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Ultrasonic Treatment Restores the Photoelectric Parameters of Silicon Solar Cells Degraded under the Action of ^{60}Co Gamma Radiation

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Abstract—The photoelectric parameters of silicon solar cells degraded under the action of ^{60}Co gamma-radiation can be partly restored using an ultrasonic treatment (UST). The growth of the maximum output power of solar cells after the UST is related to a redistribution of the radiation defects and an increase in the homogeneity of a semiconductor crystal structure.

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As is known, the irradiation of semiconductor devices by high-energy charged particles leads to the accumulation of radiation defects in the semiconductor bulk and frequently results in a significant deterioration of the electrical characteristics of devices, in particular, photovoltaic cells [1, 2]. Using the subsequent controlled action upon the defect structure in the *p–n* junction and base region of a given semiconductor device, it is possible to produce the necessary correction of the device characteristics. One traditional method of such correction is thermal annealing, but athermal treatments have also received much attention in recent years. Taking into account the results of numerous investigations devoted to the use of acoustic methods for the improvement of properties of semiconductor materials [3–6], it is reasonable to expect that ultrasound treatments (USTs) can also be effective in restoring the characteristics of devices.

This Letter presents data on the use of USTs for restoring the initial properties of silicon-based solar cells deteriorated as a result of gamma-irradiation.

The solar cells were fabricated using phosphorus diffusion into a *p*-type silicon single crystal wafer with an initial hole density of $N_a \sim 1 \times 10^{16}$ cm^{-3}. The subsurface diffusion-doped *n*-type ($N_d \sim 10^{20}$ cm^{-3}) layer thickness was $d_n = 0.3$ μm, and the *p*-type base thickness was $d_p = 280$ μm [7]. The working surface areas of solar cells were about 1 cm^2.

The solar cells were irradiated with gamma-quanta from a ^{60}Co source to a total dose of ~10^6 rad. Then, the samples were sequentially subjected to a two-stage UST using longitudinal acoustic waves, which were introduced into the plate from the rear side and propagated perpendicular to the working surface. In the first stage (UST-1), the treatment was performed in the following regime: frequency, f_{UST} = 9 MHz; intensity, W_{UST} = 0.5 W/cm^2; duration, t ~ 120 min. In the second stage (UST-2), the regime was as follows: f_{UST} = 27 MHz; W_{UST} = 1 W/cm^2; t ~ 200 min.

Prior to and after each stage of the UST, the samples were characterized by measuring the current–voltage (*I–U*) characteristics in a broad temperature range (100–350 K) and the capacitance–voltage (*C–U*) characteristics. The results of capacitance measurements were used to determine the minority carrier lifetime (τ_n) and the effective concentration of ionized centers (N_{ef}) [8]. The parameters of solar cells before and after gamma-irradiation and each stage of the UST are presented in the table.

Figure 1 shows the typical *I–U* curves of solar cells. As can be seen, the gamma- irradiation leads to deterioration of the initial characteristic, which is manifested by a decrease in the forward (direct) current I_{dir} (Fig. 1, curve *2*') and by a substantial (several orders of magnitude) increase in the reverse current I_{rev} (curve *2*). The subsequent acoustic treatments (UST-1 and especially UST-2) improved the *I–U* characteristics (curves *3* and *4*) and shifted them toward the initial curves.

Figure 2 shows the effect of gamma-irradiation and each UST stage on the photoelectric parameters of solar cells. As can be seen from these data, the irradiation decreases the open-circuit voltage (U_{oc}), the short-cir-

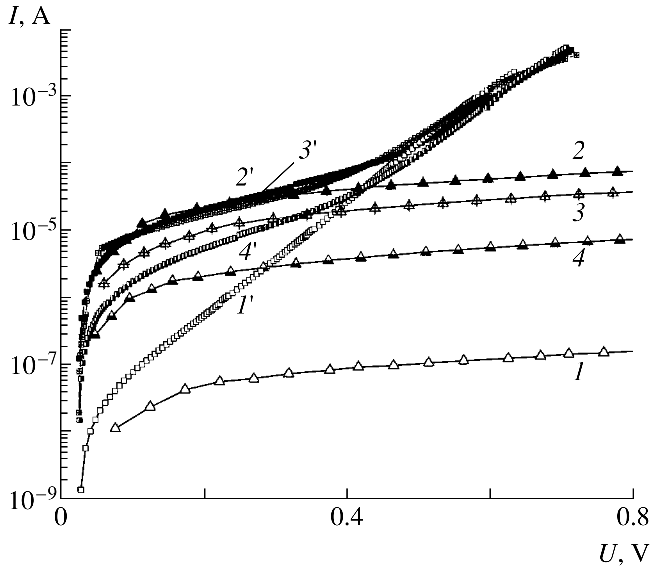

Fig. 1. Current–voltage characteristics of a silicon solar cell measured (*1*, *1*') in the initial (unirradiated) state, (*2*, *2*') upon gamma-irradiation to a dose of 10^6 rad, and after (*3*, *3*') UST-1 and (*4*, *4*') UST-2: (*1–4*) reverse branch; (*1*'–*4*') direct branch (T = 200 K).

