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A simple general analytical solution for the quantum efficiency of front-surface-field solar cells

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Abstract

The optimisation of a FSF solar cell or a BSF thin film solar cell necessitates an understanding of the characteristics of an illuminated high-low junction. However, except for minority carrier reflection, the photocurrent collection property of the light-generated carriers in the high region by a high-low junction has rarely been treated previously. It is the purpose of this paper to present a simple solution for the contribution of the light-generated current from the high region. The model shows that a high-low junction may be very efficient in light-generated current collection, and this property is primarily responsible for the increase of the short wavelength quantum efficiency using a FSF. The effects of the FSF layer doping concentration and its thickness on the quantum efficiency are discussed by using the computed results; the optimisation of the FSF is then made. The calculations take into account the high doping effects of degeneracy and bandgap narrowing.

Keywords: Semiconductors device models; Semiconductor junctions; Short-circuit currents; Solar cells

1. Introduction

Front-surface-field (FSF), rear junction solar cells have demonstrated high energy conversion efficiency [1,2]. This has generated an interest in the theoretical analysis of the performance of the FSF. In the past, extensive studies on the back-surface-field (BSF) effect in solar cells have been carried out which show that the presence of a BSF can lead to a significant improvement in both short-circuit current and open-circuit voltage. The BSF acts as a carrier mirror reflecting minority carriers back into the bulk region, and so reducing surface recombination and the dark injection current. Similar

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effects can be found in the rear junction FSF solar cells where a high–low junction is placed near the front surface. Since the light-generated carrier concentration is highest at the front and decreases into the substrate, a strong effect arising from the FSF may be expected; additionally, light-generated carriers in the heavily doped front layer (usually negligibly small in BSF solar cells) give rise to a more sophisticated effect of the FSF than that of the BSF.

The influence of the BSF is usually modelled by an effective surface recombination velocity in the vicinity of the high–low junction. The effective recombination velocity (for an abrupt n^+ - n high–low junction) can be expressed as [3]:

$$S_{e,nn^+} = \frac{N_D}{N_{D^+}} \frac{D_{p,n^+}}{L_{p,n^+}} F_{n^+}, \quad (1)$$

where

$$F_{n^+}(s_p) = \frac{(s_p L_{p,n^+}/D_{p,n^+}) \cosh(W_{n^+}/L_{p,n^+}) + \sinh(W_{n^+}/L_{p,n^+})}{\cosh(W_{n^+}/L_{p,n^+}) + (s_p L_{p,n^+}/D_{p,n^+}) \sinh(W_{n^+}/L_{p,n^+})}. \quad (2)$$

s_p is the surface recombination velocity at the remote surface of the n^+ -region; N_D and N_{D^+} are the n - and n^+ -region impurity concentrations (note that effective values may be used); D_{p,n^+} and L_{p,n^+} are the hole diffusion coefficient and diffusion length in the n^+ -region; W_{n^+} is the width of the n^+ quasi-neutral region (which approximately equals to the thickness of the n^+ -region). The derivation of Eq. (1) takes into account the recombination losses, in the n^+ -region and at the surface, of minority carriers which migrate from the n -region through the high–low junction barrier. If the surface recombination velocity, s_p , is infinite, F_{n^+} reduces to:

$$F_{n^+}(\infty) = \coth\left(\frac{W_{n^+}}{L_{p,n^+}}\right). \quad (3)$$

For a rear junction solar cell, a FSF is formed by applying a high–low junction on the illuminated surface. The front surface recombination velocity also can be effectively reduced by use of the FSF. However, using an effective recombination velocity, as for the BSF, is not enough to correctly evaluate the quantum efficiency of a FSF rear junction solar cell, particularly in the short wavelength range. The modelling which results in the Eq. (1) does not include the behaviour of the light-generated minority carriers (mostly by the short wavelength light) in the n^+ -region. Sah et al. [4] and Lindholm et al. [5] had studied in their analysis the effect of the FSF, but mainly its role in the suppression of the dark emitter recombination current. The subject of the light-generated minority carriers in the high region was not discussed in their papers. Although Yernaux et al. [6] had taken into account the influence of the highly doped surface region on short wavelength response in their study, no explicit expressions were given.

In this paper a one-dimensional model for a FSF rear junction solar cell is reported, in which the current continuity equations in both the bulk and the heavily doped front region are solved and decoupled using the superposition principle. The model results in

a simple general analytical solution for the quantum efficiency and reveals the light-generated current collection characteristic of an illuminated high–low junction. The solar cell to be discussed in the following sections is an $n^+ - n - p^+$ rear junction cell. Since the contributions to the quantum efficiency from both the rear $n - p^+$ junction charge space region and the p^+ -region are very small, and previously solved [7,8], we limit our modelling work to the study of the front $n^+ - n$ region.

