Technical Physics Letters, 2023, Vol. 49, No. 12

Influence of photogenerated currents imbalance on current-voltage characteristics of multijunction solar cells

© M.A. Mintairov, V.V. Evstropov, S.A. Mintairov, M.Z. Shvarts, N.A. Kalyuzhnyy

Ioffe Institute, St. Petersburg, Russia
E-mail: mamint@mail.ioffe.ru

Received May 12, 2023
Revised July 21, 2023
Accepted October, 30, 2023

In this work, the influence of the imbalance of photogenerated currents on the current-voltage and photovoltaic characteristics of multijunction solar cells has been studied. The imbalance effect has been shown to induce the deviation of light current-voltage characteristics from the logarithmic shape. At the same time, photovoltaic dependences measured in the open-circuit and maximum-power-point modes (including the efficiency and fill factor) appear as logarithmic but shifted by constant values from those in the case of the photogenerated currents balance. This behavior of the characteristics has been experimentally verified for a triple-junction GaInP/GaAs/Ge solar cell.

Keywords: imbalance of photogenerated currents, current-voltage characteristics, multijunction solar cells.

DOI: 10.61011/TPL.2023.12.57579.171A

The paper is devoted to the issue of influence of the effect of imbalance of photogenerated currents of multijunction (MJ) solar cells (SCs) on the light current-voltage (JV) characteristics and photovoltaic (PV) dependences derived from the analysis of light JV characteristics. Among the mentioned characteristics, there are usually the dependences on illuminance level or photogenerated (PG) current of such quantities as open-circuit voltage (V_{oc}), maximum-power-point voltage (V_m), efficiency, fill factor, maximum power output. In solar photovoltaics, the effect of the PG-current imbalance is typically regarded as a factor negatively affecting the device efficiency. Therefore, a significant part of the development projects is devoted to searching for device designs where either all the subcells or a part of them are in the current balance [1–4]. At the same time, another important effect associated with the imbalance of PG-currents, namely a change in the shape of light JV curves, is ignored. This issue is partially mentioned in [5,6] where the problem of a relationship between several light JV characteristics of MJ SCs is considered. Notice that in the case of single junction photoconverters this relationship is quite simple: the characteristics shift by different PG-current magnitudes relative to the dark JV characteristic. In MJ SCs, this relationship gets violated when PG-currents are imbalanced. In this work, this effect was studied by simulation according to the analytical model presented in [7] with subsequent experimental verification for a triple-junction GaInP/GaAs/Ge SC. The main conclusion was that the imbalance of PG-currents leads to the light JV curve deviation from the logarithmic shape. This conclusion is of great importance because there are a large number of analytical approaches that apply singlejunction models to MJ SCs under the assumption that the JV curves are logarithmic [5,6,8–11]. Notice that the basic PV-dependences retain their logarithmic shape but shift relative to those in the case of balanced PG-currents (this was confirmed by analyzing the positions on the light JV curves of points corresponding to the open-circuit and maximum-power-point modes, since just these points determine all the basic PV-characteristics).

When subcells are connected in series, the total JV characteristic (i. e. that for the entire MJ SC) gets obtained by „voltaic summation“ of the subcell JV characteristics (summation of voltages at identical currents). Thereat, in the case when subcells generate identical PG-currents (the case of the PG-currents balance), the JV curve always consists of sections (segments) which are linear on the logarithmic current scale. Based on the technique for describing the MJ SC JV characteristics [7], in this work we use for each JV curve segment a monoexponential expression containing an additional imbalanced voltage term turning to zero when PG-currents are completely balanced. Later this model is used to calculate JV curves.

