Gunn Diodes Based on Graded-Gap Semiconductor Nitrides with Boron Nitride

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Abstract **– The paper presents the results of numerical experiments on the oscillation generation using the n^+-n-n^+ transfer electron device based on InBN and GaBN graded gap semiconductor compounds at different BN distribution. We had obtained the output characteristics of diodes in a wide range of frequencies from 30 to 700 GHz. Cutoff frequency has been estimated. At optimal BN distribution graded-gap semiconductor InBN and GaBN Gunn diodes for efficiency exceed GaN and InN diodes by more than two times. Power consumption of graded-gap InBN and GaBN diodes is 11÷19% less the power consumption of InN and GaN diodes.**

Key words **– Terahertz range, transfer electron device, graded-gap semiconductor, nitride semiconductor, intervalley electron transfer, boron nitride, indium nitride, gallium nitride.**

I. INTRODUCTION

Nitrides of group III of elements attract attention as promising materials for high-speed electronic devices, including devices based on the intervalley electron transfer (IET) effect. Semiconductor generators operating in terahertz range are in demand in many fields. One of the methods of increasing the cutoff frequency of transfer electron devices (TED) is to use graded-gap semiconductors [1]. The TED based on graded-gap semiconductors have higher values of the generation efficiency (performance index) and output power with less power consumption compared to conventional Gunn diodes. This fact is important to address the use of semiconductor nitrides in the TED. Such materials include GaN, AlN and InN [2]. Experimental microwave generation on the intervalley electron transfer effect, as we know, in scientific publications has been noted. The main problems, which prevent from obtaining the microwave generation, are the heat removal from the active region of the device and the effective heating of the electron gas near the cathode contact [2–4]. Techniques that enable to solve this problem in the TED based on GaAs, revealed ineffective for semiconductor nitrides. One of the little-known directions in the area of TED 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.

An important criterion that affects the operation of graded-gap Gunn diodes is the energy gap between the Γ-valley and the closest (by energy) to it side valley Δ_{ij} in the area of cathode contact [5]. For example, in AlN-InN graded-gap compound the minimal energy gap is bounded below by $\Delta_{\Gamma U}$ = 0.7 eV, corresponding to AlN; and in GaN-InN compound by $\Delta_{\Gamma U}$ = 1.35 eV (GaN). In the InN compound the minimal energy gap $\Delta_{\Gamma A}$ = 1.68 eV. The case that allows decreasing energy gap between the valleys up to the thermal energy of the electrons has attracted our interest. Such an opportunity is due to InBN-InN-transition for InN-diodes and GaBN-GaN-transition for GaN diodes, which are technologically available, nowadays [6, 7].

The aim of this paper is to investigate the impact of BN content in the area of cathode contact on the instability of the current and the output characteristics of InN and GaN diodes.

II. PARAMETERS AND PROBLEM STATEMENT

Diodes of n^+-n-n^+ structure based on ternary compounds graded-gap InN-InBN-InN and GaN-GaBN-GaN have been considered (fig. 1). The Γ, *A* and *U* energy minima have been taken into account in our calculations. The active region length of a diode l_a was equal to 2.5; 0.8 and 0.4 μm; respective values of electron density in those regions were $3\cdot10^{16}$, $8\cdot10^{16}$ and 10^{17} cm^{-3}. The temperature of the crystal lattice was assumed constant and equaled to 300 K.

The percentage of BN in $\mathrm{In}_{1-x(z)}\mathrm{B}_{x(z)}\mathrm{N}$ and $\mathrm{Ga}_{1-x(z)}\mathrm{B}_{x(z)}\mathrm{N}$ is given by a Gaussian distribution:

$$x(z) = x_{\max}\ \exp\left\{-\frac{(z-z_0)^2}{2\sigma^2}\right\}, \qquad (1)$$

where $x_{\max}$ is the maximum content of BN in the ternary compounds, σ is the length of the transition (graded-gap) layer between different semiconductors; z_0 is coordinate specifying the location of the transition layers (in this case it is the cathode contact boundary); *z* is spatial coordinate.

The main task we set is to obtain the optimized supply voltage dependences of the microwave generation efficiency on frequency for different lengths of the active region and the graded-gap layer, as well as the optimal allocation of the binary component in BN diodes by means of numerical experiments.

