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Gunn Diodes Based on Graded InGaP-InPAs

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Nowadays, graded semiconductors attract developers' interest as prospective material which can improve the interaction of the electric field and the electrons in the devices operating on the intervalley electron transfer effect. This effect increases the efficiency and power output of the generation of current oscillations in Gunn diodes. To obtain the best effect graded semiconductor must be optimal by the dependence of the energy gap between the nonequivalent valleys of the conduction band on the coordinate. This paper deals with the results of the investigation of Gunn diodes operation based on graded InGaP-InPAs by means of the temperature model of intervalley electron transfer in graded semiconductors. The paper presents the results of the numerical experiments on efficient generation of electromagnetic waves in the range from 18 to 80 GHz using graded $In_xGa_{1-x}P$-InP_yAs_{1-y} Gunn diodes with the active region length of 2.5 μm and concentration of ionized impurities therein of 10^{16} cm^{-3}. Our findings are the dependences generation efficiency and output power on frequency for different distributions of GaP and InAs in $In_xGa_{1-x}P$-InP_yAs_{1-y}. We have compared obtained results with similar $Al_xGa_{1-x}As$-GaAs-$Ga_{1-y}In_yAs$-diodes. The maximal obtained power in $In_xGa_{1-x}P$-InP_yAs_{1-y}-diode is 11.3 kW·cm^{-2} at a frequency of 40 GHz with an efficiency of 10.2 % at $x = 0.6$ and $y = 0.6$.

Keywords: Gunn diode, Intervalley electron transfer, Graded semiconductor, Output power, Domain, Generation efficiency, The temperature model, Terahertz electronics, Microwave generation, Indium phosphide, Indium arsenide, Gallium phosphide, InGaPAs.

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1. INTRODUCTION

Despite enormous advances in manufacturing technology transistors of terahertz range [1, 2] conventional active elements of millimeter- and submillimeter-ranges such as Gunn diodes, avalanche-transit diode and resonant-tunnel diode are still in demand.

Gunn diodes still find wide applications as active elements for the generation and amplification in the millimeter wavelength range. The combination of low phase noise with moderate power and relatively low cost makes them popular devices. The basis of the Gunn diode operation is intervalley electron transfer effect. The operating frequency of the devices based on this effect is limited from the top by a number of physical problems. They include transit time finiteness of electrons from one valley of the conduction band into another, "warming up" time of electrons near the cathode contact up to the energy required for intervalley electron transfer effect, drift velocity finiteness of electrons in the semiconductor, increase of the capacity while reducing the length of the device, and others. Nowadays planar technologies and graded-gap semiconductors (sometimes heterojunction) in the cathode contact [3] are mainly used to eliminate the negative impact of some of the above listed reasons. In [3-5] it is shown that the Gunn diodes based on graded-gap semiconductors have higher generation efficiency and the output power. The injection of hot electrons through the heterojunction into the active region has long been considered as the reason for such an increase [3]. However, as it was shown in [5], the energy of such electrons in the active region of the diode decreases rapidly to the energy of crystal lattice. A local reduction of the energy gap between nonequivalent valleys in the cathode contact looks like a more plausible reason for considered increase. The optimal value of the energy gap between valleys at the cathode contact at a temperature of the crystal lattice 300 K is 0.1...0.3 eV. For example, it corresponds to $Al_{1-x}Ga_xAs$-GaAs-diode when $x = 0.15…0.3$. The most widely used graded compounds for the Gunn diodes today are AlGaAs-GaAs [3] and GaAs-InGaAs [6]. However, they, apparently, are not optimal for the following reasons. In some triple graded-gap compounds such as GaAs-InGaAs and InP-InPAs, the optimum energy gap cannot be achieved due to its lower boundary in GaAs 0.36 eV and in InP 0.6 eV. The case, which allows to reduce the energy gap between valleys down to thermal energy of electrons appeals interest. This opportunity is provided by, for example, AlGaAs, GaPAs and InGaP ternary semiconductors. On the other hand, in the Gunn diodes on the basis of $Al_xGa_{1-x}As$-GaAs with optimal content of AlAs in the cathode 15...25 % [3, 7] the optimum upper boundary of the energy gap between valleys may not be reached, since it is bounded above by the value for GaAs. It should be added that for a variety of electrical and physical properties InGaAs and InPAs are more preferable than GaAs. More complex semiconductor compounds AlGaAs-GaAs-InGaAs and InGaPAs allow to overcome the above mentioned limitations. In [7] numerical experiments with AlGaAs-GaAs-InGaAs Gunn diodes partially confirmed the hypothesis. It was shown that $Al_{0.2}Ga_{0.8}As$-GaAs-$Ga_{0.5}In_{0.5}As$ diode with

