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A simple technique for determination of the diffusion length in a solar cell

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The surface photovoltage (SPV) effect is widely used for the determination of the minority carrier diffusion length in semiconductors, particularly in solar cells. We have developed a technique based on SPV measurements using a number of calibrated light emitting diodes as monochromatic sources of different wavelengths (λ). The open circuit photovoltage as function of λ was measured at a constant photon flux. The measurements were carried out on mono- and multi-crystalline silicon solar cells. Goodman's model was used to interpret the data and, values of minority carrier diffusion length were deduced. The effect of the injection level and temperature on the minority carrier diffusion length has also been studied.

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1. Introduction

The characterization of silicon solar cells and modules is important for process development and for quality control during production. Amongst the various cell performance parameters, the minority carrier diffusion length is the most important. It provides information about the quality of the base material before and after processing, and information connected with the device performance and processing conditions. Therefore, minority carrier diffusion length determination is essential for solar cell process development and characterization. Furthermore, it is desirable to determine its value at different intermediate process stages, which indeed may require contact-less measurement techniques. Several methods for determining the minority carrier diffusion length are available in the literature [1,2]. The surface photovoltage (SPV) method is one such technique, which is routinely used for solar cell characterization [3].

In this paper, we report a simple yet elegant method for quick determination of the minority carrier diffusion length in the base material of solar cells. The open circuit photovoltage was measured as a function of wavelength (λ) at a constant photon flux, using a number of calibrated light emitting diodes (LED) as monochromatic different wavelength (λ) sources. Measurements were carried out on mono- and multi-crystalline silicon solar cells, and Goodman's model [4] was used to interpret the data. The effect of the injection level and temperature on the minority carrier diffusion length has also been studied.

2. Goodman model: theoretical aspects

Goodman's theory models the minority carrier diffusion length and measurements in semiconductors using SPV measurements. The model assumes that the excess electron concentration, Δn, is much smaller than the hole concentration (p) such that $p \gg \Delta n$ and $d \gg \alpha^{-1} \gg x_d$ and $d \gg L_n \gg x_d$, where d is the sample thickness, α(λ) is the absorption coefficient, x_d is the depth to which band bending extends due to surface states and L_n is the minority carrier diffusion length in the p-type material. The solution of the diffusion equation, involving the generation and recombination terms, in terms of Δn, is [4]:

$$\Delta n = \frac{\Phi_{eff} . L_n}{(D_n + L_n . S).(L_n + \alpha^{-1})} \tag{1}$$

where Φ_{eff}, S and D_n are the effective photon flux, recombination velocity at the surface and minority carrier diffusion coefficient, respectively. Furthermore, it is assumed that the open circuit voltage (V_{oc}) is a linear function of $\Delta n(x_d)$, particularly when the variation in the excess electron concentration is small. In this case, eq. (1) is modified as:

$$\frac{\Phi_{eff}(\lambda)}{V_{oc}(\lambda)} \propto L_n + \alpha^{-1}(\lambda) \tag{2}$$

By varying λ, V_{oc} is measured at a constant Φ_{eff} and is plotted as $V_{oc}^{-1}(\lambda)$ vs. $\alpha^{-1}(\lambda)$ (fitted to a straight line equation). The intercept on the abscissa gives L_n.

The dependence of L_n on the injection level is adequately described by the Shockley-Read-Hall (SRH) model. When recombination centers are located near the middle of the energy gap, the SRH expression (for the lifetime, τ_{SRH}) simplifies to [5]:

$$\tau_{SRH} = \tau_{no} + \tau_{po}\frac{\Delta n}{\Delta n + p_o} \quad (3)$$

where p_o is the thermal equilibrium concentration of holes. The above equation clearly indicates the dependence of the minority carrier lifetime on the carrier injection level. τ_{no} (τ_{po}) is the characteristic time for electrons (holes) and is equal to $\tau_{io} = 1/(\sigma_i V_{th} N_t)$, where i stands for p or n. V_{th} and N_t are the thermal velocity of the carriers and the density of states at an energy level E_t respectively and the minority carrier lifetime is $\tau_n = L_n^2/D_n$. Here, D_n is the diffusion coefficient of electrons. In fact, this model predicts an increased lifetime between τ_{no} and $\tau_{po}+ \tau_{no}$ between low and high injection levels [5], which will be discussed later.

