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Mesoscopic Structures for Microwave-THz Detection

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Properties of microwave detectors of various design on the base of MBE grown GaAs and AlGaAs structures are discussed in this paper: simple asymmetrically shaped structures with heavily doped GaAs and AlGaAs layers of nanometric thickness as well as diodes with two-dimensional electron gas layers. Novel models of the detectors with partially gated two-dimensional electron gas layer as well as with small area GaAs/AlGaAs heterojuction are discussed to demonstrate different ways to increase the voltage sensitivity of the detectors of electromagnetic radiation in GHz–THz frequency range.

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1. Introduction

Mesoscopic structures based on selectively doped (SD) semiconductor structures, due to the increased electron mobility, are successfully used in field effect transistors to improve their operational speed. As an example of SD structure application one can mention the detection of electromagnetic radiation (EMR), especially in a high frequency range where sensitive detectors are desired to operate at room temperature. Low value of quantum energy of EMR at THz frequencies requires non-quantum character of the operation of such detectors. The concept of EMR detectors based on carrier heating phenomena in semiconductors was successfully used to detect the radiation from microwave (MW) up to infrared region [1]. Higher voltage sensitivity of these detectors formed on semiconductor structures with electron sheets of nanoscopic dimensions was achieved due to higher electron mobility in the SD structures [2]. However, principles of operation of such MW diodes are not clear enough.

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In this paper, EMR detectors fabricated on the base of MBE grown GaAs/AlGaAs heterostructures and having various design are discussed: from simple asymmetrically shaped structures with heavily doped GaAs and AlGaAs layers of nanometric thickness, up to the ones with two-dimensional electron gas (2DEG) formed on the base of selectively doped GaAs/AlGaAs structures. Investigations revealed importance of proper device design to minimize the influence of metal–semiconductor junction on detection properties of the EMR detectors. Novel models of the detectors with partially gated 2DEG layer as well as with small area GaAs/AlGaAs heterojuction are discussed in this paper to demonstrate different ways to increase the voltage sensitivity of the detectors of EMR in GHz–THz frequency range.

2. Theoretical considerations

In case of MW detection by n–n^+ (p–p^+) junctions and warm electron approximation one can evaluate the detected signal (voltage U_d) using electrical parameters of semiconductor material and geometrical dimensions of the junction. Using the fact that the excess charge carrier temperature and concentration are negligible in comparison with equilibrium values ($\Delta T_n \ll T_0$, $\Delta n \ll n_0$) one obtains [3]:

$$U_\mathrm{d} = \frac{1}{2\pi}\left[\frac{k_\mathrm{B}T_0}{e}\int_{r_1}^{r_2}\int_0^{2\pi}(1-s)\frac{\Delta T_n}{T_0}\frac{1}{n_0(r)}\frac{\mathrm{d}n}{\mathrm{d}r} - \left(s\frac{\Delta T_n}{T_0} - \frac{\Delta n}{n_0(r)}E(r,t)\right)\right]\mathrm{d}(\omega t)\mathrm{d}r. \tag{1}$$

Here the integration is performed over the period $2\pi/\omega$ of MW signal from the point r_1 in n region to point r_2 in n^+ region of the n–n^+ junction; e is the electron charge, k_B is the Boltzmann constant, s stands for the index of power dependence of electron momentum relaxation time τ_p^s and E denotes the electric field strength. In the case of a flat asymmetrically shaped n–n^+ junction consisting of 2DEG layer (n region) and alloyed Ge/Ni/Au contact (n^+ region) the voltage sensitivity S_i of such planar structure to the incident MW power P_i in a waveguide can be expressed as follows [1]:

$$S_\mathrm{i} = \frac{U_\mathrm{d}}{P_\mathrm{i}} = \frac{\mu_0 R_\mathrm{sh}^2}{3d^2 R_\mathrm{s0}} KN(\omega, \tau_\mathrm{p}, \tau_\mathrm{E}, \tau_\mathrm{M}^n), \tag{2}$$

$$R_\mathrm{s0} = \frac{R_\mathrm{sh}}{2\tan\alpha}\ln\left(1+\frac{a}{d}\right), \tag{3}$$

