Multijunction solar cell spectral response determination at radiation damage study

S Levina¹, V Emelyanov, M Mintairov, M Nakhimovich and M Shvarts

Ioffe Institute, St. Petersburg, 194021, Russia

¹e-mail: levina@mail.ioffe.ru

Abstract. This paper discusses multijunction solar cells with optically coupled p-n junctions under radiation exposure photosensitivity spectral response study. It is shown that if the measurement technique does not consider the luminescent coupling and does not track the optical coupling degradation, then instead of a decrease (which is a natural response of a photoconverter to radiation damage), an abnormal increase in the narrow-bandgap photoresponse (receiving luminescent radiation) subcell due to radiation damage can be observed. Accordingly, with an increase in the irradiation dose, an increase in the subcell photocurrent forming a "negative" degradation dependence of MJ SC being used in space applications is recorded.

1. Introduction

The impact of damaging factors in space, such as vacuum, high energy ultraviolet radiation, high energy bombardment, and temperature cycles, makes additional troubles in solar cells (SCs) designing resulting in their long-term in-orbit exploitation. Thus, the radiation resistance of space SCs is one of the key indicators that determine the power availability and sets the operational potential of a spacecraft. Those parameters estimation is predicted from laboratory testing results, mainly from the I-V curves and spectral response measurements. For single-junction SCs, there is a practically approved standard protocol to determine the essential photovoltaic characteristics [1], whereas of multi-junction (MJ) SCs measurements require to consider additional optoelectronic interaction between photoactive subcells (p-n junctions), which takes place in monolithic heterostructure [2].

Spectral response (SR) dependencies of MJ SC can be obtained only under a strong current mismatch between subcells set by the external light source. As a result, a part of the photogenerated charge carriers recombines radiatively in optically biased subcells. The flux of secondary luminescent radiation is absorbed in the narrow-bandgap subcell layers and generates an additional photocurrent.

The established optical coupling level and the resulting current balance are easily upset by light exposure to each subcell. As a consequence, the recorded values of the SR of the narrow-bandgap subcells are underestimated. The magnitude of the errors depends on various factors: external light intensity, radiative recombination processes, and the effectiveness of optical coupling between subcells [3]. Errors in SR determination lead to incorrect data in SC energy efficiency estimation.

During solar cells testing the impact of operational factors (first of all, radiation resistance and temperature stability), the efficiency of optical interactions between subcells changes introducing additional uncertainties in standardized photovoltaic characteristics estimation.

The degradation mechanisms of MJ SC under the influence of high-energy particles have been extensively studied in recent decades [4-6]. However, the questions about the impact of radiation...
degradation on the photovoltaic characteristics of subcells coupled with luminescent interactions have been discussed very little [7-8], especially from the perspective of setting up an experiment and conducting measurements of MJ SC spectral response.

The present work is a sequel of studies of MJ SC with optically coupled p-n junctions [9-12]. It extends the potential of the experimental method proposed in [3] to irradiated SC photovoltaic characteristics determination. Discussions below provide triple-junction GaInP-Ga(In)As-Ge SCs as an example.

2. Basic principles of SR determination under the optical coupling effect

Earlier [3], the method of SR determination for MJ SC with optically coupled p-n junctions was developed. The proposed procedure is based on the following principles and tools:

1) The cascade nature of optical interaction. The activation of recombination in the wide-bandgap subcell under an external light source (fig. 1a, $\Phi'$) provokes luminescent flux that absorbs in a neighboring GaAs p-n junction. In turn, luminescence in GaAs forms a flux of infrared photons (fig. 1a, $\Phi^{III}$) toward the Ge subcell. By regulating the intensity of external illumination, an unambiguous dependence of the photocurrents induced in the narrow-bandgap subcells on the current flowing through the emitting GaInP junction is established. As a result, it is possible to estimate the luminescent impact on photocurrent response for the subcells receiving the recombination radiation.

