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Short circuit current vs cell thickness in solar cells under rear illumination: a direct evaluation of the diffusion length

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Abstract

The dependence of the short circuit current of a solar cell with its thickness is analysed for rear illumination. Under certain conditions, a simple linear regression in a semilogarithm scale is found. Using these results, an almost direct evaluation of the minority carrier diffusion length in the base region of crystalline silicon solar cells is achieved. On the other hand, from the experimental point of view, monochromatic light is not required and the equipment requirements are minimised. The model presented in this paper is theoretically evaluated using a 1-dimensional simulation code. Some preliminary experimental results are also shown.

Keywords: Silicon solar cells; Diffusion length

1. Introduction

The performance of a solar cell depends on many parameters, among which the diffusion length of minority carriers in the base (L_d) is one of the most important. In the case of monocrystalline Si solar cells, the relatively high thickness of the device makes it necessary to possess large values for L_d, in order to obtain high efficiency cells. Moreover, in some non-standard Si solar cells such as n^+pp^+ bifacial [1] and point contact [2] cells, where part or the whole radiation impinges on the surface away from the np junction, the correlation between the electrical parameters of the cell (i.e., the short circuit current) and L_d is even stronger.

L_d depends very strongly on the manufacturing technique. It may be enhanced (by reduction of the concentration of electrically active impurities through a gettering process) or diminished (due to the introduction of defects or impurities) along the different stages of the process [3]. Therefore, a good characterization of the cell requires an accurate measurement of L_d on the final device.

The present paper analyses the behavior of the short circuit current (J_{sc}), under rear illumination, as a function of the wafer thickness (d), as well as its relation with the diffusion length in the base. As a consequence of this analysis a simple method for the evaluation of L_d is proposed.

Although there are several techniques available for the determination of L_d in silicon solar cells, primarily based on the current or voltage response caused by the

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excess carriers usually generated through the absorption of electromagnetic waves [4–7], some of them are only valid when the diffusion length is appreciably smaller than the thickness of the base region, and almost all of them require monochromatic illumination and the estimation or measurement of other parameters (i.e., surface recombination velocity and spectral response).

The determination of L_d by measuring the light generated current dependence on active layer thickness has been reported before for GaAs solar cells [8,9], but the corresponding technique requires the determination of the quantum yield. The work of [10] is also of interest in which the use of samples of different thickness allows to separate the bulk lifetime (i.e. the diffusion length) and the surface recombination velocity on silicon wafers.

The model presented here shows, under not highly restrictive conditions, that there is a simple relation between $J_{sc}(d)$, under rear illumination, and L_d. In addition to this, a more general case with no restrictions on the value of L_d is considered.

2. General considerations

The photogenerated current and, thus, the short-circuit current density (J_{sc}) of a photovoltaic device with a conventional structure (n^+p or p^+n, with or without back surface field) illuminated from its backside (p or n, respectively), depend on several parameters. Among them, the most important are: (i) L_d, which basically determines the probability (with a typical exponential behavior) for the minority carriers of the base region of reaching the np junction; (ii) the surface recombination velocity, the doping concentration and the junction depth in the back side, which have a great influence on the carrier recombination in the region.

On the other hand, the intensity and the spectral distribution of the incident radiation determines the amount of carriers generated as well as their spatial distribution in the bulk (due to the strong dependence of the absorption coefficient on the wavelength) and therefore, they influence directly the short circuit current.

In summary, J_{sc} depends on the characteristics of both the device and the radiation. In spite of this, for rear illumination, the distance between the different device regions where the carriers are generated, and the front junction np that separates electrons and holes, varies monotonously with the thickness d of the wafer. Therefore, one can expect that the variation of J_{sc} with d must be a function of L_d almost exclusively.

