Investigation of the characteristics of a radioisotope source based on a (Y)PO$_4$/$^{238}$Pu self-glowing crystal and an Al$_x$Ga$_{1-x}$As/GaAs photovoltaic converter

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Abstract. The possibility of creating of a radioisotope source of energy based on a radio-luminescent crystal of YPO$_4$:Eu/$^{238}$Pu and Al$_x$Ga$_{1-x}$As/GaAs photovoltaic converter is demonstrated and its characteristics are analyzed. A prototype of an ecologically safe radioisotope source with low content ($< 0.1\%$) of the $^{238}$Pu isotope, efficiency of $\sim 1.4\%$, and long service life has been developed.

1. Introduction
A need arises in modern power engineering to have low current energy sources with ultralong service life. These sources are used in devices with low energy-consumption level, for which other power supply sources, e.g., solar arrays and chemical batteries are inadvisable and have a rather limited service life. Therefore, much attention is being given to the development and improvement of radioisotope energy sources (RESs) in which the energy of the radioactive decay of isotopes is converted to the electric energy [1].

Because of the disintegrating effect of the ionizing radiation, RESs with direct conversion require an additional radiation protection and have a substantially shorter service life, compared with RESs with intermediate conversion of the radioactive decay energy to the optical emission energy [2].

As a source of optical emission in RESs with intermediate conversion can serve radiation-hard mineral-like matrices, e.g., crystals of the xenotime (YPO$_4$) type. These crystals are doped with $^{238}$Pu radionuclide (with predominant emission of alpha particles) ($\leq 0.1$ wt.%) and with europium ions Eu$^{3+}$ as luminescent centers (2-3 wt.%) [3]. The use of high-efficiency nanoheterostructure Al$_x$Ga$_{1-x}$As/GaAs photovoltaic converters (PVCs) and safe radio-luminescent sources of optical emission can provide during a long time, on the order of a radiological half-life, the maximum output capacity of RESs.

In this study, we examined the characteristics of RESs with intermediate conversion of the radioactive-decay energy to the optical emission energy. We performed a calculation with a SilvacoAtlas TCAD software, and, using its results, optimized the Al$_x$Ga$_{1-x}$As/GaAs structures. The dark and light current-voltage characteristics of the PVCs were examined under excitation by optical emission from an ecologically safe radio-luminescent source YPO$_4$(Eu$^{3+}$/$^{238}$Pu with optical emission power of $\sim 1$ nW. A prototype RES was developed and its efficiency was evaluated. A good coincidence was revealed between the calculated RES efficiency and its experimental value.
2. Numerical studies
The Al$_{x}$Ga$_{1-x}$As/GaAs structure was preliminarily modeled and optimized for use with a low-power radio-luminescent source based on xenotime, the spectrum of which is shown in Figure 1. The modeling was performed with a SilvacoAtlas TCAD software package. The estimates were made for the p-n GaAs structure (Table 1) with dopant concentrations $N_A=3.5\cdot10^{18}$ cm$^{-3}$ and $N_D=4\cdot10^{17}$ cm$^{-3}$ and absorption coefficients $k_1=2\cdot10^4$ cm$^{-1}$ ($\lambda_1=695$ nm), $k_2=4\cdot10^3$ cm$^{-1}$ ($\lambda_2=615$ nm), and $k_3=8\cdot10^4$ cm$^{-1}$ ($\lambda_3=595$ nm).

![Figure 1](image1.png)

**Figure 1.** Optical emission spectrum of the radio-luminescent source YPO$_4$:Eu/($^{238}$Pu).

| Material  | Thickness, nm | Doping level, cm$^{-3}$ |
|-----------|---------------|-------------------------|
| p-GaAs    | 100-500       | $3.5\cdot10^{18}$       |
| n-GaAs    | 350000        | $4\cdot10^{17}$         |

2.1. Absorption simulation
Figure 2 shows the calculated curves of how the luminescent emission from the matrix of YPO$_4$:Eu/($^{238}$Pu) crystals is absorbed in the p-n junction of the GaAs PVC. It can be seen that the absorption depth at wavelengths $\lambda_1=695$ nm, $\lambda_2=615$ nm, and $\lambda_3=595$ nm falls within the range 0.15-0.5 μm. The optimal depth of the p-n junction relative to the surface of the GaAs PVC is determined by the shortest wavelength in the optical emission spectrum of the source ($\lambda_3=595$ nm) to be ~100 nm.

