Impact of technological errors of design parameters of broadband radio signals mixer based on resonant-tunneling diode on its electrical characteristics

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Abstract. The research object is a resonant-tunneling diode based broadband radio signals mixer (RTD BM) of 4-8 GHz range. The purpose of this research is to perform statistical analysis of the RTD BM design parameters' technological variation impact on its electrical characteristics' variation. RTD BM’s electrical characteristics variations under the impact of its nonlinear elements’ I-V characteristics, topology parameters and substrate thickness, and relative permittivity technological errors, as well as under their combined impact, were obtained. The ranking of the considered RTD BM’s parameters technological variations’ contribution to its electrical characteristics’ distributions was carried out. It was revealed that the biggest contribution to RTD BM’s electrical characteristics’ distribution is made by the technical errors of its nonlinear elements’ I-V characteristics. RTD BM’s electrical characteristics distributions under all design parameters’ technological errors combined influence can be used in RTD BMs’ batch reliability analysis performed by computer statistical experiment means.

1. Introduction
Radiotechnical systems (RTS) are a class of information management systems performing data transmission, gathering or destruction using radio waves. In general, RTS consists of receiving and transmitting devices. The main feature of such systems is radio signal usage as the data carrier. Depending on their purpose, RTS are subdivided into data transmission, data gathering, data destruction and radio control ones. Data transmission RTS are used to transmit the data from one point to another. Data destruction RTS are used to obtain the conditions making enemy’s RTS operation difficult or completely impossible. Data gathering RTS are made for gathering the data about certain objects. Radio control RTS are used to control various objects’ operation by the radio signals means. [1]. All RTS, excluding data destruction ones due to their obviously narrow specter of usages, are widely spread, being a part of every system and device that exchange data during the operation: from air- and spacecrafts, ships, radiolocation, radionavigation and broadcasting systems to cars, CNC machine tools and household appliances.

Nonlinear radio frequency converters (FCs) are radioelectronic systems’ key elements as they’re used to perform main radiotechnical conversions. FCs’ performance indices determine performance indices of the most of radiotechnical systems. One of the ways to improve FCs’ performance indices is to use nanoelectronics devices like resonant-tunneling diodes (RTDs) based on AlGaAs/GaAs multilayered heterostructures [2]. Being used as nonlinear element, RTD allows to improve FC’s
performance indices [3]-[4]. There’s a lot of research dedicated to the prospects of the RTD usage in various radioelectronic devices [2-9].

During FC’s design stage assuring its reliability in given operating conditions is a priority task along with achieving the required level of the device’s performance indices. The former task is especially interesting for RTD-based FCs due to being fairly less studied. One of the possible solutions of this problem is the complex micro- and nanodevices design methodology described in [10]. At this stage the corrections to the devices’ design parameters’ and its electrical characteristics’ nominal values are determined, allowing to maximize predetermined goal functions, leaving design parameters’ tolerances unchanged. Gamma percentage time to failure, yield during the given operating time or probability of fulfilling the specified functions by a batch of devices can be used as the goal function. This approach supposes the usage of simulation modeling means, including probabilistic modeling of the device’s electrical characteristics, physical processes of their degradation in given operating conditions, technological errors and is based on the results of the device’s elements degradation studies under external factors’ influence.

The optimization process is quite conventional in general. It is a loop consisting of one or several device design parameters’ corrections, device’s electrical characteristics simulation using its updated design parameters, and goal function’s value calculation. Since the optimization goal is to ensure the devices batch reliability in given operating conditions, the device’s reliability analysis is required to obtain the goal function’s value. As the devices batch reliability indices are used as goal functions, it is advisable to use probabilistic modeling techniques for the device’s reliability analysis. Such techniques allow considering the device’s design parameters technological errors impact on its electrical characteristics’ distribution. As shown in preliminary studies [11]-[12], reliability of RTD-based radio FCs is determined by its nonlinear element’s reliability. This fact allows to suppose that FC’s electrical characteristics are most susceptible to the changes of its nonlinear elements (NE) I-V characteristics. In turn, NE’s I-V characteristic depends on its design parameters, that have the variation caused by the manufacturing technology. Though, in addition to NE, technological errors also cause the variation of the parameters of the device’s topology and substrate.

