

The Effect of Thickness and Surface Recombination Velocities on the Performance of Silicon Solar Cell

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Abstract

With a low surface recombination velocity, it is possible to increase the efficiency of solar cells as the thickness is decreased. A maximum appearing in the efficiency versus thickness curve is mostly due to the same trend in the short-circuit current versus thickness curve. The trend of the short-circuit current versus thickness curve will be clearly discussed based on the view of competition between generation and recombination rates near the rear surface. If surface passivation can be well introduced, the win-win situation for the material cost and efficiency can be achieved based on our results.

Keywords: silicon solar cells; surface recombination; thickness

1. Introduction

Solar energy becomes more and more important since it has the potential to provide sufficient energy in a clean way for the immediate future [1]. Research is going on to further reduce the cost of solar energy to compete with energy sources that are adverse to the environment. In order to reduce the cost, many efforts focus on less grams of Si per Wp [2–4]. The less demand for active materials means a considerable reduction of the thickness of Si. Even though thinner Si can enhance absorption through such as photonic crystal reflectors [4], their efficiency is still strongly influenced by the surface recombination velocity (SRV). In particular, the impact of thickness reduction on open-circuit voltage (V_{OC}) depends on the magnitude of SRV—whether it improves or deteriorates is ultimately determined by SRV levels.

As the thickness decreases, the V_{OC} would increase with a low SRV, while V_{OC} would decrease with a high SRV [5]. On the other hand, short-circuit current (I_{SC}) is basically thought to be decreasing with decreasing the cell thickness when the optical path is not long enough [6,7]. However, the relation between I_{SC} and the thickness should depend on the SRV as shown in this paper. The effect of the thickness on the cell efficiency under some surface recombination velocities has been reported [8]. In this paper, the influence of SRV on curves of V_{OC} , I_{SC} , and efficiency versus thicknesses will all be systematically studied, and the curve behaviors under various surface recombination velocities (SRVs) will be fully discussed. It can be found that the optimized thickness should depend on the level of surface recombination.

2. Device Structure

In this study, the typical pn structure featuring a shallow diffused n^+ emitter layer on a p-type Si substrate was adopted with the numerical simulation tool, PC1D [9–11]. Since



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recent solar cell architectures have all evolved from the pn structure, the PERC (Passivated Emitter and Rear Cell) architecture was mainly introduced by adding passivation layers on the surface to reduce the SRV [12]. The transition from p-Si substrates to lower-defect n-Si substrates has led to two major advancements: the well-established SHJ (Silicon Hetero-Junction) structure, which utilizes a-Si for passivation, and the more recently mainstream TOPCon (Tunnel Oxide Passivated Contact), which employs a silicon oxide passivation contact on the rear side of n-Si to reduce SRV [13,14]. Throughout this progression, it becomes evident that SRV is the key factor driving these technological advancements. Therefore, in this study, we adopt a simple pn structure with varying SRV values, selecting an SRV range of 100–10,000 cm/s, as used in recent TOPCon research [15]. By using a straightforward pn structure, we systematically and comprehensively investigate the relationship between SRV, I_{sc} , and other critical solar parameters, along with the underlying physical mechanisms. This approach allows our findings to be applicable across various solar cell technologies.

The cell size was set as 100 cm². The background p-type doping was set as 5×10^{16} cm⁻³, and the bulk recombination lifetime was 7.2 μ s. The doping density of n⁺ diffusion was assumed to be 10^{19} cm⁻³ and the junction depth was 0.1 μ m. Four SRVs ($S = 100, 1000, 3000$, and 10,000 cm/s) were chosen for comparison, and the front and rear surfaces were set at the same value. The used cell parameters in this PC1D simulation is collected in Table 1.

Table 1. Cell parameters in this PC1D simulation.

