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# Planar $n^+$-$n$-$n^+$ Diode with Active Side Boundary on InP Substrate

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We have studied generation of electromagnetic oscillations in the long-wavelength part of the terahertz range by diode structures with active side border. Diodes represent planar structures 1.28 μm long, 0.32 μm wide. They include a conductive channel placed on a semi-insulating InP substrate, two contacts, and an active side boundary (ASB) in the form of an $n$-type region located between the InP channel and the metal electrode connected to the ohmic contact of the anode. Donor concentration in a channel is $6\cdot10^{22}$ m$^{-3}$. The article considers two different ASB on the bases of InP and InGaAs and analyses generation efficiency of diodes. We carried out a simulation by the Ensemble Monte Carlo technique. The characteristics of the diode are compared with the characteristics of common InP diodes with the same parameters. We found out that the $I$-$V$ characteristic of diodes does not contain a region with negative differential conductivity. However, there are high frequency current oscillations. The operation regime is close to trapped domain mode. In the course of the research, we determined the efficiency and frequency properties of the diode. The frequency range of diodes is established to be in the range from 100 to 350 GHz. Maximum generation efficiency of diodes with InP-based ASB is about 2.5 % at a frequency of 160-180 GHz. The article highlights the effect of increase in cutoff frequency in the case of using ASB to compare with a common InP diode. In particular, using InP-based ASB, gives current oscillation in the range from 300 to 350 GHz when ASB position is near the anode contact. Nevertheless, this effect is absent if InGaAs-based ASB is applied. Thus, we assume that frequency properties can be improved due to enhanced energy relaxation in ASB.

**Keywords:** Active side boundary, Electric field strength, Negative differential conductivity, Doping level, Current oscillation, Frequency range, Generation efficiency.

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## 1. INTRODUCTION

Frequency expansion of operating limit of solid-state devices is an important task in modern electronics. Terahertz systems require the development of compact oscillation sources. [1]. Diodes operating at high frequency, are small and have a very complicated charge carrier transport. The relaxation time becomes comparable to the passage of one charge carrier by throwing the device, and their motion approaches ballistic. In this case, it can be possible to impact carrier transition by changing the diode architecture and properties surrounding the medium. For example, the self-switching nanodiode (SSD) is one of the fastest electronic devices that can be made by simply creating insulating channels in a semiconductor layer [2]. The device is expected to operate in the THz frequency regime [3].

One of the ways to develop terahertz radiation sources is to improve characteristics of traditional devices like Gunn diodes or avalanche transit time (ATTD) in the above way. A gallium nitride (GaN) based on Gunn diode of 600 nm proposed in [4] is a good example. To improve diode construction, the authors used side-contact and field-plate technologies. As result, we solved the problems of temperature overheating and strong electric field at the anode, achieving a fundamental frequency in the range of 0.3-0.4 THz. The importance of this result is that the task of GaN-based Gunn experimental realization remained unresolved for a long time.

Another way is to use an active side bonder (ASB) to planar diode to change the transport conditions of the charge carrier in the channel. ASB represents semiconductor elements located on the diode side boundary, electrically connected to the diode anode. An important point to notice is that the conductivity modulation of the channel is weak to appositive to field effect transistors. Under the condition of transferred effect, we can obtain an extended frequency operation regime. Oscillation frequencies can be in the terahertz range [5-7]. This effect is mainly determined by the type of active side bonder. For example, in [5] the maximal frequency 500 GHz is achieved by using ASB in resonance tunneling structure. Frequency extension can be achieved by using a simpler ASB. In planar GaAs-based diode of 1 μm and $In_xGa_{1-x}As$-based ASB with In mole fraction $x$ less the 0.1 generation frequency can be more than 300 GHz [7]. It is, therefore, reasonable to consider other types of similar structures from the viewpoint of possible generation in the terahertz frequency range.

InP is an excellent material for high-frequency and high-power electronic devices. Therefore, the purpose of this research is to consider the possibilities to improve high frequency properties in planar structure on the base InP-substrate using ASB.

## 2. THE STRUCTURE AND SIMULATION

There are several advantages of InP over GaAs. It has superior electron velocity compared to GaAs, 4 times higher breakdown at the same operating condition. It forms lattice-matched semiconductor-semiconductor junctions with several compounds perspective for high frequency application, in particular, with InGaAs [8, 9].

The research considers planar InP-based $n^+$–$n$–$n^+$ structures similar to the ones in [6]. The cross-section

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of the diode structure under study is shown in Fig. 1.

The diode consists of InP-based planar part $L_y = 1.28$ μm, $L_x = 0.32$ μm. The diode active region 2 (channel) is located on a high-resistance substrate 1. Heavily doped contact regions 3 and 4 have a size of 0,16 × 0,32 μm and donor concentration of $6 \cdot 10^{22}$ m$^{-3}$. The width of metal contact 5 and 6 is 0.16 μm. Thus, the active region length is about 1 μm.

