Optical leakage versus luminescent coupling in a multijunction solar cell: how to recognize a source of additional photocurrent in subcells

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

Abstract. A procedure for estimating an optical leakage of incoming radiation through a wide-bandgap subcell in a GaInP/GaInAs/Ge multijunction solar cell to photoactive layers of narrow-bandgap ones is proposed. A sequence for experimental determination of currents induced in a Ge subcell owing to an optical leakage or via a luminescent coupling is described.

1. Introduction
In a number of cases, experimental study of multijunction solar cell (MJ SC) photovoltaic characteristics requires to ensure selective light exposure on separate p-n junctions (subcells) by choosing sources of narrow-bandgap radiation (lasers, light diodes), or interference filters for broadband emitters (sunlight simulators). In forming the light flux spectral composition, it is important to prevent uncontrollable radiation penetration into a narrow-bandgap subcell (being a part of a MJ SC and located under an adjacent wide-bandgap one) by searching the emitter selective band within the spectral sensitivity of a corresponding subcell. An example of an overlap of spectral ranges is presented in figure 1.

Figure 1. Spectral characteristics of: (a) – external quantum efficiency of MJ SCs and of narrow-band radiation sources (red – the overlap range of the narrow-band source spectral line with the GaAs and Ge photosensitivity areas); (b) – wide-bandgap radiation sources.
It is known that appearance of a subcell photoresponse in high-efficient MJ SCs outside a range of its photosensitivity may be associated with the luminescent coupling mechanism, when the luminescent radiation flux from a wide-bandgap subcell is absorbed in an adjacent narrow-band one inducing an additional photocurrent [1-4].

In the experimental routine, it is often impossible to separate and estimate properly the influence of these two processes (light penetration and luminescent reemission) by studying only the emitter spectral composition. For this reason, in choosing emitters for selective spectral effect on a subcell, it is important to know the cause of the arising photocurrent to be either due to optical leakage (OL) of external radiation into a corresponding subcell through thin semiconductor layers, or a result of luminescent coupling (LC) between the wide- and narrow-bandgap subcells.

In the present work, a procedure for evaluating the values of photocurrents (arising due to optical leakages or luminescent reemission) has been proposed.

2. Model

Let us consider the effect of different conditions of external illumination on the photocurrent formation dynamics in a GaInP/GaAs/Ge MJ SC with a strong luminescent coupling. There could be following practical cases:

1. Irradiation from a light source within the sensitivity range of GaInP ($E_{TOP}$): a cascade of luminescent processes is activated. In such a mode, the GaInP subcell photocurrent $J_{TOP}$ increases proportionally with the irradiation level, whereas in the adjacent GaAs narrow-bandgap one -- $J_{MID}^{MID}$ is induced by luminescence light at the internal current $J_{p-n}^{pn}$ through the GaInP p-n junction (figure 2(a)).

![Diagram of photocurrents in conditions of illumination from an external radiation source focused on the sensitivity range of: (a), (b) – GaInP; (c), (d) – GaInP and GaAs.](image)

**Figure 2.** Bar charts of photocurrents in conditions of illumination from an external radiation source focused on the sensitivity range of: (a), (b) – GaInP; (c), (d) – GaInP and GaAs.
In case of a sharp reverse branch of the Ge subcell I-V characteristic, no current limitation takes place from the bottom Ge subcell side at \( V = 0 \) V and the relation \( J_{L}^{pn} = J_{TOP}^{MD} - J_{LC}^{MD} \) is valid. In applying bias voltage of about \( V \approx 2V \), that corresponds to the short circuit current mode for the Ge subcell, the induced current \( J_{LC}^{BOT} \) is recorded, while \( J_{L}^{pn} = J_{TOP}^{MD} - J_{LC}^{BOT} \) and \( J_{LC}^{MD} < J_{LC}^{MD}^{*} \). Due to cascade emission/absorption of the luminescent reemission in a MJ SC in tuning illumination level for the top subcell, the dependencies presented in figure 3 could be formed, every point on which corresponds to its own conditions of a current balance (dependencies \( J_{LC}^{MD} (J_{pn}) \) and \( J_{LC}^{BOT} (J_{pn}) \) in figure 3). See [5] for more detailed description of the photocurrent formation processes.

2. Irradiation from two light sources in the sensitivity ranges of GaInP (\( E_{TOP} \)) and GaAs (\( E_{MID} \)) subcells for creating controllable current balance of pairs of subcells. Suppose, at the initial time, that there is a constant level of illumination of the GaInP subcell (\( I_{0}^{TOP} = \text{const} \)), and photocurrents corresponding to this irradiation are \( J_{LC0}^{MD} \) and \( J_{LC0}^{BOT} \) (points 1, 1’ in figure 3).

