Moscow University
Physics Bulletin
Vol. 48, No. 4, pp. 80–84, 1993

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UDC 621.382

MEASUREMENT OF SHORT LIFETIMES OF MINORITY CHARGE CARRIERS IN SILICON SOLAR CELLS IRRADIATED BY FAST ELECTRONS

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A new modulation method was suggested to determine short lifetimes ($\gtrsim 10^{-8}$ s) of minority charge carriers in the base region of solar cells. The method is based on compensation for the alternating photocurrent by an additional current source. Data obtained for single-crystal silicon solar cells irradiated by a fluence of electrons (below 10^{16} cm^{-2}) with 1 MeV energy are presented.

INTRODUCTION

The problem of increasing the service life of silicon solar cells, which are the main source of energy supply for space vehicles, is still very important for both the designers and the users. Of particular urgency is the task of the long-term prediction of solar cell behavior in various near-Earth orbits under conditions of exposure to cosmic radiation. In this connection, measurement of short lifetimes (τ) of minority charge carriers in the base region of solar cells is of utmost importance because this parameter determines the performance of the device and is most sensitive to the effect of radiation.

A number of methods based on the minority charge carrier injection by the current are being used to determine τ in solar cells with the *p–n* junction [1]. However, it is well known that the τ values may depend on the injection level and hence on the type of charge carrier depth distribution in the base region. For this reason, it is advisable to utilize methods based on the injection by light, whose intensity and spectral distribution are close to the sunlight. Normally solar cells are illuminated from the side of the *p–n* junction by two light sources: a sunlight simulator, which provides the necessary irradiance, and a weak probing source, which is modulated in intensity and tunable in wavelength [2]. In experiments, one determines the spectral dependence of the external quantum efficiency Q, which by definition is

$$Q = \frac{I}{A(1-R)P\lambda}, \tag{1}$$

where P is the intensity of the probing beam incident on the solar cell; λ and R are the beam wavelength and reflectance at the cell surface; I is the short-circuit photocurrent corresponding to this illumination; and A is a numerical coefficient. If I, P, and λ are expressed in μA, μW, and μm, respectively, then $A = 806$. The coefficient Q is directly related to the diffusion length (L) of minority charge carriers in the cell base. In the particular case when the light incident on a cell is practically fully absorbed by the base, the base thickness is much larger than L, and the minority charge carrier motion is diffusion-controlled, then

$$Q = \alpha L/(1+\alpha L), \tag{2}$$

where α is the absorption coefficient for the modulated light of a given wavelength λ. The formulas to be used in more general cases were reported in [3]. Therefore, using measured values of $Q(\lambda)$, one can determine L and then τ by the formula $\tau = L^2/D$, where D is the diffusion coefficient for minority charge carriers in the base.

If the illumination is carried out with a concentrated beam that scans the surface of the *p–n* junction, it becomes possible to determine the degree of cell homogeneity, which is an additional advantage of this method as compared to those based on injection by the current.

A disadvantage of the method under consideration is its low sensitivity at short τ typical of irradiated solar cells. For instance, for an n^+–p silicon cell with $\tau = 1$ μs illuminated through a standard monochromator at $\lambda = 1.1$ μm, $I \lesssim 10^{-7}$ A. Under the simulated sunlight conditions the differential resistance (r_i) usually does not exceed 1 ohm, therefore the load resistance of the cell must not be more than 0.1 ohm to provide conditions for a short-circuit current. The voltage drop then is no more than 10^{-8} V, which is difficult to measure. In irradiated cells, the τ values may be markedly shorter than 1 μs, which makes measurements of τ even more difficult.

This work is focused on the development of a new method for determining short τ ($\tau \lesssim 1$ μs) and on its application to the study of single-crystal silicon solar cells irradiated by electrons.

