Gunn Diodes Based on Graded-gap GaInPAs

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The problem of developing the terahertz range by active solid state devices remains relevant. High-speed transistors, Gunn diodes, IMPATT diodes, resonant-tunneling diodes and other devices are currently used to generate millimeter and sub-millimeter waves. However, at frequencies above 100-200 GHz, these devices have a number of physical problems that limit cut-off frequency. Nowadays, graded-gap semiconductors attract developers' interest as prospective materials for such devices, including those operating on the intervalley electron transfer effect. This paper presents the results of the numerical experiments on the current self-oscillation generation in the Gunn diodes based on graded-gap GaInPAs semiconductor alloy with the transit region length of 1.0 μm and concentration of ionized impurities therein of $9 \cdot 10^{16}$ cm^{-3}. GaPAs – GaAs, GaInP – GaAs, GaPAs – InP, GaInP – InP, GaPAs – $Ga_{0.5}In_{0.5}As$ and GaInP – $Ga_{0.5}In_{0.5}As$ diodes have been studied. The numerical simulations have been carried out by means of the temperature model of intervalley transfer of electrons in the graded-gap semiconductors. In such diodes, the domain mode of current instability can be implemented and the continuous oscillations of the current occur, unlike homogeneous GaAs, InP, and $Ga_{0.5}In_{0.5}As$ Gunn diodes, in which the continuous oscillations of the current don't occur. The findings of the paper show that the graded-gap GaInPAs increase the oscillation power of the Gunn diodes in comparison with homogeneous GaAs, InP and $Ga_{0.5}In_{0.5}As$ semiconductors, and self-oscillations contain clearly distinguishable at least third harmonic in the terahertz range. The maximum power of the fundamental mode is 19.4 mW at 98 GHz in $Ga_{0.58}In_{0.42}P$ – $Ga_{0.5}In_{0.5}As$ diode. Higher harmonics are present in the spectrum of oscillations with the power of the second harmonic of 1.0 mW and of the third harmonic of 0.2 mW.

Keywords: Gunn diode, Simulation, Graded-gap semiconductor, Transfer electron effect, Heterojunction.

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1. INTRODUCTION

The main advantages and scenarios for the development of the terahertz electromagnetic waves usage are mostly clear and of great interest. During the last two decades a number of spectacular achievements were presented which pushed forward terahertz technology and science. The relatively cheap, small-sized and effective means of generation, emission, registration and signal processing in the terahertz range are of great demand to implement terahertz technology. Looking through terahertz techniques, one can easily notice the essential difference in availability, diversity and price between detectors and sources of terahertz radiation. There are few sources of terahertz range. It is true that a large class of materials can be used in terahertz systems as antennas excited with femtosecond laser pulses. However, when someone thinks of usage of the direct current sources, it turns out that existing devices are large or very expensive, or both, for instance free electron lasers, the synchrotrons or the molecular lasers pumped with a CO_2, etc. So, the continuous-wave compact solid-state sources play an important role in many system applications of the terahertz range and are in great demand for both laboratory tests and commercial purposes.

A special place is occupied by the achievements in the creation of high-speed low-noise transistors (HBT, DHBT and HEMT) with a maximum operating frequency of 0.3-1 THz. But the cost of such transistors remains high. HEMT manufacture with a maximum operating frequency of 279 GHz by means of chemical vapor deposition process suitable for mass production is of particular interest [1].

Along with advances in the technology of manufacturing terahertz transistors, the traditional active elements such as Gunn diodes, IMPATT diodes, resonant-tunneling diodes and frequency multiplier cascades remain widely in demand. All these devices at frequencies above 100 GHz have a number of physical problems, which limit the operating frequency from above. The highest cut-off frequency in the resonant-tunneling diodes is 1.04 THz [2]; in the frequency multiplier cascades, for example on GaAs Shottky diodes, it is 2.7 THz [3]; in Gunn diodes and IMPATT or TUNNETT diodes, it is about 0.3-0.4 THz [4].

Let us reflect on the Gunn diodes. The InP Gunn diode is the most powerful fundamental semiconductor source at frequencies above 290 GHz [5]. Projections also indicate that a significant amount of power may be generated, at least up to 500 GHz [5, 6]. The basis of the Gunn diode operation is the intervalley electron transfer effect. The advantages of the Gunn diodes are (i) a high pulse power; (ii) low phase noise; (iii) a wide range of operating frequencies. The operating frequency of the diodes is limited from above 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, etc.

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Nowadays, different cathode contacts, which create conditions for the rapid increase in electron energy, are used to eliminate the negative impact of some of the above listed problems. The doping gradient, the reverse bias heterojunction and the Schottky barrier are such contacts. Cut-off frequencies of such Gunn diodes are 100-200 GHz for GaAs and 200-300 GHz for InP [4-6]. The use of cathode contacts, such as tunnel contact [7, 8] and the direct bias heterojunction, which allow electrons with a high level of energy to be injected into the transit region, was not very successful.

The second approach to solve the problem is to find semiconductor materials which have a frequency limit of operation more than GaAs or InP. Such materials include InGaAs [9], GaInPAs and semiconductor nitrides.

One of the little-known directions in the area of Gunn diodes creation is the use of graded-gap semiconductor compounds, which can overcome, to some extent, the need of heating the electron gas at the cathode. Gunn diodes based on graded-gap semiconductors have higher values of generation efficiency and output power [10, 11]. The injection of hot electrons through the heterojunction into the transit region has long been considered as the reason for such an increase [12, 13]. However, as it was shown in paper [14], the energy of such electrons in the transit region of the diode decreases rapidly to the energy of crystal lattice. A local reduction of the energy gap between non-equivalent valleys in the cathode contact looks like a more plausible reason for the considered increase [10, 11]. The optimal value of the energy gap between valleys at the cathode contact at a temperature of the crystal lattice of 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-gap compound for the Gunn diodes today is AlGaAs – GaAs. The ideas of using graded-gap GaInPAs alloy in Gunn diodes [15] are interesting and promising.

The third way to increase the frequency limit of devices is to use multi-frequency or non-linear oscillation modes in semiconductor devices to obtain output power at higher harmonics. The intervalley electron transfer effect has a number of valuable properties, which cause its wide application prospect as the sources of primary oscillations. Sources of oscillations accompanied by basic oscillations type in the Gunn diode are (i) the impact generation of electron-hole pairs in a static or moving domain [16–18]; (ii) the generation of electron-hole pairs caused by external optical pulse [19]; (iii) the ionization of neutral impurities; (iv) the effects associated with the occurrence and the drift of space charge waves in inhomogeneous media [10]; (v) the non-linear interaction with electrodynamic systems [19, 20], etc.

In the paper, we present the results of the comparative analysis of self-oscillation spectra arising in the Gunn diodes based on graded-gap GaInPAs.

