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# Radiation Degradation Individual Peculiarities of γ-irradiated Discrete Low Power Thyristors, Manufactured on Si and SiGe

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**Abstract:** Radiation degradation during γ-irradiation of discrete low-power thyristors, both control (Si) and investigated SiGe-fabricated, is a complex nonlinear process that is individual for each device. It is possible to distinguish three γ-irradiation ranges, in which the degradation of the average holding current for control and investigated thyristors proceeds in different ways. For $D_{\gamma} \approx 1\cdot10^{1}\ldots1.10^{2}$ mSv there is a decrease in $I_h(D_{\gamma})$ for control Si devices, possibly connected with the "low-dose effect"; for SiGe devices, there is an increase in the holding current, therefore, no "low dose effect". Range $D_{\gamma} \approx 1\cdot10^{2}\ldots1.10^{4}$ mSv can be considered as an area of unstable operation of the control thyristors in the γ-radiation field, devices made with SiGe are sufficiently more stable. For $D_{\gamma} \geq 1.10^{4}$ mSv there is an expected increase in $I_h(D_{\gamma})$ for Si thyristors, devices, manufactured with SiGe continue to be more stable. When $D_{\gamma} \approx 1\cdot10^{1}\ldots1.10^{4}$ mSv use of SiGe makes it possible to increase the average interval radiation resistance of thyristors by approximately 7 %, and in the range of $D_{\gamma} \approx 1\cdot10^{4}\ldots1.10^{6}$ mSv ≈ up to 12 %.

**Keywords:** Individual nonlinear process, Discrete low-power thyristor, Radiation degradation, Average interval radiation resistance, SiGe.

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## 1. Introduction

Over the next 5-10 years, the abrupt rise of commercial and military interest in space-based systems is foreseen and it includes new launch capabilities, creation of large-scale constellations for communication or earth observation [1]. The distribution of the spacecrafts are approximately as follows: commercial 46 %, government 19 %, military 15 %, civil 7 % and mixed use 13 %. As of the publication of cited report, more than 2000 satellites are in the different orbits (LEO, Low Earth Orbit (160 – 2000 km) – 66 %, GEO, Geostationary (≈ 36,000 km) – 25 %, MEO, Medium Earth Orbit (2000 – 36,000 km) – 6 %, and HEO, Highly Elliptical Orbit (e.g. 40,000 km apogee) – 3 %). The number of satellites is expected to quintuple by 2030, with 1,100 expected to be launched per year in 2025 alone (almost four times the number launched in 2018). With all this activity, by 2040, the global space industry is forecast to grow up to \$1…2.7 trillion. It may become one of the main world economy branches.

One of the most serious obstacles to the effective functioning of the satellites constellations is so called space weather [2]. The highly hazard variable space radiation environment around Earth can influence the global satellite infrastructure, causing temporary malfunctions or permanent loss of satellite functions.

From the practical point of view, especially important is the LEO radiation situation [3, 4], especially important for the military satellite functions [5], Table 1:

**Table 1.** Orbits and Tasks for Spacecrafts .

| **No.** | **Space Task** | **Orbit types** | **Sensors** |
|---|---|---|---|
| 1. | Optical Remote Sensing | LEO | Optical |
| 2. | Early Warning | GEO, HEO, LEO | Thermal |
| 3. | SAR (Synthetic Aperture Radar) Use | LEO | Imaging radar |
| 4. | Signals Intelligence | LEO, GEO | Radio receiver |

Satellites experience a partial or total mission loss directly attributed to radiation effects on electrical components [6]. The radiation situation in general on the orbits shown in [7]. This threat is growing due the fact that the highly developed technological society becomes much more dependent on satellite capabilities [8].

In the MathCAD environment, modeling and forecasting of the complication of the on-board radio-electronic equipment of space vehicles was carried out [9]. The excess quantity of the equipment components, leading to the decrease in the reliability of the spacecrafts was associated with insufficient radiation resistance of the elementary base. Therefore, the main practically important task is the search for technological solutions to increase the duration of the operation of the onboard radio electronic equipment of spacecraft. It was proposed to implement effective technologies into the manufacturing of the on-board electronic equipment for increasing of the apparatus radiation resistance; thus, active electronic elements (discrete transistors, npn structures of the IC, thyristors of the power supply system's etc.) of space vehicles are to be radiation hardened.

## 2. Radiation Hardness Improvement of the Electronic Element Base: Technological Approach

Radiation hardening covers a wide variety of techniques [10]. The concept of radiation hardening implies robustness but it does not imply total immunity to radiation, only an abatement of radiation effects such that the product will have sufficiently high reliability to fulfill its mission. The method focuses on modifying the baseline semiconductor process to reduce various physical processes that affect radiation sensitivity. This method of mitigation is called radiation hardening by process (RHBP). It can reduce a component failing a radiation metric during test irradiation. In other words, because use of an effect in the baseline process, manufactured with the modified process elements will pass the metric at the radiation testing. In addition, the main feature. RHBP solutions are expected to have an advantage in that they can make an existing product radiation-hardened (or at least tolerant) without modifying the design, thereby reducing cost and development time. It was the main matter of SiGe use in the well-known technologies.

### 2.1. Si Doping for the Decreasing of the Radiation Defects Concentration

The creation of semiconductor materials for the manufacturing of radiation-resistant microelectronic and discrete production is a part of the global problem of development, manufacture and application of materials that retain their physical properties under the influence of ionizing radiation [11]. This approach based on the defect engineering strategies [12]. Point electrically active defects that create deep energy levels in semiconductors (impurity defect complexes and/or clusters) thereof are used to control the physical properties of semiconductor materials.

The electrically active A-center (VO) in Cz-Si is the most important defect [13]. It associated with interstitial oxygen $O_i$ (oxygen interstitial atom) and vacancy V. The defect in the crystal lattice resulting from the interaction of Si with high-energy (≅ MeV) particles. A-center forming according to a quasi-chemical reaction in the fields of ionizing radiation due to the generation of diffusing to $O_i$ vacancies. The recombination properties of A-centers (effective traps for injected minority charge carriers in npn and npnp structures) significantly deteriorate the performance of irradiated semiconductor devices.

A number of publications have been devoted to the doping of Si in order to increase its radiation resistance by inhibiting the formation of A-centers. For example, [14] shows that the presence of an impurity of Er (n-Si<Er>) or La (n-Si<La>)) in silicon leads to the lowdown in the process of radiation defect formation.

Concentrations of A-centers and E-centers in the irradiated *n*-Si<Er> or *n*-Si<La> almost an order of magnitude smaller compared to the control irradiated samples. Thus, the presence of erbium or lanthanum atoms in the silicon volume significantly reduces the efficiency of the formation of vacancy-oxygen and vacancy-phosphorus complexes. According to the authors of the work under consideration, the observed decrease in the concentration of these complexes is most likely due to the binding of oxygen atoms with impurities of rare-earth elements in the complexes, as well as the interaction of Er and La atoms with point defects introduced during gamma irradiation.

The processes of formation of radiation defects in silicon doped with dysprosium (n-Si<Dy>), irradiated by γ-quanta $^{60}$Co [15]. Monocrystalline n-type conductivity silicon with resistivity ρ = 10…65 Ohm·cm was used. The content of interstitial optically active oxygen was $5 \cdot 10^{16} \leq N_{Oi} \leq$

$7\cdot10^{17}$ cm$^{-3}$. Alloying with a rare-earth element (REE) was carried out in the process of growing from a melt. The measurements were carried out by transient capacitive spectroscopy (DLTS) on Schottky barriers. It was shown that the presence of ytterbium atoms in the volume of silicon leads to a decrease in the concentration of A-centers by a factor of 2-6.

