Counter-Photo-Electromotive Force at Heterointerfaces in MJ SC: Study by Spectral Method

Mikhail Mintairov [a)], Valery Evstropov, Maxim Shvarts,
Svetlana Kozhukhovskaia, Sergey Mintairov and Nikolay Kalyuzhnyy

Ioffe Institute, 26 Polytechnicheskaya str., St.-Petersburg, 194021, Russia

[a)]Corresponding author: mamint@scell.ioffe.ru

Abstract. The influence of p-n junction heating on dependence of the open circuit voltage on the photogenerated current density (V_{oc}-J_g) has been observed and procedure for V_{oc} correction has been suggested. Using this procedure the corrected V_{oc}-J_g dependence has been obtained for triple-junction GaInP/GaAs/Ge solar cells. The shape of V_{oc}-J_g dependence has been discussed, and it was suggested that it indicates the appearance of a counter EMF of about *10 mV* at J_g = *100 A/cm*^{2}. It is assumed that this counter EMF is generated on some isotype heterointerface. The spectral method for determining the position of such heterointerface has been considered.

INTRODUCTION

Construction of a solar cells (SCs) and especially of a multijunction (MJ) one supposes a feasibility for arising a counter ("adverse") EMF, which counteracts the useful one, generated by photovoltaic p-n junctions. The counter EMF may be generated, for example, by heterointerfaces. Contribution of heterointerfaces into the series resistance was discussed earlier in [1-3]. In [3] I-V curves of heterointerfaces at different illuminations have been obtained. The shape of these curves depends on illumination. It was explained by variation of hetero-barrier tunneling transparency but also may result from EMF generation. The counter photo-EMF was mentioned in [4]. Besides, its existence may be judged by the presence of maximum (or tendency to saturate) on the experimental V_{oc}-J_g dependence. Such experiments have been collected in [5].

Study of the V_{oc}-J_g dependence allows determining parameters of the heterointerface generating the counter photo-EMF. Beside this problem, the determination of location of such type hetero-barriers is also important. As it shown it can be done by studying the spectral dependence of the photo-EMF.

In this work:

- an extrapolation procedure for obtaining corrected (with reducing influence of heat) V_{oc} has been proposed and applied;
- investigation of the corrected dependence V_{oc}-J_g for a triple-junction GaInP/GaAs/Ge SC has been carried out and parameters of supposed counter EMF were estimated;
- spectral procedure for determining location of heterointerfaces generating the counter EMF has been considered;

PROCEDURE FOR OBTAINING THE CORRECTED V_{OC}-J_G DEPENDENCE

The presence of maximum (or tendency to saturate) on the experimental V_{oc}-J_g may result from heating the p-n junction by incident radiation. Hence, it is necessary to correct V_{oc} values, which is especially important in measuring V_{oc} at ultra-high sunlight concentrations.

The proposed procedure supposes strictly rapid light switching. At such light switching, the expected voltage-time dependence should have a shape of a rectangular triangle due to a gradual temperature rise [6-8] (if the

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transition electric processes in the p-n junction and in equipment are neglected). The triangle acute apex gives the required value of the not heated p-n junction voltage. Note that light switching close to the required one takes place in pulsed sunlight simulators, which are used for obtaining I-V curves at different sunlight concentrations. Such simulators give a short pulse (about *2 ms*). The pulse shape is presented in (Fig. 1). As seen, in the region from *0.7* to *2.1 ms* the pulse has a "shelf", which is generally used for obtaining the whole I-V characteristic. In this case, it was usually assumed that there is no p-n junction heating during this time. Hence, the value of V_{oc} can be measured at any moment after the pulse start. However, the shape of the time dependence of V_{oc} shows that the voltage drops with time (Fig. 1). The V_{oc} drop is strictly linear, which also proves the constancy of the incident power after t_0 (light switching moment). The linear dependence of V_{oc} on temperature is well known[6-8], which makes easier to extrapolate V_{oc} before the zero moment of time t_0. The dependence of extrapolated V_{oc} values on J_g is presented in Fig.2b (black line). It is assumed to be close to isothermal one.

Note that the shape of experimental time dependence of light intensity (top on Fig. 1) does not coincides with idealized one. The front edge of the pulse (from *0.42* to *0.7* ms) is not sharp, so there is less light intensities and less p-n junction heating at front edge duration. In this case, the corrected V_{oc} value is overestimated. So the proposed procedure cannot give the lower V_{oc} values compared to a not heated sample. Otherwise one has to consider superlinear decrease of V_{oc} with temperature.