2. THE PROBLEM STATEMENT AND THE SIMULATION MODEL

2.1 The Device Structures

The diode with doping profile $n^+ - n - n^+$ based on graded-gap $Ga_{1-x(z)}In_{x(z)}P_{y(z)}As_{1-y(z)}$ alloy is simulated with the following parameters: transit region length 1.0 μm; ionized donor concentration therein $9\cdot 10^{16}$ cm^{-3}; length of the cathode and anode 0.4 μm; ionized donor concentration therein 10^{18} cm^{-3}. The conduction band diagram, the distributions of impurities and binary fractions in the semiconductor alloy are shown in Fig. 1. The model of Γ-L-X levels was used for $Ga_{1-x(z)}In_{x(z)}P_{y(z)}As_{1-y(z)}$.

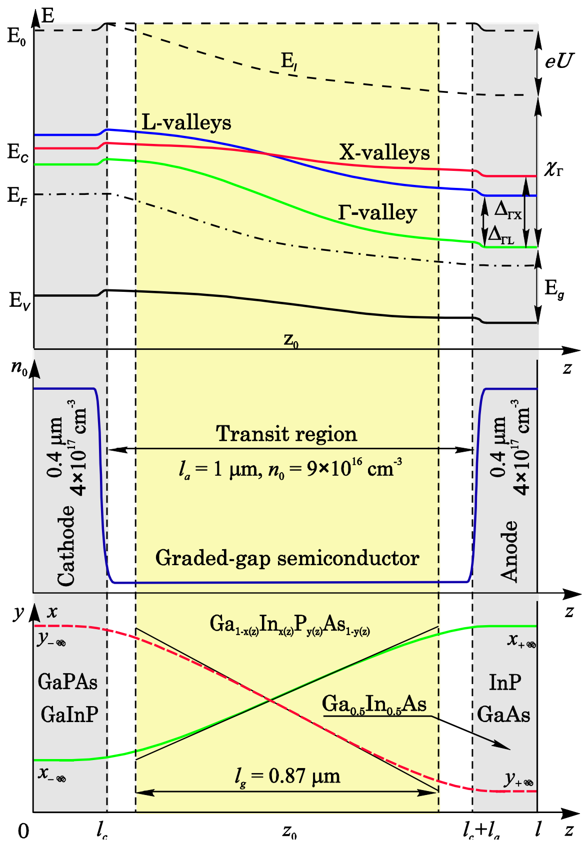

Fig. 1 – Schemes of the band diagram, doping level and distribution of x and y fractions in $Ga_{1-x}In_xP_yAs_{1-y}$ graded-gap Gunn diode

The energy minimum of i-valley depending on x and y is given by the surface:

$$E_{ixy} = E_{ix1}y + E_{ix0}(1-y) - \frac{0{,}3y(1-y)}{\sqrt{(E_{ix0}+E_{ix1})/2}}, \qquad (1)$$

where $E_{ix0} = E_{i10}x + E_{i00}(1-x) - \dfrac{0{,}3x(1-x)}{\sqrt{(E_{i00}+E_{i10})/2}}$ 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 the energy gap between Γ and L valleys is described by $\Delta_{\Gamma L}(x, y) = E_L(x, y) - E_\Gamma(x, y)$ [15].

In $Ga_{1-x}In_xP$, when $x = 0$-0.38 and in GaP_yAs_{1-y}, when $y = 0.48$-1.0, X-valley is a lower energy valley, i.e. in $Ga_{0.62}In_{0.38}P$ and $GaP_{0.48}As_{0.52}$ $\Delta_{\Gamma X} \approx 0$. In these cases, intervalley electron transfer effect does not lead to negative differential conductivity in the semiconductor and defines the boundaries of the semiconductor composition.

Composition fractions of In and P in $Ga_{1-x(z)}In_{x(z)}P_{y(z)}As_{1-y(z)}$ are given by S-dependences of the same type:

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

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 composition fractions of In, respectively, in the cathode ($z \to -\infty$) and the anode ($z \to +\infty$); $y_{-\infty}$ and $y_{+\infty}$ are composition fractions of P, respectively, in the cathode ($z \to -\infty$) and the anode ($z \to +\infty$); z is a coordinate; z_0 is the coordinate of the transition layer center; l_g is the length of transition (graded-gap) layer which is the same for x and y fractions. The change in the composition of the semiconductor along the transit region occurs in a way that the minimum energy gap between the Γ and sides valleys is an increasing function of the coordinate [10, 11]. In this research, the length of the transition layer $l_g = 0.87$ μm almost coincides with the length of the diode transit region, because under this condition the highest efficiency of the device can be expected [10], the center point of the transition region is $z_0 = 0.86$ μm. Diode has a cross section of $S = 20\times20$ μm^2. The crystal lattice temperature T_0 was considered constant and equaled to 300 K. In the research, the operation of diodes based on different graded-gap semiconductors is studied and their power spectrum for different voltages during a 1000 ps pulse is obtained.

2.2 The Simulation Model of the Device

The actual research has been carried out by means of three-level model of intervalley electron transfer effect in the graded-gap semiconductors based on the solution of the Boltzmann equation for the case of a displaced Maxwellian distribution of electrons [10, 15]. This model represents a system of equations consisting of continuity equations, the current density equations and the energy balance equations for each of the three non-equivalent valleys of the semiconductor conduction band, as well as the Poisson equation [10, 15]

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

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

$$\frac{3}{2}k_B \frac{\partial n_i T_i}{\partial t} = J_i E + \frac{J_i}{e}\frac{\partial \chi_i}{\partial z} - \frac{5}{2}k_B \frac{1}{e}\frac{\partial (J_i T_i)}{\partial z} + \frac{3}{2}k_B \left(\frac{n_j T_j}{\tau'_{E,ji}} + \frac{n_k T_k}{\tau'_{E,ki}} - \frac{n_i T_i}{\tau_{E,i}}\right); \quad (5)$$

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

In these equations, the indices i, j and k denote three non-equivalent valleys. The equations are written for the i-valley. Here, n, m, μ, T, and J denote, respectively, the concentration, effective mass, mobility, temperature and current density of electrons; $\tau_{n,ij}$, $\tau_{E,ij}$ denote the relaxation time of electron concentration and electron energy, respectively, during the intervalley transfer from i-valley to j-valley; E is the electric field strength; χ_i is the energy required to transfer electrons from energy minimum of i-valley to a local level of vacuum; n_0 is concentration of ionized donors; ε is the dielectric constant; t is time; e is module of electron charge; k_B is Boltzmann constant. Suppose that only an external electric field acts on the semiconductor.

