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# Simultaneous optical losses and current measurements in photovoltaic devices at variable angle of the incident light

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## Abstract

In this work, the apparatus and the method for a simultaneous measurement of the optical losses and short-circuit current in a solar cell, at variable incidence angle of the light, is presented. The method has been applied to an $n^+/p$ c-Si cell with a polished surface. The investigation has been performed over an angular range from 8° to 80°, using a linearly polarized laser beam, either normally or parallelly polarized with respect to the incidence plane. The experimental curves of reflectance seem to be in a good agreement with the theoretical ones derived from the Fresnel equations. Since the measurements are performed inside an integrating sphere, a procedure has been developed to derive, from the total current $I^{tot}$, the calculated direct one, $I_{dirCal}$ excluding contributions from the incoming light back-diffused to the cell under investigation; the results are compared with real direct-current measurement. Since with the proposed method both reflectance and current are measured for the same surface region and under identical illumination conditions, the results have been combined to get the internal spectral response of the $n^+/p$ c-Si polished surface solar cell.


*Keywords:* Optical losses; Current measurements; Solar cells; Integrating sphere; Variable incidence angle; Internal spectral response

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## 1. Introduction

The analysis of the optical losses in a solar cell, at variable angle of incidence, is indicative of its light-trapping properties under its effective conditions of work. Moreover, if the reflectance factor is known together with the short-circuit current, it is possible to determine the internal spectral response (ISR) of the cell, which, in turn, if studied as a function of the incidence angle, can give information about the carriers collection modality.

An estimation of the variations (relative to the normal incidence) of ISR with the angle has been recently performed [1]. These can be indicative of the mechanisms and paths of collection of the carriers into the different regions of a solar cell. However, in Ref. [1], current and reflectance measurements have been performed at different times and with different apparatus. This fact does not exclude errors in the angular correspondence between the two quantities; moreover, the optically active illuminated area cannot be considered exactly the same in the two measurements.

In this paper, an apparatus and a method for the simultaneous measurement of the optical losses and short-circuit current in a photovoltaic device at variable incidence angle of the light have been used.

## 2. The experiment

The method is based on the idea of inserting a contacted solar cell inside a variable angle reflectometer. The latter can be realized with an integrating sphere, whose dimensions allow to introduce the cell at its center, supplied with a radiation detector present at the inner side of it [2,3]. By illuminating the cell, through a port of the sphere with a direct beam of light, it is possible to collect the reflected light from its surface (and so measuring the reflectance) and, simultaneously, measuring the induced current. However, a measurement of the current, performed in this way, is affected by the circumstance that the light, reflected by the cell surface, is scattered by the walls of the sphere and, a part of it, impinges again on the optically active medium of the cell. This introduces an error in the current response evaluation under direct illumination. We will show later that the contribution of the scattered light is not negligible. The method consists in correcting, with an opportune formula, the measured values of current to eliminate the scattered light contribution.

As shown in Fig. 1, in our experiment, a linearly polarized diode laser beam, at $\lambda = 830\,\text{nm}$, is split into two beams of equal intensity. Both the beams enter the integrating sphere, by MACAM Photometrics, through the input port; the reference beam is incident on a Spectralon Diffuse Reflectance Standard (SDRS) while the other is incident on the cell under investigation, which is placed at the center of the sphere by means of a rotating holder, to allow for the variation of the incidence angle. By properly combining the measurements of the irradiance inside the sphere when the reference beam hits the SDRS and when the other beam hits the investigated sample, one can estimate not only the cell reflectance but also its short-circuit current, taking into account the contribution to the current due to the light

