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Study of the Light-Induced Degradation of Tandem α -Si:H/ μ c-Si:H Photovoltaic Converters

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Abstract—The photo-induced degradation of tandem α -Si:H/ μ c-Si:H photovoltaic converters with an initial efficiency of 10.4% under light flux densities of 1 and 10 kW m⁻² (AM1.5G) is studied. It is shown that the stabilized state is reached after 500 h of exposure to the standard light-flux density and after 300 min at a flux 10 times higher in density. In both cases, the efficiency decreases by 1.2–1.4 abs. %. The experimentally measured spectral and current–voltage characteristics of the photovoltaic converters are used to determine the nonequilibrium carrier lifetimes and to calculate variation dependences of the dangling-bond concentration in i - α -Si:H and i - μ c-Si:H layers. The dependences are approximated in terms of the floating-bond model. The calculated dangling-bond concentrations after various exposure times are used to simulate the dependences of the photovoltaic-converter parameters on light exposure. The results obtained show good coincidence between the simulated degradation rates of the current and efficiency of a tandem photovoltaic cell and the experimental data.

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1. INTRODUCTION

Solar cells based on thin films of amorphous and microcrystalline hydrogenated silicon have been increasingly widely used in recent years [1]. The record efficiencies are 10.1% for single-junction α -Si:H photovoltaic (PV) converters and 12.3 and 12.4% for tandem double-junction α -Si:H/ μ c-Si:H and three-junction α -Si:H/ μ c-Si:H/ μ c-Si:H devices, respectively [2]. Despite the fact that the efficiency of PV converters based on crystalline silicon and III–V compounds is 3–4 times higher [2, 3], thin-film PV converters, specifically, yield the lowest cost of a kilowatt of output electric power [4]. This is primarily due to the low production cost of PV converters of this kind, provided by the comparatively simple technology and small expense of semiconductor materials.

A characteristic feature of thin-film PV converters with amorphous layers is a gradual decrease in their photoelectric parameters under the action of solar light, so-called photoinduced (light-induced) degradation [5]. This process is closely associated with the phenomenon of a decrease in the photoconductivity of α -Si:H films under prolonged illumination, known as the Staebler–Wronski effect [6]. The typical decrease in the efficiency of PV converters based on

amorphous and microcrystalline silicon as a result of light-induced degradation is 10 to 30%, depending on the number of subcells and the thicknesses and chemical compositions of the photoactive layers [7–10]. Theoretical and experimental analyses of the light-induced degradation of PV converters make it possible to determine the main mechanisms governing the loss in efficiency of α -Si:H/ μ c-Si:H PV converters and to optimize the structure of photovoltaic converters to improve the stability of their characteristics.

In this study, we experimentally and theoretically analyzed the photoinduced degradation of PV converters based on an α -Si:H/ μ c-Si:H tandem structure with two photoactive p – n junctions and an initial efficiency of 10.4%. The PV converters studied were fabricated by a technique developed by Oerlikon Solar Ltd (Switzerland).

2. LIGHT TESTS OF EXPERIMENTAL PHOTOVOLTAIC CONVERTER SAMPLES

Structures for the experimental photovoltaic converters (PVCs) were fabricated on a full-size (1300 × 1100 mm) glass substrate by plasma-enhanced chemical vapor deposition. The structure is shown schematically in Fig. 1.

