Temperature behaviour of the spectral response: a new approach for silicon solar cell characterization♣

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The paper explores the possibility of measuring the temperature behaviour of the spectral response of the open-circuit voltage V_{oc}, as a tool for silicon solar cell characterization. A characteristic decrease of V_{oc} with temperature is observed at fixed values of the wavelength λ, but for varying λ the slope of $lg[V_{oc}(1/T)]$ differs. Using an activation law, the activation energy E_a has been determined at constant photon flux, for wavelengths in the range 420−1200 nm. Two regions with different slopes of the dependence $E_a(\lambda)$ are observed. The nature of E_a change with λ can be related to a widening of the "active generation region" in the solar cell.

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1. Introduction

The temperature dependence of the basic electrical parameters of silicon solar cells strongly affects the electric power converted from solar energy in outdoor conditions. When the temperature of a solar cell rises, the short circuit current I_{sc} increases slightly, with a much greater decrease in the open circuit voltage V_{oc} and the fill factor. The overall effect is a decrease in the power of c-Si solar cells, by 0.5% per degree. This problem is of great importance at high levels of solar radiation and in hot climates.

The temperature behavior of solar cells is determined by factors rising from the basic physical properties of the starting semiconductor material, as well as characteristics connected with the purity of the materials and technological processes used. In the first case, the most important material properties which determine the temperature behavior of solar cells are: the intrinsic carrier concentration n_i, the absorption coefficient α and the carrier mobility μ [1]. The lifetime of minority carriers is a parameter related to the second case, in that it can be affected by the technological processes because of defect generation and contamination [2].

The aim of the present work is to show that studying the temperature behaviour of the spectral response allows one to assess which factors determine the behaviour of the basic solar cell parameters.

The spectral response is commonly used to characterize the ability to collect charge carriers generated by the light of the sun spectrum. As light with different λ penetrates at different depths in the solar cell, the spectral response provides a depth resolution of the recombination processes, which hinder the collection of charge carriers. This is why spectral measurements at different temperatures enable the characterization of the generation-recombination processes in various regions of the device structure, through evaluation of the activation energy.

2. Experimental

The spectral response or the spectral sensitivity is defined as the solar cell reaction to radiation with a fixed photon energy (monochromatic light). This characteristic is determined by measuring the short circuit current I_{sc} or open circuit voltage V_{oc} with monochromatic light in the range 420–1200 nm.

The samples examined are industrial silicon solar cells. The starting wafers are monocrystalline p-type silicon of thickness 330μm. The surface is textured to reduce the reflection. The n^+ region is formed with phosphorus diffusion, and has a surface concentration of $5.10^{19}cm^{-3}$ and a junction depth of 0.6μm. At the rear side, the p^+ region is obtained with Ag-Al paste. The front electrical contacts are formed by a screen printing

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technique with Ag paste. The deposited antireflection coating is a PECVD silicon nitride film.

The experimental setup is presented in Fig.1. The equipment and measurement technique have been described in detail in [3]. A family of calibration spectral curves depicting the photon fluxes at different wavelengths is obtained. The data for the open circuit voltage V_{oc} and photon fluxes are used to obtain the dependence of V_{oc} on the photon flux at different wavelengths.

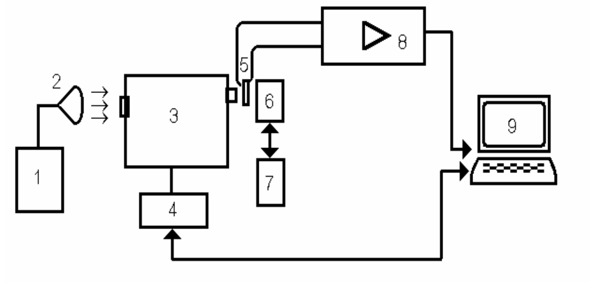

Fig. 1. The measurement scheme: 1- power control of the halogen lamp, 2- a halogen lamp, 3- a monochromator, 4 - a step engine with computer control, 5 – a sample, 6 - a Peltier element for sample heating, 7 - an electronic temperature controller, 8 - a measurement system, 9- PC