The ASB with a length of $L_B$ and width of $l_b$ is placed on the top of the channel connected to the $n^+$-region of the anode contact by metal jumper 7. All contacts in the structure are considered ohmic. ASB represents the original $n$-type diode structure with homogeneous composition. The first structure is $In_xGa_{1-x}As$ one forming heterojunction at the interface between ASB and diode channel. In the second case, InP-based ASB is used to form a quiet InP region.

We used a 2-D diode model corresponding to Fig. 1, according to [5-7]. Simulation of electron transport was carried out by Ensemble Monte Carlo (EMC) technique. The conduction band is described by a three-valley analytic model, taking into account non-parabolic Γ-, L-, and X-valleys. The model of scattering parameters and the material parameters were chosen in accordance with [8].

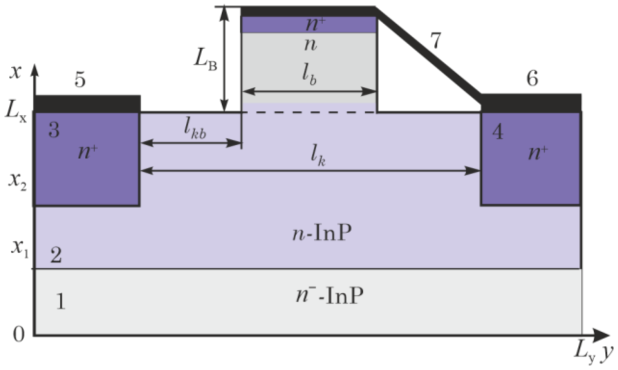


**Fig. 1** – The cross-section of diode structure: substrate (1), active region (2), highly doped contact regions ($n^+$), cathode (3) and anode (4), metal contacts (5,6), side boundary element (7), metal jumper (8)

## 3. RESULTS AND DISCUSSION

The aim of the research is to obtain active elements with a higher cutoff frequency, compared to planar InP-based diode at the same sizes. For this purpose, characteristic structures with ASB were compared to ones of the InP diode. Our approach is based on the assumption that the voltage waveform is $U(t) = U_0 + U_1 \sin 2\pi ft$, corresponding to an oscillation circuit with a high-quality factor. There $U_0$ and $U_1$ are the bias voltage and the first harmonic amplitude of alternative voltage, respectively.

The preceding examples [7] and results of the paper illustrate the general fact that regions of negative differential resistance in current-voltage characteristics are not observed in both structures with ASB and original diode with 1 μm length, since the diode operation is similar to oscillation mode with a trapped anode domain. Dependences of current density on bias voltage at different distances ASB from cathode contact are shown in Fig. 2.

All characteristics are obtained at $L_B = 0.32$ μm and $l_b = 0.16$ μm.

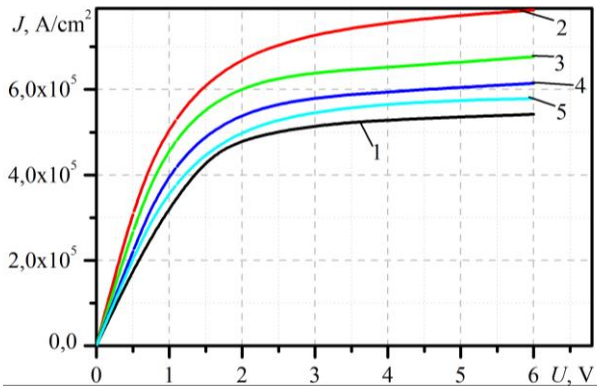


**Fig. 2** – Current density $J$ versus bias voltage $U$. 1 – common InP diode, 2-5 – diodes with InP-based ASB with $l_b = 0.16$ μm and $L_B = 0.32$ μm: 2 – $l_{kb} = 0.16$ μm; 3 – $l_{kb} = 0.32$ μm; 4 – $l_{kb} = 0.48$ μm; 5 – $l_{kb} = 0.64$ μm

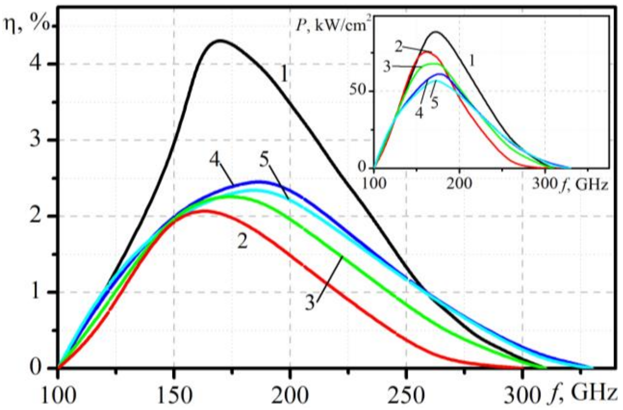


**Fig. 3** – Efficiency versus generation frequency: 1 – common InP diode, 2-5 – diodes with InP-based ASB with $l_b = 0.16$ μm and $L_B = 0.32$ μm: 2 – $l_{kb} = 0.16$ μm; 3 – $l_{kb} = 0.32$ μm; 4 – $l_{kb} = 0.48$ μm; 5 – $l_{kb} = 0.64$ μm

