Technical Physics Letters, 2023, Vol. 49, No. 1

07.3

Active coplanar transmission line based on double-barrier GaAs/AlAs resonant tunneling diodes

© *A.S. Sobolev*[1,2], *A.Yu. Pavlov*[3], *M.V. Maytama*[3,4], *I.A. Glinskiy*[5], *D.S. Ponomarev*[2,3], *K.E. Spirin*[6], *B.A. Zhmud*[2], *R.A. Khabibullin*[2,3]

[1] Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, Russia
[2] Moscow Institute of Physics and Technology (State University), Moscow, Russia
[3] Institute of Ultra High Frequency Semiconductor Electronics of RAS, Moscow, Russia
[4] Bauman Moscow State Technical University, Moscow, Russia
[5] MIREA — Russian Technological University, Moscow, Russia
[6] Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
E-mail: khabibullin_r@mail.ru

Received October 18, 2022
Revised October 31, 2022
Accepted November 9, 2022

Double-barrier GaAs/AlAs resonant tunneling diodes (RTDs) have become the promising elements for the development of sub-mm and THz emitters. We report on the fabrication of the RTD samples that were characterized via RF-reflectometry to determine the parameters of its equivalent circuit. By using numerical simulation we show that the coplanar transmission line with the RTD under study provides an amplification up to 8 GHz.

Keywords: Resonant tunneling diodes, active microstrip transmission lines, distributed emitters, diodes with double metal contacts.

DOI: 10.21883/TPL.2023.01.55350.19395

The development of methods for generation of terahertz (THz) waves opened up ample opportunities for application of this radiation in various research fields [1,2]. Considerable progress has been achieved in the generation of frequencies from 100 GHz to 1 THz with the use of multipliers, Gunn diodes [3], and high-electron-mobility transistors [4]. The operating parameters (temperature and output radiation power) of quantum cascade lasers with operating frequencies from 1.5 to 5 THz are improving constantly [5,6]. Resonant tunneling diodes (RTDs), which have the capacity to operate at room temperature and achieve emission frequencies in excess of 1 THz, are another type of promising microwave and THz radiation sources. It is important to note that both sources and detectors of THz radiation were constructed based on RTDs [7–9]; thus, they may serve as hardware components for single-chip integrated circuits. A low radiation power, which typically remains at the level of several hundred μW, is one of the drawbacks of RTD-based emitters. Two-dimensional RTD arrays with a radiating antenna, which allow one to combine the generated radiation power of a large number of diodes, are proposed to be used for enhancing the output power. Issues related to matching of RTDs within an entire array and matching of the collective array mode to a radiating antenna arise in this case. This necessitates the development of an equivalent circuit diagram of an RTD that takes the specific features of both the double-barrier heterostructure and the architecture of the fabricated diode into account.

One experimental approach to the construction of an equivalent circuit diagram of an RTD consists in measuring complex parameter S_{11} (reflection coefficients) in a wide frequency range with a probe station, calculating its impedance in this range, and approximating the impedance ReZ and ImZ curves by formulae obtained for the equivalent circuit with lumped elements. This approach was used in the present study to estimate the parameters of distributed emitters based on transmission lines with RTDs embedded periodically into them.

Double-barrier GaAs/AlAs RTD structures were grown by molecular beam epitaxy on semi-insulating (100) GaAs substrates. The active RTD region between emitter (800 nm) and collector (300 nm) n^+-GaAs layers had the following sequence of layers: 2/4.5/2.3 nm, where an i-GaAs quantum well had i-AlAs barrier layers. RTDs with collector power supply via an air bridge were fabricated based on the grown heterostructure (Fig. 1).

Test structures, which allow one to perform the needed adjustment and shift the reference plane to the diode position [10], were fabricated for impedance measurements with a dual-port vector network analyzer and a probe station. The reflection coefficient was measured up to a frequency of 65 GHz at a power -40 dB (so that the small-signal approximation would remain applicable). We used the values of R_d obtained by differentiating the measured current–voltage curve (I-V) and the following constant parameters of the equivalent circuit: $L_g = L_q = 0.1$ nH, $C = 0.35$ pF, and $r = 8\,\Omega$.