2. Theoretical modelling

Consider a one-dimensional $n^+ - n - p^+$ rear junction silicon solar cell as illustrated in Fig. 1, where the structural and physical parameter symbols used in the text are given. The illumination is incident on the n^+ surface (called the front surface) and the $n - p^+$ junction is situated near the opposite surface (called the rear surface). In order to simplify the solutions, uniform doping profiles for each of the three regions are assumed. Bounded by the dashed lines B and D is the space charge region at the high–low junction, and by the dashed lines E and G , the space charge region at the $n - p^+$ junction. The other areas in the device are assumed to satisfy quasi-neutrality conditions. The surface recombination velocities for the front and rear surfaces are respectively s_p and s_n . We assume that low-level injection conditions prevail, so the superposition principle holds. Two effective recombination velocities are introduced, s_{e,n^+n} and s_{e,nn^+} , at the virtual surfaces $y = B$ and $y = D$, respectively. The definitions of these two effective recombination velocities are essentially the same as given by Alamo [3]. The physical meaning of s_{e,nn^+n} (or s_{e,n^+n}) is that it accounts for the effects of the n^+ -region (or the n -region) on the minority carriers from the n -region (or the n^+ -region). Under steady-state conditions, the light-generated hole diffusion current, J_{pL} consists of three contributions, respectively, from the n^+ -region (AB), the space charge

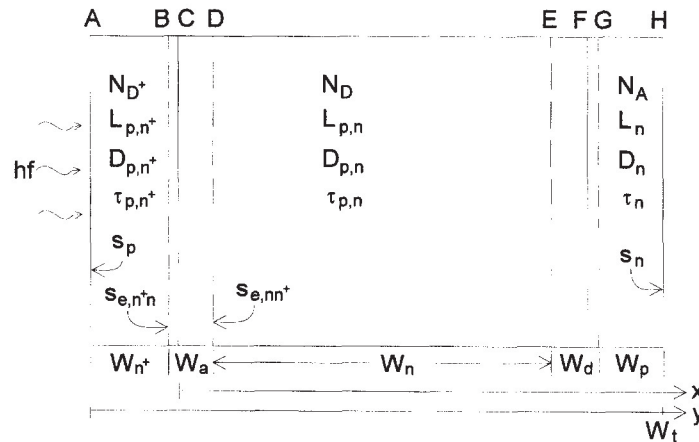


Fig. 1. Schematic diagram of a one dimensional model of an $n^+ - n - p^+$ structure rear junction solar cell, including various physical and structural parameter symbols.

region (*BD*) and the n-region (*DE*). Hence, it can be written as, at *E*:

$$J_{pL}(\lambda) = J_{pL,n^+}(\lambda) + J_{pL,a}(\lambda) + J_{pL,n}(\lambda). \quad (4)$$

The solution of the current continuity equation for $J_{pL,n}(\lambda)$ is straightforward, taking the same form as that of an n on p solar cell [8] except that the photon flux density, Γ_0 decreases to the level $\Gamma_0 \exp[-(W_{n^+} + W_a)]$ due to the absorption in the front n^+ -region and the space charge region. The result is:

$$J_{pL,n}(\lambda) = \frac{q\Gamma_0 \exp[-(W_{n^+} + W_a)](1-R)\alpha L_{p,n}}{(\alpha^2 L_{p,n}^2 - 1)} \times \left\{ \left(\frac{s_p L_{p,n}}{D_{p,n}} + \alpha L_{p,n} \right) - \exp(-\alpha W_n) \left[\frac{s_p L_{p,n}}{D_{p,n}} \cosh\left(\frac{W_n}{L_{p,n}}\right) + \sinh\left(\frac{W_n}{L_{p,n}}\right) \right] \right. \\ \left. - \frac{\frac{s_p L_{p,n}}{D_{p,n}} \sinh\left(\frac{W_n}{L_{p,n}}\right) + \cosh\left(\frac{W_n}{L_{p,n}}\right)}{\frac{s_p L_{p,n}}{D_{p,n}} \sinh\left(\frac{W_n}{L_{p,n}}\right) + \cosh\left(\frac{W_n}{L_{p,n}}\right)} \right\} - \alpha L_{p,n} \exp(-\alpha W_n) \quad (5)$$

which is subject to following boundary conditions

$$D_p \frac{d\Delta p_L}{dx} = s_{e,nn^+} \Delta p_L, \quad \text{at } x = D, \\ \Delta p_L = 0, \quad \text{at } x = E, \quad (6)$$

where ΔP_L is the light-generated excess carrier concentration. The effective recombination velocity s_{e,nn^+} can be calculated from Eq. (1) provided that the real surface recombination velocity s_p is known. The light-generated excess carriers in the front n^+ -region must be first collected by the n^+ -n high-low junction to enter the bulk, then diffuse across the entire n-region to reach the rear n- p^+ junction. Only those carriers surviving recombination can contribute to the short-circuit current. We are now considering the high-low junction collection property. Holes are minority carriers on both sides of the n^+ -n high-low junction. They may fall at the edge (*B*) from the n^+ -region into n-region, although the hole concentration at *B* exceeds the equilibrium value. If $\Delta p_{L(at B)}(\lambda)$ represents the light-generated excess hole concentration at *B*, then the boundary conditions for the n^+ -region (*AB*) can be written as

$$D_{p,n^+} \frac{d\Delta p_L}{dy} = s_p \Delta p_L, \quad \text{at } y = 0, \\ \Delta p_L = \Delta p_{L(at B)}, \quad \text{at } y = W_{n^+}. \quad (7)$$

