

**Response to “Comment on ‘Towards high efficiency thin-film crystalline silicon solar cells: The roles of light trapping and non-radiative recombinations’” [J. Appl. Phys. 117, 026101 (2015)]**

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## Response to “Comment on ‘Towards high efficiency thin-film crystalline silicon solar cells: The roles of light trapping and non-radiative recombinations’” [J. Appl. Phys. 117, 026101 (2015)]

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In Ref. 1, we investigated the performance of crystalline silicon (c-Si) solar cells, both flat and with Lambertian light trapping,<sup>2</sup> by means of analytic modelling and by numerically solving the drift-diffusion equations with the Silvaco-ATLAS simulator. We found a generally good agreement between the results of the two methods, although some systematic discrepancies were noticed. In Ref. 1, we attributed these discrepancies to the approximations made in the analytic model. In the preceding Comment,<sup>3</sup> Abenante analyzed our paper in depth and compared our Silvaco-ATLAS results with those of another analytic treatment as well as with those obtained with PC1D solar cell simulator, finding a very good quantitative agreement. The author concluded that the discrepancies in Ref. 1 may be due to two reasons:

- The value of the intrinsic carrier concentration  $n_i$  in silicon used in the analytic model differs from that used in the Silvaco-ATLAS calculations.
- Errors may be present in our analytic solution of the drift-diffusion equations, or in its implementation.

Regarding the intrinsic carrier concentration, Abenante is right. In the analytic calculations of Ref. 1, we used  $n_i = 1 \times 10^{10} \text{ cm}^{-3}$ , which is different from the default value  $1.45 \times 10^{10} \text{ cm}^{-3}$  embedded in Silvaco-ATLAS. This resulted in a lower value of the dark current  $J_{\text{dark}}(V)$  under applied bias when calculated in the analytic model, while it had no influence on the short-circuit current  $J_{\text{sc}}$  or on the fill factor  $FF$ . The net effect was a systematically higher value of the order of 10–20 mV in the analytically calculated open-circuit voltage  $V_{\text{oc}}$ . The discrepancy affected both the flat cells and those with light-trapping.

In addition, we realized that we used different numbers of energy points in the two methods when treating the cells with Lambertian light trapping. When calculating the short-circuit current by integrating over the AM1.5G solar spectrum, the Silvaco-ATLAS values were calculated with 35 points in the energy range of 1–4.4 eV, while the analytic ones were integrated with 3401 points. As a consequence of the coarse discretization,  $J_{\text{sc}}$  was not accurate enough in the Silvaco-ATLAS calculations for the case of light trapping and it resulted in the Silvaco-ATLAS results being underestimated by at most 2 mA/cm<sup>2</sup> or <7% relative: this explains most of the discrepancy in Figure 4(a) of Ref. 1. The coarse energy discretization was introduced when importing the Lambertian photogeneration

rate in Silvaco-ATLAS. The carrier generation rate of the planar cells, instead, was not imported but rather calculated directly with the T-matrix subroutine of Silvaco over 3401 energy points and it agrees perfectly with the analytic formulas.

In light of these findings, we recalculated all the results shown in Figures 4–7 of our paper<sup>1</sup> with consistent assignments for the input parameters. The intrinsic concentration  $n_i$  is set to  $1.45 \times 10^{10} \text{ cm}^{-3}$  in the analytic model, and the Silvaco-ATLAS results are recalculated over 3401 energy points by using an automatic data transfer procedure. The new results are shown in Figures 1–4 of this Response. As it is evident from Figures 1 and 3, we now get an excellent agreement for both the flat cells and for those with Lambertian light trapping. For the thickness range between 10 and 200  $\mu\text{m}$ , which is the most important for the conclusions of our work, the maximum relative discrepancy in  $J_{\text{sc}}$ ,  $V_{\text{oc}}$ ,  $FF$ , and  $\eta$  reported in Fig. 1 is less than 0.02%, 0.4%, 1.3%, and 1%, respectively. In practice, the value of  $n_i$  affected  $V_{\text{oc}}$ , the number of energy points affected  $J_{\text{sc}}$ , while the fill factor was basically unaffected. The remaining