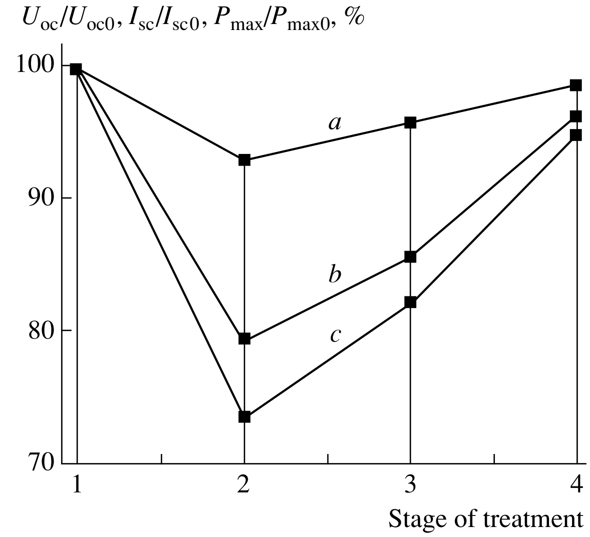

Fig. 2. Variation of the relative values of (*a*) open-circuit voltage U_{oc}/U_{oc0}, (*b*) short -circuit current I_{sc}/I_{sc0}, and (*c*) maximum output power P_{max}/P_{max0} measured at room temperature for a silicon solar cell in various states: (1) initial (unirradiated) state; (2) upon gamma-irradiation to a dose of 10^6 rad; (3, 4) after UST-1 and UST-2, respectively.

cuit current (I_{sc}), and the maximum output power (P_{max}), whereas the subsequent USTs restore these parameters, which become substantially closer to the initial values. It should be noted that the effect of UST on the parameters of initial (unirradiated) solar cells is much less dependent on the regime and is mostly determined by the acoustic-wave-induced relaxation of internal mechanical stresses [5].

The photocurrent was determined as [8]

$$I_{ph} = qSN_{ph}Q, \tag{1}$$

where q is the electron charge, SN_{ph} is the total number of electron–hole pairs photogenerated on the working area S, and Q is the charge collection coefficient. Since the SN_{ph} value remains virtually constant under the given experimental conditions, a drop in the photocurrent is evidently related to a decrease in the Q value. If the diffusion length of minority carriers in the base is much smaller than the base thickness, $L_n \ll d_p$, the Q value can be determined as [9]

$$Q = \frac{\alpha L_n}{\alpha L_n + 1}, \tag{2}$$

where α is the optical absorption coefficient, $L_n = \sqrt{D_n \tau_n}$, and D_n is the electron diffusion coefficient.

It should be recalled that, according to [8], the open-circuit voltage can be calculated using the following formula:

$$U_{oc} \approx \frac{AkT}{q} \ln \frac{I_{sc}}{I_0}, \tag{3}$$

where k is the Boltzmann constant, T is the absolute temperature, A is the dimensionless coefficient characterizing the rate of recombination in the space charge region, and I_0 is the reverse saturation current through

Calculated values of the room-temperature characteristics of silicon solar cells

State	N_{ef}, cm^{-3}	A	I_0, μA	L_n, μm	τ_n, μs
Before irradiation	2.17×10^{16}	2.58	88.2	51.0	0.78
After γ-irradiation	3.14×10^{16}	2.85	287.0	44.9	0.60
After UST-1	2.92×10^{16}	2.78	276.0	48.5	0.70
After UST-2	2.48×10^{16}	2.67	135.0	49.6	0.73