The fabricated RTDs had a closely reproducible N-shaped I-V (Fig. 2). The bend in the negative differential resistance region is induced by internal oscillations in the diode. Negative R_d values obtained by differentiating the I-V fall within the range from -12 to $\sim 150\,\Omega$, which is

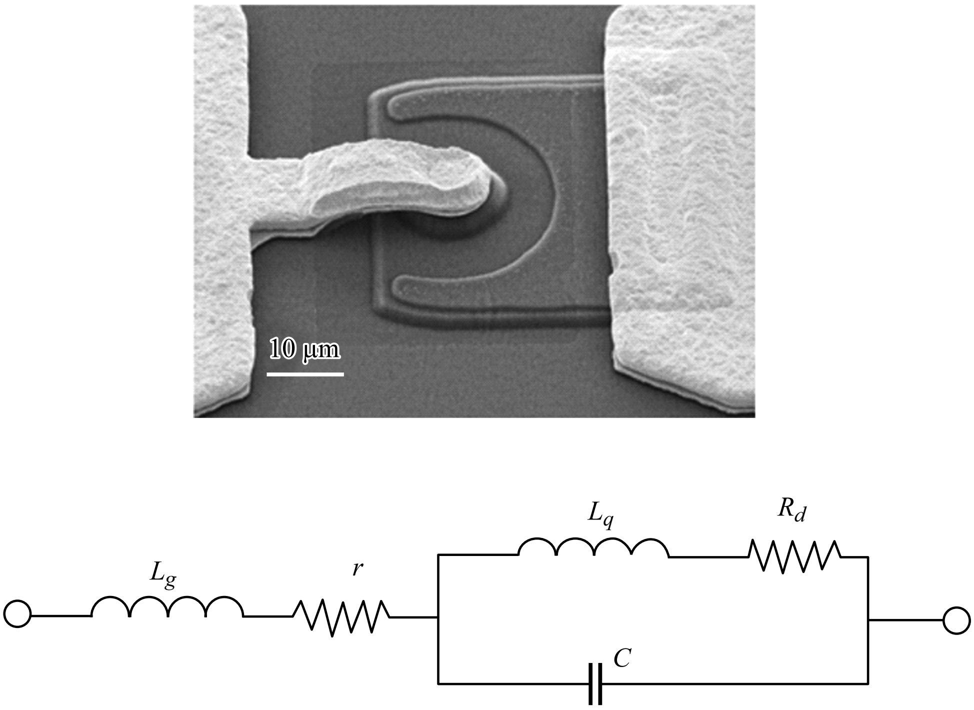

Figure 1. Fabricated GaAs/AlAs RTD (imaged with a scanning election microscope) and equivalent circuit of this diode.

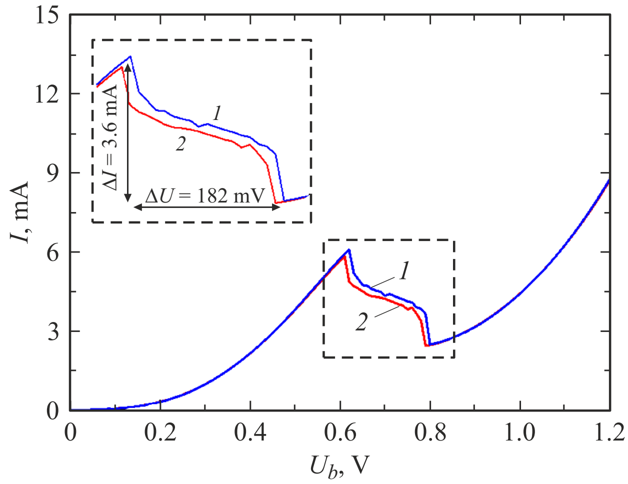

Figure 2. Current–voltage curves of the GaAs/AlAs RTD measured in forward (under an increasing voltage) (*1*) and backward (under a decreasing voltage) (*2*) directions. An enlarged view of the I-V section with hysteresis is presented in the inset.

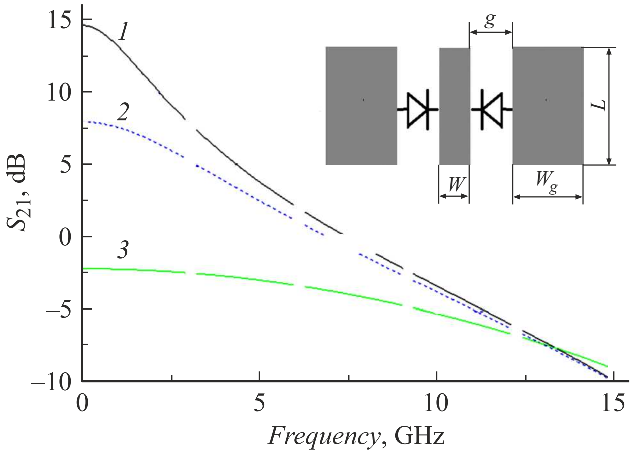

Figure 3. Gain of a unit cell of an active coplanar line with GaAs/AlAs RTDs embedded into it at $R_d = -25$ (*1*), -45 (*2*), and $-15\,\Omega$ (*3*). A simplified diagram of such a cell is shown in the inset.

attributable to the presence of hysteresis (see the inset in Fig. 2). The averaged value of R_d may be estimated as $R_d = \Delta U/\Delta V = 50\,\Omega$ (if there are no parasitic oscillations). When the bias voltage is altered, the ratio of charge densities within the quantum well and electrodes changes depending on the direction of motion of the operating point, thus shaping different self-consistent potential profiles and inducing I-V hysteresis in the region of negative R_d [11].