The average current density in the device is defined as the sum of the mean conduction currents of electrons and the bias current:

$$J(t) = J_\Gamma(t) + J_L(t) + J_X(t) + \frac{\varepsilon}{4\pi}\frac{d\vec{E}}{dt}. \quad (7)$$

The system of equations (3)-(6) is solved by numerical method using Thomas algorithm. The one-dimensional case has been used. All processes are studied only with respect to the z coordinate. The applied DC voltage U and the parameters of semiconductors are input data. Output data are the dynamic distributions of electron concentration, their energy, the electric field strength, current density, the dependences of the average current density flowing in the diode and of the voltage drop across the diode on time $V(t) = \int_0^l E(z,t)dz$. The spectrum of average power of self-oscillations has been investigated. The average power of k harmonic is $P_k = 0.5 J_k V_k S \cos(\Delta\theta_k)$, where J_k and V_k are oscillation amplitudes of the current density and voltage drop across the diode of k harmonic; $\Delta\Theta_k$ is the phase difference between the current density and voltage of k harmonic; $k = 1, 2, 3$. The average DC power is $P_0 = J_0 V_0$.

3. RESULTS OF THE RESEARCH AND ITS ANALYSIS

The generation of continuous self-oscillations cannot be implemented in classical short Gunn diodes based on GaAs and InP with ohmic $n^+ - n$ cathode. When the resonator is absent, at best the damped current oscillations can be generated. The situation changes if in the transit region the special conditions for the rapid gain in energy by electrons required for the intensive scattering into the side valleys can be created. Described conditions can be created by decreasing the doping level or using Schottky barrier or heterojunction near the cathode contact. Under the conditions, the current instabilities associated with domain drift occur in the diode. In the case of graded-gap semiconductor, the domain drift occurs in the diode as well, but the reason for its occurrence is different. Domain occurs due to the increasing dependence of the minimum energy gap between the Γ-valley and the closest to it by the energy side valley. All the details on the occurrence and propagation of space-charge waves in the graded-gap semiconductors are described in paper

[10]. Self-oscillations of the current in the Gunn diodes based on the graded-gap semiconductors depend strongly on the distribution of the composition fractions in the ternary or quaternary semiconductor compounds.

3.1 GaPAs – GaAs and GaInP – GaAs Diodes

Let us consider the processes in graded-gap Gunn diodes based on GaAs. In GaInP – GaAs diode, the transit region consists of graded $Ga_{1-x(z)}In_{x(z)}P_{y(z)}As_{1-y(z)}$ alloy and in GaPAs – GaAs diode, the transit region consists of graded $GaP_{y(z)}As_{1-y(z)}$ alloy.

The GaPAs – GaAs Gunn diodes are not used today. The established views on the need to inject high-energy electrons through a heterojunction into the transit region of Gunn diode and lattice constant matching in GaPAs – GaAs heterojunction in comparison with AlGaAs – GaAs are the reasons. Our research shows that GaPAs – GaAs diodes do not differ from the AlGaAs – GaAs diodes in both the physics of processes and output characteristics [14].

The continuous self-oscillations do not occur in GaAs diode (Fig. 2, curve 1). If we increase GaP fraction in the cathode and do not change the composition of semiconductor in the anode, the processes occurring in the diode change in the following way.

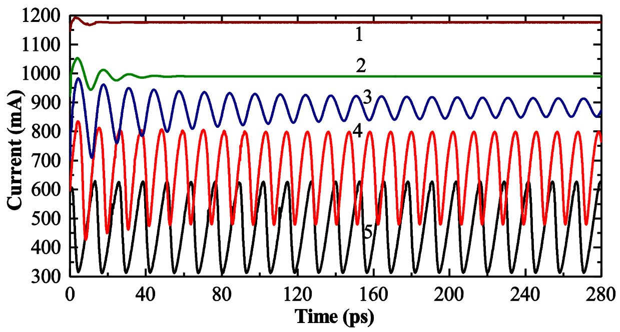

Fig. 2 – The current oscillations in GaP_yAs_{1-y} – GaAs diode for $y = 0$ (1), 0.1 (2) and 0.2 (3) with diode voltage $U = 0.8$ V, $y = 0.3$ with $U = 1.0$ V (4) and $y = 0.4$ with $U = 1.8$ V (5)

Increase in GaP fraction leads to the energy gap reduction between Γ-valley and L and X side valleys in GaPAs. If the GaP fraction increases locally near the cathode contact, then the gradient of the energy gap between the valleys along the transit region increases. There are heterogeneities of electron mobility and electron concentration in the side valleys due to the inhomogeneity of the energy gap between the valleys. The electron concentration in the side valleys near the cathode becomes large and remains small in the center of the transit region. Electron mobility on the contrary is small in the cathode and large in the center of the transit zone. The local decrease in electron mobility near the cathode leads to the accumulation of electrons in this region and to an increase in the electric field strength. Increase in the electric field strength, in turn, stimulates the growth of the kinetic energy of electrons and their scattering from the Γ-valley into the side valleys. This further increases the concentration of electrons in the side valleys and reduces their concentration in the Γ-valley. And this leads to a drop in electron mobility. A positive feedback arises, due to which the space charge accumulates in the graded-gap semiconductor layer near the cathode. If the external voltage is sufficient, this space charge begins to drift along the transit region towards the anode contact. That is, a space mobile charge is formed in a graded-gap semiconductor layer. The region where such charge instability is formed is in the graded-gap semiconductor layer in the region between the center of the transit region and the cathode. The direct current in the diode decreases (Fig. 2, curves 1-5). The length of the "dead" zone in such device is less than in the same type of GaAs diode. The damped self-oscillations occur in the graded-gap GaP_yAs_{1-y} – GaAs diode when $y = 0$-0.2 (Fig. 2, curves 1-3). The form of charge instability, which appears in this diode, is an accumulation layer. A characteristic feature of this instability is the fact that its front edge is not depleted of charge carriers. However, if $y = 0.23$-0.44, the current oscillations in the graded-gap GaP_yAs_{1-y} – GaAs diode are continuous self-oscillations (Fig. 2, curves 4-5). The form of the charge instability, which appears in the diode, is domain. In contrast to the accumulation layer, the leading edge of the domain is depleted in charge carriers. It should be noted that when y is raised from 0.20 to 0.23, the transformation of layer into domain occurs gradually. A static domain appears in the diode when the gradient of the energy gap between the valleys is very large. If y is greater than 0.45, a static domain is formed in GaP_yAs_{1-y} – GaAs diode.

The frequency of current oscillations in graded-gap GaP_yAs_{1-y} – GaAs diode increases for any y fraction if the voltage applied to the diode grows. The oscillation power in graded-gap GaP_yAs_{1-y} – GaAs diode has maximum when the applied voltage is optimal. The optimal voltage increases when y fraction in GaP_yAs_{1-y} alloy grows. For example, for $y = 0$-0.24 the optimal voltage is near 0.8 V and for $y = 0.40$-0.42 it is 2.0 V.

