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IMPACT OF DIFFERENT PARAMETERS ON THE EFFICIENCY OF GAN/POROUS-GAAS/GAAS SOLAR CELL

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Abstract: Modern requirements for high-efficiency solar cells increase interest in the development of new materials and structures, in particular the use of GaN/porous-GaAs/GaAs composite materials and heterostructures, which allow to improve the efficiency and stability of solar energy conversion. To determine the photovoltaic characteristics of the GaN/porous-GaAs/GaAs photoconverter, a system of equations is used, including the Poisson equation, the diffusion equation, and the charge conservation equation. The simulation results of GaN/porous-GaAs/GaAs solar cells using PC1D software showed values of short-circuit current I_{SC} = 33.2 mA, open-circuit voltage V_{OC} = 1.022 V, fill factor FF = 83.4% and efficiency η = 28.3% In order to optimize the parameters of the solar cell, simulations were carried out with a change in the thickness of the GaN layer, the doping levels of the GaN and porous-GaAs layers. It was established that with a thickness of the GaN layer of 1.6 μm, the efficiency of the solar cell reaches a maximum value of 29.1%. The maximum efficiency was achieved when the GaN layer was doped with $1 \cdot 10^{17}$ cm^{-3} and was 28.4%. An increase in the temperature of the solar cell leads to a decrease in the open-circuit voltage and an increase in recombination losses, which is reflected in the decrease in the efficiency of the GaN/porous-GaAs/GaAs photoconverter from 29.8% at 270 K to 23.0% at 370 K.

Keywords: solar cell, heterostructure, efficiency, GaN layer

1. INTRODUCTION

Today, the energy problem is very relevant for all countries of the world, and it is especially acute in Ukraine, which can meet its needs with its own energy resources by only 35-40%. Therefore, the conservation of traditional energy sources, i.e. those that have been used for a long time in the energy sector: coal, oil, natural gas, oil shale, nuclear energy, etc., as well as peat, firewood, hydropower of large watercourses and the muscular power of animals and people is an urgent problem (Bazaluk O., et al., 2022a; Qawaqzeh M. Z., et al., 2020). One of the ways to solve this problem is the use of alternative energy sources that convert the energy of the wind, sun, etc. (Bazaluk O., et al., 2022b; Szafraniec A., et al., 2021).

The use of solar energy, the possibility of creating large-scale production for this promising industry, requires the solution of many fundamental scientific problems and applied problems. The efficiency of using solar energy depends to a large extent on how accurately the patterns of changes in solar radiation at the place of intended operation of the solar photovoltaic station were taken into account during project development.

Modern requirements for highly efficient solar cells, which are used for the production of solar panels, increase the interest in the development of new materials and structures. In this context, much attention is paid to technologies that allow improving the efficiency of solar energy conversion and ensuring its sustainability in various operating conditions. One of the promising areas of research is the use of composite materials and new structures of solar cells (Wu C. et al., 2020; Peter Amalathas A. et al., 2019).

The study of new structures includes the use of various methods of their production (Rath J. K., 2003; Dyadenchuk A. F., Kidalov V. V., 2013), the introduction of porous materials (Wang J. et al., 2019; Alrasheedi N. H., 2023), as well as the optimization of interface boundaries (Jagadish K., Hembram K. P. S. S., 2022; Peña, T. A. D. et al., 2023) to improve the increase in light absorption and recombination losses. Improving the sustainability and optimizing the efficiency of solar cells can have a significant impact on renewable energy production, making them more competitive and suitable for widespread adoption (Savchenko O., et al., 2021). Thus, the research and development of new nanomaterials for solar cells is a key direction in the field of clean energy production.

In this article, we consider the modeling of a solar cell based on the GaN/porous-GaAs/GaAs heterostructure. The GaN/porous-GaAs/GaAs heterostructure appears promising for use in solar cells for several reasons. First, gallium nitride GaN has exceptionally high resistance to corrosion and a high transparency coefficient in the ultraviolet and visible spectral ranges (Nahhas A. M., 2018), which increases its efficiency in absorbing light. Secondly, the use of porous gallium arsenide porous-GaAs allows creating an effective transition layer (Lebib A., 2017), contributing to the reduction of recombination losses and improving the efficiency of solar energy conversion. This heterostructure can be beneficial for solving the tasks of highly efficient and degradation-resistant solar energy conversion in conditions of different ranges of light radiation and operating conditions.