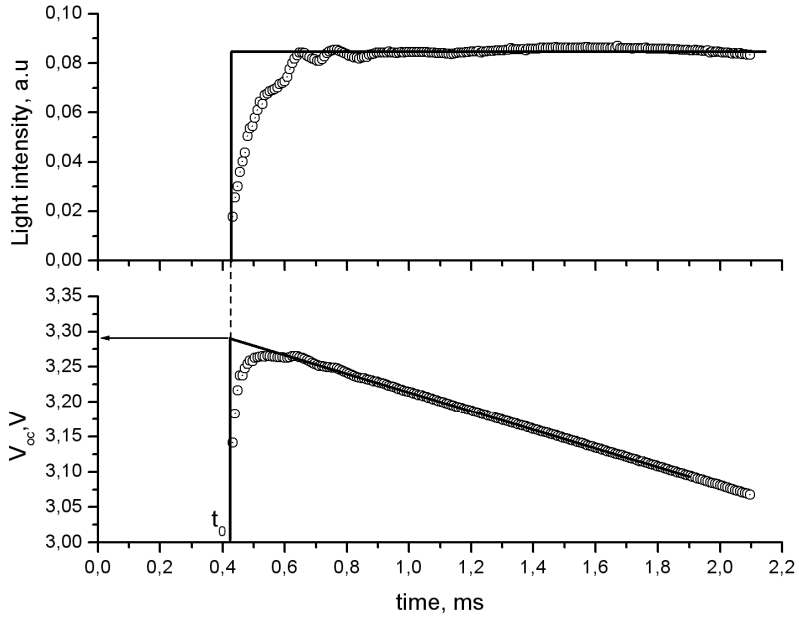

FIGURE 1. Experimental time dependence of light intensity and V_{oc} (symbols) and their extrapolation (lines). Photogenerated current density *110.6 A/cm*^{2}.

EXPERIMENTAL V_{OC}-J_G DEPENDENCES

A GaInP/GaAs/Ge triple-junction solar cell has been investigated. All measurements were carried out on a «wafer» cell (cell is a part of non-diced wafer, cell size 2x2 mm, wafer size: ~10x10 mm). At V_{oc} being recorded, the wafer was mounted on a massive thermostabilizes vacuum chuck.

Fig. 2b presents the V_{oc}-J_g dependences obtained at different moments of pulse (Fig. 2a), what corresponds to the conventional way of measuring this dependence. It is seen that the experimental curves t_1-t_7 converge to the extrapolated t_0 one. It is also clear that the extrapolated curve (black on Fig. 2b) does not reach the rated one with expected ideality factor (A=3) at ultra-high current densities. This indicates the counter EMF existence or insufficient V_{oc} correction. As it has been mentioned above, the correction procedure may give only overestimated V_{oc} values, so the real isothermal V_{oc} values are equal or smaller than the corrected ones. Thus, in this work, we suggest that such a behavior of V_{oc}-J_g dependence is explained by the presence of a counter EMF. The voltage

difference between the extrapolated and rated curves is approximately *10 mV* at current dencity of *100 A/cm*^{2} (Fig. 2b).

The deviation of V_{oc}-J_g dependence from curve with ideality factor A=3 (Fig. 2b) can be approximated by the known formula:

$$V_{oc} = E \cdot \ln\left(\frac{J_g}{J_0} + 1\right) \qquad (1)$$

according to the obtained data, the value of J_g/J_0 is less than unity. For this reason, (1) can be rewritten as:

$$V_{oc} = E \cdot \frac{J_g}{J_0} \qquad (2)$$

where E is voltage ideality facror. Using formula (2) for approximating the V_{oc}-J_g deviation gives E/J_0 value about $9 \cdot 10^{-5}$ *V/(A/cm*^{2}*)*.