The dependences of average power and frequency of oscillations for optimal voltage on the composition fraction of GaP_yAs_{1-y} are shown in the inset in Fig. 3a.

The oscillation power in graded-gap GaP_yAs_{1-y} – GaAs diode is maximum when $y = 0.38$-0.4. The power spectrum of graded-gap $GaP_{0.40}As_{0.60}$ – GaAs diode is shown in Fig. 3a. The fundamental mode power of these oscillations is 5.96 mW at a frequency of 76.5 GHz and the power of the third harmonic is 0.113 mW at a frequency of 229.5 GHz. The frequency of current oscillations in the graded-gap GaP_yAs_{1-y} – GaAs diode is maximum when $y = 0.3$. The power spectrum of graded-gap $GaP_{0.30}As_{0.70}$ – GaAs diode is also shown in Fig. 3a. The fundamental mode power of such oscillations is 3.35 mW at a frequency of 87.3 GHz and the oscillation power of the third harmonic is 0.005 mW at a frequency of 261.8 GHz.

Now let us consider the processes in graded-gap $Ga_{1-x}In_xP$ – GaAs Gunn diode, which are analogous to those in GaP_yAs_{1-y} – GaAs diode from the point of view of their properties and output characteristics.

Decrease of InP fraction in $Ga_{1-x}In_xP$ leads to a reduction of the electron mobility and of the energy gap between Γ valley and L and X side valleys. Therefore, a decrease of InP fraction in the $Ga_{1-x}In_xP$ cathode of the $Ga_{1-x}In_xP$ – GaAs device leads to the appearance of gradients of the energy gap between valleys and electron mobility in the transit region. This causes the appearance of a moving space charge and continuous current oscillations at a sufficient external voltage. The direct current in the graded-gap $Ga_{1-x}In_xP$ – GaAs diode decreases, when x fraction decreases.

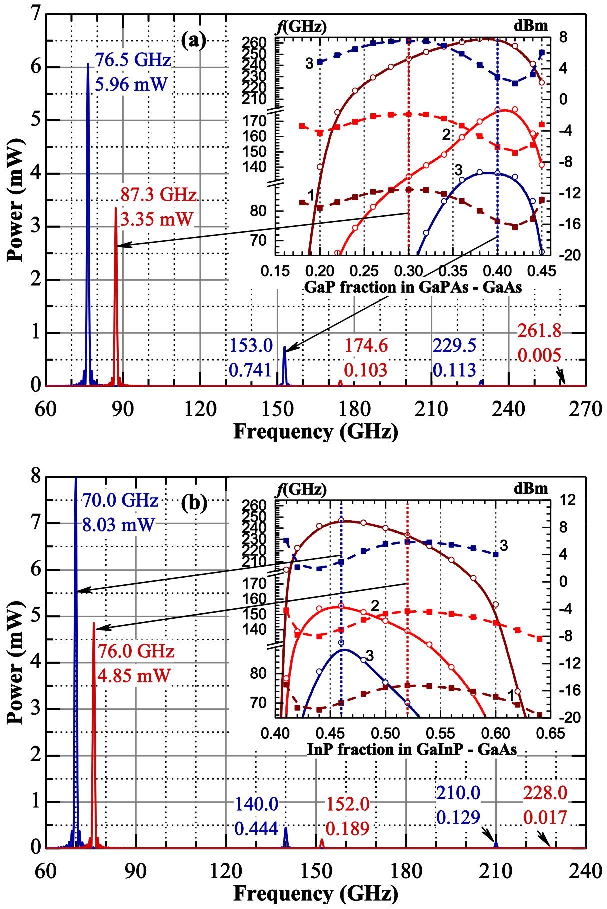

Fig. 3 – The power spectrum of the oscillations in the diodes based on graded-gap $GaP_{0.30}As_{0.70}$ – GaAs when $U = 1.0$ V (a), $GaP_{0.40}As_{0.60}$ – GaAs when $U = 1.8$ V (a), $Ga_{0.54}In_{0.46}P$ – GaAs when $U = 2.2$ V (b) and $Ga_{0.48}In_{0.52}P$ – GaAs when $U = 1.4$ V (b). The inset represents the dependence of frequency (dash lines) and average power (solid lines) of oscillations for fundamental (1), second (2) and third (3) harmonics on the fraction of GaP in GaPAs – GaAs (a) and InP in GaInP – GaAs (b) diodes

If $x = 0.62$-1.0, the damped self-oscillations occur in graded-gap $Ga_{1-x}In_xP$ – GaAs diode. The form of charge instability, which appears in this diode, is the accumulation layer. The decrease of x fraction in graded-gap $Ga_{1-x}In_xP$ – GaAs diode leads the diode to the mode with domain drift and continuous self-oscillations. The power and frequency of current oscillations in $Ga_{1-x}In_xP$ – GaAs diode depend on the $Ga_{1-x}In_xP$ composition and the applied voltage to the diode. These dependences in $Ga_{1-x}In_xP$ – GaAs and GaP_yAs_{1-y} – GaAs diodes are similar. The oscillation frequency increases almost linearly with increasing voltage, and power has maximum when the voltage is optimal. The optimal voltage increases when x fraction in $Ga_{1-x}In_xP$ alloy decreases and it is 1.2-1.4 times more than in graded-gap GaP_yAs_{1-y} – GaAs diode. For example, for $x = 0.64$ the optimal voltage is 1.0 V and for $x = 0.41$-0.44 it is 2.8 V.

The dependences of average power and frequency of oscillations for optimal voltage on the composition fraction of $Ga_{1-x}In_xP$ are shown in the inset in Fig. 3b. The power of oscillations in graded-gap $Ga_{1-x}In_xP$ – GaAs diode is maximum when $x = 0.46$. The power spectrum of graded-gap $Ga_{0.54}In_{0.46}P$ – GaAs diode, when the voltage applied to the diode is 2.2 V, is shown in Fig. 3b. The fundamental mode power of such oscillations is 8.03 mW at a frequency of 70.0 GHz and the oscillation power of the third harmonic is 0.129 mW at a frequency of 210.0 GHz. The power of the fundamental oscillations in graded-gap $Ga_{0.54}In_{0.46}P$ – GaAs diode at the optimal voltage is 1.34 times greater than in $GaP_{0.40}As_{0.60}$ – GaAs diode. The frequency of oscillations in the graded-gap $Ga_{1-x}In_xP$ – GaAs diode is maximum when $x = 0.52$. The power spectrum of graded-gap $Ga_{0.48}In_{0.52}P$ – GaAs diode is also shown in Fig. 3b. The fundamental mode power of such oscillations is 4.85 mW at a frequency of 76.0 GHz and the oscillation power of the third harmonic is 0.017 mW at a frequency of 228.0 GHz.

