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Determination of subcell parameters for multijunction solar cells at radiation exposure

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Abstract. Based on the electroluminescent method and the two-diode equivalent circuit model of a solar cell, the current-voltage characteristics of wide-bandgap subcells in the structure with the corresponding parameters of saturation dark currents are obtained. In addition, the approach has been tested on samples exposed to various radiation doses, which made it possible to determine the degradation rate of the photovoltaic characteristics of solar cells.

Keywords: multijunction solar cell, current-voltage characteristics, saturation dark currents, radiation exposure, degradation

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Материалы конференции
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Определение параметров многопереходных солнечных элементов, подвергнутых радиационному облучению

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Аннотация. В работе исследуются фотоэлектрические характеристики трехпереходных фотопреобразователей. На основе электролюминесцентного метода и двух-диодной эквивалентной модели солнечного элемента получены вольтамперные характеристики широкозонных субэлементов в структуре с соответствующими параметрами темновых токов насыщения. Дополнительно метод опробован на образцах, подверженных различным дозам облучения, что позволило определить темпы деградации параметров фотоэлектрических характеристик солнечных элементов.

Ключевые слова: многопереходный солнечный элемент, вольтамперные характеристики, темновой ток, радиационное облучение, деградация

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Introduction

In state-of-the-art photovoltaics, III–V monolithic multijunction solar cells (MJ SCs) provide the record-braking efficiency among all other semiconductor-based photoconverters [1]. The targeted area of such devices application is related to the power supply of various spacecraft (space stations, satellites, moon/mars rovers). One of the main parameters for the successful use of MJ SC in space, in addition to the high sunlight photoconversion efficiency, is tolerance to radiation expose. Therefore, it is essential to take into account the possible degradation of individual subcells in a MJ structure, since each of them can demonstrate a diverse rate of PV parameters diminishing with exposure dose due to differences in the composition, thickness, and doping levels of the semiconductor layers. The spectral dependence of the external quantum efficiency (EQE) and the current-voltage characteristic (I-V curve) make it possible to trace the effect of irradiation on such PV parameters as the efficiency of charge carrier collection in p- and n-regions, series and shunt resistances, diffusion and recombination saturation currents. Moreover, if the registration of the EQE of each p-n junctions is a well-developed practice with an approved research protocol, then the extraction of I-V curves of individual subcells being a part of monolithic MJ SC structure is a non-trivial experimental problem.

Theoretical part

The general equation describing the physical processes in individual subcells of MJ SC is based on an equivalent two-diode circuit model with distributed parameters:

$$Jdark = (V + JRs)/Rsh - Jod\left[\exp(qV/kT) - 1\right] - Jor\left[\exp(qV/2kT) - 1\right], \quad (1)$$

where *Jdark* is current density without external light source [mA/cm^2]; *J* is photocurrent density [mA/cm^2]; V is operating voltage (load voltage) [V]; *Rs* is series resistance [Ohm]; *Rsh* is shunt resistance [Ohm]; *Jod* and *Jor* are the densities of saturation reverse currents for various recombination processes (*d* corresponds to the diffusion component of the current and characterizes recombination in the quasi-neutral regions of the transition, *r* is responsible for carrier recombination in the space charge region, as well as for recombination under concentrated exposure) [mA/ cm^2]; *q* is the electron charge [C]; *k* is the Boltzmann constant [J/K]; *T* is temperature [K].

Semiconductor layers that form photovoltaic subcells are combined in MJ SC structure in a series circuit via tunnel diodes, and direct I–V curves tracing of each of p-n junctions is often impossible. The exception is MJ SC with additional busbars [2], which allow the direct electrical contacting to the subcell of interest. However, such architecture requires complex post-growth processing. Therefore, structures with the third (or fourth) terminals are used only in certain laboratory studies. In all other cases, to extract I-V curves of individual subcells indirect measurement methods are used. In addition, the target task is to determine the voltage of each p-n junctions. Such a problem can be solved by the method [3] based on reciprocity relation between *EQE* and electroluminescent emission (φ_{EL}) of SC [4]:

$$\varphi_{EL} = EQE(\lambda)\cdot\varphi_{BB}\cdot\left[\exp\left(qV(\lambda)/kT\right) - 1\right], \quad (2)$$

where *J* is the density of the photocurrent flowing through the MJ SC, $\varphi_{BB} = 2\pi hc^2/\lambda^5 \exp(-hc/\lambda kT)$ is the black body power density [W/m^2/nm] at a given temperature *T*, λ is wavelength [nm], *V* is the voltage drop across the subcell.

