The external quantum efficiency of multijunction solar cells with built-in 1D photonic crystals

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Abstract. In the present research, a multijunction solar cell with a built-in 1D photonic structure – Bragg reflector – is investigated. The joint effect of photon recycling and luminescence coupling on the spectral characteristics of the external quantum efficiency of multijunction solar cells is considered.

Introduction
Determination of photovoltaic characteristics of multijunction solar cells (MJ SCs) is a complex experimental task with the considerable attention coming from researchers in recent years [1]. Frequently, in investigating MJ SC spectral characteristics of the external quantum efficiency (EQE), the registered photoreponse of individual subcell turns out to be noticeably underestimated. Simultaneously another peculiarity of such studies shows up: manifestation of artifact photoresponse of a narrowband subcell beyond its main spectral sensitivity range [2]. Among widely discussed reasons affecting the results of the EQE determination, the following ones stand up: luminescence (optical) coupling [3], small values of the shunt resistance and low reverse breakdown voltage [4-5]. However, in a number of cases, experimental data cannot always be interpreted in a right way, relying solely on the features of the optical interaction between subcells and on electrical parameters of p-n junctions. Thus, for example, in a MJ SC structure with built-in photonic crystals, a complex interference pattern can arise due to multiple radiation reflections, which affects the shape of recorded EQE spectral dependences. The simplest and commonly used photonic crystal is a distributed Bragg reflector (BR) with periodic modulation of permittivity in one plane (1D). This ensures radiation reflection in a narrow spectral range.

BRs are successfully applied in photovoltaic structures, where they serve simultaneously as an optical mirror for radiation and a rear potential barrier for nonequilibrium charge carriers. Thus, the light optical path in thin photoactive layers increases with simultaneous efficiency gain in charge carrier generation and separation owing to multiple radiation reflections (recycling) [6]. Narrowing the photoactive layers in a MJ SC at presence of a BR also contributes to a decrease in the dark current recombination component and in an increase in the open circuit voltage. The aforementioned benefits determine the prospects of BR application in photovoltaic converters for improving their efficiency and radiation resistance.

MJ SC with BR
In the present paper, features of the EQE spectral characteristics of MJ SCs with BRs built-in into the pair of GaAs-Ge subcells are investigated. In such structures, the external long wavelength light passing through the middle GaAs p-n junction without absorption (due to narrow thickness of the layers) can be returned back into photoactive layers by a mirror. Such a "blocking" of radiation is
possible, if the BR spectral range is matched with the absorption edge of the GaAs subcell. A BR is also capable to reflect the secondary luminescent radiation being a product of recombination processes in GaAs, if its spectrum corresponds to the optical bandgap of the photonic crystal. This secondary radiation determines the luminescent coupling between GaAs-Ge subcells in MJ SC. If the parameters of photoactive (subcells) and passive (BR) structures are chosen in such a way that the luminescence is shifted relative to the BR resonant reflection, the BR layers will be partially or completely transparent for recombination light. This will inevitably affect the MJ SC photovoltaic characteristics, for example, photocurrent of Ge subcell can uncontrollably change during investigations.

To distinguish and estimate the processes of reradiation and photon recycling occurring in the structure, it is proposed to investigate the EQE spectral dependences of MJ SCs at various temperature modes and light biasing. In varying sample temperature (from 80K to 400K), a shift of the secondary (recombination) radiation wavelength and of BR high reflectivity zone with respect to each other is ensured allowing one to control the influence of absorption of external light and recycling of secondary radiation in the GaAs subcell on the Ge photoresponse, that is registered with the help of standard measurement procedures.

Tuning the light bias modes is realized with a powerful 435nm laser beam, thus enabling to control the injection of nonequilibrium charge carriers into the emitting p-n junctions. As a consequence, the efficiency of luminescent coupling (in the top-middle and middle-bottom subcells) and its effect on the recorded EQE spectral dependencies can be easily regulated during the investigation of a MJ SC [7].

**EQE measurements**

Let us consider interaction of radiation with a GaInP-GaAs-BR-Ge solar cell. At selective illumination of the top subcell, photocurrent arises not only in GaInP, but also in each narrowband subcell due to the optical coupling in the GaInP-GaAs and GaAs-Ge pairs. The magnitude of the photocurrent induced in the Ge subcell will depend on: (1) the efficiency of the radiative recombination process in the GaAs subcell; (2) the spectral sensitivity of the Ge subcell at the luminescence wavelength; (3) the reflection spectrum of BR built-in between the GaAs-Ge subcells.

