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Energy and Frequency Properties of Planar n^+-n-n^+ Diodes with Active Side Boundary

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Generation of electromagnetic oscillations in the long-wavelength part of the terahertz range by GaAs diodes is investigated. Diodes are planar structures with a length of 1.28 μm, a width of 0.32 μm and a concentration of donor impurity of $6\cdot10^{22}$ m^{-3}. Diodes include a conductive channel placed on a semi-insulating substrate, two contacts and an active side boundary in the form of an n-type region located between the channel and the metal electrode electrically connected to the ohmic contact of the anode. Electronic processes in the structure are analyzed by means of Ensemble Monte Carlo method. Current instabilities occurring in such a diode connected with the effect of inter-valley electron transfer are shown up. Dependences of direct current on voltage do not have a pronounced region with negative differential conductivity, which may be due to the existence of regions with high electric field strength in the anode part of the diode. Our research reveals that the simultaneous existence of the effect of interval valley electron transfer in the channel and in the region of lateral boundary leads to an increase in the frequency of oscillations and an expansion of the frequency range. Oscillation efficiency and frequency properties of the diodes are determined. The frequency range of diodes is established to be in the range from 100 to 300 GHz. The maximum generation efficiency is about 3 % at a frequency of 160-180 GHz. The influence of the position and size of the elements forming the active side boundary on the frequency and energy properties of diodes is explored. The operating frequency range of diodes is shown to be determined mostly by the thickness of the side boundary element. The maximum oscillation frequency (up to 300 GHz) and frequency bandwidth are obtained for diodes with a thickness of the side boundary element of 0.32 μm, but with the maximum efficiency of less than 1.4 %.

Keywords: Active side boundary, Electric field strength, Impact ionization, Negative differential conductivity, Doping level, Frequency range, Generation efficiency.

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1. INTRODUCTION

Among all known solid-state sources of sub-terahertz (sub-THz) radiation, the devices employing avalanching, transit-time mechanisms and transferred electron devises (TED) have the highest levels of output power [1]. Therefore, these devices should be preferred while creating highly efficient sources of sub-THz radiation. In terms of frequency properties, the transferred electron effect is more variable. It is due to generation dependent not only on the parameters of the material from which the device is made, the distribution of composition and concentration, but also on the device geometry, the presence of additional contacts and other structural elements [2]. This allows us to influence oscillations and frequency range of the devices by modifying the shape of the device. This fact was actively used by developers of TED.

At frequencies of the sub-THz range, dimensions of the active parts of TED are less than 1 μm. This predetermined the transition to a planar structure of diodes, the sizes of which can be obtained with high accuracy (up to several nanometers) using lithography methods. An important advantage of such devices is a possibility to form modulation-doped heterostructures with a high drift velocity of electrons [3, 4]. It was shown that in such diodes the generation frequency can reach more than 300 GHz when they are made of traditional materials and have a channel length of 0.6 μm [3, 4]. Another feature of planar diodes is the current flow between contacts along the semiconductor/surrounding material interface. Taking into account the fact that in submicron structures the motion of electrons is close to ballistic, the introduction of additional elements on the surface or change in the electrode shape can significantly change the frequency and energy characteristics of devices [5, 6]. In [5, 6], the authors consider a number of planar structures with additional semiconductor elements located on the diode side boundary and electrically connected to the diode anode. The elements represent complex structures in the form of a graded-gap layer [5] and double-barrier resonant tunneling structures [6]. The possibility to obtain generation in a wide frequency range of the millimeter and terahertz ranges is shown. However, in short structures, simple active elements to be placed on their side boundary, for example, elements based on a homogeneous material, can lead to substantial changes in their properties. The purpose of this research is to assess the influence of additional elements of this type on the generation efficiency and frequency properties of planar diodes.