EXPERIMENTAL

A specific feature of the setup developed is that the alternating photocurrent induced upon illumination of the cell with intensity-modulated light is compensated for from an external source connected to the cell via an additional resistor. The presence of a compensation is indicated by the absence of alternating voltage at the cell, and I is determined from the alternating voltage at this resistor. Owing to the compensation, the alternating-current load resistance of the cell can be markedly increased. As a result, the signal to be measured increases by several orders of magnitude, thus providing an increase in sensitivity as well as in the range of the cell photoelectric parameters to be measured.

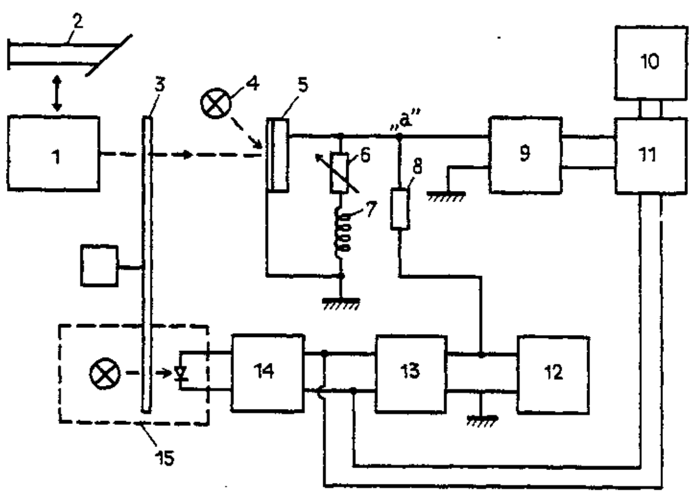

Fig. 1

The block diagram of the setup is presented in Fig. 1. Either block 1, which is an IKS-21 spectrometer in which the Globar lamp is replaced with a 170 W cinema lamp, or block 2, which is an LGN-113 or LG-126 laser, serves as a light source with tunable wavelength. The intensity modulation (70–1000 Hz) is achieved with a rotating slit chopper 3. AL-107B gallium arsenide photodiodes providing an irradiance of the cell of about 0.1 W/cm^2 are used as a source of constant illumination 4 (Sun simulator). The alternating photo-emf arising in cell 5 is measured by a voltmeter 9 of a U2-8 selective amplifier tuned to the light modulation frequency. Then this voltage is gradually diminished by applying the compensating voltage to point "a" of the cell signal outlet. The compensating voltage is supplied from phase and amplitude control 13 via resistor 8, whose resistance (r_c) is 10^2–10^5 ohms. Optron 15 was used as a transducer of the compensating voltage. The amplitude modulation of this voltage is achieved by the same modulator 3. The compensating voltage is preamplified with a U2-8 amplifier 14. The photo-emf is compensated for by the corresponding variable resistors of control 13 until the readings of voltmeter 9 attain their minimum values. A more precise compensation is achieved from the readings of meter 10 connected to the output of an SD-1 lock-in detector 11. Under compensation, the alternating-current potential at point "a" (with no regard for the noise) is zero, the current through resistor 8 is equal to I, and the readings of voltmeter 12 (U_c) correspond to the voltage at this resistor, i e., $I = U_c/r_c$. The direct-current circuit of the cell is closed by its load resistance 6 and induction coil 7. This circuit does not shunt the alternating-current circuit, because the induction resistance at the modulation frequency is much higher than r_i. The inductance and ohmic resistance of coil 7 are 0.25 H and 1 ohm, respectively. Therefore, this circuit does not lower the sensitivity of the device in the course of compensation. At the same time, by changing the resistance of resistor 6, one can vary in a wide range the direct-current component of the current through the cell from a level close to zero up to values corresponding to the short-circuit current. In particular, its value may be adjusted at a level that corresponds to the cell operation conditions.

