Electronic Tunneling and Electric Domains in GaAs/AlAs Superlattices at Room Temperature

I. V. Altukhov[1], M. S. Kagan[1], S. K. Paprotskiy[1], N. A. Khvalkovskiy[1],
I. S. Vasil'evskii[2], A. N. Vinichenko[2]

[1]V.A. Kotel'nikov Institute of Radio Engineering and Electronics, Russian Ac. Sci., Moscow, Russia, kagan@cplire.ru
[2]National Research Nuclear University MEPhI, Moscow, Russia

One of the main problems in the development of semiconductor sources of the THz radiation is their operation at room temperature. Operation frequencies of room-temperature hot-electron bulk semiconductors such as Gunn diodes are limited by the time of development of the negative differential conductivity and the dielectric relaxation time. The former time in most semiconductors is usually in the range of picoseconds. The Maxwell relaxation time at the conventional doping level on the order of 10^{15}cm^{-3} is also $\sim 10^{-12}$ s. Therefore, the operation frequency band of hot-electron devices does not exceed 100–200 GHz. This limit is eliminated by using the laser scheme, when the energy of a photon is determined by the difference between energy levels with the inverse population and does not depend on the inertia of the conductivity relaxation. However, all THz semiconductor lasers operate at cryogenic temperatures. It is hardly possible to implement the population inversion at room temperature, since $kT = 25$ meV and the energy of THz photons is ~ 10 meV. Therefore, it is reasonable to search for systems with a negative high-frequency differential conductivity, which can excite oscillations in the corresponding cavity. Good examples are resonant-tunneling diodes, in which the generation frequency has been reached 1.92 THz [1]. Another suitable semiconductor systems are superlattices (SLs).

The electron transport in semiconductor SLs has been studied in detail in recent decades [2], mainly in connection with the predicted amplification of Bloch waves, which can make it possible to create tunable sources of THz radiation. The main hindrance to the Bloch wave amplification is the formation of electrical domains owing to the static negative differential conductivity (NDC) arising in superlattices at resonant tunneling between confined states in neighboring quantum wells [3]. The domain formation in superlattices eliminates the Bloch gain. On the other hand, the samples with the electrical domains can exhibit the dynamic NDC (the real part of electrical impedance is negative) in some frequency range (similarly to bulk materials [4-8]) and can be used for high-frequency generation in a suitable resonant cavity.

Superlattices for the THz range should satisfy several conditions. To get the short conductivity relaxation time, which is the time of tunneling in SLs, one has to use SLs with thin barriers. To prevent a thermal exchange with carriers between succeeding confined states in SLs, we need to have narrow quantum wells and the large band offset. For fast space charge redistribution in SLs with electric domains, the high doping level is needed to obtain the short dielec-

tric relaxation time. Here we present studies of tunneling electronic transport in short-period GaAs/AlAs superlattices (SLs) with electric domains.

The MBE grown GaAs/AlAs SLs consisted of 100 periods of 4 nm GaAs/2 nm AlAs between heavily doped ($\sim 10^{19} \text{cm}^{-3}$) n$^+$ cap layer and n$^+$ substrate. GaAs quantum wells (QWs) were Si doped with concentration of $2*10^{17} \text{cm}^{-3}$. The ring-shaped mesa structures with the diameters from 10 to 15 μm and 0.8 to 1.5 μm widths (Fig. 1) formed the distributed THz cavity with resonant frequencies corresponding to the free-space wavelengths from ~ 110 to ~ 170 μm. Triangular voltage pulses with a sweep-up times of 0.5 to 10 μs and sweep-down times up to 100 μs applied to the sample were used to record I-V curves. Measurements were performed at room temperature.
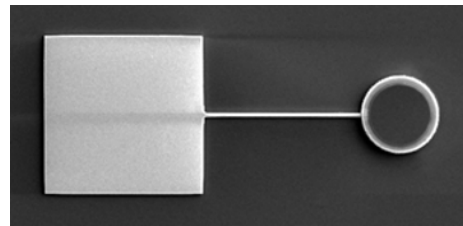

Fig. 1. View of the sample with the contact and current lead

The moving domains are formed at some threshold voltage and became apparent in a sharp decrease of current (up to 50% - Fig. 2). It was found that this threshold voltage changes considerably under the change of the cavity [9]. The cavity was changed by deposition of a droplet of conductive silver epoxy paste covering the entire top part of the mesa structure (see insets in Fig. 2). Fig. 2 shows the current–voltage
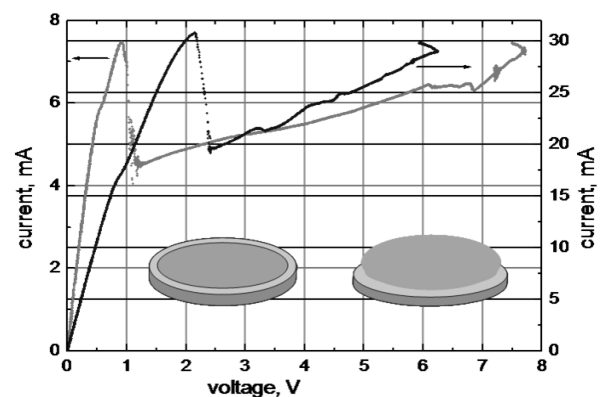

Fig. 2. Current–voltage characteristics of the GaAs/AlAs SLs under a change of the cavity: (lower curve) before and (upper curve) after the deposition of a droplet.

characteristics of the structure before and after the deposition of this droplet. The current through the sample after the deposition increased, what is natural because the contact area increased. In fact, the increase in the current approximately corresponds to the increase in the area. In addition, the threshold field of the domain formation changed, which was generally surprising because the thickness of the structure (the distance between current contacts) remained the same.