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the active region length of 2.5 μm has the output power three times higher, and the generation efficiency – almost two times higher than the corresponding values in similar $Al_{0.2}Ga_{0.8}As$-GaAs and GaAs-$Ga_{0.5}In_{0.5}As$ – diodes.

It is expected that the use GaPAs-InGaAs and InGaP-InPAs in Gunn diodes will result in a similar effect. The paper aims to explore the operation features of the diodes based on graded InGaP-InPAs, to find the optimal distribution of binary components, and to evaluate the output parameters.

2. THE DEVICE STRUCTURE

The diode with doping profile n^+–n–n^+ based on $In_{x(z)}Ga_{1-x(z)}P_{y(z)}As_{1-y(z)}$ is simulated with the following parameters: active region length was 2.5 μm; ionized donor concentration therein was 10^{16} cm^{-3}; length of the cathode and anode were 0.75 μm; ionized donor concentration therein was $5 \cdot 10^{16}$ cm^{-3}. The conduction band diagram, the distributions of impurities and binary components are shown in Fig. 1.

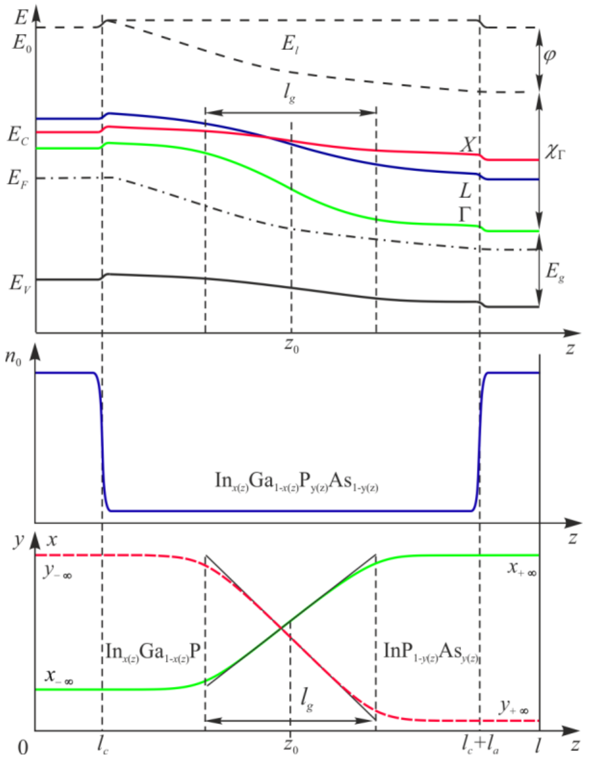


Fig. 1 – Schemes of the band diagram, doping level and distribution of x and y components in $In_{x(z)}Ga_{1-x(z)}P$-$InP_{y(z)}As_{1-y(z)}$ Gunn diodes