2. DIODE STRUCTURE AND SIMULATION MODEL

Planar GaAs diodes with a total length of 1.28 μm (Fig. 1) are considered. The diode active region with a thickness of 0.32 μm have an n^+–n–n^+ structure and is located on a high-resistance substrate. Since the thickness of the active region is quite small and comparable in magnitude with the mean free path in GaAs, the role of the substrate in such a structure is substantial. For

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this reason, we consider the case when the substrate is a semi-insulator (SI) with high impurity concentration and, accordingly, low mobility. It has a thickness from 0.32 to 0.64 μm. It is connected to the anode by a metal conductor. It is assumed that all metal-semiconductor contacts are ohmic ones. Heavily doped contact regions (n^+) have a size of 0.16 × 0.32 μm² and a donor concentration of $5 \cdot 10^{23}$ m^{-3}. Thus, the diode active region has a length of 0.98 μm. The concentration in the active n-layer is $6 \cdot 10^{22}$ m^{-3}. Structures that do not contain side boundary elements are also considered. Thus, they are conventional planar diodes. This allows us to determine the influence of the side boundary element on operation of the considered structures.

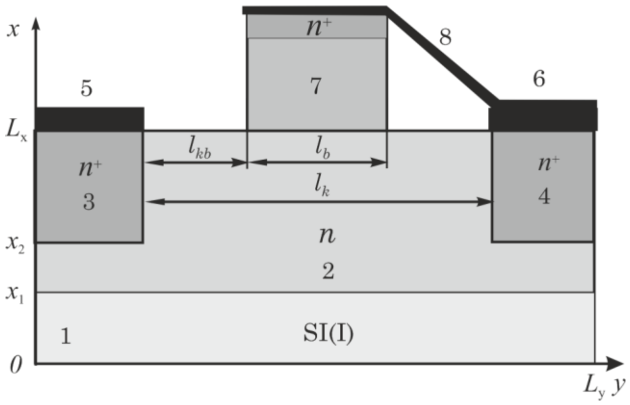

Fig. 1 – Cross section of the diode structure: substrate (1), active region (2), highly doped contact regions (n^+), cathode (3) and anode (4), metal contacts (5, 6), side boundary element (7), metal jumper (8)

2D diode model of the diode is used. Basic elements and calculating peculiarities of simulation correspond to [7]. Electronic transport performs by the Ensemble Monte Carlo (EMC) simulation. The conduction band is described by means of the three-valley model, in which Γ-, L-, and X-valleys are considered. Dispersion law of electrons takes into account non-parabolicity. All the scattering parameters and the material parameters used in the simulation are chosen in accordance with [8, 9].

3. DIRECT CURRENT CHARACTERISTICS

It is known that a diode with an n^+–n–n^+-structure maintains limited frequency capabilities [10]. This is due to the formation of a region with a negative field strength near the n^+–n-junction and the formation of a virtual cathode. However, this is correct only for vertical diodes, in which impurity distribution is along the interface of the n^+–n-junction. In the structure we have explored, due to the concentration inhomogeneity, even when a low voltage is applied, the virtual cathode is mainly observed only in the part of the n^+–n-junction close to the upper surface (Fig. 2a). But in the region closer to the substrate, the y-component of the field is positive and affects the energy gained by the electrons. A feature of the field distribution in the structures is the high value of the electric field strength at the anode (Fig. 2b). Fig. 2 shows the distribution of the y-component (E_y) of the electric field for a diode with a size of the side boundary element l_b = 0.16 μm located at a distance l_{kb} = 0.16 μm from the cathode.

As a result, when the voltage increases, the current tends to saturation, as shown in Fig. 3. The diode current-voltage characteristics in all considered cases either do not show regions of static negative differential resistance or their value is very small and insignificant. This occurs for both conventional diodes and diodes containing side boundary elements.

Our layout estimates reveal that the magnitude of the electric field in the anode region in the generation mode can exceed 150-250 kV/cm. These values are sufficiently large to cause impact ionization of carriers in the anode. To eliminate this effect, the voltage applied to the diode in the generation mode must be limited.

