Software complex for calculating the initial section of the current-voltage characteristics of a resonant-tunneling diode with the possibility of computer statistical experiment

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Abstract. The object of research is a resonance-tunneling diode (RTD) based on multilayer AlGaAs heterostructures. A software complex with high-speed algorithm modeling the RTD current-voltage (I-V) characteristic’s initial section with the possibility of carrying out a computer statistical experiment for studying the effect of technological errors of the diode design parameters on its I-V characteristic is submitted; the results of such study are shown.

1. Introduction
One of the ways of improving the indices of nonlinear radio radio-signal converters is to use nanoelectronic devices, such as resonant-tunneling diodes (RTDs) based on AlGaAs/GaAs heterostructures [1-12]. Today’s microwave electronic products (including the solid-state electronics) markets’ growth speed has caused the microwave electronics production volumes to move to the large-scale (and in some segments – the mass) area. This trend is observed for Russian and abroad markets alike. This task requires a software tool for technological errors simulation and carrying out a statistical analysis of device parameters. The objective is to develop a software tool for RTD current-voltage (I-V) characteristic’s modelling with the possibility of computer statistical experiment.

2. RTD I-V characteristic’s high-speed simulation module
The Tsu-Esaki formula is used as RTD I-V characteristic calculation mathematical model [13]. Diode’s resonant-tunneling structure’s (RTS) tunneling transparency is calculated by transfer matrix method [14].

The input arguments are RTS construction’s parameters: layers’ thickness in monolayers (ML) for two spacers, two barriers and one well areas, Al doping percent for barrier areas and spacers potential height. The bottom profile of the conduction band for different bias voltages is calculated according to the entered RTS construction parameters (Fig.1a).

The next step is to calculate RTS tunnel transparency using transparency matrix method (Fig. 1b). Tunnel transparency is calculated for each bias voltage value (after the input the maximum bias voltage value Umax is used to initialize a vector [0; Umax] with determined discretization step).

Then the RTS I-V characteristic is calculated using Tsu-Esaki formula. The influence of ohmic contacts’ resistance and mesa dimensions is also taken into account in the RTD I-V characteristic calculation.
Figure 1. RTS parameters simulated: (a) potential profile for different bias voltages; (b) tunnel transparency curves.

3. Comparison between RTD I-V characteristic simulation results and experimental data
To estimate the simulation accuracy, a comparison between RTD I-V characteristic simulation results and the experimental data obtained by measuring a batch of 27 diodes was carried out (Fig.2, diode RTS parameters is shown in Table 1).

| Layer     | Chemical composition | Conductance | Thickness, Å |
|-----------|----------------------|-------------|--------------|
| Spacer    | GaAs                 | i           | 21           |
| Barrier   | AlAs                 | i           | 29           |
| Well      | GaAs                 | i           | 49           |
| Barrier   | AlAs                 | i           | 29           |
| Spacer    | GaAs                 | i           | 21           |

I-V characteristics measurements of RTDs were performed using microprobe bench, which consists of a microprobe device, power supply Agilent E3641A and personal computer. This bench provided I-V characteristics measuring of the diodes in voltage range from 0 to 35 V (accuracy ΔU = ± 1 mV) and current range from 0 to 0.8 A (accuracy ΔI = ± 10 µA).

Dispersion of I-V characteristic lies within the measurement error range. Therefore, an averaged I-V characteristic value is used for all following comparisons. Maximum current difference between the calculated and experimental I-V characteristic in the 0...0.4 V range is 3.49%.