The solution of the current continuity equation subject to the above boundary conditions is given by, at B :

$$J_{\text{pl},n^+(\text{at } B)}(\lambda) = \frac{q\Gamma_0(1-R)\alpha L_{p,n^+}}{(\alpha^2 L_{p,n^+}^2 - 1)},$$

$$\times \left\{ \frac{\left(\frac{s_p L_{p,n^+}}{D_{p,n^+}} + \alpha L_{p,n^+} \right) - \left[\frac{\Delta p_{L(\text{at } B)}}{p_{\text{ph}}} + \exp(-\alpha W_{n^+}) \right] \left[\frac{s_p L_{p,n^+}}{D_{p,n^+}} \cosh\left(\frac{W_{n^+}}{L_{p,n^+}}\right) + \sinh\left(\frac{W_{n^+}}{L_{p,n^+}}\right) \right]}{\frac{s_p L_{p,n^+}}{D_{p,n^+}} \sinh\left(\frac{W_{n^+}}{L_{p,n^+}}\right) + \cosh\left(\frac{W_{n^+}}{L_{p,n^+}}\right)} - \alpha L_{p,n^+} \exp(-\alpha W_{n^+}) \right\} \quad (8)$$

where

$$p_{\text{ph}} = \frac{\Gamma_0(1-R)\alpha\tau_{p,n^+}}{(\alpha^2 L_{p,n^+}^2 - 1)}. \quad (9)$$

Eq. (8) is quite similar to Eq. (5) due to the apparently similar boundary conditions. When the excess hole concentration $\Delta p_{L(\text{at } B)}(\lambda) = 0$, Eq. (8) reduces to the same form as Eq. (5), which is equivalent to the case of an n^+ -p junction. The value of $J_{\text{pl},n^+(\text{at } B)}$ can be obtained if $\Delta p_{L(\text{at } B)}(\lambda)$ is known. For the boundary condition at $y = B$, we also have

$$J_{\text{pL},n^+(\text{at } B)} = q s_{e,n^+n} \Delta p_{L(\text{at } B)}. \quad (10)$$

Substituting Eq. (8) into (10) gives

$$\Delta p_{L(\text{at } B)} = \frac{J_{\text{pL0},n^+}}{q \left(\frac{L_{p,n^+}}{\tau_{p,n^+}} F_{n^+} + s_{e,n^+n} \right)}, \quad (11)$$

where J_{pL0,n^+} is the hole photocurrent density found in an n^+ -p junction solar cell, and may be calculated from Eq. (8) by setting $\Delta p_{L(\text{at } B)}(\lambda) = 0$. By combining Eqs. (10) and (11), we can rewrite $J_{\text{pL},n^+(\text{at } B)}$ in a more explicit form as

$$J_{\text{pL},n^+(\text{at } B)} = J_{\text{pL0},n^+} F_{h-1}, \quad (12)$$

where F_{h-1} is given by

$$F_{h-1} = \frac{1}{1 + \frac{N_D s_{e,nn^+}}{N_D s_{e,n^+n}}}. \quad (13)$$

Therefore, a general equation for the light current collected by the high–low junction has been derived, which is simply expressed as the current J_{pL0,n^+} reduced by the factor F_{h-l} . It will be convenient to call F_{h-l} the high–low junction factor, which actually measures the collection effectiveness of the high–low junction. The physical significance of Eq. (12) is obvious. It shows that the difference between the n^+ – n high–low junction and n^+ – p junction in light-generated current collection can be depicted by the factor F_{h-l} . So far, s_{e,n^+n} remains as an unknown parameter. To determine the effective recombination velocity s_{e,n^+n} , we concentrate on the surface at $y = E$. Note that the light-generated excess hole density $\Delta p_{L(at E)}$ is zero there, since there is the equivalent of an infinite effective surface recombination velocity at $y = E$. Therefore, referring to Eqs. (1) and (3), s_{e,n^+n} is simply obtained as

$$s_{e,n^+n} = \frac{N_D + D_{p,n}}{N_D L_{p,n}} \coth\left(\frac{W_n}{L_{p,n}}\right) = \frac{N_D + D_{p,n}}{N_D L_{p,n}} F_n(\infty). \quad (14)$$

