GaAs microwave detector

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Abstract

We investigate two types of GaAs microwave detector: point contact diode with n-n$^+$ junction and planar one, which involves asymmetrically necked thin semiconductor film containing n-n$^+$ junction in its narrowest part. The voltage sensitivity of the GaAs point contact diode, in contrast to those made from Ge or Si, increases with the strength of the microwave electric field due to the increase of both the electron energy relaxation time and the diffusion coefficient at room temperature. Investigating the voltage-power characteristic of the planar diode we have determined experimentally that the voltage sensitivity of the planar detector weakly depends on frequency within the 26 - 140 GHz range.

Introduction

Microwave (MW) detectors, which operation is based on electron heating by electric field, usually are made from germanium or silicon. The dependence of the detected signal on microwave power (volt-power characteristic) of these detectors is linear in a warm electron region, when the microwave power is not so big. In stronger microwave electric fields the voltage sensitivity decreases due to the decrease in carrier mobility and energy relaxation time. As it is well known [1], the electron energy relaxation time in GaAs at room temperature increases with increasing the electric field strength. Thus, the decrease in the electron mobility in strong electric fields can be compensated by the increase of the energy relaxation time in this material, and the voltage sensitivity of such diodes may be constant in a wider range of the electric field strength as compared with that of diodes based on Ge or Si.

One of the main parameters of the point contact diode is frequency range of operation. Its upper frequency is limited by electron momentum relaxation time [2]. However, it is a very complicated problem to use such a whisker-contacted diode in high frequencies of MW electric field due to the small size of both ohmic contact and the waveguide. For that reason frequency operation range decreases significantly. We suppose that this problem can be solved with the help of small planar surface-oriented microwave diode where both terminals lie on the same surface of the semiconductor wafer. Background of the planar diode is asymmetrically necked semiconductor structure, in which the bigradient and thermoelectric electromotive forces appear under the influence of strong electric field [3,4].

The aim of this work is to investigate the properties of small area GaAs n-n$^+$-junction in whisker-contacted and planar diodes in dc and microwave electric fields.

Samples and technique

The point contact and asymmetrically necked diodes (Fig. 1) were prepared from n$^+$-n-n$^+$ epitaxial structures. The thickness of n epitaxy layer and density of impurities there were 29 μm and $1.1 \cdot 10^{15}$ cm^{-3}, respectively. The thickness of the contact layer was 1 μm. The impurity density in the contact layer and in the substrate was $2 \cdot 10^{18}$ cm^{-3}. Electron mobility in n-layer at room temperature was $\mu = 7000$ cm^2/V·s. The ohmic contacts of the diodes were made by thermal evaporation of separate Ge/Ni/Au layers [5] through the windows created in photoresist by photolitography method and by following annealing in inert gas atmosphere. The small area n-n$^+$- junctions of point contact diode and the asymmetrically necked semiconductor structure of planar diode were formed by chemical etching of GaAs. A polyimide material was spun down on the asymmetrically necked structures in a manner similar to photoresist. Then the film was cured at 250°C for one hour. The

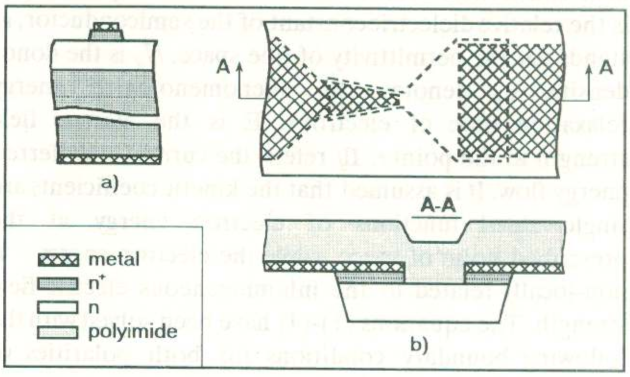

Fig. 1. Schematic of point contact (a) and planar (b) microwave diodes

cured polyimide film has a small dielectric constant ($\varepsilon<3$) and thickness in the vicinity of 10 μm. This film acts as dielectric standoff and mechanical support of semiconductor structure and metal contacts of the diode. After thinning the semiconductor wafer to a thickness of about 5 μm, the semiconductor material was removed from metal patterns by chemical etching.

In order to avoid the crystal-lattice heating, the short pulses of electric current and microwave signal with duration of a few microseconds and the repetition rate (40÷50) Hz were used. The circuit of balanced bridge was used to investigate the diode in dc electric field. As a source of MW electric field, the clystrons generating high-frequency signals in frequency range f=(26÷37.5) GHz and f=(129÷143) GHz were used. The diodes were placed in rectangular waveguide. The matched load was used on the end of the waveguide to achieve better uniformity of detected signal value over operating frequency range.

