Photon-coupled characteristic of a multijunction solar cell

S A Levina, E D Filimonov and M Z Shvarts
Ioffe Institute, St. Petersburg, 194021, Russia
E-mail: kozhukhovskaya@mail.ioffe.ru

Abstract In the work, optical coupling arising in a multijunction solar cell under powerful laser radiation is investigated. To describe the cascade of interconnected luminescent processes in a structure with optical coupling, the photon-coupled characteristic is used. Investigation for two specimens with different efficiency of luminescent interaction was carried out.

1. Introduction
Most AlIBV semiconductor materials applied in modern photovoltaics are direct-bandgap structures with high crystallographic perfection, for which domination of radiative recombination over nonradiative one is typical. Radiative recombination mechanisms can and largely have an impact on design and optimization solutions for solar cells (SCs) and on procedure approaches in studying their photo-electrical characteristics.

In recent years, raised interest is observed to investigating such a phenomenon as optical (photon) coupling in multijunction (MJ) SCs. It is an effect, at which photons arising in a wide bandgap p-n junction, as a result of radiative recombination of electron-hole pairs, are absorbed in the adjacent narrowband subcell generating in the latter an additional photocurrent. Importance of this process was considered in detail in [1-3]. However, up to now similar investigations are based only on considering the interconnection within pair of neighboring subcells being in a direct optoelectronic contact, whereas processes inside a MJ SC are more complicated.

2. Photon-coupled characteristic
In the present work, optical coupling phenomenon in GaInP-Ga(In)As-Ge SCs under powerful laser radiation was investigated. In the experiment, laser sources (corresponding by radiation wavelength to the sensitivity range of GaInP and Ga(In)As subcells) were in a pulse mode with different radiation modulation frequencies for possibility to separate and to register the Ge subcell response arising apart from each wide bandgap junction. It was established [4] that optical interaction between subcells occurs even if they are not in the immediate electrical contact (in a multilayer semiconductor structure, it is a contact through a tunnel diode). Hence, any variation of the current state in one of the subcells will immediately reflect on the current imbalance of the whole SC. The problem becomes more complicated in applying bias voltage (required for isolating a photoresponse from the tested subcell), what leads to abrupt change of currents flowing through emitting p-n junctions [4-6].

To describe processes occurring inside MJ structures, with allowing for photonic interaction between subcells, it was proposed to use the photon-coupled characteristic [4], i.e. the dependence of current induced by luminescent emission in the absorbing subcell on photocurrent resulting from action of external radiation in the top wideband p-n junction.
Let us consider in detail the principle of experimental formation of photon-coupled characteristic of a triple junction GaInP-Ga(In)As-Ge SC. At the first stage, the light bias is provided by a laser radiation source corresponding to the sensitivity range of the top wide bandgap subcell (blue laser with wavelength of 450nm), what results in proportional rise of its photocurrent. In narrow bandgap subcells, due to optical coupling in the GaInP-Ga(In)As and Ga(In)As-Ge pairs, photogenerated charge carriers also arise. Registration of photocurrents induced in the narrow bandgap junctions is performed in the voltage bias mode ($V_{BIAS1} \approx 1$V for Ga(In)As and $V_{BIAS2} \approx 2.2$V for Ge), what corresponds to the short circuit states for subcells. To determine current of GaInP, additional radiation sources are required (red and IR lasers), the application of which allows transferring the whole MJ SC into the state of current limitation from the top subcell side. With increasing light power of the main blue laser, the procedure for registering photocurrents of the subcells repeats in many times. Thus, a massive of data is formed, where three values of photocurrents of separate subcells ($J^{TOP}_{LC}, J^{MID}_{LC}, J^{BOT}_{LC}$) correspond to each level of the initial light bias. On the basis of the obtained massive, two dependencies $J^{MID}_{LC}(J^{pn})$ and $J^{BOT}_{LC}(J^{pn})$ are formed (Fig.1a), where $J^{pn}$ – internal current through the luminescent GaInP p-n junction equal to ($J^{TOP}_{LC} - J^{MID}_{LC}$) in the short circuit mode of Ga(In)As and equal to ($J^{TOP}_{LC} - J^{BOT}_{LC}$) in a similar mode for Ge.

Combining photocurrents of narrow bandgap subcells on a plane by means of $J^{pn}$ allows determining graphically “equivalent” current states, that is, MJ SC states at different bias voltages with fulfilling the equality $J^{TOP}_{LC} - J^{MID}_{LC} = J^{TOP}_{LC} - J^{BOT}_{LC}$ (points x, y in Fig.1a). Set of “equivalent” current states forms the main photon-coupled characteristic of a tested SC – the dependence $J^{BOT}_{LC}(J^{MID}_{LC})$ (Fig.1b).

![Figure 1](image-url)

**Figure 1.** a – dependences of current induced by luminescence in Ga(In)As (red) and Ge (blue) on current through emitting GaInP subcell obtained in the short circuit mode at voltages $V_{BIAS1}$ (for Ga(In)As) and $V_{BIAS2}$ (for Ge). Points x, y – “equivalent” current states of Ga(In)As ($J^{MID}_{LC}$) and Ge ($J^{BOT}_{LC}$), respectively. b – photon-coupled characteristic formed of “equivalent” current states.

At the second stage, a light bias from the source oriented on the middle cell spectral range (red laser with wavelength of 792nm) is added. This allows widening the photon-coupled characteristic possibility to describe processes inside a MJ SC. Forming the main photon-coupled characteristic in conditions of multi-wave illumination is similar to the case with one laser considered above. Then, an arbitrary level of light bias from a blue laser is selected, and the initial measurement condition corresponding to this level is fixed (points 1, 2, 3 or 4 in Fig.2). In varying the red laser intensity, photocurrents of narrow bandgap subcells in corresponding short circuit modes are registered. The GaInP subcell photocurrent at the first and second stages is determined identically. Depending on the
chosen initial conditions, the shape of the photon-coupled characteristic changes, and the position of the additional branches (b, c, d, e) will be different (Fig.2).