Levels of constant energy gap between Γ-L and Γ-X valleys in $In_xGa_{1-x}P_yAs_{1-y}$ are shown in Fig. 2. Here the energy minima of i-valley depending on x and y are given by the second order surface:

$$E_{ixy} = E_{ix1}y + E_{ix0}(1-y) + \frac{0.3y(1-y)}{\sqrt{(E_{ix0}+E_{ix1})/2}}, \quad (1)$$

where $E_{ix0} = E_{i10}x + E_{i00}(1-x) + \frac{0.3x(1-x)}{\sqrt{(E_{i00}+E_{i10})/2}}$ and

$$E_{ix1} = E_{i01}x + E_{i11}(1-x) + \frac{0.3x(1-x)}{\sqrt{(E_{i01}+E_{i11})/2}}.$$

The energy gap between Γ and X valleys is described by $\Delta_{\Gamma X}(x,y) = E_X(x,y) - E_\Gamma(x,y)$ and energy gap between Γ and L valleys is $\Delta_{\Gamma L}(x,y) = E_L(x,y) - E_\Gamma(x,y)$.

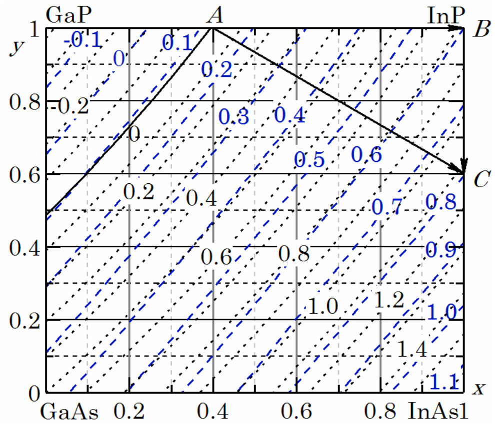


Fig. 2 – Levels in constant energy gap $In_xGa_{1-x}P_yAs_{1-y}$ between Γ- and L- valleys $\Delta_{\Gamma L}$ (long dashed line) and between Γ - and X-valleys $\Delta_{\Gamma X}$ (short dashed line). The continuous line represents $\Delta_{\Gamma X} = 0$

In $In_xGa_{1-x}P$ when $x = 0 \ldots 0.38$ minimal by energy is X-valley, i.e. at $x = 0.38$ $\Delta_{\Gamma X} = 0$. In this case, intervalley electron transfer effect does not lead to negative differential conductivity in the semiconductor. This defines one of the boundaries $x = 0.39$ of the semiconductor composition. Zone-zone ionization in InP_yAs_{1-y}. defines the second boundary. This ionization is a negative phenomenon for devices with intervalley electron transfer effect. It becomes large if the width of the energy gap is equal to or less than the minimum energy gap between the valleys $E_\Gamma = \Delta$. In InP_yAs_{1-y} it occurs at $y = 0.51$.

Therefore, we limit our research by the area of ABC triangle in Figure 2. Here, the arrows show the possible directions of how the semiconductor composition will change from the cathode to the anode. That is $In_xGa_{1-x}P$-InP_yAs_{1-y}-diodes are considered. Contents of In- and P-components in $In_{x(z)}Ga_{1-x(z)}P_{y(z)}As_{1-y(z)}$ are given by S-dependencies of the same type:

$$x(z) = (x_{-\infty} - x_{+\infty})\left[1 + \exp\left(\frac{4(z - z_0)}{l_g}\right)\right]^{-1} + x_{+\infty} \text{ and}$$

$$y(z) = (y_{-\infty} - y_{+\infty})\left[1 + \exp\left(\frac{4(z - z_0)}{l_g}\right)\right]^{-1} + y_{+\infty}, \quad (2)$$

where $x_{-\infty}$ and $x_{+\infty}$ are contents of In-component in the cathode ($z \to -\infty$) and the anode ($z \to +\infty$); $y_{-\infty}$ and $y_{+\infty}$ are contents of P-component, respectively, in the cathode ($z \to -\infty$) and the anode ($z \to +\infty$); l_g is the length of transition (graded-gap) layer which is the same for x- and y-components; z_0 is the coordinate of the transition layer center; z is a coordinate. In this research $l_g = 2.5$ μm coincides with the length of diode active region, because under this condition the highest efficiency of the device can be expected [7], the center of active region is $z_0 = 2$ μm, $0.39 \le x_{-\infty} \le 1$, $x_{+\infty} = 1$, $y_{-\infty} = 1$, $0.6 \le y_{+\infty} \le 1$.