A coplanar line with a wave impedance of $50\,\Omega$ and lumped GaAs/AlAs RTDs periodically embedded into it with period L (see the inset in Fig. 3) served as an active (amplifying) transmission line. Its amplification capacity was verified in numerical calculations of parameter S_{21} of a unit cell of this transmission line with $W = 50\,\mu$m, $W_g = 130\,\mu$m, $g = 40\,\mu$m, and $L = 200\,\mu$m. These calculations were performed using the finite difference method in the time domain. The obtained results for three negative R_d

values are shown in Fig. 3. It can be seen that $S_{21} > 0$ dB at frequencies below 8 GHz, and the highest gain is achieved at an $|R_d|$ value close to the wave impedance of the coplanar line. It should also be noted that a diode may have $\mathrm{Re}Z < 0$ at frequencies up to 26 GHz; however, in order to raise the operating frequency of active transmission lines, one needs to introduce additional tuning elements compensating the reactive diode impedance into the unit cell and reduce the Ohmic loss resistance by implementing the bottom metal electrode technology.

Thus, resonant tunneling diodes with GaAs/AlAs barriers were fabricated, and an equivalent circuit was constructed for them based on the results of measurement of the reflection coefficient at frequencies up to 67 GHz. The obtained equivalent circuit of a single RTD was used to model a coplanar transmission line with diodes embedded periodically into it. Calculated data demonstrate that the line should provide amplification up to 8 GHz (with a potential to shift this boundary higher to the diode frequency limit of 27 GHz).

Funding

The work on RTDs (their fabrication and measurement of microwave characteristics) and GaAs/AlAs heterostructure growth was supported financially by grants Nos. 22-22-00767 and 19-79-10240, respectively, from the Russian Science Foundation, and calculation and design work on the active transmission line was performed as part of program „Prioritet-2030“ (agreement No. 075-02-2021-1316).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.E. Yachmenev, S.S. Pushkarev, R.R. Reznik, R.A. Khabibullin, D.S. Ponomarev, Prog. Cryst. Growt. Charact. Mater., **66** (2), 100485 (2020). DOI: 10.1016/j.pcrysgrow.2020.100485

[2] A.E. Yachmenev, R.A. Khabibullin, D.S. Ponomarev, J. Phys. D: Appl. Phys., **55** (19), 193001 (2022). DOI: 10.1088/1361-6463/ac43dd

[3] H. Eisele, Electron. Lett., **46** (6), 422 (2010). DOI: 10.1049/el.2010.3362

[4] D.V. Lavrukhin, A.E. Yachmenev, R.R. Galiev, R.A. Khabibullin, D.S. Ponomarev, Yu.V. Fedorov, P.P. Maltsev, Semiconductors, **48** (1), 69 (2014). DOI: 10.1134/S1063782614010187.

[5] D. Ushakov, A. Afonenko, R. Khabibullin, D. Ponomarev, V. Aleshkin, S. Morozov, A. Dubinov, Opt. Express, **28** (17), 25371 (2020). DOI: 10.1364/OE.398552

[6] D.V. Ushakov, A.A. Afonenko, I.A. Glinskii, R.A. Khabibullin, Russ. Technol. J., **10** (3), 45 (2022). DOI: 10.32362/2500-316X-2022-10-3-45-55

[7] T. Maekawa, H. Kanaya, S. Suzuki, M. Asada, Appl. Phys. Express, **9** (2), 024101 (2016). DOI: 10.7567/APEX.9.024101

[8] H. Mizuta, T. Tanoue, *The physics and applications of resonant tunneling diodes* (Cambridge University Press, Cambridge, 1995).

[9] K. Kasagi, S. Suzuki, M. Asada, J. Appl. Phys., **125** (15), 151601 (2019). DOI: 10.1063/1.5051007

[10] A. Sobolev, S. Zaitsev-Zotov, M. Maytama, E. Klimov, A. Pavlov, D. Ponomarev, R. Khabibullin, Opt. Eng., **60** (8), 082019 (2021). DOI: 10.1117/1.OE.60.8.082018

[11] N.C. Kluksdahl, A.M. Kriman, D.K. Ferry, C. Ringhofer, Phys. Rev. B, **39** (11), 7720 (1989).