3. Experimental details

The schematic of the measurement set-up is shown in Fig. 1. The system consisted of current voltage measuring devices (HP and Keithley DMM) with high input impedance, a thermally controlled chuck (Peltier cooling-heating unit) and a set of calibrated LEDs of different wavelengths with narrow spectral line ($\Delta\lambda$=25 nm) as monochromatic light sources. The intensity of the incident light was determined using a calibrated photodiode (BVP10 from Vishay Semiconductors). Pressure contacts were made to the electrical contacts. The light intensity was controlled galvanostatically (in the LEDs) to maintain a photon flux constant at different wavelengths.

The system measurements were carried out on silicon solar cells under different conditions such as varying the temperature (from 290 to 383 K) and photon flux (from 10^{14} to 10^{15} photons/cm^2/s). A Pt500 resistor was used to measure the temperature, with an accuracy of ±0.5 K. The system was housed inside a black metal box for electro-magnetic shielding. The samples were mounted on a thermo-chuck for measurement at a constant temperature.

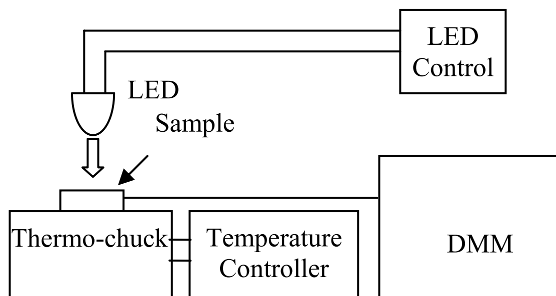

Fig. 1. Schematic of SPV set-up.

Commercial silicon cells, both mono- and multi-crystalline, were used. The cells were made on p-type wafers (125×125 mm^2) using a conventional diffusion process. The front surface had a SiN_x antireflection coating (reflectivity <7% in the 400-950 nm region).

4. Results and discussion

The SPV measurements were carried out on 10×15 mm^2 size samples, which were diced from the large solar cells. Special care was taken during dicing, so that all the diced specimens had four metal fingers and the same area of bus bar. We report the results on one representative multicrystalline (MCS, 15% efficient) and two single-crystalline silicon (CS1 and CS2, 18 and 13.2% efficient respectively) solar cells. The experimental data are plotted in terms of the absorption length, α_λ (=1/α(λ)), as a function of $V_{oc}^{-1}(\lambda)$ in Figs. 2-5.

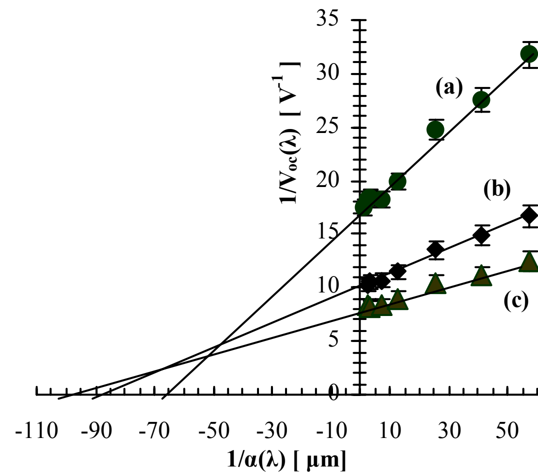

Fig. 2. Absorption length (i.e., 1/α(λ)) as an inverse function of $V_{oc}(\lambda)$ for multi-crystalline silicon (MCS) at 1.7×10^{14} (Curve a) 2.9×10^{14} (Curve b) and 4.8×10^{14} (Curve c) photons/cm^2/s. The corresponding L_n values are 68, 87 and 100 µm respectively.