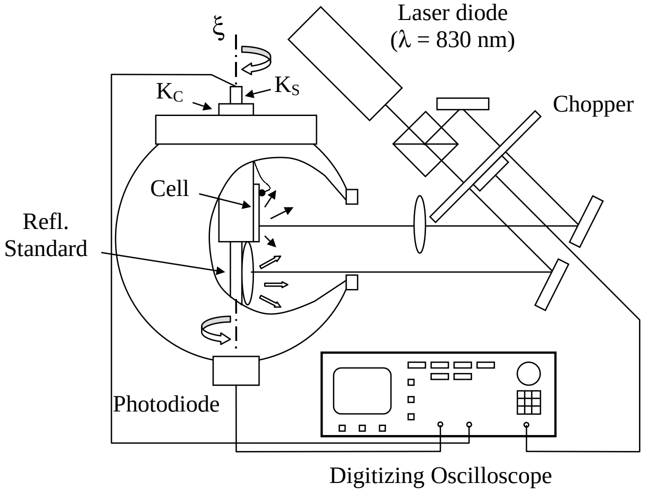


Fig. 1. Experimental layout.

which, after reflection from the sample, is back-diffused onto it by the sphere walls. Back-diffused light contribution, indeed, cannot negligible especially if, varying the incidence angle, large values of reflectance are considered.

To go into details, let us suppose that the cell knob $K_c$ is rotated in such a way that the light beam, of wavelength $\lambda$, impinges at an angle $\theta$. In the half-period the beam is transmitted, the total current, $I^{tot}(\theta, \lambda)$, that is produced inside the cell depends on the direct incident light contribution, $I^{dir}(\theta, \lambda)$, and on $I_c^{diff}(\theta, \lambda)$, due to the scattered light, reflected from the cell surface at an angle $\theta$, inside the sphere given by

$$I^{tot}(\theta, \lambda) = I^{dir}(\theta, \lambda) + I_c^{diff}(\theta, \lambda). \quad (1)$$

Currently, the photodiode produces a signal, proportional to the intensity of the light reflected by the cell that we will indicate as $V_c(\theta, \lambda)$. In the most general case, the contribution $I_c^{diff}(\theta, \lambda)$ can be expressed in the form

$$I_c^{diff}(\theta, \lambda) = F(\theta, \lambda)\mathrm{ISR}(\theta, )G_{oc}(\lambda)R_c(\theta, \lambda), \quad (2)$$

where $F(\theta, \lambda)$ is a dimensionless factor (between 0 and 1), that takes into account the fact that the cell, independent of its surface orientation, sees only a part of the irradiant walls of the sphere. In principle, assuming the inner surface of the sphere to be homogeneously coated, this factor should be constant by changing $\theta$. This prevision has been confirmed by experimental results. However, its value does not influence our correction procedure. In general, its dependence on $\lambda$ comes from the fact that the coating could reflect differently various parts of the spectrum. $G_{oc}(\lambda)$ is the intensity of the beam. $R_c(\theta, \lambda)$ is the reflectance factor of the cell at an angle $\theta$ and wavelength $\lambda$. $\mathrm{ISR}(\theta, \lambda)$ is the ISR that we assume, for the moment, depending on $\theta$ too. In the half-period the sample beam is intercepted, the reference beam impinges on the standard surface, whose orientation is fixed at 8° with respect to the incidence direction. The detected signal will be, in this case, $V_s(\theta, \lambda)$. By exploiting the linear response of the sphere, we will say that the reflectance of the cell is

$$R_c(\theta,\lambda) = \frac{V_c(\theta,\lambda)}{V_s(\theta,\lambda)} R_s(8^\circ,\lambda), \tag{3}$$

where $R_s(8^\circ,\lambda)$ is the known reflectance factor of the SDRS at $\lambda$. Because of light-scattering effects by the standard, a current is produced in the cell too, which has the form

$$I_s^{\text{diff}}(\theta,\lambda) = F(\theta,\lambda)\text{ISR}(\theta,\lambda)G_{os}(\lambda)R_s(8^\circ,\lambda), \tag{4}$$

where $G_{os}(\lambda)$ is the intensity of the reference beam.