It should be noted that graded-gap GaP_yAs_{1-y} – GaAs and $Ga_{1-x}In_xP$ – GaAs diodes can generate continuous self-oscillations also when concentration of electrons in the transit region is lower. The lower edge of the doping level of the transit region is near $1.7 \cdot 10^{16}$ cm^{-3} (for composition fractions $y = 0.25$-0.40 and $x = 0.45$-0.55) when the doping level of the cathode is from $4 \cdot 10^{16}$ to $10 \cdot 10^{16}$ cm^{-3}. If the doping level of the cathode is higher than $10 \cdot 10^{16}$ cm^{-3}, then the diode generates damped current oscillations. In this case, it is necessary to increase the concentration of electrons in the active region so that the current oscillations are continuous.

3.2 GaPAs – InP and GaInP – InP Diodes

Let us consider the processes in the graded-gap Gunn diodes based on InP. The transit region in GaInP – InP diode consists of graded $Ga_{1-x(z)}In_{x(z)}P$ alloy and in GaPAs – InP diode it consists of graded $Ga_{1-x(z)}In_{x(z)}P_{y(z)}As_{1-y(z)}$ alloy. Such diodes are analogous to the graded-gap alloy diodes based on GaAs from the point of view of their properties and output characteristics. The mechanism for improving the conditions for the occurrence of current oscillations remains the same. If the GaP fraction in GaPAs and GaInP increases, then the electron mobility and the energy gap between the Γ-valley and L or X-valleys decrease. Accordingly, an increase in the GaP fraction in the semiconductor that is in the cathode leads to spatial heterogeneity of these quantities. The consequence of these reasons is continuous current oscillations in the diode when applied voltage is high enough.

An increase in the GaP fraction near the cathode leads to a decrease in the direct current in the diode just as in diodes based on GaAs. Current damped self-oscillations in GaP_yAs_{1-y} – InP diode occur when in GaP_yAs_{1-y} alloy the y fraction is 0-0.10. The increase of GaP fraction in GaPAs alloy in the cathode up to 0.15 … 0.20 leads the diode to the mode with domain drift and to the continuous self-oscillations of the current. The mode with domain drift in GaP_yAs_{1-y} – InP diode is realized at a smaller GaP fraction than in

GaP_yAs_{1-y} – GaAs diode. The static domain in GaP_yAs_{1-y} – InP diode is formed when y fraction in GaP_yAs_{1-y} alloy is greater than 0.46.

The frequency of current oscillations in graded-gap GaP_yAs_{1-y} – InP diode increases for any y fraction when the voltage applied to the diode grows. The optimal diode voltage increases when y fraction in GaP_yAs_{1-y} alloy grows. For example, for $y = 0.14$-0.20, the optimal voltage is near 1.1 V and for $y = 0.45$ it is 2.1 V.

The dependences of average power and frequency oscillations for optimal voltage on the composition fraction of GaP_yAs_{1-y} are shown in the inset in Fig. 4a.

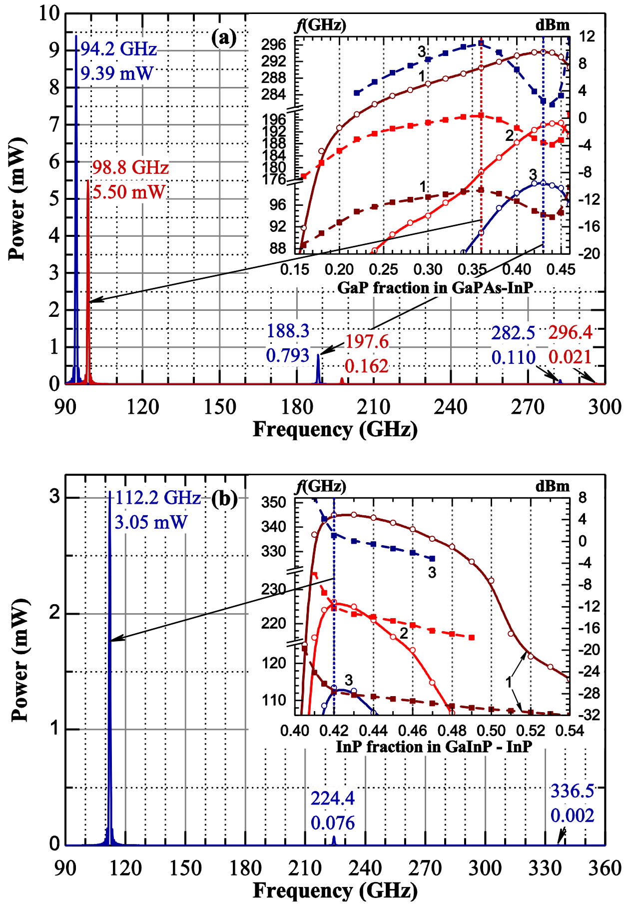

Fig. 4 – The power spectrum of oscillations in diode based on graded-gap $GaP_{0.36}As_{0.64}$ – InP when $U = 1.5$ V (a) and $GaP_{0.43}As_{0.57}$ – InP when $U = 2.0$ V (a) and $Ga_{0.58}In_{0.42}P$ – InP when $U = 1.25$ V (b). The inset represents the dependences of frequency (dash lines) and power (solid lines) of oscillations for fundamental (1), second (2) and third (3) harmonics on the fraction of GaP in GaPAs – InP (a) and InP in GaInP – InP (b)

The oscillation power in graded-gap GaP_yAs_{1-y} – InP diode is maximum when y fraction is 0.42-0.44. The power spectrum of $GaP_{0.43}As_{0.57}$ – InP diode when the voltage applied to the diode is 2.0 V is shown in Fig. 4a.

The fundamental mode power of such oscillations is 9.39 mW at a frequency of 94.2 GHz and the power of the third harmonic is 0.110 mW at a frequency of 282.5 GHz. The power and frequency of oscillations of the fundamental mode and higher harmonics in graded-gap $GaP_{0.43}As_{0.57}$ – InP diode are greater than in $GaP_{0.40}As_{0.60}$ – GaAs and $Ga_{0.54}In_{0.46}P$ – GaAs diodes.

The frequency of the current oscillations in the graded-gap GaP_yAs_{1-y} – InP diode is maximum when y is 0.36. The power spectrum of $GaP_{0.36}As_{0.64}$ – InP diode is also shown in Fig. 4a. The fundamental mode power of such oscillations is 5.50 mW at a frequency of 98.8 GHz and the power of the third harmonic is 0.021 mW at a frequency of 296.4 GHz.

The $Ga_{1-x}In_xP$ – InP diode has continuous oscillations for a narrow interval of the InP fraction in $Ga_{1-x}In_xP$ alloy. The mode with domain drift and continuous self-oscillations in graded-gap $Ga_{1-x}In_xP$ – InP is realized when x fraction in $Ga_{1-x}In_xP$ alloy is 0.41 … 0.50. If x fraction in graded-gap $Ga_{1-x}In_xP$ – InP alloy is greater than 0.52 or less than 0.41, then the current oscillations in the diode are damped.

