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Radiation hardness of AlAs/GaAs-based resonant tunneling diodes

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Abstract. The total dose effects of ^{60}Co γ-radiation on the electrical properties of double-barrier Resonant Tunneling Diodes have been studied. The devices manifest enhanced radiation hardness and conserve their operating parameters up to doses of 2×10^9 rad. It is shown that all changes in the current-voltage characteristics stem from the effect of ionizing radiation on the undoped layers. The radiation-stimulated diffusion of the heteropair components in the contact region is shown to be important for the voltage drop distribution.

Keywords: resonant tunneling, γ-irradiation, defects.

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1. Introduction

In recent years some semiconductor compounds, especially GaAs and AlAs as basic materials for microelectronic devices, have been investigated intensively in anticipation of their high tolerance to ionization radiation.

On the basis of defect kinetics it is believed that the irradiation dose rate must be considered when the effects are discussed in detail, owing to the fact that the formation probability for defect-defect or defect-impurity complexes strongly depends on the density of initial defects. The number of defects produced per unit time by γ-quanta in conventional ^{60}Co irradiation is substantially lower than that produced by high-energy electrons from accelerators. Therefore the effects of irradiation with high-energy electrons and γ-quanta are expected to be different. The γ-irradiation effects in GaAs both bulk material and epitaxial layers have been studied extensively during the last two decades [1-7]. It has been reported that low-dose γ-irradiation introduces shallow defects lying about 20 meV below the conduction band edge and acting as donors. At higher doses deep traps are introduced lying about 0.13 eV below the conduction band edge. The charge carrier removal in this case can be described by the following relation [6]:

$$\Delta N(\mathrm{cm}^{-3}) = 9.92\times10^{5}\, D^{1.17}\ (\mathrm{rad}), \qquad (1)$$

where D is the irradiation dose in rad (GaAs).

Further studies indicate that the charge carrier removal appears to change almost linearly with dose, the proportionality factor being about 3.02×10^7 cm^{-3}/rad (GaAs). Taking into account that the charge carrier removal does not depend significantly on the initial carrier concentration, it becomes obvious that in the heavily doped layers the effect of γ-irradiation is hardly noticeable at doses below 10^7 rad (GaAs).

The study of the γ-irradiation effects in AlGaAs is still limited. In [8] the DLTS method was used to determine the traps introduced by γ-irradiation in AlGaAs layers. In all the DLTS spectra the DX centers were present, having a constant concentration. At the same time the concentration of traps with activation energy about 0.78 eV increased with the γ-quanta dose. In other samples where such traps were not present the concentration of the interface defects associated with the DX centers was found to increase upon irradiation [9]. Taking these factors into account, the authors of [10] concluded that for the γ-irradiation doses up to 10^6 rad

(GaAs) the concentration of the displacement defects in heavily doped AlGaAs layers is not detectable.

For the AlGaAs/GaAs heterojunction changes in the concentration of the interface states or of some background defects can be observed upon γ-irradiation. Therefore, the defects that are introduced in the buffer and spacer layers, as well as at the heterojunction interface, may be considered to be responsible for the degradation of the 2DEG concentration and mobility, i.e. of the device current.

The subject of radiation effects in semiconductor devices is complex because several types of semiconductor devices, radiations and radiation effects must be considered. Moreover, when studying the effect of irradiation on semiconductor devices, one has to distinguish the transient, or dose-rate, effects and the effects of the total dose of ionizing radiation. The above effects change the device operation parameters in different ways, depending on the device structure and principle of action. To illustrate, high dose rate or transient radiation generates high photocurrents in Silicon. These photocurrents can cause temporary logic upset or can trigger latchup [11]. At the same time both MOS and bipolar circuits exhibit high sensitivity to the total dose radiation. For Resonant Tunneling Diodes (RTDs) the presence of many thin layers having different doping levels, gaps and interfaces can lead to unusual changes in electrical parameters under irradiation. The experimental data concerning these systems are confined, in our knowledge, by the papers on electron [12] and neutron [13] irradiation and ion implantattion [14]. Due to this reason we will discuss in present communication some effects of ^{60}Co γ-radiation on the electrical properties of double-barrier RTDs. Our attention will be focused mainly on the total dose effects.