The obtaining of the GaN/porous-GaAs/GaAs heterostructure includes several stages and technological processes (Fig. 1).

GaN pellicles can be produced using various methods: metal-organic chemical vapor deposition (MOCVD) (Chen K., et al., 2022), Molecular Bam Epitaxy (MBE) (Liang K., et al., 2020), vapor phase epitaxy (Ohnishi K., et al., 2021), hydride nitrogen epitaxy (HVPE) (Wang T., et al., 2007), pulsed laser deposition (PLD) (Cheng Y. W., et al., 2015), etc.

The choice of a specific method depends on the requirements for the thickness and quality of the pellicles.

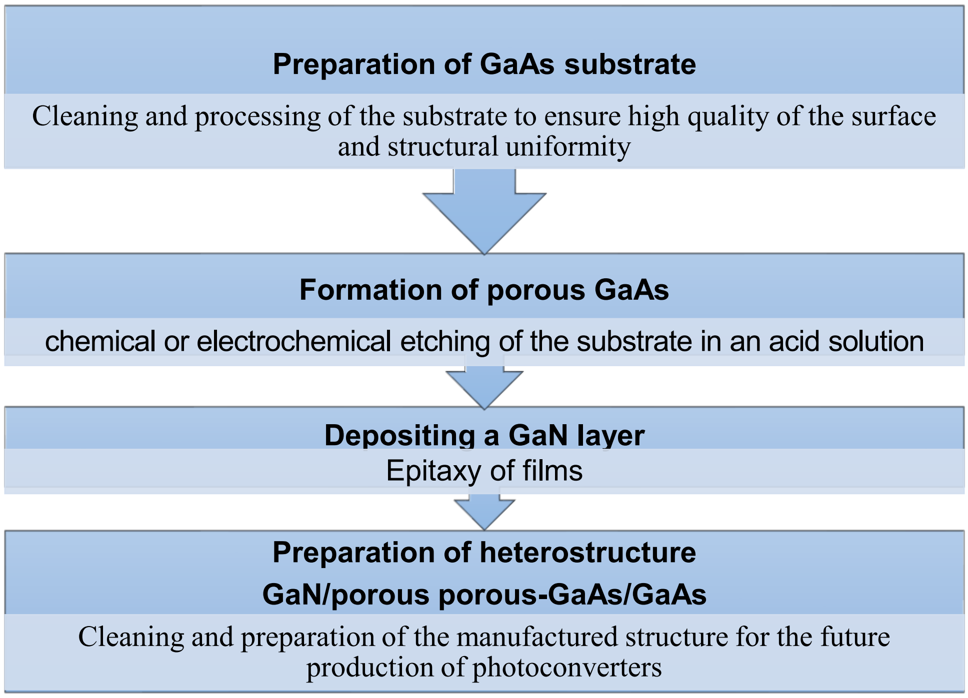

Fig. 1. Technology for obtaining GaN/porous-GaAs/GaAs heterostructure with subsequent use in photovoltaics

Modeling of photoconverters is important for optimizing their design and properties, providing a quick assessment of various parameters without physically manufacturing prototypes (Khairuddin N. S., at al., 2023a; Hussienat L. H., et al., 2023; Halko S., et al., 2023). This allows you to save time, resources and contributes to the understanding of physical processes in devices. Modeling also helps predict the performance of photoconverters under different conditions and contributes to the development of more efficient technologies. An effective tool for modeling solar cells is PC1D (Singh B., Gupta V., 2022; Irfan M., et al., 2025). With the flexibility to tune parameters including materials, geometry, and electrical characteristics, PC1D becomes an effective tool for solar cell research and optimization.

