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The Dynamic Ultrasound Influence on the Diffusion and Drift of the Charge Carriers in Silion *p-n* Structures

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ABSTRACT

Study of the current-voltage (I-V) characteristics of silicon solar cells, treated by MHz ultrasound with intensity up to 3 W/cm^2 have been carried out. It is revealed that under such non-equilibrium conditions, the minority carriers' diffusion process changes, which leads to the increase of the photocurrent (up to 15 %). An acoustostimulated reduction (down to 40 %) of the saturation current of the p-n junction is also observed. It is determined, that the observed changes depend nonlinearly on ultrasound power density, and the efficiency of the ultrasound influence increases with the vibration frequency. We consider that the ultrasound induced effects are connected with nonequilibrium processes of ionization and reorientation of structural defects in the acoustic field.

INTRODUCTION

Recent time much attention is paid to the study of ultrasound influence on the defect structure and electrophysical properties of semiconductor structures [1-8]. In particular, it is revealed, that the broadering of a solar cell (SC) spectral sensitivity range [2], low-temperature annealing of radiating defects [3-5] and passivation of grain boundary defects [6] can be realized by the intensification of the defects diffusion and restructuring in a ultrasound field. At the same time processes which occur in material under the acousto-induced nonequilibrium conditions are not clear till now and attract enhanced interest of researchers [7, 8]. For instance, investigation of changes of the characteristics of semiconductor devices, caused by the ultrasound treatment, may create preconditions for development of a new class of devices dynamically controlled by an "active" sound. In this paper, results of investigation of the influence of dynamic (*in situ*) ultrasound on the charge transfer in silicon solar cells are presented.

EXPERIMENT DETAILS

The measured SC consists of a 300-μm-thick p-type silicon substrate (doped with boron; $p=1.3\cdot10^{15}$ cm^{-3}); and a 0.5-μm-thick Si layer of electron conductivity (thickness $d_n = 0.5$ μm, $n=10^{19}$ cm^{-3}) was formed on its surface by implantation of P ions.

Longitudinal ultrasound waves have been excited by means of $LiNbO_3$ piezoelectric transducers. The excitation frequency f_{US} was assigned by two resonant modes of the transducers — 4 MHz and 13.6 MHz. Intensity W_{US} of the excited US (up to 3 W/cm^2) depends on amplitude of RF voltage (U_{RF}), applied to transducer. A soundwaveguide, which includes metallic (served for piezoelectric field shielding) and dielectric interlayers, was placed between the transducer and the semiconductor structure. Scheme of the sample arrangement is shown in Figure 1.

I-V characteristics of the solar cells were measured both in darkness and under monochromatic illumination of the n-region. In the latter case, the light wavelength was 900 nm or 600 nm. These wavelengths were chosen for the following reasons. Absorption of the 900-nm light, and correspondingly generation of the nonequilibrium charge carriers, occurs predominantly inside the p-region (for this wavelength, $\alpha^{-1} = 25$ μm, with α being the absorption coefficient; and this value is much longer than both the n layer thickness and the p-n junction thickness $d_{pn} \approx 0.9$ μm). For the second wavelength, inverse absorption coefficient $\alpha^{-1} \approx 2$ μm and, consequently, the nonequilibrium charge carriers are generated in the vicinity of the p-n junction. From I-V characteristics measured under illumination SC parameters have been received, including short current I_{SC} and open-circuit voltage V_{OC}.

A main task was to separate the elastic vibrations′ influence on SC parameters from the heating effects occurring inside a sample, loaded by ultrasound. To complete this task, measurements of temperature dependences of the investigated parameters were carried out. It was established, that V_{OC} value does decrease linearly beginning from the room temperature up to 350 K (the coefficient of relative variations equals to $E_{V900} = -1.22$ %·K^{-1} for $\lambda = 900$ nm and $E_{V600} = -2.52$ %·K^{-1} for $\lambda = 600$ nm); I_{SC} increases linearly for $\lambda = 900$ nm ($E_{I900} = 0.52$ %·K^{-1}) and remains approximately constant for $\lambda = 600$ nm in the same temperature range. We monitored the temperature of a solar cell during ultrasound action and this allowed to calculate, basing on the measured data, values of the parameters expected for an ultrasound-free heating. The difference between values, measured for ultrasound-loaded solar cell and those calculated for a certain temperature, was considered as the acoustostimulated variation. An example of such dependences are shown in Figure 2.

