Detectors of Microwave and Terahertz Radiation on the Basis of Semiconductor Nanostructures

Steponas Ašmontas#1, Viktorija Kazlauskaitė#2, Algirdas Sužiedėlis#3, Jonas Gradauskas#4, Edmundas Širmulis#5, Vadim Derkach*6

 # Semiconductor Physics Institute

A.Goštauto 11, LT-01108 Vilnius, Lithuania

vika@pfi.lt

**Institute of Radiophysics and Electronics NAS of Ukraine*

12 Ac. Proskura St., 61085 Kharkov, Ukraine

***Abstract*— Experimental results of electromagnetic radiation detection in wide frequency range using planar diode having asymmetrically necked semiconductor structure are presented. Electromotive force is induced across the diode due to nonuniform free carrier heating under the action of radiation. MBE grown selectively doped AlGaAs/GaAs as well as AlGaAs/InGaAs/GaAs structures are used for fabrication of the planar diodes. Voltage-power characteristics of the diodes are measured in frequency range from 10 GHz up to 3 THz.**

I. Introduction

Fast development of microwave (MW) electronics stimulates creation of new detectors operating in very broad frequency band, ranging from GHz up to THz frequencies. Widely used whisker-contacted semiconductor diode is unsuitable to detect high frequency MW radiation due to comparatively large size of the point contact diode in respect of small dimensions of a waveguide [1].

Therefore we propose a planar semiconductor diode in which both terminals are lying on the same surface of a semiconductor wafer. The diode operates on the basis of nonuniform electron heating by MW electric field, and this is realized using asymmetrically necked thin semiconductor film (see Fig. 1) where bigradient electromotive force is induced [2].

Usually, the narrower part of the structure is highly doped to reduce the resistance of the diode [1]. In this case the detected voltage consists of both the bigradient and hot carrier thermoelectric forces.

In this paper we present the results of investigation of detection properties of MW detectors fabricated on the base of selectively doped AlGaAs/GaAs and AlGaAs/InGaAs/GaAs heterostructures. The measurements were carried out in frequency range 10 GHz – 3 THz at room and liquid nitrogen temperatures.

II. Theoretical Consideration

Theoretical analysis on the operation of the planar diode in MW electric field is based on solution of phenomenological current density, heat balance, heat flow density, current continuity, and Poisson equations. Then, the expression for voltage sensitivity of the planar diode can be written as [1]:

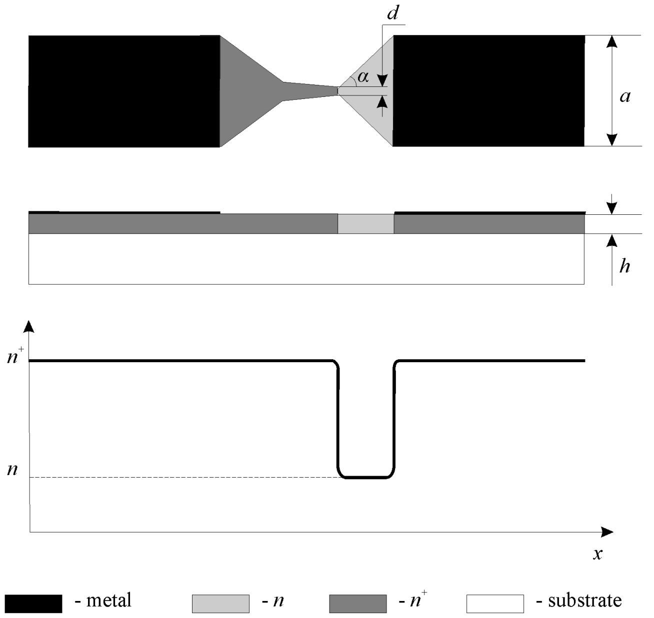

Fig. 1 Schematic view of planar diode and electron distribution in epitaxial layer.