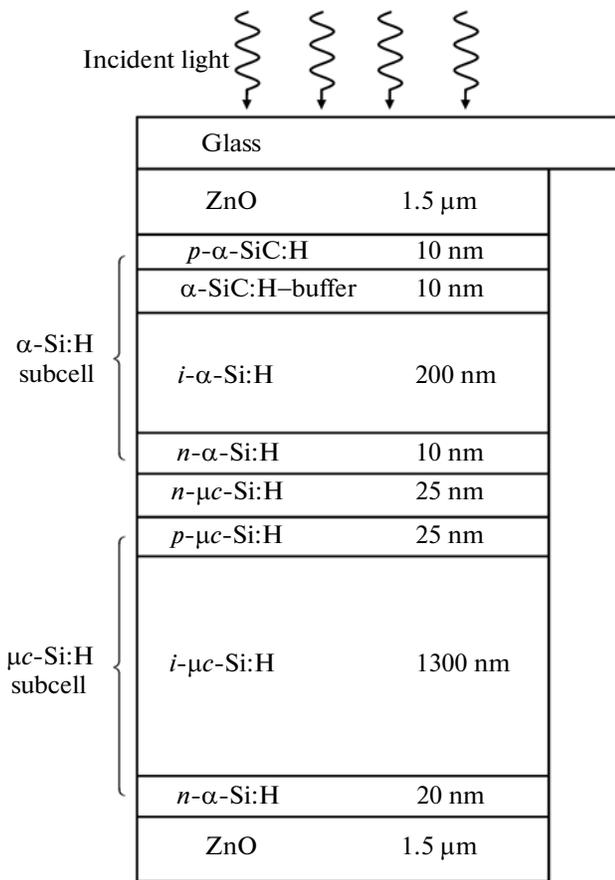


Fig. 1. Structure of the α -Si:H/ μ c-Si:H PV converters under study.

To study the light-induced degradation of the structures, 100×100 mm test PVC samples were fabricated. A 60×66 mm photoactive part with an open surface area of 37.95 cm^2 was produced in the samples by laser scribing in the form of 10 series-connected cells with equal photosensitive areas. The contacts of the test sample were formed via the adhesion of contact pads with a silver-containing paste. Then, the side with the contacts was covered with a laminate ethylene vinyl acetate film and the test sample was thermally treated at a temperature of 150°C for 15–30 min to polymerize the film.

The main reason for the degradation of PV converters based on amorphous and microcrystalline hydrogenated silicon upon prolonged exposure to light is that a number of unsaturated bonds, which are additional nonradiative-recombination centers, grow in the layers composed of these materials [11, 12]. The experimental dependence of the number of photoinduced-recombination centers on the number G of photons incident on a photovoltaic converter in unit time and on the duration t of exposure to saturation can be expressed by the formula [13]:

$$N_r(t) \propto G^{2/3} t^{1/3}. \quad (1)$$

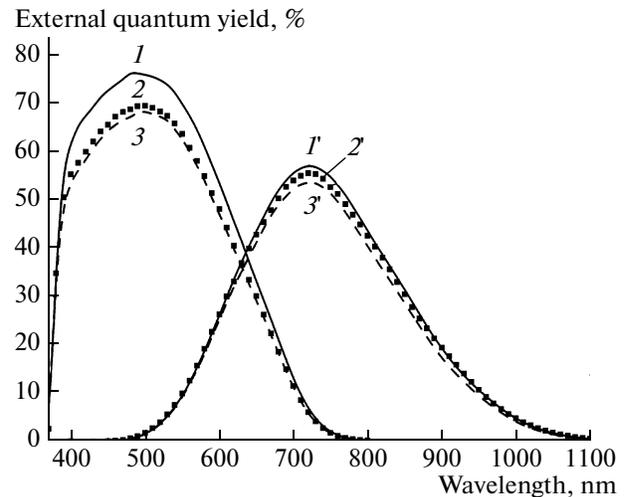


Fig. 2. Spectral characteristics of (1–3) α -Si:H and (1'–3') μ c-Si:H subcells of the α -Si:H/ μ c-Si:H tandem PV converters under study: (1, 1') before exposure, (2, 2') after 1000 h of light exposure under the conditions of 1 sun, and (3, 3') after 19 h of light exposure under the conditions of 10 suns.

It can be seen from expression (1) that the growth rate of the number of photoinduced-recombination centers is proportional to the squared illumination intensity, i.e., under exposure to light with an equivalent intensity of 10 suns; the time required for stabilization of the photoelectric parameters of a PV converter becomes 100 times shorter.