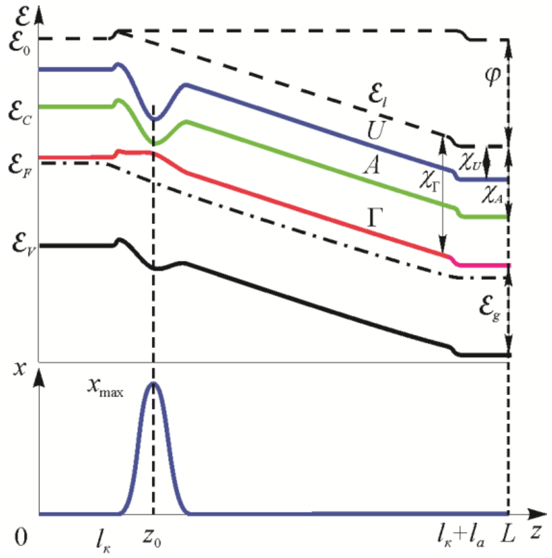


Fig. 1. Schematic band diagram and the distribution of x binary component in the graded-gap $In_{1-x}B_xN$- and $Ga_{1-x}B_xN$ TED

III. THE EXPLORATORY PROCEDURE

The research has been carried out by means of three-level model of intervalley electron transfer (IET) in the graded-gap semiconductors based on the solution of the Boltzmann equation for the case of a displaced Maxwellian distribution of electrons [5]. This model represents a system of equations consisting of continuity equations (2), the current density equations (3) and the energy balance equations (4) for each of the three non-equivalent valleys of the semiconductor conduction band, as well as the Poisson equations (5):

$$\frac{\partial n_i}{\partial t} = -\frac{1}{e}\frac{\partial j_i}{\partial z} - \frac{n_i}{\tau_{n,ij}} - \frac{n_i}{\tau_{n,i\kappa}} + \frac{n_j}{\tau'_{n,ji}} + \frac{n_\kappa}{\tau'_{n,\kappa i}} \qquad (2)$$

$$j_i = n_i \mu_i \left(eE + \frac{\partial \chi_i}{\partial z} \right) + \kappa_b \mu_i \left(\frac{3 n_i T_i}{2 m_i} \frac{\partial m_i}{\partial z} - \frac{\partial (n_i T_i)}{\partial z} \right) \qquad (3)$$

$$\frac{3}{2}\kappa_b \frac{\partial n_i T_i}{\partial t} = j_i E + \frac{j_i}{e}\frac{\partial \chi_i}{\partial z} - \frac{5}{2}\kappa_b \frac{1}{e}\frac{\partial (j_i T_i)}{\partial z} - \\ -\frac{3}{2}\kappa_b \left(\frac{n_j T_j}{\tau'_{E,ji}} + \frac{n_\kappa T_\kappa}{\tau'_{E,\kappa i}} - \frac{n_i T_i}{\tau_{E,i}} \right) \qquad (4)$$

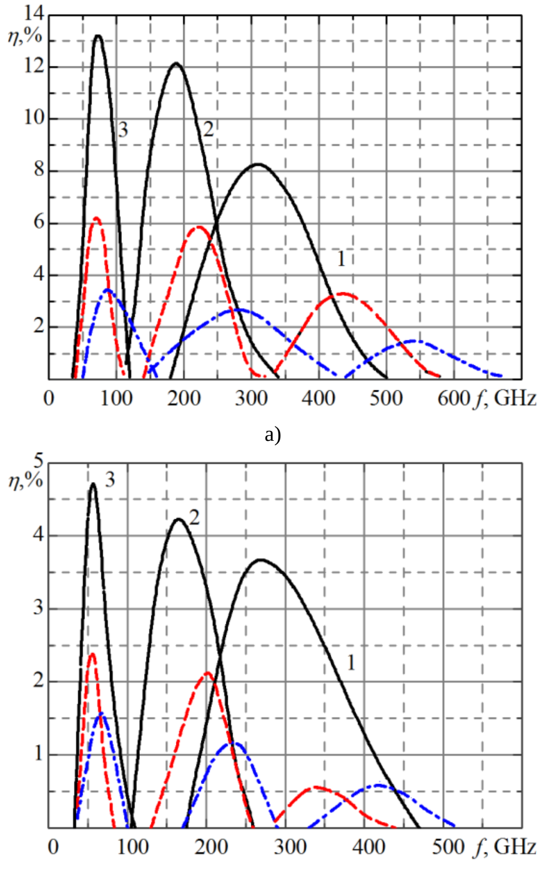
$$\frac{\partial (\varepsilon E)}{\partial z} = 4\pi e \left(n_i + n_j + n_\kappa - n_0 \right), \qquad (5)$$

