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Investigation of minority carrier diffusion length in shallow junctions by angle-resolved illumination technique

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Abstract

In this paper, we discuss a new approach to the determination of minority carrier diffusion length (L_d) on flat top surface shallow junction devices in which photocurrent is dominated by diffusion component as in solar cells. In our method, we propose the use of a single monochromatic light beam of appropriate wavelength, incident on the device surface at various angles. Under such experimental conditions, the short circuit current of the device is expressed as a function of the internal spectral response and device reflectance. Then diffusion length can be simply derived by the analysis of the experimental ratio between photocurrent measured at various incidence angles and when light impinges the device orthogonally, as function of the incident angle. An analytical model is proposed based on the modified absorption coefficient as a function of refractive angle and an experimental set-up for the evaluation of minority carrier diffusion length is proposed.
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Keywords: Diffusion length; Solar cell; Integrating sphere

1. Introduction

The present work is focused on minority carriers diffusion length (L_d) evaluation that still remains one of the fundamental parameters which characterize the photocurrent produced in the bulk region of a semiconductor junction, where no electric field aids carrier collection. In fact, L_d is the average distance that a carrier can move from point of generation until it is recombined. This parameter becomes particularly relevant in semiconductor shallow junction devices such as crystalline silicon photodiodes and solar cells, where most of the photovoltaic efficiency concerns the carrier generation out of the depletion region. Moreover, L_d gives synthetic information on both the qualities of semiconductor material involved in the device and technological aspects like the presence of a back-surface field and a back-reflecting mirror. Many aspects influence the minority carrier lifetime and the diffusion length, since they depend strongly on the type and magnitude of recombination processes in the semiconductor [1].

Typically, the estimation of L_d is obtained by quantum efficiency (QE) measurements, in which a fit procedure of the data is proposed in the spectral region ranging from 850 to 1000 nm, when crystalline silicon is concerned [2]. Here we present a different approach to L_d evaluation based on the simultaneous determination of photocurrent and total reflectance at a fixed wavelength and at various incidence angles of the light focused on the device. The detection system we used is a special type of reflectometer realized by a 25 cm diameter integrative sphere and designed in such a way to measure both the reflectance and the current of the device. This method can be very useful in the characterization of photovoltaic devices. In fact, even though solar cells are optimized to generate carriers assuming light at normal incidence with respect to the cell surface, in practical experience the light incidence differs from the normal because of the apparent motion of the sun disk in sunny days, presence of diffused light (which is a relevant component of the solar irradiation, particularly with clouded sky), presence of protective glass cover,

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and texturization of solar cell surface. To extract the L_d value by the measured data of photocurrent, we propose an analytical model, which has been specialized for monocrystalline silicon photodiodes.

2. Theoretical model

Assuming that the absorption of photons generates electron–hole pairs, the generation $G(x,\lambda)$ at a fixed wavelength (λ) in a thin slice of material is determined by the change in light intensity across this slice and is given by

$$G(x,\lambda) = \alpha(\lambda)F(\lambda)(1-R_s)\,e^{-\alpha(\lambda)x}, \tag{1}$$

where $\alpha(\lambda)$ is the absorption coefficient, $F(\lambda)$ the photon flux, R_s the semiconductor reflectance and x the distance into the material. If we consider various angles θ respect to the orthogonal incidence, an effective absorption coefficient, $\alpha^*(\lambda)$, can be introduced which is expressed as

$$\alpha^*(\lambda,\theta_r) = \frac{2}{\lambda}[2\pi k\ \mathrm{Re}(\cos\theta_r) - 2\pi n\ \mathrm{Re}(\sin\theta_r)], \tag{2}$$

where k is the extinction coefficient and n the refractive index.

In case of high values of wavelength, a simplification is allowed:

$$\alpha^*(\lambda,\theta_r) = \frac{\alpha(\lambda)}{\cos\theta_r}, \tag{3}$$

where θ_r is the refractive angle coming from the Snell equation.

