Study of PV characteristics of Al$_{x}$Ga$_{1-x}$As/GaAs photodiodes

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Abstract. Simulation of the structure of multijunction photodiodes has been performed on the assumption that an equal of the number of photons is absorbed in them, and PV characteristics have been studied Al$_x$Ga$_{1-x}$As/GaAs photodiodes fabricated by the molecular-beam epitaxy technique. According to the performed measurements and analysis of the results, it has been shown that the efficiency of single-junction photodiodes in converting monochromatic optical radiation at a wavelength of 810 nm reaches 50%. The relationship between the “saturation” currents calculated from the dark $I - V$ characteristic for the diffusion current flow (Shockley) in the space charge region of a photodiode $p-n$ junction and the obtained values for the efficiency of converting optical radiation in the wavelength range of 700 - 900 nm has been shown. When the “saturation” current flow for the diffusion mechanism rises by an order of magnitude, the efficiency value at excitation by monochromatic radiation at 810 nm and 780 nm drops by 25% and 11%, respectively.

1. Introduction
In recent years, application of multijunction nano-dimensional heterostructures of III-V photoactive $p-n$ junctions with forbidden gaps increasing towards the frontal surface and connected by tunnel diodes was, mainly, considered for creating efficient sunlight converters – multijunction solar cells (MJ SCs) [1]. At present, MJ nano-dimensional heterostructures find their application also in creating high-efficient photodiodes (PDs) converting monochromatic radiation [2, 3]. Unlike an MJ SC, a monolithic PD consists of several $p-n$ junctions with similar forbidden gaps of the approximate composition, but with different geometries of junctions connected by tunnel diodes. In the PV mode of PD operation, this allows conversion of monochromatic radiation with higher voltage of the output signal and improvement of conditions for correlation with the load. In the present paper, the structure of a monolithic triple-junction $p-i-n$ Al$_{x}$Ga$_{1-x}$As/GaAs PD has been simulated. Dark and load $I-V$ characteristics of single-junction $p-i-n$ Al$_{x}$Ga$_{1-x}$As/GaAs PDs were investigated experimentally under excitation by continuous monochromatic radiation at a wavelength of 830 nm at a power of up to 400 mW and at 780 nm at a power of up to 1.3 W. Spectral characteristics of the external quantum yield of a $p-i-n$ Al$_{x}$Ga$_{1-x}$As/GaAs PD with a small photosensitive surface (500 μm in diameter) were recorded.
2. Simulation of multijunction and single-junction Al\textsubscript{x}Ga\textsubscript{1-x}As/GaAs PD structures

A model was calculated for a monolithic triple-junction p-i-n PD based on the Al\textsubscript{x}Ga\textsubscript{1-x}As/GaAs nanoheterostructure. The schematic of the MJ PD is presented in figure 1. Each junction thickness was determined under the condition of equality of the number of absorbed radiation photons according to the expressions (1-5) presented below. The total amount of absorbed radiation in a PD was determined from the expression:

\[ I_0 = I - I_{\text{out}}, \]  

where \( I \) is the incident radiation intensity (number of photons per 1 cm\(^2\)), and \( I_{\text{out}} \) is the intensity of radiation that passes through. The amount of radiation absorbed in the \( i \)th junction of an MJ PD with allowing for absorption only in \( p, i \) and \( n \) layers is:

\[ I_{\text{out}} = I_i \left(1 - e^{-\alpha_p l_p - \alpha_i l_i - \alpha_n l_n}\right), \]  

where \( I_i \) is the intensity of radiation entering a junction; \( \alpha \) is the absorption coefficient of a corresponding layer (\( p, i \) or \( n \)), and \( l \) is the thickness of a corresponding layer (\( p, i \) or \( n \)).

The amount of radiation absorbed in the first junction at \( i = 1 \) with allowance for optical losses in the wideband window is:

\[ I_1 = I - I_{\text{win}}, \]

where \( I_{\text{win}} \) is the amount of radiation absorbed in the wideband window located in the first junction structure.

![Figure 1. Schematic of a triple-junction Al\textsubscript{x}Ga\textsubscript{1-x}As/GaAs PD.](image)

The amount of radiation absorbed in the below located junctions at \( 1 < i \leq N \) with allowance for optical absorption in tunnel \( n^{++} - p^{++} \) junctions is:

\[ I_i = I_{i-1} e^{-\alpha_{p,i-1} l_{p,i-1} - \alpha_{i,i-1} l_{i,i-1} - \alpha_{n,i-1} l_{n,i-1}} - I_{PD,i}, \]  

where \( I_{PD,i} \) is the intensity of radiation absorbed in the PD of the \( i \)th junction.
where $I_{TD}$ is the amount of radiation absorbed in a tunnel diode.

Then, the portion of radiation absorbed in each junction with allowance for photocurrent equality in all MJ PD junctions is:

$$I_{0i} = \frac{I - I_{\text{win}} - \sum_{j=1}^{N-1} I_{TD,j} - I_{\text{out}}}{N}.$$  \hspace{1cm} (5)

The calculated thicknesses of $p$, $i$, and $n$ layers for each junction and doping levels are presented in figure 2. Numbers 1, 2, and 3 denote junctions, and number 4 represents connecting tunnel junctions in correspondence with the structural schematic presented in figure 1.

