Manifestation of counteracting photovoltaic effect on IV characteristics in multi-junction solar cells

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Abstract. The existence within monolithic double- and triple-junction solar cells of a photoelectric source, which counteracts the basic photovoltaic p-n junctions, is proved. The paper presents a detailed analysis of the shape of the light IV-characteristics, as well as the dependence \( V_{oc}-J_{sc} \) (open circuit voltage - short-circuit current). It is established that the counteracting source is tunnel \( p^-n^-n^- \) junction. The photoelectric characteristics of samples with different tunnel diode peak current values were investigated, including the case of a zero value. When the tunnel \( p^-n^-n^- \) junction is photoactive, the \( V_{oc}-J_{sc} \) dependence has a dropping part, including a sharp jump. This undesirable effect decreases with increasing peak current.

1. Introduction

Multi-junction solar cells (MJ SC) - a promising direction for the development of semiconductor photovoltaics. Due to its sophisticated design the specific effects are possible. One of such effect is the producing of a photo-electromotive force (photo-emf), which counteracts the operation of basic photovoltaic p-n junctions (sub-cells). This is revealed in the deformation of the normal shape of the \( V_{oc}-J_{sc} \) characteristic (open-circuit voltage - short-circuit current), which can have an abnormal portion - the drop of \( V_{oc} \) with \( J_{sc} \) growth. Such deformations were observed in a number of experiments [1,2]. As shown in [3] the same \( V_{oc}-J_{sc} \) deformation may be connected with the effect of incident radiation heating. The heating effect can be eliminated by using the extrapolation method, described in details in [3]. The experiments showed that the heating effect should be taken into account (with an error of <1%) only if the concentration of solar radiation is greater than 2000 suns. Meanwhile, in the process of search and investigation work on the optimization of triple-junction GaInP/GaAs/Ge and double-junction GaInP/GaAs SCs, a number of samples were obtained with the \( V_{oc}-J_{sc} \) anomaly observed at concentration less than 2000 suns.

The present work deals with the origin of this anomaly which is the appearance of photo-emf source, counteracting the basic photovoltaic p-n junctions. This source is located in the tunnel region between InGaP and GaAs sub-cells (\( p^-\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}/n^+\text{GaAs} \)). The counteracting photo-emf supresses the growth of \( V_{oc} \) with the \( J_{sc} \) and leads to the appearance of a \( V_{oc} \) drop portion. It was found that, this effect is also accompanied by a sharp \( V_{oc} \) jump (Figure 1, sample C) when the photocurrent flowing through the tunnel region is equal to tunnel peak current. If there is no jump (Figure 1, sample B), then it means that the peak on the dark IV-characteristics of the tunnel pn junction is practically absent – tunnel peak current equals zero. The counteracting photovoltaic effect was observed on both triple- and double-junction SCs. In all cases, the tunnel region between GaInP and GaAs p-n junctions was grown identically. This effect is most convincingly shown on the family of experimental light IV characteristics for sample C (Figure 2c).
2. Object of study

Three samples of double-junction GaInP/GaAs SCs were studied. All samples were grown by metal-organic vapour phase epitaxy (MOVPE). In all samples the tunnel junctions were grown in the same way - 30 nm p⁺: Alox,Ga0.6As doped to a concentration of (1-5)×10¹⁹ cm⁻³ and 15 nm n⁺: GaAs doped to (5-7)×10¹⁸ cm⁻³. The design of GaAs and GaInP sub-cells differs slightly. Sample C has important structural difference compare to other samples. Its structure doesn't have a wide-gap barrier between the GaInP sub-cell and the tunnel diode. That makes possible the injection of photogenerated carriers from GaInP sub-cell into the tunnel diode.

Measurements of IV-curves were carried out on a pulsed solar radiation simulator. The simulator is equipped with devices for monitoring the level of illumination and temperature of the SC under examination, as well as a four-probe system for measuring the IV characteristics. The peak current of the tunnel diodes was registered with the voltage decreasing scanning direction. Maximum concentration of solar radiation reaches about 10,000 suns.

3. Light IV characteristics of the tunnel part

For all studied samples, a set of light IV-curves recorded at different illumination was obtained. On the basis of these measurements, the $V_{oc}$-$J_{sc}$ dependencies (Figure 1) were constructed. Similar to [4] procedure for connecting part IV-curve extraction was performed. The result of the extraction is shown in Figure 2. It can be seen from Figure 1 that all the dependences contain a portion of the linear growth (in the logarithmic current scale) of $V_{oc}$. In the case of sample A, this region extends up to a current of 25 A/cm². This current corresponds to the illumination of the order about 1500 suns. Perhaps the stop of further linear growth of $V_{oc}$ may be due to the aforementioned heating of the sample [4]. The $V_{oc}$ drop on sample C occurs at lower currents (about 3 A/cm²), and there is also a jump in the region of 20 A/cm². This is due to the photoactivity of the tunnel diode, which can be clearly seen in Figure 2c. The presence of a jump is related to the fact that the peak vertex of the tunnel diode becomes below the zero axis, this is discussed in detail in Section 4. The $V_{oc}$ drop for sample B occurs even earlier (about 0.1 A/cm²), which is also related to the counter photo-emf in the tunnel part. In this case, the value of the counter photo-emf is much larger than for other samples. This is due to the fact that the peak current is zero, so there is no pre-jump portion, which is well observed for sample C. This is demonstrated in detail and discussed in Section 4.