EXPERIMENTAL RESULTS AND DISCUSSION

The initial I_{SC} and V_{OC} values at room temperature were equal, respectively, 225 μA and 210 mV for $\lambda = 900$ nm, and 25 μA and 45 mV for $\lambda = 600$ nm. Under the ultrasound loading

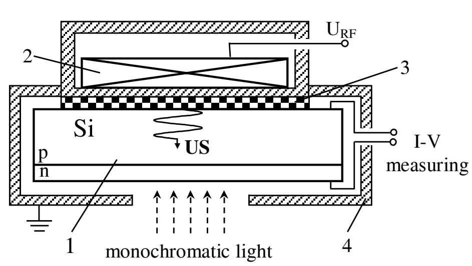

Figure 1. The scheme of experimental cell: 1 – solar cell; 2 – piezoelectric transducer, 3 – dielectric layer, 4 – electric shield.

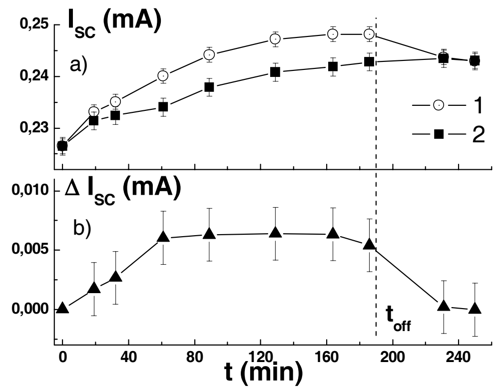

Figure 2. Dependence of I_{SC} versus duration of the ultrasound treatment under f_{US} = 4 MHz and W_{US} = 1.5 W/cm^2 (λ = 900 nm) (a): curve 1 shows measured values, curve 2 shows data calculated from the temperature dependence, and (b) – difference between these values. The ultrasound loading lasted from $t = 0$ to $t = t_{off}$

these parameters increase, showing nonlinear dependence on W_{US}. The dependences for the relative variations are shown in Figure 3. From the data presented it is seen that: i) ultrasound of higher frequencies influences more effectively; ii) influence of the same ultrasound on the short-current value is more profound for 900-nm illumination (curves 1 and 2 in Figure 3(a) are above the curves 3 and 4, accordingly), while the ultrasound influence on V_{OC} is more essential for the carriers generation in the vicinity of *p-n* junction (Figure 3(b)).

Current I_{SC} is connected with the photogenerated carriers passed up to the p-n junction. For a light, absorbed in the p-region's bulk, one can write:

$$I_{SC} = \frac{W_{ph}\,(1-R)\,e\beta S_F\lambda}{hc}\frac{\alpha L_n}{1+\alpha L_n}, \tag{1}$$

where W_{ph} is an intensity of the illumination light, R — reflection coefficient, β — quantum

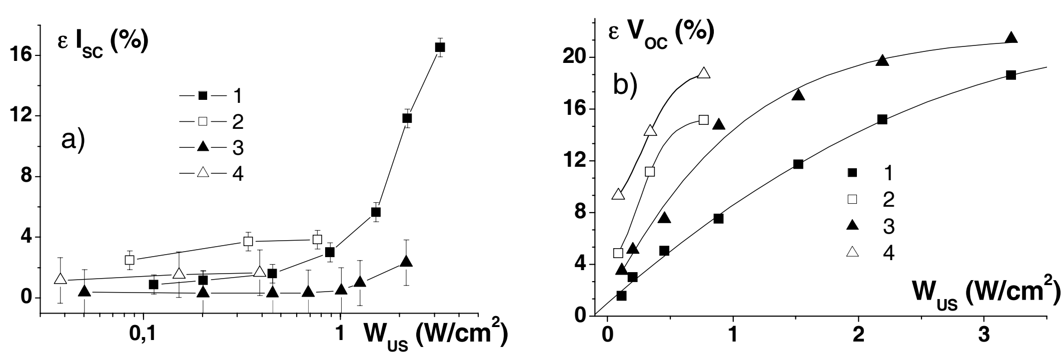

Figure 3. Dependences of relative acoustostimulated variations I_{SC} (a) and V_{OC} (b) on applied ultrasound intensity W_{US}. The different curves correspond to the different ultrasound frequencies and illumination wavelengths: 1 – λ = 900 nm, f_{US} = 4 MHz; 2 – λ = 900 nm, f_{US} = 13.6 MHz; 3 – λ = 600 nm, f_{US} = 4 MHz; 4 – λ = 600 nm , f_{US} = 13.6 MHz

