Spacer layers' thickness impact on the resonant-tunneling diode's and frequency mixer's operational parameters

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Abstract. The impact of spacer layers' thickness on the resonant-tunneling diode's (RTD) current-voltage characteristic and operational parameters of the RTD-based subharmonic mixer was studied during the described research using the software package developed by authors to simulate the RTD's functional parameters while mixer's parameters were simulated using existing microelectronic CAD. The research has revealed that the main impact on both RTD's I-V characteristic's shape and operational parameters of the studied subharmonic mixers is made by the emitter spacer layer's thickness while the collector spacer's thickness' variation is insignificant in both cases. Such, it is shown that by varying the emitter spacer's thickness from a single monolayer to twice its nominal value it's possible to alter the RTD's peak current from 0,28 to 1,92 of its nominal value. spacer layer's thickness deviation of ±1 monolayer has a noticeable effect on the studied mixer's operational parameters, especially on its dynamic range.

1 Introduction

Constantly growing requirements to the transceiver equipment's quality and performance result in the need to improve their operational parameters. Expanding the operating frequency range is one of the ways to achieve this goal. In turn, transceiver equipment's operational parameters are determined by parameters of nonlinear frequency converters (FC). A promising way to widen FCs' operating frequency range is to use nonlinear elements operating on quantum-scale effects [1], such as resonant-tunneling diodes (RTD) based on A3B5 resonant-tunneling heterostructures (RTHS). RTD operation is based on the resonant tunneling phenomena, providing the transverse current transfer through RTHS layers. This current transfer mechanism is many times quicker than classical current transport, what allows to widen operating frequency range up to THz [2-11]. Additionally, shape of RTD's current-voltage (I-V) characteristic is very sensitive to variation of the RTHS' layers thicknesses and chemical composition, what allows to design RTHS with optimal I-V characteristics for certain FCs [12, 13]. Also, RTDs can be manufactured using proven microelectronic technologies.

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Besides the goal of improving FC's operational parameters, it is crucial to ensure their reliability in given operating conditions. Solving the RTD-based FCs' reliability ensurance task is most effective using computer simulation to obtain devices' electrical parameters and assess their kinetics under operational factors' impact.

2 Research topicality

To achieve the said goal of ensuring FCs' reliability authors have developed a reliability model of RTD-based FCs. The model takes into account the impact of FCs' design parameters' technical errors on their operational parameters. Also, the model includes mathematical models of operational factors' impact on FC's functional parameters for temperature and gamma-irradiation. During previous studies authors have revealed that technological distribution of RTD's I-V characteristic makes a major impact on FC's operational parameters' distribution. The main failure mechanism of said devices is gradual failure due to the irreversible degradation of RTD's design parameters (and, hence, its I-V characteristic) caused by operational factors' impact.

The RTD-based FCs' reliability model allows to assess FCs' reliability during the design stage, but said model doesn't take the impact of diffusion processes in RTHS' spacer layers during operation and manufacturing stages on the device's operational parameters into accordance, though assessments of the technological errors of RTHS' layers' thicknesses impact on RTDs' I-V characteristics' distributions and FCs' operational parameters allow to suppose that these factors will have significant impact on the FCs' reliability as well, especially if typical thickness of RTHS' layers is about 10 nm.

Therefore, researching the impact of RTHS' spacer layers' thickness on RTD's electrical parameters and operational parameters of RTD-based FCs seems to be topical and is important for future researches of RTD-based devices' reliability.

3 Research goal

The purpose of this research is to assess the impact of RTHS' spacer layers' thickness on the diode's I-V characteristic and operational parameters of the RTD-based subharmonic mixer.

4 Theoretical part

4.1 Hypothesis

RTHS RTD is a "barrier-well-barrier" structure with spacers framing it from both sides, separating RTHS from highly-doped areas between it and ohmic contacts. Quantum well and spacers are made of intrinsic GaAs, barriers – of intrinsic AlAs, thicknesses of all mentioned layers are no bigger than 10 nm. Under bias voltage's impact the conduction band's profile bends, and a triangular quantum well forms in the emitter spacer layer, the greater the bias voltage is, the deeper this well will be. Said triangular well has its own set of allowed states, depending on the bias voltage and spacer's thickness. Therefore, it can be supposed that spacer layer's thickness variation shall affect the RTD's I-V characteristic. Hence, the goal of this research is to numerically assess this impact on the RTD's I-V characteristic and operational parameters of the RTD-based subharmonic mixer.

4.2 Research techniques

The simulation of RTD's electrical parameters by the means of computer experiment is the main technique used in this research. To implement this technique, a software package was developed by authors. The package is designed to carry out a design and technological optimization of RTD-based devices' operational parameters. It consists of four modules – control module (CM), nonlinear elements' degradation processes' analysis module (NERA), microelectronic devices' reliability analysis module (MeDRA), and microelectronic devices' design and technological optimization module (MeDEDTORA) to improve their reliability.