To study photoinduced degradation, we chose α -Si:H/ μ c-Si:H test samples with initially close characteristics, one of which was exposed to light with a standard flux density of 1 kW m^{-2} (1 sun), and the second, to that with an increased intensity of 10 kW m^{-2} (10 suns).

For tests under 1-sun conditions, we designed and assembled a special test bench based on a 250 W Philips 13163/5H halogen lamp with a service life of 500 h. Tests at 10 suns were made with an IS-160 sunlight simulator. The total exposure duration was 1000 and 19 h (equivalent to 1900 h) at 1 and 10 suns, respectively. Before and after the tests, we measured the spectral characteristics of the test samples (Fig. 2). The current–voltage (I – V) characteristics of the test PV samples were recorded at regular time intervals during the course of their photoinduced degradation. The photoelectric parameters determined in these measurements (short-circuit current I_{sc} , open-circuit voltage V_{oc} , fill factor FF of the I – V characteristic, and efficiency) are represented by symbols in Fig. 3.

The rate of photoinduced degradation of the I – V characteristic parameters of the second sample (illumination intensity if 10 suns) was monitored directly during the course of the tests via measuring facilities of the laboratory installation based on the IS-160 sunlight simulator. The illumination intensity was

reduced to 1 sun by moving the sample farther from the light source. The I - V characteristics of the first sample and those of the second sample before illumination and upon exposure for 10, 14.5, and 19 h were measured on a SS-80AA fixed-light sun simulator (AM1.5G, 1000 W m^{-2} , simulator class AAA by IEC 60904-9).

3. MODEL FOR THE DESCRIPTION OF PHOTOINDUCED DEGRADATION

At present, there exist a considerable number of models developed for understanding the photoinduced degradation in PV converters based on amorphous hydrogenated silicon. Nevertheless, no commonly accepted theory of this phenomenon has been formulated so far. Among the best known approaches, the following should be noted.

- (i) Impurity model [14, 15].
- (ii) Model of charge-state variation [16, 17].
- (iii) Model of broken weak bonds between silicon atoms [13].
- (iv) Hydrogen collision (“H-collision”) model [18–20].
- (v) “Floating-bond” model [21–24].

These models were briefly reviewed in [25]. The first two proved inadequate to the experimental results, and in the third, there are a number of insurmountable difficulties indicative of its incompleteness. Therefore, the last two models or variations of these are the most widely used at present. In particular, the “H-collision” model was employed in [26] to describe the dependence of the open-circuit voltage of an α -Si:H solar cell on the light-exposure time.

It should be noted that the “H-collision” model assumes that isolated Si–H states are dominant over Si–H–H–Si, which contradicts the experiment [27] and gives no way of explaining the correlation between the processes of the annealing of floating bonds of silicon and germanium in their amorphous alloys [28]. For this reason, we decided to base our theoretical constructions in this study on the “floating-bond” model.

3.1. Determination of the Dangling-Bond Concentration in the Layers of α -Si:H/ μ c-Si:H PV converters

For simulation analysis of photoinduced degradation, it is necessary to determine the experimental dependences of the concentrations of recombination centers in the photoactive layers on the sample-exposure time. In the α -Si:H and μ c-Si:H PV converters under study, the subcells have p - i - n structures in which the thicknesses of the intrinsic i layers substantially exceed those of layers doped with donors and acceptors (see Fig. 1), and the total photocurrent is generated in the i - α -Si:H and i - μ c-Si:H layers. With this circumstance taken into account, the problem is