The performance benchmark of the developed software complex (named RTSVAC) and its analogues (WinGreen [15], Nanohub [16] and dif2RTD [17]) displayed that the calculating of the I-V characteristics using RTSVAC takes 20 seconds, while it takes 90-120 minutes in dif2RTD for the same task, 25-35 seconds in WinGreen, and 35-40 seconds in Nanohub. It is evident that the developed algorithm has 100 times higher performance in comparison with dif2RTD. Also, it is not inferior to WinGreen and Nanohub in the calculation speed.
Figure 2. Measured (curve 1) and simulated (curve 2) RTD I-V characteristics

The improved performance is obtained by implementing the described algorithm in Matlab environment, which is highly optimized for working with vector and matrix data, and by some algorithmic optimizations, related with memory allocation and general simulation flow, e.g. by moving duplicated source code in independent subroutines.

The achieved acceleration of the algorithm allows us to proceed to the statistical analysis of RTD I-V characteristic.

4. Computer statistical experiment module

During the computer statistical experiment module development the following technological errors groups were identified as affecting the RTD I-V characteristic: diode RTS parameters (thickness and chemical composition of the layers), ohmic contacts’ resistances and mesa area errors. Basing on the RTD I-V characteristic initial section calculation algorithm, a module of computer statistical experiment was developed.

Listed parameters are considered stochastic and are represented in pairs «nominal value – standard deviation». All parameters are considered as continuous random variables and are varied randomly by Gaussian distribution law. Mesa dimensions are correlated with each other with +1 correlation coefficient. This fact is taken into account when modeling rectangle mesa area errors.

RTD I-V characteristic’s simulation with random parameters is carried out according to algorithm described in point 2 on every iteration loop. Each iteration’s simulation results are saved in different files.

5. The study of RTD technological errors’ influence on diode I-V characteristic’s variance

The main RTD technological errors influence on RTD I-V characteristic was studied by using the developed software package. The studied errors are diode’s RTS technological errors, ohmic contacts resistance errors, and mesa area errors. The study was based on the samples of 100 RTD I-V characteristics obtained by computer statistical experiment. The influence of RTS technological errors and combined influence of ohmic contacts’ resistance and mesa area errors on RTD I-V characteristic were studied separately. Parameters’ maximum deviations values are given in Table 2.
Table 2. Maximum deviations values of RTD parameters

| Group      | Parameter                      | Deviations                        |
|------------|--------------------------------|-----------------------------------|
| RTS        | Layers thickness               | +/- 0.5 ML                        |
| RTS        | Al percentage in barriers      | +/- 1%                            |
| Ohmic contacts | Ohmic contacts resistance   | +/- 0.29 Ohm (nominal value 1.32 Ohm) |
| Mesa       | Mesa dimensions                | +/- 3 μm (nominal value 30x30 μm) |

Two batches were modeled (Fig.3a, b). Only RTS parameters errors were taken into account in the first one, while ohmic contacts errors and mesa area errors were considered zeros. In the second batch RTS parameters errors were considered zeros while combined influence of ohmic contacts' errors and mesa area errors was studied.

Figure 3. Distributions of the current at the RTD operating point: (a) RTS technological errors influence; (b) combined influence of ohmic contacts resistances and mesa area errors.

Comparison of obtained RTD current distributions revealed that the maximum contribution to the I-V characteristics variance is made by the diode RTS technological errors.

6. Results adequacy assessment
To evaluate the adequacy of the current distributions obtained in point 5, the most realistic case was modeled – a combined influence of all factors listed in Table 2 (Fig.4).
Figure 4 Distributions of the current at the RTD operating point under combined influence of RTS technological errors, ohmic contacts’ resistance and mesa area errors.

I-V characteristics of 30 diodes batch were measured experimentally. Both modeled and measured current distributions parameters are listed in Table 3.

Table 3. Distributions parameters of current at the RTD operating point.

|                  | Expected value, mA | Variance, mA² | Standard deviation, mA |
|------------------|--------------------|---------------|------------------------|
| Modeling result  | 1.97               | 0.5064        | 0.7116                 |
| Experimental data| 1.86               | 0.3098        | 0.5565                 |

Mean values’ and variances equality hypotheses verification were tested by Student and Fisher criteria respectively at the 0.05 significance level. It was determined that the tested hypotheses do not confront with the experimental data. Hence, the RTD statistical model can be considered adequate.