In our research we set the task to obtain the dependencies optimized by the supply voltage, of output power and generation efficiency of the diodes on the frequency for different content limit values of In- and P-components via the numerical experiments. Limiting contents of In- and P-components were varied in increments of 0.1. Crystal lattice temperature T_0 was considered to be constant and equaled to 300 K.

3. THE SIMULATION MODEL OF THE DEVICE

The research was conducted by the means of three-level model of intervalley electron transfer effect in the graded-gap semiconductors. The model is based on the solution of Boltzmann equation under the assumption of a displaced Maxwellian electron distribution [5] and represents a system of the following equations: continuity equations (3), equations of current density (4) and the energy balance for each of the Γ, L and X nonequivalent valleys of the semiconductor conduction band (5), and the Poisson equation (6):

$$\frac{\partial n_i}{\partial t} = -\frac{1}{e}\frac{\partial J_i}{\partial z} - \frac{n_i}{\tau_{n,ij}} - \frac{n_i}{\tau_{n,i\kappa}} + \frac{n_j}{\tau'_{n,ji}} + \frac{n_k}{\tau'_{n,\kappa i}}; \qquad (3)$$

$$J_i = n_i\mu_i\left(eE + \frac{\partial \chi_i}{\partial z}\right) + k_B\mu_i\left(\frac{3n_iT_i}{2m_i}\frac{\partial m_i}{\partial z} - \frac{\partial (n_iT_i)}{\partial z}\right); \qquad (4)$$

$$\begin{aligned}\frac{3}{2}k_B\frac{\partial n_iT_i}{\partial t} = J_iE + \frac{J_i}{e}\frac{\partial \chi_i}{\partial z} - \frac{5}{2}k_B\frac{1}{e}\frac{\partial (J_iT_i)}{\partial z} - \\ -\frac{3}{2}\kappa_B\left(\frac{n_jT_j}{\tau'_{E,ji}} + \frac{n_kT_k}{\tau'_{E,ki}} - \frac{n_iT_i}{\tau_{E,i}}\right)\end{aligned}; \qquad (5)$$

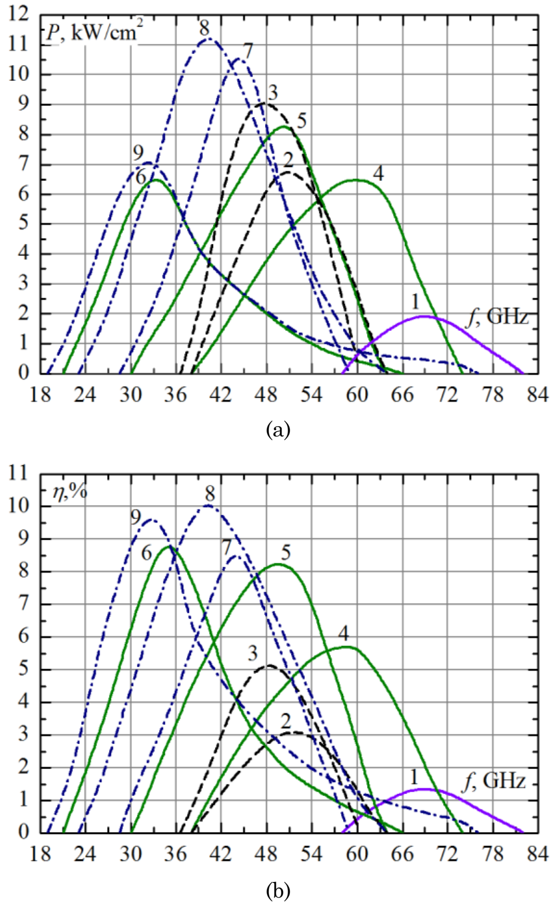
$$\frac{\partial (\varepsilon E)}{\partial z} = 4\pi e\left(n_i + n_j + n_k - n_0\right) \qquad (6)$$

