The GaAs laser photoconverter (\( \lambda = 809 \text{ nm} \)) current flow mechanisms at the temperature range of 100-420 K

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Abstract. The temperature dependences of the diffusion and recombination saturation currents and the energy gap have been obtained for a GaAs photoelectric converters. Saturation currents by IV characteristic analysis, and the energy gap by electroluminescence peak position have been determined. It has been shown that the relationship between saturation currents and energy band gap is characterized by the only parameter \( J_1 \) (current invariant). At the temperature range of 100 - 420 K this parameter does not depend on the temperature.

1. Introduction

Currently, there is an active development of photovoltaic converters (PVC) of laser radiation for their use in communications [1] and energy transmission through the atmosphere and outer space [2-5]. The efficiency of the PVC is largely determined by energy band gap \( (E_g) \) of its \( p-n \) junction and by current flow parameters — diffusion \( (J_{01}) \) and recombination \( (J_{02}) \) saturation currents. Previously [6], it has been found that in the \( Ga_{1-x}In_xAs \) \( p-n \) junctions the \( E_g \), \( J_{01} \), and \( J_{02} \) values are connected by one parameter — the current invariant \( J_z \). Another relation has been shown in [7], where the authors found that open-circuit voltage \( (V_{oc}) \) dependence on \( E_g \) in the wide energy gap range (from 0.6 to 2.2 eV) can be described by one parameter - voltage offset. It is known [8, 9] that \( V_{oc} \) is determined by the saturation currents and photogenerated current \( J_g \) (note, that the \( V_{oc}-J_g \) dependence is well studied and coincides with the resistance-less dark IV-characteristic [9]). Moreover, \( J_g \) is not a \( p-n \) junction parameter and its magnitude can be controlled by varying the power of the incident radiation. Thus, the main parameters connecting \( V_{oc} \) and \( E_g \) are the saturation currents. Therefore, the fact that the \( V_{oc}-E_g \) dependence is described by a single parameter [7] allows assuming that the \( J_{01}-E_g \) and \( J_{02}-E_g \) dependences are also described by one parameter, namely, the earlier found current invariant \( J_z \).

Another important aspect of PVCs studies is the dependence of their characteristics on temperature. It is especially important for PVCs, which operated under high-power monochromatic laser radiation because high-current operating mode leads to devices overheating [5, 10]). In a narrow temperature range, the dependence of the the laser PVC characteristics can be described by one parameter \( b = \Delta E_g/\Delta T \) (\( T \) is the absolute temperature) [10], which characterized the \( p-n \) junction \( E_g \) change upon overheating. So in this case we also have the situation when PVCs parameters depend only on energy band gap.

In this work, we investigate the assumption that the current invariant \( J_z \) obtained earlier can be the parameter, which determines the dependence of \( Ga_{1-x}In_xAs \) PVCs characteristics on \( E_g \). Such
dependence on $x$ parameter has been studied in [6], and in this work we continue this study by investigating the temperature dependences.

2. Obtaining temperature dependences of saturation currents and p-n junction energy gap

Investigated GaAs structure was grown by metalorganic vapor-phase epitaxy on GaAs$-n$ (100) substrates. Metal alkyls were used as III-group atom sources: threemethylgallium and threemethylaluminum. Arsine was used as a source of As. Monosilane and diethylzinc were used for n- and p-type doped layers, respectively. A detailed description of the epitaxial structure and GaAs PVC design is presented in [11].

The sample temperature was varied in the range from 100 to 420 K using a homemade optical cryostat. An electroluminescence emission was initiated in the in the direct current mode through the sample. To preset exact current magnitude and to trace IV curves the source-meter Keithley 2400 was used. The electroluminescence spectra were recorded using AvaSpec-ULS2048 StarLine Versatile Fiber-optic Spectrometer form Avantes Ltd. At each sample temperature, IV curves have been recorded, one at 460 nm and another one at 809 nm of laser radiation, respectively.