where R_s0 denotes the low field electrical resistance of the structure, d and a are the widths of the planar semiconductor structure in the narrowest and widest parts, α is the widening angle of the n region, μ_0 stands for the low field electron mobility, and R_sh denotes sheet resistance of the n region. τ_E and τ_M^n are, respectively, electron energy and Maxwell relaxation times in the n region. K is the factor that expresses the amount of the absorbed MW power by the diode; N is a factor that depends on ω, τ_{p}, τ_{E}, τ_{M}^{n}. Expression (2) holds for flat n–n^{+} junction when its width L_{n-n+} is much greater than electron diffusion length $L_{\mathrm{D}} = \sqrt{D\tau_{\mathrm{ee}}}$ (here D is hot carrier diffusion coefficient and τ_{ee} denotes the inter electronic collision time). In the case of abrupt n–n^{+} junction the voltage sensitivity of the MW diode decreases by $\approx 30\%$ due to electron heat flow divergence in the junction [4]. It was assumed that identical electron scattering mechanisms are presented in n and n^{+} regions. However the electron scattering rate in n^{+} and n regions may differ. In the latter case numerical integration of Eq. (1) should be done. Considering the alloyed Ge/Ni/Au contact to the 2DEG layer of SD structure as an n–n^{+} junction, the width of such junction would be of the order of a Debye length [5]. Thus, in the case of 2DEG density $n_{\mathrm{s}} = 10^{12}$ cm^{-2}, the n–n^{+} junction width appears to be 50 times shorter than L_{D} at room temperature and more than two orders shorter at $T = 80$ K. Moreover, as shown in Ref. [6], the metal/semiconductor junctions may influence the detection properties of the microwave diode on the base of asymmetrically and symmetrically shaped 2DEG layer by changing the value of detected voltage and even its polarity, in the case of finite height of the metal/semiconductor barrier.

3. Samples

Application of MW diodes at high frequencies requires their planar design, because bulk diodes fabricated on thick semiconductor substrates notably are difficult to match with high frequency waveguide transmission line. The diodes were fabricated by transferring tiny semiconductor mesa onto elastic dielectric film (polyimide). Since dielectric constant of the polyimide is close to one, the quasi-free-standing structure of the MW diodes was achieved. This design of the diodes allowed to achieve better voltage sensitivity due to suppressed MW bias currents through the semiconductor substrate.

The first step in the fabrication process of the diodes based on n–n^{+} junction was the shaping of semiconductor mesas of either asymmetric or symmetric configurations by a wet chemical etching through the photomask windows. The same step was used for fabrication of asymmetrically shaped bigradient MW diodes. In the next step the metallic patterns of the diodes were formed by lift-off technique after thermal evaporation of Ni/Au/Ge/Ni/Au layers. Ohmic contacts were fabricated using rapid thermal annealing of the evaporated metals in a forming gas atmosphere. Quality of contacts was controlled by transmission line method. The specific contact resistance did not exceed 1 Ω mm. The Hall measurements were performed to evaluate electron mobility and sheet electron density of the structures. To introduce a gate above the active layer of the diode an additional Au layer was evaporated close to one ohmic contact in the case of gated diodes. Thin Cr layer was evaporated before the gate metallization for better adhesion of Au with GaAs.

The fabrication process of filmy diodes began with photolithography process for framing of the diode structures by wet chemical etching of deep trenches around the diode's mesas. At this fabrication step deep etched alignment marks were created in the last photolithography. The polyimide was spun down on the surface of the diodes matrix and then annealed for one hour in the air. Back-thinning of the semiconductor substrate was performed after sticking it onto glass plate. The thickness of the back-thinned substrate was controlled with the help of the alignment marks fabricated during the trench etching. The last photolithography process formed the patterns for following deep mesas etching and stripping the metal contacts from the substrate side of the diode.