The oscillation power in diode based on graded-gap $Ga_{1-x}In_xP$ – InP is maximum when x fraction is 0.42-0.43 (inset in Fig. 4b). The optimal voltage applied to graded-gap $Ga_{0.58}In_{0.42}P$ – InP diode is 1.25 V. It is about 2 times less than in the previous three versions of the diodes. If x fraction in $Ga_{1-x}In_xP$ – InP diode is greater than 0.48, then the optimal voltage is the same as in the diodes considered earlier and is 0.9 V. The oscillation power in the $Ga_{1-x}In_xP$ – InP diode is 2-3 times less than in the diodes already considered. The power spectrum of $Ga_{0.58}In_{0.42}P$ – InP diode when the voltage applied to the diode is 1.25 V is shown in Fig. 4b. The fundamental mode power of such oscillations is 3.05 mW at a frequency of 112.2 GHz and the oscillation power of the third harmonic is 0.002 mW at a frequency of 344.2 GHz.

A distinctive feature of $Ga_{1-x}In_xP$ – InP diode is the lack of an optimal fraction of InP in $Ga_{1-x}In_xP$ for obtaining current oscillations with the highest frequency. If x fraction in $Ga_{1-x}In_xP$ – InP is less than 0.42, then the oscillation frequency increases, but the oscillation power drops sharply to zero (inset in Fig. 4b). The advantage of $Ga_{0.58}In_{0.42}P$ – InP diode over the previously considered versions of the diodes is to achieve the maximum frequency of the fundamental mode of oscillations, equal to 112.2 GHz.

The graded-gap alloy Gunn diode based on InP can generate continuous self-oscillations if the doping level of the transit region is higher than $1.7 \cdot 10^{16}$-$2.0 \cdot 10^{16}$ cm^{-3}. For this electron concentration in the transit region the doping level of the cathode is from $4 \cdot 10^{16}$ to $10 \cdot 10^{16}$ cm^{-3}.

3.3 GaPAs – $Ga_{0.5}In_{0.5}As$ and GaInP – $Ga_{0.5}In_{0.5}As$ Diodes

Let us consider the processes in the graded-gap Gunn diodes based on $Ga_{0.50}In_{0.50}As$. In GaP_yAs_{1-y} – $Ga_{0.50}In_{0.50}As$ and $Ga_{1-x}In_xP$ – $Ga_{0.50}In_{0.50}As$ diodes, the transit region consists of graded $Ga_{1-x(z)}In_{x(z)}P_{y(z)}As_{1-y(z)}$ alloy. The effect of the composition of GaPAs and GaInP in the cathode on the processes in the graded-gap Gunn diodes based on $Ga_{0.50}In_{0.50}As$ is similar to its influence in the graded-gap Gunn diodes based on GaAs and InP.

The mode with domain drift and continuous current self-oscillations in graded-gap diodes based on $Ga_{0.50}In_{0.50}As$ occurs when y fraction in GaP_yAs_{1-y} is 0.20-0.46 and x fraction in $Ga_{1-x}In_xP$ is 0.40-0.64. Damped self-oscillations occur in graded-gap diodes based on $Ga_{0.50}In_{0.50}As$ when y fraction in GaP_yAs_{1-y} and x fraction in $Ga_{1-x}In_xP$ are all other values.

The frequency of current oscillations in such graded-gap diodes increases when voltage applied to the diode increases for any y and x fractions in GaP_yAs_{1-y} and $Ga_{1-x}In_xP$ alloys. The optimal voltage for the power increases when GaP fraction in GaP_yAs_{1-y} and $Ga_{1-x}In_xP$ alloys grows. For example, the optimal voltage in GaP_yAs_{1-y} – $Ga_{0.50}In_{0.50}As$ diode for $y = 0.12$ is near 0.95 V and for $y = 0.44$ it is 2.8 V. The optimal voltage in $Ga_{1-x}In_xP – Ga_{0.50}In_{0.50}As$ diode for $x = 0.6$-0.7 is near 1.5 V and for $x = 0.42$ it is 2.9 V.

The dependences of frequency and power oscillations for optimal voltage on the composition fraction of GaP_yAs_{1-y} and $Ga_{1-x}In_xP$ are presented in the inset Fig. 5. The oscillation power in graded-gap GaP_yAs_{1-y} – $Ga_{0.50}In_{0.50}As$ diode is maximum when y fraction is 0.44-0.45 (inset in Fig. 5a). The power spectrum of $GaP_{0.44}As_{0.56} – Ga_{0.50}In_{0.50}As$ diode is presented in Fig. 5a. The fundamental mode power of such oscillations is 19.11 mW at a frequency of 95.1 GHz and the oscillation power of the third harmonic is 0.288 mW at a frequency of 285.3 GHz.

The oscillation power in $Ga_{1-x}In_xP$ – $Ga_{0.50}In_{0.50}As$ diode is maximum when x fraction is 0.41-0.42 (inset in Fig. 5b). The power spectrum of $Ga_{0.58}In_{0.42}P$ – $Ga_{0.50}In_{0.50}As$ diode is shown in Fig. 5b. The fundamental mode power of such oscillations is 19.36 mW at a frequency of 98.1 GHz and the power of the third harmonic is 0.184 mW at a frequency of 294.3 GHz.

The frequency of current oscillations in GaP_yAs_{1-y} – $Ga_{0.50}In_{0.50}As$ diode is maximum when y fraction is 0.32. The power spectrum of $GaP_{0.32}As_{0.68} – Ga_{0.50}In_{0.50}As$ diode is shown in Fig. 5a. The fundamental mode power is 10.31 mW at a frequency of 102.2 GHz and the power of the third harmonic is 0.054 mW at a frequency of 306.6 GHz. The frequency of current oscillations in $Ga_{1-x}In_xP – Ga_{0.50}In_{0.50}As$ diode is maximum when x fraction is 0.52. The power spectrum of $Ga_{0.48}In_{0.52}P$ – $Ga_{0.50}In_{0.50}As$ diode is shown in Fig. 5b. The fundamental mode power is 8.64 mW at a frequency of 101.5 GHz and the power of the third harmonic is 0.018 mW at a frequency of 304.5 GHz.

The graded-gap Gunn diodes based on $Ga_{0.50}In_{0.50}As$ can generate continuous self-oscillations at a lower concentration of electrons in the transit region. The lower edge of the doping level is near $1.7 \cdot 10^{16}$ cm^{-3} for $GaP_{0.42}As_{0.58} – Ga_{0.50}In_{0.50}As$ diode and near $2.0 \cdot 10^{16}$ cm^{-3} for $Ga_{0.58}In_{0.42}P$ – $Ga_{0.50}In_{0.50}As$ diode when the doping level of the cathode is from $4 \cdot 10^{16}$ to $10 \cdot 10^{16}$ cm^{-3}.

