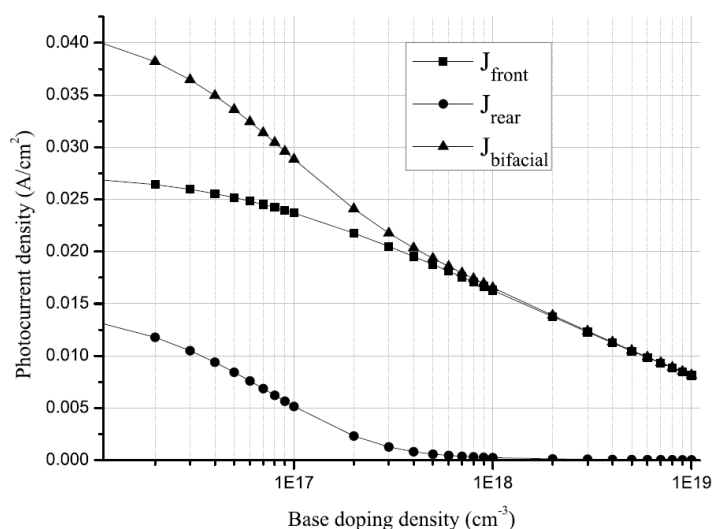
J_{sc_rear} is more sensitive to the base doping density than the front illumination short circuit photocurrent density J_{sc_front}, considering that the bifaciality coefficient correspond to the ratio J_{sc_rear} to J_{sc_front}, that is, the bifaciality coefficient should decrease with base doping density as noted on Fig. 3. The factor given here (illumination level for the rear side) is related to the nature of the reflection surface for the rear side of the bifacial cell [12].

Fig. 2. Photocurrent density versus base doping density for front, rear and bifacial illumination (H=0.02 cm, Sb = 10^3 cm/s)

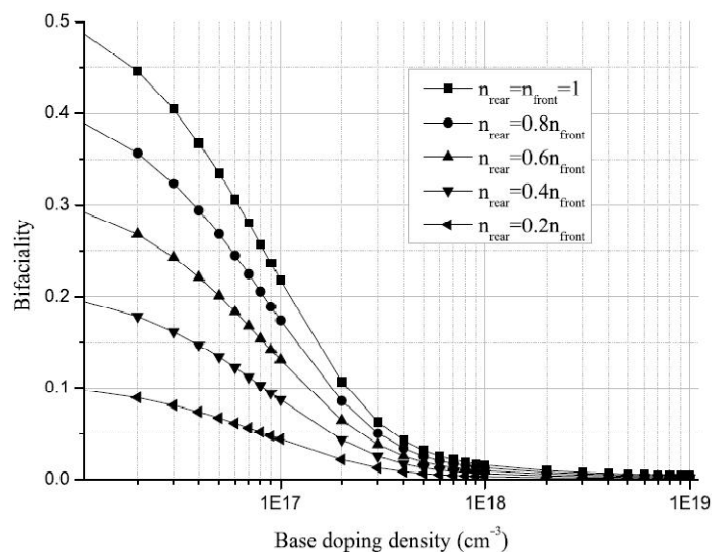**Fig. 3. Bifaciality coefficient versus base doping density for different rear illumination level (H=0.02 cm, Sb = 10^3 cm/s)**

Fig. 3 shows that decreasing rear illumination level lead to a decrease of the bifaciality coefficient. Effectively, a decrease of the rear illumination level will directly impact negatively on the short circuit current density J_{sc_rear} so that the bifaciality coefficient should decrease (Fig. 3) given that front illumination remain unchanged.

If one want to increase the bifaciality coefficient, that is increase the rear illumination short circuit current density, the back surface reflexing properties should be taken with care since the nature of the back reflexing surface of the rear side of the bifacial cell dictate the value of n_{rear}. The more the surface is reflective the more the rear illumination level increase and the more rear side photocurrent density is greater, leading to a higher bifaciality coefficient.