2. MATERIALS AND METHODS OF RESEARCH

To determine the photovoltaic characteristics of the GaN/porous-GaAs/GaAs photoconverter, it is necessary to solve a system of equations that includes the Poisson equation, the diffusion equation, and the charge conservation equation (Subramanian M., et al., 2022; Farrell P., et al., 2017; Yang Y., et al., 2021). Poisson's equation:

$$\frac{d^2V}{dx^2} = \frac{q}{\varepsilon}(p - n + N_d - N_a), \tag{1}$$

where V - is the voltage, x - is the coordinate, q - is the elementary charge, p and n are the concentrations of holes and electrons, respectively, N_d and N_a are the concentrations of donors and acceptors, ε - is the dielectric constant.

Diffusion equation:

$$\frac{dn}{dx} = \frac{1}{q}\frac{dJ_n}{dx}, \quad (2)$$

$$\frac{dp}{dx} = -\frac{1}{q}\frac{dJ_p}{dx}, \quad (3)$$

where J_n and J_p are current densities for electrons and holes, respectively:

$$J_n = en\mu_n + eD_n\frac{dn}{dx}, \quad (4)$$

$$J_p = en\mu_p E - eD_p\frac{dp}{dx}. \quad (5)$$

Here, μ_n and μ_p are the absolute value of the mobility of electrons and holes, and the diffusion coefficients are calculated according to Einstein's relations:

$$D_n = \frac{\mu_n kT}{e}, \quad (6)$$

$$D_p = \frac{\mu_p kT}{e}. \quad (7)$$

The charge conservation equation:

$$\frac{d^2V}{dx^2} = \frac{q}{\varepsilon}(p - n + N_d - N_a), \quad (8)$$

where ρ - is the volume charge density.

Since several layers of different semiconductors are located between the electrodes, the conditions for crosslinking functions are established at the boundary of these layers. By numerically solving the system of equations with boundary conditions for different values of the potential difference between the electrodes V, we obtain the I-V.

The main parameters and properties of GaN, porous-GaAs, and GaAs materials used in this study (Table 1) were obtained from (Parajuli D., et al., 2023; Khairuddin N. S., et al., 2023b; Dyadenchuk A. F., et al., 2005; Dyadenchuk, A. F., Kidalov, V. V., 2014; Tridane, M., et al., 2022). Other layer options used from internal model of PC1D.

Table 1. List of parameters used in the simulation

Parameter	Value
Layer porous-GaAs	
Thickness	0.2 mkm
Band gap	1.42 eV
Dielectric constant	10.1
Background doping	$1\cdot10^{16}$ cm^{-3}
Bulk recombination	1 μs
Layer GaAs	
Thickness	10 mkm
Band gap	1.424 eV
Dielectric constant	11.8
Background doping	$1\cdot10^{17}$ cm^{-3}
Bulk recombination	10 μs
Layer GaN	
Thickness	varied
Band gap	3.42 eV
Dielectric constant	8.9 eV
Background doping	varied
Bulk recombination	$2\cdot10^{-3}$ μs

The PC1D simulator is used to calculate short-circuit current (Dyadenchuk A. F., Kidalov V. V., 2018; Devendra K. C., et al., 2020), open-circuit voltage and maximum output power

P_{max}. The short-circuit current I_{SC}, the open-circuit voltage V_{OC} were obtained from simulations, the filling factor FF and the efficiency η were calculated according to:

$$F = \frac{P_{max}}{V_{OC} \cdot I_{SC}}, \tag{9}$$

$$\eta = V_{OC} \cdot I_{SC} \cdot FF. \tag{10}$$

To optimize the electrical properties of this design, the voltage of the base circuit was set from –0.8 V to +0.8 V with a constant intensity of 0.1 W/cm^2.

3. RESULTS AND DISCUSSION

3.1. I-V characteristics

Based on the simulation results of GaN/porous-GaAs/GaAs solar cells, the current-voltage characteristics were obtained (Fig. 2). The values of short-circuit current I_{SC}, open-circuit voltage V_{OC}, fill factor FF and efficiency η were found to be 33.2 mA, 1.022 V, 83.4% and 28.3%, respectively. The next stage was the study of GaN/porous-GaAs/GaAs solar cells with changes in the thickness of the GaN layer, the doping level of the GaN layer, and the temperature of the solar cell.