Although we call s_{e,n^+n} the effective recombination velocity here, it actually reflects how quickly the light-generated holes can be extracted out of the n^+ –region. As seen from Eq. (14), s_{e,n^+n} is proportional to the abruptness of the high–low junction. Substituting s_{e,n^+n} and s_{e,nn^+} into Eq. (13) results in

$$F_{h-l} = \frac{1}{1 + \frac{N_D D_{p,n} + L_{p,n} F_n(\infty)}{N_D + D_{p,n} L_{p,n} F_n(\infty)}}. \quad (15)$$

This shows that the high–low junction factor, F_{h-l} , is only a function of device parameters and easy to determine when the parameters are provided. Next, we should consider the recombination loss in the n –region. If the recombination in the space charge region (BD) is negligible, then the light-generated hole current collected by the high–low junction flows without any loss to $y = D$, i.e., $J_{pL,n^+(at B)} = J_{pL,n^+(at D)}$. The hole current collected at the depletion edge E of the p – n junction due to the injection of $J_{pL,n^+(at D)}$, can be easily derived as (e.g., see McKelvey's book [9]):

$$\begin{aligned} J_{pL,n^+} &= J_{pL,n^+(at D)} \left[\cosh\left(\frac{W_n}{L_{p,n}}\right) - \frac{1}{\coth\left(\frac{W_n}{L_{p,n}}\right)} \sinh\left(\frac{W_n}{L_{p,n}}\right) \right] \\ &= J_{pL0,n^+} F_{h-l} \operatorname{sech}\left(\frac{W_n}{L_{p,n}}\right). \end{aligned} \quad (16)$$

Eq. (16) gives the final expression for the contribution of the light-generated hole current from the n^+ –region taking into account both the high–low junction extraction and the recombination loss in the n –region. As can be seen from Eq. (16), the effects of the n –layer attached to the n^+ –layer appear as two linear reduction factors, F_{h-l} and $\operatorname{sech}(W_n/L_{p,n})$; they both will be unity when $W_n = 0$.

The solution for the contribution, $J_{\text{pL},a}$, from the space-charge region at the high–low junction is quite straightforward with neglect of the recombination in the region. The light-generated hole current is equal to the number of photons absorbed [8] yielding, at D ,

$$J_{\text{pL},a(\text{at } D)} = q\Gamma_0(1-R)\exp(-\alpha W_{n^+})[1 - \exp(-\alpha W_a)]. \quad (17)$$

The hole current collected at E for this injection is

$$J_{\text{pL},a} = q\Gamma_0(1-R)\exp(-\alpha W_{n^+})[1 - \exp(-\alpha W_a)]\text{sech}\left(\frac{W_n}{L_{p,n}}\right). \quad (18)$$

The space-charge region (BD) at the high–low junction extends mostly into the low-doping side (n -region), where it is a majority carrier accumulation layer. Hence, W_a can be approximated by the width of the accumulation layer, which is given by [10]

$$W_a \cong 2^{1/2} \left(\frac{\epsilon_0 \epsilon_{\text{si}} kT}{q^2 N_D} \right)^{1/2} \arctan \left[\frac{qV_h}{2^{1/2} kT} \left(\frac{N_{D^+}}{N_D} \right)^{1/2} \right], \quad (19)$$

where V_h is the potential drop across the high-doping side and is the root of the following transcendental equation

$$\frac{qV_h}{kT} + \ln \left[\frac{N_D}{N_{D^+}} + \frac{1}{2} \left(\frac{qV_h}{kT} \right)^2 \right] = 0. \quad (20)$$

Once $J_{\text{pL},n}$, J_{pL,n^+} and $J_{\text{pL},a}$ have been determined, the total light-generated hole current J_{pL} collected at E is given by their sum (Eq. (4)), and the calculation of the internal quantum efficiencies may be carried out.

3. Computed results and discussion

The low-level injection Auger recombination lifetime is used for the calculations. It is given by [11]

$$\tau_{\text{Auger}} = \frac{1}{CN_D^2}, \quad (21)$$

where $C = 2.8 \times 10^{-31} \text{ cm}^6/\text{s}$. The SRH lifetime is modelled by [12]

$$\tau_{\text{SRH}} = \frac{\tau_0}{1 + \frac{N_D}{N_0}}, \quad (22)$$

where the empirical parameters are: $\tau_0 = 1.6 \text{ msec}$ and $N_0 = 5 \times 10^{16} \text{ cm}^{-3}$. Since the n^+ -region may be heavily doped, both the effects of degeneracy and bandgap narrowing

have to be taken into account. They may be lumped into an effective intrinsic carrier concentration given by

$$n_{ie}^2 = n_i^2 \exp\left(\frac{\Delta E_g}{kT}\right) \frac{F_{1/2}(\zeta)}{\exp(\zeta)}, \quad (23)$$

where $n_i = 1.0 \times 10^{10} \text{ cm}^{-3}$ [13] and $\zeta = (E_F - E_C)/kT$. The bandgap narrowing is given by the following experimentally fitted formula [14]

$$\Delta E_g = 9 \times 10^{-3} \left[\ln \frac{N_D}{10^{17}} \sqrt{\left(\ln \frac{N_D}{10^{17}} \right)^2 + \frac{1}{2}} \right] \text{ eV}. \quad (24)$$

The experimental results from King's published work [15] are adopted as the basis for the surface recombination velocities. Since we are considering cells with an inverted pyramid front surface, the values used in the present calculations are about two times higher than those given by King.