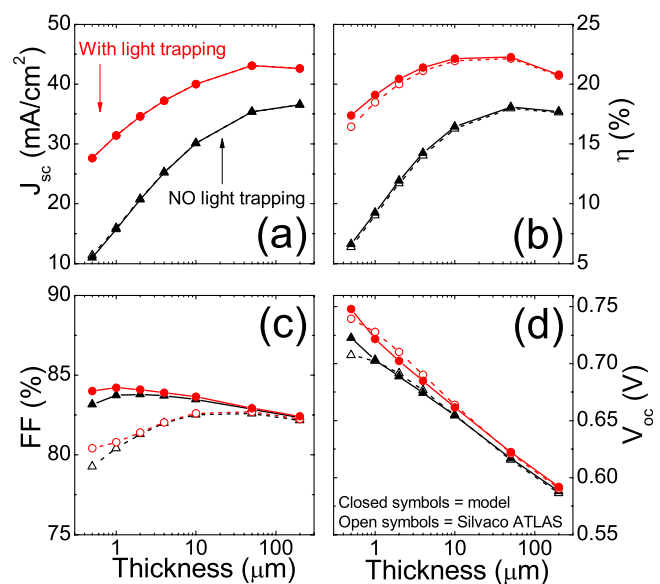


FIG. 1. The main electric parameters for c-Si solar cells with perfect surface passivation ( $S_n = S_p = 0 \text{ cm/s}$ ): short-circuit current density  $J_{\text{sc}}$  (a), conversion efficiency  $\eta$  (b), fill factor  $FF$  (c), and open-circuit voltage  $V_{\text{oc}}$  (d). Analytic results are reported with closed symbols (triangles for the planar case, and circles for the light-trapping case) and solid connecting lines; while numerical results from Silvaco ATLAS are reported with open symbols and dashed connecting lines. Compared to Figure 4 in Ref. 1,  $n_i$  has been set to  $1.45 \times 10^{10} \text{ cm}^{-3}$  in the analytic model, and the Silvaco data are calculated over 3401 energy points.

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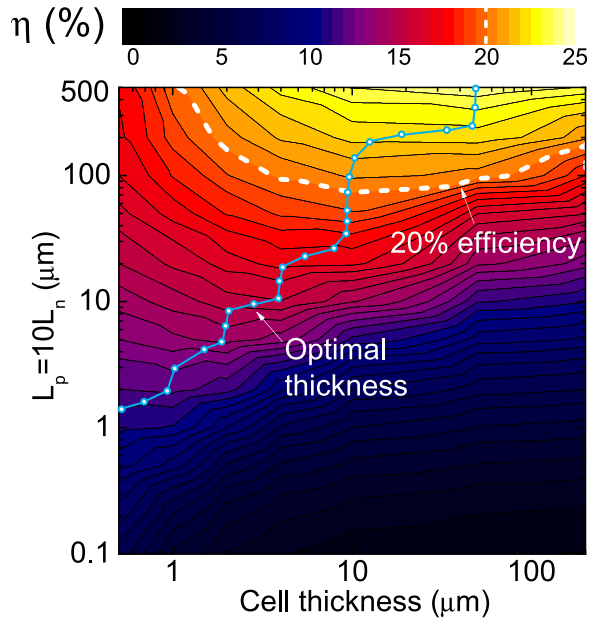


FIG. 2. Energy conversion efficiency for c-Si solar cells with Lambertian light trapping and perfect surface passivation ( $S_n = S_p = 0$  cm/s) as a function of the bulk quality ( $L_p = 10L_n$ ) and cell thickness. The useful range with  $\eta$  exceeding 20% is reported within a white dashed line, while the optimal configurations lie along the blue solid line. Compared to Figure 5 in Ref. 1,  $n_i$  has been set to  $1.45 \times 10^{10} \text{ cm}^{-3}$  in the analytic model.

small discrepancy between analytic and numerical efficiency (Figure 1(b)) becomes appreciable only for very thin cells (thickness  $< 10 \mu\text{m}$ ), and it reaches 6% relative at 500 nm thickness. This remaining discrepancy can now be attributed to the different treatments of the transport process in the two methods. In the analytic model, the depletion region approximation and an ideal collection from the space charge region are assumed. In the numerical calculations, the drift-diffusion equations are solved with finite-elements techniques considering both the drift and the diffusion terms in each point of the device.

We also double-checked all the formulas of our analytic treatment which were implemented in obtaining the results of our paper, finding no errors. However, we found misprints in Eqs. (A6)–(A8) in the Appendix of our paper.<sup>1</sup> The correct expressions for the excess carrier densities are given below

$$\Delta n(z, E) = \frac{\alpha_{lt} \phi_{AM1.5}(E) L_p^2 (R_b e^{-2\alpha_{lt} w} e^{\alpha_{lt} z} + e^{-\alpha_{lt} z})}{D_p [1 - R_b e^{-2\alpha_{lt} w} (1 - 1/n_{Si}^2)] (1 - \alpha_{lt}^2 L_p^2)} + c_1 e^{z/L_p} + c_2 e^{-z/L_p}, \quad (1)$$