In the formation of radiation defects in n-type silicon single crystals (Si<P>) was studied at various levels of doping with transition element impurities [16], Cu, Ni, Ir, Rh, Pt and Au, hereinafter denoted as M. The initial material used was n-type silicon with ρ from 2 to 5 Ohm·cm, grown according to the Czochralski method. Silicon doping was carried out by thermal diffusion from the deposited M layer on the surface of the silicon wafer at 850-1200 °C for ~5 hours. Under these diffusion conditions, all the considered impurities are distributed almost evenly over the entire depth of the samples. All silicon samples were irradiated with γ-quanta of the source Co$^{60}$ up to the dose 109 R. With an increase in the radiation dose, the concentrations of radiation A-centers increase in the doped samples n-Si <P, Rh>, n-Si <P, Pt>, n-Si <P, Au>. Therefore, the use of these impurities to increase the radiation resistance of silicon is not possible.

Measured concentration of A-centers in the n-Si <P,Ni>, n-Si <P,Cu> samples less than in the control Si [17]. The authors of the publication attribute the result to the formation of electrically inactive defects, compounds of metals and oxygen. The last reduce the concentration of $O_i$ in doped Si, due to which it can decrease in the efficiency of A- and K-center formation. In the Si doped with Ni samples, star-shaped defects are observed. Numerous interconnected clusters of nickel atoms exist in the form of specific clusters with the size of 10…15 μm. This excludes the use of this method to increase the radiation resistance of typical microelectronic structures with layer widths $\approx10^{-1}$μm.

There is no data in the available literature on the use of silicon doped with rare earth elements or transition metals for the manufacture of active IC structures or discrete devices with increased radiation resistance. Perhaps this is because in silicon p-n junctions, when decorating dislocations with metallic impurities, there is an increase in leakage currents up to a short circuit of the junction [18].

## 2.2. Use of the Isovalent Impurities to Control Radiation Defect Formation in Silicon

The use of SiGe to improve the radiation resistance of silicon has long been seen as an effective method for improving the radiation resistance of a semiconductor material [19]. For Si with germanium concentration $N_{Ge} = 2\cdot10^{20}$ cm$^{-3}$ a significant increase in radiation resistance has been achieved, estimated by slowing down the change in the concentration of the main charge carriers.This is considered by the authors as the most promising silicon technology used for the manufacture of precision detectors used in nuclear radiation fields [20]. The application of isovalent silicon doping (Ge, Pb and Sn) was considered as a major trend in the control of radiation defect formation in Si used for the production of devices with low radiation sensitivity [21].

To suppress the concentration of A-centers, engineering strategies are needed to control defect formation in the material of inhomogeneous active structures of microelectronic and discrete devices [22, 23]. In particular, the use of isovalent impurities (carbon (C), germanium (Ge) and tin (Sn)) to control the formation of VO complexes in Si has been proposed. Isovalent impurities replace Si atoms but are electrically inactive. When they are embedded in the lattice of Si, its elastic stress is created (tensile in the case of C and compression for Ge, Sn and Pb). This is due to the change in its structural and physical properties due to different covalent radii of impurities and the doped matrix. Carbon has the smallest covalent radius $r_C = 0.77$ Å compared with Si ($r_{Si} = 1.17$ Å), covalent radius of Ge, $r_{Ge} = 1.22$ Å. For Sn and Pb $r_{Sn} = 1.41$ Å, $r_{Pb} = 1.44$ Å respectively. The introduction of these impurities into the crystal lattice does not affect the concentration of carriers in Si, but their presence can alter the mobility of the carriers. Isovalent impurities interact with vacancies, e.g., Ge, Sn, Pb – effective stocks for vacancies. Entrapment of vacancies by impurities with a covalent radius greater than that of Si can lead to a slowdown in the formation of radiation defects. The interaction of isovalent impurities (Sn, Pb C, Ge), designated D, with A-centers leads to the formation of DVO complexes for the D+VO →DVO reaction, the stability of which is higher compared to defects of the VO type. SnVO complexes are significantly more stable than GeVO; Sn does not form bonds with Oi and inhibits the formation of VO centers in irradiated Si. Doping with this impurity could be considered as a way to improve radiation resistance, but, in addition to reducing the efficiency of the formation of A-centers, divacancies and E-centers, the Sn−V complex creates deep energy levels (recombination centers) in the silicon bandgap, i.e., in fact, one type of radiation defect is supplemented by the other two [24]. The peculiarities of the accumulation of radiation defects in n-Si⟨Sn⟩ fully explain the accelerated degradation of the lifetime of non-equilibrium charge carriers in this material when irradiated [25]. Consequently, the direct use of n-Si⟨Sn⟩ as a material intended for the manufacture of solid-state electronic products, the use of which is supposed to be in the fields of ionizing radiation, is not possible.

Lead (Pb) in silicon forms clumps of atoms with a size ≅ 10 μm [26]. This excludes the use of this material for the production of standard npn structures with a base width ≤ 0.02 μm and, most likely, high-voltage npnp structures due to shorting of the active layers. The presence of Pb in silicon does not inhibit the formation of deep acceptors, which include vacancies, from which the authors [27] conclude that the use of this impurity is ineffective to increase the radiation resistance of Si.

From the point of view of assessing the possibility of practical application of isovalent doping to reduce the concentration of vacancy-oxygen complexes, the calculation of impurity-defect interaction can be carried out using the law of acting masses (mass action analysis) [28]. Defect concentration (is denoted as [XY]) with binding energy $E_b$ with respect to the concentration of unbound defects X и Y (i.e. [X] и [Y] respectively) is defined as follows:

$$\frac{[XY]}{[X][Y]} = exp\left(\frac{-E_b}{k_B T}\right), \quad (1)$$

where $k_B$ is the Boltzmann constant, T is the temperature.

$$E_b = E_{defect\ cluster} - \sum E_{isolated\ defects}, \quad (2)$$

where $E_b$ is the binding energy of defects in a cluster.

The negative binding energy of defects in a cluster is energetically more advantageous (the energy of defects in a cluster is less than in an isolated state). For the data given in the cited work, a certain pattern can be traced [29]. At the $E_b$ of the DV complex ≅ 0.5 of this value for the DVO complex, impurity-vacancy complexes are predominantly formed, which are recombination centers (Sn-V, Pb-V). The GeV complex is not formed at 300K, it is possible to form a GeVO complex (instead of the A-center), which makes such complexes effective in terms of increasing the radiation resistance of Si.

### 2.3. Use of SiGe to Increase the Radiation Resistance of npnp Structures – Previous Results

The thyristor n-p-n-p-structure is a convenient physical model for conducting studies to improve radiation resistance using non-standard impurity-doped Si. Most of the characteristics of a thyristor are determined by the quality of its wide base area (~150 μm with a wafer thickness of ~200 μm). Research has been carried out on the use of CZ-Si single crystals <P,Ge > in the manufacture of low-power thyristors (reverse applied voltage up to 100 V) [30, 31]. The method of constructing dose dependencies for the mean value of the holding current, leakage current for the sample of irradiated thyristors was applied.

