Radiation hardness of bipolar transistor based integrated circuits improved by ECR hydrogen plasma treatment and Si-wafers gettering

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Received December 19, 2022
Revised April 4, 2023
Accepted April 5, 2023

We demonstrate significant improvement of the radiation immunity of the integrated circuits based on silicon bipolar transistors. Strong decrease of the current gain degradation and significant yield improvement after high-energy gamma irradiation are both shown. This was achieved by development of efficient hydrogenation process for the silicon bulk and the surface dielectric layer using electron cyclotron resonance (ECR) plasma, as well as implementation of effective Si-wafer gettering option.

Keywords: integrated circuits, bipolar transistors, ECR-plasma, hydrogenation of semiconductor structures, trap state passivation, gettering of semiconductor wafers, γ-irradiation, radiation hardness, yield of workable transistors.

DOI: 10.21883/SC.2023.03.56235.4467

1. Introduction

Bipolar transistors are widely used in modern analog and mixed signal integrated circuits (IC) due to their high current gain and low leakage current, as well as excellent compatibility with CMOS technology (complementary metal–oxide–semiconductor). For some special applications, bipolar transistors should be highly resistant to exposure to high energy neutrons, electrons and γ-quanta [1–8]. The deterioration of gain upon irradiation is mainly caused by the formation of point defects and their complexes in the semiconductor lattice [9,10]. These defects act as recombination centers and therefore shorten the minority carrier lifetime. Another key reason for gain degradation is the effect of ionization in a passivating dielectric layer such as silicon oxide or silicon nitride [11]. Irradiation-induced charges in the dielectric and at the interface with the semiconductor, especially the charges formed in the passivating dielectric layer covering the emitter-base junction region, cause an increase in the surface recombination rate of minority carriers, which leads to a decrease in the gain [12]. The degradation of the current amplification factor of a bipolar transistor during irradiation depends on the dose, energy and type of radiation. It also depends on the type and structure of the transistor, for example, vertical $n-p-n$ transistors show a significant decrease in gain, while $p-n-p$ transistors are relatively resistant to ionising radiation [13]. In turn, the type and concentration of recombination centers in the semiconductor lattice strongly depend on the type and concentration of electrically active impurities, for example, phosphorus and boron [14]. Electrically inactive impurities, such as oxygen and carbon, during irradiation interact with the formed vacancies and interstices to form effective recombination centers [15]. In addition, point defects formed during irradiation can interact with metal impurities, for example, copper [16] and nickel [17]. As a result of such an interaction, new defects with deep levels can be formed, which contribute to a decrease in the lifetime of minority charge carriers. The ability of atomic hydrogen to reduce the rate of defect generation upon irradiation and to passivate radiation defects in the silicon lattice is widely used to improve the radiation resistance of bipolar transistors. Pretreatment of silicon in hydrogen plasma leads to a significant increase in its radiation resistance and a decrease in the annealing temperature of radiation defects [18]. Meanwhile, the introduction of hydrogen before irradiation makes the devices more sensitive to ionising radiation, which leads to some decrease in the current amplification factor [19].

2. Research methods

Commercially available ICs with an analog voltage comparator, which were fabricated on Si-wafers using bipolar technology, were chosen as the object of study.

Hydrogenation of Si-plates was carried out under conditions of electron cyclotron resonance (ECR) plasma on a laboratory assembly facility with controlled energy $\varepsilon = 0-160$ eV of ions H_2^+ and protons H^+. An ECR plasma with a generation frequency of 2.45 GHz was maintained in a mixture of hydrogen and argon. The gas mixture was injected coaxially symmetrically into a chamber 150 in diameter and 160 mm in length, in which the ECR conditions were maintained. The silicon plate was installed in a substrate holder located coaxially at a distance of 120 mm from the exit of the ECR chamber. A high-frequency (HF) voltage with a frequency of 13.56 MHz was

applied to the substrate holder relative to the body of the ECR plasma setup. Under the action of a force pulse from the HF field, the displacement amplitude of the electron gas cloud is M_i/m_e times higher than the displacement amplitude of the ion array. As a consequence, relative to the neutral plasma Si-substrate is charged by a negative bias potential U_b, the value of which is determined by the amplitude of the RF field. The energies of ions and protons attacking the sample surface were fixed by the displacement potential: $U_b = 0-(-160)$ V. The optimal conditions for ECR plasma treatment were selected by varying the substrate temperature $T = 40-300^\circ$C, microwave power $W = 50-200$ W, pressure $P = 0.1-2.5$ mTorr, and the ratio $R = 0.2-1.0$ flux H_2/Ar.