Under the hypothesis that $G_{os}(\lambda) = G_{oc}(\lambda) = G_o(\lambda)$ (i.e., the test and reference beams have the same intensity), by inserting Eq. (3) into Eq. (2), we get

$$I_c^{\text{diff}}(\theta,\lambda) = F(\theta,\lambda)\text{ISR}(\theta,\lambda)G_o(\lambda)\frac{V_c(\theta,\lambda)}{V_s(\theta,\lambda)} R_s(8^\circ,\lambda). \tag{5}$$

From Eq. (4), we find that Eq. (5) can be expressed as

$$I_c^{\text{diff}}(\theta,\lambda) = I_s^{\text{diff}}(\theta,\lambda)\frac{V_c(\theta,\lambda)}{V_s(\theta,\lambda)}. \tag{6}$$

Consequently, the value of $I^{\text{dir}}(\theta,\lambda)$ can be extracted from Eq. (1):

$$I^{\text{dir}}(\theta,\lambda) = I^{\text{tot}}(\theta,\lambda) - I_c^{\text{diff}}(\theta,\lambda) = I^{\text{tot}}(\theta,\lambda) - I_s^{\text{diff}}(\theta,\lambda)\frac{V_c(\theta,\lambda)}{V_s(\theta,\lambda)}. \tag{7}$$

In the right-hand side of Eq. (7), all the measured quantities appear, so that we can, with this method, simultaneously get both the reflectance factor and the short-circuit current for the cell.

## 3. Results and discussion

In order to test the method and the apparatus, we have characterized a screen-printed $n^+$/p c-Si cell with a polished surface. It presents an optically active area of $3 \times 3\,\text{cm}^2$ and a distance of 3 mm between the fingers. We have used as a reflectance standard a Labsphere SDRS, whose reflectance factor, in the UV/Vis/NIR range, at an angle of incidence of $8^\circ$, is certified.

To validate the correction procedure on the current, we proceeded in the following way. The sphere was leaned to the sample holder in such way that it could be removed, while the optical system and the sample holder remained fixed to the optical table. In this way, we measured the current flowing into the cell without the contribution of the scattered light. By leaning again the sphere we could measure the total current (direct + scattered) and, simultaneously, the reflectance factor.

For what concerns the latter, being the light polarized and the surface polished, we performed a comparison between our experimental results and the curves foreseen by the Fresnel equations. For a wavelength of 830 nm, we assumed an effective refractive index of $n = 3.6$.

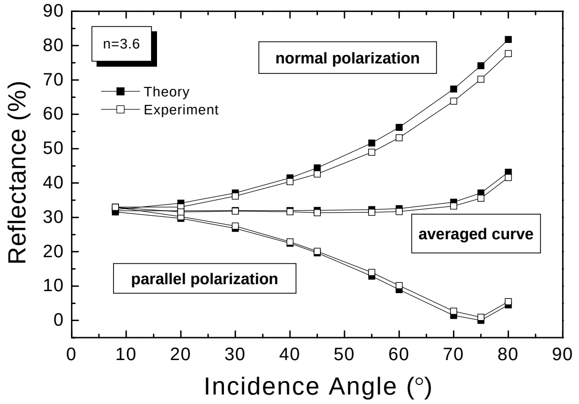


Fig. 2. Angular dependence of total reflectance of a polished surface c-Si cell for a linearly polarized beam at $\lambda = 830\,\mathrm{nm}$.

In Fig. 2, the angular dependence of total reflectance of the cell is reported; the curves relative to reflectance values for the two polarization states are compared with the curves given by the Fresnel equations assuming, as said, an effective refractive index of the sample $n = 3.6$. The agreement is quite satisfactory.

Then, current measurement for both the polarization states have been carried out. The angular range went from 8° to 80°. Results are shown in Figs. 3a and b. $I^{tot}$ indicates the total (direct + diffuse) current measured in the presence of the sphere; $I^{dir}$ is the direct one measured by removing the sphere, while $I_{dirCal}$ is the same quantity calculated according to the developed model.

