

Original Research Article

**BASE DOPING AND ILLUMINATION LEVEL
EFFECTS ON A BIFACIAL SILICON SOLAR
CELL**

ABSTRACT

In this paper, we are investigating 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 illumination 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.

Keywords: Bifaciality, doping, conversion efficiency, solar cell.

1. INTRODUCTION

Bifacial solar cells are solar cells that can be illuminated on both sides and produce current. Since their introduction [1] these devices continue to be improved 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 to the rear surface illumination condition (background surface reflection property or rear illumination level) and the quality of the rear side of the cell (back surface recombination velocity, passivation, back surface field...).

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 figure 1.

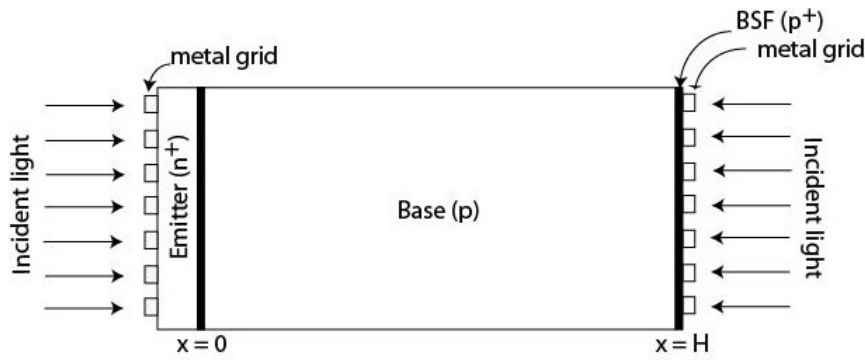


Fig. 1. Schematic diagram of a bifacial silicon solar cell

Carrier generation, recombination and drift/diffusion are the three major phenomenon 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:

$$\frac{\partial^2 \delta_a(x)}{\partial x^2} - \frac{\delta_a(x)}{L^2} = -\frac{G_a(x)}{D} \quad (1)$$

δ_a is the excess minority carrier density, L is their diffusion length and D their diffusion coefficient.

The diffusion coefficient is written as [5]:

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

where Nb is the base doping density.

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

$$\tau(Nb) = \frac{12}{1 + \frac{Nb}{5 \cdot 10^{16}}} \quad (\text{in } \mu\text{s}) \quad (3)$$

The diffusion length can then be deduced as:

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

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

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

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

$$G_{bifacial}(x) = \sum_{m=1}^3 a_m \cdot [n_{front} \cdot \exp(-b_m \cdot x) + n_{back} \exp\{-b_m \cdot (H - x)\}]$$

51 n_{front} , n_{rear} indicate illumination levels for front and back illumination respectively. Illumination
52 level is taken to be the ratio between incident power and AM1.5 reference power
53 (100mW.cm⁻²). Coefficients a_m and b_m are tabulated values obtained from solar irradiance
54 and the dependence of the absorption coefficient on the illumination wavelength [8].

55 Solution of equation (1) is:

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

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

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

56 Coefficients $C1_\alpha$ and $C2_\alpha$ (subscript α refer to the bifacial silicon solar cell illumination mode)
57 can be evaluated if we consider the two following boundary conditions:
58 - at the junction ($x=0$):

$$\left. \frac{\partial \delta_\alpha(x)}{\partial x} \right|_{x=0} = \frac{Sf_\alpha}{D} \cdot \delta_\alpha(0) \quad (7)$$

59 - at the backside ($x=H$):

$$\left. \frac{\partial \delta_\alpha(x)}{\partial x} \right|_{x=H} = -\frac{Sb_\alpha}{D} \cdot \delta_\alpha(H) \quad (8)$$

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

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

$$Jph_x = q \cdot D \cdot \left. \frac{\partial \delta_\alpha(x)}{\partial x} \right|_{x=0} \quad (9)$$

64

$$V_{ph} = V_T \cdot \ln \left(\frac{N_B \cdot \delta(x=0)}{n_i^2} + 1 \right) \quad (10)$$

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

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

$$\text{bifaciality } y = \frac{J_{sc_rear}}{J_{sc_front}} \quad (11)$$

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:

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

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 figure 2 the photocurrent densities for the bifacial solar cell front illumination, rear illumination and then bifacial illumination.