Parameters	Value
Cell area	100 cm ²
Front surface texture depth	3 mm
Exterior front reflection	10%
Base contact	$1.5 \times 10^{-3} \Omega$
Dielectric constant	11.9
Band gap	1.12
Intrinsic concentration	1×10^{10} cm ⁻³
Bulk recombination	$t_n = t_p = 7.2$ ms
Temperature	25 °C
Light intensity	0.1 Wcm ⁻²
Light spectrum	AM 1.5G

3. Results

Figure 1 shows V_{OC} as a function of the cell thickness under various SRVs. When the SRV is low, V_{OC} increases as the thickness decreases. This trend keeps from $S = 100$ cm/s to $S = 1000$ cm/s. When the SRV is as high as 3000 cm/s, the trend then changes. It can be found that V_{OC} decreases as the thickness decreases when the SRV is above 3000 cm/s. Since the curve of $S = 1000$ cm/s has a totally different behavior as compared with the curve of $S = 3000$ cm/s, the following study will focus on the comparison between these two cases.

V_{OC} is given by: [16]

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_L}{I_0} + 1\right) \quad (1)$$

where k is the Boltzmann's constant, T is the absolute temperature, and q is the electronic charge. I_L is the photo-generated current. I_0 is the dark saturation current, and for a cell of finite dimensions, I_0 has the form:

$$I_0 = A\left(\frac{qD_en_i^2}{L_eN_A} * F_P + \frac{qD_hn_i^2}{L_hN_D} * F_N\right) \quad (2)$$

where A is the cross-sectional area, n_i is the intrinsic concentration. D_e and D_h are electron and hole diffusion coefficients, respectively, and L_e and L_h are the corresponding diffusion lengths. N_A and N_D represent the doping concentration of the p-type and n-type semiconductor, respectively. F_P and F_N can be seen as modification factors for finite dimensions. In a typical derivation of the I–V characteristics of a pn diode, the terms F_P and F_N do not usually appear. This is because such derivations assume that the p- and n-sides of the junction are infinitely thick. However, real cells have finite dimensions, and the surface recombination at the outer edges of both sides can influence carrier behavior. In this case, the boundary conditions are affected by the SRV, which in turn influences F_P and F_N , represented in Equation (3) and Equation (4), respectively. As a result, these two terms appear in the I–V relationship expressed in Equation (2). From Ref. [16], F_P and F_N are given by

$$F_P = \frac{S * \cosh(W_P/L_e) + D_e/L_e \sinh(W_P/L_e)}{D_e/L_e \cosh(W_P/L_e) + S * \sinh(W_P/L_e)} \quad (3)$$

$$F_N = \frac{S * \cosh(W_N/L_h) + D_h/L_h \sinh(W_N/L_h)}{D_h/L_h \cosh(W_N/L_h) + S * \sinh(W_N/L_h)} \quad (4)$$

where W_P and W_N are the thicknesses of the p-type and n-type semiconductor regions, excluding the depletion region (i.e., the thicknesses of the neutral p-type and n-type regions).

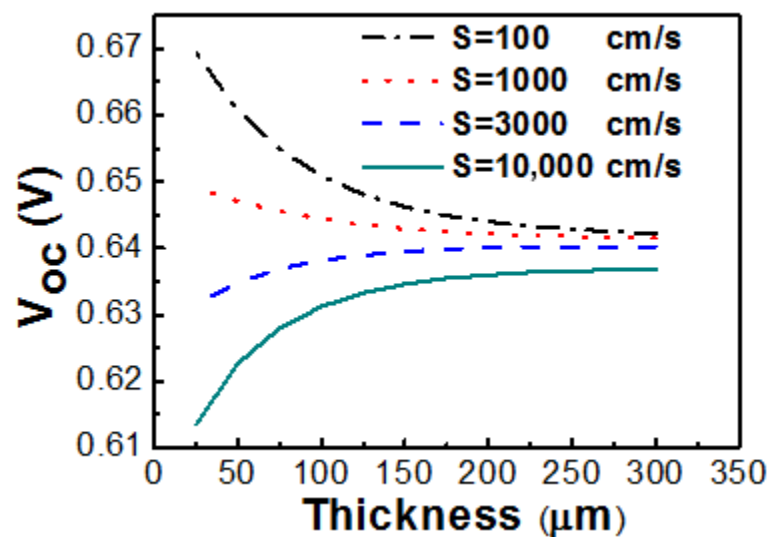


Figure 1. The open-circuit voltage as a function of the cell thickness under various SRVs. As the thickness decreases, the open-circuit voltage would increase with a low SRV, while V_{OC} would decrease with a high SRV.