where the indices i, j and k determine the three nonequivalent valleys. Equations (3)-(5) are written for the i^{th} valley. Here, n_i, μ_i, m_i, J_i, T_i , concentration, mobility, effective mass, current density and temperature of the electrons in the i^{th} valley, respectively; $\tau_{n,ij}$ and $\tau_{E,ij}$ are concentration and energy relaxation times of the electrons under the intervalley transfer from i^{th} to j^{th} valley; $\tau_{E,i}$ is energy relaxation time of the electrons in the i^{th} valley; χ_i is the energy required to transfer electrons from energy minimum of i^{th} valley to a local level of vacuum; E is electric field intensity; n_0 is the concentration of ionized donors; ε is dielectric constant; e is the absolute value of electron charge; k_B is Boltzmann's constant; t is time; z is a coordinate. The average density of current in the diode is defined as the sum of averages in three valleys. The system of equations (3)-(6) is solved by numerical method using two-sided Thomas algorithm. The following situation is simulated: a sinusoidal voltage with a constant component is applied to the diode which corresponds to the diode placed into a single loop resonator. Input data: applied voltage U_0 to the device, the amplitude U_1 and frequency f of its oscillations, the parameters of binary semiconductors. Output data: dynamical distributions of electron concentration, their energy, current densities, electric field intensities, the dependence of the average current density flowing in the diode on time, the power and generation efficiency of electric oscillations. Output data are optimized for different frequencies of the bias voltage and the amplitude of the first harmonic.

4. RESULTS OF THE RESEARCH AND ITS ANALYSIS

We suggest analyzing the physical processes occurring in $In_xGa_{1-x}P$-InP_yAs_{1-y} -diodes for three cases: (i) $In_xGa_{1-x}P$-InP ($y = 1$); (ii) InP-InP_yAs_{1-y} (x=1); (iii) $In_xGa_{1-x}P$-$InP_{0.4}As_{0.6}$ ($y = 0.4$).

InP-diode is classical Gunn-diode with ohmic n^+–n-cathode. If a voltage of above a threshold value is applied to the diode, then current fluctuations associated with consistent appearance, drift and disappearance of accumulative layers occur in it. Near the cathode contact kinetic energy of the electrons is insufficient to scatter them into the side valleys of the conduction band. The necessary kinetic energy for electron scattering is accumulated by electrons due to their drift in



(a)

(b)

Fig. 3 – The dependencies of the output power (a) and the generation efficiency (b) on frequency for different diodes: 1 – InP; 2 – InP-$InP_{0.8}As_{0.2}$; 3 – InP-$InP_{0.6}As_{0.4}$; 4 – $In_{0.8}Ga_{0.2}P$-InP; 5 – $In_{0.6}Ga_{0.4}P$-InP; 6 – $In_{0.4}Ga_{0.6}P$-InP; 7 – $In_{0.8}Ga_{0.2}P$-$InP_{0.6}As_{0.4}$; 8 – $In_{0.6}Ga_{0.4}P$-$InP_{0.6}As_{0.4}$; 9 – $In_{0.4}Ga_{0.6}P$-$InP_{0.6}As_{0.4}$

an electric field at mainly elastic scattering only when approaching the middle part of the active region. Current oscillations arising in the diode differ slightly in amplitude and high frequency. Frequency of current oscillations is mainly determined by the average drift velocity of the charge instability and the length of the region, where it extends. Therefore, the output power and the generation efficiency are small at a relatively high generation frequency (Fig. 3, curve 1).