Typical measurements of the open circuit voltage V_{oc} as function of the photon flux $F(\lambda)$ at different λ are presented in Fig. 2. The measurements are performed under the condition of very low photon flux, and that assumes a low density of the photo-generated minority carriers n_{ph}. In this case, we are just able to use the approximation of so called “low injection” in the SRH (Shockley-Read-Hall) model, and n_{ph} is in the same range as the total concentration of recombination traps N_t (N_t=1.10^{13}cm^{-3}). At a very low intensity of light, the dependence of V_{oc} on the photon flux is linear. For λ in the range of 480-820 nm, the slope of V_{oc} (F) stays constant. At λ > 820 nm, the slope of V_{oc} (F) changes with λ. This is due to the decrease in the quantum efficiency in the near infrared region.

3. Results and discussion

The standard spectral technique in solar cell characterization is the spectral response of the short-circuit current. Voltage measurements, however, can be performed as soon as a junction

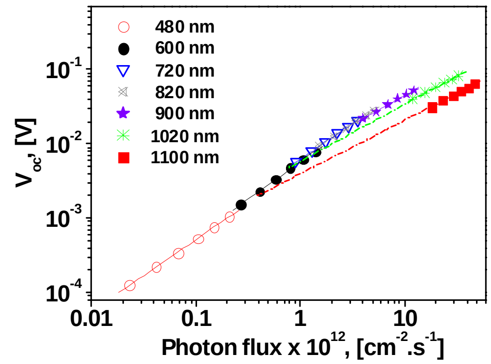

Fig 2. Dependence of V_{oc} on the photon flux at different wavelengths at temperature 44 °C.

has been formed in the silicon substrate, offering the advantage of quality control of the steps [4]. As light of different wavelengths is absorbed at different depths in the solar cell, the spectral response provides a depth resolution of the recombination processes.

Upon illumination with monochromatic light with wavelength λ, an electric current is generated with a density:

$$I_L(\lambda) = \int_{x=0}^{x=L} q\alpha(\lambda)F(\lambda)e^{-\alpha(\lambda)x}dx \qquad (1)$$

where x is the distance from the illuminated surface, $\alpha(\lambda)$ the absorption coefficient, and $F(\lambda)$ the photon flux. The total current at the illuminated surface of the n$^+$/p junction is:

$$I_{ph}(\lambda) = I_D - I_L \qquad (2)$$

where the dark current I_D is:

$$I_D = I_S(e^{\frac{qV}{kT}} - 1) \qquad (3)$$

V is the applied bias and I_s is the saturation current density. It depends on the temperature through $n_i(T)$ - the intrinsic carrier density, $\mu_{p,n}$ - the carrier mobility and $D_{n,p}$ – the diffusion coefficient of electrons or holes and the carrier lifetime.

Most generally, this temperature dependence can be presented as:

$$I_S = K(T)e^{-\frac{Eg}{kT}} \qquad (4)$$

where $K(T)$ is a temperature coefficient and E_g is the band gap. When no bias voltage V is applied, the photocurrent under the illumination (Eq. 2) is I_{ph} = - I_L and it is called the short circuit current I_{sc}. The temperature dependence of I_{ph} can be represented as:

$$I_{ph}(\lambda) = K(T)e^{-\frac{Eg}{kT}}(e^{\frac{qV}{kT}} - 1) - I_L(\lambda) \quad (5)$$

The temperature behaviour of I_L *(T)* is determined from the temperature dependence of the absorption coefficient α *(T)*, which is different for each λ [5].