Described circumstances make it appropriate to assess the influence of the various device’s design parameters groups’ technological errors on the device’s electrical characteristics. The assessment’s results allow to obtain the device’s electrical characteristics’ distributions that are required for the reliability analysis. The purpose of this research is to perform statistical analysis of a resonant-tunneling diode based broadband radio signals mixer (RTD BM) design parameters' technological variation impact on its electrical characteristics’ variation.

2. The object of study
The object of study is the RTD BM of 4-8 GHz range. The influence of the various device’s design parameters groups’ technological errors on the RTD BM’s electrical characteristics distributions was assessed. An RTD with the following design parameters was used as BM’s NE: resonant-tunneling structure or “barrier-well-barrier” type, barrier layers are. made of AlAs and have thickness of 28,3 nm, well layer is made of GaAs and has thickness of 28,2 nm. RTD’s I-V characteristic’s initial section is shown on fig. 1.
Figure 1. Initial section of the RTD’s I-V characteristic.

The combination frequencies’ (CF) 1-1 and 2-2 transmission coefficients were used as BM’s electrical characteristics (fig. 2). Combination frequencies appear during the signal conversion process due to nonlinearity of the BM’s NE I-V characteristics. They’re described by the following equation:

$$f_{CF} = |mf_s \pm nf_h|$$

(1)

Where $f_{s,h}$ are signal’s and heterodyne’s frequencies respectively, $m, n$ – numbers of signal’s and heterodyne’s harmonics, that form the CF.

Figure 2. RTD BM’s CF 1-1 and 2-2 transmission coefficients’ nominal values

RTD BM’s design parameters are subdivided into the following groups: NE’s I-V characteristics, BM’s topology parameters and substrate parameters. All parameters’ distributions obey to the normal law. The BM’s NE I-V characteristic’s distribution is caused by the combined influence of its design parameters’ technological variations: thicknesses and chemical compositions of the contact areas and RTD’s resonant-tunneling structure’s layers, mesa’s area and the ohmic contacts’ area and resistivity. BM’s topology parameters consist of the microstrip lines’ dimensions (width and length). Width and length deviation values are correlated with each other with +1 correlation coefficient, these parameters’
tolerance is ±12 μm. The substrate parameters are its thickness and relative permittivity. The substrate is supposed to be made of polycor, its relative permittivity is 9,8±0,1 F/m, its thickness –1±0,03 mm.

3. Results
The study was carried out by the means of computer statistical experiment. RTD BM’s model was made in AWR Microwave Office (MWO) CAD, Yield Analysis module of which was used to obtain the mixers’ electrical characteristics and their distributions. The RTD’s I-V characteristic and its current variation under the diode’s design parameters’ technological variations’ impact was simulated by the means of the program package developed by this article’s authors for this purpose [13], as there’s no RTD model allowing to obtain diode’s I-V characteristic basing on its design parameters in MWO, as well as in other modern microelectronic CADs. For the research needs the batch of 100 diodes was simulated using the package (RTD’s design parameters maximal deviations are listed in table 1).

Table 1. RTD’s design parameters maximal deviations

| Parameter                                | Maximal deviation                        |
|------------------------------------------|------------------------------------------|
| Barriers and well layers’ thicknesses    | ± 1 monolayer                            |
| Al doping percentage in barriers         | ± 1 %                                    |
|                                         | ± 0,25 μOhm·cm² (nominal value – 1       |
| Ohmic contacts’ resistivity              | μOhm·cm²)                                |
| Mesa diameter                            | ± 2 μm (nominal value 20 μm)             |

To assess the various BM’s design parameters groups’ impact on its electrical characteristics’ distribution five batches of BMs were modeled, per 100 devices each. The RTD’s design parameters were the only group being varied during the modeling of the first batch, while parameters of all other groups were considered constant and equal to their nominal values. In the second batch only the BM’s microstrip lines’ widths and heights, in the third one – only the substrate’s thickness, in the fourth – the substrate’s relative permittivity. Finally, the fifth batch was simulated under the combined influence of the all listed BM’s design parameters’ technological variations.