By transforming equation 2 with respect to the variable *V* and neglecting the "–1" term after the exponent, it is possible to form the I–V curve of each subcell:

$$V(J) = kT/q\left[\ln\varphi_{EL}(J) - \ln EQE(\lambda) - \ln\varphi_{BB}(\lambda) - \ln C\right], \quad (3)$$

where the term $kT/q\cdot\ln C = \delta V = \text{const}$ is introduced to compensate the difference between the relative value of the registered luminescent flux φ_{EL} and its absolute magnitude, and is the throughput function of the optical system used in the experiment. The constant δV for each subcell of a given MJ SC is the same and does not depend on *E* and *J*.

Thus, for a solar cell with three (i = 3) p-n junctions, the total voltage V_{mjsc} can be found as:

$$V_{mjsc} = \sum_i V_i - 3\delta V. \quad (4)$$

Experimental part

For each MJ SCs, the spectral dependences of EQE were obtained using the lock-in technique (Fig. 1, *a*) and a set of light I–V curves under pulsed illumination (solar simulator AM0 spectrum 1366 W/cm^2) was recorded [5, 6]. The latter allowed to determine dark characteristics without the effects of series resistance (Fig. 1, *b*) using the Isc-Voc method [7].

The electroluminescence flux φ_{EL} was recorded by fiber-guided spectrometers (spectral ranges 300–1100 nm and 1000–2500 nm) while current (range 10–500 mA/cm^2) was passed through MJ SC. To improve the electroluminescence light collection and to enhance the recorded signal the input end of the fiber was equipped with collimator. The measurements were carried out for two direct band gap GaInP and GaAs subcells. Radiative recombination flux of the lower Ge junction with indirect band gap (luminescence peak at energies around 0.68 eV) is very week and was observed only at high photocurrent densities (more than 1 A/cm^2), which exceeds the allowable operating limits of MJ SCs used in this study.

The calculation of equation 3 was carried out at wavelength at which $V(J)$ does not depend on λ (the methodology of this approach is described in [3]): for GaInP subcell it is approximately 650 nm, for middle GaAs junction it is 870 nm.

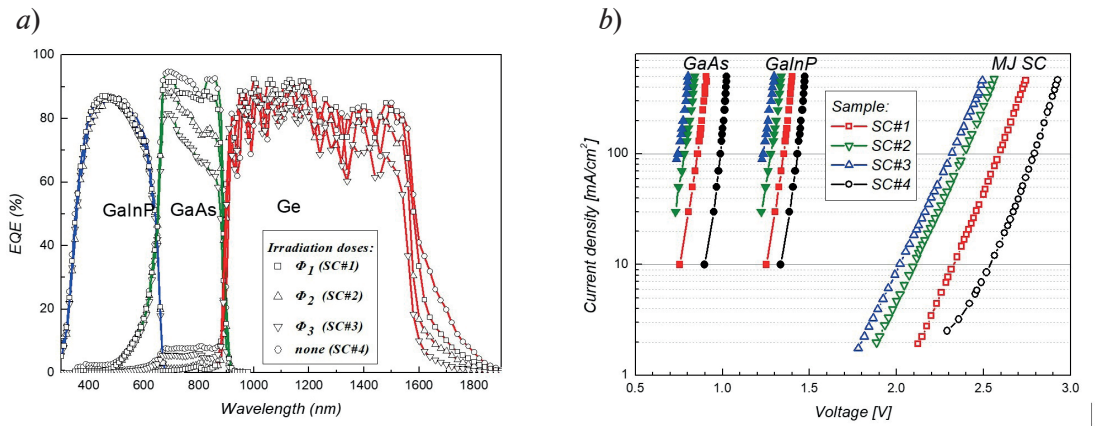

Fig. 1. EQE spectral dependencies of MJ SC irradiated by 1 MeV neutrons with fluencies of Φ1=1.5·10^{13} n/cm^2 (SC#1), Φ2=1.5·10^{14} n/cm^2 (SC#2), Φ3=5·10^{14} n/cm^2 (SC#3) (*a*); I-V curves (filled symbols) of GaAs and GaInP subcells obtained from EL measurements (Eq. 2), and I-V curves (open symbols) of MJ SCs obtained by direct Isc-Voc measurements using a four-probe system (*b*)