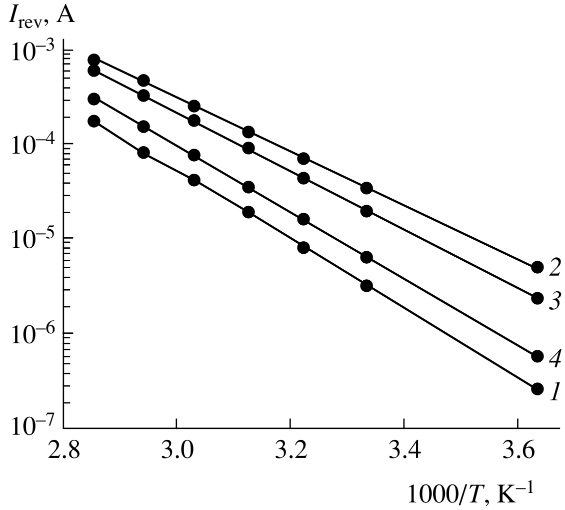

Fig. 3. Temperature dependences of the reverse current I_{rev} measured at U_{rev} = 0.4 V in a silicon solar cell in various states: (*1*) initial (unirradiated) state; (*2*) upon gamma-irradiation to a dose of 10^6 rad; (*3*, *4*) after UST-1 and UST-2, respectively.

the *p–n* junction. Our estimates show that gamma-irradiation does not lead to significant changes in the *A* value (see table). The open-circuit voltage must also be not significantly influenced by variations in the I_{sc} and I_0 values, which enter into Eq. (3) under the logarithm sign.

As is known [10], the current due to thermogenerated carriers is directly proportional to the concentration of generation–recombination centers. Then, an increase or decrease in the I_{rev} value at a virtually constant slope of the *I–U* curve after various treatments is evidence of the proportional increase or decrease in the concentration of these centers, whereas a change in slope of the *I–V* curves with the I_{rev} value after the corresponding treatment is indicative of changes both in the concentration of generation–recombination centers and in the mechanism of current transfer. This conclusion is confirmed by the temperature dependences of I_{rev} measured at U_{rev} = 0.4 V (Fig. 3).

Let us consider possible mechanisms responsible for the observed behavior. The radiation defects produced in solar cells by the gamma-quanta from ^{60}Co interact with the existing defects. This interaction can lead to the formation of additional electrically and optically active centers in the *p–n* junction and base regions, which play the role of new generation–recombination centers and lead to a decrease in τ_n and, hence, in the Q and I_{ph} values (which depend on τ_n). The thickness of illuminated diffusion-doped layer in our samples was significantly smaller than the diffusion length of minority carriers ($d_n \ll L_p$). Therefore, according to Eq. (2), the irradiation-induced decrease in L_p in this *n*-type layer does not influence Q and I_{ph}. On the other hand, the base thickness is much greater than the diffusion length of minority carriers ($d_p \gg L_n$) and, hence, the variations of L_n (see table) must significantly influence Q and I_{ph}. Thus, the introduction of radiation defects into the semiconductor structure has a much stronger influence on τ_n and L_n than on L_p and, accordingly, Q varies predominantly due to a change in L_n [11].

We believe that the mechanism described above is responsible for the main changes in the photoelectric parameters of solar cells observed upon the irradiation with gamma-quanta from ^{60}Co. The UST is accompanied by the diffusion of radiation defects predominantly in depth of the base [6], which leads to the restoration of τ_n and L_n. The withdrawal of mobile radiation defects from the *p–n* junction is confirmed by the results of capacitance measurements, which were used to determine N_{ef}. As can be seen from the table, the gamma-irradiation increases while the subsequent UST decreases the effective concentration of ionized centers in the *p*-type region. Note that the dependence of I_{rev} on the reverse bias voltage U_{rev} (for U_{rev} > 0.1 V) in both the initial and treated solar cells obeys the relation $I_{rev} \sim \sqrt{U_{rev}}$, which is indicative of the primarily thermogeneration nature of the reverse current. In the initial state, the activation energy of current transfer determined from the slope of the temperature dependence of I_{rev} (Fig. 3, curve *1*) is ~0.71 eV, which is evidence for both diffusion and generation mechanisms of current transfer. The slope of the I_{rev} versus $1/T$ plot upon gamma-irradiation (curve *2)* decreases and the activation energy drops to ~0.55 eV (i.e., to about $E_g/2$, where E_g is the bandgap width of silicon), which is characteristic of the thermogeneration current. After the UST-1 and especially UST-2, the slope of the temperature dependence of I_{rev} increases (curves *3* and *4*) and the activation energy reaches ~0.69 eV. This is indicative of the appearance of a diffusion component in the current transfer and a decrease in the concentration of generation–recombination centers in the *p–n* junction region.

Therefore, in contrast to the thermal energy that is uniformly absorbed over the entire semiconductor volume, the acoustic wave energy is absorbed predominantly by the crystal lattice defects and favors their redistribution toward the equilibrium state [3, 5, 6]. Since the irradiation with gamma-quanta mostly creates mobile radiation defects in solar cells, the UST acts predominantly upon these defects and favors their redistribution (acoustic annealing) [12]. Thus, the results of this study demonstrate that the UST partly restores the semiconductor crystal structure of solar cells damaged as a result of gamma-irradiation.

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