Theory

Let us consider the electric current passing through the small area n-n$^+$- junction of point contact and planar diode on the basis of phenomenological current density, heat balance, heat flow density and Poisson equations

$$\vec{j}(r)=en(r)\mu(\mathcal{E})[\vec{E}(r)+\alpha\nabla_{\vec{r}}]+eD(\mathcal{E})\nabla_{\vec{r}}n \tag{1}$$

$$\vec{j}\vec{E}=n\frac{\mathcal{E}-\mathcal{E}_o}{\tau_{\mathcal{E}}}+\nabla_r\vec{Q} \tag{2}$$

$$\vec{Q}(r)=\Pi\vec{j}-\kappa\nabla_{\vec{r}}\mathcal{E} \tag{3}$$

$$\nabla_r\vec{E}=-\frac{e}{\varepsilon\varepsilon_o}[n(r)-N_d(r)], \tag{4}$$

where e, $n(r)$, $\mathcal{E}$, $\mu(\mathcal{E})$, α, $D(\mathcal{E})$, Q, κ are the charge, density, mean energy, mobility, volumetric thermo-e.m.f. coefficient, diffusion coefficient, heat flow density, and heat conduction coefficient of electrons, respectively, ε is the relative dielectric constant of the semiconductor, ε_0 stands for the permittivity of free space, N_d is the donor density, $\tau_{\mathcal{E}}$ denotes the phenomenological energy relaxation time of electrons, E is the electric field strength at the point r, Πj refers the current transferred energy flow. It is assumed that the kinetic coefficients are single-valued functions of electron energy at the prescribed point of space, while the electron energy is non-locally related to the inhomogeneous electric field strength. The equations (1)-(4) have been solved with the following boundary conditions for both polarities of applied voltage:

$$E(r_1)=E_1,\quad n(r_1)=N_d,\quad \mathcal{E}(r_1)=\mathcal{E}_0 \tag{5}$$

$$E(r_2)=E_2,\quad n(r_2)=N_d^+,\quad \mathcal{E}(r_2)=\mathcal{E}_0 \tag{6}$$

where $r=r_1$ denotes the point in the n- layer far from the n-n$^+$- junction, and $r=r_2$ denotes the point in contact layer near the n-n$^+$- junction, where the diffusion current can be neglected. Under these conditions, electric field strength is low in the points that are far enough from the n-n$^+$- junction, and the energy of electron-gas is equal to its equilibrium value. Electron density is equal to the donor density there. In the case of asymmetrically necked structure the curvilinear coordinate system is set so, that the x-direction is parallel to the direction of the electric field [6]. The total strength of the electric field in each point r can be written as a sum of

$$E(r)=E_i(r)+E_a(r) \tag{7}$$

where E_i is the strength of intrinsic electric field of n-n$^+$- junction, when $j(r)=0$, and E_a is the strength of electric field created by external source. Expressing E_a from (1), and integrating the obtained expression over the length of the sample, the relationship between the electric current $I=j(r)S(r)$ passing through the n-n$^+$- junction and the applied voltage V can be found

$$V=I\left\{\int_{r_1}^{r_2}\frac{dr}{en(r)\mu(\mathcal{E})S(r)}+\frac{1}{I}\int_{r_1}^{r_2}\left[\frac{\mathcal{E}-\mathcal{E}_o}{\mathcal{E}_o}E_i(r)-\alpha\nabla_{\vec{r}}\mathcal{E}\right]dr\right\}. \tag{8}$$

When I tends to zero, the first integral in (8), gives the usual expression of spreading resistance R_{s0} of semiconductor structure (e.g., in the case of flat point contact with radius r_0, $R_{s0}=1/4en\,\mu_0 r_0$) and the second integral in (8) gives the additional resistance δR of the semiconductor structure

$$\delta R=\frac{kT\tau_{\mathcal{E}}}{e^2S_0\lambda n}, \tag{9}$$

where k is the Boltzmann constant, T is a lattice temperature, S denotes the area of n-n$^+$- junction, λ is the characteristic width of n-n$^+$- junction in which the impurity density falls by e times. The δR results from the change of electron energy, when they are passing through n-n$^+$-junction, i.e. due to the Peltier effect of hot electrons [3]. Expressing electron density $n(r)$ from (4), and electron energy $\mathcal{E}$ from (2), and , taking into consideration their first-order terms (warm electron region approximation, when $\mathcal{E}-\mathcal{E}_0<<\mathcal{E}_0$), and then, integrating (8), we have obtained the difference of the diode resistance, when the reverse and forward voltages are applied for the semiconductor material with $\tau_{\mathcal{E}}$ independent of electron density on energy. In the case of the flat point contact semiconductor structure and in the case of the planar asymmetrically necked semiconductor structure this difference can be expressed, respectively, as follows