3. Theoretical model

The short circuit current density for a n^+pp^+ cell of thickness d, rear illuminated with monochromatic radiation of wavelength λ and incident power P_{in}, is expressed by [5]:

$$J_{sc} = -\frac{qP_{in}\lambda(1-R_\lambda)L_d\alpha_\lambda}{hc(L_d^2\alpha_\lambda^2-1)}\exp(-t\alpha_\lambda) \times \left\{ \frac{\beta + L_d\alpha_\lambda}{\cosh\left(\frac{d}{L_d}\right)+\beta\sinh\left(\frac{d}{L_d}\right)} - \exp(-d\alpha_\lambda) \times \left[L_d\alpha_\lambda + \frac{\cosh\left(\frac{d}{L_d}\right)}{\sinh\left(\frac{d}{L_d}\right)} - \frac{1}{\sinh\left(\frac{d}{L_d}\right)\left(\cosh\left(\frac{d}{L_d}\right)+\beta\sinh\left(\frac{d}{L_d}\right)\right)} \right] \right\},$$

where t is the thickness of the p^+ region; α_λ, the absorption coefficient of silicon at λ; R_λ, the reflectivity of the rear face; and $\beta = S_b L_d / D_n$ (adimensional parameter), where D_n is the diffusion coefficient of electrons in the base p and S_b the effective recombination velocity at the p^+p junction end of the base region [4]. q, h and c are the electronic charge, the Planck's constant and the speed of light, respectively.

Taking into account the fact that typical values of d for crystalline silicon solar cells range between 200 and 400 μm, the function $\exp(-d\alpha_\lambda)$ can be neglected for wavelengths far enough from 1.1 μm (typically, $\lambda <$ 800 nm). Dropping this term, applying logarithm and differentiating with respect to d, we obtain:

$$f'(d) = \frac{\partial}{\partial d}\ln[J_{sc}] \cong -\frac{1}{L_d}\frac{(1+\beta)\exp\left(\frac{d}{L_d}\right)-(1-\beta)\exp\left(-\frac{d}{L_d}\right)}{(1+\beta)\exp\left(\frac{d}{L_d}\right)+(1-\beta)\exp\left(-\frac{d}{L_d}\right)}, \tag{2}$$

where the function $f'(d)$ is defined so as to simplify the notation from here on.

Eq. (2) results, independent of the wavelength and in the range of validity of the approach performed ($\lambda <$ 800 nm), can be used with non-monochromatic light.

A simple interpretation may be done to understand this wavelength independence.

For $\lambda = 800$ nm, more than 90% of the photogenerated pairs are generated near the rear surface within a 20 μm zone. The depth of this zone decreases for smaller values of the wavelength. Taking into account that the n^+p junction is far away from the illuminated surface (typically, 200–400 μm), it may be concluded that the distance photogenerated minority carriers should "travel" to reach the junction, is almost independent of λ for λ far enough from 1.1 μm.

If $L_d < 0.6\ d$, $f'(d)$ (Eq. 2) results practically independent of d and is equal to $(-1/L_d)$, with an error of less than 10%. Under these conditions, L_d is worked out directly from the slope of $\ln(J_{sc})$ as a function of d. This may be easily applied to actual devices in several cases of interest (i.e., for low quality Si solar cells based on Czochralski wafers). In Section 4 it will be shown that even for values of d comparable to L_d, this simple linear approximation gives a reasonable estimation of L_d.

Even though the interesting case from the practical point of view is the one described in the previous paragraph, for completeness the general problem (any relation between d and L_d) is theoreticaly presented. Now, $f'(d)$ does not depend on L_d exclusively, but also on β. Therefore, the computation of L_d demands a numerical resolution of Eq. (2), for which more information about the variation of $f'(d)$ is required. There are several alternatives for the resolution of this problem. For example, an easy iterative method is proposed which uses the value of $f'(d)$ for two values of d.

Let us consider $f'(d)$ known from measurements of short-circuit current for d_1 and d_2, with $d_1 < d_2$. Taking into account that the influence of the parameter β diminishes for large values of d (Eq. 2), the following zero order solution is proposed:

$$\beta^{(0)} = 1$$

$$f'(d_2) = -\frac{1}{L_d^{(0)}} \Longrightarrow L_d^{(0)} = -\frac{1}{f'(d_2)} \tag{3}$$