![Figure 1](image)

**Figure 1.** (a) – equivalent circuit of MJ SC and illustration of cascade mechanism of optical coupling for a triple junction (TJ) SC (left). $\Phi'$ – external bias light absorbed in the top subcell (LED or laser light in experiment); $\Phi^{I}_{LC}, \Phi^{II}_{LC}$ – internal luminescent flux generated in the middle and bottom subcells, respectively. (b) – IV curves of TJ SC under external light exposure $\Phi'$: solid (c) – induced luminescent currents of the GaAs $(J_{LC}^{III}(J_{pn}^{I})|_{V^{III}})$ and Ge $(J_{LC}^{II}(J_{pn}^{I})|_{V^{III}})$ subcells as a function of the current flowing through the top wide-bandgap p-n junction.

2) Equivalent photocurrent states. To register photocurrent of each subcell, the mode of its short circuit at a specific bias voltage needs to be established (fig. 1b, $V^{II}, V^{III}$). In this case, other p-n junctions work as emitting diodes, and the intensity of the luminescent fluxes (fig. 1a, $\Phi^{I}_{LC}, \Phi^{II}_{LC}$) directly depends on the voltage applied to the MJ SC. The switching of short-circuit modes especially strongly influences the internal current flowing through the GaInP subcell (fig. 1b, compare $J_{0,pn}^{II}(V^{II})$ and $J_{1,pn}^{II}(V^{III})$), hence on the current induced by luminescence $J_{0,LC}^{II} < J_{1,LC}^{II}$. To establish a correct dependence of the induced currents (fig. 1c), so-called equivalent current mismatch conditions were determined, under which the same current flows through GaInP at different voltages. This condition corresponds to the vertical lines in figure 1c, and the resulting dependences play the role of additional equations of system (1), which describes the currents inside the semiconductor structure.

3) Sequenced manner of SR determination. The procedure begins with the wide-bandgap subcell since, at each subsequent experimental step, the photocurrents values obtained at previous steps are
used. Searched photoresponse to monochromatic radiation ($J_{\lambda II}^I$ for GaAs, $J_{\lambda III}^I$ for Ge) is determined by solving the system of equations (1), accounting for the current balance violation driven by cascade radiative processes. In more detail, the method and principles for determining the SR of MJ SC with optically coupled p – n junctions are presented in [3].

\[
\begin{cases}
J_{L,C}^{I}(J_{pn}^{I}) \\
J_{1,pn}^{I} = J_{0,pn}^{I} - \Delta J_{\lambda}^{II} - \Delta J_{\lambda}^{III} + J_{\lambda}^{I} \\
J_{\lambda}^{II} = J_{0,LC}^{II} + \Delta J_{\lambda}^{III} - J_{1,LC}^{II} \\
J_{1,pn}^{II} = J_{0,pn}^{II} - \Delta J_{\lambda}^{III} - \delta J_{\lambda}^{II} + J_{\lambda}^{II} \\
J_{\lambda}^{III} = J_{0,LC}^{III} + \Delta J_{\lambda}^{II} - J_{1,LC}^{II}
\end{cases}
\] (1)

3. Radiation damaged MJ SC

As is known, radiation exposure leads to a general degradation of SC photovoltaic characteristics [6, 7]. With an increase in the radiation dose, more and more defects and recombination centers (capture of charge carriers) appear in the semiconductor layers. Consequently, the diffusion length of minority charge carriers decreases. This corresponds to a change in the proportion between the radiative and nonradiative recombination mechanisms in favor of the latter with a corresponding decrease in the fluxes of luminescent radiation in the MJ structure. All these processes lead to a drop in the efficiency of optical interactions between subcells.

\[
\begin{align*}
\lim_{F \to 10^{16}} \Delta J_{\lambda}^{III}(F) &= J_{\lambda}^{III} \\
\lim_{F \to 10^{16}} J_{\lambda}^{III}(F) &= 0
\end{align*}
\] (2)

A gradual change in the recombination mechanisms within p-n junctions (from the domination of radiative to nonradiative) leads to less pronounced $J_{L,C}^{I}(J_{pn}^{I})$ and $J_{L,C}^{II}(J_{pn}^{II})$ dependences, and the discrepancy between the recorded $\Delta J_{\lambda}^{III}$ and true $J_{\lambda}^{III}$ values gradually disappears (fig. 2). At the maximum radiation doses (in this study, 7 MeV, $F=3 \cdot 10^{15}$ e/cm²), complete destruction of optical coupling between subcells occurs (eq. 2). At this moment, the photoresponse to the induced reradiation disappears in IV curves of Ge short circuit mode and $J_{0,pn}(V_{\lambda}) = J_{1,pn}(V_{\lambda})$.