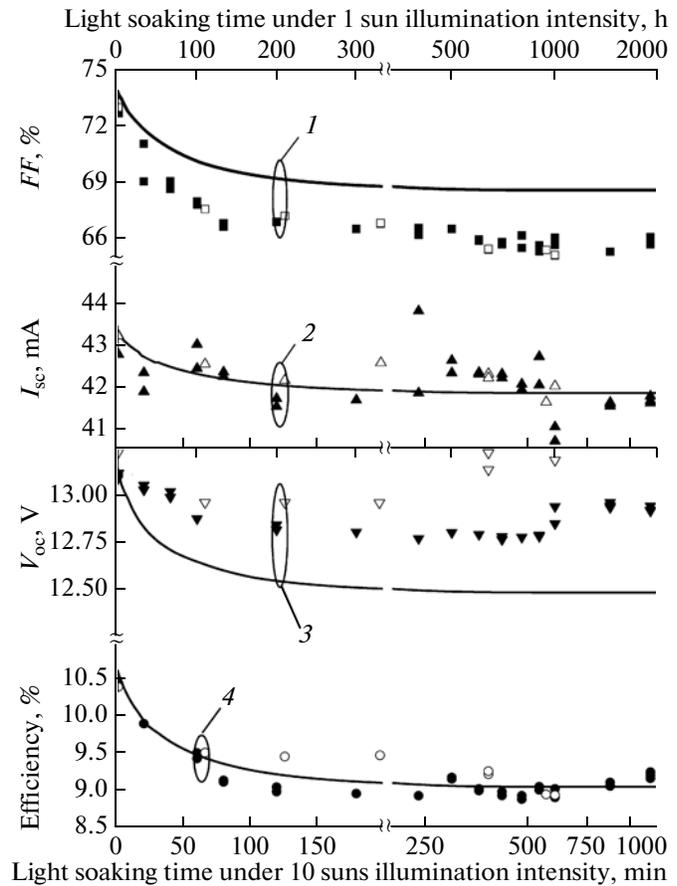


Fig.3. Degradation dependences of the photoelectric parameters of α -Si:H/ μ c-Si:H PV converters: (1) fill factor of the I - V characteristics, (2) short-circuit current, (3) open-circuit voltage, and (4) efficiency. The lines show the simulation results, the open and full symbols represent the experimental values obtained under the conditions of 1 and 10 suns, respectively.

reduced to determining the concentrations of recombination centers in these layers.

Table 1 lists the ratios of subcell photocurrents before and after exposure to 1 and 10 suns. It can be seen that, despite the differences in the amount of degradation for the μ c-Si:H subcell photocurrent, the photocurrent of the α -Si:H subcell is higher in all cases. Thus, the experimental dependence of the short-circuit current of the α -Si:H/ μ c-Si:H PVC test sample reflects the degradation dynamics of the i - μ c-Si:H layer, and the remaining parameters, that of the i - μ c-Si:H and i - α -Si:H layers simultaneously. This circumstance makes it possible to reconstruct the dependences of the number of recombination centers in these layers on the exposure time by simulation of the spectral and I - V characteristics of the α -Si:H/ μ c-Si:H PVC test samples.

To obtain the dependences of the photocurrent densities in PV subcells on the nonequilibrium charge-carrier (NCC) lifetime, we simulated the spectral

Table 1. Changes in the subcell photocurrents of the α -Si:H/ μ c-Si:H PV converters under study upon photoinduced degradation

Parameter	Illumination intensity		
	1 sun	10 suns	
Decrease in the subcell photocurrent upon exposure, %	α -Si:H	10	11
	μ c-Si:H	2	7
α -Si:H and μ c-Si:H subcell photocurrent ratio $I_{ph}^{\alpha\text{-Si:H}}/I_{ph}^{\mu\text{c-Si:H}}$	Before light exposure	1.10	
	After light exposure	1.02	1.08

Table 2. Carrier mobilities used in simulation of the spectral and I - V characteristics

Layer	Mobility, $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ [32]	
	electrons μ_n	holes μ_p
i - α -Si:H	13	0.67
i - μ c-Si:H	32	8.0

characteristics within the framework of the model described in [29]. The results obtained were used to calculate the I - V characteristics by the method described in [30]. The optical parameters of the layers in the structure were taken from [31]. The carrier mobilities corresponding to those in [32] are listed in Table 2. The simulation took into account a decrease in the voltage of the PV test sample and an increase in its series resistance.