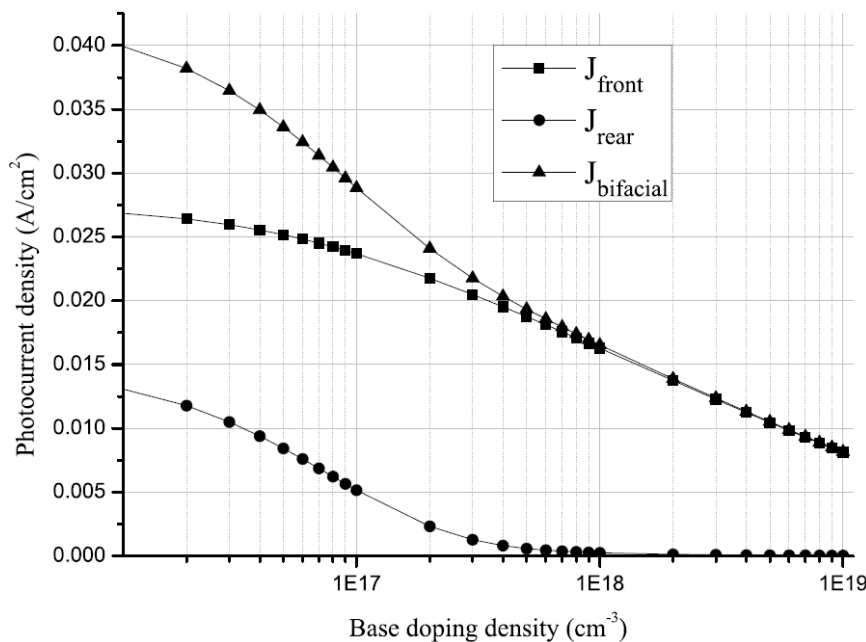


Fig. 2. Photocurrent density versus base doping density for front, rear and bifacial illumination ($H=0.02\text{cm}$, $S_b = 10^3\text{cm/s}$).

This figure shows clearly that bifacial illumination is more interesting given that it provide the more photocurrent density while the base doping density is of the order of 10^{17} . 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} .

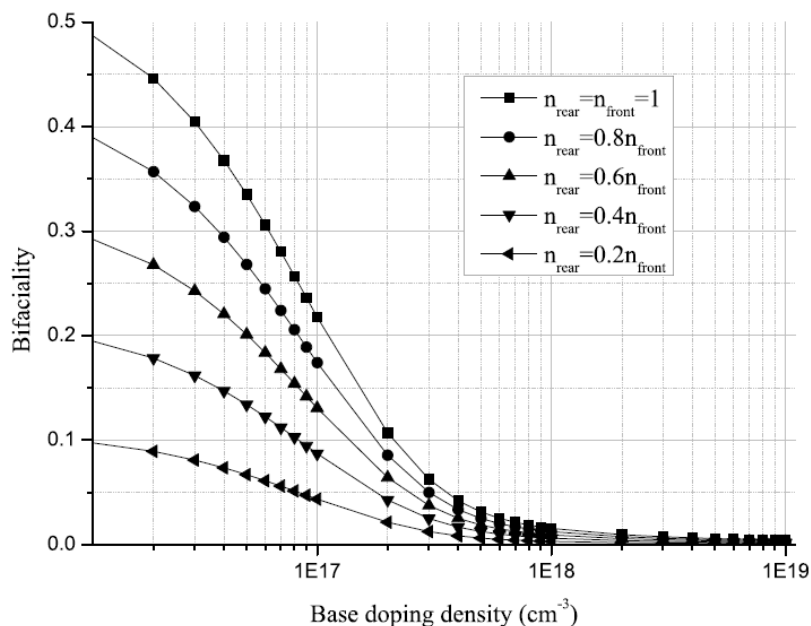
The back side illumination produce the lower current density since carrier path to junction is greater than that of front side illumination but this is also directly related to the back surface recombination velocity. Effectively for very low back surface recombination velocity, carrier are not lost at the back 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, S_b will be very low and the presence of the BSF will improve significantly the rear illumination photocurrent as presented by [14, 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 back side and have in mind that thinner will be better.