Shown in Fig. 2 is a plot of the high–low junction factor F_{h-l} versus the n^+ -region concentration, N_{D+} , as given by Eq. (15). When $N_{D+} \gg N_D$ but is less than about $4 \times 10^{18} \text{ cm}^{-3}$, F_{h-l} approximates unity, resulting in $J_{pL,+(atB)} \cong J_{pL0,n^+}$. This also means that the excess hole concentration at B , $\Delta p_{L(atB)}$ is small. In this case, the high–low junction is very efficient in light-generated current collection (similar to an n^+ -p junction). The loss of the light-generated hole current for J_{pL,n^+} may mainly come from low J_{pL0,n^+} due to the increased Auger recombination in the n^+ -region. The high–low junction factor, F_{h-l} decreases with N_{D+} . For low N_{D+} , then, the collection of

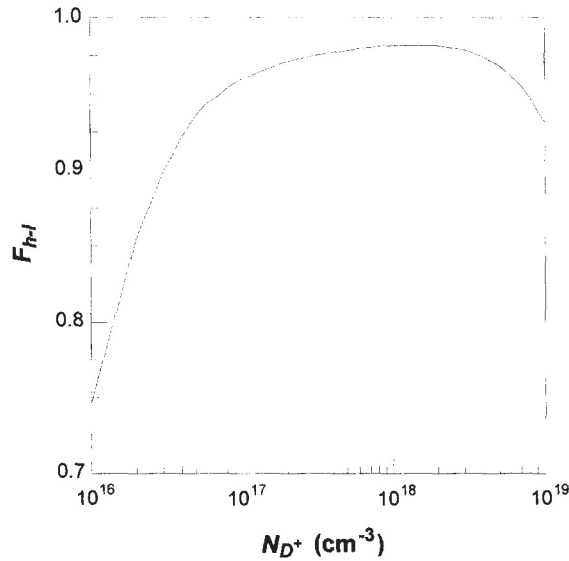


Fig. 2. Calculated high–low junction factor, F_{h-l} , versus FSF dopant concentration, N_{D+} (with $W_n = 1.0$ {FUNC { μ }} m); Fermi–Dirac statistics and bandgap narrowing included. $s_p = 300 \text{ cm/s}$, $N_D = 4.75 \cdot 10^{15} \text{ cm}^{-3}$, $W_l = 280 \text{ }\mu\text{m}$, rear junction depth = $1.0 \text{ }\mu\text{m}$.

the high–low junction is less efficient, and the loss for J_{pL,N^+} is attributed to low F_{h-l} . F_{h-l} decreases because the excess hole concentration at the space-charge region edge B , $\Delta p_{L(at B)}$, increases as N_{D^+} decreases. Therefore, the light-generated excess holes in the n^+ -region are increasingly confined to that region, increasing the recombination losses. It may be of interest to note that Eq. (15) can be rewritten in the following form

$$F_{h-l} = \frac{1}{1 + \frac{J_{sp,n^+}}{J_{sp,n}}}, \quad (25)$$

where

$$J_{sp,n^+} = \frac{qD_{p,n}n_i^2}{N_{D^+}L_{p,n^+}}F_{n^+}(s_p) \text{ and } J_{sp,n} = \frac{qD_{p,n}n_i^2}{N_{D^+}L_{p,n}}F_n(\infty), \quad (26)$$

are, respectively, the hole saturation current densities associated with the n^+ - and n -region. We may regard them as two opposite leakage currents flowing from one side of the high–low junction to the other side. J_{sp,n^+} goes towards the front surface and is required to be as small as possible. $J_{sp,n}$, towards the rear junction, needs to be as large as possible. The ratio of the two determines the high–low junction factor, F_{h-l} . The actual value of $J_{sp,n}$ is limited by the substrate resistivity while J_{sp,n^+} varies with the concentration N_{D^+} . For very high concentration of N_{D^+} , where the Auger recombination process becomes dominant, J_{sp,n^+} increases with N_{D^+} . As a result, F_{h-l} decreases as N_{D^+} increases. The optimum concentration range for N_{D^+} can be found in Fig. 2.