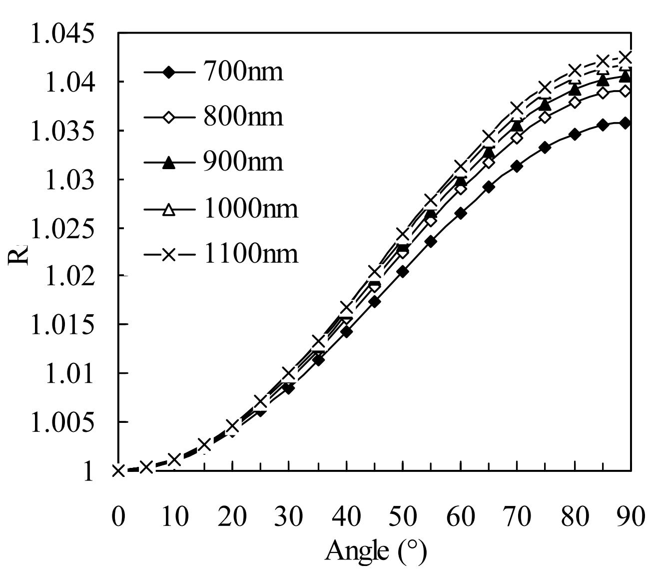

Fig. 1. Ratio between the effective absorption coefficient at various angles of incident light and that at normal incidence as a function of angle for various wavelengths in case of crystalline silicon.

In Fig. 1, the ratio between the absorption coefficient [3] at different angles and the absorption coefficient at normal incidence is reported for crystalline silicon semiconductor, as a function of incident angle and for different wavelengths. From Fig. 1, it is evident that the expected ratio increases with both the incident angle and the wavelength.

If we assume an abrupt shallow junction with both side materials uniformly doped and no antireflection coating, the photocurrent in short circuit condition under illumination can be expressed as a sum of two terms. The first is a photocurrent due to the generation in the depletion region; the second arise from crystalline bulk material, taking into account the filtering of top layer and depletion region. Then the carriers photo-generated in the bulk diffuse towards the junction or the back-contact. In the bulk region, the generation rate per unit volume and per second is expressed in terms of the minority carrier diffusion length L_d by the following equation:

$$G_{\mathrm{diff}}(\lambda) = \frac{1-R_s}{W}F(\lambda)\,e^{-\alpha(\lambda)\,\mathrm{d}x}\left[\frac{\alpha(\lambda)_d}{\alpha(\lambda)L_d+1}\right], \tag{4}$$

where dx is the sum of the depletion region width and the thickness of the top thin material, and W is the thickness of the device [4].

The validity of Eq. (4) is under the hypothesis of a device thickness larger than the diffusion length and the existence of an ohmic back-contact. If we assume that this generation is the largest contribute to the total photocurrent of the device at a fixed wavelength, L_d can easily be extracted from the ratio between carrier generation under monochromatic light at various incident angles and generation in normal condition:

$$R(\lambda,\theta_r) = \frac{\alpha^*\,e^{-\alpha^*\,\mathrm{d}x}/\alpha^*L_d+1}{\alpha\,e^{-\alpha\,\mathrm{d}x}/\alpha L_d+1}. \tag{5}$$

The ratio expressed in Eq. (5) is reported in Fig. 2 as a

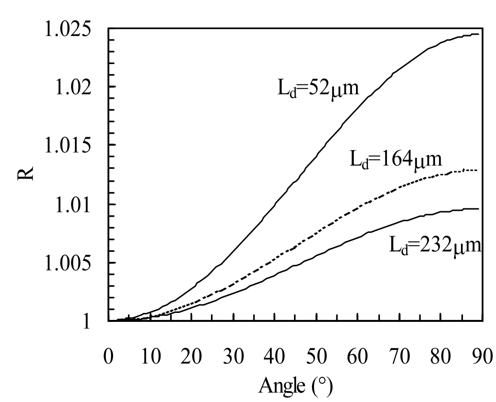

Fig. 2. Ratio between generation under monochromatic light at various incidence angles and in normal condition, as function of the incidence angle, at a fixed wavelength of 1000 nm and for crystalline silicon devices with various diffusion lengths.

function of incidence angle for some crystalline silicon devices showing different diffusion lengths, at a fixed wavelength of 1000 nm. The higher values of the ratio correspond to the shorter minority carrier diffusion lengths. Of course, the ratio cannot be evaluated when $\alpha L_d \gg 1$, longer wavelength is needed therefore in order to increase the sensitivity of the method. These hypotheses are verified in a crystalline silicon photovoltaic device, where higher contribute to the photocurrent arises from the bulk where diffusion is the conduction mechanism.

We finally want to remark that from the proposed model, neither the intensity in the light beam nor a wavelength scan are needed to evaluate L_d. On the other hand, high accuracy in incidence angle measurement and in photocurrent detection are essential to evaluate the small variation with the incident angle of the ratio expressed in Eq. (5).