3. 2 Bifaciality coefficient

The idea of the bifaciality coefficient was first introduced by [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 figure 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.



111

Fig. 3. Bifaciality coefficient versus base doping density for different rear illumination level ($H=0.02 \text{ cm}$, $S_b = 10^3 \text{ cm/s}$).

114

As noted on figure 2, the photocurrent density decrease as the base doping density increase, especially above 10^{17} cm^{-3} . This influence directly the bifaciality coefficient given that the rear illumination photocurrent density is more sensitive to the base doping density. 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 figure 4 and proved by [15].

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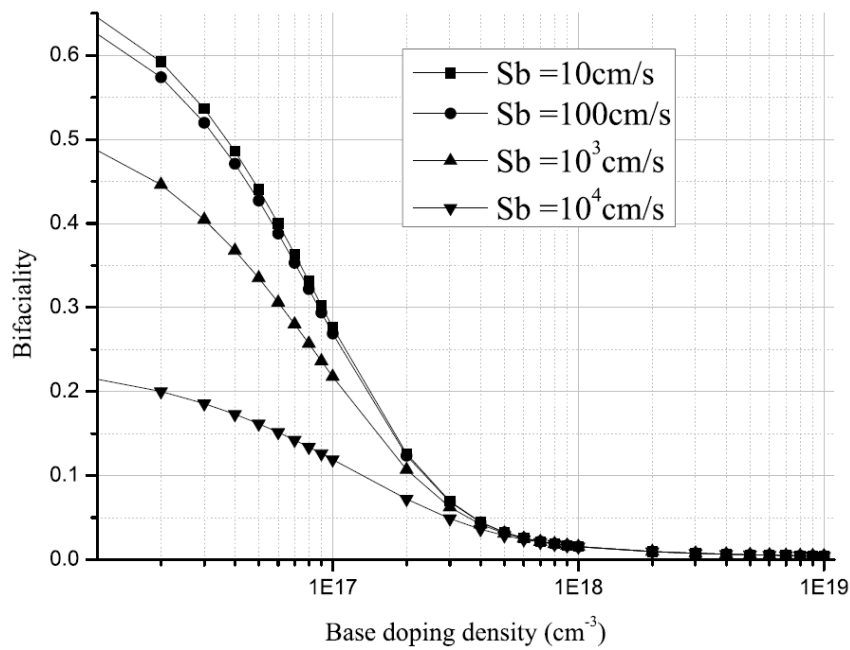


Fig. 4. Bifaciality coefficient versus base doping density for various back surface recombination velocities ($H=0.02\text{cm}$, $S_b = 10^3\text{cm/s}$).

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].

The more the surface is reflective the more the rear side photocurrent density is greater.

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 figure 5.

