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Original paper

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THE PROTON FLUX INFLUENCE ON ELECTRICAL CHARACTERISTICS OF A DUAL-CHANNEL HEMT BASED ON GAAS

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Abstract. The results of the simulation the influence of the proton flux on the electrical characteristics of the device structure of dual-channel high electron mobility field effect transistor based on GaAs are presented. The dependences of the drain current I_D and cut-off voltage on the fluence value and proton energy, as well as on the ambient temperature are shown.

Keywords: HEMT, GaAs, proton fluence, displacement effects, nonionizing energy loss, simulation.

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Introduction

The Element base of modern objects of space and nuclear technology is exposed to ionizing radiations, the primary of which are gamma rays (γ), neutron (n), electron (e), and proton (p) radiations. Alfa-particles (α), fission fragments F_p, and other particles from a nuclear reactor or nuclear explosion zone can also influence the degradation of performance characteristics. However, their influence is not so significant (for example, neutrinos, mesons, etc.) [1].

When a particle flux affects a microelectronic device structure, two main mechanisms are possible: ionization and damages caused as a result of elastic scattering of primary particles and fragments formed in nuclear reactions (inelastic scattering) of incident protons or neutrons on target's nucleuses. Ionization is not considered in this work. Neutrons, protons, alpha particles, heavy ions, and photons with very high energies cause displacement effects: the arrangement of atoms in the crystal lattice changes and the number of recombination centers (defects) increases, decreasing the concentration of free charge carriers and deteriorating the performance of device structures.

The parameters of the bulk material most sensitive to the effects of displacements are the lifetime and diffusion length of minority charge carriers, the mobility and concentration of charge carriers [2].

The magnitude of the manifestation of displacement effects depends on the type of particle radiation, the total dose, radiation flux and energy, ambient temperature, operating voltage, as well as the state of the device at the moment of irradiation. These problems complicate testing, increase the complexity of using theoretical calculations to predict radiation effects, increase the time of designing device structures and require a significant number of test samples. In modern computer-aided design systems in microelectronics like Silvaco [3] and Synopsys [4], the modules for accounting for displacement effects are implemented, which require adjustment and calibration.

Thus, the paper represents the results of evaluating the processes of degradation of the electrical characteristics of device structures dual-channel high electron mobility field effect transistor (HEMT) based on GaAs under the influence of the proton flux by means of a computer simulation.

Dual-channel GaAs-HEMT device structure and experimental technique

A typical device structure of a dual-channel GaAs-HEMT is shown in Fig. 1. The cut-off voltage and drain current for the resulting structure at ambient temperature $T = 303$ K are equal to $V_{TH} = -0.9$ V and $I_D = 0.48$ mA (at drain voltage $V_D = 1$ V and gate $V_G = 0$ V), respectively.

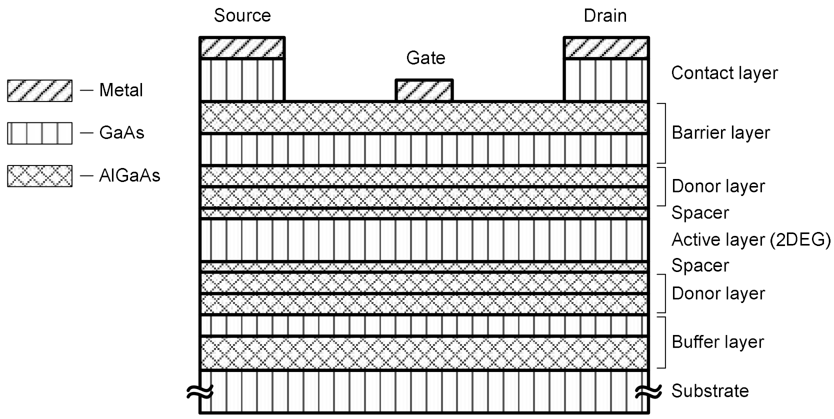


Fig. 1. Device structure of a dual-channel GaAs-HEMT

Fig 2. shows an energy diagram of the region under the gate for a device structure of a dual-channel GaAs-HEMT.