It is shown that for the measured values of the characteristics of discrete low-power devices, high deviations of the numerical values of electrophysical characteristics from their average values are observed, especially for the holding current of devices manufactured on SiGe. Statistical analyses were performed for min and max values of $D_\gamma$. The most probable values (extremes of distributions) of the thyristor holding currents on Si and Si<Ge> before and after irradiation are almost the same. Therefore, it is necessary to construct a dose dependence of $I_h(D\gamma)$ for thyristors manufactured on Si (control) and SiGe (investigated devices) in order to determine the real technological feasibility of using isovalent doping with Germanium to increase radiation resistance. In addition, the physical causes of the high "noise" of the experimental data, i.e. their multidirectional deviation from the mean value, have not been considered before. In the publication [32] it is shown that a change in the concentration of Ge (it can be a deviation in the properties of the raw materials used) has a strong impact on the quality of products and, thus, on their radiation resistance during further operation in the hazard environment. For example, as shown in [33], there is a sharp deterioration in the radiation resistance of npn structures, fabricated on SiGe with $N_{Ge}$ = 0.05 at. % ($2.5 \cdot 10^{19}$ cm$^{-3}$). Therefor, with an accuracy, sufficient for the practical application of SiGe, it can be considered that the concentration of Ge, which is acceptable for the manufacturing of planar diffusion npn structures (it may be assumed that as well as for npnp structures) is approximately equal to 0.1 at. %, or, in other units for reference: $N_{Ge}$ ≅ 0.2 mass %; $5 \cdot 10^{19}$ cm$^{-3}$. From the technological point of view area $N_{Ge} < 0.1$ at. % is unstable, with abrupt changes in yield of suitable products. Use SiGe with a concentration of $N_{Ge} > 0.2$ at. % for the manufacture of high voltage npnp structures is not effective.

Thus, the main purpose of this work was to compare the processes of radiation degradation of individual thyristors made on Si and SiGe, and not on a sample of devices made on the control and test material. A special feature of the work is the emphasis on the analysis of the individual properties of the devices in order to assess the physical causes that determine their radiation resistance.

## 3. Specific Features of SiGe and Control Thyristors Before Irradiation

### 3.1. Materials and Devices to be Tested, Irradiation

CZ-SiGe single crystals doped with phosphorus with ρ ≈ 35 Ω•cm were used in the research. In the manufacture of low-power thyristors (inverse applied voltage up to 100 V), single crystals of silicon grown by the Czochralski method (CZ−Si<P, Ge>) with a phosphorus concentration ~ $3 \cdot 10^{14}$ см$^{-3}$, Ge ~ $5 \cdot 10^{19}$ см$^{-3}$ were used and as well as control single crystals with the same concentration of phosphorus. For the manufacture of thyristors, the standard planar-diffusion technology of 2У102Г was chosen as the basic technology, Fig. 1.

The appearance and dimensions of the irradiated thyristors is given in Fig. 2.

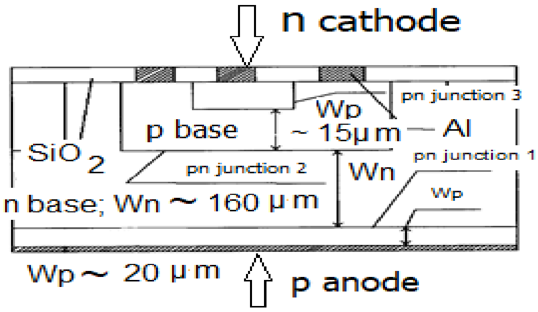


**Fig. 1.** Vertical structure of the experimental thyristor [34].

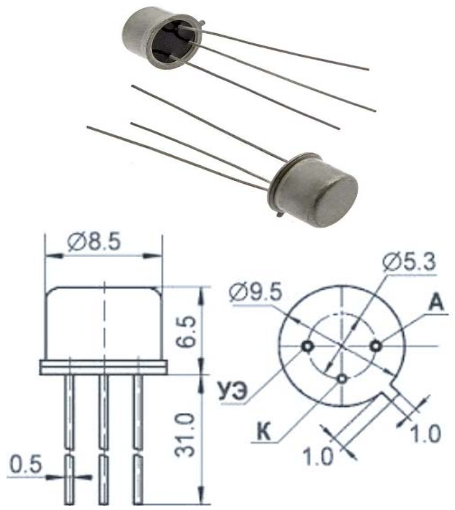


**Fig. 2.** Appearance and dimensions of the thyristors manufactured with the use of SiGe [35].

### 3.2. Holding Current ($I_h$), Leakage Current (I_leakage) of Control Thyristors and Those Manufactured on SiGe Before Irradiation

The thyristor structure can be switched off, if the voltage between the cathode and the anode decreases to a value at which the anode current becomes less than the so-called "holding current", $I_h$, which is one of the important parameters characterizing the device structure [36]. Its numerical value determines the possibility of adequate operation of the thyristor in specific applications, especially under irradiation. Measuring the holding current is a fairly simple task, see Fig. 3. $I_h$ and $V_h$ are the coordinates of the holding point beyond which the device is in the on state. In the holding current measurement, the open current is reduced from the set point until the thyristor is switched to the closed state, and the open state current is measured at the time immediately preceding the thyristor enters the closed state.

For the statistical processing of the experimental data, were used Origin PRO, STATISTICA10 and MathCAD15. The results visualization of $I_h$ measurements before irradiation are in the Fig. 4, distribution characteristics are in the Table 2.

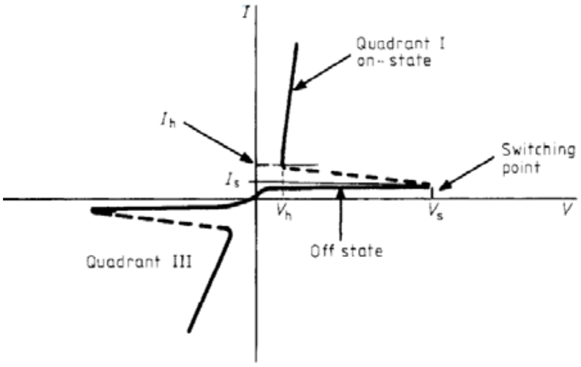


**Fig. 3.** Volt-ampere characteristic of a thyristor. $I_s$ and $V_s$, are the coordinates of the variously called switching, turn-on or breakover point.

**Table 2.** Si and SiGe thyristors holding current ($I_h$) statistical distribution characteristics.

| No. | Characteristic | Control Si | SiGe |
|---|---|---|---|
| 1. | Mean value | 14.699 | 14.72 |
| 2. | Standard deviation | ±2.02 | ±1.422 |

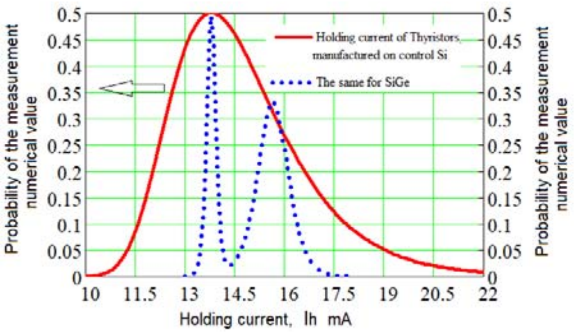


**Fig. 4.** Probability of the numerical values of holding current (mA) for thyristors fabricated with Si and SiGe.

The leakage currents of the test thyristors are 3 times higher, than those of thyristors, made on isovalently-doped silicon, Fig. 5, Table 3.

