The diode heterostructures for THz devices

D. G. Pavelyev*, A.P.Vasilev[2], V.A. Kozlov [1,3], E.S.Obolensky[1], S.V.Obolensky [1], V.M. Ustinov [4]
[1]*Lobachevsky State University, Nizhny Novgorod, Russia*
[2] *SHM R&E Center, RAS, Saint Petersburg, Russia*
[3]*IPM RAS, Nizhny Novgorod, Russia*
[4]*Ioffe Institute, Saint Petersburg, Russia*
*Contact: pavelev@rf.unn.ru

Abstract. – **Planar diode structures with small area active region (~ 1 μm²) based on highly doped GaAs / AlAs superlattices are investigated. The possibility of effective application of such diodes in the terahertz (THz) frequency range is discussed. Monte Carlo simulation of electron transport in 6-period superlattices was carried out. The possibility of increasing the operating frequencies of devices on superlattices by optimizing their parameters and selecting the appropriate diode design is discussed.**

At present time, big interests to high resolution gas spectroscopy in the terahertz (THz) frequency range were observed. Nowadays, the quantum-cascade laser (QCL) is very promising source for spectroscopy. For stabilization of QCL frequency, uncooled harmonic mixers with Schottky planar diodes [1] and superlattice (SL) diodes are currently used [2, 3]. The usage of highly doped SL diodes gives the possibility to stabilize the operating frequencies up to several terahertz [3]. It was shown [4] the possibility of such diodes allow receiving a signal at harmonics up to 8 THz. In [2], a theoretical and experimental comparison of the parameters of the 18- and 6-period superlattices was made. The advantages of usage of small number of periods in terahertz SL diodes were demonstrated.

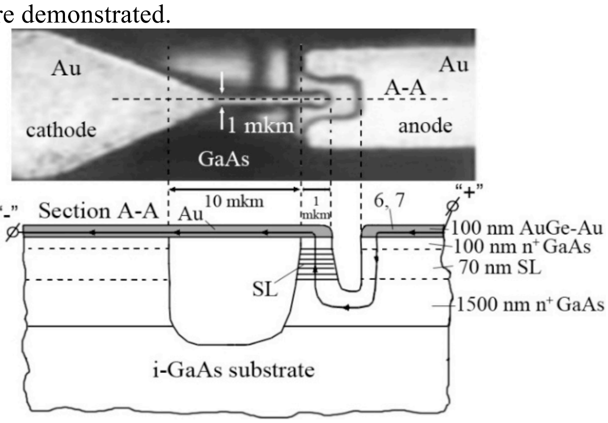

Fig. 1. Design of the planar diode heterostructure. Label "SL" and hatching marked the working area of the diode. Diode working area means the place of high current density flow. This area determines the external parameters of the diode. The heterostructure parts with low current density do not play a fundamental role in the operation of the diode. They are not hatched and are not marked with the label "SL".

In this paper, the transport of electrons in SL is studied by the simulation of electrons motion in the quasihydrodynamic approximation [5] and by the Monte Carlo method [5, 6]. The results of calculations point to the possibility of increasing the operating frequencies of small period SL diodes using the optimization of their parameters and design. For investigation the SL consisted of heterostructure with 6-periods GaAs/AlAs was prepared (Fig. 1). The heterostructure were grown by molecular-beam epitaxy in a Riber 32P unit on semi-insulating GaAs substrates with the (100) orientation. The growth rates of the binary components AlAs and GaAs were calibrated by the observation of x-ray sweep curves at a wide angle near the reflex (004) from the GaAs / AlAs test superlattices. The growth rates were about 1 monolayer / s for GaAs and 0.5 monolayer / s for AlAs. Si was used as the doping impurity.

Figure 1 shows the picture of the planar diode structure. The upper part of the picture is the top view photo. The lower part of the picture is the section A-A. The label «SL» indicates the diode working area, formed by liquid etching. The arrows in the figure show the channel of current flow in the diode: through the metal contact of the cathode, through the diode working area, and then into the metal contact of the anode.

To simulate electron transport in small-period SL, the quasi-hydrodynamic approximation and the Monte Carlo method [6] were applied, and the band diagram of the superlattice was taken into account.