7. Conclusion
An RTD I-V characteristic’s modelling software package allowing carrying out computer statistical experiment was developed. The developed tool allows to study technological errors influence on I-V characteristic’s variance. RTD I-V characteristic modelling algorithm provides high modeling accuracy and the speed sufficient for computer statistical experiment implementation based on it.

The study of various error groups’ influence on RTD I-V characteristic’s variance using the developed software revealed that the maximum contribution to the RTD batch’s I-V characteristics variance is made by diode RTS technological errors.

Comparison between experimental and simulated current distributions statistical parameters proved that simulated data is adequate to experiment results.

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References

[1] Ivanov Yu A, Meshkov S A, Fedorenko I A, Fedorkova N V and Shashurin V D 2010 J. Commun. Technol. Electron. 55 921

[2] Ivanov Yu A, Meshkov S A, Fedorenko I A, Fedorkova N V and Shashurin V D 2011 Microwave & Telecommunication Technology (CriMiCo), 2011 21th Int. Crimean Conf. p 181

[3] Ivanov Yu A, Gudkov A G, Agasieva S V, Meshkov S A, Sinyakin V Yu and Makeev M O 2014 Microwave & Telecommunication Technology (CriMiCo), 2014 24th Int. Crimean Conf. p 1063

[4] Sinyakin V Yu, Makeev M O and Meshkov S A 2016 J. Phys.: Conf. Ser. 741 012160

[5] Makeev M O, Meshkov S A, Sinyakin V Yu and Razoumny Yu N 2017 Adv. in Astronautical Sci. 161 475

[6] Kanaya H, Shibayama H, Suzuki S and Asada M 2012 Appl. Phys. Express 5 124101

[7] Maekawa T, Kanaya H, Suzuki S and Asada M 2016 Appl. Phys. Express 9 024101

[8] Wang J, Al-Khalidi A, Alharbi K, Ofiare A, Zhou H, Wasige E and Figueiredo J 2017 Proc. European Microwave Conf. (London) vol.1 (New York: Curran Associates, Inc.) p 341

[9] Mizuta H and Tanoue T High-speed and functional applications of resonant tunnelling diodes. In The Physics and Applications of Resonant Tunnelling Diodes 2006 (New York: Cambridge university press) p 133

[10] Nagatsuma T, Fujita M, Kaku A, Tsuji D, Nakai S, Tsuruda K and Mukai T 2014 Proc. Int. Conf. Telecomm. and Rem. Sens. (Luxembourg) vol. 1 (Bulgaria: SciTePress) p 41

[11] Srivastava A 2015 Eur. J. of Adv. in Eng. and Techn. 2 54

[12] Diebold S, Tsuruda K, Kim J-Y, Mukai T, Fujita M and Nagatsuma T 2016 Proc. SPIE 9856, Terahertz Physics, Devices, and Systems X: Advanced Applications in Industry and Defense (Baltimore) vol. 9856 (Washington: SPIE) 98560U

[13] Esaki L and Tsu R 1970 IBM J. of Res. and Dev. 14 1 61

[14] Pérez-Álvarez R and Garcia-Molliner F 2004 Transfer Matrix, Green Function and Related Techniques: Tools for the Study of Multilayer Heterostructures (Castelló de la Plana: Publicacions de la Universitat Jaume I) 285 p

[15] Hochschule RheinMain https://www.hs-rm.de/en/rheinmain-university/people/indlekofer-klaus-michael/research-and-development/wingreen/

[16] Nanohub: largest nanotechnology online resource https://nanohub.org/resources/rtd/

[17] Makeev M O, Litvak Yu N, Ivanov Yu A, Meshkov S A and Migal D E 2012 dif2RTD: certificate of state registration of a computer program № 2012661001