These modules' internal structure and main algorithms are described in details in [14, 15]. In this paper our main interest is NERA module, or, more precisely, its part responsible for simulating nonlinear element's (in this case, a RTD) electrical parameters.

The main function of this module is to simulate the studied nonlinear element's electrical parameters basing on its design parameters. The simulation technique used in NERA module is based on the Tsu-Esaki equation [16]. Fermi-Dirac's distribution is used as charge carriers' supply function, RTHS' tunnel transparency is calculated using transfer matrices method [17].

RTHS's I-V characteristic is simulated using heterostructure's design parameters $\mathbf{X}_{\mathrm{RTHS}}$ as input data: thicknesses and chemical composition of spacers, barriers and well layers. To obtain the nonlinear element's I-V characteristic, it is necessary to take the ohmic contacts' (OC) and near-contact areas' (NCA) impact on the element's I-V characteristic.

Input parameters for simulating the nonlinear element's I-V characteristic are: simulated I-V characteristic of the element's RTHS (as "current-voltage" pairs), OCs' contact resistivity and space, NCAs' thickness, doping and cross-section space. Simulation algorithms and mathematical models used to simulate RTDs' electrical parameters are described in [14, 15].

4.3 Object of research

RTD with following design parameters is the object of this research: symmetrical AlAs barriers' thickness – 2,83 nm, GaAs quantum well's thickness – 2,83 nm. GaAs spacer layers' thickness is 2,26 nm. I-V characteristic's initial section is shown on Fig. 1.

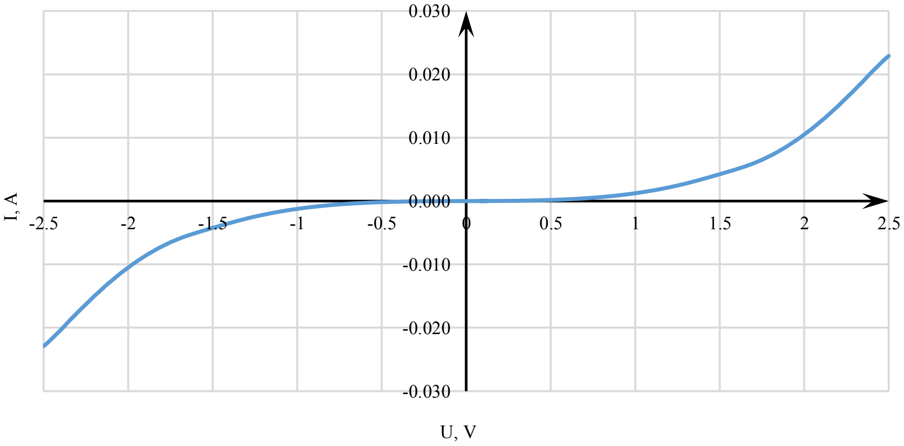

Fig. 1. RTD I-V characteristic's initial section.

5 Results

During this research the impact of spacer layers' thickness on RTD's I-V characteristic was studied. To perform it, RTD's I-V characteristic was simulated for different spacer layers' thicknesses. First, only the emitter spacer's thickness was varied, then only collector spacer's, with variation step of 1 monolayer (ML). As a result, RTD's current at I-V characteristic's operating point versus spacer layer's thickness dependencies were plotted (Fig. 2).

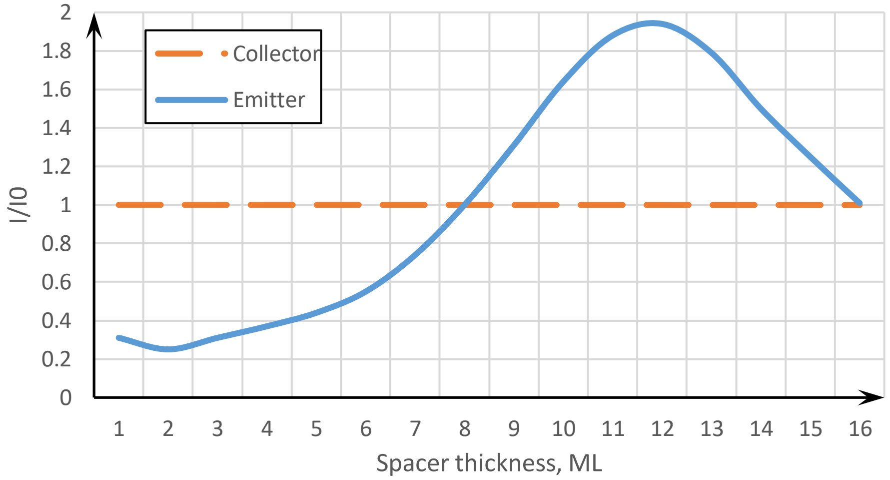

Fig. 2. The RTD's current dependency on spacer levels' thickness.