For the simplicity of the analysis, the calculation was performed for a double junction SC whose $p-n$-junction currents are governed only by the diffusion flow mechanism. As the subcells, the GaInP and GaAs ones were chosen, whose PG-currents at the unit ratio were $J_{g,1} = 0.015\,\mathrm{A/cm^2}$ and $J_{g,2} = 0.02\,\mathrm{A/cm^2}$. Diffusion saturation currents were assumed to be $J_{01} = 1 \cdot 10^{-25}\,\mathrm{A/cm^2}$ and $J_{01} = 1 \cdot 10^{-20}\,\mathrm{A/cm^2}$ for the GaInP and GaAs $p-n$-junctions, respectively. As in [7], the MJ SC current-voltage characteristic was calculated as

$$V(J) = \frac{AkT}{q} \ln\left[\frac{J_g - J}{J_0}\right] + \frac{kT}{q} \ln\left[\Pi_{i=1}^{n} \left(\frac{\kappa_i J_g - J}{J_g - J}\right)^{A_i}\right] = \frac{AkT}{q} \ln\left[\frac{J_g - J}{J_0}\right] + V_a, \qquad (1)$$

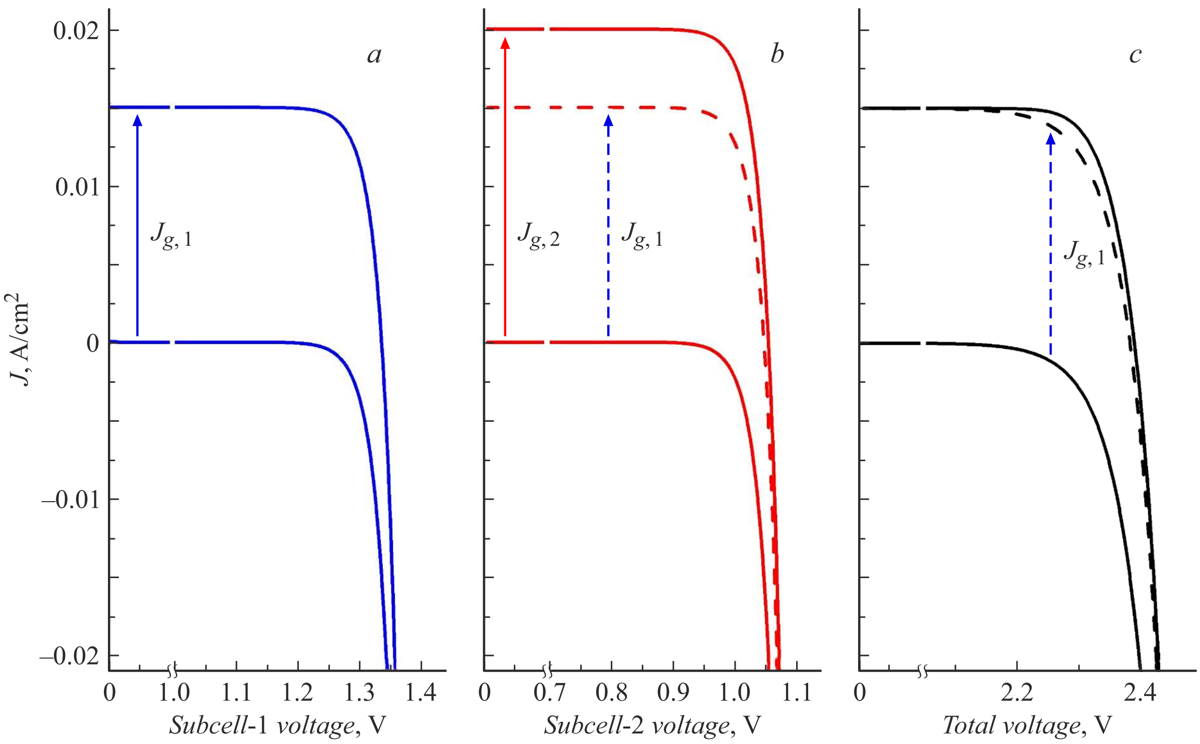

Figure 1. Calculated set of JV characteristics for subcells and MJ SCs of the structure under modeling. a — top GaInP-subcell, b — bottom GaAs-subcell, c — double-junction GaInP/GaAs SC. Lower solid lines are dark JV curves. Upper solid lines are light JV curves for the case of the PG-currents imbalance ($J_{g,GaInP} = 0.015\,\mathrm{A/cm^2}$ and $J_{g,GaAs} = 0.02\,\mathrm{A/cm^2}$). JV characteristics represented by dashed lines were obtained by shifting the dark JV characteristic by the magnitude of the SC short-circuit current.

where i is the subcell number, A_i is the subcell diode coefficient, $A = \sum_{i=1}^{n} A_i$, $J_0 = \sqrt[A]{\prod_{n=1}^{n} J_{0,i}^{A_i}}$ is the segment saturation current, $J_{0,i}$ is the subcell saturation current, k is the Boltzmann constant, T is the absolute temperature, q is the electron charge, κ_i is the subcell imbalance ratio (the ratio of the subcell PG-current to SC PG-current), J_g is the SC PG-current. The second term in (1) (V_a) is referred to as additional imbalance voltage (turns to zero when the PG-currents are completely balanced).