$$S = \frac{U_d}{P_i} = \frac{1}{3}\frac{R_{sh}^2}{d^2 R_{s0}}\frac{P}{P_i}\mu_0 N\left(\omega, \tau, \tau_M^n, \tau_{\varepsilon}\right), \qquad (1)$$

where P_i is the incident MW power and P is the power absorbed by the diode. R_{sh} stands for the sheet resistance of n-region, d denotes width of the semiconductor structure in the narrowest part of the planar diode, and R_{s0} is the geometric resistance of the diode which is expressed as follows:

$$R_{s0} = \frac{R_{sh}}{2\tan\alpha_1}\ln\left(1+\frac{a}{d}\right), \qquad (2)$$

where a denotes width of the widest part of the semiconductor structure, and α_1 is the widening angle of n-region. Factor N denotes a parameter which determines dependence of U_d on frequency. When electron energy relaxation time is independent of electron density in semiconductor, N is expressed as:

$$
\begin{aligned}
N = {} & \frac{1}{1+(\omega\tau)^2}\,\frac{1+\left(\omega\tau_M^n\right)^2}{\left(\omega\tau_M^n\right)^2}\times \\
& \times\left\{\tau_{\mathscr{E}}\left[1+\frac{s^2}{1+(\omega\tau_{\mathscr{E}})^2}\right]\ln\left[1+\left(\omega\tau_M^n\right)^2\right]+\right. \\
& +\tau_M^n\left[\frac{3}{2}-\frac{s(1-s)(\omega\tau_{\mathscr{E}})^2}{1+(\omega\tau_{\mathscr{E}})^2}\right]\times \\
& \left.\times\left[\frac{1}{\omega\tau_M^n}\arctan\omega\tau_M^n-\frac{1}{1+\left(\omega\tau_M^n\right)^2}\right]\right\}+ \\
& +\frac{s(1-s)\tau_{\mathscr{E}}}{1+(\omega\tau_{\mathscr{E}})^2}\,\frac{1}{1+(\omega\tau)^2}
\end{aligned}
\quad , \qquad (3)
$$

here ω is angular frequency of MW electric field, τ_M^n is Maxwell relaxation time in n-region, $\tau_{\mathscr{E}}$ denotes electron energy relaxation time, τ stands for electron momentum relaxation time, s is the dependence of electron momentum relaxation time on power.

Equation (1) shows that sensitivity of the planar diode can be increased reducing the narrowest part d of the diode and using materials or structures having higher mobility of charge carriers. Decreasing d increases geometrical resistance of the diode (see equation (2)), therefore more narrowed part of the diode is usually doped heavily (see Fig. 1). The use of selectively doped heterostructures benefits voltage sensitivity as the mobility of free electrons is increased. In such structures electrons are confined within several nanometres near the interface forming two dimensional electron gas (2DEG).

III. Samples and Experimental Technique

Molecular beam epitaxy (MBE) grown selectively doped AlGaAs/GaAs and pseudomorfic AlGaAs/InGaAs/GaAs structures were used to fabricate the planar diodes. Two types of selectively doped AlGaAs/GaAs structures were grown: one, with δ-doped AlGaAs layer (Fig.2. (a)) and another, with homogeneously doped AlGaAs layer (Fig.2. (b)). 2DEG channel is formed in the vicinity of the interface in i-GaAs layer. 2DEG channel in pseudomorphic AlGaAs/InGaAs/GaAs structure was formed by incorporating strained quantum well of InGaAs (Fig. 2 (c)).

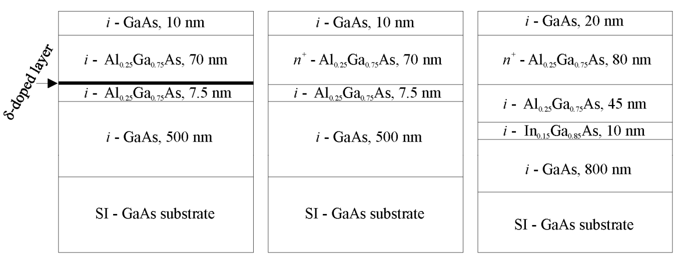

Fig. 2 Molecular beam epitaxy grown selectively doped AlGaAs/GaAs structure with δ-doped barrier layer (a), with homogeneously doped barrier layer (b) and pseudomorphic AlGaAs/InGaAs/GaAs structure (c).

Application of microwave diodes in high frequencies requires planar design with both contacts distributed on the same plane of the diode. Moreover, lateral dimensions of the diode of hundreds of micrometers range specifies its micrometric thickness for easy and reliable mounting in single mode waveguide of millimetre wavelength range. We have investigated two types of diodes: "crystal" diodes fabricated on crystal substrate and "filmy" ones on an elastic polyimide film (see Fig. 3). The "filmy" diode had dimensional advantage against the "crystal" diode. Moreover, due to low dielectric constant of the polyimide ($\varepsilon = 2\div3$) a quasi-free-standing design of microwave diode can be achieved, and the displacement microwave currents that could shunt the active region through the substrate can be suppressed. This property benefits in higher voltage sensitivity of the "filmy" diodes in comparison with that of the "crystal" ones.