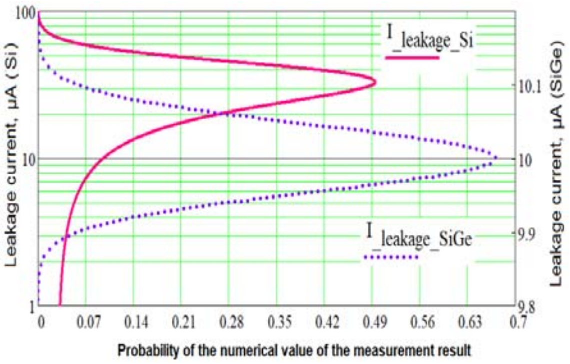


**Fig. 5.** Probability of numerical values of leakage current (μA) for the thyristors manufactured with Si and SiGe.

**Table 3.** Si and SiGe thyristors leakage current (I leakage) statistical distribution characteristics.

| No. | Characteristic | Control Si | SiGe |
|---|---|---|---|
| 1. | Mean value | 32.896 | 10.0 |
| 2. | Standard deviation | ±13.031 | ±0.045 |

Thyristors manufactured with SiGe are of higher quality from the very beginning, prior to irradiation, which suggests their higher radiation resistance to γ- exposure.

## 4. Doping of Si by Germanium: Experience of Use to Increase npnp – Structures Radiation Resistance

### 4.1. Effect of γ-irradiation on the Holding Current (Ih) of Low-power Control Thyristors

The presence of pronounced distributions (including bimodal distributions) of the physical characteristics of npnp structures indicates the possibility of an individual response of each sampling device to external influences, including the action of ionizing radiation [37].

This phenomenon is due to the spread of properties of raw materials and materials, the instability of the modes of technological operations etc. All real semiconductor devices are in quasi-stationary states, the levels of stability of which may differ from each other. Therefore, the already complex internal state of Si abruptly changes under the influence of external excitations, i.e., destabilizing factors, especially ionizing irradiation. Under the influence of these factors, in the case of inevitable statistical variations in the properties of raw materials and random deviations of the modes of technological operations, each of semiconductor devices has an individually specific internal state at each moment of time, which determines its technical characteristics, as existing, as well as future in hazard environment.

The specific individual characteristics of each of the thyristors provide the individual way of degradation of their physical properties, when irradiated. For example, experimental results for the X5 thyristor (dependence $I_h(D\_\gamma)$) in MathCAD can be approximated as follows, Fig. 6.

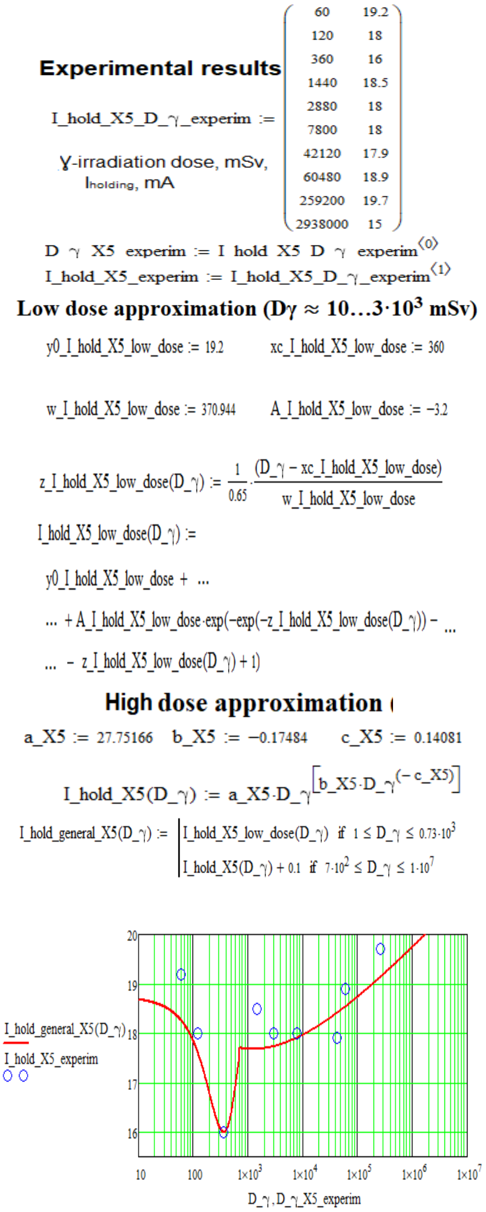
For $D_\gamma \leq 10^3$ mSv Extreme model was used, for higher doses – FreundlichEXT [38].

So, individual way of degradation of the thyristors physical properties, when irradiated, was confirmed experimentally. The individual characteristics of each of the thyristors vary in the wide range, Figs. 7, 8 and other drawings.

The process of the devices X5, X6 radiation degradation may be explained as follows. A decrease in $I_h$ can be observed with an increase in lifetime value of the minority charge carriers, $\tau_p$, in the wide n-base of control thyristors, in accordance with well-known formula [39]. It approximately (qualitatively) expressing the dependence of the holding (switching off) current of the thyristor, taking into the consideration its geometric dimensions and electrical characteristics of the material, on which the device was manufactured:

$$I_h \sim \frac{W_n}{\tau_p \cdot \mu_p \cdot \rho_n \cdot ln\left(\frac{1}{1-\alpha_2}\right)}, \qquad (3)$$

where $W_n$ is the thickness of the thyristor n- base; $\tau_p$, $\mu_p$ is the lifetime and mobility of minor charge carriers in the n-base of the thyristor, respectively; $\rho_n$ is the resistivity of the thyristor n-base material; $\alpha_2$ is the current transfer coefficient of a thyristor n-p-n fragment with a narrow p-base.



**Experimental results**

$$\text{I\_hold\_X5\_D\_}\gamma\text{\_experim} := \begin{pmatrix} 60 & 19.2 \\ 120 & 18 \\ 360 & 16 \\ 1440 & 18.5 \\ 2880 & 18 \\ 7800 & 18 \\ 42120 & 17.9 \\ 60480 & 18.9 \\ 259200 & 19.7 \\ 2938000 & 15 \end{pmatrix}$$

γ-irradiation dose, mSv, $I_{holding}$, mA

$$\text{D } \gamma \text{ X5 experim} := \text{I hold X5 D } \gamma \text{ experim}^{\langle 0 \rangle}$$

$$\text{I\_hold\_X5\_experim} := \text{I\_hold\_X5\_D\_}\gamma\text{\_experim}^{\langle 1 \rangle}$$

**Low dose approximation (Dγ ≈ 10…3·10³ mSv)**

$$\text{y0\_I\_hold\_X5\_low\_dose} := 19.2 \qquad \text{xc\_I\_hold\_X5\_low\_dose} := 360$$

$$\text{w\_I\_hold\_X5\_low\_dose} := 370.944 \qquad \text{A\_I\_hold\_X5\_low\_dose} := -3.2$$

$$\text{z\_I\_hold\_X5\_low\_dose(D\_}\gamma) := \frac{1}{0.65} \cdot \frac{(\text{D\_}\gamma - \text{xc\_I\_hold\_X5\_low\_dose})}{\text{w\_I\_hold\_X5\_low\_dose}}$$

$$\begin{aligned} &\text{I\_hold\_X5\_low\_dose(D\_}\gamma) := \\ &\quad \text{y0\_I\_hold\_X5\_low\_dose} + \dots \\ &\quad \dots + \text{A\_I\_hold\_X5\_low\_dose} \cdot \exp(-\exp(-\text{z\_I\_hold\_X5\_low\_dose(D\_}\gamma)) - \dots \\ &\quad \dots - \text{z\_I\_hold\_X5\_low\_dose(D\_}\gamma) + 1) \end{aligned}$$