To determine the spectral dependence $Q(\lambda)$ in arbitrary units, the intensity of light passing from the cinema lamp through a monochromator was calibrated with a bolometer built into the spectrometer. Calibration to absolute units was performed by means of laser 2 at $\lambda = 0.63$ and 1.15 μm. The values of Q corresponding to the laser illumination were determined by the formula:

$$Q = \frac{\sqrt{2}\pi U_c}{2Ar_cP_{=}(1-R)\lambda}, \quad (3)$$

where $P_{=}$ is the constant component of the laser radiation intensity after passing through the modulator as measured with an IMO-2N radiometer. The factor $\sqrt{2}$ was introduced to convert the voltmeter readings to the effective voltage. The factor $\pi/2$ accounts for the fact that U_c is determined only by the Fourier component of the signal (at the frequency of modulation), whereas the signal taken off the cell has the meander-like shape.

The setup provides reliable measurements of $I = 10^{-9}$ A, $Q = 10^{-3}$, and $\tau = 10^{-8}$ s. Further updating of the setup will enable one to increase its sensitivity and extend the range of measurement.

RESULTS AND DISCUSSION

The method proposed was applied to a batch of solar cells of the n^+–p–p^+ type made of the p-type single crystal silicon with a specific resistance of 1.5 ohm cm grown by the crucibleless zone melting. The cells were irradiated by a fluence of 1 MeV electrons ($\Phi \leqslant 10^{16}$ cm^{-2}). The surface area, the thickness of the n^+ layer and of the base were 4.8 cm^2, 0.5 μm, and 300 μm, respectively.

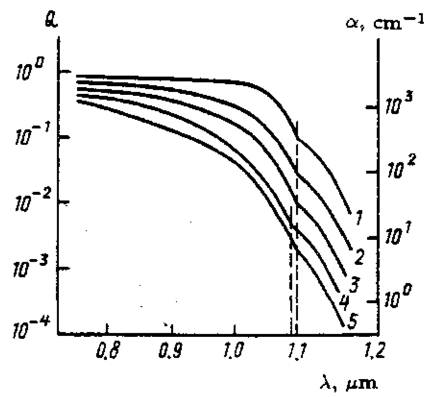

Fig. 2

The Q versus λ curves obtained upon illumination of solar cell only by the monochromatic light from the spectrometer are shown in Fig. 2 (curves 1–4). The numbers of the curves correspond to the cell numbers in Table 1. Curve 5 represents the experimentally measured α as a function of λ for silicon taken from [4, 5]. The $Q(\lambda)$ curves are in qualitative agreement with the reported data [6] and with the data calculated by formula (2). In the literature, however, this dependence can be found only down to $Q \gtrsim 10^{-2}$; our method makes it possible to reliably measure $Q \simeq 10^{-3}$. As is seen in Fig. 2, in the range of $\lambda > 1$ μm the $Q(\lambda)$ curve is much the same as the $\alpha(\lambda)$ curve, which indicates that the condition $\alpha L < 1$ (see formula (2)) for all the cells under study is fulfilled. With increasing irradiation dose, the monotonic decrease of Q is observed over the entire spectral range studied, especially in the long-wave region. The additional constant illumination exerted no influence on Q in the short-wave region, whereas in the long-wave region ($\lambda > 1$ μm) it resulted in only a slight increase of Q (several percent), which is in line with the data obtained by other workers (see, e.g., [7]). The ratio of the external quantum efficiencies obtained under simulated solar illumination (0.1 W/cm^2) to those obtained without it (η) as a function of λ is shown in Fig. 3. The curve numbers here are the same as in Fig. 2. It is worth noting that the η value is a nonmonotonic function of the electron fluence. Apparently, this is due to the operation of at least two mechanisms of recombination, whose influence on τ is different and depends on Φ. The experiments also showed that Q is independent of the cell direct-current load when it was varied within the range 1–10^4 ohms. This fact together with a weak dependence of Q on the intensity of simulated solar illumination indicate that the dependence of τ on the injection level for the cells under study is insignificant.