We want to evaluate now how the back surface properties (in term of recombination) act on the bifaciality coefficient. We then varied the back surface recombination velocity and plotted the bifaciality coefficient against base doping density on Fig. 4.

We can see the importance of the back surface recombination velocity (Fig. 4) as the bifaciality factor decrease markedly with increasing back surface recombination velocity. As noted previously, the rear side of the cell is more sensitive to back surface effect. This suggest that passivation of the back surface and back surface field should play an important role in the performance of the bifacial cells, given that the lower the back surface recombination velocity is, the higher the bifaciality factor becomes.

If we take into account passivation and back surface field effects, then J_{rear} is significantly increased leading to J_{rear} close to J_{front} and the bifaciality can be very close to 1 as illustrated on Fig. 4 and proved by Gonsui S et al. [15].

3.3 Conversion Efficiency

The conversion efficiency of the bifacial cell has also been evaluated for front, rear and bifacial illumination. The obtained curves are presented on Fig. 5.

This figure shows that the conversion efficiency of the solar cell decreases with base doping density as recombination processes increase with base doping density. The bifacial efficiency is more important compared to that of the commonly front illumination, as expected. This is due to the contribution of the rear illumination; note that rear illumination condition should be improved (passivation of the rear side, back surface field BSF, ground surface reflection properties) to gain effect of bifacial illumination.

We supposed here that for rear illumination we have the same incident flux. Really this may be wrong due to different factors [12,13]. To evaluate more accurately the bifacial efficiency, we then varied the rear incident flux (n_{rear} factor). The resulting dependencies are plotted on Fig. 6.
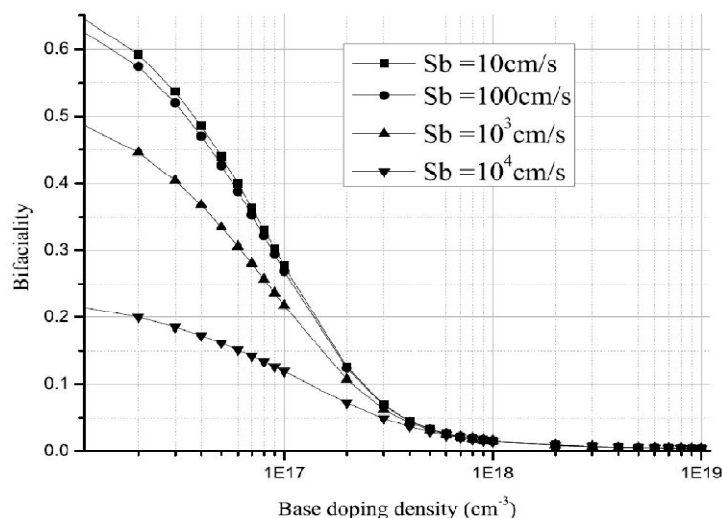