**High dose approximation (**

$$\text{a\_X5} := 27.75166 \quad \text{b\_X5} := -0.17484 \quad \text{c\_X5} := 0.14081$$

$$\text{I\_hold\_X5(D\_}\gamma) := \text{a\_X5} \cdot \text{D\_}\gamma^{\left[\text{b\_X5} \cdot \text{D\_}\gamma^{(-\text{c\_X5})}\right]}$$

$$\text{I\_hold\_general\_X5(D\_}\gamma) := \left| \begin{array}{l} \text{I\_hold\_X5\_low\_dose(D\_}\gamma) \text{ if } 1 \leq \text{D\_}\gamma \leq 0.73 \cdot 10^3 \\ \text{I\_hold\_X5(D\_}\gamma) + 0.1 \text{ if } 7 \cdot 10^2 \leq \text{D\_}\gamma \leq 1 \cdot 10^7 \end{array} \right.$$

**Fig. 6.** Holding current calculation in MathCAD. Example: control thyristor X5, manufactured on Si.

Probable cause of the $\tau_p$ change there may be a so-called "low-dose effect" of radiation exposure [40]. The action of irradiation of γ-rays on defect-containing semiconductor crystals, with a dose less than $10^3$ J/kg does not lead to additional accumulation of defects but conversely leads to elimination of defects and transition of the crystal to a more equilibrium state. Ionization processes rearrange defects in crystals. It occurs as a result of liberation of stored energy in the crystal due to the chain reactions of annihilation of defects, initiated by ionization. Transition of the crystal to the equilibrium state is accompanied by improvement of its physical properties, $\tau_p$, first of all. This provides a significant improvement (sharp peaks) in the radiation resistance of the X5 and X6 devices – reduction in their holding currents.

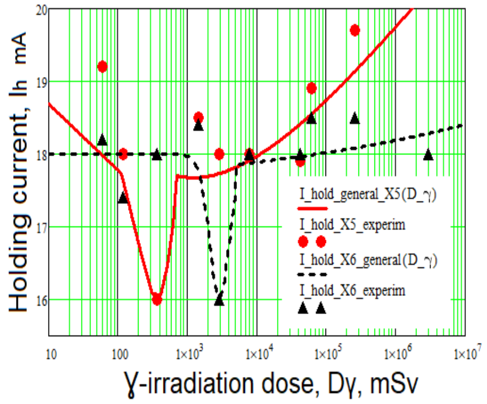


**Fig. 7.** Degradation of the holding current of thyristors X5 and X6, manufactured on the control Si (in all figures: solid, dashed or point lines – models; symbols – experimental data)

Degradation of the second group of the control thyristors (1X and X1_zv) in the range $D_\gamma \approx 1.10^2…1.10^4$ mSv (zone of the transition processes) shown on Fig. 8. There is an obvious deterioration in the properties of the control thyristors, which is expressed in the appearance of one or two extremes of $I_h$, the occurrence of which, apparently, can also be explained by the application of the formula (_), i.e., by a decrease in $\tau_p$, $\mu_p$ in the thyristors wide n−base. For these devices (the second group of thyristors) in the transient Dγ zone, there is a decrease in the individual radiation resistance of the control thyristors, and, obviously, their parametric failure (unauthorized switching of the thyristors to a closed state) is possible when irradiated.

The transient area associated with the "low dose" effect may be smoothed out, Fig. 9.

Unstable radiative change in thyristor holding current X2 at $D_\gamma \approx 1 \cdot 10^2…1.10^4$ mSv resembling an oscillatory process, resulting in high stability of $I_h(D_\gamma)$ при $D_\gamma \approx 1 \cdot 10^4…3.10^6$ mSv (Fig. 10).

For $D_\gamma \geq 10^4$ mSv for control thyristors, there is a monotonic relationship $I_h(D_\gamma)$, which is individual for each device, too.

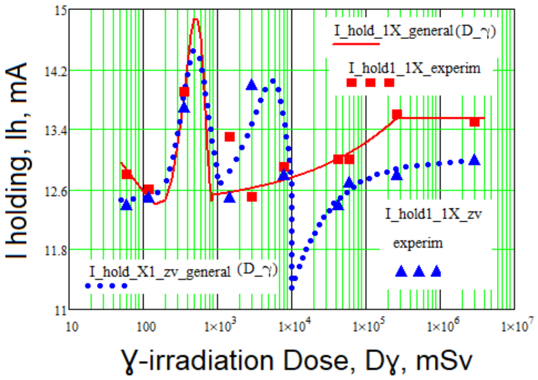


**Fig. 8.** Degradation of the holding current of thyristors 1X and X1_zv, manufactured on the control Si.

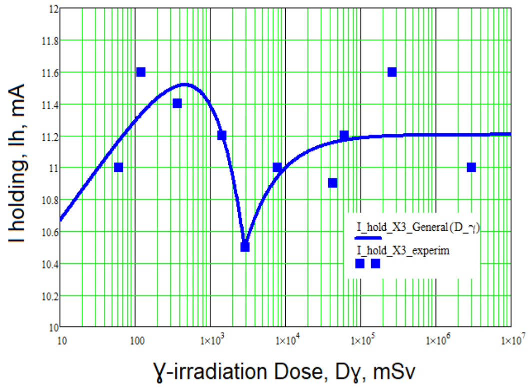


**Fig. 9.** Holding current radiation degradation of the thyristor X3, manufactured on the control Si.

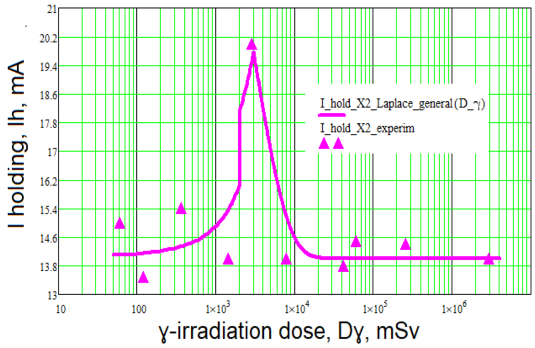


**Fig. 10.** Dependency modeling $I_h(D_\gamma)$ of the thyristor X2.

### 4.2. Effect of γ-Irradiation on the Holding Current (Ih) of Low-power Thyristors, Manufactured on SiGe

Doping of Si by Ge sufficiently changes nature of the radiation degradation of the thyristors, Figs. 11-13.

For some devices (e.g. G5) the shape of the $I_h(D_\gamma)$, which suggests the presence of two regions of Dγ in which the thyristor holding current changes due to processes resembling the "low-dose effect", namely – $D_\gamma \approx 2 \cdot 10^1…1.10^3$ mSv and $D_\gamma \approx 5 \cdot 10^4…3.10^6$ mSv.

This correlates with availability of bimodal distribution of SiGe thyristors $I_h$ before γ-irradiation. Dependency of $I_h(D_\gamma)$ for the other devices (Fig. 12, Fig. 13) is less complicated, but not repetitive.

