

# Current relaxation in MJ SCs and its influence on IV curve formation in presence of light coupling

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**Abstract.** In the work, a procedure for simulating I-V characteristics of multijunction solar cells (MJ SCs) with accounting for the processes of current relaxation determined by the luminescent coupling between separate p-n junctions has been considered. The effect of the mentioned above processes on the I-V characteristic shape was investigated. It has been shown that, in the case of well pronounced reemission processes in high-efficient MJ SCs, in recording their I-V characteristics, variation of fill factor and rise of the open circuit voltage values being registered take place.

## 1. Introduction

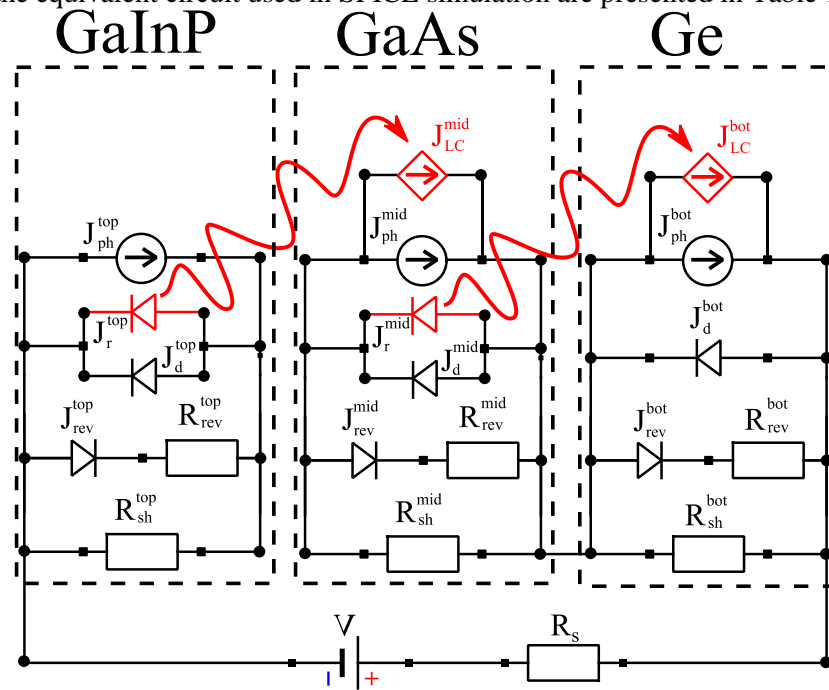
Gains in the sunlight conversion efficiency being demonstrated in the last two decades in developing III-V MJ SCs have, on the one hand, outlined the practical feasibility of record SC efficiency values at the level of more than 45% [1-3] and, on the other hand, - a set of problems in determining these values. First of all, the problems are associated with transfer to using high-quality semiconductor materials characterized by a high quantum yield of charge carrier radiative recombination [4, 5]. The luminescent coupling determined by these processes is expressed in the appearance of an induced current in the narrow-bandgap (NB) p-n junction due to absorption of recombination radiation from an optically adjacent wide-bandgap (WB) subcell. The effects of emission-absorption of luminescent photons will affect the photocurrent redistribution between photoactive p-n junctions, on the dark current values and on the MJ SC open circuit voltage, which complicates the simulation procedure and investigation of MJ SC characteristics and affects the accuracy of results being obtained. However, the widely applied methods for simulating of MJ SC I-V characteristic do not always account fully for the pointed out optical interaction between separate p-n junctions (subcells), which results in an inconsistency between the I-V characteristic and values of photovoltaic parameters being obtained, first of all evaluated values of the open circuit voltage  $V_{oc}$ , and data experimentally registered.

## 2. The model

In the work, the SPICE method for simulation is considered. Method is based on a standard equivalent circuit of a MJ SC modified for I-V curve tailoring with allowing for the luminescent coupling between subcells. The equivalent circuit (Figure.1) includes three photovoltaic p-n junctions, each of which consists of the following components:  $J_{ph}$ — generator setting a subcell photocurrent value;  $J_d$ — diode allowing for the p-n junction diffusion component;  $J_r$ — p-n junction current recombination component;



$J_{rev}$  – diode for forming an I-V characteristic reverse branch;  $R_{sh}$  – shunt resistance simulating various current leakages and losses on internal resistances. Additionally, resistance  $R_s$ , which plays a role of a linear series resistance and electronic load (source of a constant voltage  $V$ ) are included into the scheme. Parameters of the equivalent circuit used in SPICE simulation are presented in Table 1 [6]:



**Figure 1.** Equivalent circuit of a triple-junction GaInP/GaAs/Ge SC.

**Table 1.** Parameters of the equivalent circuit.

Parameter	Subcell		
	GaInP	GaAs	Ge
$R_s, \text{ohm/cm}^2$	0.023		
$J_{pn}, \text{mA/cm}^2$	100	30	15
$J_r, \text{A/cm}^2$	$8 \cdot 10^{-15}$	$1.85 \cdot 10^{-11}$	–
$J_d, \text{A/cm}^2$	$9.5 \cdot 10^{-27}$	$1.05 \cdot 10^{-20}$	$1.8 \cdot 10^{-6}$
$\gamma$	0.07		0.5

Optical interaction between p-n junctions is ensured by adding emitting diodes to the WB subcells circuits. The  $J_{pn}^{top}$  and  $J_{pn}^{mid}$  recombination currents produce luminescent light and as a result the corresponding induced currents ( $J_{LC}^{mid}$  or  $J_{LC}^{bot}$ ) in an adjacent NB p-n junctions:

$$\begin{cases} J_{LC}^{mid} = \gamma_1 \cdot J_{pn}^{top} = \gamma_1 (J_{ph}^{top} - J_{ph}^{mid} + J_{LC}^{mid}); \\ J_{LC}^{bot} = \gamma_2 \cdot J_{pn}^{mid} = \gamma_2 (J_{ph}^{mid} + J_{LC}^{mid} - J_{ph}^{bot} + J_{LC}^{bot}), \end{cases} \quad (1)$$

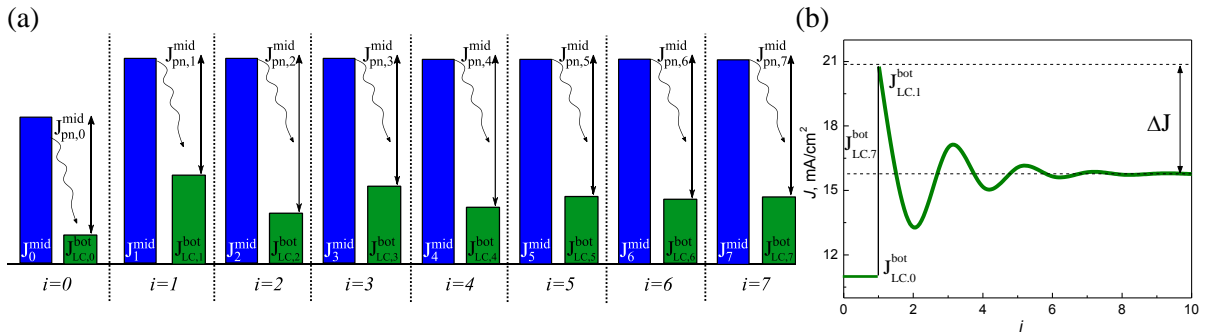
where  $J_{ph}^{top}$ ,  $J_{ph}^{mid}$ ,  $J_{ph}^{bot}$  – photocurrents generated in top GaInP, middle GaAs and bottom Ge subcells owing to external light;  $\gamma_k$  ( $k = 1, 2$ ) – effectiveness of the luminescent coupling for subcell pairs GaInP-GaAs ( $k=1$ ) and GaAs-Ge ( $k=2$ ),  $\gamma_s$  – the limiting (saturated) value of the luminescent coupling effectiveness for corresponding pair of subcells [7]:

$$\gamma_k = \gamma_s \frac{J_{rd}}{4J_{pn}} \left( 1 - \sqrt{1 + \frac{4J_{pn}}{J_{rd}}} \right); \gamma_s = \lim_{J_{pn} \rightarrow \infty} \gamma_k (J_{pn}), \quad (2)$$

$J_{pn}$  - current flowing through a p-n junction of the emitting WB subcell;  $J_{rd}$  - a conditional current boundary between the recombination and diffusion sections of the dark I-V characteristic for the radiating p-n junction

It is obvious (formula 1) that the greater the coupling effectiveness  $\gamma_k$ , the greater is the effect of the WB subcell on the adjacent NB one. It is known [7] that, in a triple-junction GaInP/GaAs/Ge SC  $\gamma_1 \ll \gamma_2$ . For this reason, from the point of view of studying optical interaction of subcells, the greatest interest is the GaAs-Ge pair, which is the object for simulation in the present work.