3.4 The Analysis of Simulation Results

The analysis of simulation results of graded-gap Gunn diodes based on different semiconductors, such as GaAs, InP and $Ga_{0.5}In_{0.5}As$, shows that the physical processes occurring in the diodes are identical.

If the GaP fraction grows locally in GaP_yAs_{1-y} or $Ga_{1-x}In_xP$ cathode contact, then the gradient of the energy gap between the valleys and electron mobility along the transit region increases. The electron concentration in the side valleys near the cathode becomes large and remains small in the center of the transit

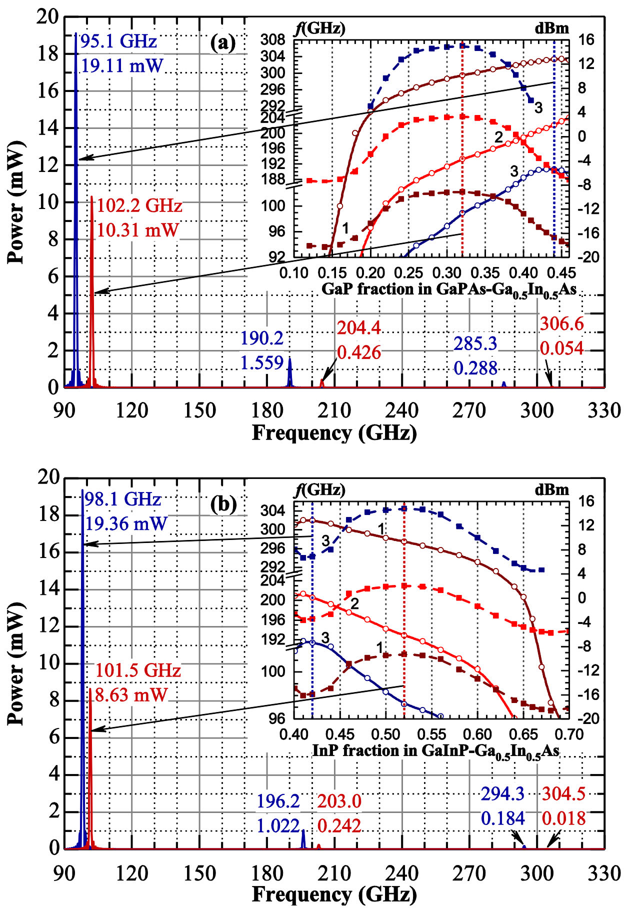

Fig. 5 – The power spectrum of oscillations in diodes based on graded-gap $GaP_{0.32}As_{0.68} – Ga_{0.50}In_{0.50}As$ when $U = 1.8$ V (a), $GaP_{0.44}As_{0.56}$ – $Ga_{0.50}In_{0.50}As$ when $U = 2.8$ V (a), $Ga_{0.54}In_{0.42}P$ – $Ga_{0.50}In_{0.50}As$ when $U = 2.9$ V (b), $Ga_{0.48}In_{0.52}P$ – $Ga_{0.50}In_{0.50}As$ when $U = 1.8$ V (b). The inset represents the dependences of frequency (dash lines) and power (solid lines) of oscillations for fundamental (1), second (2) and third (2) harmonics on the fraction of GaP in GaPAs – $Ga_{0.50}In_{0.50}As$ (a) and InP in GaInP – $Ga_{0.50}In_{0.50}As$ (b)

region. Electron mobility, on the contrary, is small in the cathode and large in the center of the transit zone. The local decrease in electron mobility near the cathode leads to the accumulation of electrons in this region and to an increase in the electric field strength. A positive feedback arises, due to which the space charge accumulates in the graded-gap semiconductor layer near the cathode. If the external voltage is sufficient, this space charge begins to drift along the transit region towards the anode contact. The region where such charge instability is formed is in the graded-gap semiconductor layer in the region between the center of the transit region and the cathode. The diode with the graded-gap alloy in the transit region has mode with domain drift and continuous self-oscillations of the current.

The optimal composition of the alloys in the cathode turned out to be almost the same for graded-gap Gunn diodes based on GaAs, InP and $Ga_{0.5}In_{0.5}As$ (Table 1). The power of oscillations in Gunn diodes with graded-gap $Ga_{1-x(z)}In_{x(z)}P_{y(z)}As_{1-y(z)}$ alloy in the transit region is more than in diodes with graded-gap $Ga_{1-x(z)}In_{x(z)}P$ or $GaP_{y(z)}As_{1-y(z)}$ alloys. The highest power and efficiency of current oscillations occurs in graded-gap alloy diodes based on $Ga_{0.50}In_{0.50}As$. Output characteristics of GaP_yAs_{1-y} – $Ga_{0.50}In_{0.50}As$ and $Ga_{1-x}In_xP$ – $Ga_{0.50}In_{0.50}As$ diodes are almost identical. The oscillation power is the greatest in $Ga_{0.58}In_{0.42}P$ – $Ga_{0.50}In_{0.50}As$ diode and the oscillation frequency is the greatest in $Ga_{0.58}In_{0.42}P$ – InP diode. The maximum power of the fundamental mode is 19 mW at 95 GHz. The self-oscillations in diodes based on graded-gap GaInPAs alloy contain clearly distinguishable at least third harmonic. Higher harmonics are present in the spectrum of oscillations with the power of the second harmonic of 1.6 mW and the third harmonic of 0.3 mW.

Two important points should be noted.

(i) In the course of the research, it has been determined that the amplitude and frequency of current oscillations in graded-gap Gunn diodes depend on the doping level of the cathode and the transit region. The doping level of the cathode influences the mechanism of the occurrence of charge instabilities in diodes. The Gunn diodes based on graded GaInPAs can generate continuous self-oscillations at a lower concentration of electrons in the transit region. The lower edge of the doping level of the transit region is near $2.0 \cdot 10^{16}$ cm^{-3} if the doping level of the cathode is from $4 \cdot 10^{16}$ to $10 \cdot 10^{16}$ cm^{-3}. But a comprehensive study of the effect has not been done yet.

(ii) The continuous self-oscillations of the current in Gunn diodes based on graded-gap alloys of semiconductors are the object of this research. The operation of the diodes in the resonator has not been studied. Some diodes without the resonator have only fast-damped current oscillations. However, such diodes probably may generate power in the resonator. For example, a Gunn diode based on $Ga_{0.5}In_{0.5}As$ homogeneous semiconductor is such a case. A detailed research of these issues is beyond the scope of the paper and to be done in the nearest future.