The possible origin of the change in the threshold field at changing the contact area is the appearance of an alternating field with sufficiently high amplitude in the cavity. Indeed, if an ac voltage of comparable amplitude is applied to the sample with a nonlinear current–voltage characteristic in addition to the dc voltage, an additional dc voltage appears because of the detection and shifts the operating point. Thus, this experiment indicates the excitation of THz oscillations in the cavity owing to the negative resistance of the superlattice with domains. We note that an analogous effect of an alternating electric field on the shape of direct current–voltage characteristics was observed in the bulk GaAs with the Gunn effect [10].

For not resonated structures, several features appeared in I-V curves (Fig. 3). First one is the hysteresis at forward and backward bias sweep. The size and shape of hysteresis loop depends on the peak voltage of the triangular pulse. The maximal loop observed when the current grows up to its peak value in the I-V curve. In this case the current saturation appears in some voltage range (Fig. 3), being essentially larger at bias sweep-down. The current saturation is due to static domain formation. So, the current hysteresis can be explained by a transition from moving to static field domain at sweeping the bias up and the return at its sweeping down. The large asymmetry of the transition times was found: the transition from travelling to static domain regime passes in a time shorter 0.1 microsecond, while the time of the reverse transition - from static to travelling domain regime – is ~100 microseconds. It is seen from I-V curves in Fig. 3 measured at different sweep-down duration. The long time is referred to deep impurities at the SL-buffer layer boundary.
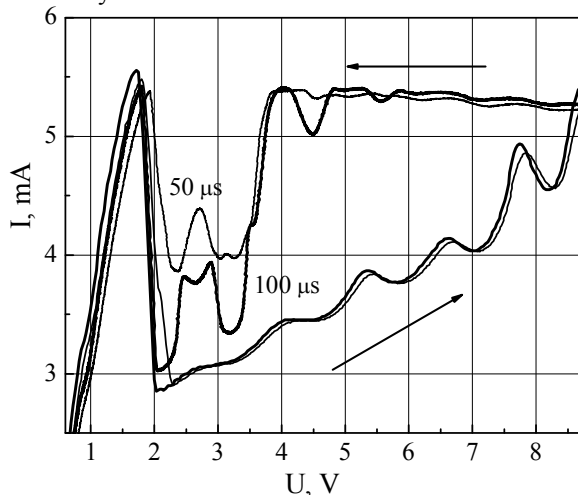

Fig. 3. I-V curves at different voltage sweep-down times

The second feature is the series of almost voltage-periodic maxima in current-voltage characteristics. The maxima are on a background of current rise in the mean. The current rise is evidence of triangular form of the domain: the negative charge at one of domain boundaries (in one quantum well) is due to free electrons with the concentration of more than one order larger than the donor concentration supporting the necessary field step, while the positive charge at opposite domain boundary is due to positively charged donors [11, 12]. The linear spatial grows of electric field inside the domain is just the result of donor depletion.

The positions of the maxima in the I-V curves did not depend on the frequency of THz cavity, they coincided at different ring cavity diameters, while essentially changed at cooling. The average period of the maxima at nitrogen temperature was by 1.5 times larger than that at room temperature. The origin of these maxima is attributed to the optical phonon assisted tunneling between quantum wells inside the triangular domain.

References

1. *Maekawa, T., Kanaya, H., Suzuki, S., Asada, M.* Oscillation up to 1.92 THz in resonant tunneling diode by reduced conduction loss // Applied Physics Express 2016. V. 9, No. 2. P. 024101

2. *Wacker, A.* Semiconductor superlattices: a model system for nonlinear transport // Physics Reports, 2002. V. 357, P. 1

3. *Klappenberger, F., Alekseev, K. N., Renk, K. F.*, et al. Ultrafast creation and annihilation of space-charge domains in a semiconductor superlattice observed by use of Terahertz fields // Eur. Phys. J. B 2004. V. 39, P. 483

4. *Thim, H. W.*, Linear microwave amplification with Gunn oscillators // IEEE Trans. Electron. Dev. 1967. V. 14, P. 517

5. *Hakki, B. W.* Amplification in Two-Valley Semiconductors // J. Appl. Phys. 1967. V. 38, P. 808

6. *Zhdanova, N. G., Kagan, M. S., Kalashnikov, S. G.* Impedance of semiconductor with static domain // Sov. Phys. Semicond. 1974. V. 8, P. 1121; 1126

7. *Altukhov, I. V., Kagan, M. S., Kalashnikov, S. G.*, et al. Electromagnetic wave amplification by Gunn diodes with moving domains // Sov. Tech. Phys. Lett. 1980. V. 6, P. 237

8. *Kagan, M.S., Landsberg, E.G., Chernyshov, I.V.* Negative conductivity due to vibrations of the wall of a static domain, Sov. Phys. Semicond. 1984. V. 18, P. 615

9. *Altukhov, I. V. Dizhur, S. E. Kagan, M. S.*, et al. Effect of a Terahertz Cavity on the Conductivity of Short-Period GaAs/AlAs Superlattices // JETP Letters 2016. V. 103, No. 2, P. 122

10. *Altukhov, I. V. Kagan, M. S. Kalashnikov, S. G.*, et al. Electrical instability of a semicondutor with a negative differential conductivity due to simultaneous heating of electrons by static and alternating electric fields // Sov. Phys. Semicond. 1978. V. 12, P. 172

11. *Suris R. A.* Inhomogeneous structures in semiconductors with superlattices // Sov. Phys. Semicond. 1973. V. 7, No. 8 P. 1035

12. *Bonilla, L. L., Grahn H. T.* Non-linear dynamics of semiconductor superlattices // Rep. Prog. Phys. 2005. V. 68, No. 3, P. 577