For the case I_{ph} = 0 (open circuit), the open circuit voltage V_{oc} is defined from Eg. 5 as:

$$V_{oc}(\lambda) = \frac{kT}{q}\ln(\frac{I_L(\lambda)}{I_S} + 1) \quad (6)$$

The temperature dependence $V_{oc}(T)$ for each wavelength λ can be represented as:

$$V_{oc}^{\lambda}(T) = \frac{kT}{q}\ln(\frac{I_L(T)}{K(T)e^{-\frac{Eg}{kT}}} + 1) \quad (7)$$

According to Eq. 4, the saturation current density I_s does not depend on the wavelength λ. When illuminating with monochromatic light, the temperature dependence of $V_{oc}^{\lambda}(T)$ is defined by the temperature behavior of $I_L(T)$. The linear dependence of *lg[*V_{oc}*(1/T)]*, as found during the experiment, allows us to apply the activation law:

$$V_{oc}^{\lambda}(T) \approx e^{\frac{Ea}{kT}} \quad (8)$$

where E_a is the activation energy, which reflects the total temperature dependence on a number of factors and is determined by the generation- recombination process in the solar cell. Using Eq. 8, the activation energy E_a can be calculated for each λ.

Fig. 3 shows the temperature dependence of the V_{oc} measured at different λ. For every λ, the open circuit voltage V_{oc} is measured for the same photon flux. A characteristic decrease of V_{oc} with temperature is observed at fixed values of λ, but for different wavelengths the slope is different. The activation energy E_a was determined for each value of λ from Eq. 8.

The dependence of the activation energy E_a on wavelength is given in Fig. 4, at a photon flux F=5x10^{12} cm^{-2}.s^{-1}. Two regions with different slopes in the dependence of E_a *(λ)* are observed. The character of the E_a change with λ could be related to the widening of the "active generation region" in the solar cell. The changes in E_a *(λ)* can be interpreted, having in mind the generation-recombination processes. The reason for the different behaviours of the E_a *(λ)* separation is the presence of two different recombination processes in the bulk of the Si device. For λ in the range 450−850 nm, the essential contribution of photo-carrier generation occurs in the depth region 0.5−23µm (using on absorption coefficient at 20ºC) from the silicon surface. The generation-recombination process could be controlled by deep levels in the Si, defects or centres of impurity created during the diffusion process.

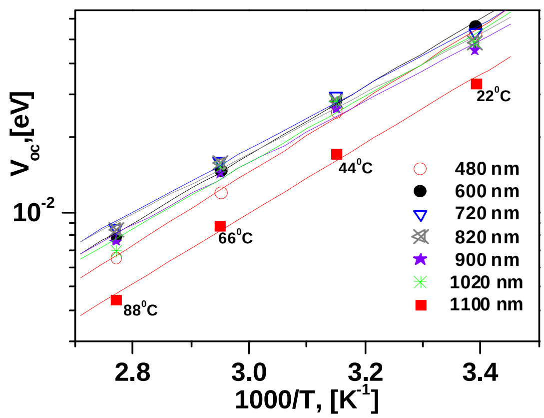

Fig. 3. Temperature dependence of V_{oc} measured at different λ.

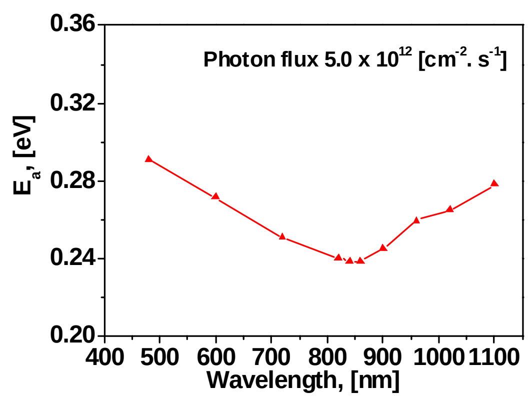

Fig. 4. Dependence of the activation energy E_a on the wavelength at photon flux F=5x10^{12} cm^{-2}.s^{-1}.

In the wavelength range 850−1100nm, the dominant generation of the carriers occurs at a depth of 25−300µm. In this region, the bulk lifetime of minority carriers is determined by the recombination-generation processes, as well as by the influence of the back surface.

In this way, the contribution of the two different regions in the silicon crystal to the temperature dependence of V_{oc} is assumed.

4. Conclusions

The temperature behavior of the spectral response of the open circuit voltage of a silicon solar cell has been analyzed. The results show that the measurement technique used is able to detect the recombination and absorption losses of various origins. It can be applied as a diagnostic tool in solar cell characterization, and more specifically to monitor technology.

Acknowledgements

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