2. Experimental procedure

The vertical electron transport in the double-barrier RTDs based on AlAs/GaAs/AlAs has been investigated. Forward, as well as reverse, bias voltages have been applied to the devices. The 16×16 μm^2 devices were fabricated from the structure MBE-grown on the n^+-GaAs (100) substrate. The layer sequence in the structure was as follows: (i) a doped (N_{Si} = 10^{18} cm^{-3}) n^+-GaAs layer (100 nm thick) adjacent to the substrate; (ii) an undoped GaAs spacer layer (about 100 nm thick); (iii) an undoped AlAs barrier (2 nm thick); (iv) an undoped GaAs well (4 nm thick); (v) an undoped AlAs barrier (2 nm thick); (vi) a doped (N_{Si} = 10^{18} cm^{-3}) n^+-GaAs layer (100 nm thick) serving as a top contact layer. The Au-AuGe ohmic contacts were fabricated on the mesa surface and on the substrate. The *I-V* curves were taken in the quasistationary mode (both voltage pulse duration and repetition time were 10 μs) at temperatures of 77 and 300 K. γ-irradiation (twelve dosage points from 10^5 to 2×10^9 rad, the γ-quanta average energy being about 1.2 MeV) was performed in a ^{60}Co irradiator at room temperature. The device temperature during irradiation did not exceed 40 °C. All measurements were made within several hours after irradiation procedure.

3. Experimental results and discussion

The *I-V* curves taken before and after γ-irradiation are shown in Fig. 1. The forward bias corresponds to the voltage polarity when electrons are injected from the spacer side. The estimates of the voltage drop across the structure enable one to conclude that the first and the second peaks for both forward and reverse biases are due to the alignment of the energies of incident electrons and the quasibound states in the well. In most structures the third peak appeared for the forward bias at a helium temperature. This peak stems from the accumulation layer formation before the emitter barrier [15].

At the first stage of γ-irradiation (doses up to 10^8 rad) there were no visible changes in *I-V* curves. (It should be noted that the equivalent doses of the electron irradiation caused the conversion of the conductivity type in the bulk GaAs material [16].) In our structures visible

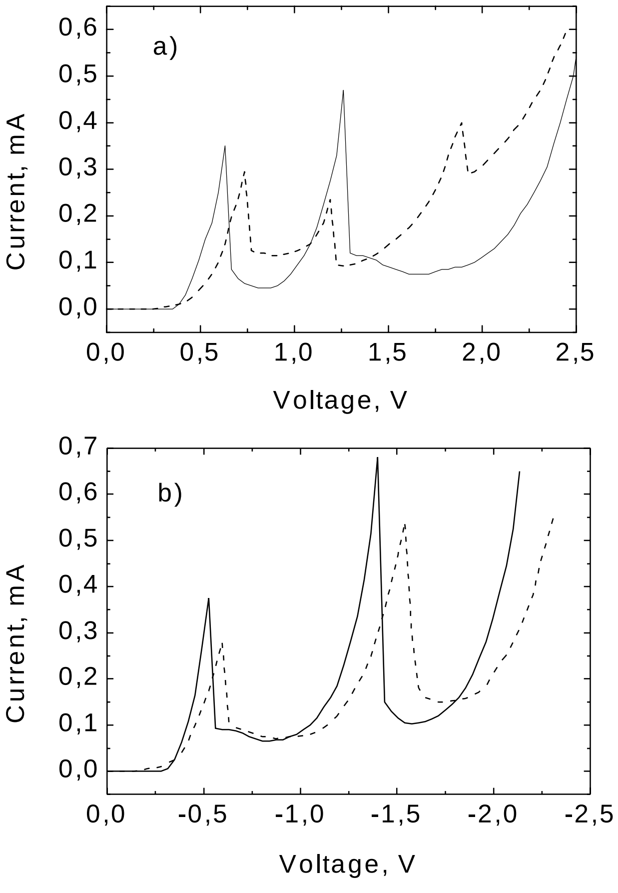

Fig. 1. Current-voltage characteristics of resonant-tunneling diode under forward (a) and reverse (b) biases measured at 77 K. Solid lines correspond to non-irradiated device, dashed lines correspond to the device irradiated by γ-quanta with total dose of 2×10^9 rad.

changes of parameters could be observed only at the doses over 10^8 rad. Moreover, the RTD principal parameters, such as the peak current, I_p, and the peak-to-valley current ratio, I_p / I_v, were improved after irradiation. Really, it is seen from Fig. 2, if the initial I_p / I_v value was equal on the average to 5 at 77 K, then after irradiation it increased by up to 15 % (due mainly to the I_v decrease) at doses of 5×10^8 rad. But starting from the total dose of 10^9 rad we have observed only decrease of the RTD principal parameters. The peak-to valley current ratio (PVCR) dropped by a factor of 3 at a dose of 2×10^9 rad, as compared to its value at a dose of 3×10^8 rad.