If we increase Ga content in the cathode with unchanged content of InP in the anode, then the processes occurring in the diode change. For $x = 0.85…1.0$ in $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{P}$-InP the form of a charge instability which appears in the diode is still the accumulating layer. A characteristic feature of this instability is the fact that its front edge is not depleted of charge carriers. Drift velocity of layers is slightly higher than of domains. Increase of Ga content in the cathode leads to a reduction of the energy gap between Γ-valley and *L* and *X*-side valleys the near the cathode contact. This in turn causes both the local increase in the population of side valleys and lowering of electron mobility. Area, where charge instability forms, displaces from the center of the active region to the cathode. The length of the "dead" zone reduces. dc component of the current flowing in the diode decreases, the amplitude increases and the oscillation frequency of current decreases. It affects the output characteristics in the following way: the frequency decreases and output power and generation efficiency increase (Fig. 3, curves 1, 4, 5 and Fig. 4).

For $x = 0.39…0.85$ in $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{P}$-InP the form of the charge instability which appears in the diode is domain. It should be noted that when x is reduced the transformation of layers into domains occurs gradually. Thus, at $x = 0.83...0.87$ the enriched layer appears near the cathode, but as it moves toward the anode it rearranges into the domain. Moreover, this process is dependent on the applied voltage. So, the boundary $x = 0.85$ is conditional as a value at which in the moving charge instability the leading edge is depleted of charge carriers at any operating voltage.

When x is decreasing the electron concentration in the side valleys in the cathode increases, which leads to a drop in the average electron mobility. Inhomogeneity of valleys filling in its turn leads to the appearance of the domain near the cathode, even without the external field [5]. Drift velocity of the domain with an increase of x-components decreases. All above mentioned phenomena affect the current oscillations in the diode. The frequency and the dc component of the current oscillations reduce. The amplitude of the current oscillations has maximum at $x = 0.5$. This value corresponds to the maximum of power (Fig. 4). For $x = 0.39…0.5$ the influence of inhomogeneous energy gap between valleys becomes very strong. The amplitude of current oscillations reduces sharply. The diode begins to lose its active properties. The power and frequency reduce at a relatively constant generation efficiency (Fig. 3, curve 6 and Fig. 4). However, at the used in calculations the length of graded-gap layer, the static domain in the diode does not appear. Let's consider InP-$\mathrm{InP}_y\mathrm{As}_{1-y}$-diode (Figure 3, curves 1-3). In this diode the minimum energy gap between valleys $\Delta_{\Gamma L}(z)$ is the increasing function of a coordinate. The increase of InAs content in the anode increases the value of energy gap gradient, but does not change its minimum value in the cathode. The population of electrons in side-valleys in the cathode is negligible at any value of y-component.