Fig. 1 presents the calculated JV characteristic. For both subcells (Fig. 1, a, b), two JV characteristics were calculated: the dark and light ones. After that, voltaic summation of the corresponding JV characteristics was performed, and total dark and light characteristics of the double-junction SC were obtained (Fig. 1, c). Other light JV characteristics were also obtained by shifting in current the dark JV curve by the value of the SC short-circuit current. In view of the chosen values, the first-subcell PG-current (designated as $J_{g,1}$ in Fig. 1) is the lowest one and equals the SC short-circuit current. Therefore, for the given subcell, the JV characteristic obtained by shifting coincides with its light JV characteristic. For the second-subcell PG-current, an excessive value was chosen; therefore, shifting of its dark JV characteristic by the same current value gives the JV characteristic represented in Fig. 1, b by the dashed line. Such a JV characteristic would be inherent to the second subcell in the case of completely balanced PG-currents. The same shifting was performed also for the total SC JV characteristic; the result is represented by the dashed line in Fig. 1, c. The plots clearly demonstrate that this JV characteristic is balanced and may also be obtained by voltaic summation of the light JV characteristic of the first subcell with that of the second subcell under balance (dashed line).

Obviously, the voltaic difference of the light JV characteristics in Fig. 1, c is equal to that of the light JV characteristics of the second subcell possessing excess current (Fig. 1, b), and, as per (1), is described by the additional imbalance voltage

$$V_a = \frac{kT}{q} \ln\left(\frac{\kappa_i J_g - J}{J_g - J}\right), \qquad (2)$$

where J_g is the MJ SC PG-current equal to the lowest of the PG-currents ($J_g = J_{g,1}$ in this calculation), $\kappa_i = \frac{J_{g,2}}{J_{g,1}}$ is the imbalance ratio. On the linear current scale (Fig. 1, b), the presence of additional voltage changes the light JV curve shape only slightly; however, such a change in the curve is indeed critical for using logarithmic models of JV characteristics. Fig. 2 illustrates the comparison of the dark and light JV characteristics calculated for different incident-radiation concentration ratios X (the curve with $X = 1$ corresponds to the light JV characteristic presented in Fig. 1, c). The comparison was performed in the logarithmic

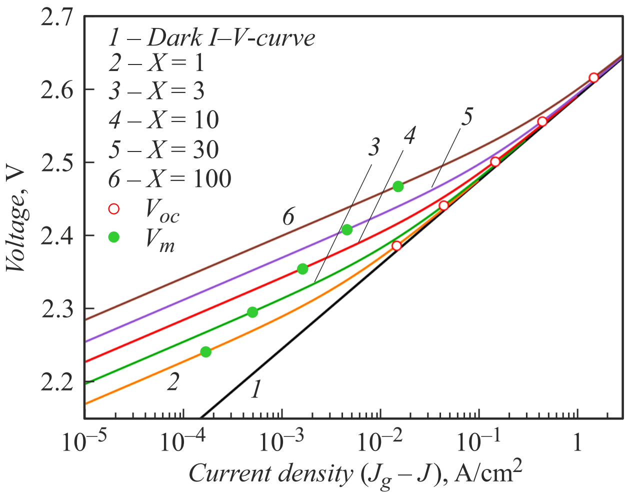

Figure 2. Comparison of the calculated dark (*Dark I–V-curve*) and light JV characteristics of the generation part of the simulated MJ SC structure. The light JV curves are plotted as a function of $V(J_g - J)$, i.e., they are transformed JV curves. The light JV characteristics were obtained for different concentration ratios X of incident radiation. The symbols mark the positions of the open-circuit voltages (open circles) and maximum-power-point voltages (filled circles) on the light JV curves.