In Fig. 3 the internal quantum efficiency is plotted as a function of wavelength for different N_{D^+} . As seen from the figure, the internal quantum efficiency has a strong dependence on N_{D^+} over almost the entire wavelength range of silicon absorption. Except for the loss through bulk recombination, the light-generated holes in the n -region either diffuse to the rear p-n junction, or are drawn to the front surface. The latter tendency depends on the effective recombination velocity s_{e,nn^+} . If N_{D^+} is low, the performance of the high–low junction as a reflector for the n -region minority holes is less effective. The front surface recombination then becomes significant. Often, the hole diffusion length L_{p,n^+} is much larger than the thickness of the n^+ -region so that the recombination loss in the n^+ -region may be negligible, leading to the case of a transparent heavily doped layer. Therefore, for low N_{D^+} , the internal quantum efficiency of the n -region is mainly dominated by the front surface recombination velocity. In a similar manner, the light-generated holes in the n^+ -region experience the competition between s_p and s_{e,nn^+} ; the former drawing the holes towards the front surface to recombine with electrons there, and the latter driving the holes across the high–low junction into the n -region where they have a better chance to be collected. For low N_{D^+} , as discussed earlier, the hole collection by the high–low junction is less efficient due to low F_{h-l} . As N_{D^+} increases but remains under about $4 \times 10^{18} \text{ cm}^{-3}$, the effect of the FSF increases as well and more light-generated holes in the n -region are prevented from leaking across the high–low junction, indicating the decrease of the effective surface recombination velocity, s_{e,nn^+} . The quantum collection efficiency of long wavelength light (absorbed mainly in the n -region) is, hence, boosted. It is shown in Fig. 3 that the

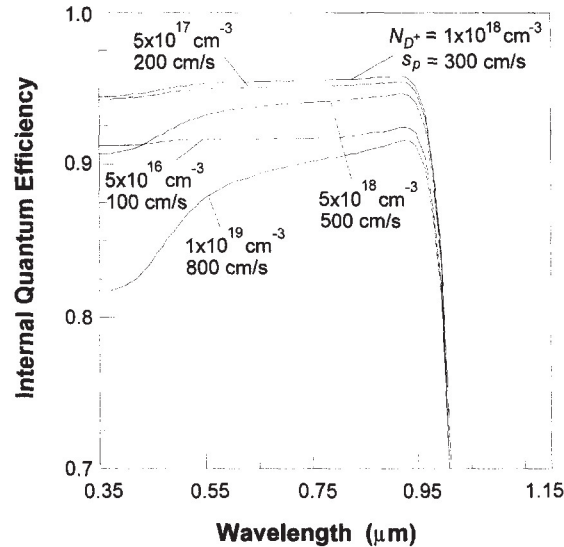


Fig. 3. Calculated internal quantum efficiency for various FSF dopant concentrations, N_{D^+} (with $W_{n^+} = 1.0$ μm); Fermi–Dirac statistics and bandgap narrowing included. Front surface recombination velocity, s_p varies with N_{D^+} . $N_D = 4.75 \cdot 10^{15} \text{ cm}^{-3}$, $W_i = 280 \text{ } \mu\text{m}$, rear junction depth = $1.0 \text{ } \mu\text{m}$.

quantum efficiency for short wavelength light (absorbed in the n^+ -region) also increases with N_{D^+} although the hole lifetime in the n^+ -region is reduced. This phenomenon involves a different mechanism from the reflecting property, namely the hole current collection by the high–low junction. As discussed previously, the collection effectiveness measured by the factor F_{h-l} increases with N_{D^+} , so improving the short wavelength quantum efficiency. This characteristic of the high–low junction provides a great advantage for FSF application.

The optimal concentration N_{D^+} appears about between $\times 10^{18} \sim 4 \times 10^{18} \text{ cm}^{-3}$. In this case, the high–low junction becomes a nearly ideal minority carrier reflector due to a very low effective surface recombination velocity s_{e,nn^+} , and a good collector for the holes in the n^+ -region with F_{h-l} close to 1. Auger recombination mechanisms start to dominate the bulk recombination process beyond this range of concentration. When N_{D^+} increases further, the current $J_{pL,0n^+}$ decreases rapidly due to high Auger recombination (note that F_{h-l} starts decreasing as well, see Fig. 2). Accordingly, the short wavelength quantum efficiency drops rapidly. The long wavelength quantum efficiency also drops since the high Auger recombination increases the effective surface recombination velocity s_{e,nn^+} .

Fig. 4 shows the effect of the n^+ -region thickness W_{n^+} on the quantum efficiency. It may be easy to understand that a thick n^+ -layer is a good reflector to the holes in the n -region but increases the bulk recombination losses in the n^+ -region, while a thin n^+ -layer has the opposite property.

