

InGaAs-based Graded Gap Active Elements with Static Cathode Domain for Terahertz Range

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Terahertz radiometric systems, two-dimensional visualization systems, terahertz tomography and spectroscopy, etc. need noise sources at frequencies above 100 GHz. Frequency capabilities of commonly used elements are limited. Diodes with a static cathode domain or DCSD are known to be noise sources in mentioned ranges as well. Due to low doping, DCSD can be considered as perspective active elements for an ultra-high frequency application. The paper describes InGaAs-based graded-gap active diode elements with a static cathode domain. They have structure of $n^+-n^-n-n^+$ types and length about 1 μm , where n^- is a low doping level region with 0.3-0.5 μm thick. Diodes are considered to be active elements for both generating noise and electromagnetic current oscillations. The working principle of diodes is impact ionization in static domain of a strong electric field in cathode. The results of modeling by using the ensemble Monte Carlo method are presented. Possibility of noise generation in the range from 100 to 500 GHz is shown. Power spectral density of noise was determined in important specific areas of the electromagnetic spectrum which corresponds to atmospheric windows. The influence of doping levels and gallium fraction on GaInAs region of cathode contact is considered.

Current oscillations generation in the range of 100-200 GHz is found. The estimations of generation efficiency are given. Maximum efficiency corresponds to a frequency of about 130 GHz and its value of 1-2 % is obtained. Frequency oscillation limit of the diode exceeds 180 GHz. Considered regime is similar to limit space charge accumulation mode.

Keywords: Diodes, Impact ionization, Graded gap layer, Domain, Electric field strength, Compound composition.

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1. INTRODUCTION

Centimeter and millimeter wave noise generators are applied for calibration of radiometric systems, communication system receivers, radar and navigation systems, for measuring parameters of receiving devices, etc. [1, 2]. Impact ionization avalanche transit-time diode (IMPATT) and Schottky diodes are the most often used noise solid state sources [3]. The reason for noise current in diodes is arising of impact ionization. Development of terahertz radiometric systems, two-dimensional visualization systems, terahertz tomography and spectroscopy, etc. requires noise sources at frequencies above 100 GHz [4].

At high frequency, operation of commonly used elements is limited by their time response. This parameter is determined by four main time constants, such as RC time constant associated with junction capacitance, carrier transit time, multiplication time and diffusion time through quasi-neutral regions. It is clear that, all time constants cannot be simultaneously decreased. For example, to decrease transit time and diffusion time, it is necessary to decrease a diode length. In this case, obtaining of impact ionization is difficult.

Diodes with a static cathode domain or DCSD are known to be noise sources in mentioned ranges as well. Diodes can be GaAs-based structure of $m(n^+)-n^-n-n^+(m)$ types, where n^- is a low doping level region, for example, a semi-insulating material, m - metal, n^+ is a high doping region. A high field region (cathode static domain) arises in the n^-n -junction. An increase in the noise level is observed at applied bias voltage close to

value of a breakdown voltage. That is explained by shot current fluctuations associated with charge carrier transit in the high-field domain [5]. Due to low doping, DCSD can be considered as perspective active elements for an ultra-high frequency application.

The aim of the paper is to study DCSDs capable to operate in a long-wavelength part of the terahertz wave range. Diodes are considered to be active elements both for generating noise and electromagnetic current oscillations.

2. DIODE STRUCTURE AND SIMULATION MODEL

The experimental results and simulation of the centimeter GaAs-based DCSD show that the diode properties are determined mainly by strong-field domain parameters. Noise characteristics of the diode depend on the length of the n^- -region weakly [5].

Therefore, to realize noise diodes, first of all, it is necessary to create conditions for the formation of a strong field static domain. For this purpose, it is sufficient to create an inhomogeneous distribution of electron concentration in cathode region. The condition of an existing static domain can be most easily satisfied by requiring $n_k < 0.2-0.25n_0$, where n_k and n_0 are the doping concentrations in n^- and n -regions, respectively [5].