where the indices i, j and κ determine the three non-equivalent valleys. Equations (2) – (4) are written down for the i-th valley. n_i, μ_i, m_i, j_i, T_i are the concentration, mobility, effective mass, current density and electron temperature in the i-th valley, respectively; τ is the relaxation time; χ_i is the energy, which is necessary to transfer electrons from the minimum energy level of the i-th valley to the local vacuum level; E is electric field intensity, n_0 is the concentration of ionized donors; ε is the dielectric constant; e is the absolute value of electron charge; κ_b is the Boltzmann constant; t is time; z is a coordinate. The average current density in the diode is defined as the sum of the averages in the three valleys. Γ, A and U energy minima have been taken into account in our calculations. The average current density in the diode is defined as the sum of the averages in the three valleys. The system of equations (2) – (5) was being solved numerically. The situation was simulated when the sinusoidal voltage with a constant component was applied to the diode, which corresponds to placing the diode into the single-circuit resonator. The output performances were being optimized for different frequencies with respect to the bias voltage and the amplitude of the first harmonic. The computation of the generation efficiency of the diodes was being carried out for the second and third periods of the oscillations.

IV. RESULTS AND DISCUSSIONS

An important feature of the TED based on graded-gap semiconductors is the dependence of the output characteristics of the variable-gap layer length. The occurrence of current oscillations in n^+-n-n^+ InN and GaN TED associated with drift accumulating layers [2]. The output power and efficiency of the devices to the domain instability usually above. It needs at the cathode contact region to form local reduction of the energy gap between the valleys [5, 7]. In graded-gap InBN TED of n^+-n-n^+structure drifting domains appear even at low content of BN ($x_{\max}$) near the cathode in the active region, and when $x_{\max} > 0.32$ a static domain is formed. The reason for the instability of the domain is the high concentration of electrons in the side valleys of the cathode area. This is due to a decrease in the energy gap between the valleys of the local area at the cathode contact. Diodes based on graded-gap GaBN do not have any distinguishing features in formation and drift instabilities of charge compared to InBN devices.

Domain type of instability in InBN and GaBN determines higher values of generation efficiency and output power compared with the same type of n^+-n-n^+ devices based on InN and GaN (fig. 2). When content of BN increases the peak values of generation efficiency and power output are increased, which is due to the optimization of formation and the drift of domains (fig. 3). This increase leads to a decrease in the optimum generation frequency. For example, when changing $x_{\max}$ from 0 to 0.30 in InBN Gunn diodes optimal frequency is reduced from 90 to 70 GHz and for GaBN TED it reduces from 70 to 60 GHz. For all types of TED the maximum generation efficiency decreases with the decreasing of the length of active region, but a significant reduction in efficiency occurs when l_a drops below 0.8 μm (fig. 2).



a)

b)

Fig. 2. The dependence of the efficiency on the frequency of InN (a) and GaN (b) (dash-dotted lines), graded-gap AlInN (a) and AlGaN (b) (dashed lines), graded-gap InBN (a) and GaBN (b) (solid lines) TED at optimum graded gap layer length and different active region length: 1 – 0.4; 2 – 0.8; 3 – 2.5 μm.

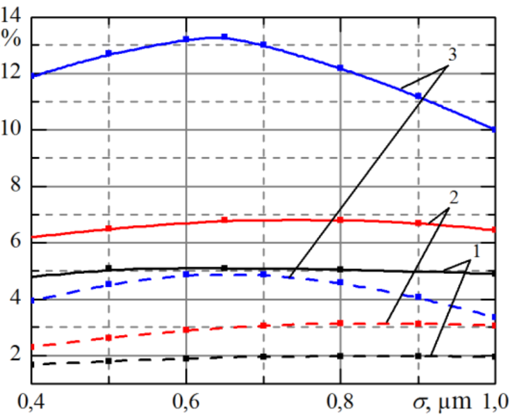


Fig. 3. The dependence of the efficiency peak on the graded-gap layer length in the TED at the l_a=2,5 μm and different $x_{\max}$: 1 – 0.1; 2 – 0.2, 3 – 0.3. Solid lines are InBN TED. Dashed lines are GaBN TED.