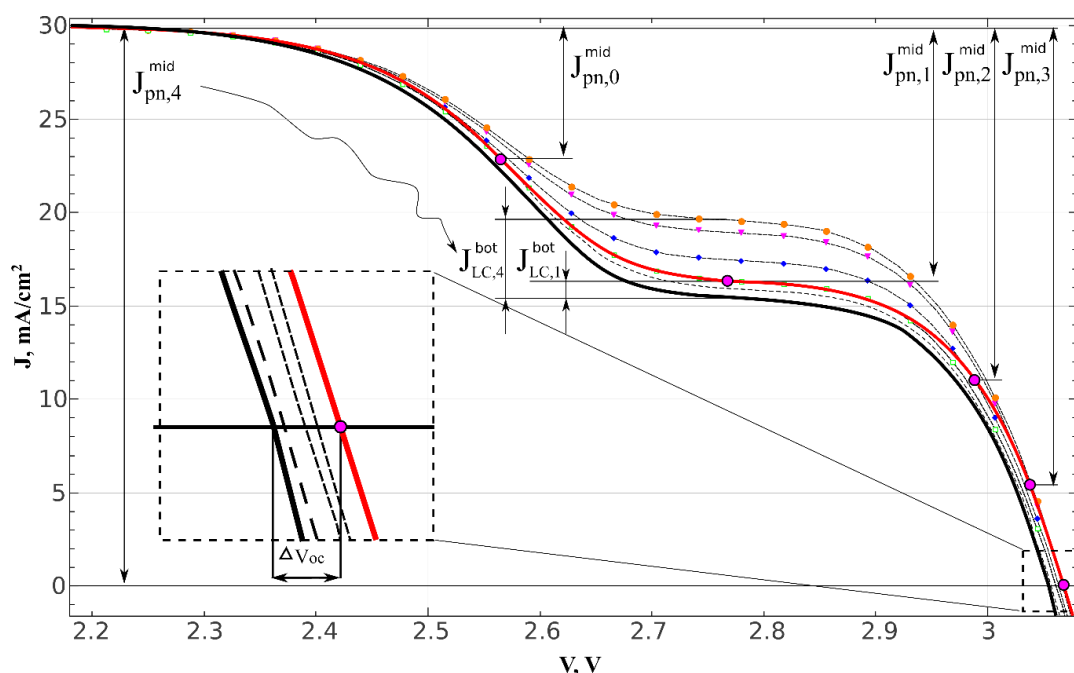
In modelling a MJ SC I-V characteristic, the optical interaction between subcells should be taken into account by a process describing the current relaxation [8]. In the initial moment of time, the subcells are in conditions of current equilibrium ( $i = 0$ ) and the photocurrent in the WB subcell is  $J^{mid} = J_{ph}^{mid} + J_{LC}^{mid}$  corresponding to a definite level of external illumination, and in the NB one is the induced by luminescence current  $J_{LC}^{bot}$ , which is determined by the current flowing through the p-n junction of WB subcell. Any variation in illumination on the emitting or absorbing p-n junctions results in arising of uncontrolled change of conditions for photocurrent matching and actuates the relaxation process (Figure.2). After its completion, a new steady state mode  $J_{LC,i}^{bot}(J_{pn,i}^{mid})$  comes at  $i \approx 7$ . As shown on figure.2, b for the presented practical cases the difference between  $J_{LC,1}^{bot}$  and  $J_{LC,7}^{bot}$  ( $J_{LC,1}^{bot} > J_{LC,7}^{bot}$ ) is  $\Delta J \approx 5 \text{ mA/cm}^2$ . So, in simulating real output characteristics of a MJ SC, it is necessary to take into account the given process to avoid the use of a too high value of induced current in NB subcell.



**Figure 2.** Relaxation of luminescent current. Insert “a” - bar chart ( $i$  – is the iteration number). Insert “b” - graph chart.  $\Delta J$  – difference between expected and recorded current values.

### 3. Results and discussion

Transfer to a new equilibrium state  $J_{LC,i}^{bot}(J_{pn,i}^{mid})$  can be initiated also in varying the current through the emitting p-n junction, as, for example, in recording the I-V characteristic: the value of current in the external circuit is set by applying a bias voltage  $V_{bias}$ , and, in “moving” along the I-V characteristic from  $J_{sc}$  to  $V_{oc}$ , the current flowing through the emitting WB p-n junction is thus increased ( $J_{pn,0}^{mid} < \dots < J_{pn,4}^{mid}$ ) (Figure.3). In turn, in the optical coupling conditions, this current causes the rise of the current induced in the NB subcell:  $J_{LC,1}^{bot} < \dots < J_{LC,4}^{bot}$ . Thus, as a result, new conditions for the photocurrent matching arise, for which a new “grown” up value of the NB subcell current and, correspondingly, a new voltage value at this current are typical. Hence, for every preset current value there is an increased registered voltage magnitude (including the open circuit point on the I-V characteristic), i.e., we have a shift of points on the MJ SC I-V characteristic towards the region of great voltages with the  $\Delta V_{oc}$  values of about 20mV (Figure.3).



**Figure 3.** Effect of the luminescent coupling on shaping of an I-V characteristic leading to the open circuit voltage increase.

#### 4. Conclusion

The reemission effects and the processes of current relaxation in a MJ SC associated with them are capable to affect substantially the NB subcell photocurrent and, as a result, the open circuit voltage values being registered in recording the I-V characteristic. It is obvious that, in interpreting experimental data and in obtaining adequate results of simulation of MJ SC characteristics, it is extremely important to take into account the considered mechanism of optical interaction between subcells in a multijunction structure.

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