Dashed lines shown in Fig. 1 are the *I-V* curves taken after the total dose of 2×10^9 rad. One should note the appearance of the third peak at 77 K, while for the non-irradiated devices this peak was observed at helium temperatures only. In the structures studied the above peak appears at 1.6 V after the total dose of 10^8 rad. The peak and valley current values corresponding to the third resonance increase monotonously with the further γ-irradiation.

Comparing the data obtained for the forward and reverse biases one can conclude that γ-irradiation causes more pronounced changes in the *I-V* curve shape when the charge carriers are injected from the spacer side. For example, the valley current increase for the forward bias is three times bigger than that for the reverse bias. The peak-to-valley current ratio for the first resonant peak (forward bias) drops by a factor of 2.6 as compared to the case of the non-irradiated samples; for the reverse bias this factor was only 1.4. The voltage peaks are shifted under irradiation toward the higher voltages excluding the second peak for the forward bias whose position remains practically the same (Fig. 3) . At the same time the first and the second peaks become wider and lower.

It was stated before that the RTD studied presented a sequence of thin layers with different doping levels. Generation of the radiation defects in semiconductor materials under irradiation is accompanied by the majority charge carriers removal [17]. Taking into account that the removal rate remains constant (about 0.01 cm^{-1}) in a wide range of dopant concentrations in the case of γ-irradiation, we can conclude that the layers with the dopant concentrations over 10^{17} cm^{-3} do not appreciably change their electrical properties up to the total dose of 10^9 rad. Thus, all the changes in the *I-V* curves stem from the effect of ionizing radiation on the undoped layers. In this case potential profile of the active part of the structure (barrier-well-barrier) is raised slightly with respect to the heavily doped contact layers. This, in its turn, leads to the increase of the peak voltage, V_p, as well as to the drop in the peak current, I_p. The exponential dependence of the thermoactivated current can be seen quite well in the *I-V* curves taken at the reverse bias.

Another effect of γ-irradiation is also important. It was found recently [18] that γ-radiation treatment results in a considerable decrease of resistivity of the Au-AuGe contacts. This effect was explained by the intense Ge diffusion into GaAs and Ga dissolving in the gold layer. Really, as a result of the radiation-stimulated diffusion of the heteropair components, the concentration depth profiles of Ge, Au, Ga and As in the transition region change. The concentration depth profiles in the transition region were taken with XPS combined with layer-by-layer ion etching. Considerable changes in these profiles were observed at irradiation doses of 10^9 rad. Typical concentration depth profiles of the components of AuGe-GaAs contact pair, taken before and after its exposure to ^{60}Co γ-irradiation are shown in Fig. 4. One can see that γ-radiation considerably affects the parameters of the contact transition region. Unfortunately, we cannot plot this graph in the layer thickness scale because of variable sputtering rate for different materials and, especially, due to possible interphase interaction. Neverthe-

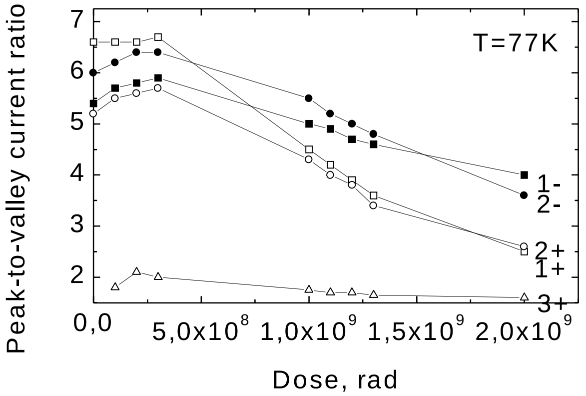

Fig. 2. Peak-to-valley current ratio versus radiation dose measured at 77 K. Numbers correspond to resonant peaks at forward (+) and reverse (-) biases.