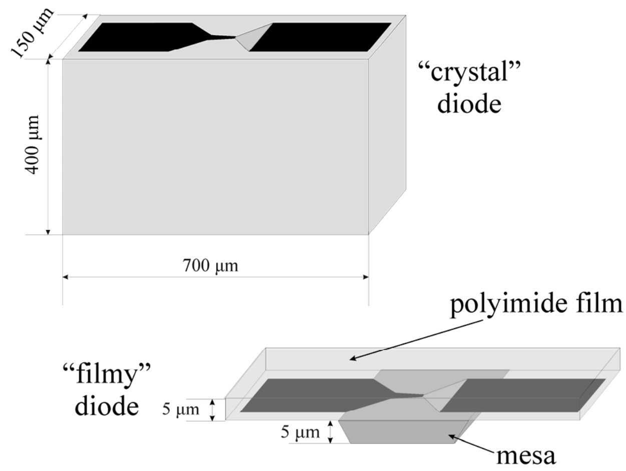

Fig. 3 Schematic view of planar MW diode on a crystal substrate ("crystal diode") and on an elastic polyimide film ("filmy" diode).

Fabrication process of the diodes starts with photolithography process by forming mesa shape of the asymmetrically configured structure. The mesa is formed using wet etching of the active layer down to the semiconductor substrate. Second photolithography process is done to form metallic contacts. Ni/Au/Ge/Ni/Au layers are evaporated thermally in the vacuum of approximately 3×10^{-6} torr. The thickness of the metal layers is 10 nm/200 nm/100 nm/70 nm/200 nm, respectively. The pattern of metal contacts is formed by lift-off technique. Rapid thermal annealing of the contacts is performed at 430^0C temperature in forming gas atmosphere. The quality of ohmic contacts is controlled by transmission line method. Fabrication process of the "crystal" diodes is finished after this step and the "filmy" diodes are processed further. Polyimide is spun down on the surface of diodes matrix and then annealed for one hour in the air. The back-thinning of the semiconductor substrate is performed after sticking it onto glass plate. The last photolithography process forms the patterns for the following deep mesas etching and exposing the metal contacts from the substrate side.

We have fabricated the "crystal" diodes using AlGaAs/GaAs structures with homogeneously doped barrier and pseudomorphic AlGaAs/InGaAs/GaAs structures; and the "filmy" diodes using AlGaAs/GaAs structures with δ-doped and homogeneously doped barrier.

The dimension of the narrowest part of the asymmetrically shaped structure was about 5÷7 μm for pseudomorphic AlGaAs/InGaAs/GaAs structure and in the range of 1÷3 μm for AlGaAs/GaAs structure.

The wafers of the "crystal" diodes array were sliced into separate diode units, and then Au wires were bonded to each metallic ohmic contact by thermo-compression technique. The diodes were mounted into a universal rectangular waveguide head.

The array of the "filmy" diodes was divided into single diodes that were mounted into a universal rectangular waveguide head using conductive epoxy resin.

For measurements we have employed different types of sources. In the microwave region at 10 GHz we used magnetron generator, from 26 GHz to 37 GHz we used klystron generator, within 78 GHz÷120 GHz –backward wave oscillator was used. The microwave signals were modulated by rectangular pulses from tenth to several microseconds at repetition rate of 40 Hz to avoid crystal lattice heating. The radiation in THz frequency range (from 0.58 THz to 3 THz) was generated by an optically pumped FIR molecular laser.

IV. Results and discussion

Voltage power characteristics of the "filmy" AlGaAs/GaAs diodes with homogeneously and δ-doped barriers at room and liquid nitrogen temperatures are shown in Fig. 4.

The detected voltage linearly depends on MW power of both types of the diodes at room and liquid nitrogen temperatures. Voltage sensitivity of the diode having homogeneously doped barrier is 0.3 V/W at room temperature and increases to about 20 V/W at liquid nitrogen temperature.

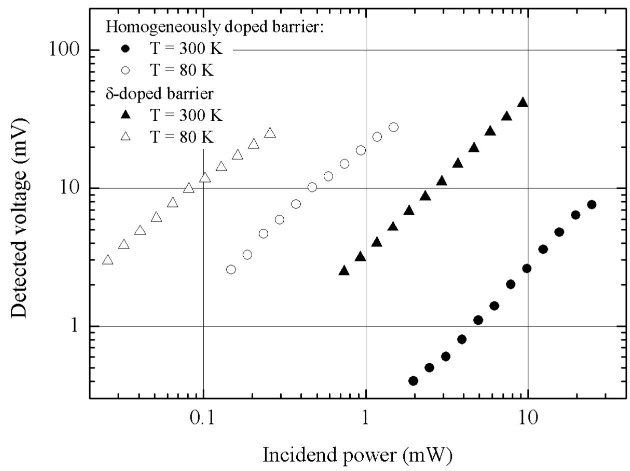

Fig. 4 Voltage power characteristics of the planar "filmy" diodes on the base of AlGaAs/GaAs structures with homogeneously (circles) and with δ-doped (triangles) barrier layers at room (solid symbols) and liquid nitrogen (open symbols) temperatures.