From Eq. (2), we obtain the equations that define β and L_d for the $(i+1)$-order from the solutions of the i-order:

$$\beta^{(i+1)} = -\frac{[f'(d_1)L_d^{(i)} + 1]E_1 + [f'(d_1)L_d^{(i)} - 1]E_1^{-1}}{[f'(d_1)L_d^{(i)} + 1]E_1 - [f'(d_1)L_d^{(i)} - 1]E_1^{-1}}$$

$$L_d^{(i+1)} = -\frac{1}{f'(d_2)} \times \frac{(1+\beta^{(i+1)})E_2 - (1-\beta^{(i+1)})E_2^{-1}}{(1+\beta^{(i+1)})E_2 + (1-\beta^{(i+1)})E_2^{-1}} \tag{4}$$

where

$$E_{1,2} = \exp\left(\frac{d_{1,2}}{L_d^{(i)}}\right)$$

and

$$E_{1,2}^{-1} = \exp\left(-\frac{d_{1,2}}{L_d^{(i)}}\right).$$

Then, the problem is solved iteratively up to a point where convergence in the values of β and L_d is reached.

4. Numerical simulations

In order to evaluate the theoretical model presented by means of a complete numerical simulation, it was applied to results from the semiconductor modeling program PC-1D [11]. Throughout this program, J_{sc} was calculated with rear illumination, for crystalline silicon cells with different thicknesses. Then, L_d was obtained using equations presented in Section 3.

Cells with diverse characteristics were considered, especially in what concerns L_d and the surface recombination velocity. With the purpose of framing the problem into the hypotheses of the theoretical model mentioned above, illumination spectrum with a wavelength up to 0.8 μm were analysed. Particularly, an AM1.5 solar spectrum truncated in such wavelength was used (experimentally, this condition is achieved with a short-pass edge filter).

As an example, we present the results obtained for n^+pp^+ crystalline silicon cells with an n^+ region with a sheet resistance of 38 Ω/□ and a junction depth of 0.3 μm, and a p^+ region with a junction depth of 0.9 μm and a surface doping of 2×10^{18} cm^{-3}.

Numerical results obtained using the linear approximation and some examples for the general case are presented.

4.1. Linear approximation

Fig. 1 shows $\ln(J_{sc})$ vs d for silicon solar cells with $L_d = 200$ μm and two surface recombination velocities S_{p+} (100 and 10^5 cm/s). Values up to $d = L_d$ are included. It must be stressed that the surface recombination velocity S_{p+} is not the parameter S_b defined in Section 3 (except in the simple case of an n^+p cell),

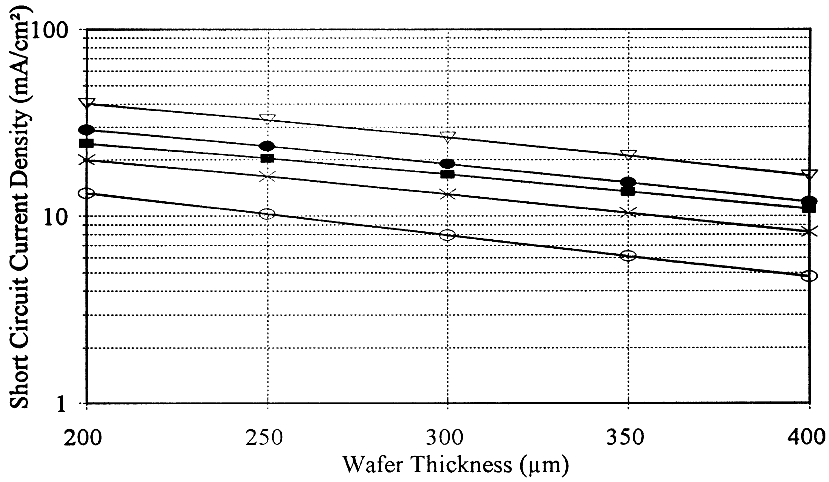

Fig. 1. $\ln(J_{sc})$ vs d curves obtained with PC-1D, for different illumination spectra and two rear surface recombination velocities (S_{p+}): $S_{p+} = 100$ cm/s and AM1.5 (■), $S_{p+} = 100$ cm/s and truncated-AM1.5 (●), $S_{p+} = 100$ cm/s and $\lambda = 400$ nm (×), $S_{p+} = 100$ cm/s and $\lambda = 800$ nm (▽), $S_{p+} = 10^5$ cm/s and truncated-AM1.5 (○).

since the latter corresponds to the recombination velocity in the junction pp^+ and the former represents the recombination velocity in the external surface of the cell. Both parameters are related by an expression which involves the characteristics of the p^+ region [4].