In GaAs-based diodes, impact ionization in cathode static domain occurs if the electric field strength is about 200 kV/cm. The field reaches its maximum at the boundary of n^- and n -regions. Main part of the applied bias drops across n -region, because of difference in size

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of n^- and n -regions (n^- -region length is a tenth of n -region length) and accordingly increasing electron concentration in n^- -region. Thus, the domain expands to anode. As a result, diode size cannot be less than width of the space-charge region of n^-n -junction. To obtain above electric field strength in the DCSD with an operation frequency corresponding to centimeter and millimeter bands, n^- -region thickness must be about 1-5 μm and a high voltage is required [5].

Since generation frequency of microwave noise in the DCSD is linked to domain width, it is possible to obtain noise generation at a higher frequency range by reducing strong field domain size.

To solve this problem, a $\text{Ga}_z\text{In}_{1-z}\text{As}$ -based semiconductor material layer in cathode contact region has been offered. Gallium fraction increases from small values at cathode $z(0)$ to GaAs at n^-n -junction ($z(x_4)=1$) (Fig. 1).

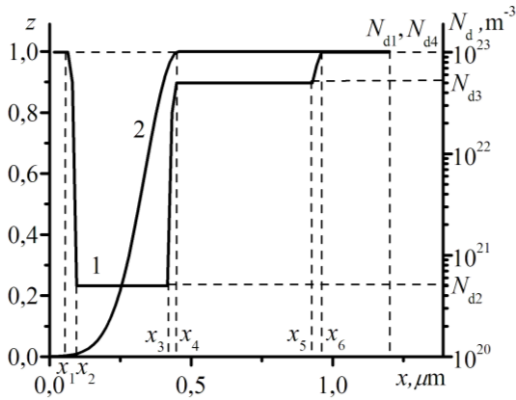


Fig. 1 – The offered diode structure: 1 – doping profile; 2 – distribution of gallium mole fraction $z(x)$

The diode parameters are taken as follows. Diode length is about 1 μm and n^- -region can be 0.3-0.5 μm thick. n^- -region has doping concentration $N_{d2} = 5 \cdot 10^{20} \text{ m}^{-3}$, and n -region is doped to $N_{d3} = 10^{22} \text{ m}^{-3}$. Doping levels in anode and cathode regions are of higher values ($N_{d1} = N_{d4} = 10^{23} \text{ m}^{-3}$) to provide ohmic contacts to the diode.

Properties of the $\text{Ga}_z\text{In}_{1-z}\text{As}$ -based cathode region semiconductor layer are determined by compound composition dependence (Ga fraction in $\text{Ga}_z\text{In}_{1-z}\text{As}$ compound) on the coordinate $z(x)$. The increase in Ga value from cathode to n^-n -junction forms a corresponding coordinate dependence of all semiconductor parameters. Among them band gap, effective masses of charge carriers, threshold energy necessary to have carriers for impact ionization are decisive.

Low threshold energy for $\text{Ga}_z\text{In}_{1-z}\text{As}$ with small Ga containing leads to impact ionization at a much lower electric field than in GaAs.

Diode simulation has been performed using the Monte Carlo technique. Three-valley (lower – Γ and upper L and X – valleys) model of conduction band has been given. Relationship between the energy of the particles $E_e(k)$ and their wave vector is defined as:

$$E_e(1 + \alpha E_e) = \frac{\hbar^2 k^2}{2m^*}, \quad (1)$$

where α is the nonparabolicity factor, m^* is the effective electron mass and \hbar is the reduced Planck constant. The valence band was taken into account by heavy holes parabolic band Γ_{V1} .

Model of electronic simulation and material parameters is similar to the discussed ones [6, 7]. Impact ionization is considered according to [8].

3. DIODE STATIC CHARACTERISTICS

Electric field strength versus coordinates for gallium fraction on cathode of $z(0) = 0$ and ratio values of n^- -region lengths to n -region $\delta = 0.67$ is shown in Fig. 2.