Table 1 – Average power of harmonics for optimal compositions of GaInPAs graded-gap Gunn diode

Semiconductor	GaP_yAs_{1-y}							$Ga_{1-x}In_xP$						
	y	U (V)	f_1 (GHz)	P_1 (mW)	P_2 (mW)	P_3 (mW)	P_0 (mW)	x	U (V)	f_1 (GHz)	P_1 (mW)	P_2 (mW)	P_3 (mW)	P_0 (mW)
GaAs	0.30	1.0	87.3	3.35	0.103	0.005	584	0.52	1.4	76.0	4.85	0.189	0.017	735
	0.40	1.8	76.5	5.96	0.741	0.113	821	0.46	2.2	70.0	8.03	0.444	0.129	1006
InP	0.36	1.5	98.8	5.50	0.162	0.021	869	0.42	1.25	112.2	3.05	0.076	0.002	1096
	0.43	2.0	94.2	9.39	0.793	0.110	1213							
$Ga_{0.5}In_{0.5}As$	0.32	1.8	102.2	10.31	0.426	0.054	1312	0.52	1.8	101.5	8.64	0.248	0.018	1309
	0.44	2.8	95.1	19.11	1.559	0.288	2067	0.42	2.9	98.1	19.36	1.022	0.184	2075

4. CONCLUSIONS

The generation of self-oscillations in the Gunn diodes based on GaInPAs graded-gap semiconductors has been researched. This semiconductor has not been previously investigated as a material for terahertz wave devices with intervalley electron transfer effect. The transit region length was 1.0 μm and the ionized donor concentration therein was $9 \cdot 10^{16}$ cm^{-3}.

The research has shown in such diodes the domain drift mode and efficient generation of current oscillations can be implemented. The graded-gap semiconductors increase the oscillation power of the Gunn diodes in comparison with homogeneous semiconductors. The main condition for the existence of this effect is the increasing dependence of the energy gap between the Γ valley and its nearest side valleys on the coordinate in the transit region of the diode.

The composition of the semiconductor in the cathode determines the processes occurring in the diode and its output characteristics.

The maximum power of oscillations in graded-gap Gunn diodes based on three different GaAs, InP and $Ga_{0.5}In_{0.5}As$ semiconductors is achieved with approximately the same composition of GaP_yAs_{1-y} and $Ga_{1-x}In_xP$ in the cathode.

Semiconductor alloy in the anode of the graded-gap diode influences the maximum amplitude and frequency of current oscillations, but does not determine the processes in the entire diode.

The power of oscillations in Gunn diodes with graded-gap $Ga_{1-x(z)}In_{x(z)}P_{y(z)}As_{1-y(z)}$ alloy in the transit region is more than in diodes with graded-gap $Ga_{1-x(z)}In_{x(z)}P$ or $GaP_{y(z)}As_{1-y(z)}$ alloys.

The graded-gap alloy diode based on $Ga_{0.50}In_{0.50}As$ has advantages in terms of oscillation power over the graded-gap alloy diodes based on GaAs and InP.

Graded-gap $Ga_{0.58}In_{0.42}P$ – $Ga_{0.50}In_{0.50}As$ diode generates oscillations of the highest average power of 19.36 mW and graded-gap $Ga_{0.58}In_{0.42}P$ – InP diode has oscillations of the highest frequency of 112.2 GHz.

The self-oscillations in diodes based on graded-gap GaInPAs alloy contain clearly distinguishable at least third harmonic in the terahertz range. For example, graded-gap $GaP_{0.32}As_{0.68}$ – $Ga_{0.50}In_{0.50}As$ diode has a third-harmonic oscillation power of 0.054 mW at a frequency of 306.6 GHz and graded-gap $Ga_{0.48}In_{0.52}P$ – InP diode of 0.002 mW at a frequency of 336.5 GHz.

The Gunn diodes based on graded GaInPAs can generate continuous self-oscillations at a lower concentration of electrons in the transit region. The lower edge of the doping level of the transit region is near $2.0 \cdot 10^{16}$ cm^{-3} if the doping level of the cathode is from $4 \cdot 10^{16}$ to $10 \cdot 10^{16}$ cm^{-3}.

The frequency and power of the self-oscillations of the graded-gap Gunn diodes depend on the composition of the semiconductor compound in the cathode and anode. As a rule, the oscillations of higher power occur at a lower frequency. Therefore, there is a need to find the compromise between the expected power and the frequency of oscillation source for practical applications.

The research has shown the possibility of efficient generation of electromagnetic waves, including terahertz waves, by means of the Gunn diode based on graded-gap semiconductors. The graded-gap semiconductors increase the oscillation power of the Gunn diodes in comparison with homogeneous semiconductors.

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Діоди Ганна на основі варизонного GaInPAs

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Проблема освоєння терагерцового діапазону за допомогою активних твердотільних приладів залишається актуальною. Для генерації міліметрових та субміліметрових електромагнітних хвиль використовують високошвидкісні транзистори, діоди Ганна, IMPATT діоди, резонансно-тунельні діоди та інші прилади. Однак на частотах понад 100-200 ГГц ці пристрої мають ряд фізичних проблем, які обмежують граничну частоту. В даний час варизонні напівпровідники привертають інтерес розробників як перспективний матеріал для таких пристроїв, у тому числі тих, що працюють на ефекті міждолинного переносу електронів. У даній роботі представлені результати числових експериментів по генерації автоколивань струму в діодах Ганна на основі варизонного напівпровідника GaInPAs із довжиною транзитної області 1,0 мкм та концентрацією іонізованих домішок в ній $9\cdot10^{16}$ см$^{-3}$. Були досліджені GaPAs – GaAs, GaInP – GaAs, GaPAs – InP, GaInP – InP, GaPAs – $Ga_{0.5}In_{0.5}As$ і GaInP – $Ga_{0.5}In_{0.5}As$ діоди. Моделювання проведено за допомогою температурної моделі міждолинного переносу електронів у варизонних напівпровідниках. У таких діодах може бути реалізований доменний режим нестабільності струму і відбуватися незатухаючі коливання струму, на відміну від діодів Ганна на основі однорідних GaAs, InP і $Ga_{0.5}In_{0.5}As$, в яких незатухаючі коливання струму не відбуваються. В статті показано, що застосування варизонного GaInPA збільшує потужність коливань діодів Ганна у порівнянні з однорідними напівпровідниками GaAs, InP та $Ga_{0.5}In_{0.5}As$, а спектр автоколивань, що виникають в приладі, містять чітко розпізнану принаймні третю гармоніку в терагерцовому діапазоні. Максимальна потужність основного режиму складає 19,4 мВт на частоті 98 ГГц в $Ga_{0.58}In_{0.42}P$ – $Ga_{0.5}In_{0.5}As$ діоді. Вищі гармоніки, що присутні в спектрі коливань, мають потужність другої гармоніки – 1,0 мВт і третьої гармоніки – 0,2 мВт.

Ключові слова: Діод Ганна, Моделювання, Варизонний напівпровідник, Міждолинний перенос електронів, Гетероперехід.