External gettering was carried out by grinding the backside of the Si-wafer, followed by heat treatment in an argon atmosphere and sputtering of amorphous silicon. The grinding conditions were fixed in the optical workshop.

The „Cobalt-60" station was used as a source of γ-radiation. To accumulate the required irradiation dose, Si-wafers with ICs were placed on a calibrated pad in the bunker of the „Cobalt-60" station.

All electrophysical measurements were carried out on an automatic probe EM-6190A, which is installed on the production control line IC.

To study the effect of plasma and radiation treatment on the amount of charge in dielectric layers, test MDS (metal–dielectric–semiconductor) $Si/SiO_2/Al$ and $Si/Si_3N_4/Al$ structures with a thickness 50 nm of SiO_2 layer and 80 nm of Si_3N_4 layer were formed on Si-wafers. Test MDS structures were fabricated by depositing aluminum contacts with a diameter of 500 μm on the surface of SiO_2 and Si_3N_4 by thermal vacuum deposition. The fixed charge in the dielectric and the interface charge at the semiconductor/dielectric interface were studied by the method of high-frequency capacitance-voltage (C–V) technique [20] using an EG&G PAR-410 capacitance meter with a test frequency 1 MHz.

3. Research results

In the present article, we demonstrate a significant improvement in the radiation resistance of silicon bipolar transistors. Reducing the degradation of the current gain under γ-irradiation was achieved by developing an efficient hydrogenation process aimed at reducing the rate of generation of radiation defects in silicon and at changing the charge concentration in the passivating dielectric layer. In addition, to reduce the concentration of metallic impurities such as copper and nickel, an effective gettering option was implemented at an early stage in the manufacture of the device.

Metallic impurities can be easily introduced either during crystal growth or at various stages of wafer processing (e.g. polishing) and device manufacturing [21]. These impurities are also difficult to detect unless they interact with other lattice defects, especially irradiation-induced defects, and do not form electrically active complexes with deep levels [16,17]. The paper shows that the combination of efficient gettering and hydrogen plasma treatment is a very reliable solution for improving the yield and functionality when irradiating integrated circuits based on bipolar transistors.

At interaction of γ-quanta with the material of a semiconductor wafer, electron-hole pairs and Compton electrons are formed. The energies of Compton electrons are comparable to the energy of γ-quanta. Compton electrons most likely experience inelastic scattering on electron shells, which causes ionization of atoms. Another inelastic process is a short-term (for the time of several periods of valence vibrations) breaking of a chemical bond between a pair of atoms $\equiv Si\cdots Si\equiv$ in the crystal lattice. Due to the elastic Coulomb interaction with the nuclei of atoms, for Compton electrons, a process is also possible in which the energy transferred to the atomic nucleus is sufficient to break all chemical bonds of the target atom (four bonds for a Si atom). If after such a „release" the energy exceeds the threshold energy, this atom is displaced, penetrating into the interstice as an interstitial atom. At the site where the atom was before the interaction with the Compton electron, a vacancy is formed.

Vacant nodes, interstitial atoms and short-term breaks of chemical bonds form a group of primary (point) structural defects in a crystalline body, induced by the action of γ-irradiation.

Copper and nickel are strong valence electron donors. Under certain conditions, copper and nickel atoms are able to interact with silicon atoms to form an ionic chemical bond. Initially, these atoms are dissolved in the interstices of the crystal lattice and move by jump diffusion in the bulk of the semiconductor wafer.

We assume that the following processes occur in the crystal structure of a semiconductor wafer with the participation of nickel and copper: When IC is introduced into the radiation field, the generation of primary structural defects is switched on. A copper or nickel atom forms an ionic chemical bond $\equiv Si-Cu$ or $\equiv Si-Ni$ with a silicon atom, if such atom $\equiv Si\cdot$ with a dangling covalent bond $(\cdot)$ is nearby. Both the valency of copper and the most probable valency of nickel are two. Consequently, these atoms are able to integrate between silicon atoms with the formation of two ionic bonds $\equiv Si-Cu-Si\equiv$ or $\equiv Si-Ni-Si\equiv$, if the short-term broken bond $\equiv Si\cdots Si\equiv$is nearby. Thus, as the irradiation dose is accumulated, new stable defects with deep levels in the forbidden energy gap of the semiconductor are also accumulated. As a consequence, the lifetime and the number of minority charge carriers decrease. The lifetime of minority charge carriers is determined not by direct zone-to-zone recombination, but through the energy levels of traps located in the forbidden energy gap.