When the reflectance increases, the difference between $I^{tot}$ and $I^{dir}$ has to grow because of the scattered light contribution. This effect is clearly visible in Fig. 3a in the s-polarization case. In the limit at which the reflectance goes to zero, the current has to be the same. This is, indeed, observed in Fig. 3b, for the p-polarization case, corresponding to the Brewster's angle ($\sim 75°$).

The experimental curve $I^{dir}$ is always slightly above the calculated one, $I_{dirCal}$; this is probably due to the contribution of a bias illumination present in the laboratory when the sphere had been removed. To underline the dependence of the current behavior on the reflectance, in Figs. 3a and b we have also reported the reflectance curves.

Angular relative variations of ISR for a screen-printed $n^+/p$ c-Si cell have been, finally, estimated. How we underlined in the preceding section, the simultaneous knowledge of the optical losses and of the short-circuit current in a solar cell can be utilized to get the relative variation of ISR into the device. In this case, we valued this parameter in relation to its value at an incidence angle of 8°. In this way we were able to eliminate the intensity light parameter, and, secondly, to estimate the performance of a solar cell in real working conditions (i.e., under the apparent motion of the sun).

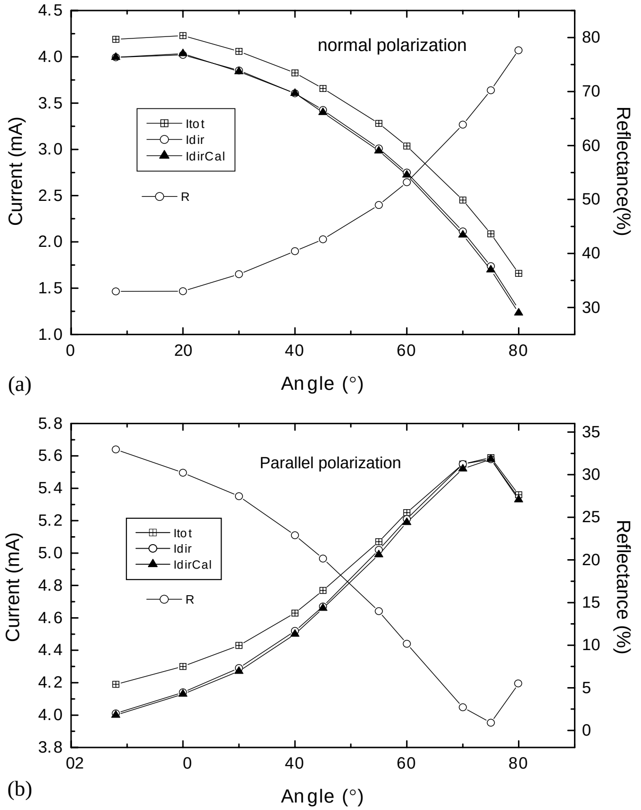


Fig. 3. Current and reflectance angular dependence for a polished surface $n^+/p$ c-Si cell: (a) the incident beam is s-polarized, (b) the incident beam is p-polarized.

If a beam of intensity $G_o$ and wavelength $\lambda$ impinges at 8° on the cell surface, the expected short-circuit current can be written as

$$I(8^\circ, \lambda) = G_o[1 - R_c(8^\circ, \lambda)]\mathrm{ISR}(8^\circ, \lambda) = G_o T(8^\circ, \lambda)\mathrm{ISR}(8^\circ, \lambda), \tag{8}$$

where $R_c(8^\circ, \lambda)$ is the reflectance factor. If we can neglect the absorbance, the expression $[1 - R_c(8^\circ, \lambda)]$ coincides with the transmittance $T(8^\circ, \lambda)$. In Eq. (8), both $I(8^\circ, \lambda)$ and $R_c(8^\circ, \lambda)$ can be measured adopting the method described above.