If the luminescence spectrum of the middle p-n junction is in the BR total reflection range, the optical coupling between the subcells is blocked. If BR reflection coefficient is less than 100%, some portion of recombination light passes through the mirror layers into the narrowband subcell layers and contributes to its photocurrent. At a small overall thickness of the GaAs subcell (up to 2μm), the external monochromatic light within the 800-890nm range, being not fully absorbed, will reach the BR. In this case, only the long wavelength part of radiation (840-900nm) is completely reflected, whereas light in the 800-840nm wavelength range passes through the mirror layers and with some probability will be absorbed in the Ge subcell.

As a result, on the EQE spectral dependencies of GaAs subcell, a region with an underestimated photoresponse will appear, determined as the "optical leakage" (the spectral region around 820nm). Accordingly, an increase (proportional to the optical leakage) in the spectral characteristics of Ge subcell at the same wavelengths, is observed (Fig. 1 a, b, c).

To match the sensitivity spectral ranges of the narrowband subcells with the BR photonic forbidden gap, MJ SC was studied in various temperature regimes (from liquid nitrogen temperature to 100°C). As the temperature increases, the middle subcell sensitivity edge shifts towards long wavelengths with the rate of 0.4 nm/°C in accordance with the change of the GaAs forbidden gap [8], whereas the BR optical forbidden gap moves with a rate of 0.07nm/°C (Fig. 1d). Obviously, there is a certain range of temperatures, within which the GaAs subcell (for a given thickness of photoactive layers) absorbs the external and recycled radiations most efficiently. In turn, BR completely blocks penetration of the luminescent light into the Ge subcell. Therefore, the optical coupling effect on the EQE measuring procedure is eliminated and true values of the Ge subcell photoresponse can be obtained [7]. For the considered MJ SC structure with a BR, this optimal operation mode corresponds to the temperature of 60°C (Fig. 1e). Further heating of the sample leads to a shift of the GaAs...
luminescence peak beyond the range of the BR photonic forbidden gap and to light coupling appearance in GaAs-Ge pair.

Figure 1. The EQE spectral characteristics of the GaAs (blue) and Ge (wine) subcells; spectra of BR reflectance (green) and GaAs electroluminescence (red) obtained at different temperatures: -180 °C (a), -100 °C (b), +60 °C (c). (d) – BR spectral dependencies at different temperatures. The coefficient of temperature shift is equal to 0.06÷0.08 nm per degree. (e) – Temperature dependencies for BR long wavelength edge by the reflectance level of 90% (green); for the electroluminescence peak of the GaAs subcell (red) and for artifact response of the Ge subcell at the wavelength of monochromatic light – 820 nm (blue).

Figure 2. The EQE spectral characteristics of GaAs-BR-Ge at various levels of external light bias (blue laser 435nm) and at temperature of -100 °C.
As can be seen from Fig.2, in the 850-900nm wavelength range, the luminescent light is completely blocked, what has been additionally confirmed by the reduction (to the level of 5-7%) of the artifact photosresponse in the considered range. It should be pointed out that the artifact value is regardless of the external illumination level for the GaInP subcell producing coupling cascade. The correlation between the light bias and the photosresponse artifact pronounced in the Ge subcell, but outside the BR photonic forbidden gap (<820nm), suggests that the bottom junction sensitivity is caused by its internal leakage, for example, by a low shunt resistance, and is not associated with light coupling between photoactive layers inside a MJ SC.

Conclusions
In the research, the EQE spectral characteristics of a MJ SC with built-in photonic crystals have been investigated. The causes for optical and recombination losses have been determined, as well as the ways of their blocking.

Experimental results indicate the possibility to achieve total blocking of luminescent coupling between subcells by matching BR resonance reflectance with GaAs electroluminescence spectrum at some optimum temperature and illumination regime. However, for MJ SC with low shunt resistance of a narrow band subcell, the artifact response is still observed and the presence of optical coupling is erroneously indicated. Therefore, in such semiconductor structures, the obtaining of true values of the EQE spectral dependence can be determined only by analytical methods [9].

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