2.2. Simulation of the efficiency in the dependence on the p-layer thickness and source power
Figure 3 shows the calculated dependences of the efficiency of GaAs PVCs on the p-layer thickness under excitation with light having a wavelength $\lambda_3=595$ nm at an optical power in the range from 50 nW to 1 W. The optimal thickness of the p-layer in the p-n junction is ~100 nm. It should be noted that at the thicknesses of the epitaxial layers of the structure, doping impurity concentrations, and p-n junction parameters, used in the calculations, the efficiency strongly depends on the incident light power and is less than 10% at a power ≤ 100 nW.
Figure 2. Calculated curves of absorption in n-GaAs of the optical emission from the radioisotope source YPO₄:Eu/(²³⁸Pu) at (1) $\lambda_1 = 695$ nm, (2) $\lambda_2 = 615$ nm, and (3) $\lambda_3 = 595$ nm.

Figure 3. Dependence of the GaAs PVC efficiency on the p-layer thickness at $\lambda_3 = 595$ nm and the following values of the optical emission power: (1) 50 nW, (2) 100 nW, (3) 10 μW, (4) 1 mW, and (5) 1 W.

3. Experimental
The dark and light current-voltage (J-V) characteristics of the optimized $Al_xGa_{1-x}As/GaAs$ PVC were measured. The RES efficiency was evaluated.

To perform the experiment in which determining the RES efficiency was determined, the $Al_xGa_{1-x}As/GaAs$ structure was grown by the method of molecular-beam epitaxy (MBE) (p-GaAs thickness 100 nm, $N_A=7\cdot10^{17}$ cm$^{-3}$; n-GaAs thickness 3000 nm, $N_D=1\cdot10^{17}$ cm$^{-3}$) on a 350-μm-thick n-GaAs substrate doped to $2\cdot10^{18}$ cm$^{-3}$ (Figure 4). Also a radioisotope optical emission source grown by the growth-from-solution method on the basis of a mineral-like crystal of xenotime YPO₄:Eu/(²³⁸Pu) with $^{238}$Pu content of less than 0.1 wt.% and Eu$^{3+}$ content of 2-3 wt.% was used in the experiment.
300 nm GaAs:Be $4 \cdot 10^{18}$ cm$^{-3}$  
35 nm Al$_{0.3}$Ga$_{0.7}$As:Be $7 \cdot 10^{17}$ cm$^{-3}$  
100 nm GaAs:Be $7 \cdot 10^{17}$ cm$^{-3}$  
3000 nm GaAs:Si $1 \cdot 10^{17}$ cm$^{-3}$  
50 nm Al$_{0.2}$Ga$_{0.8}$As:Si $3 \cdot 10^{18}$ cm$^{-3}$  
200 nm GaAs:Si $5 \cdot 10^{18}$ cm$^{-3}$  
350000 nm GaAs:Si $2 \cdot 10^{18}$ cm$^{-3}$

**Figure 4.** Experimental structure of the Al$_x$Ga$_{1-x}$As/GaAs PVC.

### 3.1. Dark J-V characteristic

Figure 5 shows the experimental and calculated dark characteristics of the Al$_x$Ga$_{1-x}$As/GaAs PVC. The values of the "saturation" currents for the tunneling-trap-assisted (excessive), recombination, and diffusion current transport mechanisms in the space-charge region were found to be $J_{0t} = 3.4 \cdot 10^{-10}$ A/cm$^2$, (diode coefficient: $A_t = 3$); $J_{0r} = 2 \cdot 10^{-11}$ A/cm$^2$, (diode coefficient: $A_r = 2$); $J_{0d} = 2.4 \cdot 10^{-20}$ A/cm$^2$, (diode coefficient: $A_d = 1$), respectively.