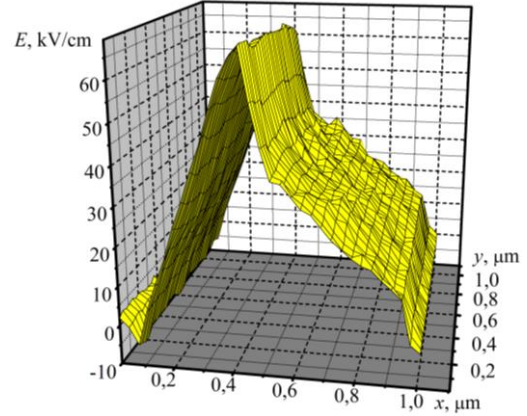


Fig. 2 – The electric field strength versus coordinate: $z(0) = 0$; $U_0 = 2 \text{ V}$

In case of using a graded band region, the electric field's maximum position does not coincide with impact ionization region one. Impact ionization appears closer to cathode contact, thereby hole drift length is reduced. It improves diode frequency properties with a high quasi-drift electric field value of the graded band layer, thus, with the high quasi-drift electric field value of the graded band layer improves diode frequency properties.

Impact ionization contributes electron transfer delay to satellite valleys. Thus, high carrier mobility provides it that affects the current magnitude.

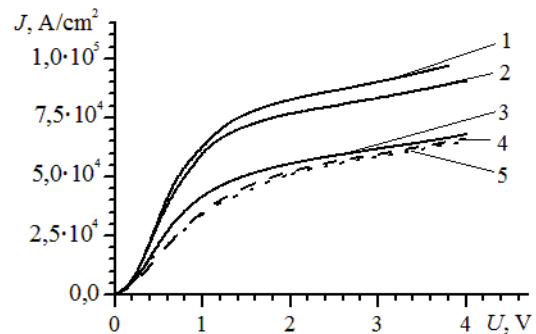


Fig. 3 – I-V characteristics of diodes containing cathode static domain at varying composition distribution and ratio values of n^- -region lengths to n -region: 1 – $\delta = 0.67$, $z(0) = 0$; 2 – $\delta = 1$, $z(0) = 0$; 3 – $\delta = 1.5$, $z(0) = 0$; 4 – $\delta = 0.67$, $z(0) = 0.2$; 5 – $\delta = 0.67$, $z(0) = 0.4$

The current-voltage (I-V) characteristics of these diodes are showed in Fig. 3.

The highest current density values correspond to the diode with graded band layer and InAs on cathode contact, as it is shown at the presented dependencies.

Low increasing Ga fraction in $\text{Ga}_z\text{In}_{1-z}\text{As}$ compound at cathode contact leads to carrier mobility decreasing due to the effect of alloy potential scattering (Fig. 3, curves 4, 5). In the same way, low-doped region extension to anode influences the current magnitude.

4. DIODE NOISE CHARACTERISTICS

The current fluctuation analysis is performed to determine diode noise characteristics. Diode noise characteristics were estimated from the power spectral density (PSD) of noise. It was determined from autocorrelation function of the current fluctuation similarly to those discussed in [7]. Diode PSD has been analyzed in important specific areas of the electromagnetic spectrum which corresponds to atmospheric windows (little radiation absorption). Thus, the considered frequency ranges contain the following frequencies: 95, 140, 220, 500 GHz. The PSD dependencies are shown in Fig. 4 for three different diodes, two of which are homogeneous composition distribution diodes based on GaAs and $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$. The third diode has $\text{Ga}_z\text{In}_{1-z}\text{As}$ -based graded band region and normal composition distribution $z(x)$ from 0 at cathode to 1 in the border of n -region. The characteristics correspond to the identical diode applied voltage equal to 2 V.

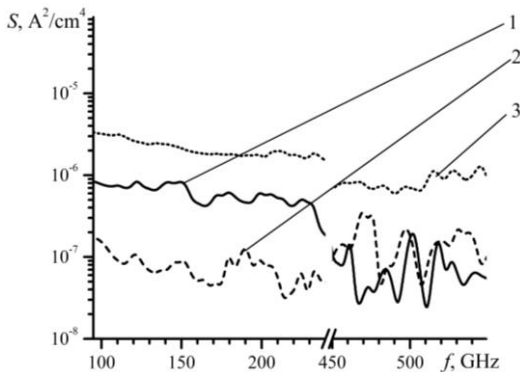


Fig. 4 – Diode spectral characteristics with parameter $\delta = 0.67$ and applied voltage $U = 2$ V: 1 – $z(x) = 1$; 2 – $z(x) = 0.47$; 3 – $z(0) = 0$

As it is shown, the PSD value increases if Ga mole fraction decreases from $z(0) = 1.0$ to $z(0) = 0$ on cathode at all considered frequencies. It is of an order of magnitude greater than that in homogenous composition diode at all considered frequencies. PSD levels difference is becoming less noticed at frequencies more than 450 GHz. The greater frequency is, the less it is.