It was assumed that the main reason for the change in the voltage of the PV converter during the course of degradation is an increase in the recombination current density j_r , whose value is inversely proportional to the NCC lifetime τ in the i region [33]:

$$j_r \propto \tau^{-1}, \quad \tau = (\gamma_{\text{eff}} N_r)^{-1}, \quad (2)$$

where N_r is the concentration of recombination centers; $\gamma_{\text{eff}} = \gamma_n \gamma_p / (\gamma_n + \gamma_p)$ is the effective coefficient of NCC capture by a recombination center; and $\gamma_{n,p}$ are the coefficients of electron and hole capture by the recombination center, respectively.

The average conductivity of the i region of a photovoltaic converter with a forward-biased junction can be expressed by the formula [33]:

$$\sigma = \frac{(\mu_n + \mu_p)(G - j)\tau}{d}, \quad (3)$$

where $\mu_{n,p}$ are the electron and hole mobilities, respectively; G is the number of photons absorbed in the i region per unit PV-converter area; j is the PV-converter current density; and d is the thickness of the i layer.

With expression (3) taken into account, the series resistance of the PV converter is given by

$$R_{\text{series}} = R_{\text{series}}^0 + \frac{M}{S} \left(\frac{d_{\alpha\text{-Si:H}}}{\sigma_{\alpha\text{-Si:H}}} + \frac{d_{\mu\text{c-Si:H}}}{\sigma_{\mu\text{c-Si:H}}} \right), \quad (4)$$

where M is the number of series-connected cells in the PV converter; S is the PV-cell area; and R_{series}^0 is the series resistance of the PV converter, with the exception of the resistance of the i layers.

Despite the larger thickness of the i layer in the μ c-Si:H subcell, compared with the α -Si:H subcell, the second term in parentheses in formula (4) is substantially smaller than the first term near the maximum-power point due to the significant difference between the NCC lifetimes and mobilities in the i - α -Si:H and i - μ c-Si:H layers. Therefore, the variation rate of the series resistance of the PV converter for photoinduced degradation primarily reflects that of parameters of the i - α -Si:H layers.

We used formulas (2)–(4) to calculate the recombination current and the series resistance for various NCC lifetimes. Combined with the dependences of the photocurrent densities on the NCC lifetimes, found from spectral characteristics, these values made it possible to obtain a series of I - V characteristics corresponding to various NCC lifetimes in the i - α -Si:H and i - μ c-Si:H layers. The initial values of the recombination currents were taken to be 3.4×10^{-10} and $1.8 \times 10^{-6} \text{ A cm}^{-2}$ for the i - α -Si:H and i - μ c-Si:H subcells, respectively. The value of the series resistance before photoinduced degradation was chosen so as to provide the best agreement between the experimental I - V characteristics and the simulated dependence. Its value at the maximum-power point was 18.4Ω .

The series of simulated I - V characteristics was used to determine the NCC lifetimes in the i - α -Si:H and i - μ c-Si:H layers in relation to the light-exposure time. The NCC lifetimes in i - μ c-Si:H were found from the equality condition of the calculated and measured short-circuit currents at a given exposure time, and those in i - α -Si:H were determined from the equality condition of the simulated and measured efficiencies at a given light-exposure time, with consideration for the parameters already found for the i - μ c-Si:H layer.

In the i - α -Si:H layer, the saturated concentration of dangling bonds serving as recombination centers was taken from [25]. With consideration for this circumstance, we calculated from the determined NCC lifetimes the effective capture coefficient and the concentration of dangling bonds for the i - α -Si:H layer. Assuming that the effective capture coefficients for the i - α -Si:H and i - μ c-Si:H layers are equal, we also calculated the dangling-bond concentrations from the NCC lifetimes for the i - μ c-Si:H layer. The dependences obtained are represented by points in Fig. 4. The corresponding recombination parameters are listed in Table 3. It should be noted that the estimates

of the initial NCC lifetimes, obtained from the spectral and $I-V$ (from the series resistance at the maximum-power point) characteristics differ by a factor of 1.5. This is in all probability due to errors in measurements of the spectral characteristics and in the optical model used to calculate the external quantum yield. These errors resulted in a certain underestimation in the actual NCC lifetimes.