Different characteristics of the illumination are considered: monochromatic light (400, 630 and 800 nm) and a truncated AM1.5 spectrum; for comparison, results for a complete AM1.5 spectrum are also shown. In all the cases, a 1 kW/m^2 intensity has been used in the simulation. It could be seen that $\ln(J_{sc})$ shows a linear dependence on d, and that the corresponding slope is almost independent of the rear surface recombination velocity and of the characteristics of the illumination, in good agreement with the theoretical model presented in the previous section. It has also been verified that the slope is independent of the illumination intensity.

Table 1 summarises the values for L_d obtained as $-1/f'(d)$, where the slope $f'(d)$ is calculated by a least square linear approximation. Results obtained show differences with respect to the correct value of L_d (200 μm) of approximately 10% (over estimated), for a passivated rear surface, and less than 5% (under estimated), for a non-passivated one. Even for an AM1.5 spectrum, which does not satisfy $\lambda < 800$ nm, the value obtained for L_d could be considered a relatively good approximation.

4.2. General case

Computations for three values of L_d (100, 200 and 1000 μm) and two surface recombination velocities S_{p+} (100 and 10^5 cm/sec) were performed for the general case (this means, any relation between L_d and d).

Using the values of J_{sc} (from PC-1D) for different thicknesses d, $f'(d)$ for several values of d was calculated. Then, the method proposed (Eqs. 3 and 4) was applied for computing L_d and β from $f'(d_1)$ and $f'(d_2)$. Table 2 shows the results obtained with $d_1 = 200$ μm and $d_2 = 350$ μm.

It can be observed that the method proposed recovers the values of L_d used as inputs in the simulation program with an error of less than 1%. On the other hand, although β does not have a simple relation with S_{p+}, the values obtained give an idea of the order of magnitude of the recombination velocity in the p^+

Table 1
Values of $L_d = -1/f'(d)$ obtained by a least square linear regression applied to $\ln(J_{sc})$ vs d curves obtained using PC-1D, for 200 μm < d < 400 μm. Regression coefficients R^2 are included

S_{p+} (cm/s)	100					10^5	
Illumination	400 nm	630 nm	800 nm	Tr. AM1.5	AM1.5	Tr. AM1.5	AM1.5
L_d (μm)	224	225	225	224	246	196	231
R^2	0.9989	0.9987	0.9984	0.9987	0.9987	0.9999	0.9999

Table 2
Calculated values for L_d and β, using the method with $d_1 = 200$ μm and $d_2 = 350$ μm

L_d (μm)	100		200		1000	
S_{p+} (cm/s)	100	10^5	100	10^5	100	10^5
L_d (μm) calc.	99.7	99.8	200.0	200.0	1004	1003
β calc.	−0.053	0.289	0.013	0.717	0.162	3.67

region (note that β results at least one order greater for $S_{p+} = 10^5$ cm/s than for $S_{p+} = 100$ cm/s, for the same L_d). The negative value of β obtained in some cases lacks of any physical sense and is probably a consequence of numerical problems.

5. Experimental results

Bifacial n^+p silicon solar cells were elaborated on p-type (5 Ωcm) commercial Czochralski wafers, with values of d in the range 240–360 μm. Different thicknesses were obtained through current chemical etching. The fabrication process used consists basically of three steps: oxidation; dopant diffusion; and contacts deposition. Dry oxidation was used to grow up a SiO_2 layer of adequate thickness in order to mask the dopant diffusion. Furthermore, the SiO_2 grown passivates the rear surface. After removing the SiO_2 front layer, a one step process [12] is used to build up the n^+p junction. Usual Ti–Pd–Ag multilayer contact is deposited on the front (n^+-type) layer, while Al–Ti–Ag is evaporated on the rear (p-type) one.

J_{sc} vs d is obtained by illuminating the cells on the rear side with a simple solar radiation simulator and interposing optical filters in order to cut the radiation spectrum to an appropriate range. Fig. 2 shows $\ln(J_{sc})$ vs d for different spectras: solar simulator without filters and with three filters ($\lambda < 750$, $\lambda < 600$ and $\lambda < 500$ nm). It could be seen that $\ln(J_{sc})$ shows a linear dependence with d, and that the corresponding slope is almost independent of the characteristics of the illumination. Table 3 summarises the values for L_d obtained as $-1/f'(d)$, where the slope $f'(d)$ is calculated by a least square linear approximation.