3. Experimental

3.1. Sample preparation

In order to verify the validity of the model and to set-up the experiment, we prepare several junction devices starting from a polished, p-type silicon wafer $\langle 1\,0\,0 \rangle$-oriented and of 1 Ω cm resistivity. The topside of the wafers is n^+-type diffused 40 Ω/? (after spray on) and the back is aluminium screen-printed and diffused to realize both an ohmic contact and a back-surface field. The front side is also screen-printed with a silver paste to obtain a collection grid. No antireflection coating was deposited to avoid contamination in reflectance measurements. The device has an optical active area of 2×2 cm^2 and the distance between two adjacent fingers of metal grid was 3 mm. A diffusion length of about 200 μm is estimated from fitting procedure of QE measurement data.

3.2. Measurement set-up

The photocurrent evaluation at various incidence angles is performed in an integrating sphere that allows to perform measurements of total reflectance and short circuit current, interesting exactly the same area of the top surface of the device under the same illumination condition, taking also into account the contribution to the photocurrent due to light back-reflected to the cell from the sphere wall [5,6]. A monochromatic light coming out from a halogen lamp and filtered by an UV/VIS/NIR 1/8 m monochromator is splitted into two beams; the first is collected by a reference detector, able to monitor the lamp intensity variation during the measurements; the second beam is focused on the top of the sample surface between two adjacent fingers of the grid shape metal contact. During the measurement, the device is mounted at the centre of the sphere by means of a rotating holder and is inclined with the incident plane kept parallel to the grid to avoid shadowing effect. Both photocurrent of the sample and of the Si-detector monitoring the illumination intensity of the integrating sphere are collected by the Stanford SR830 lock-in amplifier, with the same reference imposed by a chopper mounted outside the monochromator. A Spectralon diffuse reflectance standard (SDRS) certified by Labsphere at an incident angle of 8° is mounted at the backside of the cell and is turned to replace the cell at the beginning and the end of the measurements to verify the reflectance of the cell. In Fig. 3, a schematic view of the experimental apparatus is depicted. Combining the measurements of irradiance inside the sphere when the beam hits the SDRS and when the beam hits the investigated sample, it is possible to evaluate the device reflectance as well as its short circuit current, taking into account the diffused light component produced inside the sphere by the reflected beam that strikes back the cell. This contribution cannot be negligible when large values of reflectance are obtained, in particular when the incident angle turned toward 90°. Then angular range of the incident beam is varied from 5° to 80°. In order to reduce the noise in the measurements, a high wave pass filter is used to avoid the secondary reflection coming out from the monochromator.

4. Results and discussion

The current and reflectance of the device as a function of light incident angle for three different wavelengths is reported in Fig. 4. As previously mentioned, we chose wavelengths high enough to ensure a uniform generation in the bulk and higher sensitivity in the ratio reported in Eq. (5). When the incident angle increases, the reflectance increases, according to Fresnel equations, therefore the current decreases. As a consequence of the increasing refractive angle, light penetrates less into the bulk material. This behaviour is similar to a reduction in wavelength of the impinging light. In this way, the investigation of material can be performed at only a fixed wavelength, whereas in QE measurements various wavelengths are needed to evaluate the L_d value and then the properties of the material. This suggests the use of just a laser beam of opportune wavelength, instead of a filtered lamp light. In such a case, the measurement set-up can be simpler and the experimental data more accurate. This helps a better evaluation of the ratio R, as a particular care in the collection of experimental data required in these measurements.

In Fig. 5, we report the experimental and the simulated ratio R as expressed in Eq. (5) as a function

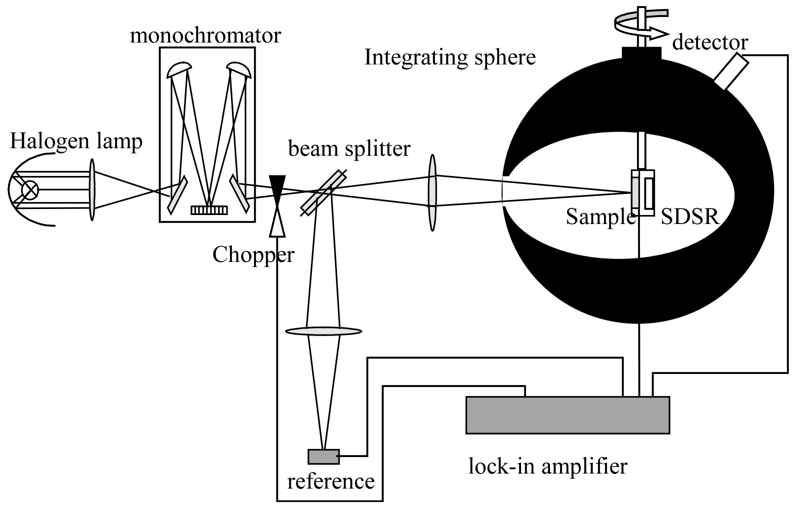

Fig. 3. Schematic view of the experimental apparatus for the L_d evaluation.