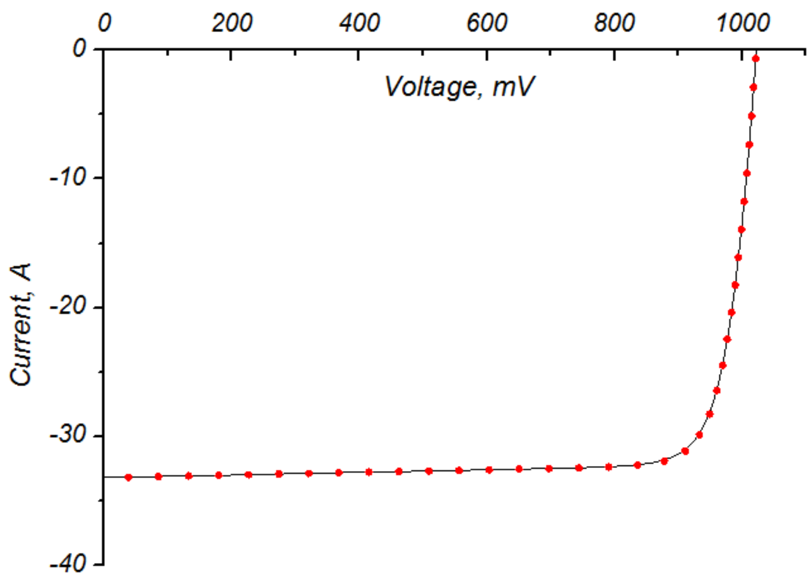

Fig. 2. Voltage-ampere characteristic of a photoconverter GaN/porous-GaAs/GaAs using PC1D simulation

3.2. Effect of Thickness of GaN Layer on Efficiency of Solar Cell

The thickness of the GaN layer of a solar cell has a significant effect on its efficiency: a thin layer can contribute to the deepening of light in the active semiconductor layer, improving the efficiency of photon absorption. Conducting detailed simulations and experiments is key to determining the optimal parameters of the GaN layer under specific conditions. The short-circuit current results from the generation and collection of the generated light carrier. The open-circuit voltage is a measure of the recombination of electron-hole pairs in a solar cell. The influence of the thickness of the conducting layer on the short-circuit current and the no-load voltage is shown in Fig. 3. The thickness of the GaN layer varied from 100 nm to 2 μm. The maximum value of the short-circuit current is reached at a thickness of the GaN layer of 1.6 μm. The open-circuit voltage begins to decrease at a GaN layer thickness of 900 nm.

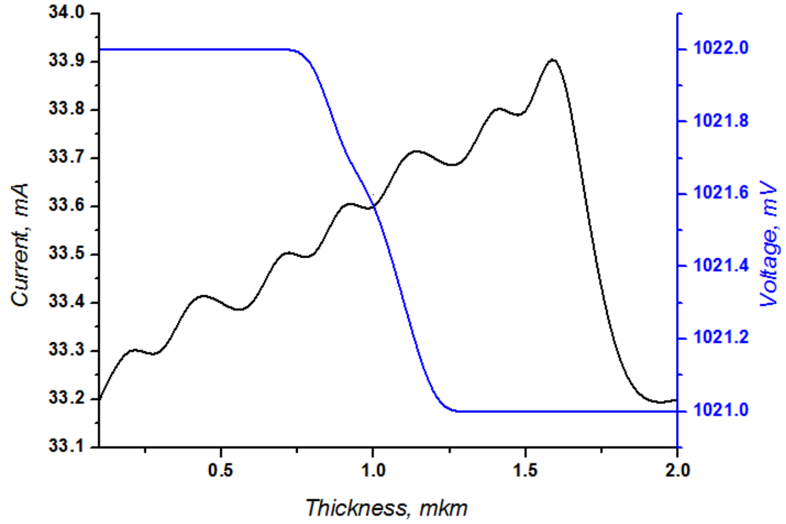

Fig. 3. Dependence of short-circuit current and open-circuit voltage on the thickness of the GaN layer

With GaN layer thicknesses of 0.1-1.6 μm, the efficiency of the solar cell gradually increases, reaching a maximum value of 29.1%, as shown in Fig. 4, and with a further increase in thickness, the efficiency begins to decrease to the values of 28.5%.