It was found that the predominant current-transport mechanisms in GaAs PVCs at low optical power levels (1 nW) of the radio-luminescent source based on a xenotime crystal is the tunneling-trap-assisted ("excessive") and recombination mechanisms. It was shown in [4] that, when a weak optical emission is converted, the efficiency of a GaAs PVC strongly depends on these two current components. The more pronounced these mechanisms at working current densities ($\leq 10^9$ A/cm$^2$), the lower the efficiency of the Al$_x$Ga$_{1-x}$As/GaAs PVC.

**Figure 5.** Forward dark J-V characteristic of the Al$_x$Ga$_{1-x}$As/GaAs PVC: (1)experiment, (2)calculation, (3) tunnel-trap (excess) component, (4) recombination component.

### 3.2. Light J-V characteristic

Figure 6 shows an experimental light J-V characteristic of a GaAs PVC and the dependence, calculated from this characteristic, of the efficiency on the bias voltage under excitation with the optical emission from the radioisotope source with power of 1 nW. Table 2 lists the main parameters of the Al$_x$Ga$_{1-x}$As/GaAs PVC for the RES.
The spectral matching and the optimization of the $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ structure to the power of 1 nW of the optical emission source made it possible to obtain the maximum efficiency (1.4%) for the given RES design.

3.3. Calculated $\eta$-$P$ characteristic and the experimental $\eta$

Figure 7 shows the calculated dependence of the efficiency on the power of incident light for the modeled GaAs RES structure with a 100-nm-thick p-type layer and the experimental value of the efficiency at an absorbed power from the source of ~1 nW. A good agreement is observed between the experimental and calculated values of efficiency.

Table 2. Parameters of a RES based on an $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ PVC and YPO$_4$:Eu$^{238}$Pu optical source.

| $U_{\text{opt}}$, V | $I_{\text{opt}}$, pA | $P_{\text{opt}}$, pW | $U_{\text{oc}}$, V | $I_{\text{sc}}$, pA | FF, % | $\eta$, % |
|---------------------|----------------------|---------------------|-------------------|-------------------|-------|-----------|
| 0.12                | 140                  | 17                  | 0.18              | 175               | 52    | 1.4       |

Figure 6. (1) Experimental light I-V characteristic and (2) values of efficiency, calculated from the characteristic, for the $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ RES under excitation with the optical emission from the radioisotope source of the xenotime type with power of 1 nW.

Figure 7. (1) Calculated dependence and (2) experimental value of the efficiency on the power of incident optical emission for the $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ PVC.
4. Conclusion
It was shown that Al$_{x}$Ga$_{1-x}$As /GaAs PVCs can be used in safe and long-lived RESs. Calculation and experimental studies of the main parameters and characteristics of a radioisotope photovoltaic power supply unit intended for devices with low energy consumption were carried out. This source is a complex constituted by a radioisotope source of optical emission, based on YPO$_4$:Eu($^{238}$Pu) and a PVC nanoheterostructure Al$_{x}$Ga$_{1-x}$As /GaAs.

The spectral matching and the optimization of MBE-grown Al$_{x}$Ga$_{1-x}$As /GaAs PVCs to the power level (1 nW) of the optical emission source made it possible to obtain the efficiency of ~1.4%, which is the maximum possible value for the given RES design. The experimental value obtained in the studies is in good agreement with the results of modeling.

The procedure for studying and optimizing the high-efficiency radiation-hard GaAs PVCs for radioisotope sources of optical emission, reported in the communication, makes it possible to model, measure, compare, and analyze the efficiency of the general design of RESs. It can be used to study RESs based on other mineral-like crystalline matrices and optimized, for these matrices, PVCs based on A$^+$B$^5$ or A$^+$B$^8$. The efficiency can be estimated by this procedure for any small values of the optical emission power from a radioisotope source.

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