The gettering option was implemented on a series of experimental Si-wafers, which were then processed to the metallization stage along with control wafers from the

same batch. Before metallization, the wafers with the gettering option, as well as a number of control wafers, were subjected to ECR plasma treatment, the purpose of which was to introduce hydrogen into the volume of the silicon wafer and control the charge concentration in the surface passivation bilayer SiO_2/Si_3N_4. The presence of Van der Waals bonded hydrogen atoms leads to the passivation of structural defects (for example, dangling $\equiv Si\cdots Si\equiv$ bonds) in the bulk of silicon and at the insulator/semiconductor interface [22,23]. A quantitative study of locally stable states of monatomic hydrogen dissolved in crystalline silicon was carried out in [24].

The effect of radiation exposure on dielectric layers and the dielectric/semiconductor interface was studied. The amount of charge in the passivation bilayer SiO_2/Si_3N_4 of the studied IC was measured on test MDS structures $Si/SiO_2/Al$ and $Si/Si_3N_4/Al$ by the method of high-frequency C–V technique. Aluminum contacts (see Sec. 2) were deposited after treatment of Si/SiO_2 and Si/Si_3N_4 layers in an ECR plasma ($H_2 + Ar$).

It was found that the processing of test MDS structures in an ECR plasma can introduce both a positive and a negative charge into the dielectric layer, depending on the bias potential U_b (see Sec. 2). For instance, processing at a bias of $U_b = 0$ V leads to the introduction of a positive charge into the dielectric SiO_2 with a surface density of $N_{qi} \approx 4 \cdot 10^{12}$ cm^{-2}. In this case, the Si/SiO_2 interface also deteriorates significantly. However, during processing with a bias $U_b = -120$ V, the voltage of flat zones U_{fb} of the test MDS structure $Si/SiO_2/Al$ shifts towards positive voltages by ≈ 1.5 V, which corresponds to the introduction of a negative charge with a surface density $N_{qi} \approx 6 \cdot 10^{11}$ cm^{-2} into the dielectric. In this case, with subsequent γ-irradiation, U_{fb} does not change, unlike „not plasma-treated“ test MDS structures, in which there a shift of U_{fb} to the negative region by the value of -1 V. After exposure of γ-radiation to MDS structures pretreated in ECR plasma ($H_2 + Ar$) with bias $U_b = -120$ V, no noticeable effect on the Si/SiO_2 interface and the charge in the dielectric was detected.

Our recent paper [25] demonstrated the opportunity of minimizing the introduced charge under γ-irradiation by pretreatment of test MDS structures in hydrogen ECR plasma.

The studies that we carried out with the test MDS structure $Si/Si_3N_4/Al$, do not allow us to construct any logical regularities at this stage. This is due to the significant difference between the chemical formula Si_3N_4 and the atomic composition $H_xSi_rN_zH_y$ of the real layer material, which is usually called „silicon nitride“ in microelectronic technology. The notation of the chemical formula $H_xSi_rN_zH_y$ was proposed in [26]. In this record, x, r, z, y — atomic percentages: $x + r + z + y = 100\%$; $x = C(Si\text{--}H)$, $r = C(Si)$, $z = C(N)$, $y = C(N\text{–}H)$. The percentages of hydrogen atoms x and y depend on the process and temperature of deposition of the layer „silicon nitride“. The minimum amount of $x + y = 5\%$ can be achieved with high temperature ($T > 1200$ K) pyrolytic layer deposition.