current scale. For this purpose, the current of all the light JV characteristics was reduced by the value of PG-current and taken with the opposite sign, which is identical to a reverse shift of the light JV characteristic. This operation for the single-junction solar cells results in coincidence of the light and dark JV curves. Thus, if all the JV dependences $V(J)$ are transformed into $V(J_g - J)$ dependences (where V is the voltage of the light JV characteristic, J_g is the PG-current, J is the current of the light JV characteristic), then the obtained characteristics will coincide.

Since in calculations the saturation current of only one type (diffusion) was taken into account, the general MJ SC JV characteristic is to consist of one segment and look linear on the logarithmic current scale. Fig. 2 clearly demonstrates that these criteria (all PG-currents are zero) are met only by the dark JV characteristic which is balanced in terms of PG-currents. Fig. 2 clearly demonstrates that these criteria are met only by the dark JV characteristic which is balanced in terms of PG-currents (all PG-currents are zero). Light JV characteristics deviate significantly but towards the side where the voltage increases with decreasing current, which is abnormal for JV characteristics. Thus, we can conclude that, though the shapes of the light JV characteristics of MJ SCs are similar to those of typical JV characteristics of single-junction SCs, applying the classic (multi-diode) models to the former is incorrect. Notice also that at high $J_g - J$ all the light characteristics merge together. This is because low values of J make J_g in expression (2) negligible with respect to J. Then the additional imbalance voltage becomes zero.

Of a particular note is the behavior of JV-curve points corresponding to the open-circuit and maximum-power-point modes (open and filled circles in Fig. 2, respectively). One can see that these PV- characteristics, $V_{oc}(J_g)$ and $V_m(J_g - J_m)$, retain the logarithmic shape and are shifted in voltage relative to the dark JV curve. As per the estimates made in [7], this is because the additional voltages for the open-circuit and maximum-power-point voltages are constants independent of ratio X. Rigorous proof of this fact is the goal of further research. In this work, to verify the observed behavior of both the light JV characteristics and PV- dependences, experimental characteristics (similar to the calculated ones presented in Fig. 2) were measured and plotted for a triple-junction GaInP/GaAs/Ge SC. The characteristics are presented in Fig. 3. All the measurements were made in the mode of varying illumination with the AM1.5D light flux.

Experimental light JV characteristics differ from the dark JV characteristic in the same way (as in the calculations shown in Fig. 2). In the considered range of currents, the dark JV characteristic consists of two segments with different diode coefficients ($A = 12$ and 4). In accordance with (1), the additional imbalance voltage is different in each segment; therefore, shifts of points V_{oc} and V_m should be different. Notice that the smallness of the shift of the open-circuit voltage point prevents its experimental observation, while for the maximum-power-point voltage a constant shift of characteristic $V_m(J_g - J_m)$ relative to the dark JV characteristic is observed in each segment.

Thus, this work is devoted to investigating the effect of the PG-currents imbalance on the light JV characteristics and positions of the maximum-power-point and open-circuit voltages of these characteristics. Notice that just those two voltage points determine the main SC photovoltaic charac-

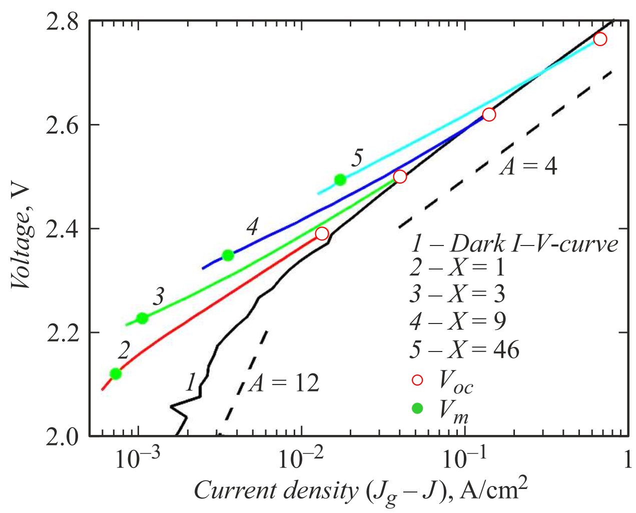

Figure 3. Experimental dark and light JV characteristics of the generation part of the triple-junction GaInP/GaAs/Ge SC. All the plots are constructed in the same way as in the case of the calculated JV characteristics in Fig. 2. The dashed lines represent characteristics with diode coefficients $A = 12$ and 4.