One implicit hypothesis in the technique is the necessity of having the same L_d in all the devices used to define the curve $\ln(J_{sc})$ vs d. This should be so because all the cells are processed in the same batch, and consequently L_d should be a characteristic of such process of fabrication.

In order to validate the determination of L_d carried out with the technique proposed, complementary lifetime measurements were done on all the cells used.

The estimation of the minority carrier lifetime in the base region was performed using a novel modified OCVD technique [13]. In this method, the lifetime is obtained from the variation of the voltage decay time constant as a function of the constant bias. It could be shown [13] that the asymptotic value for this time constant is equal to the effective minority carriers lifetime in the base region. All the cells considered in Fig. 2 show asymptotical values of approximately 2 μs, which correspond to a diffusion length of 80 μm, in reasonable agreement with the estimation of L_d presented previously.

6. Conclusions

The short circuit current as a function of the wafer thickness has been studied for solar cells illuminated by the rear side. For certain conditions of the radiation spectrum and L_d minor or equal to the cell thickness, a simple linear relation between $\ln(J_{sc})$ and d is found. As a consequence, an almost direct measurement of the diffusion length in the base region of crystalline silicon solar cells has been proposed and analysed.

If L_d is greater than d, the surface recombination velocity on the rear side (included in the parameter β) plays an important role in the relation between J_{sc} and d (Eq. 2), making it necessary to solve a more complicated equation in order to obtain L_d. Simulations performed with a PC-1D code show a functional dependence in good agreement with the model described. Moreover, the application of this model

Table 3
Values of L_d obtained by a least square linear regression applied to $\ln(J_{sc})$ vs d experimental curves, for different spectra. Regression coefficients R^2 are included

Illumination	Simulator	< 750 nm	< 600 nm	< 500 nm
L_d (μm)	80 μm ± 7%	64 μm ± 7%	58 μm ± 9%	61 μm ± 16%
R^2	0.9916	0.9929	0.9853	0.9522

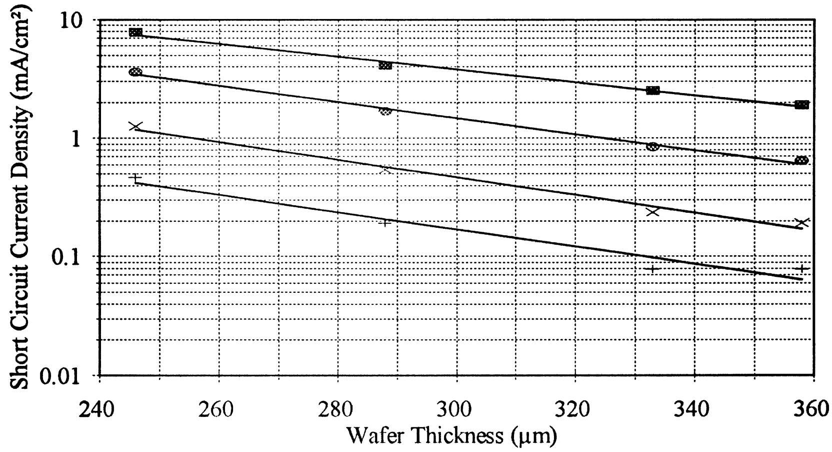

Fig. 2. $\ln(J_{sc})$ vs d experimental curves, for different illumination spectra: solar radiation simulator without any filter (■), $\lambda <$ 750 nm (●), $\lambda <$ 600 nm (×), and $\lambda <$ 500 nm (+).

allows us to recover the value of L_d used in the simulation by means of a simple numerical method.

From the experimental point of view, the evaluation of L_d for the particular case $L_d < 0.6\ d$ (or even, $L_d < d$) presents the great advantage that the measurement of J_{sc} does not need to be so accurate, and hence only a few samples (two may be enough) with different thickness are required. Preliminary experimental measurements on n^+p silicon solar cells confirm the validity of the model presented.

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