3.2 Simulation of Photoinduced Degradation

To approximate the dependences of the dangling-bond concentrations in i - α -Si:H and i - μ c-Si:H layers on the exposure duration, we chose the “floating-bond” model [23]. In this model, the rate equations are written as

$$\frac{dN_r}{dt} = C_1 - C_2 N_r N_f + C_3 N_f - C_4 N_r, \quad (5)$$

$$\frac{dN_f}{dt} = C_1 - C_2 N_r N_f - C_3 N_f + C_4 N_r, \quad (6)$$

where N_r is the concentration of dangling bonds serving as recombination centers, N_f is the concentration of floating bonds, C_1 and C_2 are the terms reflecting the generation and annihilation of “dangling bond”–“floating bond” pairs, and C_3 and C_4 are the terms reflecting the transformation of a floating bond into a dangling bond and back.

In the normalized form, Eqs. (5) and (6) are written as

$$\frac{d\tilde{N}_r}{d\tilde{t}} = b_1 \left(\frac{\tilde{g}}{\tilde{N}_r} \right)^2 - b_2 \tilde{g} \tilde{N}_r \tilde{N}_f + b_3 \tilde{g} \tilde{N}_f - b_4 \tilde{g} \tilde{N}_r, \quad (7)$$

$$\frac{d\tilde{N}_f}{d\tilde{t}} = b_1 \left(\frac{\tilde{g}}{\tilde{N}_r} \right)^2 - b_2 \tilde{g} \tilde{N}_r \tilde{N}_f - b_3 \tilde{g} \tilde{N}_f + b_4 \tilde{g} \tilde{N}_r, \quad (8)$$

where \tilde{N}_r and \tilde{N}_f are the normalized values of N_r and N_f , measured in 10^{16} cm^{-3} ; \tilde{g} is the reduced generation function measured in $10^{22} \text{ cm}^{-3} \text{ s}^{-1}$; \tilde{t} is the reduced time measured in 10^3 s ; and the coefficients b_1 – b_4 are independent of the bond concentrations and incident light flux.

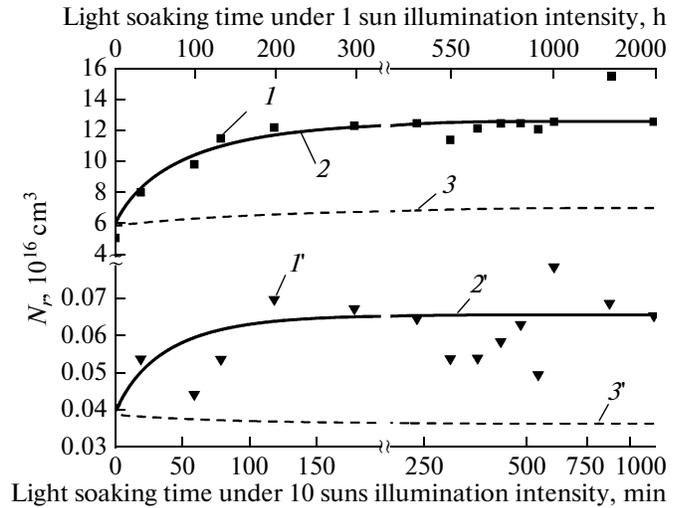


Fig. 4. Variation in the number of dangling bonds in the (I – 3) i - α -Si:H and (I' – $3'$) i - μ c-Si:H regions of the PV converter under study with the light-exposure duration: (I , I') values found from the experimental I - V characteristics of the PV converters, (2 , $2'$) result of the simulation in terms of the modified “floating-bond” model, and (3 , $3'$) result of the simulation in terms of the original “floating-bond” model under exposure to 1 sun.

It can be shown that, in the case of photoinduced degradation, the dangling-bond concentration corresponding to the saturation condition is expressed as

$$N_r^* = \sqrt[4]{\frac{b_1 b_3}{b_2 b_4} g} \times 10^{42} = \sqrt[4]{\frac{b_1 b_3 \tilde{g}}{b_2 b_4}} \times 10^{16}, \quad (9)$$

where g is the volume density of electron–hole pair generation by light (generation function).