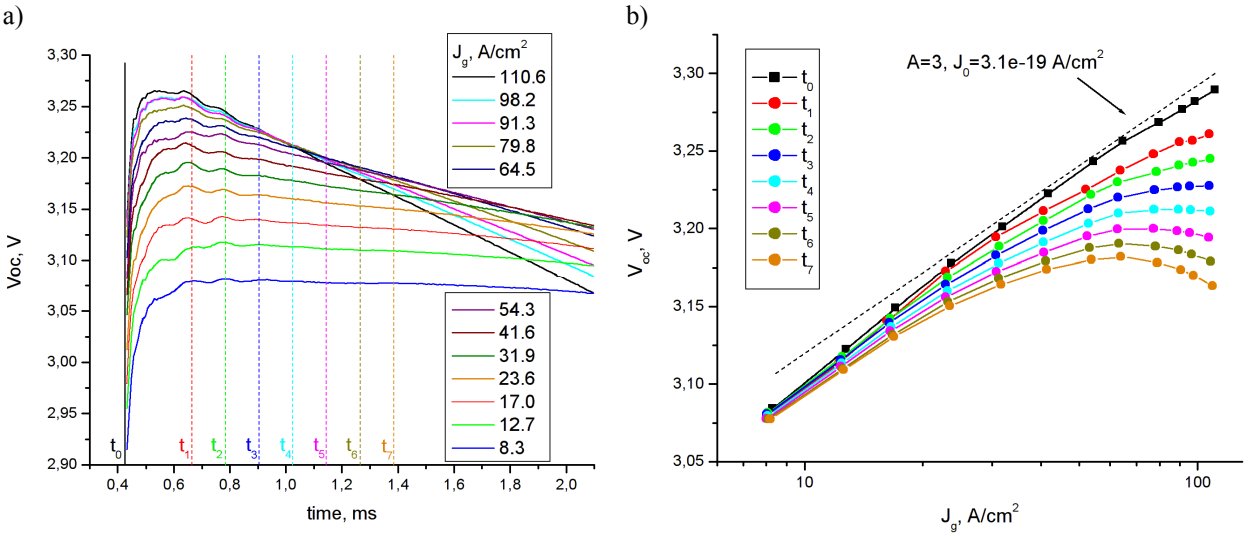

FIGURE 2. a) - Experimental time dependences of V_{oc} at different illumination. b) - V_{oc}-J_g dependences obtained at different time of pulse (t_1-t_7) and isothermal one (t_0) obtained by extrapolation (see previous section).

SPECTRAL DEPENDENCE OF V_{OC}

The location of the counter EMF source could be obtained by the study of the spectral dependences of V_{oc} at different illuminations. The method is based on that photons of different wavelengths are absorbed in different structure layers. For this reason, in varying the incident radiation spectral composition, one can observe EMF generation by different parts of the structure (photovoltaic p-n junctions or heterointerfaces).

Fig. 3 presents calculation of spectral dependences for a GaInP/GaAs/Ge SC structure with and without a counter EMF. The calculation is based on the exponential character of light absorption in the SC structure. The structure was represented as a row of regions with their own width and absorption spectra. Each region represents one part of the structure - optical window, back surface filed barrier, photovoltaic p-n junction or a set of layers between subcells. In calculating the spectral dependences, the following simplifications were made, which does not change the common characteristic shape of the spectral dependence. First, dependence of the absorption coefficient on the doping level was not taken into account; second, the interferential effects arising at the boundaries of different materials were not taken into account either; third, it believed that, in the layers between subcells, the absorption coefficient does not change and is equal to that for GaInP (for the layers between the top and middle subcells) and for GaAs (for the layers between the middle and bottom subcells).