Generation efficiency was determined as a ratio of the alternative current (ac) power at the resonator frequency to the direct current (DC) power. Maximum efficiency is achieved by optimization of $U_0$ at the resonance frequency. The ac voltage gives the highest power for each dc bias voltage. Efficiency is estimated for structures with different sizes of ASB, and their position with respect to the cathode. Donor concentration of $6 \cdot 10^{22}$ m$^{-3}$ is taken to the device studied in [5, 7]. Fig. 3 shows optimal efficiency maximized with respect to the bias and voltage amplitude as a function of resonator frequency for structure with InP-based ASB. Donor concentration in both doped regions is the same.

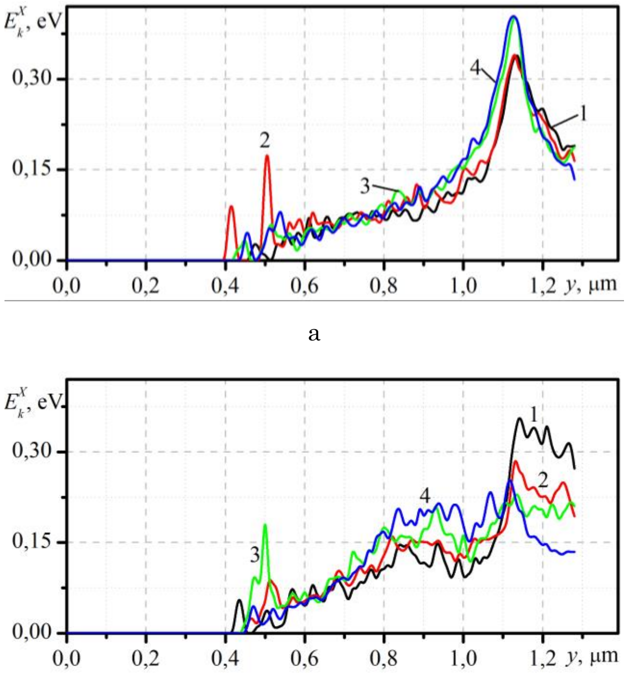
Here, we also present the dependences of optimal efficiency on frequency for common planar InP diode obtained at the same condition.

As can be seen from the figure, ASB significantly affects efficiency. Peak efficiency is reached for frequency 170 GHz in the case of a diode in a range from 160 to 190 GHz for structure with ASB twice less than in an InP diode. The optimal bias is $5U_p$ for the diode, and $(4...5)U_p$ for the diode with ASB. Maximal generation efficiency of 2.5 % is obtained at a distance ASB of

$l_b = 0.48$ μm from the cathode ($L_B = 0.32$ μm). Despite the much lower efficiency of diodes with ASB, their output power is comparable to the InP diode one.

We see increasing cutoff frequency compared with InP in cases when ASB is close to anode contact ($l_{kb} = 0.48$ μm and $l_{kb} = 0.64$ μm). That leads to increased efficiency in a frequency range of more than 280 GHz, and frequency expanding up to 350 GHz. Here, it is worth noting that current instabilities, in this case, exist mainly in the channel region. This is different from the results of our previous work [7], where we considered GaAs substrate and InGaAs-based ASB.

The upper-frequency limit for the transferred electron oscillator is determined by the energy relaxation time. ASB compensates negative act of strong electric fields in the region near the anode. Fig. 4 shows distribution of electron energy in common InP diode and diode structure with InP-based ASB in X-valley corresponding to different moments of the oscillation period. Donor concentration in both regions is the same.



a

b

**Fig. 4** – Energy distribution in X-valley at an oscillation frequency of 300 GHz: a) InP diode; b) diode structure with InP-based ASB, 1 – $t = 0$; 2 – $t = T/4$; 3 – $t = T/2$; 4 – $t = 3T/4$; $U_0 = 3.5$ V, $U_1 = 0.2$ V

Distribution (b) corresponds to $l_b = 0.16$ μm and $l_{kb} = 0.64$ μm. Dependences are obtained at the same bias voltage and ac voltage. As we can see from the figure, kinetic electron energy in the anode region change weakly in the InP diode. Peak energy corresponds to a maximum electric field in the channel and exceeds 0.3 eV.