$$\Delta R=R_2-R_1=\frac{8V\rho\mu_0[\tau_{\mathcal{E}}(1+s)+\tau_M]}{3\pi^2r_0^3}, \tag{10}$$

$$\Delta R = \frac{4V\rho\mu_0 \tan\alpha_1 [\tau_{\varepsilon}(1+s)+\tau_M]}{3hd^2 \ln(1+a/d)}, \qquad (11)$$

where s denotes the index of power dependence of electron momentum relaxation time, τ_M is the Maxwell relaxation time in n-region, d is the widths of the semiconductor structure in the narrowest part and a is that in the widest part of the planar diode, respectively; α_1 is the widening angle of n region; h stands for the thickness of the structure and ρ for the resistivity of the semiconductor material. In obtaining (10) and (11) the electron heat conductivity in (3), and the voltage drop in n^+-region were neglected. The former assumption is true in the case of graded n-n^+- junctions, when the width of those exceeds electron cooling length [3]. The last expressions show that the resistances difference is direct proportional to applied voltage. On the other hand, when the relaxation of average energy of hot electrons can be neglected, i.e. $(\omega\tau_{\varepsilon})^2 << 1$ (ω is angular frequency of MW field) and conductivity current exceeds displacement one, the voltage sensitivity of the detector with n-n^+- junction is related to the current-voltage (I-V) characteristics asymmetry as [7]

$$S = U_d / P = \Delta R / 2V, \qquad (12)$$

where U_d is the detected signal, P is the MW power which the detector have absorbed.

Experimental results

The dc measurements of I-V characteristics of both the point contact and the planar diodes at room (T=300 K) and liquid nitrogen (T=80 K) temperatures have shown that the quality of investigated n-n^+- structures was good enough to verify the theoretical results presented above. Fig. 2 depicts the experimental dependences of the relative resistances difference on applied voltage of point contact diode at room (light dots) and liquid nitrogen (dark dots) temperatures. In the figure the theoretical dependences obtained from (10) are presented also. The values of electron energy relaxation time at T=295 K and T=80 K were taken from [8]. At liquid nitrogen temperature the relative resistances difference of the diode is greater than that at the room temperature for the same value of applied voltage. It is connected with the higher value of electron mobility and energy relaxation time in n- GaAs at T=80 K in comparison with those at room temperature. The good agreement of theoretical and experimental straight lines enables to determine energy relaxation time of electrons in n-GaAs in wide temperature range from the slope value of the experimental lines. We determined the temperature dependence of τ_{ε} by such a way [9], and have found a good agreement of results with those by other authors.

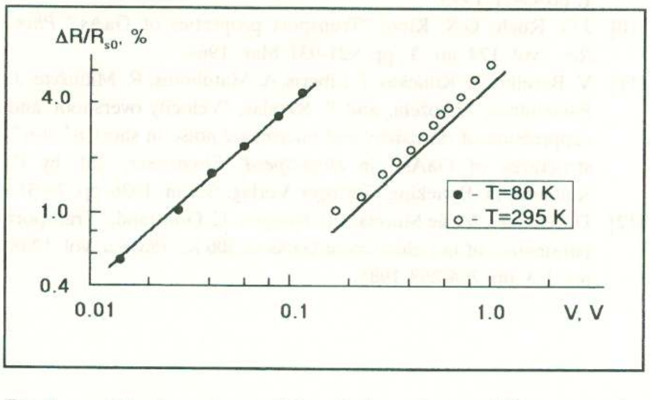

Fig. 2. The dependence of the relative resistance difference on the applied voltage of point contact diode

Using the microwave electric field, the dependence of the detected signal on the applied MW power was measured at room and liquid nitrogen temperatures. When the MW power is small (the electrons are slightly heated by the electric field) the value of the detected signal is directly proportional to the microwave power. Therefore, those semiconductor structures may be used as the measurement element of MW power. The volt-power characteristic at room temperature is linear in wider range of MW power than that at liquid nitrogen temperature. This is associated with the fact that at T=295 K τ_{ε} depends slightly on the instantaneous value of the MW electric field strength E_m, whereas at liquid nitrogen temperature the electron energy relaxation time decreases rapidly with E_m increase.