However, a thick n^+ -layer is not always a good reflector. The actual effect of the thickness strongly depends on the dopant concentration N_{D^+} since the n^+ -region bulk

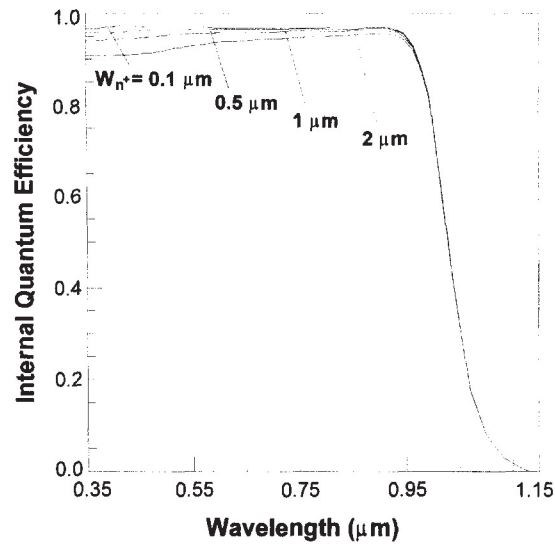


Fig. 4. Calculated internal quantum efficiency for various FSF n^+ -layer thicknesses, W_{n^+} with concentration, N_{D^+} of $3.0 \cdot 10^{18} \text{ cm}^{-3}$; Fermi–Dirac statistics and bandgap narrowing included. $s_p = 400 \text{ cm/s}$, $N_D = 4.75 \cdot 10^{15} \text{ cm}^{-3}$, $W_t = 280 \text{ μm}$, rear junction depth = 1.0 μm .

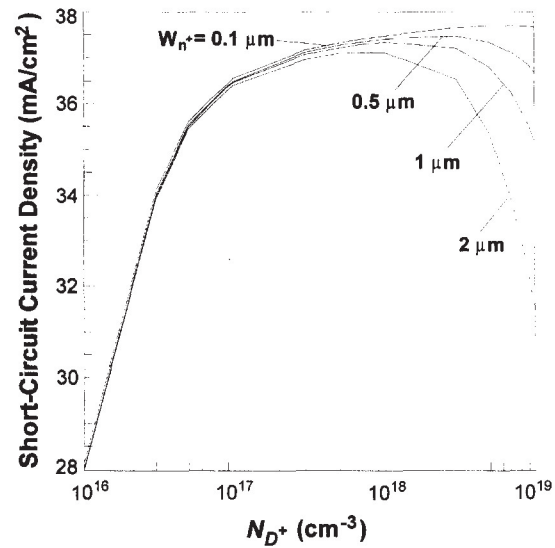


Fig. 5. Calculated short-circuit current versus FSF dopant concentration, N_{D^+} for various FSF n^+ -layer thicknesses, W_{n^+} ; Fermi–Dirac statistics and bandgap narrowing included. Solar spectrum AM1.5G. $s_p = 400 \text{ cm/s}$, $N_D = 4.75 \cdot 10^{15} \text{ cm}^{-3}$, $W_t = 250 \text{ μm}$, rear junction depth = 1.0 μm .

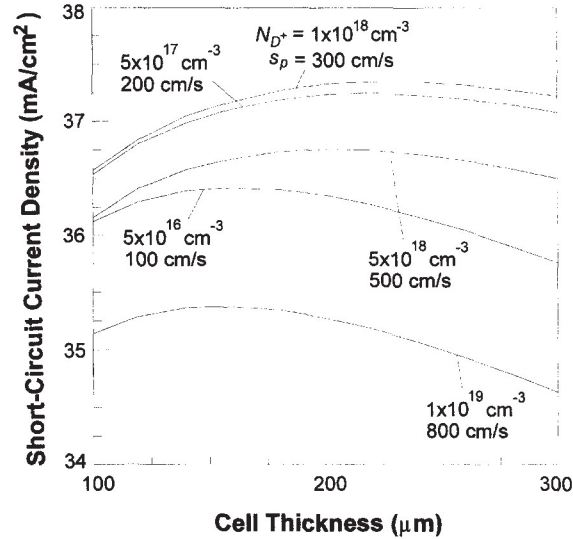


Fig. 6. Calculated short-circuit current versus cell thickness, W_t for various FSF dopant concentrations, N_{D+} (with $W_{n+} = 1.0 \mu\text{m}$); Fermi–Dirac statistics and bandgap narrowing included. Solar spectrum AM1.5G. Front surface recombination velocity, s_p varies with N_{D+} . $N_D = 4.75 \cdot 10^{15} \text{ cm}^{-3}$, rear junction depth = $1.0 \mu\text{m}$.

recombination can affect both the effective recombination velocities, $s_{e,n+n}$ and $s_{e,nn+}$. The optimal thickness of the n^+ -layer should be determined in conjunction with the concentration N_{D+} . In the ranges of the thickness W_{n+} and the concentration N_{D+} with which we are concerned, the quantum efficiency seems to follow a simple rule: the thinner, the better. Fig. 4 shows that at a concentration, N_{D+} , of $\times 10^{18} \text{ cm}^{-3}$, an n^+ -layer as thin as $0.1 \mu\text{m}$ is still a good reflector and provides the best quantum efficiency in terms of both short and long wavelengths.