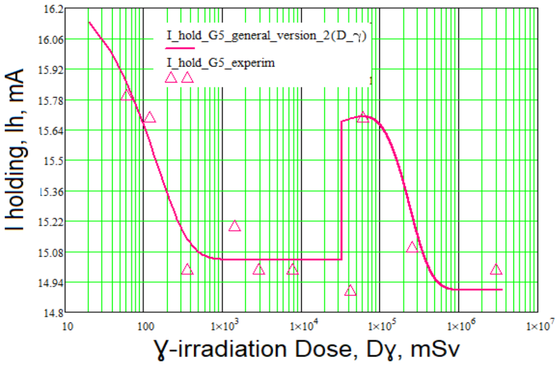


**Fig. 11.** Degradation of the holding current of a G5 thyristor, manufactured on SiGe.

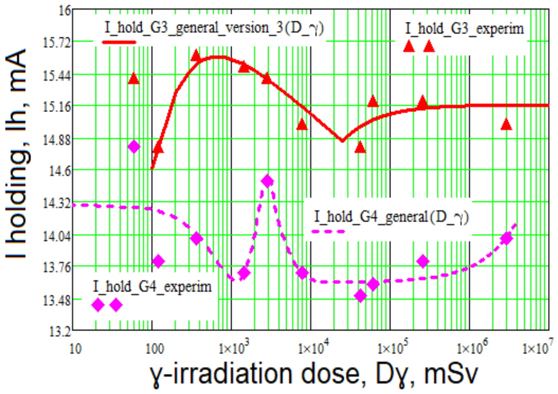


**Fig. 12.** Degradation of the holding current of G3 and G4 thyristors, manufactured on SiGe.

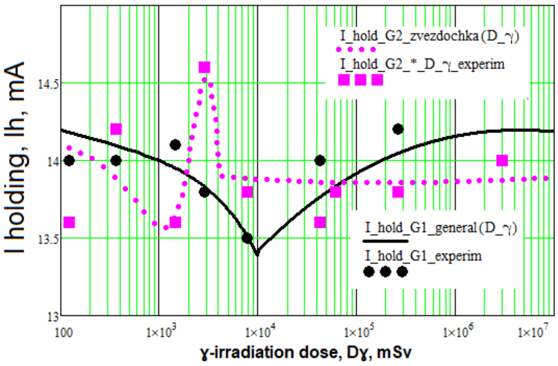


**Fig. 13.** Degradation of the thyristors holding current G1 and G2_zvezdochka (or *), manufactured on SiGe.

Is it possible to use SiGe to increase the radiation resistance of discrete low-power thyristors? For the illustrative answer, it is necessary to compare the average values of $I_h(D_\gamma)$ in accordance with (4) for the thyristors, manufactured with Si and SiGe.

$$I_{hold\_average}(D_\gamma) = \frac{1}{n}\cdot\sum_i^n I_{hold_i}(D_\gamma), \qquad (4)$$

where $I_{holdi}$ $(D_\gamma)$ is the holding current of the *i-th* thyristor; n is the number of the thyristors to be averaged.

Results of calculations are shown in Fig. 14.

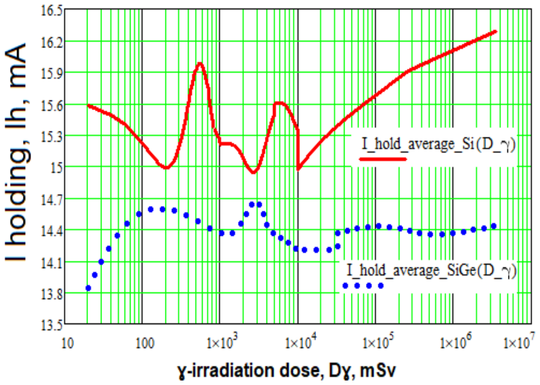


**Fig. 14.** Comparison of changes in $I_{hold\_average}(D_\gamma)$ in the dose range of γ-irradiation for the thyristors, manufactured on Si and SiGe.

The radiation resistance of the control Si thyristors decrease significantly at $D_\gamma \approx 1\cdot10^4 \ldots 3\cdot10^6$ mSv – $I_h(D_\gamma)$ increases markedly both in absolute units, mA, (Fig. 14), and in relative terms, Fig. 15.

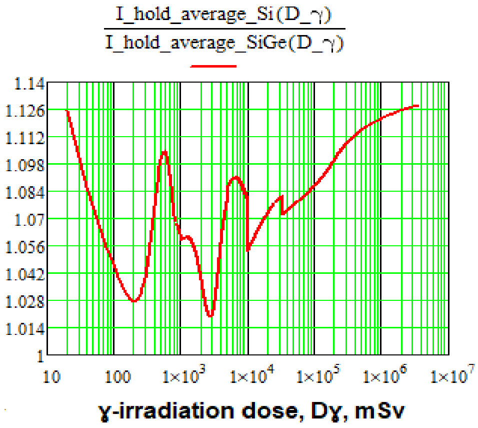


**Fig. 15.** Ratio of average holding current (I_hold_average_Si(D_γ)) of the thyristors X5,X6,1X,X1zv), (Si) to the same characteristic (I_hold_average_SiGe(D_γ)) of the G1,G4,G5,G3 (SiGe).

For $D_\gamma \approx 1\cdot10^1 \ldots 1\cdot10^2$ mSv there is a decrease in $I_h(D_\gamma)$. Most likely, this is the area of manifestation of the "low-dose effect" of γ-irradiation for control devices (slight growth $\tau_p$ in the n-base of the thyristors, manufactured on Si). For SiGe devices, there is an increase in the holding current, therefore, the "low dose effect" is not manifested. Range $D_\gamma \approx 1\cdot10^2 \ldots 1\cdot10^4$ mSv can be considered as an area of unstable operation of the control thyristors in the radiation field. Perhaps it is more accurate to call it the "degradation noise area" $I_h(D_\gamma)$. For the control devices (Si), the amplitude of the oscillations reaches 0.9 mA, and for the thyristors on SiGe 0.3 mA. Fluctuations are "smoothed out" by about three times. For $D_\gamma \geq 1 \cdot 10^4$ mSv there is an expected increase in $I_h(D_\gamma)$ for thyristors, fabricated in Si (Fig. 16). Devices made with SiGe are sufficiently more stable.

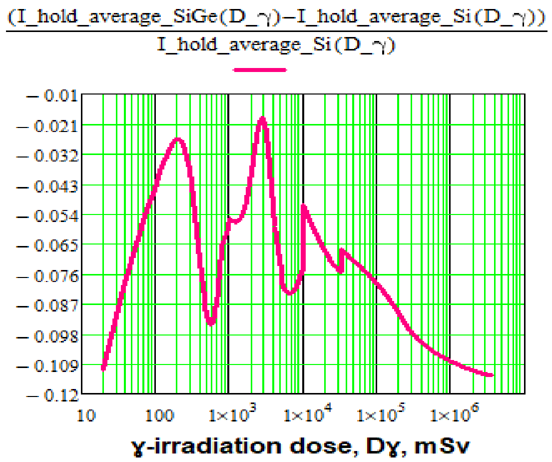
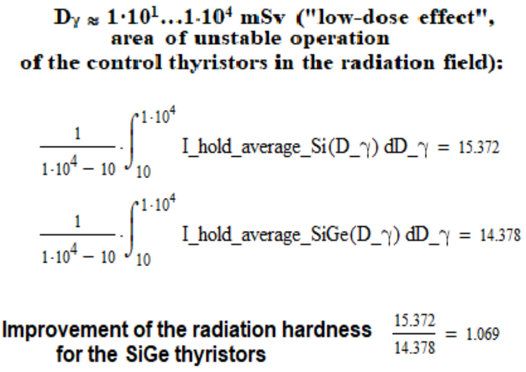


**Fig. 16.** Relative decrease in $I_h(D_\gamma)$ of the thyristors, manufactured on SiGe, compared to control devices under γ -irradiation.

The effect of isovalent doping on radiation resistance was calculated in MathCAD using the interval average value, Figs. 17, 18. The holding current ratio is the degree of increase in the radiation resistance of thyristors manufactured with SiGe compared to control devices (the *higher* the I_hold_average at a given radiation dose, the *lower* is the radiation resistance of the thyristor).