It follows from expression (9) that, upon a 10-fold change in the illumination intensity, the maximum achievable concentration of dangling bonds will change by approximately a factor of 1.8. Thus, the photoelectric parameters of the test PV sample exposed to 10 suns should have stabilized at a substantially lower level than those for the PV converter exposed to 1 sun. However, nothing of the kind was observed in the experimental results we obtained (see Figs. 2 and 3).

Table 3. Recombination parameters of the α -Si:H/ μ c-Si:H PV converters under study

Parameter	Layer	Value of a parameter, determined by	
		spectral characteristic	series resistance
Nonequilibrium charge-carrier lifetime τ_0 before degradation, s	i - α -Si:H	7×10^{-10}	1.1×10^{-9}
	i - μ c-Si:H	1×10^{-7}	—*
Effective capture coefficient at a recombination center related to dangling bonds, γ_{eff} , $\text{cm}^3 \text{ s}^{-1}$		2.5×10^{-8}	1.6×10^{-8}

Note: *The parameter cannot be found because the series resistance of the unit is largely determined by the series resistance of the i - α -Si:H layers.

Table 4. “Floating-bond” model parameters used in the calculation

Coefficient	Value of the coefficient for the indicated layer	
	<i>i</i> -α-Si:H	<i>i</i> -μc-Si:H
<i>b</i> ₁	4.5	6 × 10 ⁻⁵
<i>b</i> ₂	0.017	310
<i>b</i> ₃		67*
<i>b</i> ₄		0.67*

Note: The values of these parameters were taken from [25].

If we assume that the second term in Eqs. (7) and (8) is proportional to the squared generation function (this may mean that excitation of both dangling and floating bonds is necessary for an annihilation event to occur), we can obtain the modified dynamics equations:

$$\frac{d\tilde{N}_r}{dt} = b_1 \left(\frac{\tilde{g}}{N_r}\right)^2 - b_2 \tilde{g}^2 \tilde{N}_r \tilde{N}_f + b_3 \tilde{g} \tilde{N}_f - b_4 \tilde{g} \tilde{N}_r, \quad (10)$$

$$\frac{d\tilde{N}_f}{dt} = b_1 \left(\frac{\tilde{g}}{N_r}\right)^2 - b_2 \tilde{g}^2 \tilde{N}_r \tilde{N}_f - b_3 \tilde{g} \tilde{N}_f + b_4 \tilde{g} \tilde{N}_r. \quad (11)$$

In the modified model, the dangling-bond concentration upon the saturation of photoinduced degradation will no longer depend on the irradiation level:

$$N_r^* = \sqrt[4]{\frac{b_1 b_3}{b_2 b_4}} \times 10^{16}. \quad (12)$$

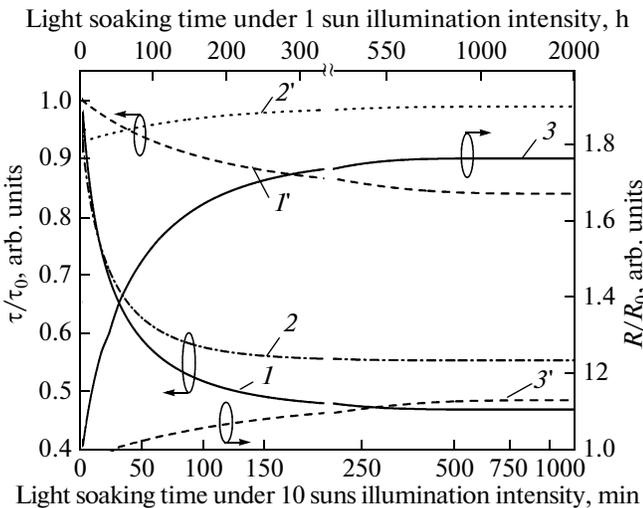


Fig. 5. Relative variation in the lifetimes of photogenerated carriers in the (1, 1') *i*-α-Si:H and (2, 2') *i*-μc-Si:H layers and (3, 3') of the series resistance of the structure at the maximum-power point with the light-exposure duration: (1, 2, 3) result of the simulation in terms of the modified “floating-bond” model and (1', 2', 3') result of the simulation in terms of the original “floating-bond” model under exposure to 1 sun.