The measurement of the detected signal of diode at room temperature in stronger MW electric fields have been shown, that the volt-power characteristic becomes superlinear in contrast to the diodes fabricated on the base of Ge and Si. The voltage sensitivity of GaAs diodes increases with the absorbed MW power, reaches a maximum and then starts to decrease. The dependences of the relative voltage sensitivity S/S_0 (S_0 is sensitivity in the warm electron region) on E_m are shown in Fig. 3. The electric field strength in the n-region near the flat n-n^+- junction may be expressed as

$$E_m = \frac{4V}{\pi r_0} = \frac{4\sqrt{2R_s P}}{\pi r_0}. \qquad (13)$$

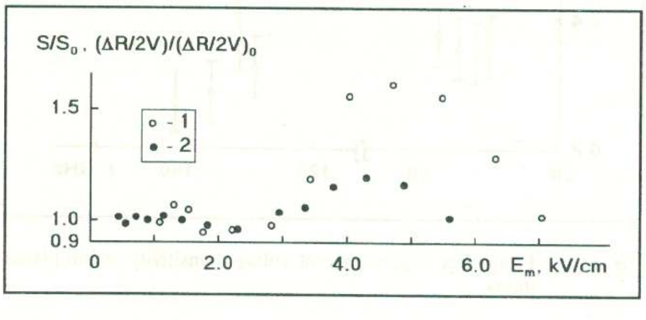

Fig. 3. Dependences of the voltage sensitivity (1) and I-V characteristics asymmetry (2) of the point contact diode on the electric field strength

In the same figure the dependence of quantity $(\Delta R/2V)/(\Delta R/2V)_0$ on the electric field strength in the n-n$^+$-junction is shown ($(\Delta R/2V)_0$ is the asymmetry value in the small electric field). As it is seen from the presented curves, the sensitivity and the I-V characteristics asymmetry of the point contact diode has a maximum near E_m=4.5 kV/cm. In addition, the relative increase of I-V characteristic asymmetry is somewhat greater than the increase of the diode voltage sensitivity in the MW electric field. The former increase could be explained by an enhancement of the electron diffusion coefficient in strong electric field, established by time-of-flight method [10] and from noise temperature measurements [11,12]. It is interesting to note that in some samples we observed non-monotonicaldependences of the voltage sensitivity and I-V characteristics asymmetry on electric field strength. If in stronger electric fields these parameters increase, then in lower electric fields the slight trend to decrease is noticeable. Such a peculiarity also observed in [11] for the spectral density of the current fluctuation, which was attributed to the decrease of electron diffusivity in short n$^+$-n-n$^+$-structures of GaAs. From the foregoing it may be concluded, that the increase of the voltage sensitivity of the diode based on the small area GaAs n-n$^+$-junction account for both electron energy relaxation time and the diffusion coefficient increase in strong electric field.

Frequency dependence of voltage sensitivityof the planar diode at room temperature is shown in Fig. 4. The insignificant decrease of voltage sensitivity (the value of that at f=140 GHz is 20% lower than at f=26 GHz) is not predicted by theoretical frequency dependence of voltage sensitivity for this frequency range and for the diode based on n-GaAs with those electrical parameters. This decrease could be explained by means of waveguide features, which determines the value of absorbed MW power of diode, consequently the value of voltage sensitivity.

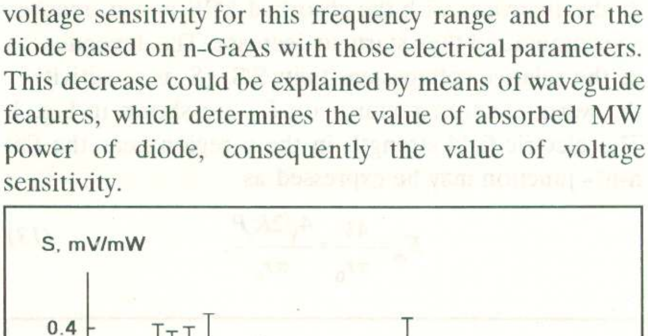

Fig. 4. Frequency dependence of voltage sensitivity of the planar diode

Conclusions

i. The voltage sensitivityof the diode based on small area GaAs n-n$^+$-junction increases with electric field strength due to the increase of both the electron energy relaxation time and the diffusion coefficient.

ii. The voltage sensitivityof the planar diode based on the asymmetrically necked n-GaAs structure with n-n$^+$-junction weakly depends on frequency within 26÷140 GHz.

iii. Those results, in our opinion, are important for practical purpose, since the dynamic and frequency range of the diode based on GaAs n-n$^+$-junction may be extended.

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