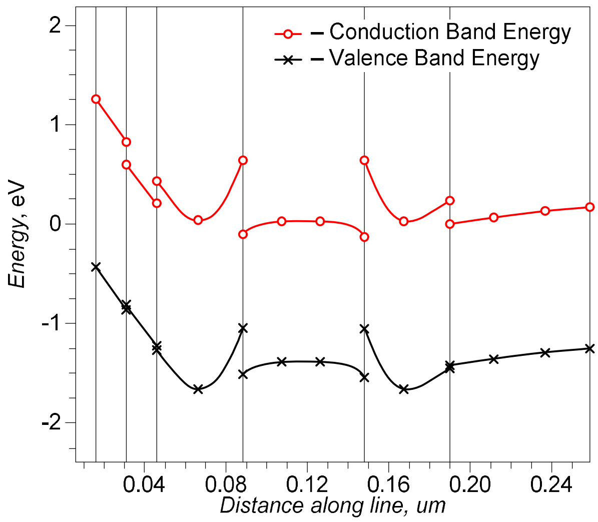


Fig. 2. Energy diagram of the region under the gate for a device structure of a dual-channel GaAs-HEMT

To predict the degradation of device parameters caused by penetrating radiation, it is often sufficient to consider only the first stage of the defect formation process. The formation of bulk defects in a semiconductor device structure is proportional to a *non-ionizing energy loss* (*NIEL*) – the total kinetic energy transferred to the lattice atoms. In modeling and calculations, in addition to the *NIEL* parameter [MeV·cm^2/g], the term kinetic energy released in matter *Kinetic Energy Released in Material* (*KERMA*) is also used. The relationship between *KERMA* and *NIEL* can be written as

$$KERMA = NIEL \cdot F \cdot m, \qquad (1)$$

where F – integral radiation flux (fluence), cm^{-2}; m – mass of irradiated material, g.

Parameter *NIEL* can be used to the extrapolation of a device parameter degradation measured for a particle with the given energy to other energies ("NIEL scaling"). The Radiation Fluence Model is used in the microelectronics TCAD software packages to describe the impact of particle flux on material characteristics, which makes it possible to predict the rate of defect generation. According to the model the total density of defect states depends on the radiation flux, *NIEL*, damage coefficient, and the density of material.

The non-ionizing energy losses for GaAs are determined using the SR-NIEL[5] project for displacement threshold energy values E_{d1} = 9,5 eV [6], E_{d2} = 10 eV [7], E_{d3} = 21 eV [8], and E_{d4} = 25 eV [9]. For the obtained values, mean values were determined, which are described by approximating dependence (Fig. 3).