Radiation from a 460 nm laser was effectively absorbed in a wide-gap optical window of PVC and produced a relatively small generation current. So the obtained IV-curve was interpreted as “cold” (no p-n junction overheating). When the laser wavelength was 809 nm, the $J_g$ was significantly higher and this allows recording the IV-curve segment at which the diffusion current flow mechanism can be observed. At the same time, a large current led both to a resistive loss increase and to p-n junction overheating. Both of these factors were taken into account and the IV characteristics were corrected. After correction the characteristics were approximated by a two-diode model [10], and the diffusion (diode coefficient $A = 1$) and recombination ($A = 2$) saturation currents have been obtained. An example of the correction procedure for temperature $T = 298$ K is presented in Figure 1. The procedure is clearly visible on a logarithmic scale. First, the lumped series resistance ($R_s$) value was found. Then, voltage ($V$) of the experimental IV-curves (circles in Figure 1), was corrected by the value equal to $J R_s$, where $J$ is the measured current density. The value of $R_s$ was selected in such a way that the corrected experimental IV-curves were parallel to each other. In Figure 1, the corrected curve obtained under 809 nm laser illumination is shown by a solid red line, it runs parallel to the measured IV-curve under 460 nm laser. The parallelism indicates a constant voltage shift $dV$ caused by overheating of the p-n junction [11]. The characteristic correction (voltage shift by $dV$) shown in Figure 1 (red squares); it coincides with the “cold” IV-curve (blue circles). The approximation, which gives $J_{01}$ and $J_{02}$ values, by a two-diode model is also shown in Figure 1 (solid black line).

| $T$(K) | $R_s$ (Ohm cm$^2$) | $dV$ (mV) | $J_{01}$ (A/cm$^2$) | $J_{02}$ (A/cm$^2$) | $E_g$, eV |
|--------|------------------|-----------|-------------------|------------------|-----------|
| 103    | 15.0·10$^{-3}$   | -         | -                 | 1.79·10$^{-34}$  | 1.505     |
| 123    | 12.0·10$^{-3}$   | -         | -                 | 1.13·10$^{-28}$  | 1.498     |
| 173    | 7.0·10$^{-3}$    | -         | -                 | 9.77·10$^{-20}$  | 1.476     |
| 223    | 6.5·10$^{-3}$    | 20        | 1.05·10$^{-29}$   | 1.36·10$^{-14}$  | 1.455     |
| 273    | 4.8·10$^{-3}$    | 30        | 1.39·10$^{-23}$   | 2.74·10$^{-11}$  | 1.432     |
| 298    | 4.8·10$^{-3}$    | 33        | 6.91·10$^{-21}$   | 4.47·10$^{-10}$  | 1.422     |
| 323    | 4.8·10$^{-3}$    | 35        | 5.68·10$^{-19}$   | 5.33·10$^{-09}$  | 1.409     |
| 373    | 4.3·10$^{-3}$    | 43        | 7.87·10$^{-16}$   | 2.56·10$^{-07}$  | 1.384     |
| 423    | 3.5·10$^{-3}$    | 50        | 2.28·10$^{-13}$   | 5.13·10$^{-06}$  | 1.362     |
Figure 1. The IV characteristics of GaAs PVC at a temperature of 298 K in linear (left) and logarithmic (right) scales. The circles show the experimental data. The IV-curves obtained by illuminating the sample by an 809 nm laser are shown in red, and by 460 nm laser in blue. Two corrected IV-curves shown: red solid line (resistance-less) and red squares (resistance-less and without p-n junction overheating). Black lines show two-diode model approximation: diffusion ($A=1$) and recombination ($A=2$) current components are shown by dashed lines, the result of approximation is shown by solid line.

Corrected IV-curves and their approximation by the two-diode model are shown in Figure 2. Note that for low temperatures the above-described IV-curve correction procedure was not performed. This is due to the fact that the shape of the characteristics obtained under 809 nm laser irradiation indicates nonlinear resistive losses. Therefore, only the IV characteristics obtained under a 460nm laser were used for these temperatures and this allowed us to determine only the recombination saturation currents $J_{02}$. Figure 2 also shows the electroluminescence spectra. The energy gap ($E_g$) for all temperatures was determined by the position of the electroluminescence spectra peak. The obtained $E_g$, $J_{01}$, $J_{02}$, $R_s$, $dV$ values are combined in Table 1.
3. Determination of the current invariant