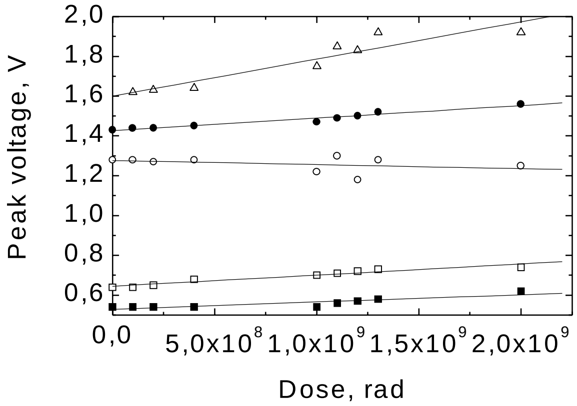

Fig. 3. Peak voltage position versus radiation dose measured at 77 K. Solid and open symbols correspond to the first (squares), second (circles), and third (triangles) peaks observed under forward and reverse biases, respectively.

less, it was established that a considerable mass transfer occurs across the metal-semiconductor interface. The estimates performed with due regard for the layers thickness in an approximation of constant sputtering rate showed that the diffusion from the substrate side may be neglected. On the other hand, the diffusion from the top contact layer side shifts the interface between the n^+ and n layers toward the barrier. The position of the virtual cathode at forward biases shifts in the same manner. The radiation-induced diffusion not only affects the spacer potential profile but also amplifies the charge carrier scattering by defects. And the latter causes a decrease in the amplitudes of the first two resonant peaks, an increase of the valley currents and also leads to the appearance of the third peak (whose amplitude increases with the total dose) even at 77 K. We also have to take into account scattering effects on resonant tunneling in double-barrier heterostructures. The recent calculations [19] showed that scattering centers induced by irradiation result in a shift in the position of the transmission probability peak, give rise to a reduction of the peak current value, and lead to a broadening of the resonant peak. This is in agreement with experimentally observed changes of I-V characteristics.

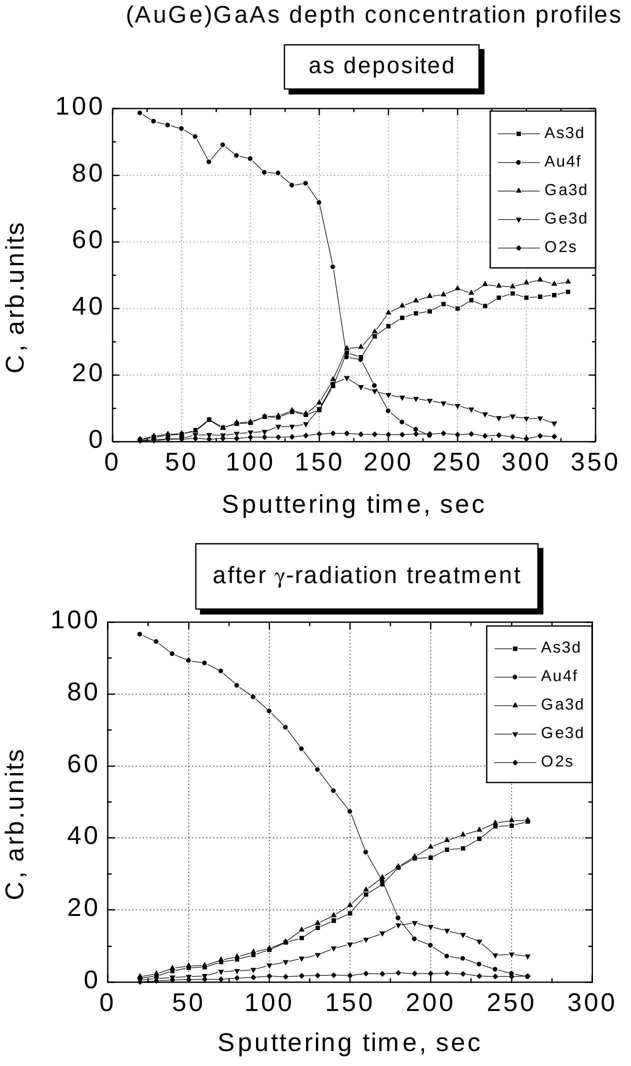

Fig. 4. Concentration profile of components distribution in AuGe-GaAs contact before (a) and after (b) irradiation by γ-quanta with total dose of 2×10^9 rad.

4. Summary

It is shown that Resonant Tunneling Diodes manifest higher radiation hardness in comparison with HEMT, FET, and other devices based on parallel transport. A certain improvement of the RTD operational parameters that was observed in the 10^8 to 5×10^8 rad dose range can be understood if one takes into account the following arguments. On the one hand, even the undoped layers have the residual impurity concentrations about 10^{15} cm^{-3} and the effect of the charge carrier removal does not manifest itself. On the other hand, the structural ordering of native defects is possible.

Acknowledgements

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