Figure 2 shows the calculated F_P as a function of the thickness in our case. Since N_A is much lower than N_D , I_0 is dominated by the first term in Equation (2). Hence, I_0 as a function of the thickness has the same trend as F_P . In the case of a low SRV ($S = 1000$ cm/s for example), I_0 is found to decrease as the thickness decreases (Figure 2). Subsequently, from Equation (1), V_{OC} increases as the thickness decreases. In the case of a high SRV ($S = 3000$ cm/s for example), the trend of I_0 is reversed, and hence V_{OC} decreases as the thickness decreases. It should be noted that the thickness dependence on I_L will also influence the V_{OC} curve as revealed in Equation (1). However, from the following discussion on the thickness dependence on I_{SC} ($\sim I_L$), the variation of ratio on I_{SC} is much smaller than I_0 . Therefore, the trend of the V_{OC} curve is dominated by I_0 . From a physics perspective, the behaviors shown in Figures 1 and 2 can be explained as follows: when photo-generated carriers have a higher tendency to recombine—such as due to a high SRV—the recombination loss increases (corresponding to a higher I_0), which in turn leads

to a lower open-circuit voltage (V_{OC}) that the solar cell can provide. This explains the inverse relationship between V_{OC} and I_0 presented in Equation (1): a less SRV leads to a higher V_{OC} , while a higher SRV results in a lower V_{OC} . This effect is especially pronounced when the solar cell is thin (as discussed at the beginning of this section, the thickness here mainly refers to the thickness of the doped p-type region with N_A). When the cell is thin, surface recombination becomes significant and can no longer be neglected, and the F_p term in Equation (2) must therefore be included. However, as the thickness increases, the impact of surface recombination becomes weaker (returning to the typical I–V characteristics where F_p equals 1), variations in SRVs will no longer cause significant differences in V_{OC} .

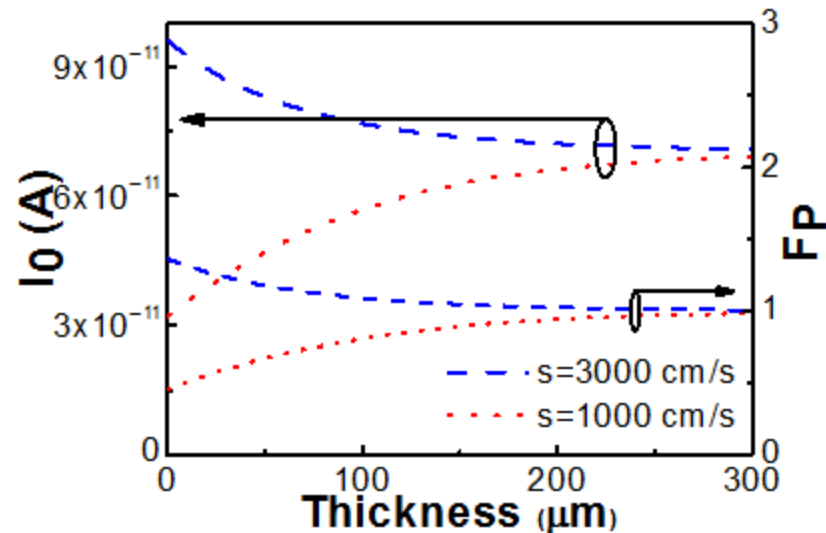


Figure 2. The calculated F_p and the corresponding I_0 as a function of the thickness. The curve of $S = 3000$ cm/s represents the condition of a high SRV, while $S = 1000$ cm/s represents the condition of a low SRV.