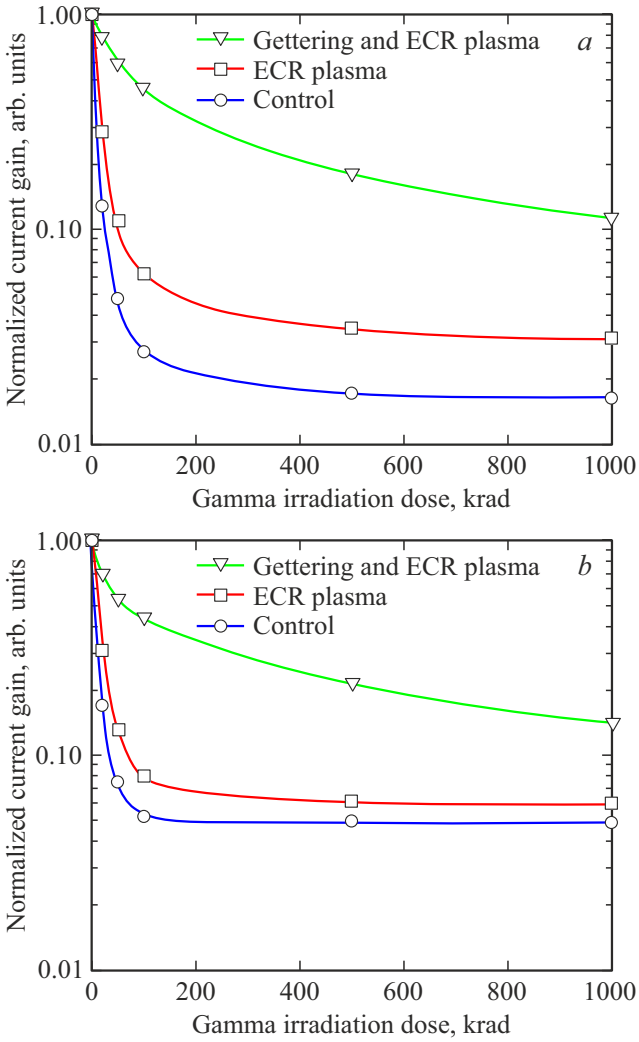

Figure 1. Dose dependences of the normalized transistor current amplification factor. All dependences are normalized to the value before irradiation. For control wafers (curve marked with O), for hydrogenated wafers (curve marked with □) and for hydrogenated wafers with the getter option (curve marked with ▽). Dependencies are presented for p–n–p (a) and n–p–n (b) transistors. (A color version of the figure is provided in the online version of the paper).

With low-temperature ($T < 600$ K) plasma-chemical layer deposition, the total percentage of hydrogen atoms can reach 38% [27].

Thus, the layer „silicon nitride“ $H_xSi_rN_zH_y$ is a polymer-like material, and the test MDS structure $Si/H_xSi_rN_zH_y/Al$ initially contains chemically bound ($\equiv Si{-}H$, $=N{-}H$) hydrogen atoms. At treatment in ECR plasma ($H_2 + Ar$), a flux of plasma ultraviolet radiation falls on the $Si/H_xSi_rN_zH_y$ layer. This radiation „penetrates through“ into a layer 80 nm thick and at energies > 5 eV the quanta interact with the end bonds ($\equiv Si{-}H$, $=N{-}H$) of hydrogen atoms. Chemical bonds are broken and hydrogen atoms pass into Van der Waals bound states. Accordingly, radical centers $\equiv Si\cdot$ and $=N\cdot$ are formed. With the passage of time

for the planned experiments, due to jump diffusion, the reverse process occurs and Van der Waals bound hydrogen atoms recombine with radical centers ≡Si·, =N· and also recombine with each other to form hydrogen H_2 inside the layer.

The effect of γ-irradiation on the characteristics of the IC was determined by changing the gain β of bipolar $p-n-p$ and $n-p-n$ transistors located on the same wafer, as well as by the values of the input and output currents of the IC. These parameters are most sensitive to the accumulated radiation dose. Figure 1, *a* shows the degradation of the current gain, normalized to its initial value, for bipolar $p-n-p$ transistors after their γ-irradiation with different doses. Before irradiation, the gain value on the control wafers was approximately 1000, while after irradiation with a dose of 100 kRad, the gain was degraded by 37 times.

