Elimination of light coupling negative effect on the accuracy of external quantum yield determination in a MJ SC

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Abstract. This paper presents a new technique allows to eliminate negative effect of light coupling and to determine true value of external quantum yield of a multijunction solar cell.

1. Introduction
The light coupling (LC) observed inside monolithic semiconductor heterostructures and discussed actively during recent years, which results in appearance of induced current in a p-n junction (subcell) owing to absorption of luminescence from the adjacent wideband p-n junction, can lead to such positive effects as the rise of the short circuit current, of the open circuit voltage and, as a result, of the efficiency of a GaInP/GaAs/Ge multijunction solar cell (MJ SC). The processes mentioned above complicate methodology of the experimental study of MJ SCs and can substantially affect the accuracy in determining spectral and I-V characteristics [1-6].

It is known that, in investigating MJ SC spectral characteristics, an abnormal photoresponse out of typical spectral sensitivity range of the subcell under study is fixed. So a Ge subcell can demonstrate a high sensitivity in the short wavelength spectrum region, radiation from which is absorbed completely in photoactive GaInP and GaAs layers located above. In this case, the absolute external quantum yield (EQY) values of the Ge subcell being registered appear to be low. In the majority of cases, the registered abnormal photoresponse (out of main photoresponse range) of Ge subcell appears to be as a result of a complex negative effect of fundamental (light coupling) processes and of properties of p-n junctions (low shunting resistance) inherent in the semiconductor structure on the photosensitivity spectral dependences being determined by standard methods [2-5, 7]. This highlighted the need to improve corresponding experimental procedures.

In standard procedures for obtaining the spectral dependence of the EQY, the current signal from a subcell under study is registered at frequency-modulated monochromatic light in a required spectral range. Influence of other p-n junctions being not investigated at the moment is eliminated by constant broadband illumination creating conditions of current limitation from the side of a tested subcell, and shift of the tested subcell to the short circuit current condition is ensured by additional bias voltage [7].

Depicting photocurrents generated in the subcells in the form of bar chart (Fig.1), it is easy to see that, at intense illumination of the wideband (WB) subcell, in the narrowband (NB) p-n junction, an induced current $J_{0}^{N}$ can arise caused by luminescent radiation, value of which will be proportional to internal current $J_{0}^{N}$ flowing through the WB p-n junction (Fig. 1a). In adding photocurrent $I^{\lambda}$ caused by chopped monochromatic light into the NB subcell (Fig. 1b), an instantaneous drop of internal current through the WB p-n junction down to $J_{1}^{N}$ occurs. As a result, the reaction on the
monochromatic radiation, i.e. registered “alternative” photoresponse $\Delta J$, will be less than the value $J_{\lambda}^N$, and, hence, the magnitude of the EQY for the NB subcell will be underestimated:

$$\text{QE} = \frac{\Delta J}{J_{\text{ref}}} \cdot \text{QE}_{\text{ref}},$$  

(1)

where $\Delta J$ – registered increment of the photocurrent caused by monochromatic light and used in standard measurement procedures for determining the EQY of the photoresponse (expression 2); $J_{\text{ref}}$ – photocurrent of a reference SC at its illumination by chopped monochromatic light; $\text{QE}_{\text{ref}}$ – external quantum yield of the reference SC at chosen wavelength.

![Figure 1](image1.png)  
**Figure 1.** Bar chart of photocurrents of WB and NB subcells in conditions of standard procedure for recording spectral dependence of the EQY of photoresponse.

![Figure 2](image2.png)  
**Figure 2.** Graphical representation of photocurrent values for I-V curves, obtained under various illumination conditions: initial (A), in adding chopped monochromatic light for NB (B) and WB (C), correspondingly.

2. **Experimental details**

In the work, a new approach to determining true EQY values of NB subcells in a MJ SC, based on study of spectral characteristics only with application of sources of frequency-modulated radiation ensuring also a bias light for the uninvestigated WB subcells, is presented.

The use of sources of only alternative (frequency-modulated) radiation leads to that registered signals will be noticeably different from those obtained in a standard measurement procedure. At absence of monochromatic illumination, an induced alternative photocurrent $J_0^N$ will be registered, but in adding it $J_1^N + J_{\lambda}^N$ (see Fig. 1b). At a chosen level of illumination of WB subcell, the following relation for photocurrent values at the bias voltage $V_{\text{BIAS}}$ (Fig.2) is valid:

$$\Delta J + J_0^N = I_{\lambda}^N + I_1^N,$$  

(2)

where the desired value $J_{\lambda}^N$ is associated with currents of the WB subcell as $J_0^W - J_1^W = J_{\lambda}^N$ (see Fig.1b) and can be determined graphically by the subtraction method.