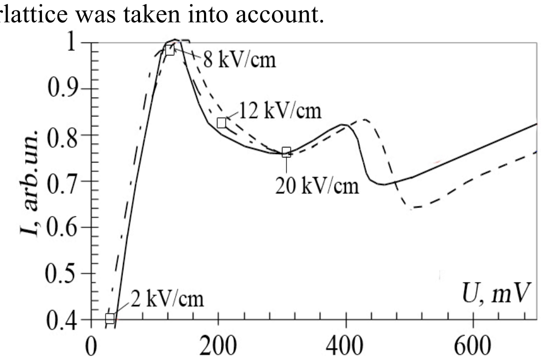

Fig. 2. Experimental line (solid line), inverse (dotted line) and calculated (dash-dotted) volt-ampere characteristics for 6-period SL. The abscissa represents the total voltage applied to the diode. The ratio of the field strength in the superlattice and the external supply voltage was determined by taking into account the resistance of the contacts. The figure shows the applied field to the diode.

Fig. 2 shows experimental and calculated volt-ampere curve for a 6-period superlattice. Two areas are observed for each polarity of voltage: the first area - the ohmic type current flow, the second area – is negative differential conductivity (NDC) which consists of two characteristic areas: first voltage «drop» and second voltage «drop». One can be seen that the values of the corresponding voltage «drops» for forward and reverse bias are different.

It is necessary to note, that ballistic electrons may produce additional dynamic negative differential conductivity in the THz frequency range [7, 8, 9]. Structures on superlattices consisting of 14, 16, 18, 20 monolayers of GaAs and 2, 4, and 6 monolayers of AlAs were investigated theoretically.

The produced 6-period (18x4 monolayers) diode structures were studied experimentally in harmonic mixers of the frequency range 0.2-4.76 THz. Harmonic mixers were used in a precision terahertz spectroscopy apparatus in which a frequency comb was used as the source, excited by femtosecond laser pulses [10, 11], as well as gas and quantum-cascade lasers. The conversion losses for the second (300 GHz, 12 dB) and fourth (450 GHz, 20 dB) LO harmonics on the backward wave tube were determined.

Figure 3 shows a block diagram of a heterodyne receiver with a harmonic mixer based on the investigated diode, where 1 is the pump waveguide (WR-06) with a comb line, 2 - the place where the diode is connected to the output waveguide with a cut-off frequency more than 800 GHz , 3 – the diagonal horn. The investigated beat signal between the harmonics arising in the diode under the influence of pumping and the signal from the terahertz source are fed to the intermediate frequency amplifier and then to the spectro-analyzer.

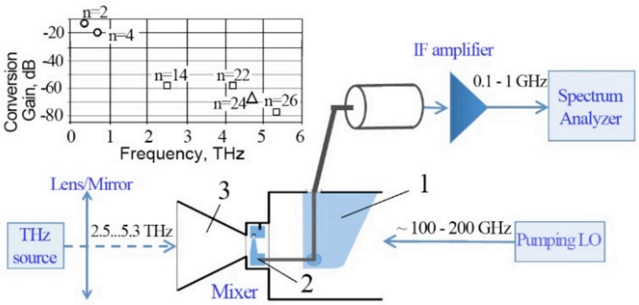

Fig. 3 Block diagram of a heterodyne receiver with a harmonic mixer based on the investigated diode, where 1 is the pump waveguide (WR-06) with a comb line, 2 - the place where the diode is connected to the output waveguide with a cut-off frequency more than 800 GHz , 3 - diagonal horn. The inset shows the dependence of the conversion coefficient on the frequency of the signal for the diode from 6-period superlattice. This dependence was measured using several sources of a terahertz signal: frequency comb excited by a femtosecond laser (n = 2.4); gas laser on CH_3OH (n = 14, 22, 26); and QCL (n = 24). The digits (2,4, ... 26) on the sidebar indicate the numbers of harmonics used by the harmonic mixer pumped from the local oscillator at a frequency of 0.1 - 0.2 THz.

The conversion losses were compared for mixers made on planar diode structures containing superlattices with 18 and 6 periods. A significant difference in the conversion parameters of the fabricated structures was noticed during usage them in phase-stabilization systems of the frequency of quantum cascade lasers at frequencies above 3 THz. Structures with six periods have a conversion loss of 20 dB less, and were successfully applied to stabilize the frequency of such lasers at 4.7 THz [12].

Application of external DC bias leads to arising of self-oscillation in the investigated planar structures. The frequencies of self-oscillation in the SL structures were measured. For the measurements, a similar block diagram was used (Fig. 3), in which DC bias was applied to the mixing diode. The self-oscillation power was measured from the back output of the pump waveguide using a Fourier transform spectrometer with a cryogenic Bolometer as a receiver. Measured frequencies of self-oscillation were 0.25 THz for positive bias and 0.18 THz for negative bias. The maximum power was observed when the operating point was selected in the region of the second "drop" at a bias voltage of ± 500-600 mV.

