Degradation study of AlAs/GaAs resonant tunneling diode IV curves under influence of high temperatures

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Abstract. In the present work the thermal degradation of IV curves of AlAs/GaAs resonant tunneling diodes using artificial aging method was investigated. The dependency of AuGeNi specific ohmic contact resistance on time and temperature was determined.

1. Introduction
One of the ways to improve quality of radio electronic systems is the use of semiconductor devices operating on the base of quantum-size charge-transport effects. Resonant-tunneling diodes (RTDs) based on AlAs/GaAs nanoscale heterostructures with transverse charge transport are among such devices. The prospects of RTD for modern radio electronics is caused by the following circumstances:
- The limit frequency for RTD spreads up to units of THz [1-4], which makes the RTD a promising device for SHF, EHF, and THF electronics.
- RTD operates in the range of temperatures and other external factors necessary for technical applications.
- Technologies and the equipment for RTD production exist at Russian enterprises producing heterostructural electronics devices.
- It is possible to control the shape of a current-voltage (IV) curve and create a diode with the optimum IV curve shape for the specific type of nonlinear conversion by changing the parameters of the heterostructure layers (thickness, chemical composition). The set of possible nonlinear transformations using RTD is very wide: generation of radio signals, frequency modulation, mixing of radio signals, amplitude detection, rectification, frequency labels grid generation and etc.

The extensive bibliography is devoted to the application of RTD as an active element of various wireless devices, in particular the benefits of using RTD for the micropower SHF signal mixers and rectifiers is shown in [5-8]. However, there are not many works devoted to the resistance of RTD to the destabilizing factor influence. This work is aimed at filling this gap, the main task of it is to research the thermal degradation of the IV curves of RTD.

2. Methods
Experimental research was carried out for the line of AlAs/GaAs RTD of 30 pieces. The diodes structure is shown in Figure 1. RTD consist of resonant tunneling structure (RTS) (active region, AlAs/GaAs layers), near contact regions (doped GaAs layers) and ohmic contacts.
The equivalent RTD circuit, whereby the IV curve kinetics analysis was carried out, is shown in Figure 2. $R_{OC}$ is the upper and lower ohmic contacts resistance; $R_{SCR}$ is near contact regions resistance; $R_{RTS}$ is the RTS resistance, which is nonlinear and is determined by the RTS quantum mechanical properties.

The total ohmic contacts resistance $R_{OC}$ is defined as

$$R_{OC} = \rho_c \cdot \frac{(S_{OC,U} + S_{OC,L})}{S_{OC,U} \cdot S_{OC,L}}$$

(1)

where $\rho_c$ – ohmic contact resistivity, Ohm·cm²; $S_{OC,U}$ and $S_{OC,L}$ – the upper and lower contacts areas, cm².

For experimental research, the technique of accelerated aging by means of the thermal annealing on the sample was used. The temperature of annealing was 300 ºC. The authors assumed that at this temperature, the failure mechanisms are the same as on normal operating conditions [9-10].

RTDs annealing was carried out on laboratory air thermostat, which provides to vary the temperature in the range from 40 to 300 ºC with accuracy ± 5 ºC. Total time of thermal annealing was 8 hours.

IV curve measurements of RTDs before and after thermal annealing were performed using microprobe bench, which consists of a microprobe device, power supply Agilent E3641A and personal computer. This bench provided IV curve measuring of the diodes in voltage range from 0 to 35 V (accuracy $\Delta U = \pm 1$ mV) and current range from 0 to 0.8 A (accuracy $\Delta I = \pm 10$ µA).

3. Results and discussion
RTD IV curves before and after the thermal annealing were measured, and the statistical analysis was performed. Dispersion of IV curves lies within the measurement error range. In Figure 3 only forward-bias region of IV curves, averaged over whole line, are shown.
As the result of degradation IV-curves shift on voltage axis was took place. IV curve changes could be caused by degradation processes in the resonant tunneling structure and contact areas as well as ohmic contact degradation.