Optical interactions “quenching” due to radiation damage simplifies the measurement procedure significantly and ensures correct SR dependences be obtained for an irradiated MJ SC (fig. 3a).

However, if the initial measurement technique does not consider the specifics of optical coupling, the underestimation of the initial SR values and, consequently, the photocurrent before irradiation can reach 10-15%. The weakening of optical interaction efficiency, as the radiation dose increases, provides a “support” to the recorded values of the photoresponse (the less pronounced the interaction, the higher the recorded values obtained without applying the corrective procedure [3]). As a result, so-called “negative” radiation degradation of the photocurrent will be recorded for passive (absorbing luminescent radiation) subcells (fig. 3b).

Obviously, such a scenario in predicting the radiation resistance and lifetime of solar arrays cannot meet the requirements for spacecraft.

It should be noted that a change in a MJ SC design, for example, incorporation of selective Bragg reflectors to increase subcells radiation hardness, have an additional effect on the optical coupling efficiency (up to the complete suppression of luminescent radiation and triggering photon recycling within the semiconductor layer) [11-12]. Accordingly, the constant monitoring of any changes in the efficiency of luminescent interactions between subcells should be an integral part of the radiation tests of the MJ SC.
4. Conclusions

The work aims to develop a methodology for studying the photovoltaic characteristics of MJ SC with optically coupled p-n junctions. It was found that when solving the problem of determining the actual values of the photosensitivity of space SC, a change in the efficiency of the optical coupling under radiation exposure leads to a significant (deviation of up to 10% from the actual value) distortion of the...
measurement results. It was pointed out that the proposed method for searching the SR of MJ SC makes it possible to consider the specifics of luminescent interactions between subcells, in particular after irradiation.

References

[1] Emery K 2003 Handbook of Photovoltaic Science and Engineering 16 701-747
[2] Barrigón E, Espinet-González P, Contreras Y, Rey-Stolle I 2015 AIP Conf. Proc. 1679 050002
[3] Levina S A, Emelyanov V M, Filimonov E D, Mintairov M A, Shvarts M Z, Andreev V M 2020 Solar Energy Materials & Solar Cells 213 110560
[4] Lim S H, Li J J, Steenbergen E H, Zhang Y H 2011 Prog. in Photovoltaics: R&A 10 102
[5] Siefer G, Baur C, Bett A W 2010 35th IEEE Photovoltaic Specialists Conf. 978 000704-000710
[6] Li J J, Zhang Y H 2013 IEEE J. Photovoltaics 3(1) 364-369
[7] Steiner M A, Kurtz S R, Geisz J F, et al 2012 IEEE J. Photovoltaics 2(4) 424-433
[8] Allen C R, Lim S H, Li J J, Zhang Y H 2011 37th IEEE Photovoltaic Specialists Conf. 25 000452–000453
[9] Shvarts M Z, Mintairov M A, Emelyanov V M, Evstropov V V, Lantratov V M, Timoshina N K 2013 AIP Conference Proceedings 1556 147
[10] Filimonov E D, Kozhukhovskaia S A, Bogomolova S A, Shvarts M Z 2017 AIP Conference Proceedings 917(5) 052026
[11] Shvarts M Z, Emelyanov V M, Evstropov V V, Mintairov M A, Filimonov E D, Kozhukhovskaia S A 2016 AIP Conference Proceedings 1766 060005
[12] Levina S A, Filimonov E D, Emelyanov V M, Shvarts M Z 2019 AIP Conference Proceedings 1124(4) 041033