From the experimental light IV-curves (circles of Figure 2), the light IV-curves of the connecting part were extracted. For this purpose, the light IV-curves of the basic photovoltaic (generator) part of the solar cell were reproduced. The basic (generator) part, as in [4], consist of GaInP and GaAs p-n junctions with identical photogenerated currents. Reproduced IV-curves are described by the formulas:

$$J = J_g - J_{dark}$$

$$J_{dark} = J_{02} \left( \frac{V_{dark}}{2kT} - 1 \right) + J_{03} \left( \frac{V_{dark}}{3kT} - 1 \right)$$

where k – Boltzmann constant, T – absolute temperature. The pre-exponents $J_{02}$ and $J_{03}$ necessary for reproduction are taken from the fitting of the linear parts of the experimental $V_{oc}$-$J_{sc}$ characteristics. The fitting result is shown of Figure 1 (dashed black line). This characteristic functionally coincides with the dark IV-curve $(J_{dark} \rightarrow J_{sc}, V_{dark} \rightarrow V_{oc})$ if the photo-generated sub-cell currents are equal [4]. The reproduced IV-characteristics are shown by solid lines in Figures 2a, 2b, 2c. Then a voltaic subtraction of the experimental and reproduced IV characteristics was made. The obtained (extracted) IV-curves are the IV-curves of a SC connecting part (tunnel-junction and resistive elements of SC). The IV-curves are shown in the left part of Figure 2a, 2b, 2c by triangles symbols. It is seen that connection IV-curves are moving "down", i.e. contrary to the "up" movement of the basic IV-characteristics.
Figure 1. Experimental $V_{oc}$-$J_{sc}$ dependencies (circles) for GaInP/GaAs SC, deformed by the action of the counter phot/emf. All experimental dependences deviate from a normal dependence (dashed curve). Normal curve obtained by fitting linear parts of the experimental $V_{oc}$-$J_{sc}$ characteristics with formula 1b. The obtained fitting parameters are $J_{02}=1.5\times10^{-24}$ A/cm$^2$, $J_{03}=5.5\times10^{-16}$ A/cm$^2$.

On Figure 2a and 2b (especially 2b) it is clearly seen that the vertex of the tunnel junction peak moves «down» (in the direction of decrease), while the short-circuit current of SC goes «up». These opposite motions prove that the photoelectric effect is connected with the tunnel AlGaAs/GaAs hetero- $p^+-n^+$ junction, which counteracts the photoelectric effect of the basic GaInP and GaAs p-n junctions. Note that the sample B (Figure 2b) does not have a peak current, but the motion of the extracted IV characteristics, which is opposite to the base motion, is still observed. The investigated samples differed in the initial coordinate of the peak vertex (25 A/cm$^2$, 0 A/cm$^2$, 8 A/cm$^2$ for A,B,C sample respectively). These differences are reflected in the nature of the fall of $V_{oc}$ with the growth of $J_{sc}$ (Figure 1). The sample C shows the $V_{oc}$ sharp jump (Figure 1, green circles) when the peak vertex of the tunnel junction passes through the zero value (Figure 2c green IV-curves). At the sample B there are no jumps because the sample does not have a peak current. The sample A has a high peak current value, and the voltage drop effect starts at higher currents.
Figure 2. Light IV-curves (a – for sample A, b – for sample B and c – for sample C) at different illumination: circles - experimental IV-curves; solid lines - IV-curves of the generator part (constructed with the help of formula 1, with parameters taken from the analysis of the $V_{OC}$-$J_{SC}$ characteristics Figure 1); triangles - IV curves of connecting (tunnel plus resistive) parts, obtained by volt subtraction of IV curves of the experimental and generator parts.

4. The principles of the anomalous of Voc-Jsc dependence formation
The IV-curves of double-junctions SC was calculated to demonstrate the interpretation of the obtained results. The calculation of each IV-curve was carried out as follows. According to eq. 1, the generator IV-curve was calculated, the parameters for calculation were taken as those used to calculate the generator IV-curves in Section 3. To calculate the IV curves of the tunnel part, we used the expression like [5].

$$J = -J_{gt} + \left[ J_p \left( \frac{-V}{E_p} \right) \cdot \exp \left( 1 - \frac{-V}{E_p} \right) + J_{0t} \cdot \exp \left( \frac{-V}{E_t} - 1 \right) \right]$$

(2)