$$c_1 = \frac{\alpha_{lt} L_p^2 \phi_{AM1.5}}{D_p (1 - R_b e^{-2\alpha_{lt} w} (1 - 1/n_{Si}^2)) (\alpha_{lt}^2 L_p^2 - 1)} \times \left[ e^{-\alpha_{lt} w} \left( R_b \left( \alpha_{lt} + \frac{S_{eff,p}}{D_p} \right) - \alpha_{lt} + \frac{S_{eff,p}}{D_p} \right) + e^{-\alpha_{lt} h - w_p/L_p} (1 + R_b e^{-2\alpha_{lt} w_p}) \left( \frac{1}{L_p} - \frac{S_{eff,p}}{D_p} \right) \right] / \left[ e^{w/L_p} \left( \frac{1}{L_p} + \frac{S_{eff,p}}{D_p} \right) + e^{(2h-w)/L_p} \left( \frac{1}{L_p} - \frac{S_{eff,p}}{D_p} \right) \right], \quad (2)$$

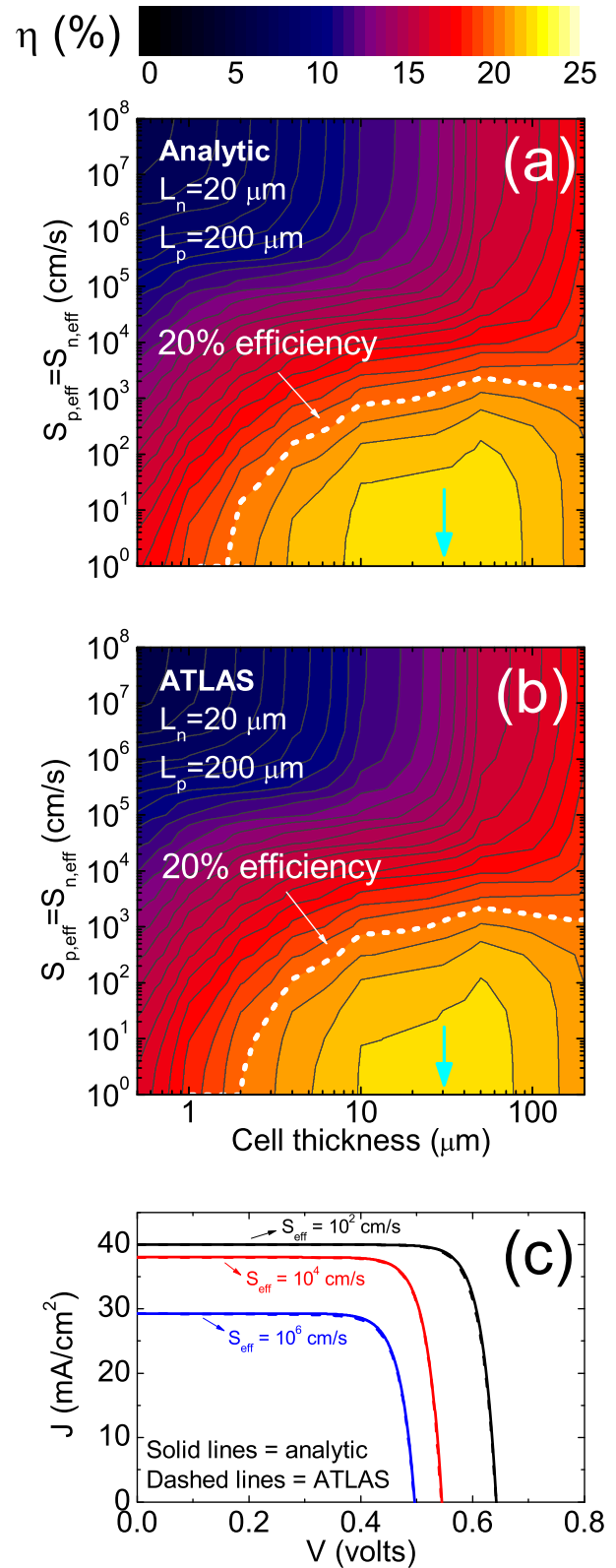


FIG. 3. Effects of solar cells thickness and effective surface recombination velocity on the conversion efficiency  $\eta$  for c-Si solar cells with Lambertian light trapping: analytic (a) and ATLAS results (b). JV curves for c-Si solar cells with thickness  $10 \mu\text{m}$ , and  $S_{eff} = 10^2$  cm/s (black lines),  $S_{eff} = 10^4$  cm/s (red lines), and  $S_{eff} = 10^6$  cm/s (blue lines) (c). Analytic results are reported with solid lines, while ATLAS results with dashed lines. In all cases, Lambertian light trapping is assumed, and  $L_n = 20 \mu\text{m}$ ,  $L_p = 200 \mu\text{m}$ . Compared to Figure 6 in Ref. 1,  $n_i$  has been set to  $1.45 \times 10^{10} \text{ cm}^{-3}$  in the analytic model, and the Silvaco data are calculated over 3401 energy points.