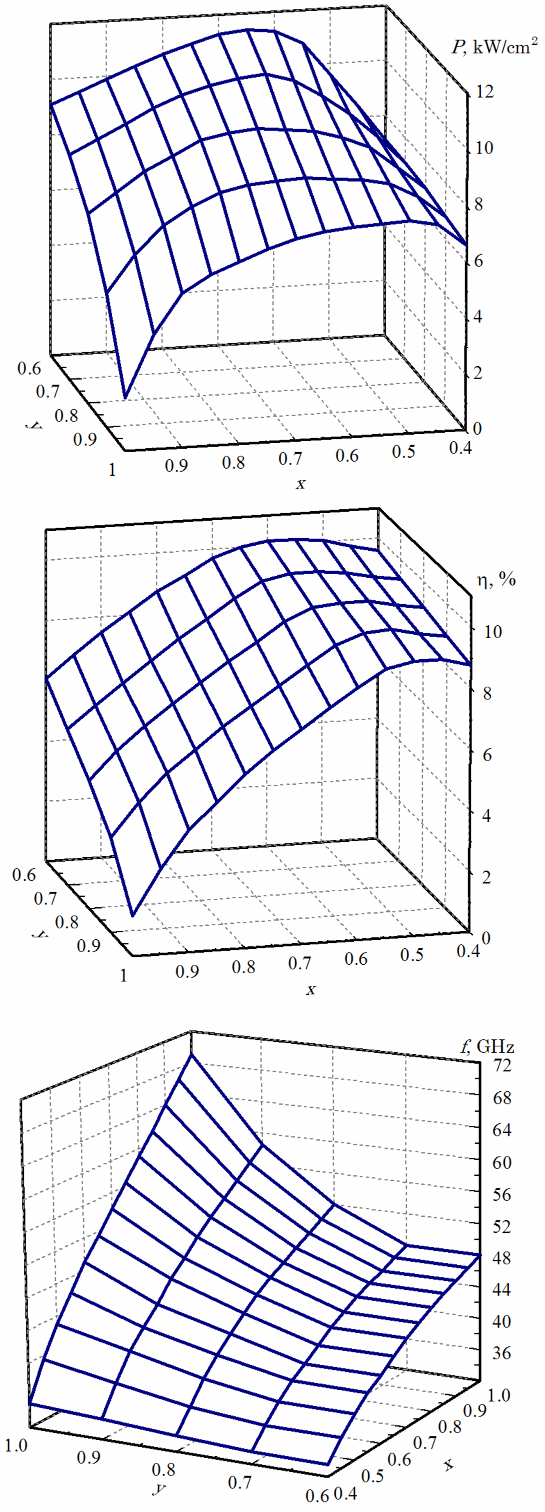


Fig. 4 – Surfaces of maximum values of power P, generation efficiency η and generation optimum frequency f for $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{P}$-$\mathrm{InP}_y\mathrm{As}_{1-y}$-diodes

That is, in the cathode contact the local lowering of the carrier mobility is inevitable and negligible. The reason for current oscillations in the diode is the drift of accumulating layers at any InAs content. Moreover, the power and generation efficiency grow, and the oscillation frequency decreases with increasing content of InAs in the anode.

The main reason of power increase is the energy gap $\Delta_{\Gamma L}$ gradient in the active region. The drop of generation frequency is associated with a decrease in the average drift velocity of electrons in InP_yAs_{1-y} when InAs content is increasing. Evaluations performed in our investigation show that the natural oscillation frequency of the current in the InP-$InP_{0.6}As_{0.4}$-diodes at any voltage supply is 2...4 GHz greater than in $InP_{0.6}As_{0.4}$-diodes.

The output characteristics of the $In_xGa_{1-x}P$-$InP_{0.4}As_{0.6}$-diode and processes occurring therein (see Figure 3, curves 7-9) differ little from the $In_xGa_{1-x}P$-InP-diode (Figure 3, curves 4-6). The $In_xGa_{1-x}P$-$InP_{0.4}As_{0.6}$-diodes have slightly larger peak of output power and efficiency, and the corresponding oscillation frequency is less than in $In_xGa_{1-x}P$-InP-diodes. Maximum output power in $In_xGa_{1-x}P$-$InP_{0.4}As_{0.6}$-diode occurs at $x = 0.5…0.7$ (Fig. 4). This interval of the x-component corresponds to the minimum energy gap in the cathode from 0.18 to 0.38 eV.

So, it is typical for the $In_xGa_{1-x}P$-InP_yAs_{1-y}-diodes that their output power, efficiency and frequency generation are strongly affected by the composition of $In_xGa_{1-x}P$ in the cathode and are relatively weak affected by the composition of InP_yAs_{1-y} in the anode (Fig. 4). The absolute maximum of output power of 11.3 kW·cm^{-2} with an efficiency of 10.2 % at a frequency of 40 GHz is achieved in $In_{0.4}Ga_{0.6}P$-$InP_{0.4}As_{0.6}$-diode. It almost coincides with the characteristics of $Al_xGa_{1-x}As$-GaAs-$Ga_{0.5}In_{0.5}As$-diodes at $x = 0.15...0.20$ ($\Delta_{\Gamma L} = 0.23...0.18$ eV) [7]. $Al_{0.2}Ga_{0.8}$-GaAs-$Ga_{0.5}In_{0.5}As$-diode has the output power of $P = 10.6$ kW·cm^{-2} and the generation efficiency $\eta = 11.3$ % at a frequency of $f = 41$ GHz.