The distribution effect of $\text{Ga}_z\text{In}_{1-z}\text{As}$ composition along diode length is shown in Fig. 5. These dependences of noise spectral density correspond to normal composition distributions. The initial compound composition at cathode $z(0)$ corresponds to different Ga fraction of (0; 0.2; 0.4), and starting from point x_4 (the end of the reduced doping region) the composition remains unchanged and corresponds to GaAs. The characteristics correspond to the identical diode applied voltage equal to 2 V.

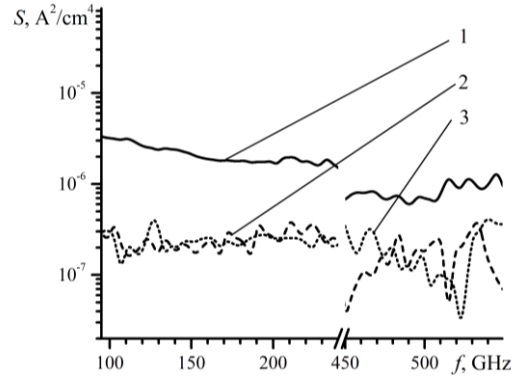


Fig. 5 – Diode spectral characteristics with parameter $\delta = 0.67$, applied voltage $U = 2$ V and different Ga fraction at cathode contact: 1 – $z(0) = 0$; 2 – $z(0) = 0.2$; 3 – $z(0) = 0.4$

These dependences of noise spectral density correspond to normal composition distributions. The initial compound composition at cathode $z(0)$ corresponds to different Ga fraction of (0; 0.2; 0.4), and starting from point x_4 (the end of the reduced doping region) the composition remains unchanged and corresponds to GaAs. The characteristics correspond to the identical diode applied voltage equal to 2 V.

PSD value depends on the doping profile particularly upon parameters of the reduced doping region. The analysis showed that in low-frequency region for the fixed diode length, the highest PSD magnitude is achieved at small ratios of the reduced doping region length to active region length $\delta < 1$.

Dependence of PSD of noise on bias voltage amplitude corresponded to diode with parameters $\delta = 0.67$ and $z(0) = 0.2$ are similar for all the considered diodes. There is PSD minimum corresponding to area of current saturation site on current-voltage characteristics. PSD grow is associated with the existence of impact ionization.

5. HIGH FREQUENCY CURRENT OSCILLATIONS IN DCSD

As it was shown in [9], at certain frequencies, the impedance characteristics of diode with cathode static domain can have the negative differential conductivity regions. Thus, there is a possibility to obtain generation on the selected frequencies.

The DCSD can be considered as active element for generation of electromagnetic oscillations in terahertz range. The basic idea of such an active element is the combination of intervalley electron transfer effect and modulation of the static domain parameters. The field outside the domain is less than intervalley transfer field. This corresponds to case of high magnitudes of mobility and conductivity. Electrons falling into cathode static domain region scatter into lateral valleys and their velocity is close to saturation velocity.

Diode operating voltage is sufficiently low, and the static domain width becomes comparable to the diode sizes. As a result, a small variation of the applied voltage leads to a noticeable change of domain parameters. As a consequence, magnitude of the current flowing through the diode is changed as well. If voltage increases, domain width increases and the diode current

will decrease. In case of voltage decrease, current magnitude will increase, correspondingly.

Thus, dynamic negative resistance of the diode is formed. It should be noted that static characteristics of diodes do not contain negative resistance sites as it takes place in transferred electron devices.