4. Experimental results

Experimental values of DC electrical resistance of MW diodes on the base of thin heavily doped GaAs and AlGaAs layers were higher than theoretically predicted, especially for diodes with narrower n–n^+ junction. The asymmetry of the I–V characteristics was opposite to that of n–n^+ junction. However, at MW frequencies, the sign of the detected DC voltage was found to be of the same polarity as that due to electromotive force of electrons across the n–n^+ junction. In Fig. 1 the dependences of the DC detected voltage on MW power

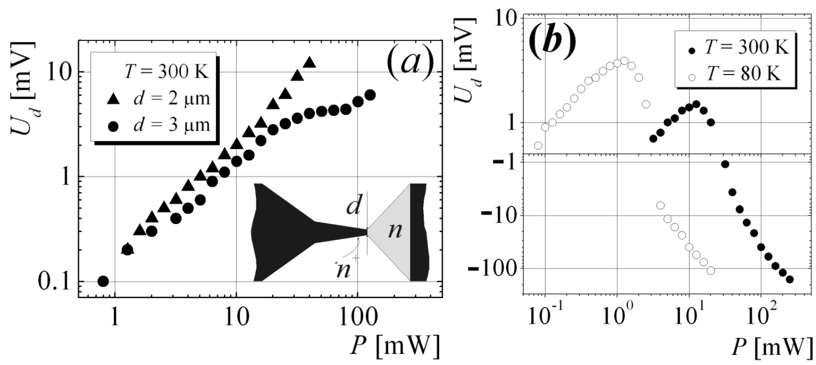

Fig. 1. Voltage–power characteristics of MW diodes with asymmetrically shaped n–n^+ junction inset in (a). The n region is GaAs (a) and AlGaAs (b).

(voltage–power characteristic) of asymmetrically shaped diodes on the base of heavily doped GaAs and AlGaAs layers are shown. Diodes with GaAs n–n^+ junction revealed linear characteristics , Fig. 1a, while the diodes on the base of heavily doped AlGaAs layer, Fig. 1b, had non-monotonic character of the voltage–power characteristic both at room and liquid nitrogen temperatures. The linear dependence of the detected voltage on power was observed only at low values of MW power. As the MW power increased, especially in case of heavily doped AlGaAs, the sublinear characteristics were found, which at still higher powers have changed the polarity, Fig. 1b. We relate the sign reversal of the detected voltage with intervalley scattering phenomenon, which is more pronounced in AlGaAs. We explain the contradiction between the polarity of the detected voltage and the sign of $I{-}V$ characteristics asymmetry by electron transfer to surface states that are present in the vicinity of the "neck" of the asymmetrically shaped semiconductor structure in strong electric fields.

Figure 2 shows voltage–power characteristics of MW diodes fabricated from GaAs/AlGaAs SD. In these diodes the magnitude of the detected signal depends on quality of the structure, spacer width, and doping manner of AlGaAs barrier layer [6]. If the barrier layer of the diodes were δ-doped the parasitic influence of metal/semiconductor junction in the layers that form the SD structure onto detective properties was minimized. Fig. 2a compares voltage–power characteristics of the MW diodes with homogeneously and δ-doped barrier layers. Better linearity of the characteristic is seen in diodes with δ-doped barrier. Also, the diodes exhibited stronger dependence of the voltage sensitivity on frequency in THz frequency range, Fig. 2b, as Eq. (2) predicts. Worse linearity of the voltage–power characteristics of these MW diodes at room temperature (see Fig. 2a) as well as rapid decrease in the voltage sensitivity with frequency can be explained by competing detection mechanisms to electromotive force in $n{-}n^+$ junction of the SD structure.

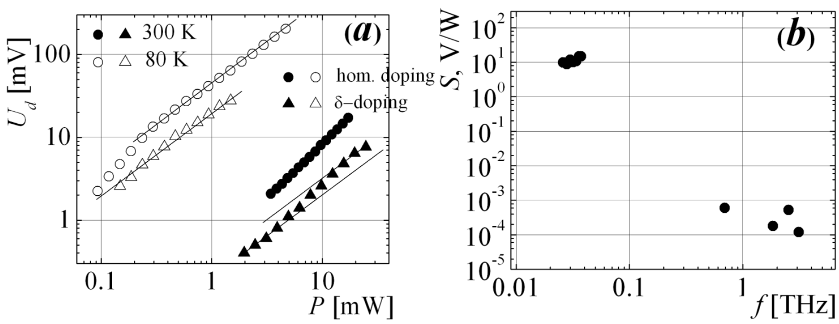

Fig. 2. Voltage–power characteristics of MW diodes based on SD structures with homogeneously and δ-doped barriers (a), and frequency dependence of the diodes with δ-doped barrier (b).

