Determining the photogenerated current imbalance in multijunction laser photoconverters

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A method is proposed to determine the photogenerated current imbalance coefficient of multijunction photoconverters using volt-ampere characteristic analysis. The method was applied to a GaAs/GaAs two-junction laser photoconverter optimized to 800 nm. The method was demonstrated using the characteristics measured in incident radiation spectrum AM0 (solar spectrum in space) with the photoconverter running in the photogenerated current imbalance mode. The method showed that imbalance in that case was $\kappa = 1.8$.

Keywords: photoconverter, laser radiation, efficiency, photocurrent, mathematical simulation.

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Multijunction (MJ) laser photoconverters (LPC) are devices required for optoelectronic systems due to their capability of generating high voltage [1–3]. In monolithic MJ structures where subcells are connected in series, the total voltage is known to be equal to a sum of voltages generated by subcells, and the photogenerated current (PGC) is equal to the lowest current generated by subcells. Thus, to reach the maximum MJ LPC efficiency, the case where PGCs are equal is the best possible [4]. Therefore, when developing MJ LPC, it is important to choose subcell layer thicknesses such that all structure subcells have the same PGC during conversion of laser light with a desired wavelength.

PGC in MJ solar cells (SC) is usually controlled using experimental techniques for measuring external quantum efficiency of photoconductive response [5,6]. However, these methods are based on the fact that there is such incident light wavelength for each MJ SC subcell that is absorbed only in this subcomponent. In other words, these methods are applicable to MJ SC whose subcells have different band gap widths. Application of these methods for MJ LPC structures where subcells are made of the same materials is a very complicated and often unachievable metrological problem. Therefore, searching for new methods to detect the MJ LPC PGC imbalance is an essential challenge.

One of solutions is proposed in [7] where the authors measure volt-ampere characteristics and detect reverse-bias photocurrents of individual subcells due to the presence of large reverse leakage currents in all subcells. The mandatory reverse leakage current requirements limit the use of this method considerably.

This work proposes a new approach based on the experimental detection and analysis of the additional imbalance voltage [8]. Application of the proposed approach to a GaAs/GaAs MJ LPCstructure is described in the work.

The structure of the studied MJ LPC was grown by the metalorganic vapor phase epitaxy (MOVPE) using a horizontal low pressure reactor. Trimethylgallium and trimethylaluminum were used as sources of group III atoms, arsine was used as a source of arsenic, silane and diethylzink were used as sources of n-type and p-type impurities, respectively. The LPC structure consisted of two GaAs $p{-}n$ junctions connected in series via a tunnel diode, with AlGaAs barrier layers and the ideality factors A_1 and A_2, respectively. Imbalance coefficient κ is the ratio between a higher PGC an lower PGC.

According to [8], the equivalent circuit of such MJ LPC may be rearranged to two cells connected in series. The first cell consists of two $p{-}n$-junctions connected in series with the same PGCs that are equal to the lowest subcell current. Such cell may be replaced with one $p{-}n$-junction with $A_s = A_1 + A_2$ and saturation current (J_0) equal to geometric mean saturation current of the $p{-}n$-junctions. The second cell generates the voltage V_a that is called additional imbalance voltage in [8]:

$$V_a = \frac{A \cdot kT}{q} \ln\left(\frac{\kappa J_g - J}{J_g - J}\right), \qquad (1)$$

where q is the electron charge, k is the Boltzmann constant, T is the absolute temperature, A is the ideality factor of a subcell with excess photocurrent (may take the value of A_1orA_2 depending on which subcell is in imbalance A . The total VAC of the device is described as

$$V = \frac{A_s \cdot kT}{q} \ln\left(\frac{J_g - J}{J_0}\right) + V_a. \qquad (2)$$

κ may be determined using expression (1). V_a may be measured experimentally. For this, compare the light volt-ampere characteristic (VAC) with the dark one. The latter is always recorded in the PGC balance mode (PGCs of all subcells are equal to zero). Then, the dark VAC is compared with a set of light VACs measured at different incident radiation powers. Thus, V_a may be recorded repeatedly.