Generation regime has been investigated for a diode with $z(0) = 0$ and $\delta = 0.67$. Influence of the resonator is taken into account by setting the corresponding voltage on the diode in the form

$$U(t) = U_0 + U_1 \sin \omega t, \quad (2)$$

where U_0 is the bias voltage, U_1 is the first harmonic amplitude of alternating voltage (determined by resonator), f is the resonance frequency. Oscillation efficiency (η) is determined as in [10].

In order to obtain maximum generation efficiency, various doping profiles were considered. In this case, length of low doping area and doping value did not change. It should be noted that the smallest carrier concentration in n -region has determined the intrinsic concentration, which is large at small Ga fraction in InGaAs. Therefore, diode parameters are determined by doping concentration in the active region.

Fig. 6 and Fig. 7 show a distribution of electric field strength and electron concentration for different moments of time during the oscillation period T , respectively. Here, resonance frequency is $f = 130$ GHz, donor concentration is $N_{d3} = 5 \cdot 10^{22} \text{ m}^{-3}$, diode voltage is $U_0 = 3 \text{ V}$ and $U_1 = 1.2 \text{ V}$.

As can be seen from Fig. 7, in this case, there are several peculiarities of current instability formation. In particular, during oscillation period, amplitude of a strong field domain does not grow, as in case of an ordinary Gunn effect. Strong field domain practically occupies all active regions of the diode and electric field is redistributed in it. Because of a large energy gap between central Γ -valley and satellite valleys in InGaAs, in graded-gap cathode region electrons take their energy from the field very effectively. Intervals transfer mainly occurs in GaAs active region. Thus, electrons that appear due to generation process move within the domain. An increase in carrier concentration occurs in domain front at a distance of an order of free transit length. This value is about $0.1 \mu\text{m}$ for GaAs and that is an optimal value for realization of this oscillation regime.

Fluctuation growth time is minimal and therefore the considered regime is similar to limit space charge accumulation mode.

Fig. 8 shows dependence of generation efficiency on diode frequency with different donor impurity concentration in active region. All dependences are obtained by optimizing efficiency magnitude chosen from voltage values (bias voltage and amplitude of the first harmonic in expression (2)).

As seen from Fig. 8, at high doping levels of active region, maximum efficiency corresponds to a frequency of about 130 GHz. Its value is 1-2 %. Frequency oscillation limit of the diode exceeds 180 GHz.

It is possible to note that frequency generation band is wide. Maximal efficiency depends on active region

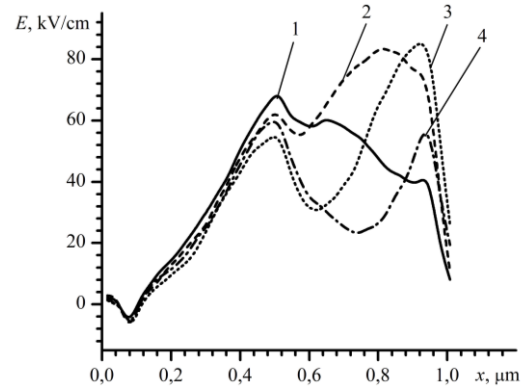


Fig. 6 – Electric field strength value at different time moments τ 1 – $\tau = 0$, 2 – $\tau = T/4$, 3 – $\tau = T/2$, 4 – $\tau = 3T/4$

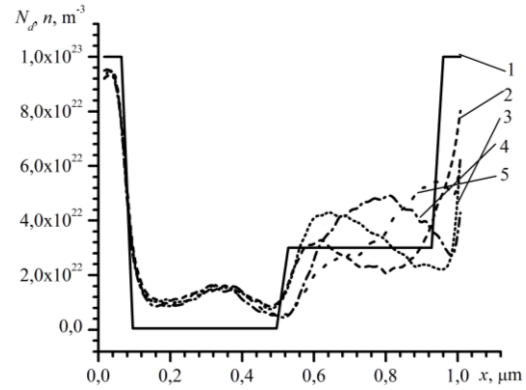


Fig. 7 – Donor concentration 1 and electron concentration 2-5 versus coordinate at different time moments τ 2 – $\tau = 0$, 3 – $\tau = T/4$, 4 – $\tau = T/2$, 5 – $\tau = 3T/4$