In [11-12] it was indicated, that diffusion blur in the resonant tunneling structure affects RTD IV curve shape. Diffusion processes modelling the for the selected parameters of thermal impact [13] indicates that the diffusion blur of the researched resonant tunneling structure is negligibly small and does not change RTD IV curve shape significantly. This means that $R_{RTC}$ can be considered to be constant under the conditions of this experiment.

The diffusion blur of Si in the near contact region is more observable, but the analysis showed that it also does not significantly affect the series resistance and IV curve of RTD. $R_{NCR}$ is considered to be a constant under the conditions of this experiment.

Therefore, it is expected that RTDs IV curve shift under the experiment conditions is causes by an increasing of AuGeNi ohmic contact resistance as the result of its thermal degradation. The dependence of AuGeNi ohmic contact resistivity $\rho_c$ on time $t$ and temperature $T$ can be described by the following relationship:

$$
\rho_c = \rho_{co} + \chi \exp\left(-\frac{E_a}{2kT}\right) \cdot \sqrt{t}
$$

where $\rho_{co}$ – initial ohmic contact resistivity (after the production), Ohm·cm$^2$; $\chi$ – coefficient, depending on the design and technology of ohmic contacts, (Ohm·cm$^2$)/s$^{1/2}$; $E_a$ – activation energy, eV. Activation energy $E_a$ of degradation phenomena of AuGeNi ohmic contacts equals 1 eV [14]; $T$ – temperature, K; $k$ – Boltzmann constant ($k = 8,617 \times 10^{-5}$ eV·K$^{-1}$); $t$ – time, s.

![Figure 3. Experimental IV curves of RTDs before (1) and after (2) the thermal annealing.](image)

The technique was developed to determine the dependence of ohmic contacts resistivity $\rho_c$ on time and temperature and to estimate RTD’s time to failure at specified conditions. It is structurally composed of the following basic steps:

- RTDs IV curves measuring before and after the selected number of cycles of thermal annealing;
- RTS diffusion blur mathematic simulation;
- RTS IV curve mathematic simulation based on quantum-mechanical description;
- determination of the ohmic contacts series resistance increasing $\Delta R_{OC}$ after each cycle of thermal annealing;
\[
\Delta R_{OC} = \frac{\sum_{i=1}^{N} \Delta \bar{U}_i}{I_i} 
\]

where \(\Delta \bar{U}_i\) – difference in the voltage values of the averaged IV curves at a fixed current value \(I_i\) before and after of thermal annealing, \(N\) – IV curve points number;

- determination of \(\chi\) coefficient corresponding to a specific contact resistance change in (2).

The simulation of the RTS diffusive blurring and IV curve is necessary to confirm the fact that the change in the diode IV curve caused by the RTS degradation is much less than its changes caused by the contact degradation. Otherwise, it is necessary to separate the change in the RTD IV curve caused by the RTS degradation from changes caused by contact degradation. The RTS degradation of the investigated diodes is small under the experiment conditions, therefore, it is not considered in this work.

As a result of the processing of experimental data the coefficients \(\chi\) was determined, which shows the degradation velocity of ohmic contacts. It was equal \((2.95 \pm 0.01) \times 10^3\) (Ohm·cm\(^2\))/s\(^{1/2}\) for the investigated line of diodes.

Under the assumption of a high-quality manufacturing of resonant tunneling structure, the developed technique allows to control manufacturing quality of ohmic contacts and to forecast RTD reliability (for the gradual degradation) and devices based on it. In addition, this technique will also be useful in developing new ohmic contacts.

4. Conclusion

RTDs IV curve shift under the experiment conditions is basically causes the ohmic contacts degradation. Obtained dependence of ohmic contact resistivity on time and temperature can be used for determination of RTD IV curve kinetics and to forecast the reliability of resonant tunneling diodes and devices based on it and for the low degradation ohmic contacts engineering.

The resonant tunneling structure degradation of the researched RTD is small under the experiment conditions. Nevertheless, Al and Si diffusion rate will be higher if the semiconductor heterostructure imperfection is higher. That can cause more severe and rapid changes of RTD IV curve shape and indices of devices based on RTD. In this case it is necessary to take into account not only ohmic contacts degradation, but also RTS degradation, for prediction the reliability of RTDs and devices based on it.

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