As is known [9, 12] in general, the temperature dependence of the saturation currents \( J_{01} \) and \( J_{02} \) can be described by the following expressions:

\[
J_{01}(T) = B_1 T^3 \exp \left( \frac{-E_g(T)}{kT} \right), \tag{1.1}
\]

\[
J_{02}(T) = B_1 T^{2.5} \exp \left( \frac{-E_g(T)}{2kT} \right), \tag{1.2}
\]

where \( k \) – Boltzmann constant, \( B_1 \) and \( B_2 \) are constants independent on temperature. It is also known that \( E_g - T \) dependence is well described by the Varshni formula [13] (note that in a wide temperature range, \( E_g - T \) is a linear dependence). Thus, temperature dependences (1.1) and (1.2) are proportional to a power law of temperature multiplied by an exponential one. We assumed that the exponential term will dominate, and then expressions (1.1) and (1.2) can be written in the form proposed in [6]:

\[
J_{0A}(T) = J_{xA} \exp \left( \frac{-E_g(T)}{AkT} \right), \quad A = 1 \text{ or } 2 \tag{2}
\]

This form is more convenient, and it allows us to use the current invariant \( J_z \) (its dimension is current density). Thus, the dependences of the saturation currents are proportional to \( \exp \left( \frac{-E_g(T)}{T} \right) \). The experimental dependence of \( J_{01} \) and \( J_{02} \) on the \( \frac{-E_g(T)}{T} \) value is shown on Figure 3 (symbols). It can be seen that they are close to a straight lines on a semi-logarithmic scale, which indicates the suitability of expression (2). To search current invariants for the diffusion and recombination mechanism we used expression (2) and \( E_g(T) \) dependence [14] with typical for GaAs material parameters: the temperature

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**Figure 2.** Electroluminescence spectra (top) and IV characteristics (bottom) of GaAs PVC at different temperatures. The circles - the corrected experimental IV-curves, the solid lines are two-diode model approximation.
coefficient \((5.405 \times 10^{-4} \text{ eV/K})\) and Debye Temperature \((204 \text{ K})\). The \(E_g(T)\) dependence (solid line in the insert on Figure 3) describes well the experimental data (symbols in the insert on Figure 3). The approximation by expression (2) is shown in Figure 3 (solid lines). The obtained currents invariant values are the following \(J_{z1}=1 \times 10^4 \text{ A/cm}^2\) and \(J_{z2}=2 \times 10^2 \text{ A/cm}^2\). These values almost coincide with those obtained in [6], for the \(Ga_{1-x}In_xAs\) PVCs with different solid solution compositions.

Figure 3. Experimental (symbols) and calculated (solid lines) dependences of the recombination and diffusion saturation currents on the energy band gap. The insert shows the experimental (symbols) and calculated (solid line) dependences of the energy band gap on the temperature.

4. Conclusion
In this work, in a wide temperature range (from 100 to 420 K), the electroluminescence spectra and the current–voltage characteristics of the GaAs PVCs have been measured. The temperature dependence of energy gap \(E_g(T)\) has been determined from the position of the electroluminescence peaks. The IV characteristics analysis allows determining diffusion \(J_{01}(T)\) and recombination \(J_{02}(T)\) saturation current temperature dependences. The analysis of obtained data confirms the assumption that there are current invariants that determine the relationship between saturation currents and energy band gap for \(GaAs\) p-n junctions with at any temperature. Obtained invariant values \(J_{z1}=1 \times 10^4 \text{ A/cm}^2\) and \(J_{z2}=2 \times 10^2 \text{ A/cm}^2\) almost coincide with those obtained in [6], where such invariants were used to describe \(J_{01}, J_{02}\) and \(E_g\) dependences on \(x\) - indium concentration in \(Ga_{1-x}In_xAs\) solid alloys.

Thus, the results of the work show the possibility of predicting the saturation currents of \(Ga_{1-x}In_xAs\) p-n junctions for any \(x\) (indium concentration) and temperature, which allows designing the photovoltaic converters and calculating their photovoltaic characteristics.

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