Peak values of efficiency for similar devices with length of 0.8 and 2.5 μm are practically identical. The highest peak values of diodes efficiency with l_a of 2.5 and 0.8 μm belong to InBN TED. For example, when l_a = 2.5 μm in InBN Gunn diodes the efficiency is 13.2% and for GaBN it is 4.9%.

The estimations made for graded-gap InBN and GaBN with l_a = 0.2 μm as well as the dependence of efficiency on the active region length and frequency show that the minimum active region length is about 0.2 μm and cutoff frequency is near 1 THz. The maximum operating frequency for InBN TED with l_a = 0.4 μm is 0.5 THz and for GaBN TED it is 0.47 THz.

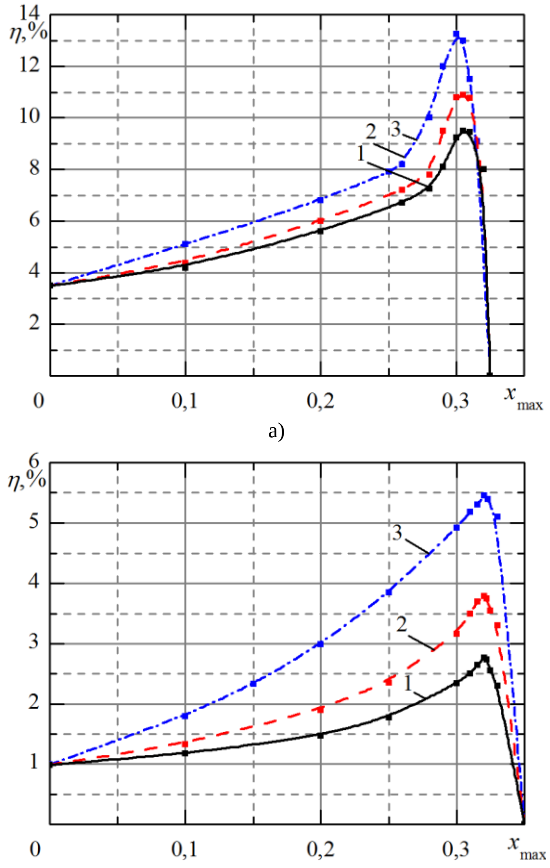
Comparative analysis of the output characteristics (see fig. 2 and Table.1) shows that the investigated graded-gap GaBN and InBN TED outperform the same type of devices based on GaN and InN, depending on the length of the active region by the efficiency in 3 ÷ 3.8 times; also they outperform graded-gap AlGaN and AlInN TED in 2 ÷ 2.07 times.

Power consumption of graded-gap InBN and GaBN TED is 11 ÷ 19% less than that of InN, GaN, AlInN Gunn diodes. The optimum value of the length of the transition layers of semiconductors depends weakly on the maximum BN content $x_{\max}$ in compounds (fig. 3). In InBN TED (l_a = 2.5 μm) with increasing $x_{\max}$ from 0.1 to 0.3 optimum value σ decreases from 0.72 to 0.65 microns. In GaBN TED (l_a = 2.5 μm) at the same increasing of $x_{\max}$ optimum value σ decreases from 0.81 to 0.65 μm. We would like to note that for InBN and GaBN TED the optimum content of BN σ is also weakly dependent on the length of the transition layers of semiconductors (fig. 5). For example, the optimal value of $x_{\max}$ for InBN TED decreases only from 0.31 to 0.30 when σ is increasing from 0.2 to 1.0 μm. If $x_{\max}$ is greater than the optimum value then the efficiency decreases rapidly, reaching 0 at $x_{\max}$ = 0.33. Termination of the microwave generation is due to the formation of static domains. In GaBN TED static domain is formed at a slightly higher content of BN $x_{\max}$ = 0.35. With a decrease in the length of the active region l_a the optimum of maximum content of BN remains approximately constant, and the optimal length of the graded-gap layer σ is decreasing (for l_a equal to 2.5, 0.8 and 0.4 μm the optimum σ is equal to 0.65, 0.30 and 0.15 μm, respectively).