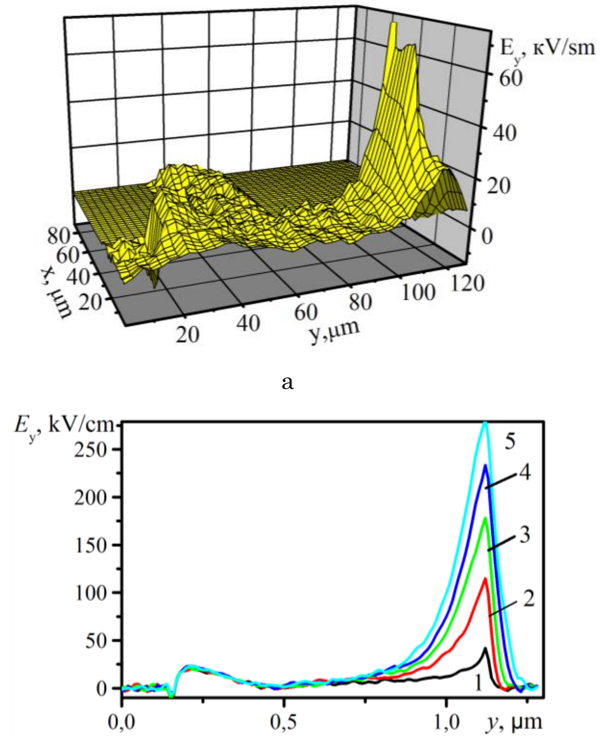

Fig. 2 – Distribution of the y-component (E_y) of the electric field: a) in the diode area at a bias voltage of 1.5 V; b) in the section x = 0.27 μm at different values of the bias voltage: 1 – 1 V, 2 – 2 V, 3 – 3 V, 4 – 4 V, 5 – 5 V

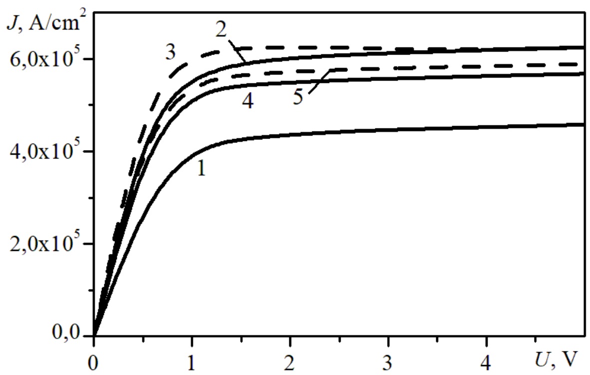

Fig. 3 – Dependences of the current density on the applied voltage: 1 – conventional diode, 2-5 – diodes with a side boundary element: 2, 4 – l_b = 0.16 μm, 3, 5 – l_b = 0.32 μm, 2, 3 – l_{kb} = 0.16 μm, 4, 5 – l_{kb} = 0.16 μm

4. HIGH FREQUENCY GENERATION

The analysis of the operation of diodes in the generation mode is carried out similarly to [6, 7]. The diode is assumed to be located in a resonator. The resonator influence is taken into account in correspondence with the wave form voltage applied to the diode:

$$U(t) = U_0 + U_1 \sin 2\pi f t\,, \tag{1}$$

where f is the resonant frequency, U_0 and U_1 are the bias voltage and the first harmonic amplitude of the alternative voltage, respectively. We specified the condition of voltage limiting in the form of $U_0 + U_1 < 2.5$ V, which excludes the impact ionization effect. The generation efficiency is determined by the ratio of the AC power at the resonator frequency to the DC power. To estimate the maximum value, the efficiency value is optimized according to the parameters U_0 and U_1. Different sizes of side boundary elements and their position on the upper diode surface are considered. The dependence of the optimized generation efficiency on the frequency for diodes with an SI substrate is shown in Fig. 4.