We observed dependence energy on voltage in the diode structure with ASB. Energy peak of 0.3 eV corresponds to $t = 0$ and twice less at $t = 3T/4$. Thus, these results are consistent with the assumption that ASB impacts on energy relaxation diode and extends the cutoff frequency.

An $In_{0.47}Ga_{0.53}As$ compound matched to InP was considered too. Fig. 5 shows optimal efficiency as a function of resonator frequency for structure with InGaAs-based ASB at a frequency of more than 200 GHz.

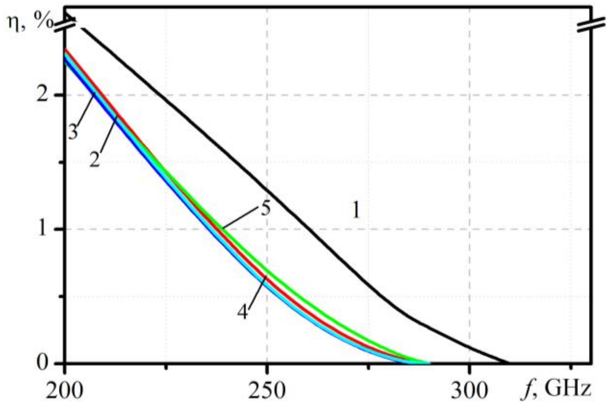


**Fig. 4** – Efficiency versus generation frequency: 1 – common InP diode, 2-5 – diodes with $In_{0,47}Ga_{0,53}As$-based ASB with $l_b = 0.16$ μm, $L_B = 0.64$ μm: 2 – $l_{kb} = 0.16$ μm; 3 – $l_{kb} = 0.32$ μm; 4 – $l_{kb} = 0.48$ μm; 5 – $l_{kb} = 0.64$ μm

As can be seen from the figure, efficiency structures are less than in the InP diode. Threshold voltages of transferred effect for InP-channel and InGaAs-based ASB differed significantly. Because of the heterojunction and the position of the ASB with respect to the cathode contact, the average kinetic energy of the electron is still always sufficient for direct transfer in the satellite valley of the conduction band. At the same time, the impedance of the part of the structure between the ASB position and the anode contact does not increase, and has little effect on the total resistance of the diode.

## 4. CONCLUSIONS

The modification of diode architecture and properties surrounding the medium is a perspective way to improve high frequency properties of submicron structure in the terahertz region. The research has shown positive influence of ASB on the energy relaxation of charge carriers. Thus, the introduction of additional elements electrically connected to the anode contact can lead to an expansion of the diode frequency range. However, this effect can be achieved in a different way. In the case studied in [7], we used GaAs-based substrate and channel with ASB based on $In_xGa_{1-x}As$ with a low mole fraction of In. Parameters of materials have small differences and current instability arises in both channel and ASB. No such effects were observed while considering the InP structure. The impedance of ASB is still positive, as well as ASB impact on the transport of charge carriers in the channel.

Our consideration, however, does not account for the influence of the self-heating effect arising due to the strong field in the anode region. Such analysis is to be made in the future.

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## Планарний $n^+$-$n$-$n^+$ діод з бічними активними границями на InP підкладці

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Досліджено генерацію електромагнітних коливань в довгохвильовій частині терагерцового діапазону діодними структурами з активними бічними границями. Діоди являють собою планарні структури довжиною 1,28 мкм і шириною 0,32 мкм. Вони являють собою провідний канал, розміщений на напівізолюючій підкладці з InP, два контакти та активну бічну границю(АБГ) у вигляді області *n*-типу, розташовану між InP каналом і металевим електродом, який з’єднано з омічним контактом анода. Концентрація донорів в каналі $6 \cdot 10^{22}$ м$^{-3}$. Розглядаються дві різні АБГ, на основі InP та InGaAs. Проаналізовано ефективність генерації діодів. Моделювання проводилося з використанням багаточасткового методу Монте-Карло. Характеристики діодів порівнюється зі характеристиками звичайних InP діодів з такими ж параметрами. Показано, що ВАХ діодів не містить області з негативною диференціальною провідністю, проте мають місце високочастотні коливання струму. Режим роботи діодів близький до режиму із захопленим доменом. Визначено ефективність і частотні властивості діода. Діапазон частот діодів встановлено в діапазоні від 100 до 350 ГГц. Максимальна ефективність генерації діодів з АБГ на основі InP становить близько 2,5 % на частотах 160-180 ГГц. Показано існування ефекту підвищення граничної частоти у випадку використання АБГ в порівнянні зі звичайним діодом InP. Зокрема, використання АБГ на основі InP призводить до виникнення коливань струму в діапазоні від 300 до 350 ГГц у разі розташування АБГ біля анодного контакту. Проте цей ефект не спостерігається якщо застосовується АБГ на основі InGaAs. Зроблено припущення, що поліпшення частотних властивостей досягається за рахунок посилення енергетичної релаксації в АБГ.

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