efficiency coefficient, S_F — light-absorbing area, L_n — diffusion length of electrons in the p-region. Reduction of the reflection coefficient of the silicon surface due to the acoustostimulated diffusion of phosphorus into the semiconductor's depth was observed in [2]. Phenomenon of dynamic growth of L_n induced by the ultrasound field was observed in work [9], this phenomenon being connected with reorientation of the complexes of defects, which include boron atoms, and with corresponding decrease of the carriers capture cross-section. In our opinion these phenomena are responsible for the observed I_{SC} increase under the acoustic loading. In particular, the increasing of the L_n is preferred and a similarity of the specific features of the acoustostimulated increments of L_n in [9] and I_{SC} in given study are an evidence of this, namely presence of the US intensity threshold (see Figure 3(a)) and the characteristic time of the process – tens of minutes (see Figure 2). Besides, for λ = 600 nm, the expression for I_{SC} should undergone a little modification:

$$I_{SC} = \frac{W_{ph}\,(1-R)\,e\,\beta S_F \lambda}{hc}\left[\frac{1-\exp(-\alpha d_n)}{1+sd_n/D_p} + \left[1-\exp(-\alpha d_{pn})\right]\exp(-\alpha d_n) + \frac{\alpha L_n}{1+\alpha L_n}\exp\left(-\alpha\left(d_n + d_{pn}\right)\right)\right] \quad (2)$$

where s is surface recombination rate, and D_p — holes' diffusion coefficient inside the n region. Our measurements have shown that $L_n \approx 120$ μm for the investigated solar cells, hence, for 600-nm illumination $L_n\alpha >> 1$ and I_{SC} does not practically depend on L_n. In our opinion, this fact explains the smaller increase of the acousto-induced I_{SC} for the shorter wave illumination (see Figure 3(a)): in this case, only the effect of a quite small reduction of R the occurs.

The estimations made in Equation 1 have shown that, for λ = 900 nm a 10-percent increase of I_{SC} can be achieved by increasing the L_n value from 120 μm to 260 μm (more than twice).

The measured forward-biased I–V curves were approximated according [10]:

$$I(V,T) = I_0\left[\exp\left(eV/E_T\right)-1\right] + V/R_{SH} - I_{SC}, \quad (3)$$

where I_0 – saturation current, E_T – characteristic energy, R_{SH} – shunt resistance; the last item is absent for the dark I-V characteristics. The experiments have shown that temperature dependence of I_0 could be properly fitted (see Figure 4(a)) by formula:

$$I_{0T} = I_{00}\exp\left(\chi T\right). \quad (4)$$

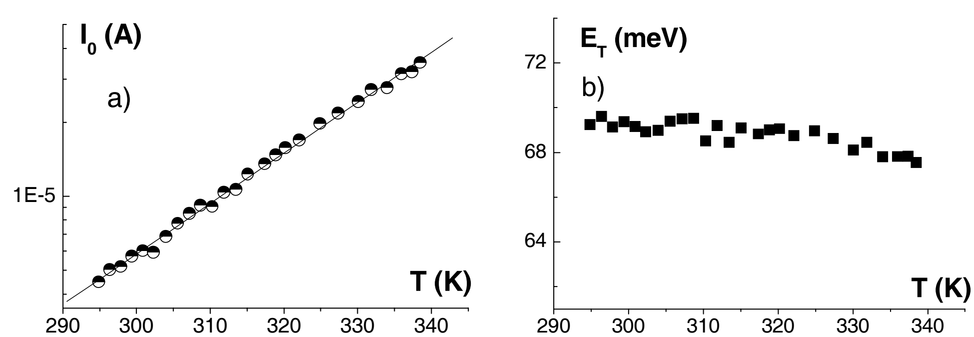

Figure 4. Temperature dependence of the saturation current (a) and the characteristic energy (b).