Fig. 4. Bifaciality coefficient versus base doping density for various back surface recombination velocities (H=0.02 cm, Sb = 10^3 cm/s)
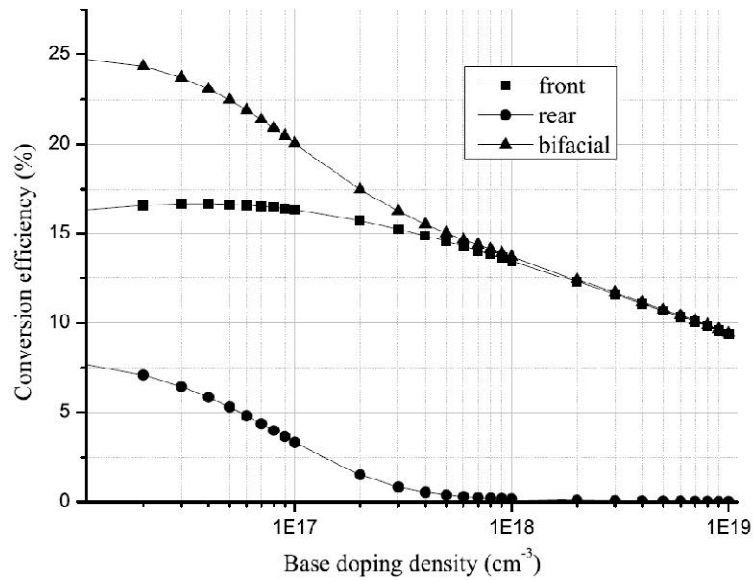
Fig. 5. Conversion efficiency versus base doping density for front, rear and bifacial illumination (H=0.02 cm, Sb = 10^3 cm/s)
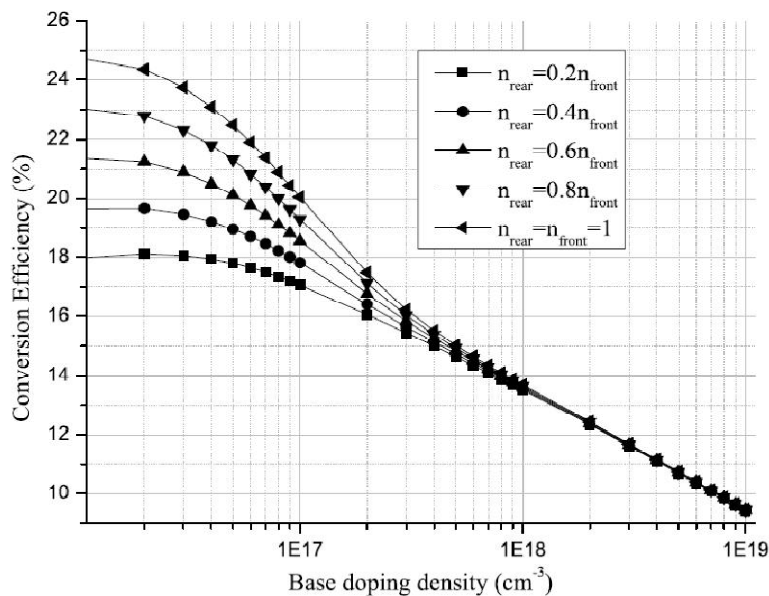

Fig. 6. Bifacial conversion efficiency versus base doping density for various rear illumination levels (H=0.02 cm, Sb = 10^3 cm/s)

We considered that the illumination level on the rear side of the bifacial solar cell is directly proportional to the reflection surface; generally, bifacial solar cells are installed in a way where front surface is on top and rear surface is on bottom side. The rear side is not then illuminated directly as front side so its illumination comes from reflection on ground surface (albedo effect). Given that the incidence power on front is P_{inc},

the incidence power on rear side will be P_{inc}x (reflection factor) we plotted the conversion efficiency against base doping density for various rear illumination levels, taking the front illumination level as reference.

As expected, the bifacial efficiency increase as the rear illumination level n_{rear} increases. Effectively, as n_{rear} increases, the rear

contribution to photoconversion increases also so that the bifacial efficiency becomes higher with n_{rear}. Given that rear illumination level n_{rear} is directly related to the reflection factor of the ground surface [12], it is important that this ground surface be treated to improve its refection factor.

We can also note that the conversion efficiency doesn't vary markedly with rear illumination level for base doping level above about 3.10^{17} cm^{-3}. This may be due to the fact that recombination phenomena become more predominant compared to generation phenomenon, leading to a global decrease of the conversion efficiency with base doping density.

4. CONCLUSION

In this work, a theoretical investigation of a bifacial silicon solar cell has been made.

We showed that the bifaciality coefficient as well as the conversion efficiency decrease with base doping density and back surface recombination velocity.

It has been demonstrated that the reflection surface for rear illumination (traduced here by the rear illumination level) play an important role on both conversion efficiency and bifaciality factor. An increasing illumination level (increasing reflection factor for the ground reflection surface) lead to an increasing bifaciality and conversion efficiency.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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