Kinetics of electrical characteristics of balanced SHF mixer based on resonant-tunnelling diodes under operational factors influence

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Abstract. The purpose of this study is to analyze the impact of high temperature and gamma-irradiation on the electrical characteristics of the balanced SHF mixer based on the resonant-tunnelling diodes during its operation. Failures caused by irreversible changes in the nonlinear element's electrical characteristics under the mentioned operational factors' effect investigated. Revealed that the failure is caused by the mixer's combination frequency 1-1 conversion loss' growth. Individual times to failure, matching the mixer's actual operating conditions, were obtained.

1. Introduction

Nonlinear radio frequency converters (FCs) are radioelectronic systems’ key elements as they are used to perform main radiotechnical conversions. FCs’ performance indices determine performance indices of 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 [1]. Being used as nonlinear element, RTD allows to improve FC’s performance indices by picking an optimal shape of current-voltage (I-V) characteristic. Optimal I-V characteristic’s shape can be achieved by changing thicknesses and chemical composition of RTD’s resonant-tunneling structure (RTS) layers [2]-[4]. RTD’s working frequency range reaches up to THz, what allows to consider it as prospective UHF and EHF electronics element [5]-[9]. Using RTDs as radio frequency signal mixers’ nonlinear elements allows to widen their dynamic range. The RTDs can be manufactured using proven microelectronics technologies.

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. As shown in preliminary studies [10]-[11], reliability of RTD-based radio FCs is determined by its nonlinear element’s reliability. Therefore, it is advisable to perform further studies in this direction using a reliability model by gradual failures based on analysis of FC’s performance indices’ drift patterns caused by irreversible degradation processes under operating conditions’ influence. Such analysis shall be carried out to the point of performance indices leaving device designer-set constraints, what’s equal to the device’s failure.

The purpose of this study is to analyze the impact of high temperature and gamma-irradiation on the RTD-based balanced SHF broadband mixer (RTD BM) electrical characteristics during its operation.
2. The object of study
The object of study is the RTD BM of 4-8 GHz range. The kinetics of the mixer's electrical characteristics under the elevated temperature's and ionizing radiation's (II) absorbed dose influence is studied. The RTD of RTD3 type used as the studied RTD BM's nonlinear element. (diode RTS shown in Table 1, I-V characteristic’s initial section – on fig. 1).

Table 1. Diode RTS parameters

| Layer  | Chemical composition | Conductance | Thickness, Å |
|--------|----------------------|-------------|--------------|
| Spacer | GaAs i               |             | 22.6         |
| Barrier| AlAs i               |             | 28.3         |
| Well   | GaAs i               |             | 28.2         |
| Barrier| AlAs i               |             | 28.3         |
| Spacer | GaAs i               |             | 22.6         |

Figure 1. The initial section of the RTD3-type I-V characteristics.

Combination frequencies (CF) 1-1 and 2-2 conversion losses are used as the RTD BM’s electrical characteristics.

3. Results
For nonlinear elements, the effects of temperature of 250 °C for 21 hours and a dose of gamma radiation of 375.1 Mrad simulated. In both cases, the measurement result for this type of RTD is used as the initial I – V characteristic. Degradation modeling was carried out with RTD ohmic contacts’ (OCs) specific degradation coefficient of 2.5·10^{-4} Ohm*cm^2*s^{1/2}, the activation energy of the RTD degradation processes under temperature factor's influence of 1 eV and OCs susceptibility coefficient to irradiation’s effect of 5.2·10^{-5} rad^{-1/2} using the models described in [12] - [14]. Simulated I-V characteristics were put in the studied RTD BM’s model as approximated polynomial current-voltage dependencies. Basing on the mixer’s characteristic simulation results, their kinetics under high
temperature’s and II’s influence was obtained for the 7.5 GHz signal frequency (fig.2a, b). The failure is registered if conversion loss becomes more than 16 dB for CF 1-1 or less than 66 dB for CF 2-2.

![Graph](image1)

**Figure 2.** Kinetics of the BM RTD’s CF 1-1 and 2-2 conversion losses at 7.5 GHz signal frequency: (a) under the temperature of 250 °C effect; (b) under gamma-radiation’s absorbed dose effect.

Conversion loss’ kinetics at both studied CFs grow monotonously both in high temperature’s and II’s effect case as shown at fig.2a, b. Thresholds are shown as horizontal lines. The threshold value for conversion loss at CF 2-2 lies outside the plot area since it is the lower boundary, and conversion losses increase monotonously under the operational factors’ effect. Therefore, failure can be caused only by exceeding the threshold value for CF 1-1 conversion loss. In the case of II’s effect failure occurs at an absorbed dose of 325 Mrad. Failure under the high-temperature effect wasn’t fixed during the considered time interval. Extrapolation of the curve equation of the CF 1-1 conversion loss' kinetics revealed that failure occurs at 25 h of 250 °C temperature exposure.

In order to obtain RTD BM’s time to failure (TTF) matching real operational conditions obtained values were recalculated into the TTF matching given operational conditions. Three values are considered as real operation temperatures: 85, 125 and 150 °C. Recalculation was made using the technique described in [12] - [14], results are listed in Table 2.

| TTF at T=250 °C, h | TTF at T=85 °C, h (years) | TTF at T=125 °C, h (years) | TTF at T=150 °C, h (years) |
|---------------------|---------------------------|---------------------------|---------------------------|
| 25                  | 690900 (78.87)            | 182413 (20.82)            | 32550 (3.72)              |

To evaluate the TTF under II influence, the absorbed dose matching the BM’s failure was recalculated into operation time. According to [15], [16], absorbed dose for spacecraft onboard equipment behind mass protection of 1...2 g/cm² (what matches typical values for protective material used in spacecrafts)
is about 10…30 krad per year. For such dose rate, the absorbed dose of 325 Mrad equals to 11000 years on the orbit. In this research, individual TTFs and the kinetics of electrical characteristics under high temperature’s and II’s influence obtained for the studied RTD BM. Reliability assessment requires obtaining the group reliability indices for given RTD BM, such as mean time to failure or gamma percentage operation time. These indices can be obtained through computer statistical experiment using the RTD BM’s electrical characteristics kinetics obtained in this study.

4. Conclusion
In this study, the impact of high temperature and gamma-irradiation on the RTD BM electrical characteristics during its operation is analyzed. Revealed that the RTD BM’s failure can be caused only by exceeding the threshold value for CF 1-1 conversion loss. TTFs assessments matching real operational conditions obtained for studied RTD BM. RTD BM’s electrical characteristics kinetics, obtained in the study, can be used in further device reliability analysis through computer statistical experiment to obtain gamma-percentage operation time.

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