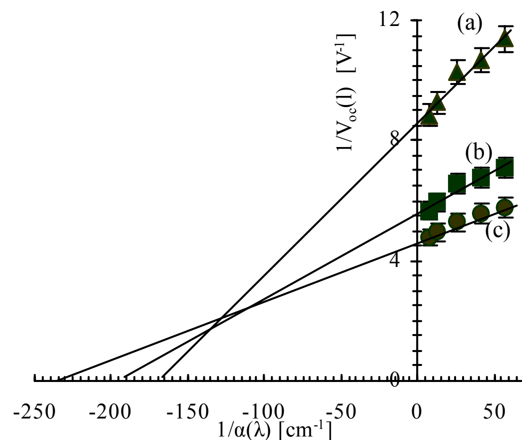

Fig.3. $\alpha^{-1}(\lambda)$ vs. $V_{oc}^{-1}(\lambda)$ for crystalline silicon (CS1) at 1.7x10^{14} (Curve a) 2.9x10^{14} (Curve b) and 4.8x10^{14} (Curve c) photons/cm^2/s. The corresponding L_n values are 180, 200 and 240 µm respectively.

During the measurements, five to seven LEDs of different wavelengths (e.g., 710, 740, 810, 840, 875, 945 and 970nm) were used at three different photon flux densities, i.e. 1.7×10^{14}, 2.9×10^{14} and 4.8×10^{14}

photons/cm^2/s. The corresponding curves for these intensities of illumination are marked as a, b and c respectively in the figures. The experimental $\alpha^{-1}(\lambda)$ vs. $V_{oc}^{-1}(\lambda)$ data were fitted to a linear relationship, using chi-square fitting. The intercept on $-\alpha^{-1}(\lambda)$ axis (extended line) gave the value of the minority carrier diffusion length. In sample MCS (Fig.2) the values of L_n were 68, 87 and 100μm at 1.7x10^{14}, 2.9x10^{14} and 4.8x10^{14} photons/cm^2/s fluxes respectively. The L_n values in the single-crystal silicon CS1 cell (18% efficient) were 180, 200 and 240μm (Fig. 3), whereas in sample CS2 (13.2% efficient) the values were 140, 117 and 110μm respectively (Fig.4) for the three corresponding photon flux densities. To verify our results, the diffusion length was measured using the LWSR (Long Wavelength Spectral Response) method [6] at a fixed Φ_{eff} = 1,7.10^{14} photons/cm^2/s at NPL, Delhi in sample MCS. The value was 70 μm, which is close to that determined by SPV (i.e., 68 μm). The light intensity could not be varied, due to the system limitations.

It was found that the L_n in MCS and CS1 increased with increaseing photon flux whereas the opposite behavior is observed in CS2. An increase in the minority carrier diffusion length (or lifetime) is expected with increasing injection level, after the SRH model (eq.2, predicts an increased lifetime at moderate to high injection levels). It is to be remarked here that each recombination center is characterized by a distinctive set of parameters E_t, τ_{po} and τ_{no}, which leads to different injection and temperature dependences of the lifetime [3,4]. We attribute the decrease in L_n (from 140 to 110 μm) with increasing photon flux (as observed in CS2) to the nature of the recombination centers present in the silicon. A decrease in the minority carrier lifetime was observed under high-level injection conditions (above Δn = 10^{14} cm^{-3}) by Rein et al. [7] and Schroder et al [2,4]. CS2, which is a low efficiency cell, may be decorated with impurities or pairs (e.g., Fe-B) that lie about 0.1eV above the valance band.

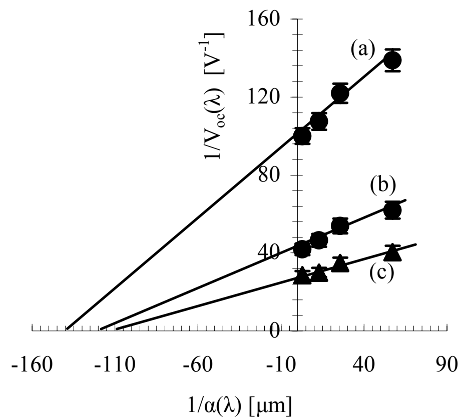

Fig. 4. $\alpha^{-1}(\lambda)$ vs. $V_{oc}^{-1}(\lambda)$ curve for multi-crystalline silicon (MCS) at 1.7x10^{14} (Curve a) 2.9x10^{14} (Curve b) and 4.8x10^{14} (Curve c) photons/cm^2/s. The corresponding L_n values are 140, 117 and 110μm respectively.