Figure 3 shows I_{SC} as a function of the thickness under various SRVs. From a physical point of view, a smaller SRV means that fewer photogenerated carriers are lost through surface recombination. Therefore, more carriers can be collected as current under illumination, resulting in a higher I_{SC} . This explains why, in Figure 3, the I_{SC} values are higher for lower SRVs. When the SRV is low, the I_{SC} exhibits a non-monotonic behavior as the thickness decreases—it first increases to a maximum and then decreases. This trend is explained by considering the competing effects of generation and recombination within the cell as its thickness changes. Specifically, a reduction in thickness decreases both the amount of photogeneration and the amount of recombination (due to less material). This tradeoff is illustrated in Figure 4. In Figure 4a, which corresponds to an SRV of 1000 cm/s and a thickness of 175 μm , the recombination rate near the rear surface (at ~ 175 μm depth) is higher than the generation rate. If we reduce the cell thickness slightly (e.g., from 175 μm to 174 μm), both generation and recombination from the region between 174 μm and 175 μm are eliminated. However, the loss due to recombination in this region is greater than the gain from generation, so the net effect is an increase in I_{SC} . That is, the reduced recombination outweighs the reduced generation, resulting in a positive contribution to I_{SC} . This explains the initial increase of I_{SC} as the thickness decreases when SRV is low.

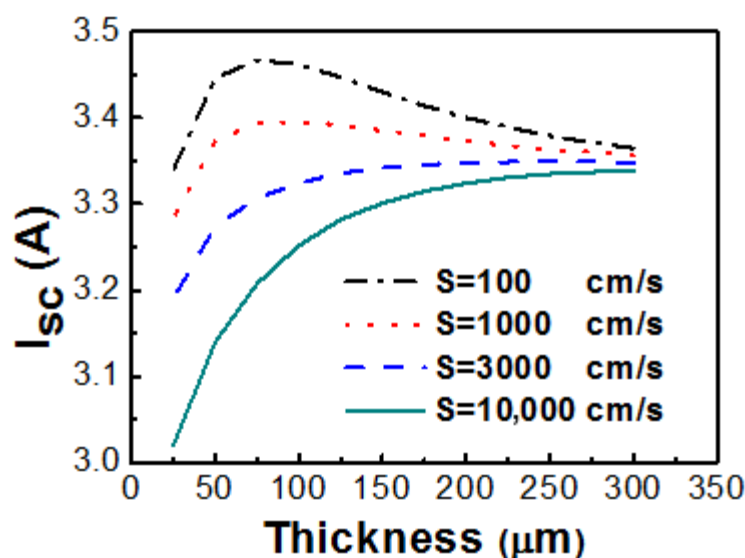


Figure 3. The short-circuit current as a function of the cell thickness under various SRVs. The cell size is 100 cm^2 . As long as the SRV is low enough, a maximum will appear in the curve.