Planar diode having δ-doped barrier layer demonstrates voltage sensitivity of 2 V/W at room temperature and up to 120 V/W at liquid nitrogen temperature. Higher sensitivity of both diodes at liquid nitrogen temperature is caused by higher electron mobility and electron energy relaxation time. Planar diodes on the base of AlGaAs/GaAs structures with δ-doped barrier layer have higher sensitivity due to higher electron mobility as the thickness of the doped layer is decreased [4].

Frequency dependences of the voltage sensitivity of the planar AlGaAs/GaAs diodes with homogeneously doped barrier layer having different width of the narrowest part are depicted in Fig. 5.

Voltage sensitivity increases from 0.2 V/W up to 2 V/W as the narrowest part of the planar diode is narrowed from 3 μm down to 1 μm. Experimentally obtained voltage sensitivity does not change in the 26 GHz to 120 GHz frequency range.

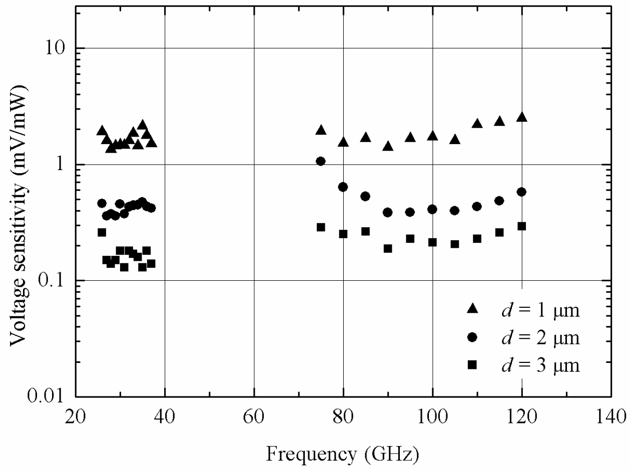

Fig. 5 Frequency dependence of voltage senility of the planar "filmy" diode on the base of AlGaAs/GaAs structure with homogeneously doped barrier.

Voltage sensitivity values from GHz up to THz frequencies of "filmy" AlGaAs/GaAs diode with δ-doped barrier are depicted in Fig. 6.

Calculation shows that sensitivity of the planar diode does not change with frequency up to 60 GHz and begins to decrease at higher frequencies. When $\omega\tau >> 1$, the sensitivity decreases with ω according ω^{-2} (see equation (3)).

However, experiment shows that S is nearly constant at microwave frequencies range (25 GHz – 120 GHz) but at THz frequencies (0.7 THz – 3 THz) it decreases more rapidly than theory predicts. We associate this decrease with significant change of absorbed power by the diode.

The increase of electron mobility can be implemented by employing the pseudomorphic selectively doped AlGaAs/InGaAs/GaAs structures containing single $In_{0.15}Ga_{0.85}As$ layer. These heterostructures benefit from higher electron mobility and saturation velocity in the InGaAs quantum well channel accompanied by better confinement properties and higher two-dimensional electron gas density when compared to conventional AlGaAs/GaAs heterostructures [5].

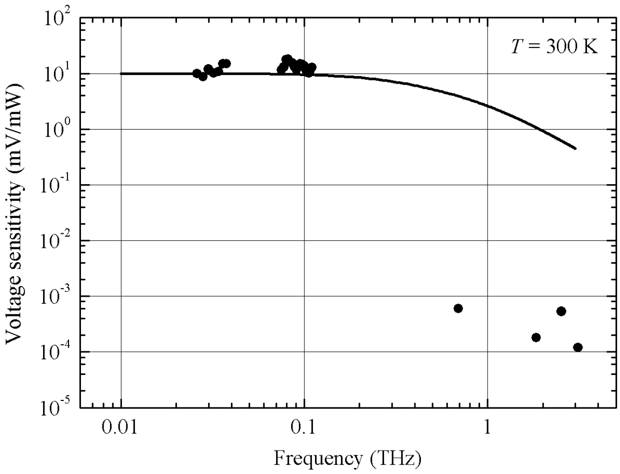

Fig. 6 Frequency dependence of voltage sensitivity of planar 'filmy" diode with asymmetrically shaped n-n$^+$ junction on the base modulation doped structure with δ-doped barrier. Points are experimental values, solid line – theoretical calculation.