![Figure 3](image.png)

Figure 3. Dynamic plane of photocurrents of GaAs (\( J_{MID}^{TOP} \)) and Ge (\( J_{BOT}^{MID} \)) subcells at different illumination conditions. Points 1, 1’ on the plane correspond to the initial measurement conditions. Points 2, 2’ – describe different current states at external illumination of the GaAs. Points 4, 5 are the states equivalent to the 2’, 2 ones, but in presence of the luminescence reemission in pairs GaInP-GaAs and GaAs-Ge. Point 3 represents the value of Ge current induced by LC in presence of OL through GaAs.

The increase in illumination of GaAs results in the rise of its photocurrent up to the value \( J_{0}^{TOP} \), being registered at \( 0 V \) (figure 2(c)). Hence, the dependence \( J_{LC}^{MD} (J_{pn}) \) is formed (violet line in figure 3). To determine the photocurrent \( J_{BOT}^{MD} \) induced in the Ge subcell, it is necessary to create different illumination conditions for subcells. Note that the value \( J_{BOT}^{MD} \) cannot be determined by simple moving along the I-V characteristic towards the \( V \approx 2V \) point [5]. Then, illumination of GaInP should be decreased until \( J_{BOT}^{MD} = J_{TOP}^{MD} \) (figure 2(d)). In such a case, the dependence \( J_{BOT}^{MD} (J_{pn}) \) is formed (green line in figure 3). Both lines \( J_{LC}^{MD} (J_{pn}) \) and \( J_{LC}^{BOT} (J_{pn}) \) can be determined graphically by pairs of points.
\( (J^{pn}; J^{BOT}_{LC0} + J^{pn}) \) and \( (J^{pn}; J^{MID}_{LC0} + J^{pn}) \). In such a way, a dynamic plane reflecting the response of each subcell to external illumination variation is arranged.

To determine the causes of the induced current arising in Ge, it is required to find equivalent current conditions \( J^{MID} = J^{MID}_{LC1} \) for GaAs at presence of external illumination, when the latter either penetrates into Ge \( (E^{MID} \neq 0) \) or does not \( (E^{MID} = 0) \). On the dynamic plane, which links all the currents mentioned above and their interrelations, this is equivalent to the transition from the state 1 to the state 2 for Ge (the total current in Ge is equal to \( J^0_{BOT} + J^{BOT} \)) and, correspondingly, for the GaAs subcell – from the state 2’ (total current in GaAs is determined by a sum \( J^{MID}_{EXT} \) and \( J^{MID}_{LC0} \), where \( J^{MID}_{EXT} \) is the current induced by external radiation \( E^{MID} \)) to the state 4 (the current in GaAs is determined only by LC nature). In the state 4, the internal current through the emitting GaAs p-n junction would induce \( J^{BOT}_{LC2} \) in Ge (point 5), and \( J^{BOT} + J^{BOT}_{LC0} = J^{BOT}_{LC2} + J_{OL} \) would be valid, where \( J_{OL} \) – is a photocurrent originated as a result of penetration of external radiation \( E^{MID} \) into the Ge subcell. If during graphical passway the Y-component of the points 4 and 5 \( (J_{OL} = 0) \), then \( J^{BOT} \) is a response only to the LC processes in a MJ SC. If the Y-coordinate of the point 2 is above a corresponding coordinate of the point 5, then an optical leakage takes place \( (J_{OL} \neq 0) \), and the induced photocurrent \( J^{BOT}_{LC1} \) (point 3) represents the impact of luminescence coupling.

3. Conclusion

The causes of generation of additional photocurrent in MJ SC narrow-bandgap subcells at selective light exposure in certain wavelengths ranges are considered. Principles for plotting of the current plane linking the lines of currents induced by luminescence and external radiation in subcells of MJ SCs are described. A procedure for determining the values of the current induced by luminescence and of that resulting from transmission of short wavelength radiation through the semiconductor layers into the narrow-bandgap subcells has been proposed.

Acknowledgments

This work was supported by the Russian Science Foundation (Grant № 14-29-00178).

References

[1] Yoon H, King R R, Kinsey G S, Kurtz S and Krut D D 2003 Proc. 3rd World Conf. Photovoltaic Energy Convers 1 745-748
[2] Baur C, Hermle M, Dimroth F and Bett A W 2005 Appl. Phys. Lett. 90 192109
[3] Steiner M, Geisz J, Moriarty T, France R, McMahon W, Olson J, Kurtz S and Friedman D 2013 Journal of Photovoltaics, IEEE 3(2) 879 – 887
[4] Allen C R, Lim S H, Li J-J and Zhang Y.-H. 2011 Proc. 37th IEEE Photovoltaic Spec. Conf., 000452 - 000453
[5] Shvarts M Z, Emelyanov V M, Evstropov V V, Mintaiv M A, Filimonov E D and Kozhukhovskaia S A 2016 AIP Conference Proceedings 1766 060005