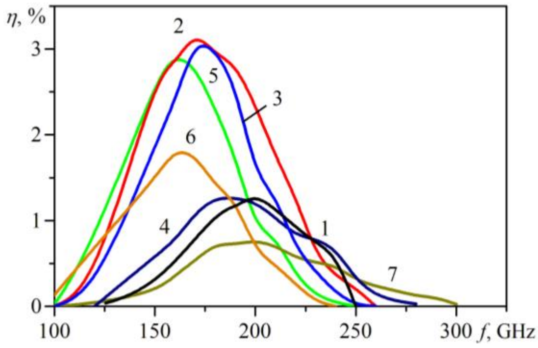

Fig. 4 – Optimized generation efficiency: 1 – conventional diode; 2-7 – diodes with a side boundary element: 2-4 – $l_b = 0.16$ μm, 5-7 – $l_b = 0.32$ μm, 2, 4, 5, 7 – $l_{kb} = 0.16$ μm, 3, 6 – $l_{kb} = 0.16$ μm

As seen from the above results, conventional planar diodes themselves have good frequency properties. The maximum gain is achived at a frequency of 180 GHz with a generation efficiency of more than 1.2 %. It can be seen that for diodes having a side boundary element, an expansion of the generation frequency range in both high-frequency and low-frequency regions, as well as a significant increase in the generation efficiency, are observed. The maximum generation efficiency is about 3.0 %. This corresponds to structures in which additional elements with a thickness of 0.64 μm were located at a distance of $l_b = 0.16$ μm from the cathode and had a length of 0.16 μm. Nevertheless, an increase in the thickness of additional elements in dimensions of l_b or l_{kb} leads to a decrease in both the efficiency and the maximum oscillation frequency. The frequency corresponding to the maximum efficiency is shifted to the low-frequency region. It is worth noting that the operating frequency range is extended in all cases in comparison with conventional diodes.

The currents flowing in the active part of the diode and in the side boundary element are perpendicular. Fig. 5 shows the distributions of two perpendicular field components at different times during the period: E_y along the y-axis and E_x along the x-axis.

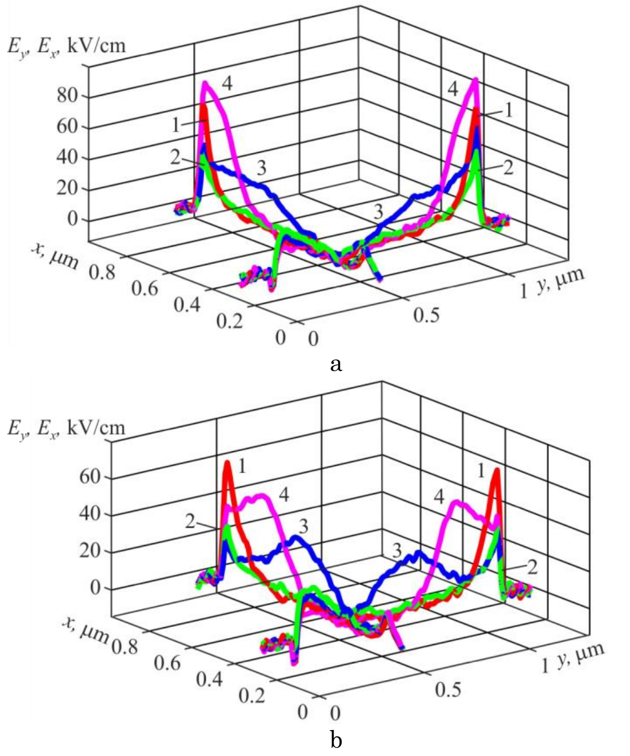

Fig. 5 – Distribution of the y-component in section $x = 0.56$ μm and the x-component in section $y = 0.27$ μm at different times during the oscillation period T for two types of side boundaries a) $l_b = 0.32$ μm, b) $l_b = 0.32$ μm: 1 – $t = 0$, 2 – $t = T/4$, 3 – $t = T/2$, 4 – $t = 3T/4$

As one can see from the above distributions, space-charge waves arise both in the main part of the diode and in the side boundary element. Moreover, space-charge waves are formed in the same way in both regions. An increase in the size of the side boundary element from 0.16 to 0.32 μm results in a change in the instability type. The "accumulation layer" mode transforms into the domain-type one. This explains the shift of the generation maximum towards lower frequencies since the time of domain formation is longer.