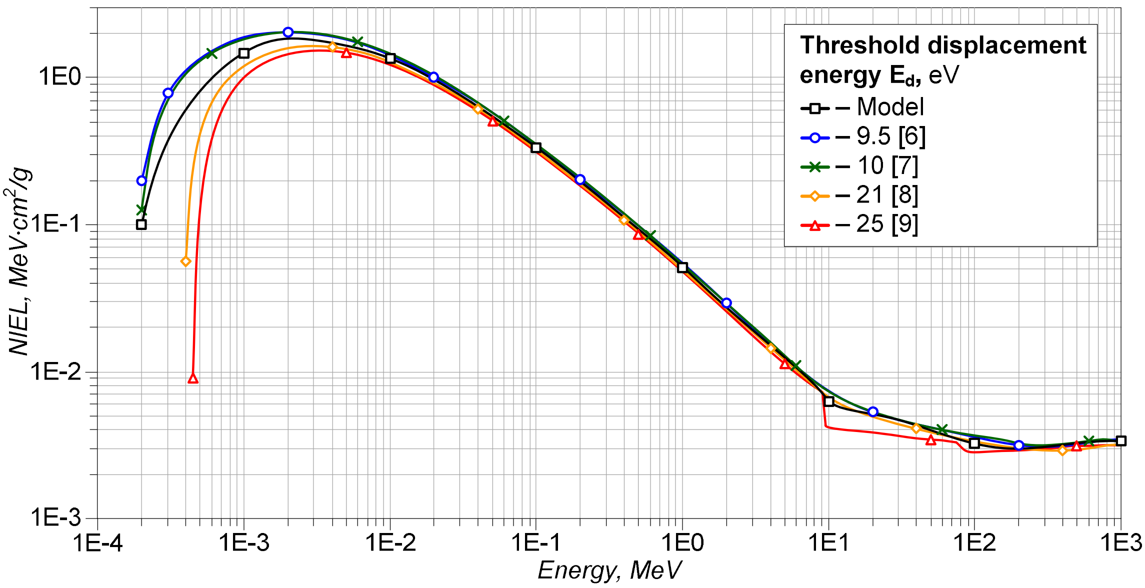


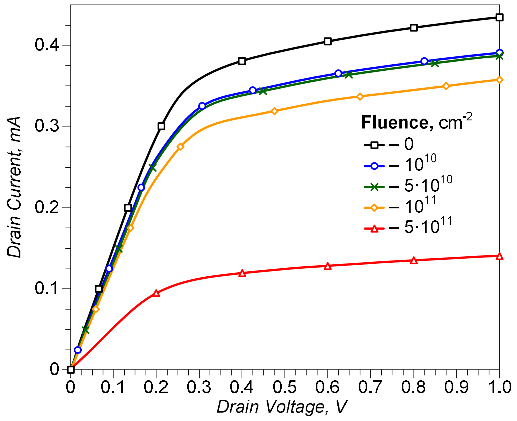
Fig. 3. The dependence of non-ionizing energy loss on the proton energy

The obtained results fully agree with the data presented in the paper [10]. The total NIEL for GaAs is calculated by summing the contributions of each element weighted by its atomic fraction [11].

The simulation of the effect of a proton flux on the performance of a device structure of a dual-channel GaAs-HEMT is carried out. The results of the influence of the flux of protons with an energy of E = 2 keV at the temperature of T = 303 K are shown in Fig. 4.

Fig. 5 shows the graphs of the dependence of the drain current I_D (at V_G = 0 V and V_D = 1 V) and the cut-off voltage on the fluence of protons F with energy E = 2 keV. The parameters are expressed in relative units (the values without penetrating radiation are taken as 100 %).

It is shown that the effect of the proton fluence on the values of the drain current and cut-off voltage does not coincide in magnitude, however, starting from values of 10^{12} cm^{-2}, a significant deterioration in the operational parameters of the transistor is observed. So, at F = 10^{12} cm^{-2}, the drain current and cut-off voltage are 0.357 mA and –0.757 V, respectively, and at $F = 5 \cdot 10^{12}$ cm^{-2} – I_D = 0.243 mA (decrease by 32.4 %) and V_{TH} = –0.698 V (7.8 %). The dependence of the drain current and cutoff voltage deviation obeys the linear law (approximation reliability R_2 = 0.993 for I_D and R_2 = 0.996 for V_{TH}).



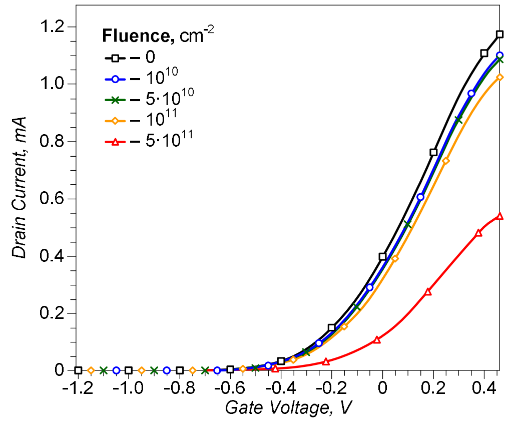


Fig. 4. *I–V* characteristics with a change in the fluence of protons with an energy of $E = 20$ keV:
a – Drain-Drain; *b* – Drain-Gate

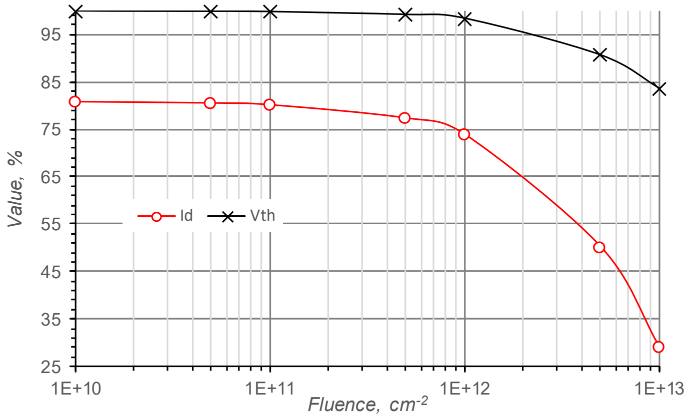


Fig. 5. Dependence of the parameters of dual-channel GaAs-HEMT on the proton fluence F
(energy $E = 2$ keV, temperature $T = 303$ K)