Equations (10) and (11) were used to simulate the dependences of the dangling-bond concentration on the light-exposure time. The values of coefficients *b*₃ and *b*₄ were taken from [24], and those of *b*₁ and *b*₂ were varied to provide the best agreement between the calculated and experimental dependences, with the chosen values listed in Table 4. The simulation results are shown in Fig. 4 (lines 2 and 2'). The runs of the plots for 1 and 10 suns fully coincide within the figure plotting error. Figure 5 shows the results obtained in simulating the variation of the NCC lifetimes and the series resistance of the test PV sample (lines 1–3).

To illustrate the difference between the results obtained using the original [formulas (7)–(9)] and modified [formulas (10)–(12)] “floating-bond” models, we also performed calculations using the original model. Coefficients *b*₁–*b*₄ were varied to provide full coincidence for the calculated dependence of the floating-bond concentration under exposure to 10 suns. Then, we calculated plots describing how the floating-bond concentration varies for 1 sun. These plots are also shown in Fig. 4 (lines 3 and 3'), and the curves describing the variation in the NCC lifetimes and the series resistance corresponding to these concentrations are shown in Fig. 5 (lines 1', 2', and 3'). It can be seen that the observed changes in the parameters are extremely small. This means that, if the estimates of the photoinduced-degradation rate under 10 suns are considered correct, then no significant degradation would be observed under 1 sun in the original “floating-bonds” model.

The calculated dependences of the dangling-bond concentration on the exposure duration, obtained with the modified model, were used to simulate the *I*–*V* characteristics of the PV converter samples under study. The results obtained when calculating the main parameters of their *I*–*V* characteristics during the course of photoinduced degradation are represented by lines in Fig. 3. It can be seen that the modified floating-bonds model enables a sufficiently good description of the experimental dependences for the efficiency and short-circuit current. At the same time, in the range of stabilization of the photoelectric parameters, the calculated decrease in the fill factor of the *I*–*V* characteristics is larger than the experimentally measured value, and that in the open-circuit voltage is smaller. It should be noted that a similar result has also been obtained with the “H-collision” model [26].

4. CONCLUSIONS

This study was concerned with the photoinduced degradation of photovoltaic (PV) converters based on α-Si:H/μc-Si:H tandem structures under standard (1 sun, 1 kW m⁻²) and increased (10 suns, 10 kW m⁻²) illumination intensities. The spectral and *I*–*V* characteristics of specially fabricated PV converter test samples were measured. With consideration for differences

in the measurement temperatures, procedures, and errors, the estimated changes in the photoelectric properties upon exposure to light with standard (1 sun) and increased (10 suns) intensities are consistent. The absolute decrease in efficiency upon stabilization of the photoelectric parameters is 1.2–1.4% upon 500 h of exposure to 1 sun or 300 min at 10 suns.

The nonequilibrium carrier lifetimes in the i regions of the α -Si:H and μ c-Si:H subcells during the course of photoinduced degradation and the coefficients of capture at recombination centers related to dangling bonds were found from the experimentally measured spectral and I – V characteristics.

The degradation dynamics of the PV converters under study was described in terms of the “floating-bond” model. It was shown that the original “floating-bond” model cannot describe the experimentally observed characteristics of the α -Si:H/ μ c-Si:H PV converters under study. To solve this problem, the model was modified. A comparison of the experimental dependences with those obtained using the modified “floating-bond” model demonstrated good agreement for the short-circuit current and efficiency, with a certain discrepancy for the fill factor of the I – V characteristics and open-circuit voltage.

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