In Fig. 5, the short-circuit current as a function the concentration $\langle N \rangle_{\{ \text{FUNC} \{ D \} \} \{ + \} \langle /F \rangle}$ is plotted for different W_{n+} . The solar spectrum used for the calculation is AM1.5G [16]; the front surface light reflectance, R , is fixed at 0.03 (note that light trapping is not included in the calculation). Consistent with Fig. 6, a thickness of $W_{n+} = 0.1 \mu\text{m}$ gives the highest short-circuit current. The optimum concentration, N_{D+} , tends to shift towards the high range as the thickness, W_{n+} , decreases. The most optimal concentrations, N_{D+} , lie between $\times 10^{18} \sim 4 \times 10^{18} \text{ cm}^{-3}$. When N_{D+} increases above the optimum concentrations, the short-circuit current start to drop for the reasons discussed earlier.

The effect of the FSF cell thickness is shown in Fig. 6, where the short-circuit current versus the cell thickness is plotted for different N_{D+} . As the FSF effect increases with N_{D+} , the optimal thickness tends to become larger and more light is absorbed. The highest short-circuit current, in Fig. 6, occurs at cell thicknesses between $200 \sim 250 \mu\text{m}$ along with N_{D+} equal to $\times 10^{18} \text{ cm}^{-3}$.

4. Conclusions

In this work, the collection of the light-generated carriers in the high region by a high–low junction has been discussed and an one-dimensional model of it has been then developed, which results in a simple general analytical solution for the contribution of the light-generated current from the high region. The model reveals the characteristics of an illuminated high–low junction, showing that the current collected from an n^+ -region by a FSF (n^+ - n high–low junction) is just the current collected by an n^+ - p junction reduced by a factor of F_{h-l} , which is a function of device parameters. A high–low junction may be very efficient in light current collection with F_{h-l} close to unity. This is the property that gives rise to an increase of the short wavelength quantum efficiency in FSF rear junction solar cells. The optimisation of a FSF is made possible using the present one-dimensional model. In computer calculations, the high doping effects of degeneracy and bandgap narrowing are taken into account. The present model is applicable to other solar cell structures whenever low level injection is satisfied. One of the examples is a thin film solar cell with a rear high–low junction (BSF), in which the high–low junction is so close to the sunward front surface that the light-generated carriers in the high region can not be neglected. For solar cells not satisfying the low level injection condition, further modelling work is needed and will require consideration of high-level injection effects.

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References

- [1] X.M. Dai, M.A. Green and S.R. Wenham, High efficiency N-Silicon solar cells using rear junction structures, 23rd IEEE Photovoltaic Specialists Conf., Louisville, KY, 1993, p. 153.
- [2] R.R. King, R.A. Sinton and R.M. Swanson, Doped surface in one sun, point-contact solar cells, *Appl. Phys. Lett.* 54 (1989) 1460.
- [3] J.D. Alamo, J.V. Meerbergen et al., High–low junction for solar cell applications, *Solid-State Electronics* 24 (1981) 533.
- [4] C.T. Sah, F.A. Lindholm and J.G. Fossum, A high–low junction emitter structure for improving silicon solar cell efficiency, *IEEE Trans. on Electron Dev.* ED-25 (1978) 66.
- [5] F.A. Lindholm, A. Neugroschel, S.C. Pao, J.G. Fossum and C.T. Sah, Design considerations for silicon HLE solar cells, *Proc. 13th IEEE Photovoltaic Specialists Conf.*, Washington, DC, June 1978, p. 1300.
- [6] M.I. Yernaux, C. Battochio, P. Verlinden and F. Van De Wiele, A one-dimensional model for the quantum efficiency of front-surface-field solar cell, *Solar Cells* 13 (1984) 83.

- [7] H.J. Hovel, *Semiconductors and Semimetals*, Vol. 11 (Academic Press, NY, 1975).
- [8] S.M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, NY, 1981).
- [9] J.P. McKelvey, *Solid State and Semiconductor Physics* (Harper and Row, NY, 1966).
- [10] J.R. Hauser and M.A. Littlejohn, Approximations for accumulation and inversion space-charge layers in semiconductors, *Solid-State Electronics* 11 (1968) 667.
- [11] D.K. Schroder, *Semiconductor Material and Device Characterisation* (Wiley, NY, 1990).
- [12] J.G. Fossum, Computer aided numerical analysis of silicon solar cells, *Solid-State Electronics* 19 (1976) 269.
- [13] A.B. Sproul and M.A. Green, Improved value for the silicon intrinsic carrier concentration from 275 to 375K, *J. Appl. Phys.* 70 (1991) 846.
- [14] J.W. Slotboom and H.C. De Graaff, Measurements of bandgap narrowing in Si bipolar transistor, *Solid-State Electronics* 19 (1976) 857.
- [15] R.R. King, R.A. Sinton and R.M. Swanson, Studies of diffused phosphorus emitters: saturation current, surface recombination velocity, and quantum efficiency, *IEEE Trans. Electron Dev.* ED-37 (1990) 365.
- [16] R. Hulstrom, R. Bird and C. Riordan, Spectral solar irradiance data sets for selected terrestrial conditions, *Solar Cells* 15 (1985) 365.