Also noteworthy is the different effect of the proton flux on the drain current at different drain voltages (Fig. 6). At proton fluence $F < 5\times10^{12}$ cm^{-2}, its effect on the drain current is higher, the lower the drain voltage is. This is especially noticeable when the voltage at the drain is $V_D < 0.3$ V. At values of the proton fluence $F \geq 5\times10^{12}$ cm^{-2}, there is a shift in the voltage at the drain, at which the effect of radiation is the greatest. It is recommended to limit the use of low drain voltages at the circuit level to increase the radiation resistance of devices using the considered instrument structures.

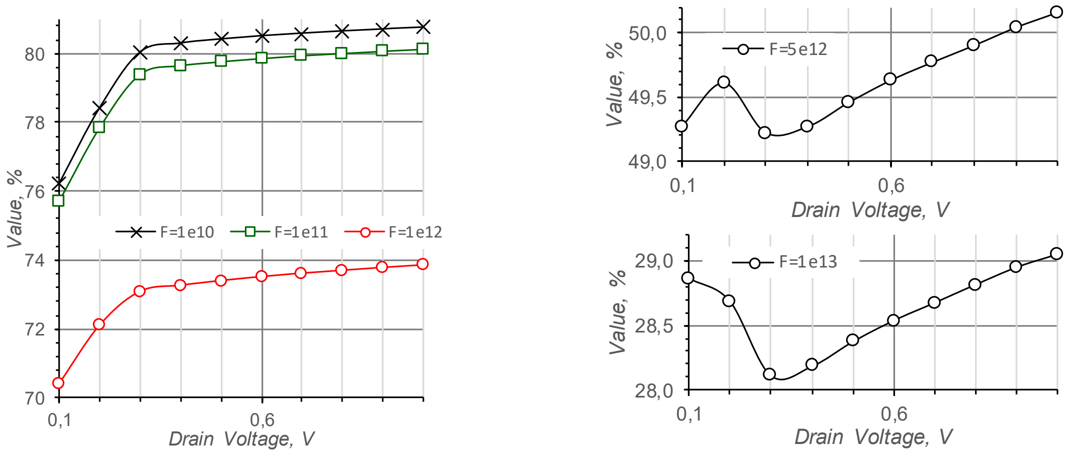


Fig. 6. Drain current versus drain voltage at proton fluence values (energy $E = 2$ keV, temperature $T = 303$ K):
a – $F < 5\cdot10^{12}$ cm^{-2}; *b* – $F \geq 5\cdot10^{12}$ cm^{-2}

Fig. 7 shows the graphs of the dependence of the drain current and cutoff voltage on the value of the proton energy E for the fluence $F = 10^{12}$ cm^{-2}.

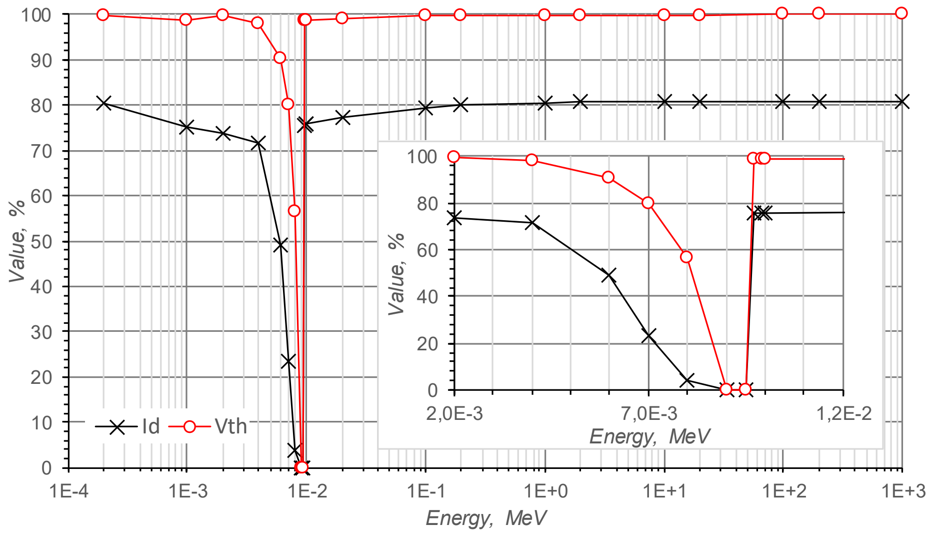


Fig. 7. Dependence of the parameters of a gallium arsenide field-effect transistor on the proton energy E (fluence $F = 5 \cdot 10^{10}$ cm^{-2}, temperature $T = 303$ K)