The vital question is to determine the oscillation frequency dependence on the thickness of the side boundary element. The generation efficiency of a diode with a thickness of the side boundary element of 0.32 μm is shown in Fig. 4 (curves 6, 7). It is seen that an increase in the generation frequency in the high-frequency region can be significant. However, the efficiency is still small, and the maximum generation is the same as that of conventional diodes. Thus, planar diodes with additional side boundary elements are quite broad-band devices. One should note that the optimal position of the side boundary elements is near the cathode contact, as in the previously considered planar structures [6, 7]. The highest generation efficiency corresponds to the highest doping level of the active region. In our opinion, the considered donor concentration of $6 \cdot 10^{22}$ m^{-3} is optimal, as follows from the results [6, 7], both from the point of view of impact ionization control and to obtain a high drift velocity. Calculations show that the generation efficiency without limiting the voltage applied to the diode, in most cases considered, gives a significantly higher generation efficiency exceeding 10 % and maximum frequencies of more than 300 GHz. In this regard, further analysis of electronic processes in the proposed diode structures, taking into account impact ionization, is necessary to determine the exact range of operating voltages and frequency properties.

5. CONCLUSIONS

Electronic processes and the generation efficiency of planar n^+–n–n^+ structures, containing side boundary elements in the form of an n-type region, have been explored by means of EMC simulation.

The article shows that the introduction of additional elements electrically connected to the anode contact leads to an expansion of the diode frequency range towards higher frequencies. Thus, it is detected that submicron structures with a complex geometric shape have a good perspective for generating oscillations in the millimeter and terahertz ranges. Good examples are the above-mentioned planar diode with complex contacts [8] and a self-switching nanodiode operating in the Gunn mode [11]. It is natural that classical effects such as the Gunn effect can be used in short structures, in which the role of ballistic transport is important and there are conditions for the rapid accumulation and subsequent relaxation of energy.

In the studied structures, the elements that were used on the side boundaries had properties close to the planar part of the diode, which predetermined the similarity in their processes. However, the difference in properties, as in [6], can improve the frequency parameters of the diode. From this point of view, a promising line of research is the use of two-dimensional materials, for example, transition metal dichalcogenides [12], as side boundaries.

The influence of impact ionization on the considered structures is an unexplored and promising subject for our further research.

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Енергетичні та частотні властивості планарних n^+-n-n^+ діодів з бічними активними границями

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У роботі досліджується генерація електромагнітних коливань у довгохвильовій частині терагерцового діапазону GaAs діодами. Діоди є планарними структурами довжиною 1,28 мкм, шириною 0,32 мкм та концентрацією донорної домішки $6 \cdot 10^{22}$ м$^{-3}$. Вони мають провідний канал, який розміщено на напівізолюючій підкладці, два контакти та активну бічну границю у вигляді області n-типу, яка розміщуються між каналом і металевим електродом та електрично з'єднана з омічним контактом аноду. Електронні процеси в структурі аналізуються з використанням багаточастинкового методу Монте-Карло. Показано, що в таких діодах виникають нестійкості струму, які можна пов'язати з ефектом міждолинного переносу електронів. Проте залежності постійного струму від напруги не мають вираженої ділянки з від'ємною диференціальною провідністю, що пов'язано з існуванням областей з високою напруженістю електричного поля в анодній частині діода. Одночасне існування ефекту міждолинного переносу електронів в каналі та в області бічної границі призводить до збільшення частоти коливань та розширення частотного діапазону роботи. Визначено ефективність коливань та частотні властивості приладів та встановлено, що їх частотний діапазон роботи знаходиться в інтервалі від 100 до 300 ГГц, а максимальні значення ефективності генерації складають близько 3 % на частоті 150-180 ГГц. Досліджено вплив положення і розміру елементів бічної границі на частотні та енергетичні властивості приладів. Показано, що частотний діапазон діодів визначається в основному товщиною бічного активного елемента. Максимальну частоту генерації (до 300 ГГц) та ширину частотного діапазону отримано для діодів з товщиною бічного елементу 0,32 мкм, проте їх максимальна ефективність менше 1,4 %.

Ключові слова: Активна бічна границя, Напруженість електричного поля, Ударна іонізація, Негативна диференціальна провідність, Рівень легування, Частотний діапазон, Ефективність генерації.