For this it is necessary, first of all, to determine experimentally the dependence of the photocurrent in the NB subcell ($J_{LC}^N$), induced by luminescence, on photocurrent generated in the adjacent irradiating subcell ($J^W$) (Fig. 3). In setting initial conditions in experiment ($J_0^W$, $J_0^N$), one can, in deviating consistently to the left (zone 1 in Fig.3) of the value $J_0^W$ by some value $J_{\lambda}^N$, search for a pair of values ($J_1^N$, $J_{\lambda}^N$), at which equation (2) will be fulfilled.

The proposed method for determining values of $J_{\lambda}^N$ appears to be rather sensitive to both initial conditions ($J_0^W$, $J_0^N$) and value $J_{\lambda}^N$ itself depending on the level of illumination with monochromatic radiation.
Figure 3. The dependence of the photocurrent induced by luminescence in the NB subcell ($J_{G_N}$) on the photocurrent generated in the neighboring WB subcell ($J_W$): 1 and 2 designate the zones for $J_{G_N}$ determination, when $\lambda$ is within the NB (1) or WB (2) subcell photosensitivity range.

Figure 4. Spectral dependence of the external quantum yield of the photoresponse obtained in two ways: standard method and subtraction method.

Since the magnitudes of WB subcell photocurrent $J_0^W$ and of induced current $J_0^N$ are bound through the luminescent coupling effectiveness $\gamma_0$, as well as $J_1^N$ and $J_1^W$ through $\gamma_1$ [1]:

$$\gamma_0 = \frac{J_0^N}{J_0^W} = \frac{J_0^N}{J_0^W - J_{\lambda N}},$$

$$\gamma_1 = \frac{J_1^N}{J_1^W} = \frac{J_1^N}{J_1^W - J_{\lambda N}} = \frac{J_1^N}{J_0^W - J_{\lambda N}},$$

then, at low effectiveness of luminescent coupling, the $J_{G_N}(J_W)$ dependence will be gently sloping ($\gamma_0^\approx J_0^N/J_0^W$; $\gamma_1^\approx J_1^N/J_1^W$), which will make the difference between values of $J_0^N$ and $J_1^N$ extremely minor (compared with the accuracy of registration of the pointed out values) even at high levels of illumination with monochromatic light and large $J_{\lambda N}$. It is apparent that at considerable luminescent coupling the $J_{G_N}(J_W)$ dependence will be steeper, and more “comfortable” initial conditions ($J_0^W$, $J_0^N$) can be preset in experiment. Requirements to ensuring high illumination from the monochromatic source are also reduced. Nevertheless, in allowing for probable rather strong change of monochromatic illumination at scanning the optical range (inherent in the systems based on monochromators and xenon/halogen light sources), which will affect the value of $J_{\lambda N}$, it should be preferred to such initial conditions (point $(J_0^W$, $J_0^N)$ in Fig.3), in which the tangent to the $J_{G_N}(J_W)$ dependence will have a slope of about 45 angular degrees.

It should be emphasized that the dependence $J_{G_N}(J_W)$ for each pair of subcells and for any MJ SC is individual and will be determined by the luminescent coupling effectiveness. In case of high luminescent coupling effectiveness and in using standard measuring methods, an error in determining values of the EQY of photoresponse of a NB (absorbing luminescent radiation) subcell can be substantial (up to 20 rel.%) [8]. For this reason, the described above multistage procedure to obtain correct (without “artifacts”) spectral characteristics of MJ SCs is proposed to be used:

- construction of the $J_{G_N}(J_W)$ dependence and determination of the initial conditions ($J_0^W$, $J_0^N$);
- scanning the spectral sensitivity range with recording values of $J_1^N + J_{\lambda N}$ for subcell under test and corresponding to them values of reference photodetector photocurrent ($J_{rel}$) at illumination with chopped monochromatic radiation;
- calculation of \( J_\lambda^N \) values for each wavelength of monochromatic radiation and using them in constructing the spectral dependence of external quantum yield of photoresponse (EQY (\( \lambda \))) in correspondence with the formula (1), where \( \Delta J \) is substitute for \( J_\lambda^N \).

3. Conclusion
The proposed procedure has been realized on an installation for recording spectral dependencies of MJ SC [9], in which an optical chopper was placed in front of the tested specimen thereby modulating fluxes of monochromatic radiation and bias light.

Even the first experiments have shown that the proposed multistage method gives the increase to the photocurrent of a germanium subcell greater than in 1% within its spectral sensitivity range and practically completely excludes the effect of anomalous photoresponse in the short wavelength part of spectrum (Fig.4).

Further development and application of the proposed measuring procedure will allow determining more correctly output and metrological characteristics of MJ SCs at research practice and life tests associated with action of different damaging factors on the SC semiconductor structure.

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