For this, a technique was proposed where VAC, voltage-current dependence ($V - J$), is converted into $V - J/J_g$, i.e. dependence of voltage on current/PGC ratio. Let's introduce ε equal to this ratio, $\varepsilon = J/J_g$. By substituting $J = \varepsilon \cdot J_g$ into (1), we get

$$V_{a,\epsilon} = \frac{A \cdot kT}{q} \ln\left(\frac{\kappa J_g - \epsilon J_g}{J_g - \epsilon J_g}\right) = \frac{A \cdot kT}{q} \ln\left(\frac{\kappa - \epsilon}{1 - \epsilon}\right). \quad (3)$$

From (3), it follows that the additional voltage is independent of the illumination level at currents being a constant fraction of the photogenerated current ε. Let's introduce V_ε and J_ε, where V_ε is the voltage on the light VAC at $J = J_\varepsilon = \varepsilon \cdot J_g$. As known, photoconverter (PC) voltages in different modes (for example, light and dark) shall be compared at the same current flowing through the PC p–n-junction, i.e. at $J_{pn} = J_g - J$. For the dark voltage, this current is equal to the dark current $J_{pn} = J_{\text{dark}}$, for the light VACs for J_ε, we get $J_{pn} = J_g - \varepsilon \cdot J_g = J_g(1 - \varepsilon)$. Thus, a new photovoltaic dependence of V_ε on $J_g(1 - \varepsilon)$ may be formed from the light VACs and will be shifted with respect to the dark VAC by a constant value of additional imbalance voltage $V_{a,\varepsilon}$calculated using expression (3). Based on this, a set of light VACs were measured, $V_{a,\varepsilon} - J_g(1 - \varepsilon)$ curves were plotted and compared with a resistance-free VAC. Comparison was made at different ε, thus, an experimental dependence of $V_{a,\varepsilon}$ was plotted and approximated by expression (3) to determine κ.

The GaAs/GaAs two-junction LPC used for the experimental trial of the above-mentioned technique was improved to convert the 800 nm laser light. For the improvement, subcell thicknesses were selected by calculating 800 nm light absorption in GaAs layers. The calculation assumed that absorption at this wavelength occurs exponentially with the absorption coefficient $a = 1.2161$ [9]. The calculated thicknesses were 558 nm for the upper subcell and 3700 nm for the lower one. The PG current balance was proved experimentally by the fact that its $V_\varepsilon - J_g(1 - \varepsilon)$ characteristics measured in 800 nm laser illumination conditions coincided, which is possible if $V_{a,\varepsilon} = 0$ and $\kappa = 1$. To demonstrate the proposed approach to determining κ, the same sample was illuminated by an AM0 solar simulator [10], which led to PGC imbalance. Then, a set of experimental VACs of the sample was measured and processed. The dependence of no-load voltage on short-circuit current ($V_{OC} - J_g$) measured in he PGC balance conditions was used as the dark VAC. It was used because it coincided with the dark VAC, but, in contrast to the latter, was resistance-free, thus, making it possible to demonstrate the proposed method more vividly.

Figure 1 shows V_ε vs. $(J_g - J_\varepsilon)$ measured experimentally for different ε. The studied characteristics showed that there were several VAC segments (Figure 2). A segment is defined as a potion of characteristic where its ideality factor doesn't vary (ideality factor of the segment A_s). To calculate the desired values accurately, the experimental characteristics were approximated by a sum of three exponents with different A_s (2, 3 and 4). The experimental

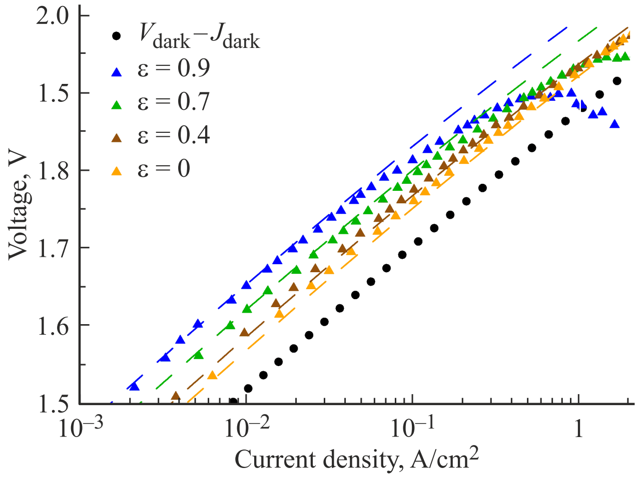

Figure 1. Dependences of V_ε on $(J_g - J_\varepsilon)$ for different ε and dark resistance-free VAC derived from the $V_{OC} - J_g$ characteristic in PGC balance conditions.