The expression in square bracket consists of two parts, iso-energetic (given by parameters $J_p$ – peak current, $E_p$ – voltage peak parameter), and tunnel-trap (given by parameters $J_{0t}$ – preexponent, $E_t$ – diode voltage coefficient). The resulting full IV-curve was obtained by voltaic summation of both generator and tunnel parts IV-curves. This calculation was carried out for two cases: in one case the tunnel peak current $J_p$ was equal to 20 A/cm$^2$, in the other 0. The remaining parameters for calculating the tunnel part were the same in both cases: $E_p=0.05$ V, $J_{0t}=2.5$ A/cm$^2$, $E_t=0.2$ V.
Figure 3 shows the result of these estimates. On the right there are IV curves of the tunnel parts with a peak current of 20 A/cm² (at the upper left, Figure 3) and 0 (lower left). The magnitude of the counter photo-emf, is marked with lines with numbers. On the right there is a calculation of the \( V_{oc}-J_{sc} \). The black dashed line - the dependence in the absence of the counteracting photo-emf, the green and blue dotted lines - the counter photo-emf is generated by the tunnel part with a peak current of 20 and 0 A/cm², respectively. Numbers and symbols mark the points corresponding to the points on the graph on the left. As one can see (Figure 3, upper left), the tunnel part with \( J_p = 20 \) A/cm² generates small photo-emf (points 1, 2, 3 ’). This occurs as long as the peak current is above 0 and the generation of photo-emf is going in the iso-energetic regime. Further, the generation of photo-emf occurs on the tunnel-trap regime (points 3 ”, 4,5,6). The transition from one regime to the other (between the points 3 ” and 3 ’) is manifested in a jump of the \( V_{oc}-J_{sc} \) dependence. For the case when the tunnel part has a zero peak current (Figure 3, left, bottom), the iso-energetic term of the tunnel junction IV-curve is absent, so a large counter photo-emf is immediately generated.

The similar behavior as shown in Figure 3 can be seen in the presented experimental \( V_{oc}-J_{sc} \) dependencies (Figure 1) and extracted IV curves (triangles in Figure 2). For sample A, the peak vertex of the tunnel part is always above 0, so the "jump" of the \( V_{oc}-J_{sc} \) characteristic does not come, and we can expect a delayed "jump". The sample B tunnel part IV-curves does not have peaks (Figure 2b), and the behavior of the \( V_{oc}-J_{sc} \) dependence is the same as for 0-peak current simulation on Figure 3. The sample C tunnel part IV-curves have a peak. The peak cross 0-axis at \( J_{sc} \) about 15 A/cm² (Figure 2c) and its \( V_{oc}-J_{sc} \) dependence has a sharp Voc jump. So the behavior of these characteristics is the same as for simulated ones (green on Figure 3).
5. Conclusion
The photovoltaic effect in the connecting part of the MJ SC between GaInP and GaAs basic p-n junctions is found and considered. This connecting part includes p'-n' heterojunction – p' Al_{0.4}Ga_{0.6}As/n' GaAs. The photoelectric effect in the connecting part is directed against the action of the basic p-n junctions. This counteraction is manifested as a deviation of the $V_{oc}$-$J_{sc}$ dependence from the normal shape (linear in a semilogarithmic scale).
Especially convincingly, the effect can be seen on the set of light IV-curves for the sample C (double-junction GaInP/GaAs SC). These IV-curves show the peak current of the tunnel diode. The current vertex of the peak decreases (goes "down"), when the short-circuit current SC increases (goes "up"), i.e. movement is opposite.
IV-curves of the connecting part were extracted from experimental light IV characteristics. Their shape practically reflects the shape of tunnel junction IV-curves, with taking into account the influence of resistivity. It was shown that the shape of $V_{oc}$-$J_{sc}$ dependence is connected with tunnel junction IV-curve shape. The principles of $V_{oc}$-$J_{sc}$ dependence formation is considered and it is shown that the $V_{oc}$ jump is appears when the tunnel junction peak current vertex cross zero-axis. After this happen the value of voltage drop becomes dramatically high. The $V_{oc}$ jump can be used to diagnose the counter emf source existence.

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References
[1] M Stevens, C Downs, D Emerson, J Adler, S Maclachlan and T E Vandervelde, 2015 Proc. of 31 PVSEC, Hamburg (Germany) pp. 1474 – 1477
[2] B Chhabra, S Jacobs, C B Honsberg, 2006 IEEE PV Spec. Conf. pp 791 - 794,
[3] M A Mintairov, V V Evstropov, M Z Shvarts, S A Kozhukhovskaja, S A Mintairov and N A Kalyuzhnyy, 2016, AIP Conf. Proc. Freiburg (Germany) v 1766 p. 050005
[4] M A Mintairov, V V Evstropov, N A Kalyuzhnyy, S A Mintairov, N Kh Timoshina, M Z Shvarts, 2015 AIP Conf. Proc. Aix-les-Bains (France) v 1679 p. 050007
[5] S M Sze, 1981 *Physics of Semiconductor Devices* J. Willey and Sons, New York.