In order to verify the above statement, the diffusion length L_n was measured at different temperatures (varying from 25 to 95 ^{o}C in steps of 5 ^{o}C), as shown in Fig. 5. The temperature dependence of the absorption coefficient was taken into account in the calculations (data in the solar cell simulator PC1D).

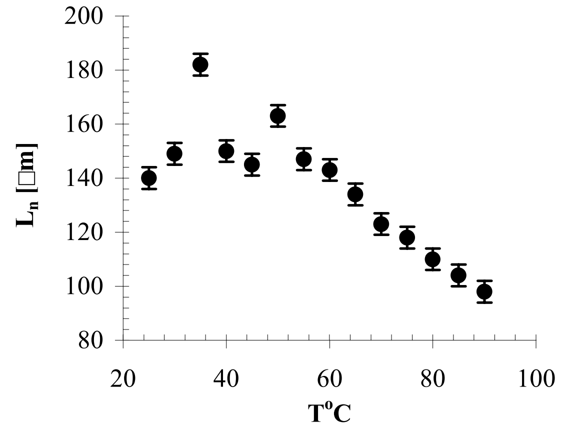

Fig. 5. Temperature dependence of the minority carrier diffusion length measured in CS2.

It is known that the mobility (μ) of minority carriers in silicon has a $T^{-3/2}$ dependence due to acoustic phonon scattering. At doping levels of ~10^{16} cm^{-3} or less, μ decreases with increasing temperature, whereas the diffusion coefficient remains almost constant. The lifetime is also a function of temperature ($T^{1/2}$ through the thermal velocity) and the capture cross section, which can have either a positive or negative temperature coefficient, depending on the nature of recombination centres [8].

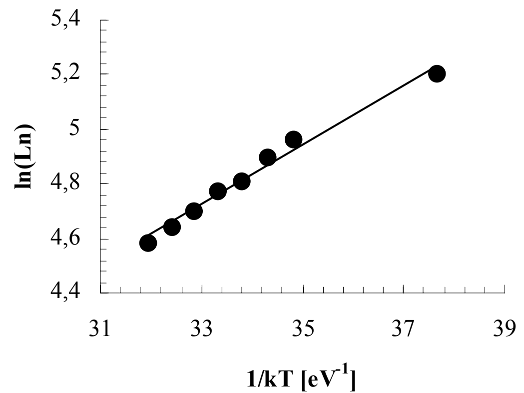

Fig. 6. Arrhenius plot of L_n for CS2.

It is to be pointed out that SPV is a steady-state method. and thus is immune to time constants associated with bulk and surface processes, which is a limitation in other methods, such as the photoconductive decay. Furthermore, recombination processes have an influence

only through the surface recombination velocity (S), where a change in S can change the magnitude of SPV and the slope of the curve used to extract L_n. However, it does not affect the intercept and hence the L_n value.

The activation energy, as determined from the Arrhenius plot of diffusion length (Fig. 6 for CS2) was E_a= 0.12eV. This value is close to that of E_t=0.11eV reported by Schroder et al [4] for Fe-B pairs, where a decrease in L_n with Φ_{eff} was observed. The observed decreases in L_n (Fig. 5) in the 40 to 100 ^{o}C range may be attributed to shallow recombination centres [4,7].

5. Conclusions

A simple technique for the determination of the diffusion length of solar cells has been developed using open circuit photovoltage measurements at different wavelengths. The dependence of the diffusion length on the injection level and temperature has been studied. The observed decrease in L_n with increasing temperature may be attributed to the characteristics of the recombination centres in the material.

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