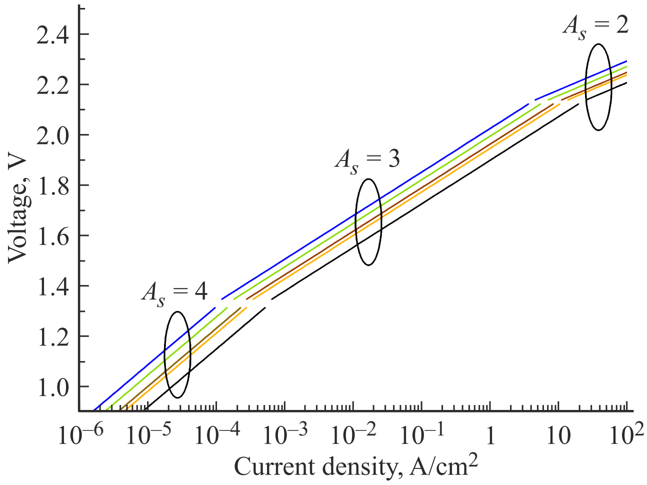

Figure 2. Segments of the dependences of V_ε on $(J_g - J_\varepsilon)$shown in Figure 1. Colors of the lines correspond to the colors in Figure 1.

data and approximation result are shown in Figure 2. The approximation result is shown in two forms: Figure 2 shown VACs found for segments, and Figure 1 shows the total VAC (addition of VAC segment currents at the same voltage).

VACs for three segment are shown in Figure 2. Note that expression (3) is applicable to characteristics with one segment, therefore, to find $V_{a,\varepsilon}$, sets of $V_\varepsilon - J_g(1 - \varepsilon)$ characteristics shown in Figure 2 related to the same segment were used. Thus, V_a was determined for segments with $A_s = 2$, $A_s = 3$ and $A_s = 4$. Figure 2 shows that the voltage difference between the dark VAC and $V_\varepsilon - (J_g - J_\varepsilon)$ characteristics increases as A_s grows. This suggests that the increase in the additional imbalance voltage is induced by the variation of A included in expression (3). A was chosen so that V_a/A was the same for all three

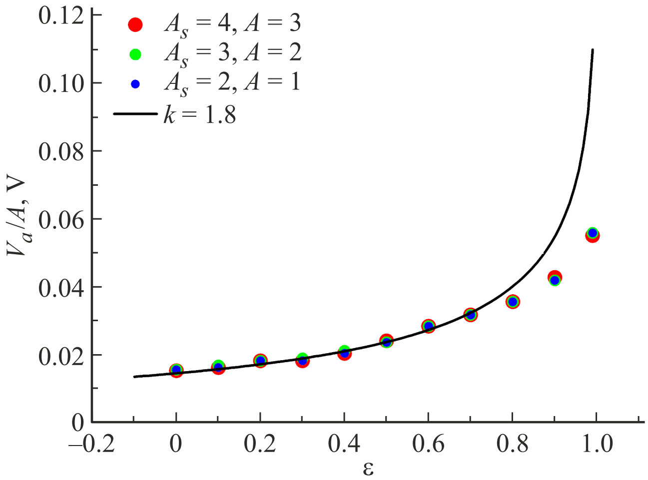

Figure 3. Dependences of the additional voltage divided by the ideality factor V_a/A on the fraction of photogenerated current ε (symbols — dependences for three segments with different A_s; line — approximation by expression (3)).

segments. From (3), it is obvious that this quantity shall be constant. Figure 3 shows the result.

By approximating the resulting dependences V_a/A, $\kappa = 1.8$ was found. Thus, a method was developed to find experimentally additional imbalance voltages from a set of experimental VACs for a set of currents being a constant fraction of PGC. It is shown that this quantity may be obtained for different VAC segments and, therefore, recorded several times. By choosing the segments so that the given V_a/A coincides for the same currents, validity of the obtained V_a may be increased and A may be determined for the subcell with excess PGC. V_a/A vs. ε obtained using the proposed method may be approximated by expression (3) with one fitting parameter — imbalance coefficient κ. Thus, a method was proposed to determine the PGC imbalance for laser PVC with several p–n-junctions through VAC analysis. The method was applied to the two-junction PVC, however, may be also used for laser PVC with any number of subcells without any significant modifications.

Conflict of interest

The authors declare no conflict of interest.

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