3.3. Effect on Efficiency by Varying Doping Concentration of GaN/porous-GaAs/GaAs Solar Cell

The doping concentration of the layers of the heterostructure solar cell plays an important role in the performance of the solar cell (Ngoy K. R., et al., 2021). In this work, the doping concentration varied from $1 \cdot 10^{12}$ to $1 \cdot 10^{20}$ cm^{-3}. The short-circuit current did not change significantly, and at a value of $1 \cdot 10^{19}$ cm^{-3} the short-circuit current decreases. The open-circuit voltage slightly increased due to an increase in the doping concentration, at $1 \cdot 10^{17}$ cm^{-3} the maximum value was reached (Chub A., et al., 2019; Halko S., et al., 2021), but at $1 \cdot 10^{18}$ cm^{-3} a decrease in voltage is again observed (Fig. 5).

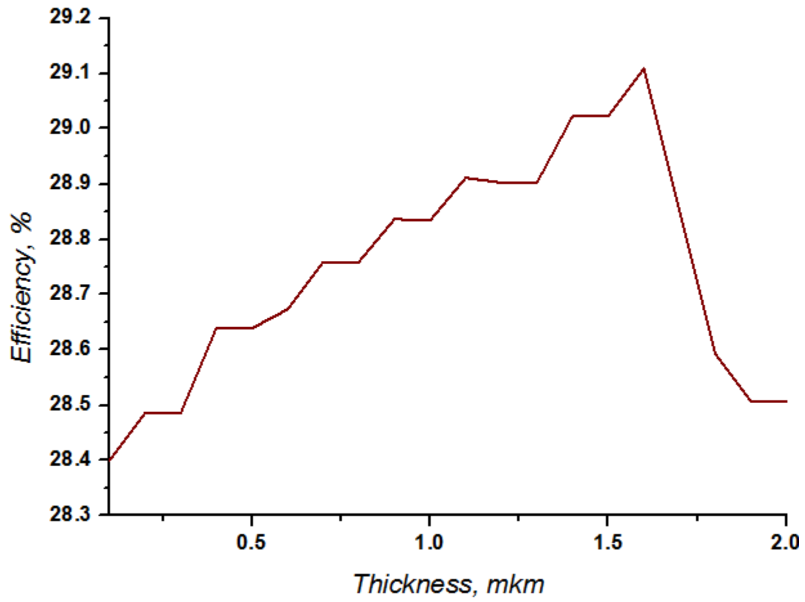

Fig. 4. Change in efficiency depending on the GaN layer thickness

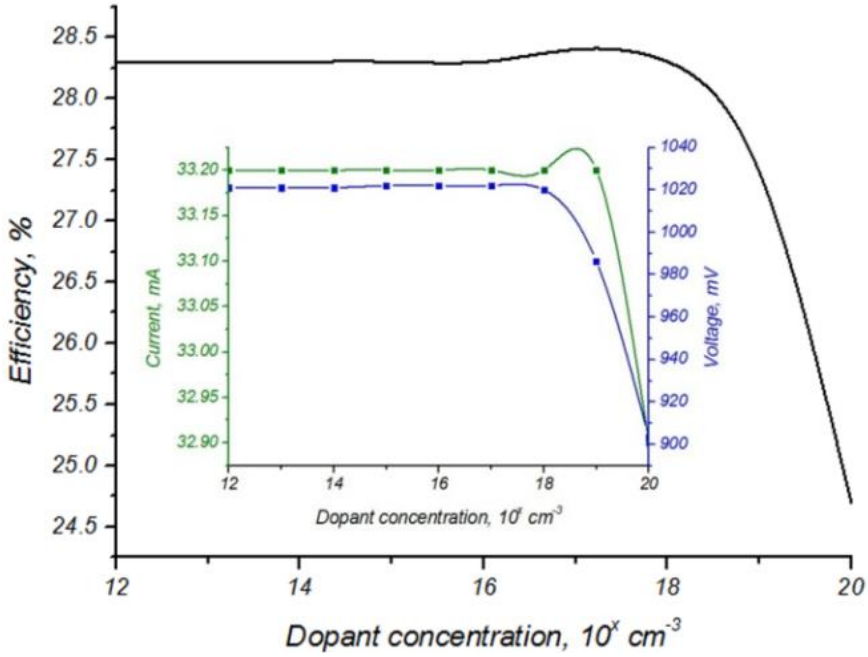

Fig. 5. Efficiency of the GaN/porous-GaAs/GaAs photoconverter at different doping concentrations of the GaN layer. Inset – change in short-circuit current and open-circuit voltage depending on the doping concentration of the GaN layer

The role of doping concentration in the solar cell on the efficiency of the solar cell is very important for an efficient solar cell. A higher level of doping causes damage to the crystalline structure of the solar cell, which is the main reason for reducing the efficiency of the solar cell (Halko S., at al., 2022). By varying the doping levels of the GaN layer, the efficiency of