At the same time, E_T practically remains constant (see Figure 4(b)). These facts allows to conclude that the prevailing drift mechanism in the measured solar cells is the charge carriers' tunneling through the energy barrier [10]. In work [11] it is suggested that such tunneling may occur due to the charge carriers' transition through a chain of deep levels formed by structural defects in the space charge region. In this case, the Equation 3 describes I-V curves with E_T depending on the defects' type. If the defects, which form such levels, are dislocations, then, according to [11]

$$I_{00} = e\rho\nu_D \exp(-E_G/E_T) \quad , \tag{5}$$

where ρ is the dislocations density, ν_D – the Debye frequency, E_G – the energy gap.

It was revealed experimentally that, under the US excitation of a solar cell I_0 decreases (see Figure 5), R_{SH} increases (up to 20 % for maximal W_{US}), and E_T does not vary practically ($E_T = (0.070 \pm 0.003)\,\mathrm{eV}$). Within the above-mentioned model, reduction of I_0 is an evidence of the ionization of defects' levels in the acoustic field, and this process is more effective for a higher frequency (see Figure 5).

Also, measurement of the temperature dependences of I-V characteristics had been carried out under the ultrasound action. Basing on these experimental data and the equations 3-5, density of the solar cell dislocations was calculated. The obtained results are listed in Table I. In our opinion, the results testify not the reduction of quantity of the linear defects, but rather a reduction of the effective number of dislocations participating in the charge transfer and nonionized by the ultrasound loading. An evidence of this is the fact that the value of ρ returns to its initial meaning after cancellation of the ultrasound.

Using Equation 1, one can write for V_{OC}

$$V_{OC} = (E_T/e)\ln[I_{SC}/I_0 - V_{OC}/(I_0 R_{SH}) + 1] \tag{6}$$

Therefore, the V_{OC} variation can be caused by both the acoustostimulated reorientation of the defect complexes in the p-region bulk, and the defects' ionization in the vicinity of the p-n junction (in Equation 6, both dependences — on I_0 and on I_{SC} — are present). However, absolute value of the reduction of I_0 (up to 40 %) is larger than the value of I_{SC} increase (up to 15 %) – see Figures 5 and 3(a), hence, the second process is more essential. This fact explains the observed

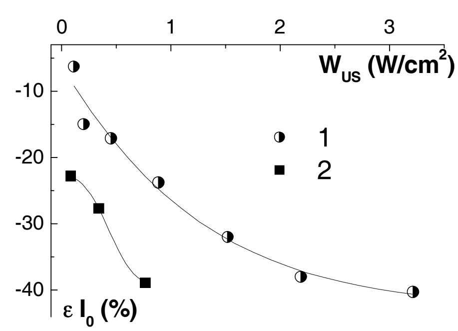

Figure 5. Dependences of the relative acoustostimulated variations of the solar cells' saturation current on the applied ultrasound intensity: 1 – f_{US} = 4 MHz; 2 – f_{US} = 13.6 MHz

higher variations of V_{OC} when the charge carriers are generated near the p-n junction in contrast to the in-bulk generation — in Figure 3(b) curves 3 and 4 pass above the curves 1 and 2, respectively.

Table I. Parameters of the solar cells calculated from experimental data.

	Before US loading	During US loading	
		f_{US}=4 MHz, W_{US}=2.2 W/cm^2	f_{US}=13 MHz, W_{US}=0.8 W/cm^2
I_{00}, $\times 10^{-12}$ A	4.0	1.4	2.2
ρ, cm^{-2}	60	20	35

CONCLUSIONS

Thus, through experimental investigation, this work establishes the fact of dynamic *(in situ)* influence of ultrasound waves on the processes of charge transfer in the silicon solar cells. It has been revealed that the efficiency of acousto-induced influence increases with ultrasound frequency heightening. Peculiarities of the effects under observation could be explained through acoustic ionization of the defects' levels in the vicinity of the p-n junction as well as reorientation of impurity pairs inside the diode base depth.

The results of the research could be considered as a basic application for the development of the method of semiconductor devices structure modification by means of acousto-induced influence.

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