![Figure 2](image)

**Figure 2.** Photon-coupled characteristics in conditions of variation of the external illumination of GaInP only (branch a) and at addition of a light bias by red laser radiation (branches b, c, d, e) corresponding to different initial conditions of illumination (1, 2, 3, 4).

### 3. Results and discussion

In the work, photon-coupled characteristics for two GaInP-Ga(In)As-Ge SCs have been investigated: #1 – lattice-matched (LM) and #2 – lattice-mismatched metamorphic (MM). It has been found that photon-coupled characteristics of such cells are significantly different (Fig. 3). LM SC is characterized by a rapid increase in the induced current in Ge as the light bias of GaAs increases, and, consequently, the additional branch of the photon-coupled characteristic goes sharply upward. On the contrary, in MM SC the growth rate of induced current $J_{LC}^{BOT}$ is lower, so the additional branch passes under the main dependence. The difference in velocities can be estimated from the angles of the tangents $\alpha$, $\beta$ (Fig. 3). It is evident, that $\alpha > \beta$ for the metamorphic SC.

![Figure 3](image)

**Figure 3.** Main photon-coupled characteristics (lines 1, 2) and additional branches (lines 3, 4) for two MJ SCs: (a) – #1 LM; (b) – #2 MM. Angles $\alpha$, $\beta$ – tangents to the main and additional branches, respectively.
Such behavior can be explained by the quality of the optical interaction in the pairs of middle-bottom subcells, which is defined by the efficiency of the luminescent coupling process.

In general case luminescent coupling efficiency $\gamma$ is determined by the ratio of the current induced by reemission to that flowing through the emitting p-n junction. Physically, parameter $\gamma$ helps to understand what the portion of charge carriers in one of the subcells will pass to the external circuit, and what part will recombine radiatively in order for luminescent photons to be absorbed in the layers of the adjacent narrow bandgap subcell giving contribution to the photocurrent. In a triple-junction structure, the photon-coupling efficiency (Fig.4) is characterized by equations (1) and (2) for GaInP-Ga(In)As and Ga(In)As-Ge pairs, respectively:

$$\gamma_{TOP-MID} = \frac{J_{LC}^{MID}}{J_{TOP} - J_{LC}^{MID}}$$  \hspace{1cm} (1)$$

$$\gamma_{MID-BOT} = \frac{J_{LC}^{BOT}}{J_{MID}^{BOT} - J_{LC}^{BOT}}$$  \hspace{1cm} (2)$$

Depending on a MJ SC design and properties of semiconductor layers, $\gamma_{TOP-MID}$ and $\gamma_{MID-BOT}$ will be different. Thus, for LM structures the efficiency of luminescent coupling is greater (Fig. 4a) than for MM SC (Fig. 4b), especially for the middle-bottom pair of subcells.

$\gamma_{TOP-MID} << \gamma_{MID-BOT}$

4. Conclusion

In the work, the optical coupling in a MJ SC was investigated. A principle for forming the main photon-coupled characteristic and its additional branches is described and results for two specimens of MJ SC (based on lattice-matched GaInP-GaAs-Ge and metamorphic GaInP-GaInAs-Ge structures) are presented. It has been shown, that the luminescent coupling for the pair “middle-bottom” subcells is more pronounced in LM structure than in MM one, which is reflected in the faster growth of the values of $J_{LC}^{BOT}$ for the corresponding additional branches of photon-coupled characteristics with increasing $J_{MID}$.  

**Figure 4.** Dependencies of the luminescent coupling efficiency on the internal current through the emitting subcell for two MJ SCs: (a) – #1 LM: (b) – #2 MM. The $\gamma_{TOP-MID}$ and $\gamma_{MID-BOT}$ characteristics describe the optical coupling within the pairs of top-middle and of middle-bottom subcells, correspondingly.
Acknowledgments
The work has been supported by the Russian Science Foundation (grant №17-79-30035).

References
[1] Meusel M., Baur C., Let’ay G., Bett A.W., Warta W., Fernandez E. 2003 Spectral response measurements of monolithic GaInP/Ga(In)As/Ge triple-junction solar cells: measurement artifacts and their explanation Progress in Photovoltaics: Research and Applications 11 499–514
[2] Lim S H, Li J J, Steenbergen E H and Zhang Y H 2011 Luminescence coupling effects on multi-junction solar cell external quantum efficiency measurements Progress in PV: Research and Applications 21 344
[3] Li J J, Lim S H, Allen C R, Ding D and Zhang Y H 2011 Combined effects of shunt and luminescence coupling on external quantum efficiency measurements of multi-junction solar cells IEEE J. Photovoltaics 1 225–230
[4] Shvarts M Z, Mintairov M A, Emelyanov V M, Evstropov V V, Lantratov V M, and Timoshina N Kh 2013 Method for direct measurements of luminescent coupling efficiency in concentrator MJ SCs AIP Conference Proceedings 1556 147
[5] Shvarts M Z, Emelyanov V M, Mintairov M A, Evstropov V V, and Timoshina N Kh 2015 Temperature influence on luminescent coupling efficiency in concentrator MJ SCs AIP Conference Proceedings 1679 120003
[6] Shvarts M Z, Emelyanov V M, Evstropov V V, Mintairov M A, Filimonov E D, and Kozhuhkovskaia S A 2016 Overcoming the luminescent coupling effect in experimental search for the actual quantum efficiency values in multi-junction solar cells AIP Conference Proceedings 1766 060005