![Figure 2](image-url)

**Figure 2.** Schematic of a triple-junction monolithic $p$-$i$-$n$ Al$_{0.12}$Ga$_{0.88}$As/GaAs PD with indicated calculated thicknesses of $p$-$i$-$n$ junctions and $n^{++}$-$p^{++}$ connecting diodes along the x-axis, and rated doping levels shown along the y-axis: (1) top, (2) middle, (3) bottom, (4) tunnel junctions.

3. Static and dynamic characteristics of single-junction $p$-$i$-$n$ GaAs/Al$_{0.12}$Ga$_{0.88}$As PDs

The heterostructure of Al$_{0.12}$Ga$_{0.88}$As/GaAs fabricated by molecular-beam epitaxy was used to investigate characteristics of single-junction $p$-$i$-$n$ PDs with frontally entering monochromatic radiation (figure 3). PD chips sized 1 mm × 1 mm were formed on the grown epitaxial wafer.

Directly on the epitaxial wafer, dark $I$-$V$ characteristics of single-junction PDs were recorded within the forward voltage bias range of 0 - 1.5 V. The forward dark $I$-$V$ characteristics were analyzed according to the procedure described in [4, 5], using a three-component exponential model of a PD $I$-$V$ characteristic:
Obtained were the values of the pre-exponential factors (“saturation” currents for the main mechanisms of minority charge carrier transport), $J_{0i}$, diode coefficients (ideality coefficients), $A_i$, and structure series resistance, $R_s$, for three minority charge carrier transport mechanisms in the space charge region of a $p$-$i$-$n$ junction: tunnel-trap (“overabundant”) with a diode coefficient $A_t$ greater than 2, recombination (Sah-Noyce-Shockley) with $A_r = 2$ and diffusion (Shockley) with $A_d = 1$.

$$J = \sum_{i=1}^{3} J_{0i} \left( \exp \left( \frac{V}{A_i e} \right) - 1 \right)$$

(6)

**Figure 3.** Heterostructure of $Al_{x}Ga_{1-x}$As/GaAs $p$-$i$-$n$ PDs fabricated by the MBE technique.

| Region   | Concentration |
|----------|---------------|
| Window   | $p$-$Al_{0.12}Ga_{0.88}$As, $5 \cdot 10^{19}$ cm$^{-3}$ |
|          | $p$-GaAs, $2 \cdot 10^{18}$ cm$^{-3}$ |
| I-region | $n_0$-GaAs, $1 \cdot 10^{14}$ cm$^{-3}$ |
| Base     | $n$-GaAs, $5 \cdot 10^{17}$ cm$^{-3}$ |
| N-region | $n$-$Al_{0.2}Ga_{0.8}$As, $3 \cdot 10^{18}$ cm$^{-3}$ |
| Substrate| $n^+$-GaAs, $(2-3) \cdot 10^{18}$ cm$^{-3}$ |

Figure 3. Heterostructure of $Al_{x}Ga_{1-x}$As/GaAs $p$-$i$-$n$ PDs fabricated by the MBE technique.

From the above-mentioned PDs whose characteristics were recorded and analyzed, those with different values of pre-exponential factors corresponding to the diffusion component $J_{0d}$ were selected. The selection was made for estimating the influence of the pre-exponential factors $J_{0d}$ on the single-junction PD efficiency in the case of converting monochromatic radiation in the range of 700 – 900 nm. The dark $I$-$V$ characteristics of the selected PDs are shown in figure 4 and marked as b2, d13, and b10, which corresponds to the indices on the epitaxial wafer. Table 1 presents the rated values of “saturation” currents $J_{0t}$, $J_{0r}$, $J_{0d}$ (pre-exponential factors) for the tunnel-trap, recombination and diffusion current flow mechanisms and, accordingly, the specific series resistance $R_s$ of a $p$-$i$-$n$ junction structure, all obtained in analyzing experimental dark $I$-$V$ characteristics (figure 4).

To determine the spectral range of the sensitivity of a tested PD epitaxial structure, external quantum efficiency characteristics were recorded in the wavelength range of 700 – 900 nm. The dependences are presented in figure 5.

For the selected PDs, load $I$-$V$ characteristics were recorded upon exposure to monochromatic 0.1-0.4 W radiation at a wavelength of 830 nm. The efficiency values calculated from the load $I$-$V$ characteristics in dependence on the incident radiation power (0.1 – 0.4 W) are presented in figure 6 (curves 1, 2 and 3) and table 1. Based on the data presented in figure 6 and table 1, it follows that the b2 PD with a minimal “saturation” current density value $J_{0d} = 1 \cdot 10^{-20}$ A/cm$^2$ has the maximum value of the efficiency in conversion of constant laser radiation (50%) at a wavelength of 830 nm and a power of 0.4 W. The b10 PD with the maximum value of $J_{0d} = 1 \cdot 10^{-19}$ A/cm$^2$ and $R_s > 10$ mOhm·cm$^{-2}$ has the minimum efficiency of 37.8% at an incident laser radiation power of 0.4 W.