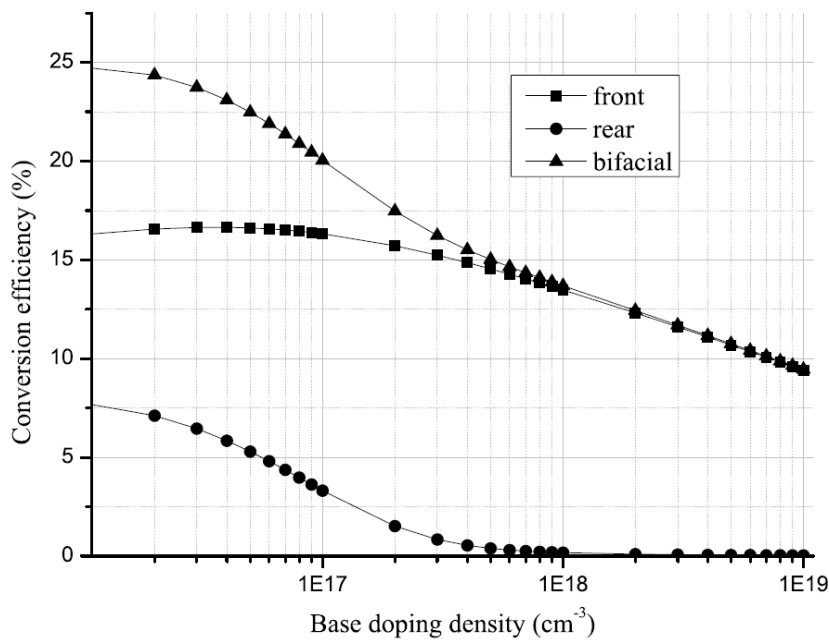
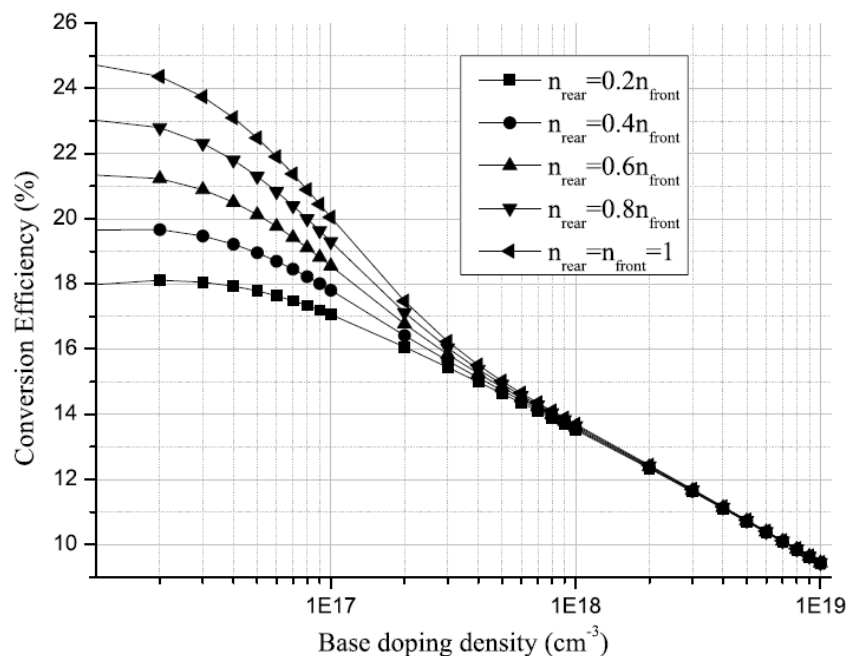


Fig. 5. Conversion efficiency versus base doping density for front, rear and bifacial illumination ($H=0.02\text{cm}$, $S_b = 10^3\text{cm/s}$).

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135 The conversion efficiency decreases with base doping density as recombination processes
136 increase with base doping density. The bifacial efficiency is more important as expected.

137 For the curve, we supposed that for rear illumination we have the same incident flux. Really
138 this may be wrong due to different factors [12, 13]. To evaluate more accurately the bifacial
139 efficiency, we varied the rear incident flux (n_{rear} factor). The resulting dependences are plotted
140 on figure 6:



141

142 **Fig. 6. Bifacial conversion efficiency versus base doping density for various rear**
143 **illumination levels ($H=0.02\text{cm}$, $S_b = 10^3\text{cm/s}$).**

144

145 We considered that the illumination level is directly related to the reflection surface so we
146 plotted the conversion efficiency against the illumination level taking the front illumination
147 level as reference.

148 As expected, the bifacial efficiency increase as the rear illumination level increase that is as
149 the refection factor is important [12].