BM’s electrical characteristics’ distributions under the combined influence of the all listed BM’s design parameters’ technological variations are shown in the fig. 3a, b. Dispersions of the electrical characteristics’ distributions under the impact of various BM’s design parameters’ groups can be assessed basing in the fig. 3 and the corresponding BM’s design parameters’ technological variations’ contributions in the total dispersion (fig. 4, 5).

Figure 3. Distributions of the BM’s CF 1-1 (a) and 2-2 (b) transmission coefficients at the 7,5 GHz frequency under the combined impact of technological variations of the NE’s I-V characteristics’, substrate’s thickness, and its relative permittivity, and microstrip lines’ dimensions.
To rank the technological variations of the BM’s parameters’ contributions in its electrical characteristics’ variation the diagrams, demonstrating each parameter’s contribution in total dispersion, were plotted. Technological variations’ contributions are assessed by the relation of two dispersions - one obtained under the certain design parameter’s technological variation’s impact and another one is the total dispersion obtained under the combined impact of all parameters’ technological variations (fig. 4, 5).

**Figure 4.** The contributions of the various BM’s design parameters’ technological variations in the total dispersion of the CF 1-1 transmission coefficient.

**Figure 5.** The contributions of the various BM’s design parameters’ technological variations in the total dispersion of the CF 2-2 transmission coefficient.

The obtained diagrams’ analysis revealed that the biggest impact on the CF 1-1 transmission coefficient has the NE’s I-V characteristic’s technological variation. Other technological variations have no significant impact on this electrical characteristic. As shown in the fig. 4, the NE’s I-V characteristic’s technological variation’s contribution to the total dispersion is about 91%, 7% is the contribution of the microstrip lines’ dimensions’ technological variation. This can be explained by the following: CF 1-1 transmission coefficient mainly depends on NE’s I-V characteristic’s shape and the matching of the BM’s diode sections’ microstrip lines’ impedances with the NEs’ resistances. Therefore, we can conclude that CF 1-1 transmission coefficient is mostly sensitive to the NE’s I-V characteristic’s shape.
The analysis of the diagram shown in fig. 5 for the CF 2-2 transmission coefficient revealed that the most significant contribution in this parameter’s variation is made by the NE’s I-V characteristic’s technological variation. The combined contribution of the NE’s I-V characteristic’s and microstrip lines’ dimensions’ technological variations is about 98%, which allows coming to similar conclusions about the importance of the matching of the mixer’s diode sections’ impedances with its NE’s resistances. The least contributions to the CF 2-2 transmission coefficient’s total dispersion have the technological variations of the substrate’s thickness and its relative permittivity. Basing on all listed above we can conclude that the dominant factor for these electrical characteristics is still the matching of the mixer’s diode sections’ impedances with its NE’s resistances. At the same time, the impact of the technological variation of wave resistances of microstrip lines forming the filters also increased.

4. Conclusion
The statistical analysis of a resonant-tunneling diode-based broadband radio signals mixer (RTD BM) design parameters’ technological variation impact on its electrical characteristics’ variation was carried out. It was revealed that the biggest contribution to RTD BM’s electrical characteristics’ distribution is made by the technical errors of its nonlinear elements’ I-V characteristics. RTD BM’s electrical characteristics variations under the impact of its nonlinear elements’ I-V characteristics, topology parameters and substrate thickness, and relative permittivity technological errors, as well as under their combined impact, were obtained. RTD BM’s electrical characteristics distributions under all design parameters’ technological errors combined influence can be used in RTD BMs’ batch reliability analysis performed by means of computer statistical experiment.

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