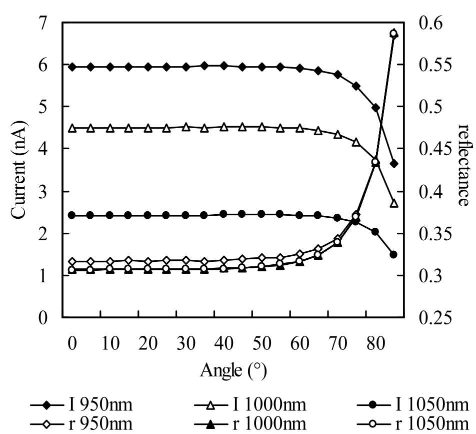

Fig. 4. Short circuit current and reflectance of a polished surface of an n^+/p c-Si cell as a function of light incidence angle for three different wavelengths.

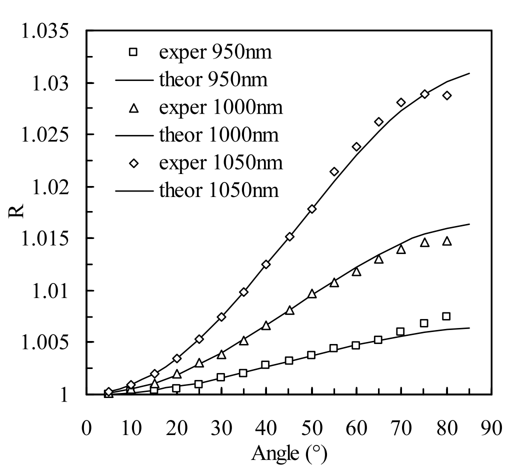

Fig. 5. Ratio expressed in Eq. (5) as a function of the incidence angle for various wavelengths of incident monochromatic light. Solid curves refer to the model; symbols to the measured data.

of the incident angle for various wavelengths of incident monochromatic light. In particular, solid curves refer to the model; symbols to the measured data. In order to obtain a fit between experimental data and theoretical model, in the three simulations we used always a dx value of 5 μm and a L_d value of 200 μm, while the absorption coefficient and the refractive index are reported in Table 1 [3].

In the evaluation of the ratio of Eq. (5), current measurements, reported in Fig. 4, are corrected by taking into account the contribution arising from the diffused light produced into the sphere. Even though a single wavelength is needed in the evaluation of L_d by the ratio R, we show in Fig. 5 how important is the choice of an appropriate wavelength in the measurement set-up. In fact, better sensitivity in the ratio R is obtained with longer wavelengths, even if in that case the measured photocurrent is lower. Then a trade-off in wavelength selection is needed in the accuracy of the measurements.

The discrepancy in the experimental data, with respect to the model, can be ascribed to a slight undesirable polarization of the light impinging the surface of the cell. This can be reduced by a calibration of the apparatus. Also at higher incidence angles, the data are error-affected due to the reduction in current value. Finally, we highlight the same value of L_d obtained with this method and with QE measurement. That confirms the

Table 1
Absorption coefficient and refractive index of c-Si

Wavelength (nm)	$\alpha(\lambda)$ (cm^{-1})	n
950	157	3.592
1000	64	3.570
1050	16.3	3.554

validity of both the set-up and the proposed analytical model.

5. Conclusions

In this work, we present an alternative method for the investigation of minority carrier diffusion length of a junction device in which it is possible to isolate the contribution to the photocurrent arising from the neutral bulk region. In particular, the evaluation of L_d was performed putting a n^+/p cell in an apparatus involving an integrating sphere that gives information on both reflectance and photocurrent involving the same region of the sample. Only current measurements performed at various incidence angles and at a single fixed wavelength are needed in order to obtain a correct L_d evaluation. In fact, the diffusion length can be derived by the analysis of the experimental ratio between photocurrent measured at various incidence angles and when light impinges the device at orthogonal condition, as function of the incident angle. An analytical model, based on the modified absorption coefficient as a function of refractive angle, and an experimental set-up for the estimation of minority carrier diffusion length are proposed and discussed.

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