150

151

152 4. CONCLUSION

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

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

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

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REFERENCES

- 165 1. Mori H. Radiation energy transducing device. U.S. Patent 3.278.811, Oct.1966 (priority
166 Oct. 1960).
- 169 2. Cuevas A. The early history of bifacial solar cells. Proceedings of the 20th European
170 Photovoltaic Solar Energy Conference, Barcelona (Spain). 2005:801-805.
- 171 3. Moehlecke A, Osório VC, Zanesco I. Analysis of Thin Bifacial Silicon Solar Cells with
172 Locally Diffused and Selective Back Surface Field. Material research, 2014, DOI:
173 <http://dx.doi.org/10.1590/1516-1439.294614>
- 174 4. Untila GG, Kost TN, Chebotareva AB, Zaks MB, Sitnikov AM, Solodukha OI, Shvarts Z.
175 Bifacial low concentrator argentine free crystalline silicon solar cells based on ARC of TCO
176 and current collecting grid of copper wire. AIP Conference Proceedings 1556, 106 (2013);
177 doi: 10.1063/1.4822210.
- 178 5. Liou JJ, Wong WW. Comparison and optimization of the performance of Si and GaAs solar
179 cells. Solar Energy Materials and Solar Cells. 1992; 1(28):9-28.
- 180 6. Furlan J, Amon S. Approximation of the carrier generation rate in illuminated silicon. Solid-
181 State Electronics. 1985; 12 (28):241-1243.
- 182 7. Mohammad S N. An alternative method for the performance analysis of silicon solar cells.
183 J.Appl.Phys. 1987; 61(2):767-772.
- 184 8. Rajman, K., Singh, R, Shewchun. Absorption coefficient of silicon for solar cell
185 calculations. J. Solid-State Electronics.1979 (22):793-795.
- 186 9. Diallo HL, Maiga AS, Wereme A, Sissoko G. New approach of both junction and back
187 surface recombination velocity in a 3D modelling study of a polycrystalline silicon solar cell.
188 Eur. Phys. J. Appl. Phys. 2008 (42):203-211.
- 189 10. Barro FI, Sané M, Sahin G. Silicon solar cell space charge region and capacitance
190 behavior under electric field. Sylwan. 2014; 158(5):58-66. <http://sylwan.ibles.org/index.html>
- 191 11. Ooshaksaraei P, Sopian K, Zulkifli R, Alghoul MA, Zaidi SH. Characterization of a Bifacial
192 Photovoltaic Panel Integrated with External Diffuse and Semimirror Type Reflectors.
193 International Journal of Photoenergy. 2013; (Volume), 7pages, ID 465837
194 <http://dx.doi.org/10.1155/2013/465837>.
- 195 12. Sugibuchi K, Ishikawa N, Obara S. Bifacial-PV Power Output Gain in the Field Test Using
196 "Earthon" High Bifaciality Solar Cells. Proceedings of the 28th European Photovoltaic Solar
197 Energy Conference, Paris (France). 2013:4312-4317.
- 198 13. Grigorieva G, Kagan M, Unishkov V, Zviagina K, Kreinin L, Bordin N, Broder J, Eisenberg
199 Y, Eisenberg N. Efficiency Of Bifacial Si Solar Cells At Low Irradiance. Effect of Design and
200 Fabrication Technology Factors. Proceedings of the 25th European Photovoltaic Solar Energy
201 Conference/5th World Conference on Photovoltaic Energy Conversion, Valencia (Spain).
202 2010:1805-1809.
- 203 14. Hübner A, Aberle AG, Hezel R. Novel cost-effective bifacial silicon solar cells with 19.4%
204 front and 18.1% rear efficiency. Applied Physics Letters. 1997; 1008(70): doi:
205 10.1063/1.118466.
- 206 15. Gonsui S, Goda S, Sugibuchi K, Ishikawa N, Honda K, Zama H. N-Type High Efficiency
207 Bifacial Silicon Solar Cell With the Extremely High Bifaciality of 96% in Average Fabricated
208 by using Conventional Diffusion Method. Proceedings of the 28th European Photovoltaic
209 Solar Energy Conference, Paris (France). 2013:718-721.