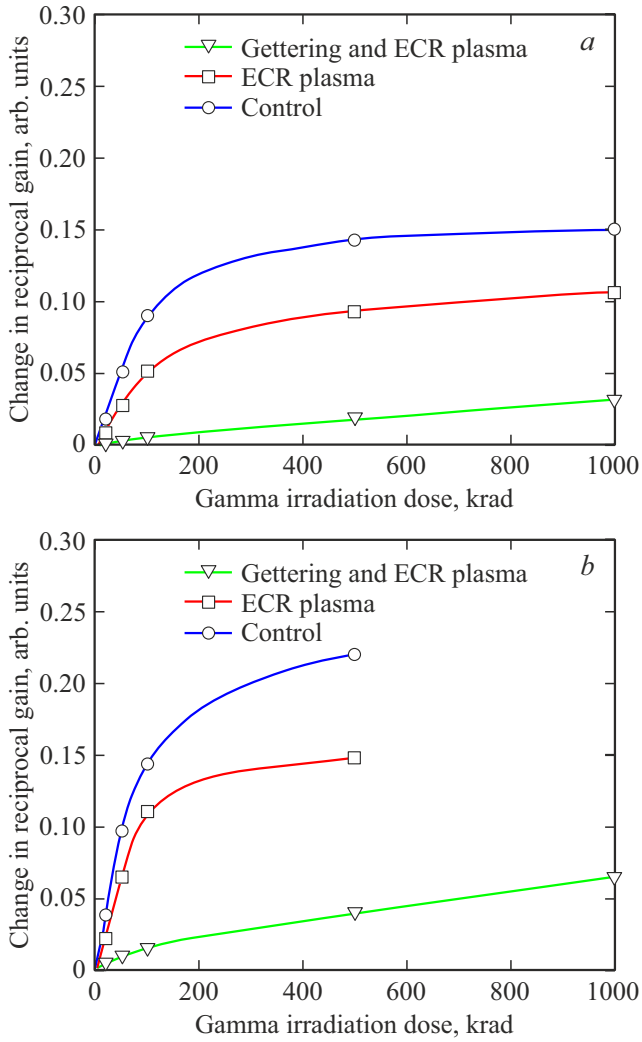

Figure 2. Dose dependences of the change in the inverse current amplification factor. The dependences are presented for control wafers (curve marked with O), for hydrogenated wafers (curve marked with □) and for hydrogenated wafers with the getter option (curve marked with ∇). Dependencies are presented for $p-n-p$ (*a*) and $n-p-n$ (*b*) transistors.

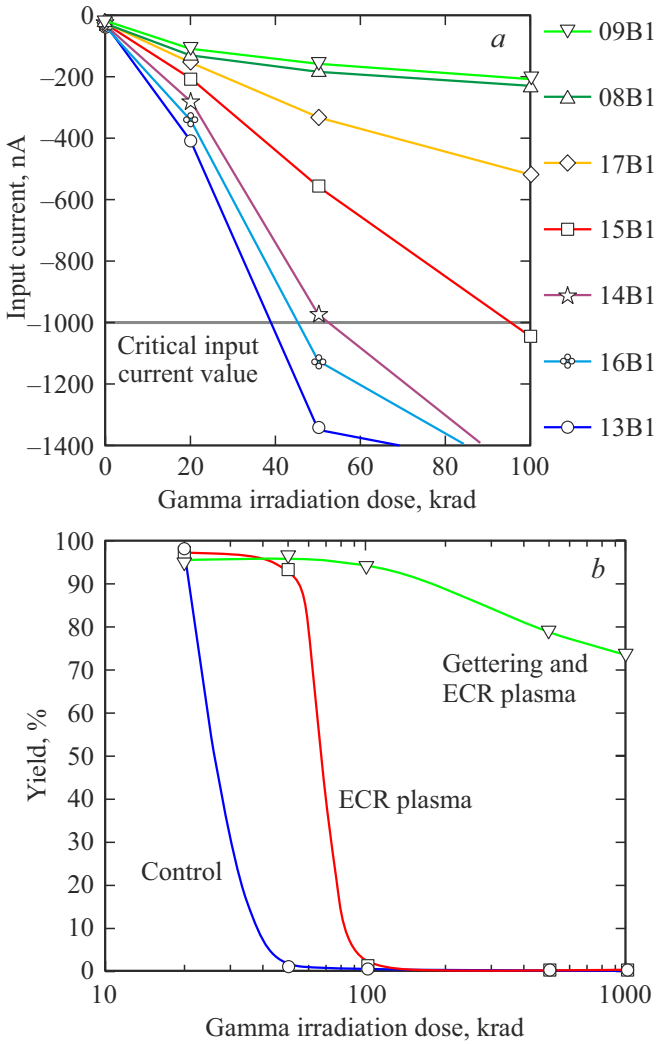

Figure 3. Dose dependences of IC input current (*a*) and yield (*b*). *a* — The dependences are shown for the control wafers (13B1, 16B1, 14B1), for the hydrogenated wafer (15B1), for the wafer with the getter option (17B1), and for the hydrogenated wafers with the getter option (08B1, 09B1). *b* — The dependences are shown for control wafers (curve marked with O), for hydrogenated wafers (curve marked with □) and for hydrogenated wafers with the getter option (curve marked with ∇).