**$D_\gamma \approx 1\cdot10^1\ldots1\cdot10^4$ mSv ("low-dose effect", area of unstable operation of the control thyristors in the radiation field):**

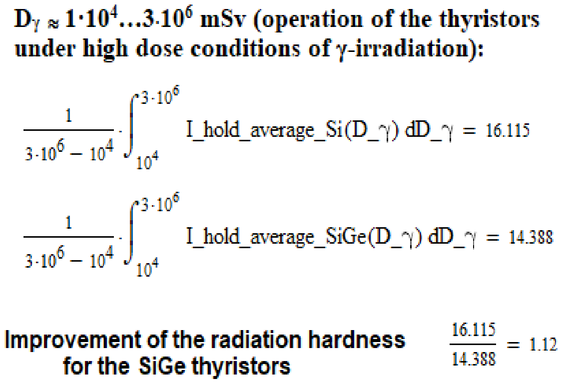
$$\frac{1}{1\cdot10^4-10}\cdot\int_{10}^{1\cdot10^4} I\_hold\_average\_Si(D\_\gamma)\,dD\_\gamma = 15.372$$

$$\frac{1}{1\cdot10^4-10}\cdot\int_{10}^{1\cdot10^4} I\_hold\_average\_SiGe(D\_\gamma)\,dD\_\gamma = 14.378$$

**Improvement of the radiation hardness for the SiGe thyristors** $\frac{15.372}{14.378} = 1.069$

**Fig. 17.** Calculation in MathCAD of average interval averages of holding currents, I_hold_average, for control thyristors manufactured on Si and devices manufactured on SiGe: low doses.

Therefore, for $D_\gamma \approx 1 \cdot 10^1 \ldots 1 \cdot 10^4$ mSv the use of SiGe makes it possible to increase the average interval radiation resistance of thyristors by approximately 7 %, and in the range of $D_\gamma \approx 1 \cdot 10^4 \ldots 1 \cdot 10^6$ mSv ≈ up to 12 %.



**$D_\gamma \approx 1\cdot10^4\ldots3\cdot10^6$ mSv (operation of the thyristors under high dose conditions of γ-irradiation):**

$$\frac{1}{3\cdot10^6-10^4}\cdot\int_{10^4}^{3\cdot10^6} I\_hold\_average\_Si(D\_\gamma)\,dD\_\gamma = 16.115$$

$$\frac{1}{3\cdot10^6-10^4}\cdot\int_{10^4}^{3\cdot10^6} I\_hold\_average\_SiGe(D\_\gamma)\,dD\_\gamma = 14.388$$

**Improvement of the radiation hardness for the SiGe thyristors** $\frac{16.115}{14.388} = 1.12$

**Fig. 18**. Calculation in MathCAD of average interval averages of holding currents, I_hold_average, for Si control thyristors and SiGe devices: high doses

The greater the nonlinearity of the processes that take place in a discrete device at certain values of $D\gamma$, the more difficult it is to increase its radiation resistance using isovalent doping by Ge.

At the same time, ensuring radiation resistance for a sample of devices does not exclude failures of individual thyristors. For individual control devices in the range $D_\gamma \approx 1 \cdot 10^5 \ldots 3 \cdot 10^6$ mSv (experimental points _hold_X5_experim, I_hold_X6_experim) there is a significant decrease in radiation resistance, which is understood as an increase in the $I_h$, compared to other control thyristors, up to ≈ 19 mA (Fig. 19).

For example, mean value of the holding current $I_h \approx 13.125$ mA for thyristors I_hold1_1X_experim, I_hold1_1X_zvezdochka_experim, i.e. about 44.8 % lower. A similar significant increase $I_h$ by 29.7 % for the thyristors X5, X6 is observed when compared to thyristors manufactured on SiGe (I_hold_G1_experim, I_hold_G1_experim, medium $I_h \approx 14.7$ mA).

The absence of observed abrupt increases in $I_h$ ("ejections") for devices, manufactured on SiGe, can partly be considered as an increase in their radiation resistance in comparison with control thyristors.

### 4.3. Effect of γ-irradiation on the Leakage Current (I leakage) of Low-power Control Thyristors

The special feature of the leakage current ($I_{leakage}$) of the control devices is the presence of two extremes (Fig. 20), located in the range $D_\gamma \cong 10^2 \ldots 10^4$ mSv.

Extremum location is closely related to the location of the $I_h$ peaks. This makes it possible to assume that leakage currents reach max at $D_\gamma$, corresponding to the min lifetime value of the minority charge carriers $\tau_p$ in the n-base of control thyristors, in which $I_h$ tends to the max value, Fig. 21.

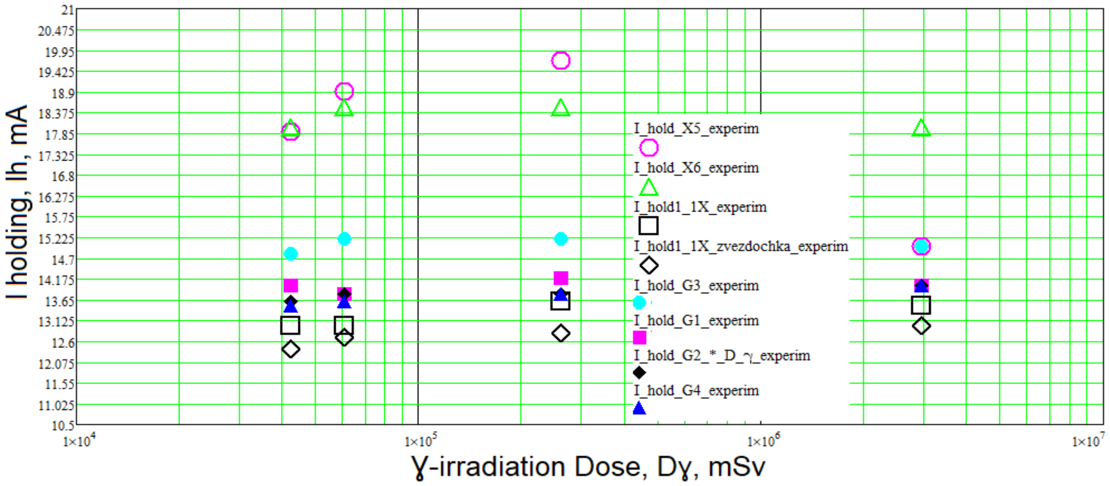


**Fig. 19.** Comparison of experimental results for selected Si and SiGe thyristors in the high dose range.

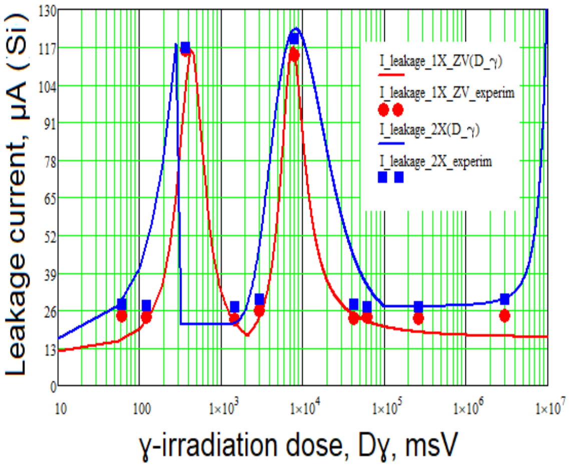


**Fig. 20.** Bimodal dose dependence of leakage currents of the control thyristors 1X_ZV, 2X.

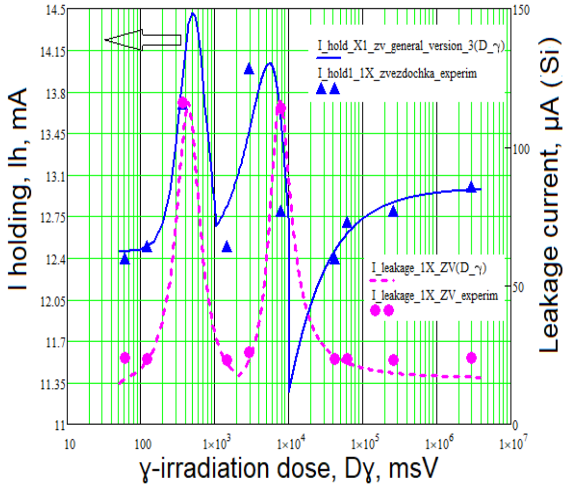


**Fig. 21.** Correlation between holding current and leakage current on the example of the control thyristor "1X with an Asterisk".