teristics, such as the filling factor and efficiency. Calculations and experimental measurements have shown that the light JV characteristics in the case of imbalanced PG-currents deviate from the typical segmental shape of the dark JV characteristic. Thereat, photovoltaic dependences V_{oc} and V_m remain logarithmic but shift by an almost constant voltage increment depending on the JV characteristic segment. Hence, the same behavior can be expected for other characteristics being obtained by analyzing the maximum-power-point and open-circuit voltages, including such a practically significant characteristic as the SC efficiency. Notice that the effect of imbalance of photogenerated currents affects the shape of the experimental SC characteristics, which should be taken into account in the analysis.

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] M. Bonnet-Eymard, M. Boccard, G. Bugnon, F. Sculati-Meillaud, M. Despeisse, C. Ballif, Solar Energy Mater. Solar Cells, **117**, 120 (2013). DOI: 10.1016/j.solmat.2013.05.046

[2] M. Wanlass, S.P. Ahrenkiel, R.K. Ahrenkiel, D.S. Albin, J.J. Carapella, A. Duda, J.F. Geisz, S. Kurtz, T. Moriarty, R.J. Wehrer, B. Wernsman, in *Conf. Record of the Thirty-first IEEE Photovoltaic Specialists Conf.* (IEEE, 2005), p. 530–535. DOI: 10.1109/PVSC.2005.1488186

[3] M. Meusel, R. Adelhelm, F. Dimroth, A.W. Bett, W. Warta, Prog. Photovolt.: Res. Appl., **10**, 243 (2002). DOI: 10.1002/pip.407

[4] I. Garcia, R.M. France, J.F. Geisz, W.E. McMahon, M.A. Steiner, S. Johnston, D.J. Friedman, IEEE J. Photovolt., **6**, 366 (2016). DOI: 10.1109/JPHOTOV.2015.2501722

[5] C. Dominguez, I. Antón, G. Sala, Prog. Photovolt.: Res. Appl., **18**, 272 (2010). DOI: 10.1002/pip.965

[6] E.F. Fernandez, G. Siefer, F. Almonacid, A.J. García Loureiro, P. Pérez-Higueras, Solar Energy, **92**, 221 (2013). DOI: 10.1016/j.solener.2013.03.012

[7] M.A. Mintairov, N.A. Kalyuzhnyy, V.V. Evstropov, V.M. Lantratov, S.A. Mintairov, M.Z. Shvarts, V.M. Andreev, A. Luque, IEEE J. Photovolt., **5**, 1229 (2015). DOI: 10.1109/JPHOTOV.2015.2416006

[8] G.S. Kinsey, P. Hebert, K.E. Barbour, D.D. Krut, H.L. Cotal, R.A. Sherif, Prog. Photovolt.: Res. Appl. **16**, 503 (2008). DOI: 10.1002/pip.834

[9] M.A. Mintairov, V.V. Evstropov, S.A. Mintairov, M.Z. Shvarts, S.A. Kozhukhovskaia, N.A. Kalyuzhnyy, J. Phys.: Conf. Ser., **917**, 052034 (2017). DOI: 10.1088/1742-6596/917/5/052034

[10] V.M. Andreev, E.A. Grebenshchikova, P.A. Dmitriev, N.D. Ilinskaya, V.S. Kalinovsky, E.V. Kontrosh, A.V. Malevskaya, A.A. Usikova, Semiconductors, **48** (9), 1217 (2014). DOI: 10.1134/S1063782614090024.

[11] R. Adelhelm, K. Bucher, Solar Energy Mater. Solar Cells, **50**, 185 (1998). DOI: 10.1016/S0927-0248(97)00143-8

Translated by Ego Translating