From plotted graphs it is evident that the major impact on the RTD's current is made by emitter spacer's thickness while collector spacer makes no significant impact. Varying the emitter spacer's thickness from 1 to 16 ML corresponds to changing the RTD's current at its I-V characteristic's operating point from 0,28 to 1,92 of its nominal value. Therefore, we've proved the hypothesis about spacer layers' thickness impact on the RTD's I-V characteristic. Said impact is caused by the change of allowed states set in the triangular quantum well formed in the emitter spacer as its thickness was varied. RTD's current growth corresponds to the overlapping of allowed states in the RTHS' quantum well and in the emitter spacer's well.

Obtained dependency seems to be periodical, what could be explained by its physical nature.

6 Results discussion

In order to confirm results' adequacy we've studied other researches regarding this problem [4, 18-30]. In all listed papers the importance of spacer layers for ensuring high static and dynamic parameters of studied elements is mentioned. Various authors tend to use different approach to RTDs' electrical parameters simulation, from relatively simple approach based on Tsu-Esaki equation and transfer matrix method [16-17] to using various additions like self-consistent calculation of RTHS' conduction band's profile, using Wigner's functions, and so on. Nonetheless, results of researches listed in [4, 18-30] have the similar explanation of the emitter spacer's thickness impact on RTD's electrical parameters – due to the triangular quantum well forming in this layer under the bias voltage's influence, there's an overlap of allowed states between this quantum well and RTHS' one, resulting in the RTD's current growth or lowering it if there's no overlap between these states. In [19, 30] forming of such quantum well by using materials with wider band gap than RTHS layers is described for AlAs/GaAs RTHS and Ga1-xInxAs emitter spacer. In this case, triangular well's depth is determined by both the bias voltage applied and In doping level in spacer layer. This approach allows to increase RTD's peak current by 5 times depending on In doping level in emitter spacer [30], and up to 4 times depending on its thickness [19]. In general, all listed papers give similar assessments of RTD peak current's changes – from 0,25 to 4 times nominal value depending on emitter spacer's thickness. Regarding collector spacer thickness' impact on RTD's electrical parameters, authors of listed papers mention that this parameter has no significant impact on RTD's electrical parameters, slightly increasing the peak current's voltage with collector spacer's thickness growth [18, 19, 21, 26, 30].

Therefore, analysis of other researches allows to conclude that results obtained in this research don't contradict other researches' data, what can serve as a proof of obtained data's adequacy. As revealed in this research, emitter spacer's thickness deviation of 1 ML corresponds to RTD's current change of 20% of its nominal value. This deviation is significant enough to study the RTD's emitter spacer thickness' impact on the RTD-based subharmonic mixer's (SM) operational parameters. Said SM operates in 10-11 GHz frequency range and uses the studied RTD as nonlinear element. The emitter spacer thickness' impact on the following SM operational parameters was studied: intermediate frequency's transmission coefficient (TCIF) and dynamic range by intermodulation and 1dB-compression. The top border of dynamic range by intermodulation was determined by the IP3 point's position. Listed parameters changes under the effect of the emitter spacer's thickness variation of ±1 ML were studied.

As it was shown earlier, varying the emitter spacer's thickness by 1 ML from nominal value results in 20% change of RTD's peak current. Lowering the spacer's thickness results in TC_{IF} growing by 0,4 dB (3,2% of nominal value) and widens the dynamic range by 1,7 dBm (5,9% of nominal value) for intemodulation, by 1 dBm for 1dB-compression (10,2% of nominal value). Increment of the emitter spacer's thickness results in TC_{IF} lowering by 0,3 dB (2,3% of nominal value), and narrows the dynamic range by 0,8 dBm for intermodulation (2,8% of nominal value), and by 1,3 dBm for 1dB-compression (13,3% of nominal value).

Therefore, it is shown that emitter spacer's thickness variation of ±1 ML has significant impact on operational parameter of the SM based on this diode, especially on SM's dynamic range.

7 Conclusion

It was revealed that variation of the emitter spacer's thickness has significant impact on the RTD's electrical parameters and operational parameters of RTD-based devices while collector spacer has no noticeable impact on RTD's I-V characteristic. Its peak current changes from 0,28 to 1,92 of nominal value under the impact of emitter spacer thickness variation.

It is shown that ±1 ML variation of emitter spacer's thickness matches ±20% variation of RTD's current. It affects the RTD-based SM's electrical parameters significantly, especially its dynamic range: increasing emitter layer's thickness by 1 ML narrows the dynamic range: by intermodulation - by 2,8% and by 1dB-compression – by 13,3%. Lowering the emitter spacer's thickness by 1 ML widens SM's dynamic range: by intermodulation – by 5,9%, by 1dB-compression — by 10,2%. TC_{IF} changes insignificantly— by 0,4 dB.

Therefore, this research has proved that RTD's I-V characteristic is sensitive to the emitter spacer's thickness variation. Said variation significantly affects operational parameters of the RTD-based SM, therefore, is able to significantly affect reliability of such devices. That proves the importance of further researches of diffusion processes in spacer layers and their impact on RTD's I-V characteristics, and the assessment of their impact on RTD-based devices' reliability.

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