solar battery changes. The maximum efficiency was achieved when doping the layer $1 \cdot 10^{17}$ cm^{-3}, after which the efficiency was reduced, as shown in Fig. 5. The highest level of conversion efficiency of 28.4% was achieved at doping levels of $1 \cdot 10^{17}$ cm^{-3}.

3.4 Effect of Temperature on Solar Cell

An increase in the temperature of the solar cell leads to an increase in recombination losses and a decrease in the open-circuit voltage, so it is important to study the issue of the effect of temperature on efficiency (Humaidan R. M., et al., 2022; Lakshmi G. S., et al., 2021). The efficiency of the GaN/porous-GaAs/GaAs solar cell is evaluated at different temperatures in the range of 270-370 K. In Fig. 6 shows the trend of the change in the shape of the I-V characteristics at different temperature values. In this structure, the output current is obtained according to the formula (Lakshmi G. S., et al., 2021):

$$I = I_{ph} - I_0 \left[e^{\left(\frac{V}{AV_T}\right)} - 1 \right], \tag{11}$$

where V - is the applied voltage, I_0 - is the saturation current, I_{ph} - is the photocurrent, and V_T - is the thermal voltage, $V_T = kT/q$.

As the temperature increases (Fig. 6), there is a decrease in the no-load voltage of the photoconverter from 1.5 V to 0.9 V. This is most likely due to an increase in the thermal motion of atoms in the materials, which leads to an increase in the scattering of electrons and, therefore, to reducing the electrical conductivity of the material (Humaidan R. M., et al., 2022).