Results

Based on the obtained data (Fig. 1, *b*) and the two-diode circuit model (eq. 1), in the studied samples the values of dark saturation currents *Jod* (and *Jor*) of wide band gap subcells at different irradiation fluencies were calculated (Fig. 2). It can be seen that the irradiation exposure of MJ SC leads to a degradation of the *Jod* and *Jor* parameters for both subcells by about three orders of magnitude. To determine which of the regions of the subcell (quasi-neutral n- and p-regions or the space charge region) demonstrates the maximum degradation rate at irradiation and has a dominant impact on the photovoltaic characteristics, the derivatives of the *Jod*(Φ) and *Jor*(Φ) dependences were estimated. The results of calculation are shown in Table 1. Each linear section of the *Jod*(Φ) and *Jor*(Φ) corresponds to different ranges (Fig. 2) of irradiation power increase: range 1 from BOL to 1.5·10^{13} n/cm^2; range 2 from 1.5·10^{13} to 1.5·10^{14} n/cm^2; range 3 from 1.5·10^{14} to 5·10^{14} n/cm^2.

Calculations have shown that in subcells the quality of the space charge region decreases most rapidly. Since the narrow band gap Ge junction, in contrast to the wide band gap GaInP and

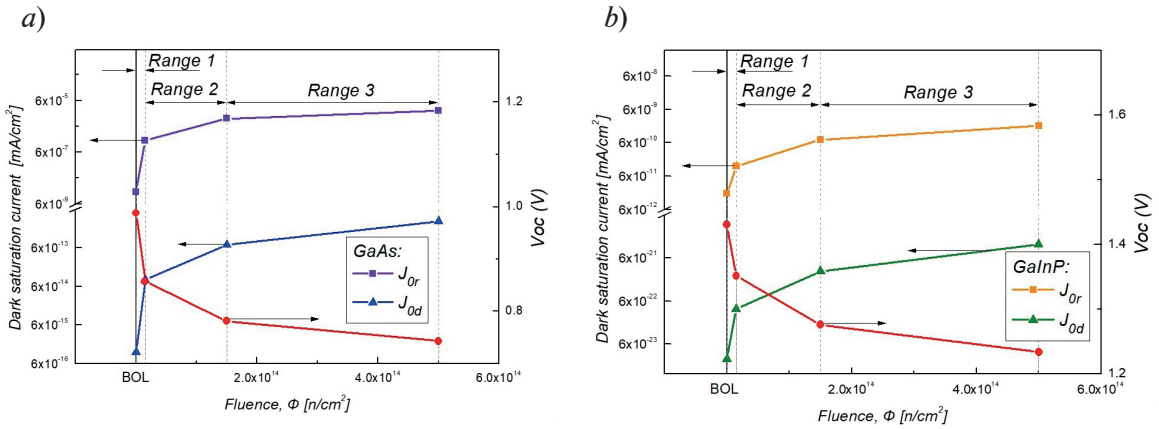

Fig. 2. Dependencies of the recombination (*Jor*) and diffusion (*Jod*) components of the dark saturation current of GaAs (*a*) and GaInP (*b*) subcells at different fluencies, and voltage degradation (red lines) at a selected current value of 100 mA/cm^2. The origin of coordinates along the *x*-axis corresponds to Beginning-Of-Life (BOL) condition for SC

GaAs, is less sensitive to the particle exposure, it can be concluded that the main contribution to the deterioration of MJ SC output parameters is originated from the middle GaAs p-n junction, which demonstrates the maximum of the $dJor/d\Phi \approx 10^{-19}$ mA/n.

Table 1

$dJ_0/d\Phi$ [mA/n] for wide-bandgap p-n junctions

Fluence range	Derivative	GaAs subcell	GaInP subcell
Range 1	$dJor/d\Phi$	$2\cdot10^{-19}$	$1\cdot10^{-23}$
	$dJod/d\Phi$	$9\cdot10^{-27}$	$4\cdot10^{-35}$
Range 2	$dJor/d\Phi$	$1\cdot10^{-19}$	$8\cdot10^{-23}$
	$dJod/d\Phi$	$8\cdot10^{-27}$	$3\cdot10^{-35}$
Range 3	$dJor/d\Phi$	$6\cdot10^{-20}$	$6\cdot10^{-24}$
	$dJod/d\Phi$	$1\cdot10^{-28}$	$5\cdot10^{-35}$

Conclusion

The work is devoted to the study of the photovoltaic characteristics of MJ SC before and after particle irradiation exposure. As a result, I-V curves of individual subcells were calculated for several fluencies. Based on the obtained data and the two-diode three-dimensional distributed circuit model of solar cell, the corresponding dark saturation currents characterize various recombination mechanisms were determined. The rates of degradation of saturation currents with increasing dose of irradiation made it possible to trace which of the regions of the subcell plays a dominant role in the deterioration of the photovoltaic characteristics of the p-n junction.

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