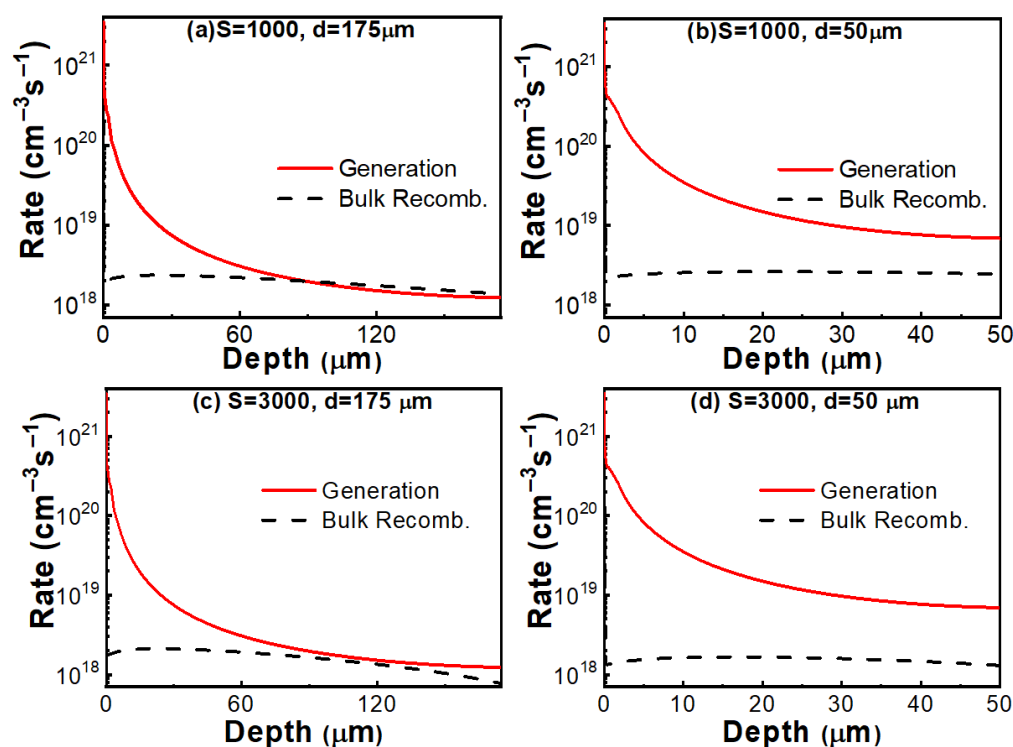


Figure 4. The distribution of generation and bulk-recombination rates. Four cases of two different SRVs ($S = 1000$ or 3000 cm/s) and two different thicknesses ($d = 175$ or $50 \text{ }\mu\text{m}$) are shown to explain the curve trends in Figure 3.

In contrast, Figure 4b shows the case of a $50\text{-}\mu\text{m}$ -thick cell (still with $SRV = 1000 \text{ cm/s}$), where the recombination rate near the rear surface is much smaller than the generation rate. In this situation, reducing the thickness further removes a region that contributes more to generation than to recombination. Thus, the loss in photogeneration dominates, leading to a drop in I_{SC} .

In Figure 4c,d, where the SRV is higher (3000 cm/s), the recombination rate remains lower than the generation rate near the rear surface for both $175 \text{ }\mu\text{m}$ and $50 \text{ }\mu\text{m}$ thick-

nesses. Thus, any reduction in thickness in these cases leads primarily to a reduction in photogeneration, and I_{SC} simply decreases as the cell becomes thinner.

The generation rate (G) decreases exponentially with depth because the light intensity diminishes exponentially due to absorption by silicon [17]. In contrast, the uniform N_A doping in p-type silicon results in an almost constant bulk recombination rate, while only the bulk recombination near the surface is slightly affected by surface recombination under different SRV conditions. Since generation is determined solely by the absorption coefficient of silicon, the generation curves in the first 50 μm of Figure 4a,b are identical. However, Figure 4a shows a thicker cell (175 μm), so the light continues to be exponentially absorbed in the deeper region (from 50 μm to 175 μm). This extended absorption causes the recombination and generation rates to become nearly equal at a depth of around 90 μm .

As mentioned earlier, with advancements in passivation technology, new structures continue to emerge, leading to continuous efficiency improvements. Therefore, we use normalized efficiency instead of absolute efficiency, making the results more applicable to different structures (Figure 5). We set the efficiency of the 300- μm -thick cell with $S = 10,000 \text{ cm/s}$ as 1 to analyze the relationship between efficiency and thickness under different SRV conditions. For solar cells with good passivated surfaces of $S = 100 \text{ cm/s}$, the efficiency can increase to maximum of 1.08 times when the thickness is decreased to 50 μm . For cases of further larger SRVs, the efficiency will continuously decrease as the thickness is decreased.