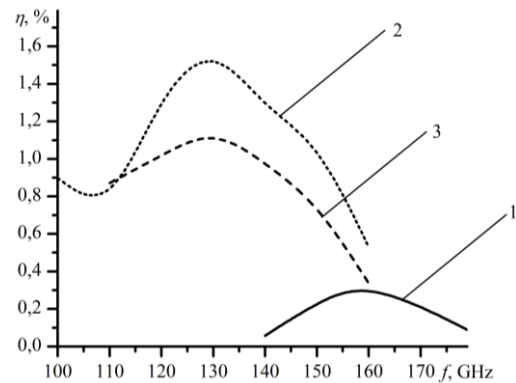


Fig. 8 – Generation efficiency for diodes with different donor impurity concentration in active region: 1 – $N_{d3} = 3 \cdot 10^{22} \text{ m}^{-3}$, 2 – $N_{d3} = 5 \cdot 10^{22} \text{ m}^{-3}$, 3 – $N_{d3} = 7 \cdot 10^{22} \text{ m}^{-3}$

doping level and decreases with decreasing donor impurity concentration. Maximum efficiency tends to high frequency region (up to around 200 GHz) as concentration in active part of the diode decreases. It gives evidence of influence of transit effects on formation of negative difference conductivity.

It is possible to assume that bunches of space charge occurring in domain region drift through it with constant velocity (saturation velocity) and spill. Interaction of bunch with a high-frequency electric field leads to appearance of negative difference whether there is static negative resistance of a diode or not.

6. CONCLUSIONS

Thus, it has been shown that a localized region with high electric field strength sufficient for arising impact ionization can be obtained in short (with an active region less than 300 nm) In_zGa_{1-z}As diodes. It was realized by using inhomogeneous distribution of the composition. Impact ionization appears only in domain front due to high In content. Electron transport within domain leads to noise generation.

At low doping levels of active diode region, frequency oscillation limit reaches 200 GHz. That is larger than frequency limit of intervalley transfer in In_zGa_{1-z}As [11].

This approach allows creating noise generators and electromagnetic oscillations in terahertz range. Frequency range of diode operation can be increased by choice of the appropriate material and diode dimensions. For this purposes, the most promising is usage of nitride compounds containing In (In_zAl_{1-z}N, In_zGa_{1-z}N). Such structures are more complicated compared to considered ones and will be analyzed in what follows.

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Активні елементи на основі InGaAs зі статичним катодним доменом для терагерцового діапазону

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Радіометричні системи терагерцового діапазону, двовимірні системи візуалізації, терагерцова томографія та спектроскопія тощо потребують джерел шуму на частотах вище 100 ГГц. Частотні можливості широко використовуваних елементів обмежені. Відомо, що діоди зі статичним катодним доменом (або DCSD) також є джерелами шуму в згаданих діапазонах. Через низький рівень легування, DCSD можна розглядати як перспективні активні елементи для застосування на ультрависоких частотах. У статті описані активні діодні елементи на основі InGaAs із змінною шириною забороненої зони зі статичним катодним доменом. Вони мають структуру n^+-n-n^+ типів і довжину близько 1 мкм, де n – область низького рівня легування товщиною 0-0,5 мкм. Діоди вважаються активними елементами як для генерації шумів, так і для електромагнітних коливань струму. Принцип роботи діодів базується на ударній іонізації в статичному домені сильного електричного поля в катоді. Наведено результати моделювання методом ансамблю Монте-Карло. Показана можливість генерації шуму в діапазоні від 100 до 500 ГГц. Спектральна щільність потужності шуму визначена у важливих областях електромагнітного спектра, що відповідає атмосферним вікнам. Розглянуто вплив рівнів легування та фракції галію на область GaInAs катодного контакту.

Знайдено генерацію коливань струму в діапазоні 100-200 ГГц. Наведено оцінки ефективності генерації. Максимальна ефективність відповідає частоті близько 130 ГГц і її значення становить 1-2 %. Межа коливань частоти діода перевищує 180 ГГц. Розглянутий режим подібний до режиму накопичення граничного просторового заряду.

Ключові слова: Діоди, Ударна іонізація, Шар із змінною шириною забороненої зони, Домен, Напруженість електричного поля, Склад з'єднання.