Based on the simulation results, it was found that the proton energy has the greatest effect on the electrical characteristics of a gallium arsenide field-effect transistor in the range from hundreds of eV to 100 keV, which correlates with the data presented in Fig. 3., with the exception of the energy range from 4 to 10 keV (i. e., when E is 6 keV higher than expected), at which there is a strong degradation of the electrical properties of the device structure up to a failure. At energies E greater than 1 MeV, the deviation of the parameters from the values without irradiation does not exceed 20 % for the drain current and 0.1 % for the cutoff voltage.

Conclusion

The model of the dependence of NIEL on the proton energy with different values of the threshold energy of defect formation for GaAs and AlGaAs, that are described in the literature and comply with the latest theoretical and experimental data, has been developed.

The analysis of the simulation results of the effect of the proton flux on the device structure of a dual-channel GaAs-HEMT allows us to reach the following conclusions: the proton fluence has a different effect on the drain current and cutoff voltage (the ratio of the degradation effect that increments $\Delta I_D / \Delta V_{TH}$ is not constant and varies from 4,07 to 6,19 for the cases under consideration); the energy of protons has the greatest influence in the region from hundreds of eV to 100 keV (up to the failure of the transistor). To increase the radiation resistance of devices using the considered device structures, it is recommended to provide protection from the proton flux in a narrow energy band (from 4 to 10 keV), and at the circuit level to limit the use of low voltage values at the drain.

References

1. Kulakov V.M., Ladygin E.A., Shahovcov V.I. The effect of penetrating radiation on electronic products. M. : Sov. Radio; 1980. (In Russ.)
2. Allam E.E., Inguimbert C., Meulenberg A., Jorio A., Zorkani I. Gamma non-ionizing energy loss:Comparison with the damage factor in silicon devices. Journal of Applied Physics. 2018;123 (095703):1-5.
3. Silvaco International. Victory Device : User Manual, Santa Clara : Silvaco; 2019.
4. Synopsys Inc. Sentaurus Device : User Guide, Version L-2016.03. San Jose : Synopsys; 2016.
5. Site of the SR-NIEL project [Electronic resource]. – Access mode: http://www.sr-niel.org/index.php.

6. Mansouri E. Studies on Radiation-induced Defects in InP/InAsP Nanowire-based Quantum Disc-in-wire Photodetectors. Halmstad : Halmstad University; 2018.
7. Pons D., Mooney P.M., Bourgoin J.C. Energy Dependence of Deep Level Introduction in Electron Irradiated GaAs. J. Appl. Phys. 1980;51:2038-2042.
8. Allam M.E., Inguimbert C., Nuns T., Meulenberg A., Jorio A., Zorkani I. Gamma and Electron NIEL Dependence of Irradiated GaAs. NSREC. 2016:7.
9. Claeys C., Simoen E. Radiation effects in Advanced Semiconductor Materials and Devices. Berlin: Springer; 2002.
10. Chen N., Gray S., Hernandez-Rivera E., Huang D., LeVan P. D., Gao F.. Computational simulation of threshold displacement energies of GaAs. Journal of Materials Research. 2017; 32(8):1555-1562.
11. Ziegler J.F., Biersack J. P., Littmark U. The Stopping and Range of Ions in Solids. Pergamon; 1985.

Authors' contribution

Lovshenko I.Yu. developed a model of the dependence of NIEL on the energy of protons, prepared the manuscript of the article.

Voronov A.Yu., Roshchenko P.S., Ternov R.E. performed computer calculations and processed the obtained data.

Galkin Ya. D., Kunts A. V. has simulated and took part in measuring device parameters.

Stempitsky V.R. and Bi Jinshun set a task for the study and analyzed the results.

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