As can be seen from Fig. 1, *a*, the hydrogenation of the wafers in ECR plasma led to a decrease in gain at a dose of 100 kRad by approximately ∼ 16 times (instead of 37 times), which notably improved immunity of $p-n-p$ transistors to γ-irradiation.

The combination of wafer hydrogenation with an implemented gettering option demonstrated dramatic improvement in the radiation resistance of devices even after high dose irradiation — the gain value remains > 180 at a dose of 500 kRad. Compared to $p-n-p$ transistors, which showed strong gain degradation on the control wafer, $n-p-n$ transistors showed somewhat better tolerance to γ-irradiation (Fig. 1, *b*). The effect of hydrogenation

on gain tolerance to irradiation is also clearly revealed (Fig. 1, *b*), whereas the wafers with both hydrogenation and gettering option demonstrated superior performance.

The change in the reciprocal of the current gain, which is also called „Gain damage figure" [28], is shown in Fig. 2 for $p-n-p$ and $n-p-n$ transistors. Hydrogenation of the wafers in ECR plasma resulted in the slope decrease of the „Gain damage figure" curves. For $p-n-p$ transistors, the slope decreased by 2 times, and for $n-p-n$ transistors, by 30% compared to devices on control wafers. The combination of hydrogenation and the implemented gettering resulted in a 10-fold decrease in the slope of the curves for both types of bipolar transistors compared to devices on control wafers.

The input current of a manufactured IC serves as a metric for its performance and yield. Figure 3, *a* shows the dose dependences of the IC input current, measured on control wafers and on wafers with hydrogenation, gettering and hydrogenation + gettering options. The ICs on the control wafers (13B1, 16B1, 14B1) failed after irradiation with a dose of 40–50 kRad, and on hydrogenated wafers (15B1) the critical dose can reach 100 kRad. The ICs on the wafer with gettering options (17B1) demonstrated significant improvement of the radiation immunity, whereas the hydrogenated wafers with gettering option (08B1, 09B1) demonstrated superior stability of the input current under irradiation.

Yield data are summarized in Fig. 3, *b*. Hydrogenated wafers with the option of gettering show an impressive improvement in the yield up to high doses of radiation.

4. Conclusion

In summary, the combination of gettering and hydrogen ECR plasma treatment proved to be a very effective solution for improving yield and functionality at γ-irradiation of integrated circuits based on bipolar transistors. We have demonstrated that ECR plasma treatment does contribute to the radiation hardness of the bipolar transistors. Test MDS structures with an SiO_2-dielectric showed a decrease in fixed positive charges after treatment in an ECR plasma with a bias of $U_b = -120$ B. After exposure to γ-radiation on MDS structures preliminarily processed in ECR plasma with a bias of $U_b = -120$ B, a noticeable effect on the Si/SiO_2 interface and the charge in the insulator was not found.

Therefore, the hydrogen passivation process in the ECR plasma provides a double effect, namely, a decrease in the concentration of primary radical centers ($\equiv Si\cdot + \cdot H \rightarrow \equiv Si-H$) caused by irradiation in the wafer volume, and a decrease in the positive charge accumulated in the SiO_2/Si_3N_4 bilayer of IC under the action of γ-radiation. The most significant improvement in radiation resistance for both $p-n-p$ and $n-p-n$ transistors was achieved by implementing gettering. We believe that the getter layer on the back of the wafer provides an efficient drain for mobile metal impurities such as copper and nickel. The use of the deep level transient spectroscopy (DLTS) technique will be useful for detecting these impurities after their interaction with defects caused by irradiation and the formation of stable defects with deep levels. This will also make it possible to quantitatively assess the effect of injected hydrogen on the rate of radiation defects generation defects and their concentration in order to further improve the radiation resistance of bipolar transistors.

Funding

The paper was implemented within the framework of the theme of the state task of IMT RAS No. 075-01304-23-00.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by E.Potapova