Table 1

No.	Φ, cm^{-2}	L, cm	τ, s
1	0	1.9×10^{-2}	1.5×10^{-5}
2	10^{14}	4.1×10^{-3}	6.7×10^{-7}
3	8.9×10^{14}	1.7×10^{-3}	1.2×10^{-7}
4	9.5×10^{15}	5.7×10^{-4}	1.3×10^{-8}

The values of L were determined at $\lambda = 1.04$ μm by the formula:

$$Q = \frac{\alpha L}{\alpha^2 L^2 - 1}\left[\alpha L - \frac{\alpha L \exp\{-\alpha d\}}{\cosh(d/L)} - \tanh\left(\frac{d}{L}\right)\right], \tag{4}$$

where d is the base thickness. This formula is applicable when the following processes can be neglected: (i) the absorption of light in the n^+th layer; (ii) the reflection of light from the rear side of the cell; (iii) the recombination of minority charge carriers at the rear side; and (iv) the effects of the electric field in the base. The first condition is satisfied because $\alpha W \ll 1$, where W is the thickness of the n^+th layer. This condition is also satisfied in the range of shorter wavelengths (at $\lambda = 0.95$–1.0 μm), although in this case the accuracy of the L determination is much lower due to a weaker dependence of Q upon λ. The second condition is fulfilled because $\alpha d > 1$ ($\alpha d = 1.3$) at $\lambda = 1.04$ μm. The third and fourth conditions are satisfied because of the presence of the p^+th layer and the low base resistance, respectively. At low τ ($L \ll d$), formula (4) transforms into (2). The values of τ were calculated from the obtained values of L, making use of the value of $D = 25$ cm^2/s [8]. The data obtained are summarized in Table 1.

Normally the $L(\Phi)$ dependence is given by the formula $L^{-2} = L_0^{-2} + K\Phi$, where $L_0 = L$ at $\Phi = 0$ and K is the damage coefficient [6]. From the data of Table 1 we found the dependence of L^{-2} versus Φ for the cells under study, from which we determined that $K = 3 \times 10^{-10}$. This value somewhat differs from the K values (1.3×10^{-10}–2.4×10^{-10}) obtained previously [6] for similarly irradiated samples that were prepared from the silicon grown by the Czochralski method.

The high accuracy of the method enabled us not only to extend the range of $Q(\lambda)$ measurements but also to observe some more subtle effects. As is seen in Fig. 2, the $\alpha(\lambda)$ curve exhibits an inflection at $\lambda = 1.1$ μm. This inflection is associated with the fact that with decreasing λ, a change-over takes place from the absorption of light to the emission of the LA-phonons [4, 5]. The $Q(\lambda)$ curves 1, 2, and 3 show an inflection at the same λ. Since at $\lambda > 1$ μm $Q \simeq \alpha L$, it is clear that the origin of these inflections in the $Q(\lambda)$ and $\alpha(\lambda)$ curves is the same. There is also an inflection on curve 4, but it is shifted to the short-wave region by 0.014 μm (about 15 meV). The edge of the intrinsic absorption in silicon is known to be shifted toward higher λ, due to the exciton-phonon interaction, by 14.7 meV, which is equal to the exciton energy.

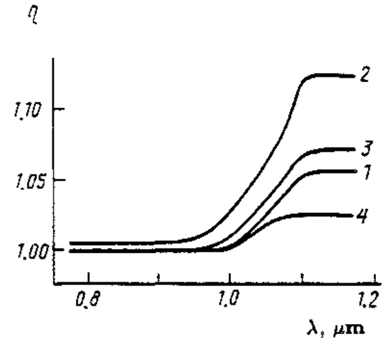

Fig. 3

Apparently, the peculiar feature of the inflection position for cell 4 (Table 1) may be related to the fact that the irradiation of silicon by electrons at $\Phi \simeq 10^{16}\,\mathrm{cm}^{-2}$ introduces defects that substantially weaken the exciton-phonon interaction.

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31 August 1992

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