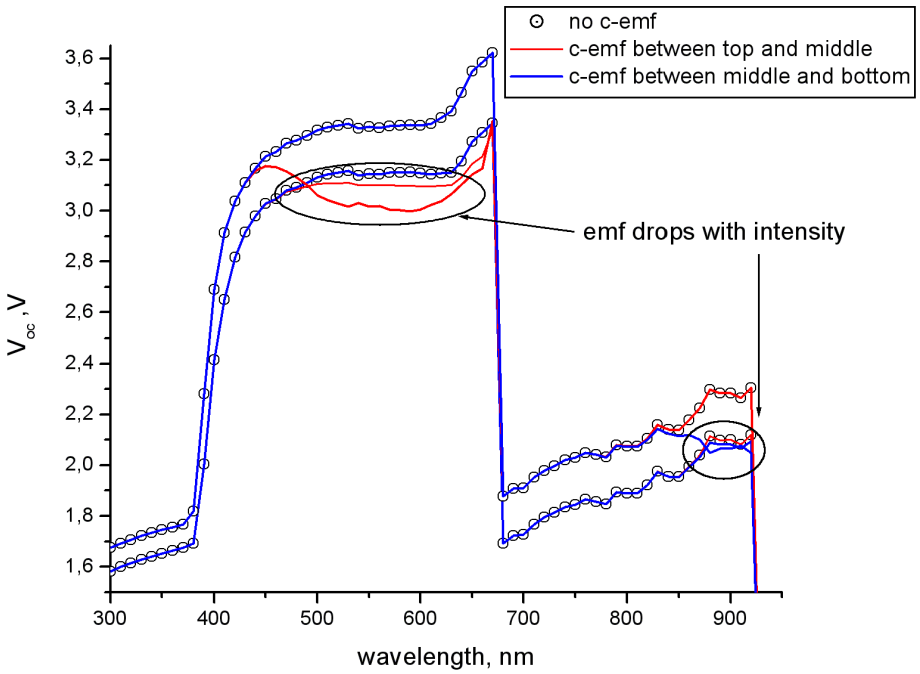

FIGURE 3. Calculated spectral dependences of V_{oc} at two light intensity for GaInP/GaAs/Ge. Black circles – no heterointerface, red lines – heterointerface between top and middle subcells, blue lines – heterointerface between middle and bottom subcells.

The V_{oc} calculation for the counter EMF was done by using (2). The E/J_0 value were taken $9 \cdot 10^{-5}$ $V/(A/cm^2)$ (same as was found in prevous section). Calculation of p-n junctions V_{oc} were done by using the following expression:

$$J_g = J_{01} \cdot \exp\left(\frac{qV_{oc}}{kT}\right) + J_{02} \cdot \exp\left(\frac{qV_{oc}}{2kT}\right) \Leftrightarrow V_{oc} = \frac{2kT}{q} \ln\left(\frac{\sqrt{J_{02}^2 + 4J_{0d}(J_g + J_{02} + J_{01})} - J_{02}}{2J_{01}}\right) \quad (3)$$

The preexponential factors J_{01} and J_{02} were taken: 10^{-25}, 10^{-13}; 10^{-20}, 10^{-10}, 10^{-6}, 0 A/cm^2 for GaInP, GaAs and Ge p-n junctions, respectively.

In case of absence of the counter EMF, the spectral dependence (Fig.3, black circles) contains parts, on which voltage is generated only by one of p-n junctions, and the parts, where voltage is generated by several p-n junctions. In this case, in increasing illumination, voltages on all parts rise. If the structure contains sources of the counter EMF, a part appears where voltage decreases with illumination. Position of this part on the spectral dependence is determined by the location of the heterointerface in the structure. Thus if heterointerface located between top and middle subcells (Fig. 3, red lines), such part located between 400-700 nm. In case of blue lines on Fig. 3 when heterointerface located between middle and bottom subcells the part located between 800-950 nm.

Thus, the described spectral method allows determining the location of the heterointerface generating the counter EMF. Note that, for using the spectral method, the illumination level should be sufficient for observing the counter EMF on the background of voltage generated by photovoltaic p-n junctions. Such an illumination level one can gain in applying pulsed simulators with filters or by means of a strong monochromatic radiation (for example, using a laser).

CONCLUSION

The experimental data for a triple-junction InGaP/GaAs/Ge SC show that the V_{oc}-J_g dependence shape at $J_g > 20$ A/cm^2 deviates from the expected $V_{oc} = AkT/q \ ln(J_g/J_0 + 1)$, where $A = 3$.

The deviation is as follows: first, the differential slope of V_{oc}-J_g is less than expected, second, it decreases in increasing J_g. There exist two probable causes for this deviation – heating and arising of the counter EMF. For

allowing for heating, an extrapolation procedure has been applied. As a result the corrected V_{oc}-J_g dependence has been obtained. It also deviates from the expected one, but significantly less than the initial experimental ones. As a result, it has been shown that, in a triple-junction GaInP/GaAs/Ge solar cell there exist conditions for appearance of the counter EMF. Its value is approximately *10 mV* at J_g of about *100 A/cm*^{2} and can be described by the formula $V_{oc}=J_g \cdot E \cdot / J_0$, where $E \cdot / J_0$ is about $9 \cdot 10^{-5}$ *V/(A/cm*^{2}*)*. Therefore the corrected V_{oc}-J_g dependence allows insisting the existence of a counter EMF in triple-junction solar cells. However, an additional evidence is desirable.

A spectral method for studying the counter EMF has been considered. Calculation of the spectral dependence of EMF for a GaInP/GaAs/Ge SC has been carried out. It has been shown that the proposed method allows determining the location of heterointerfaces generating the counter EMF. The spectral method is also useful for finding additional evidence of counter EMF existence.

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