Let suppose, therefore, to perform a second measurement at an incidence angle $\theta$; Eq. (8) becomes

$$I(\theta, \lambda) = G_o T(\theta, \lambda)\mathrm{ISR}(\theta, \lambda). \tag{9}$$

By dividing side by side Eqs. (9) and (8), we get

$$\frac{I(\theta, \lambda)}{I(8^\circ, \lambda)} = \frac{T(\theta, \lambda)}{T(8^\circ, \lambda)} \frac{\mathrm{ISR}(\theta, \lambda)}{\mathrm{ISR}(8^\circ, \lambda)} \Rightarrow \iota(\theta, \lambda) = \tau(\theta, \lambda)\sigma(\theta, \lambda), \tag{10}$$

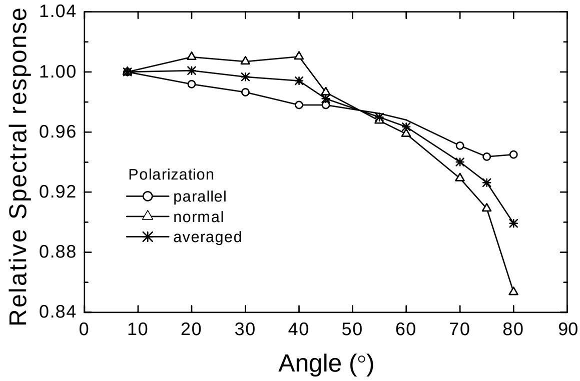


Fig. 4. Internal spectral response ISR($\theta, \lambda$) relative to ISR($8^\circ, \lambda$) for a polished surface $n^+$/p c-Si cell.

where with Greek letters, we indicate the dimensionless ratios in Eq. (10). From the latter we get

$$\sigma(\theta, \lambda) = \frac{\iota(\theta, \lambda)}{\tau(\theta, \lambda)}. \tag{11}$$

Now, if ISR were independent of $\theta$, $\sigma(\theta, \lambda)$ should always assume a unitary value. Fig. 4 shows the results for $\sigma(\theta, \lambda)$, obtained from the graphs in Figs. 2 and 3, after averaging the results for normal and parallel polarizations.

It is evident that $\sigma(\theta, \lambda)$ reduces, in a regular way, when $\theta$ increases. We deduce that, at a given transmitted light intensity, the photogenerated carriers are worse collected if the light passes obliquely in the medium with respect to the surface plane. Due to refraction, more oblique the path the light covers, the closer it is to the surface region of the generation.

## 4. Conclusions

In this work, the apparatus and the method for the simultaneous measurement of the optical losses and short-circuit current in a solar cell, at variable incidence angle of the light, have been presented. The method has been applied to an $n^+$/p c-Si cell with a polished surface. The angular range was from $8^\circ$ to $80^\circ$. We used a polarized laser beam in order to perform two sets of measurements with, respectively, normal and parallel polarization with respect to the incidence plane. The experimental curves of reflectance seem to be in good agreement with the theoretical ones foreseen by the Fresnel equations at the working wavelength. This confirmed the efficiency of the apparatus as an angle variable reflectometer. The validity of the formula and procedure correction, to be applied to the total current $I^{tot}$ to get the calculated direct one, $I_{dirCal}$, have been demonstrated by comparison with real direct-current measurement. Since this method allows knowing the optical losses and current response for a device, intersecting the same surface region and under identical illumination conditions, these results have been combined to get the ISR of an $n^+/p$ c-Si polished surface solar cell. Simultaneity of the measurements excludes any error on the angular correspondence between the two quantities. In particular, the variations of $\sigma$ with the angle of incidence, with respect to those measured at 8°, have been estimated. A regular reduction of $\sigma(\theta, \lambda)$ with the growing angle has been found, for the cell under investigation, at a wavelength of 830 nm. This indicates that in our planar cell the internal conversion efficiency is affected by the incidence angle of light onto its surface.

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