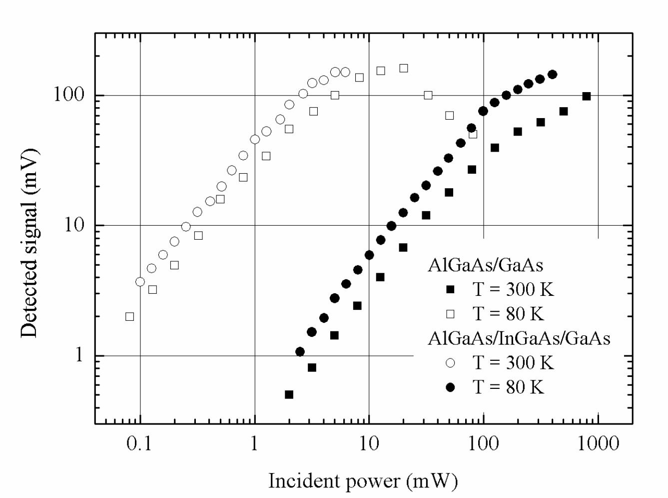

Fig. 7 Dependences of the detected voltage on microwave power of planar "crystal" diodes on the base of AlGaAs (squares) and on the base of AlGaAs/InGaAs/GaAs (circles) at room (solid symbols) and liquid nitrogen (open symbols) temperatures.at 10 GHz frequency.

Detected voltage dependences on microwave power of the "crystal" pseudomorphic diode are presented in Fig. 7. The experiment shows that the detected signal behaves linearly at low values of microwave power. Decrease of the lattice temperature greatly influences the sensitivity of the device: at 300 K it is about 0.6 V/W, while at liquid nitrogen temperature the value reaches 38 V/W, i. e. it increases more than 60 times. Comparing this number with the relative change of electron mobility with temperature one can infer that this effect is mainly responsible for the observed rise in the voltage sensitivity.

For comparison, the detected voltage dependences on MW power of the planar "crystal" diode on the base of homogeneously doped AlGaAs/GaAs structure are presented in Fig. 7 too. It is seen, that its sensitivity is lower twice than that of pseudomorphic AlGaAs/InGaAs/GaAs diode. Nonmonotonic character of the voltage power characteristics observed at high MW powers is caused by origination of negative differential resistance in *n*-GaAs layer due to the Gunn effect [3].

V. Conclusion

The results of investigation of properties of the planar diodes fabricated on the base of selectively doped AlGaAs/GaAs structures with δ- and homogeneously distributed doping impurities in the AlGaAs layer show that the diodes can be used to detect microwave radiation in wide frequency range. Reduction of barrier layer doping thickness benefits voltage sensitivity of the planar diode increasing it almost 10 times.

Voltage – power characteristic of planar diode is linear at low values of microwave power. Insertion of strained quantum well in the interface of AlGaAs/GaAs increases voltage sensitivity of the planar diode twice.

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References

[1] S. Ašmontas and A. Sužiedėlis, "New microwave detector," *Int. Journ. Infr. Millimeter Waves*, vol. 15, pp. 525-538, 1994.

[2] Steponas Ašmontas, *Electrogradient phenomena in semiconductor*, Vilnius, Lithuania: Mokslas Press, 1984.

[3] S.Ašmontas, J.Gradauskas, D.Seliuta, A.Sužiedėlis, E.Širmulis, and G.Valušis, "Application of Hot-Carrier Thermo-Electromotive Force for Measurement of Pulsed Microwave and Infrared Radiation," *J. of Thermoelectricity*, N4, pp.15-28, 1998.

[4] E. F. Schubert, L. Pfeiffer, K. W. West, and A. Izabelle, „Dopant distribution for maximum carrier mobility in selectively doped $Al_{0.3}0Ga_{0.70}As$/GaAs heterostructures," *Appl. Phys Lett.,* vol. 54, pp. 1350 – 1352, 1989.

[5] K. T. Chan, M. J. Lightner, G. A. Patterson, and K. M. Yu, "Growth studies of pseudomorphic GaAs/InGaAs/AlGaAs modulation-doped field-effect transistor structures," *Appl. Phys. Lett.*, vol. 56, pp. 2022 – 2024, 1990.