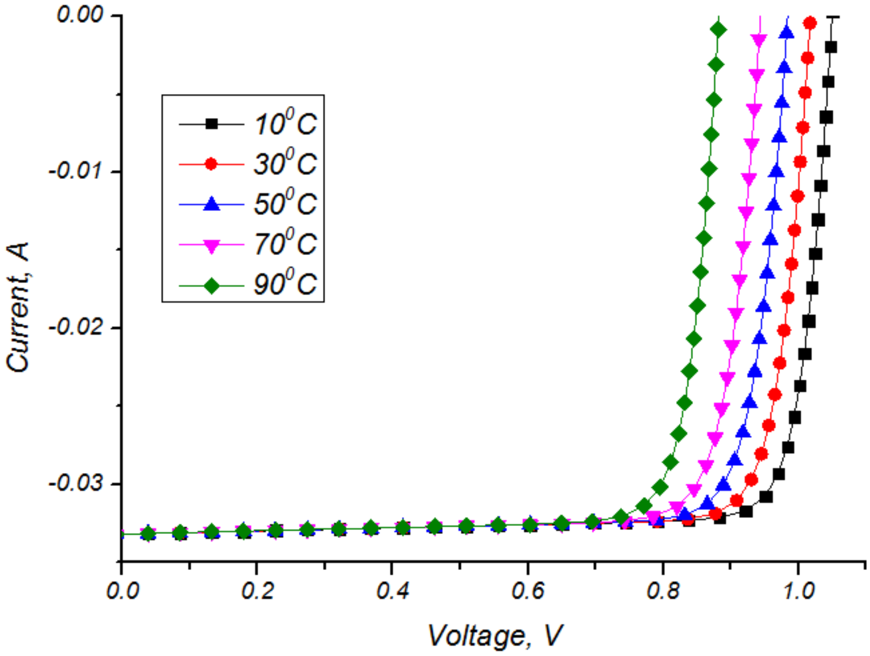

Fig. 6. I-V of the photoelectric converter GaN/porous-GaAs/GaAs at different temperature values

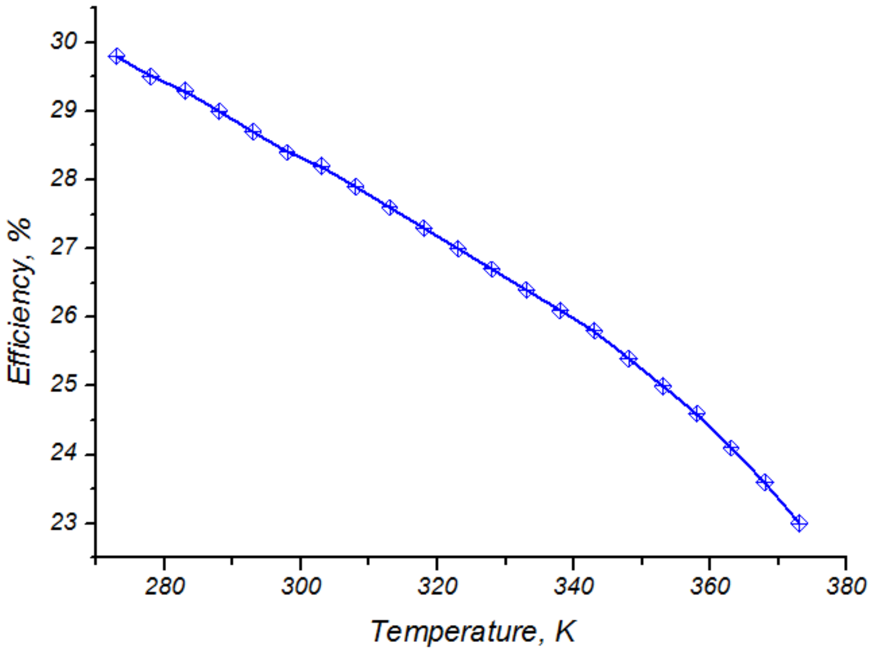

Fig. 7. Change in the efficiency of the photoelectric converter GaN/porous-GaAs/GaAs with increasing temperature

As the temperature increases, the efficiency of the GaN/porous-GaAs/GaAs photovoltaic converter decreases from 29.8% at 270 K to 23.0% at 370 K (Fig. 7).

5. CONCLUSION

The article explores the importance of modeling photoconverters to optimize their parameters, in particular with the help of the PC1D tool, which allows you to predict and understand the operation of solar cells in various conditions. The influence of such factors as GaN layer thickness, doping concentration, and temperature on the efficiency of the GaN/porous-GaAs/GaAs solar cell is analyzed in detail. The findings show that optimal parameters of the GaN layer and doping concentration can significantly increase the efficiency of the photoconverter, while increasing the temperature significantly decreases the efficiency, indicating the importance of studying this issue for further improvement of solar cells. This paper aims to contribute to the understanding and optimization of the processes involved in the development of highly efficient solar cells and can serve as a basis for further experimental research and development in the field of renewable energy. Further research will be aimed at conducting experiments on the manufacture and testing of GaN/porous-GaAs/GaAs solar cells with optimized parameters determined by simulations. So far, all the results are based on theoretical calculations, and experimental tests have not yet been carried out, which opens up opportunities for future research in this area.

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