In the $In_xGa_{1-x}P$-InP_yAs_{1-y}-diodes at $x = 0.50...0.61$ the upper limit of the frequency band is increased (Fig. 3, curves 6, 9) due to the reduction of the domain drift region. This effect is described in detail in [8].

5. CONCLUSIONS

Our research has shown the possibility of efficient generation of electromagnetic waves by means of the Gunn diode based on graded $In_xGa_{1-x}P$-InP_yAs_{1-y} compound. This graded gap semiconductor has not been previously investigated as a material for devices with intervalley electron transfer effect.

In the $In_xGa_{1-x}P$-InP_yAs_{1-y}-diodes with lengths of graded and active regions of 2.5 μm the domain mode of current instability in a wide range of values of x- and y-component can be implemented. The composition of $In_xGa_{1-x}P$ in the cathode has the greatest influence on the processes occurring in the diode and its output characteristics. The increase of GaP proportion from 0 to 30 % results in intensive frequency drop as well as increase in output power and generation efficiency. In the range from 30 to 60 % the impact of $In_xGa_{1-x}P$-cathode weakens. The value of $x = 0.5…0.7$ component must be considered optimal by output power. The composition of InP_yAs_{1-y} anode has less influence on output characteristics than the $In_xGa_{1-x}P$-cathode. Growth of InAs proportion in the anode increases the output power and efficiency and reduces the generation frequency at any value of x-component. Moreover, the InP_yAs_{1-y} effect weakens with increase in x and at $x = 0.4…0.7$ almost disappears. The absolute maximum of output power of 11.3 kW·cm^{-2} with an efficiency of 10.2 % at a frequency of 40 GHz is achieved in $In_{0.4}Ga_{0.6}P$-$InP_{0.4}As_{0.6}$-diode The values for output power and generation efficiency are more than five times greater than for the InP-diode ($P = 1.9$ kW·cm^{-2}, $f = 69$ GHz and $\eta = 1.3$ %). For the comparison: InP-InP-$InP_{0.4}As_{0.6}$-diode generates power of 9 kW·cm^{-2} at a frequency of 48 GHz with an efficiency of 5 % and $In_{0.5}Ga_{0.5}P$-InP-diode generates power of 7.6 kW·cm^{-2} at a frequency of 43 GHz with an efficiency of 9 %.

$In_{0.4}Ga_{0.6}P$-$InP_{0.4}As_{0.6}$-diode according to the physical processes occurring therein and output characteristics is almost identical to the similar $Al_{0.2}Ga_{0.8}As$-GaAs-$Ga_{0.5}In_{0.5}As$-diode. For both diodes it is characteristic to have close values of minimum energy gap between the nonequivalent valleys of conduction band in the cathode (0.2...0.3 eV for $T_0 = 300$ K). At the increase in the temperature of the crystal lattice T_0 the increase in the optimum value of the energy gap can be expected.

The disadvantage of investigated $In_xGa_{1-x}P$-InP_yAs_{1-y}-diode is the decrease in the generation frequency in comparison with InP-diodes due to low mobility of electrons in the $In_xGa_{1-x}P$. This disadvantage can be partly overcome by shifting the graded region up to the cathode and reduce its length. Another way to increase frequency is the generation of harmonics. Confirmation of these assumptions requires additional research.

So, the hypothesis we've made about the prospects of $In_xGa_{1-x}P$-InP_yAs_{1-y} Gunn diodes is confirmed by our research results. In particular, we have shown, that by varying the composition of the semiconductor in the cathode and anode one can get a wide variety of Gunn diodes which will differ in output characteristics, including the diode with maximum power.

The results obtained in this research can be used for technological development of new high-speed devices, such as transistors [1, 2], Gunn diodes [3, 5], frequency multipliers [9] and noise generators [10].

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