Figure 6 and table 1 present rated values of the efficiency for peak values of pulse amplitude of the photo-response for tested single-junction $Al_{x}Ga_{1-x}$As/GaAs $p$-$i$-$n$ PDs. According to the obtained characteristics (figure 6, curves 4, 5 and 6, table 2), the b2 PD having the minimum “saturation”
current density value converts pulsed radiation at a wavelength of 780 nm with the maximum efficiency of 35%. The decrease in the PD efficiency under excitation at a wavelength of 780 nm, compared to that at continuous radiation impact at 830 nm, occurs, first of all, by lowering the PD spectral sensitivity at 780 nm (figure 5).

![Figure 4](image1.png)

**Figure 4.** Dark I-V characteristics for the selected PDs b2 (curve 1), d13 (curve 2), b10 (curve 3) with different values of pre-exponential factors for three current flow mechanisms: tunnel-trap, $J_{0t}$, ($A > 2$); recombination, $J_{0r}$, ($A = 2$); diffusion, $J_{0d}$, ($A = 1$), and the value of the resistance $R_S$.

![Figure 5](image2.png)

**Figure 5.** Spectral characteristics of the external quantum efficiency of the structure of an Al$_x$Ga$_{1-x}$As/GaAs p-i-n PD with a photoactive surface having a diameter of 500 µm.
Table 1.

| No of PD | Efficiency, % ($\lambda = 835$ nm) | $R_s$, (mOhm·cm$^2$) | $J_{th}$, $(10^{-8}$ A/cm$^2$) ($A > 2$) | $J_{thr}$, $(10^{-10}$ A/cm$^2$) ($A = 2$) | $J_{thr}$, $(10^{-20}$ A/cm$^2$) ($A = 1$) |
|----------|----------------------------------|----------------------|-----------------------------------------|---------------------------------------|----------------------------------------|
|          | $P_{opt} = 0.1$ (W) 0.18 (W) 0.4 (W) |          |                                              |                                      |                                        |
| b2       | 47.0 49.0 50.0 < 3 1.0 5.7 1.0 |          |                                              |                                      |                                        |
| d13      | 44.0 45.4 46.0 < 3 0.1 5.5 2.0 |          |                                              |                                      |                                        |
| b10      | 39.4 39.0 37.8 >10 0.8 5.8 10 |          |                                              |                                      |                                        |

Figure 6. Dependence of the efficiency on incident power for PDs b2 (curves 1,4), d13 (curves 2,5) and b10 (curves 3,6) in a PV mode at excitation by monochromatic radiation: curves 1, 2, 3, at continuous excitation at a wavelength of 830 nm (25 °C); curves 4, 5, 6, at excitation at a wavelength of 780 nm.

Table 2.

| No of PD | Efficiency, % ($\lambda = 780$ nm) |
|----------|----------------------------------|
|          | $P_{opt} = 0.5$ (W) 1.0 (W) 1.33 (W) |
| b2       | 5.4 18 35.3 |
| d13      | 5.2 17 33.1 |
| b10      | 5 16 31.6 |

The parameters calculated from dark and load I-V characteristics and fast operation characteristics of single-junction PDs were used to build the dependences of the efficiency on “saturation” current corresponding to the diffusion mechanism for the minority charge carrier transport in the continuous generation mode (figure 7, curve 1) and in the pulsed one (figure 7, curve 2).
Figure 7. Dependences of the PD efficiency on “saturation” current for the diffusion mechanism, obtained from dark current-voltage characteristics of photodiode samples (b2, d13, b10) in the continuous generation mode (curve 1) and in the pulsed one (curve 2).

From the dependences in figures 6 and 7, the relationship between the “saturation” currents for the diffusion mechanism of minority charge carrier flow in the space charge region of photoactive p-i-n junctions and the efficiency of optical radiation conversion is well pronounced. The smaller the values of pre-exponential factors ($J_{0d}$ for the diffusion current flow mechanism), the smaller the PD efficiency. The growth of $J_{0d}$ by an order of magnitude decreases the efficiency by more than 10% in the laser excitation mode at a wavelength of 838 nm and by 4% for pulsed excitation at 780 nm.

4. Conclusion
A rated model of a triple-junction Al$_x$Ga$_{1-x}$As/GaAs photodiode for converting powerful monochromatic radiation in the wavelength range of 700 - 900 nm is proposed. Investigation of static and dynamic characteristics of single-junction p-i-n Al$_x$Ga$_{1-x}$As/GaAs PDs has been carried out. According to this investigation, it has been shown that the greater the “saturation” current values $J_{0d}$ corresponding to the diffusion current flow, the smaller the PD efficiency value at excitation by monochromatic radiation. For the tested p-i-n PDs, the growth of the “saturation” currents $J_{0d}$ by an order of magnitude causes the efficiency to decrease by more than 10% in the mode of excitation by continuous monochromatic radiation at a wavelength of 830 nm and by 4% in the modes of excitation by monochromatic pulse radiation at 780 nm.

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