TABLE I. OUTPUT POWER AND FREQUENCIES OF TED

Semiconductor	**Active region length, μм**					
	2.5		***0.8***		***0.4***	
	W	*f*	*W*	*f*	*W*	*f*
	W·cm^{-2}	GHz	W·cm^{-2}	GHz	W·cm^{-2}	GHz
InBN	$14.1\cdot10^5$	70	$12.2\cdot10^5$	180	$3.2\cdot10^5$	320
GaBN	$4.5\cdot10^5$	60	$3.9\cdot10^5$	160	$2.8\cdot10^5$	280
AlInN	$8.3\cdot10^5$	70	$6.3\cdot10^5$	220	$2.0\cdot10^5$	440
GaInN	$5.6\cdot10^5$	92	$4.3\cdot10^5$	274	$2.4\cdot10^5$	520
AlGaN	$4.8\cdot10^5$	55	$3.6\cdot10^5$	200	$1.8\cdot10^5$	340
GaN	$4.2\cdot10^5$	66	$2.8\cdot10^5$	230	$1.3\cdot10^5$	420
InN	$4.1\cdot10^5$	85	$4.6\cdot10^5$	278	$1.4\cdot10^5$	540

Unfortunately, we had not achieved a substantial reduction in power consumption. For example, for an optimal mode (l_a = 2.5 μm) power consumption for InBN TED is $1.1{\cdot}10^6$ W·cm^{-2}, for GaBN-Gunn diodes it is $0.9{\cdot}10^6$ W·cm^{-2}, for InN TED it is $1.2{\cdot}10^6$ W·cm^{-2}, for AlInN TED it is $1.3{\cdot}10^6$ W·cm^{-2} and for AlGaN TED it is $1.31{\cdot}10^6$ W·cm^{-2}.



a)

b)

Fig. 4. The dependence of the efficiency peak on the maximum content of BN in the InBN (a) and GaBN (b) TED at the l_a=2,5 μm and different length of σ: 1 – 0.2; 2 – 0.3; 3 – 0.65 μm.

V. CONCLUSIONS

To sum up our research we had concluded that in graded-gap InBN and GaBN TED depending on the content of BN enriched layers, drifting and static domains can be formed. The reason for the instability of the domain is the high concentration of electrons in the side valleys of the cathode area. This is due to a decrease in the energy gap between the valleys of the local area at the cathode contact.

The optimum content of BN $x_{\max}$ in InBN TED diodes is 0.3, and it remains constant at the optimum length of the graded-gap layer of 0.65 μm (for l_a = 2,5 μm), 0.3 μm (for l_a = 0,8 μm) and 0.15 μm (for l_a = 0.4 μm). In GaBN $x_{\max}$ is equal to 0.33 and it also remains constant at the optimum length of the graded-gap layer of 0.65 μm (for l_a = 2.5 μm), 0.3 μm (for l_a = 0.8 μm), 0.10 μm (for l_a = 0.4 μm). When reducing the length of the active region decreases the efficiency of generation, and the frequency range of the TED increases

At the optimal allocation of BN graded-gap GaBN and InBN TED outperform GaN, InN TED of the same type in terms of efficiency and output power in 3,44÷1,07 times and graded-gap AlGaN, AlInN TED in 0,93 ÷ 1, 69 times.

Power consumption of graded-gap InBN and GaBN TED is slightly less than that of InN, GaN and graded-gap AlInN, AlGaN TED.

The cutoff frequency for InBN TED is more than 0.55 THz and for GaBN TED it is more than 0.5 THz.

The advantage of graded-gap InBN and GaBN TED over similar AlInN and AlGaN diodes is due to the possibility to carry out the energy gap between the non-equivalent valleys in the cathode area for InBN and GaBN diodes.

Findings of study extend the knowledge about the physical processes of carrier transfer in complex semiconductor structures and can be used for technological designing of new high-speed devices based on semiconductor nitrides

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