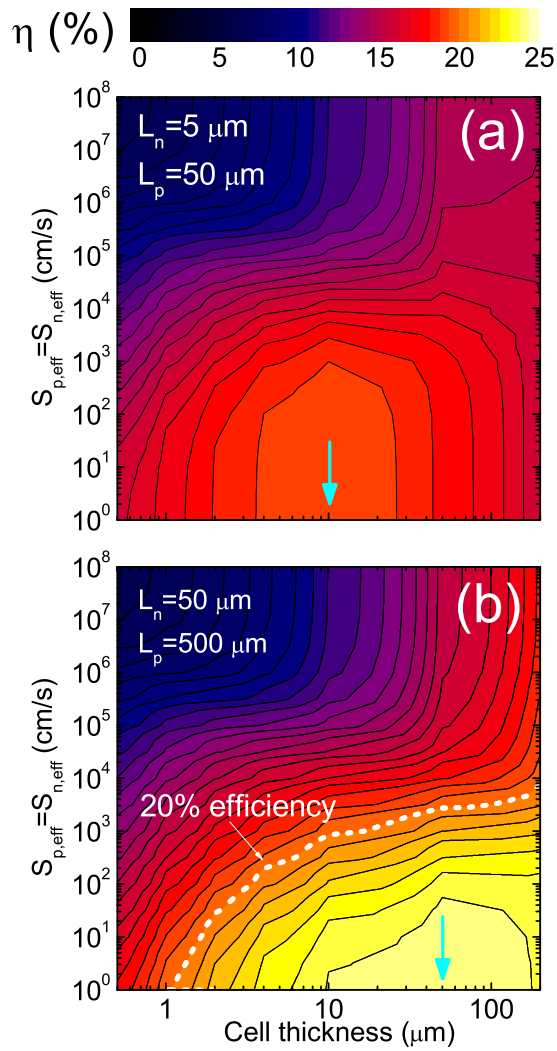


FIG. 4. Effects of solar cells thickness and effective surface recombination velocity on the conversion efficiency  $\eta$  for solar cells with Lambertian light-trapping: low quality silicon with  $L_n = 5 \mu\text{m}$ ,  $L_p = 50 \mu\text{m}$  (a), and high quality silicon with  $L_n = 50 \mu\text{m}$ ,  $L_p = 500 \mu\text{m}$  (b). Compared to Figure 7 in Ref. 1,  $n_i$  has been set to  $1.45 \times 10^{10} \text{cm}^{-3}$  in the analytic model.

$$c_2 = -c_1 e^{2h/L_p} + \frac{\alpha_{it} L_p^2 \phi_{AM1.5} (1 + R_b e^{-2\alpha_{it} w_p})}{D_p (1 - R_b e^{-2\alpha_{it} w} (1 - 1/n_{si}^2)) (\alpha_{it}^2 L_p^2 - 1)} e^{-\alpha_{it} h + h/L_p}. \quad (3)$$

A factor  $\phi_{AM1.5}(E)L_p^2$  was missing in Eq. (A6) of our paper,<sup>1</sup> as it can be seen by comparing with all the other formulas. In addition, a factor  $\alpha_{it}^2 L_p^2 - 1$  was missing in the denominator and a factor  $e^{-2\alpha_{it} w_p}$  multiplying  $R_b$  was missing in the numerator of Eqs. (A7) and (A8). Nevertheless, we emphasize that the correct formulas (1)–(3) above were implemented when generating the analytic results reported in Ref. 1. Thus, the analytic expressions we used in Ref. 1 did represent the solution of the transport equations, unlike suggested in Ref. 3.

Summarizing, we have recalculated the results of Ref. 1 with consistent assignments for the input parameters:

- (1) The intrinsic concentration  $n_i$  is set to  $1.45 \times 10^{10} \text{cm}^{-3}$  in the analytic model.
- (2) The Silvaco results are recalculated over 3401 energy points.

The agreement between our analytic and numerical approaches is appreciably improved. We remark that the differences between Figs. 1 and 3 of this Response and Figs. 4 and 6 of Ref. 1 do not affect any of the physical conclusions for c-Si solar cells. We appreciate the critical analysis by Abenante, which leads to a common conclusion: the analytic solution of the drift-diffusion equations in the depletion approximation is in very good agreement with the results of fully numerical treatments.

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<sup>1</sup>A. Bozzola, P. Kowalczewski, and L. C. Andreani, *J. Appl. Phys.* **115**, 094501 (2014).

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<sup>3</sup>L. Abenante, *J. Appl. Phys.* **117**, 026101 (2015).