The difference in the generated frequencies for opposite bias voltages is explained by the fact that the equivalent circuit for the planar diode structure contains capacitance and inductance, which form a serial low-Q circuit. The frequency of the serial resonance is given by: $f = \frac{1}{2\pi\sqrt{LC}}$, where L is the inductance of the supply conductor, and C is the capacitance of the SL. Since the inductance L of the input does not change for opposite polarities of bias voltage, then, the change in frequency is explained by a change of the capacitance by a factor of two, which is due to the difference of the conical shape working area (see Figure 1). Conical shape appears during the formation procedure of diodes by liquid etching.

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References

[1] A. Danilov, N. Erickson, A. Light, and J. Waldman, "Phase locking of 2.324 and 2.959 terahertz quantum cascade lasers using a Schottky diode harmonic mixer", *Opt. Lett*., Vol. 40, p.5090, 2015.

[2] D.G. Pavelyev, A.P. Vasilev, V.A. Kozlov, Yu.I. Koshurinov, E.S. Obolenskaya, S.V. Obolensky, and V.M. Ustinov, "Diode heterostructures for terahertz frequency range devices", *Zh. Radioelektron.*, No. 1, p. 1, 2016.

[3] D.G. Pavelyev, N.V. Demarina, Yu.I. Koshurinov, A.P. Vasilev, E.S. Semenova, A.E. Zhukov, and V.M. Ustinov, "Characteristics of planar diodes based on heavily doped GaAs/AlAs superlattices in the terahertz frequency region", *Semiconductors*, vol. 38, p.1105, 2004.

[4] D.G. Pavelyev, Yu.I. Koshurinov, A.S. Ivanov, A.N. Panin, V.L. Vaks, V.I. Gavrilenko, A.V. Antonov, V.M. Ustinov, and A.E. Zhukov, "Experimental study of frequency multipliers based on a GaAs/AlAs semiconductor superlattices in the terahertz frequency range", *Semiconductors*, vol. 46, p.121, 2012.

[5] E.S. Obolenskaya, A.Yu. Churin, S.V. Obolensky, V.I. Shashkin, and A.V. Murel', "On the radiation resistance of planar Gunn diodes with delta-doped layers", *Semiconductors*, vol. 49, p. 1459, 2015.

[6] S.V. Obolensky, A.V. Murel, N.V. Vostokov and V.I. Shashkin, "Simulation of the Electron Transport in a Mott Diode by the Monte Carlo Method", *IEEE Trans. on Electron Devices*, vol. 58, №8, p.2507, 2011.

[7] V.A. Kozlov, A.B. Kozyrev, A.V. Samokhvalov. "Population inversion and negative differential conductivity in GaN based heterostructures at terahertz frequencies", *XXVI Workshop on Compound Semiconductor Devices and Integrated Circuits held in Europe*, Chernogolovka, Russia, 21-25 May, p.157, 2002.

[8] V.A. Kozlov, A.B. Kozyrev, A.V. Samokhvalov. "Inverse population and the possibility of radiation generation in nano method structures based on GaN", *Bulletin of the Russian Academy of Sciences. Physics*, vol. 67, №2, p. 265, 2003.

[9] V.A. Kozlov, A.V. Nikolaev, A.V. Samokhvalov. *Semiconductor Science and Technology*, "The population inversion and the terahertz negative differential conductivity induced by hot carriers transit time effects in coordinate and momentum spaces", vol. 19, S99, 2004.

[10] A.V. Khudchenko, D.J. Hayton, D.G. Pavelyev, A.M. Baryshev, J.R. Gao, T.-Y. Kao, Q. Hu, J. L. Reno, and V.L. Vaks, "Phase Locking a 4.7 THz Quantum Cascade Laser using a Super-Lattice Diode as Harmonic Mixer", in *Proceedings of the 39th International Conference on Infrared*, Millimeter, and Terahertz Waves IRMMWTHz, Tucson, Arisona, Sept. 14–19, 2014.

[11] D.G. Pavelyev, A.S. Skryl, and M.I. Bakunov, "High-resolution broadband terahertz spectroscopy via electronic heterodyne detection of photonically generated terahertz frequency comb" *Opt. Lett.*, p. 5669, 2014

[12] A.S. Skryl, D.G. Pavelyev, M.Y. Tretyakov, and M.I. Bakunov, "High-resolution terahertz spectroscopy with single tunable frequency comb" *Optics Express 22*, p. 22537, 2014.