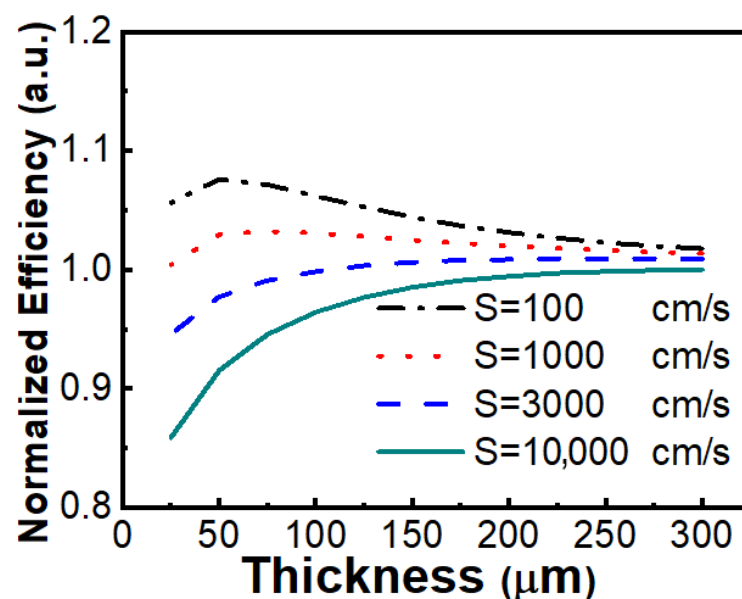


Figure 5. The normalized efficiency as a function of the cell thickness under various SRVs. For a cell with $S = 100 \text{ cm/s}$, the efficiency increases up to a maximum when the thickness is decreased to 50 μm .

Hence, it is quite important to achieve better surface passivation by any method such as that in Reference [18], since a lower material cost (thinner active layer) along with a higher efficiency as compared with the state-of-the-art industrial cells is possible with low SRVs. In other words, compared to Ref. [10], their assumption of $S = 10,000 \text{ cm/s}$ leads to a similar trend of the $S = 10,000 \text{ cm/s}$ case observed in our study, where efficiency decreases as thickness decreases. However, our research highlights that with the introduction of more advanced passivation methods, SRVs can be reduced from 10,000 cm/s , enabling higher efficiency even as the silicon thickness decreases. For PERC [19], TOPCon [20], and SHJ [21] structures, which are all effective passivation methods for thin silicon solar cells, SRVs can

be reduced to below 10 cm/s. Therefore, a win-win scenario of reduced material usage and improved efficiency can be achieved based on our results.

By examining the trends of V_{OC} in Figure 1 and I_{SC} in Figure 3, we find that under both high and low SRV conditions, the two parameters exhibit consistent behavior when the thickness is above 75 μm . As efficiency is a product of V_{OC} , I_{SC} , and FF divided by incident light power, the efficiency trends in these cases naturally follow those of V_{OC} and I_{SC} .

The only notable difference arises under low SRV conditions. For example, at $S = 100 \text{ cm/s}$, when the thickness decreases from 75 μm to 25 μm , V_{OC} increases by 2.2%, while I_{SC} decreases by 3.7%. Because the drop in I_{SC} is larger, the resulting efficiency still decreases by 1.4%. This explains why, the observed similar behavior between I_{SC} and efficiency.

4. Conclusions

In the view of the material cost, the thinner Si wafer for photovoltaic applications is desirable. Contrary to the intuitive expectation that efficiency simply decreases as cell thickness decreases, our study shows that under low surface recombination velocity conditions, reducing thickness can actually lead to increased efficiency within a certain range. If the surface recombination velocity can be reduced to the level lower than 1000 cm/s, the cell efficiency will have an obvious maximum as the thickness decreases. For $S = 100 \text{ cm/s}$, the efficiency can increase to maximum of 1.08 times when the thickness is decreased to 50 μm . The optimized thickness of each cell at a certain surface recombination velocity can be estimated. Efficiency maximum can give guidelines for request to the cell thickness based on the level of surface engineering achieved by the manufacturers.

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