The voltage sensitivity of the microwave diodes with δ-doped barrier can be increased if gate is introduced above the 2DEG layer in SD structure. The sensitivity higher by two orders is inherent to the gated MW diode, as compared to the non-gated one, as can be seen from Fig. 3a. However, the gated diode (see Fig. 3b) has demonstrated sharp decrease in the sensitivity with frequency in THz range. A faster decrease in the sensitivity than predicted by Eq. (2) indicates presence of additional detection mechanisms in addition to the electromotive force (emf) of hot carriers.

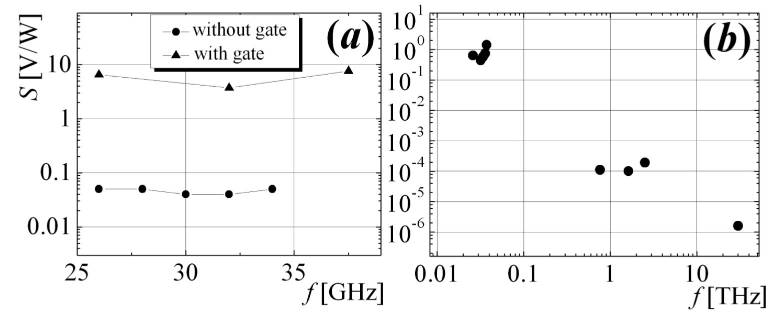

Fig. 3. Frequency dependences of voltage sensitivity of MW diodes having asymmetrically shaped SD structure with and without the gate in GHz range (a) and GHz–THz range (b).

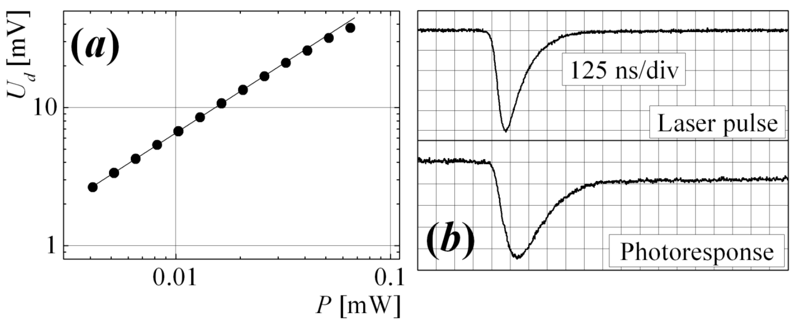

Fig. 4. Voltage–power characteristic at $f = 26$ GHz (a) and temporal behavior of photoresponse signal induced by CO_2 laser pulse (b). In parts (a) and (b) the measurements were done with small area GaAs/AlGaAs heterojunction diode at room temperature.

An essential increase in the sensitivity, compared to the above discussed, was achieved in the frequency range from 26 GHz to 37.5 GHz with diodes having area GaAs/AlGaAs heterojunction small. The value of ≈ 800 V/W was measured at $f = 26$ GHz, Fig. 4a. Good linearity of the voltage–power characteristic suggests that these MW diodes could be suitable sensors for MW power measurements. An additional promising feature of these heterojunction diodes is that they revealed themselves as fast detectors of IR radiation pulses at room temperature, Fig. 4b.

5. Summary

The experimental results on a series of GaAs/AlGasAs mesoscopic structures adapted to GHz and THz radiation detection allow us to make the following conclusions.

Thermoelectric emf of hot carriers arises in heavily doped GaAs and AlGaAs structures, witnessing importance of carrier heating phenomenon in GHz frequency range. Non-monotonic character of voltage–power characteristics of MW diodes is influenced by intervalley scattering phenomena and the Gunn domain formation in GHz frequency range. Selectively doped structures of GaAs/AlGaAs can be used to detect EMR from GHz up to THz frequencies at room temperature. However, the detection properties of SD structures strongly depend on the quality of the material. The introduction of the gate above 2DEG channel improves voltage sensitivity of MW diodes allowing to perform the measurements in THz frequency range. The structures with small GaAs/AlGaAs heterojunction area were found to be sensitive MW detectors as well as fast sensors of IR radiation.

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