### 4.4. Effect of γ-irradiation on the Leakage Current (I leakage) of Low-power Thyristors, Manufactured on SiGe

Nonlinear dependence between holding current and leakage current for the thyristors, manufactured on SiGe, also exists, but expressed differently, then for control devices, Fig. 22.

At $D_\gamma < 10^4$ mSv leakage current lags slightly behind holding current, and at $D\gamma > 10^4$ mSv it is significantly ahead of it.

From the practical point of view (increasing the radiation resistance of the thyristor according to the criterion of a significant reduction in the leakage current), the device 1G, manufactured on SiGe, is of interest, Fig. 23.

The BiHill model, approximates the dependency, Fig. 24. Results of the calculations are shown in the Fig. 25.

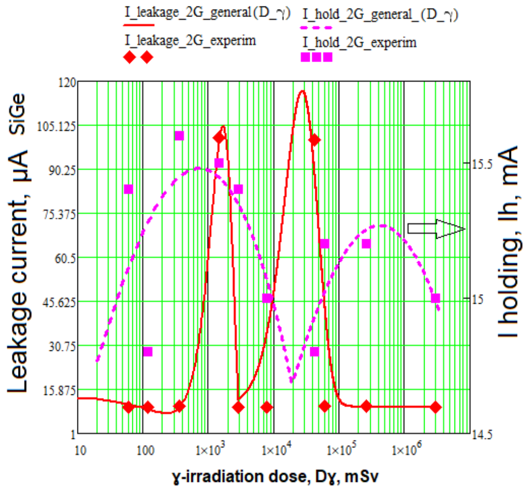


**Fig. 22.** Correlation between holding current and leakage current on the example of the SiGe thyristor "2G".

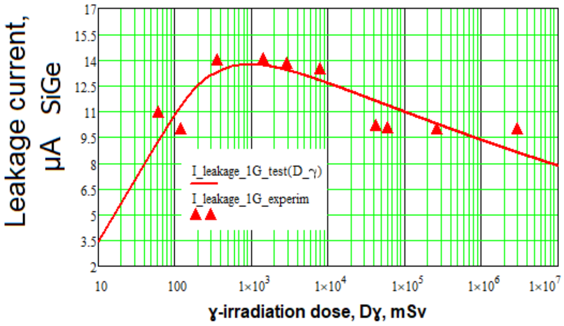
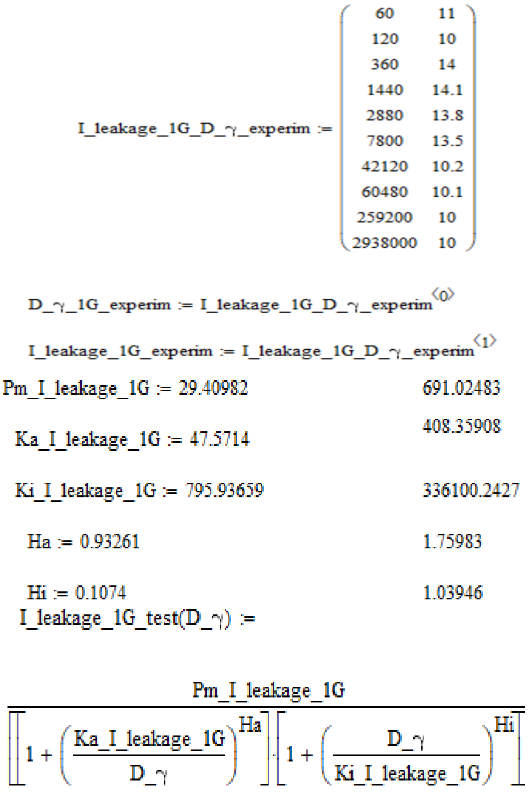


**Fig. 23.** Dependence of leakage current on $D_\gamma$ the example of the SiGe thyristor "1G".



$$\text{I\_leakage\_1G\_D\_}\gamma\text{\_experim} := \begin{pmatrix} 60 & 11 \\ 120 & 10 \\ 360 & 14 \\ 1440 & 14.1 \\ 2880 & 13.8 \\ 7800 & 13.5 \\ 42120 & 10.2 \\ 60480 & 10.1 \\ 259200 & 10 \\ 2938000 & 10 \end{pmatrix}$$

$$\text{D\_}\gamma\text{\_1G\_experim} := \text{I\_leakage\_1G\_D\_}\gamma\text{\_experim}^{\langle 0\rangle}$$

$$\text{I\_leakage\_1G\_experim} := \text{I\_leakage\_1G\_D\_}\gamma\text{\_experim}^{\langle 1\rangle}$$

$\text{Pm\_I\_leakage\_1G} := 29.40982$ 691.02483

$\text{Ka\_I\_leakage\_1G} := 47.5714$ 408.35908

$\text{Ki\_I\_leakage\_1G} := 795.93659$ 336100.2427

$\text{Ha} := 0.93261$ 1.75983

$\text{Hi} := 0.1074$ 1.03946

$$\text{I\_leakage\_1G\_test}(\text{D\_}\gamma) := \frac{\text{Pm\_I\_leakage\_1G}}{\left[1+\left(\frac{\text{Ka\_I\_leakage\_1G}}{\text{D\_}\gamma}\right)^{\text{Ha}}\right]\cdot\left[1+\left(\frac{\text{D\_}\gamma}{\text{Ki\_I\_leakage\_1G}}\right)^{\text{Hi}}\right]}$$

**Fig. 24.** Calculation in MathCAD of leakage current, for 1G thyristors manufactured on SiGe.

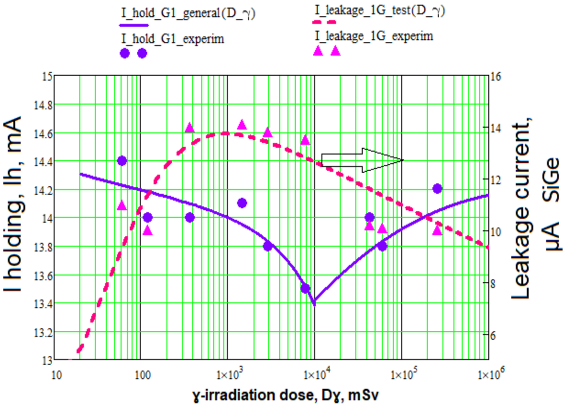


**Fig. 25.** Calculation in MathCAD of the leakage current for the 1G thyristor, manufactured on SiGe.

## 7. Conclusions

1. Radiation degradation during γ-irradiation of discrete low-power thyristors, both control (Si) and SiGe-fabricated, is a complex nonlinear process that is individual for each device.

2. It is possible to distinguish three γ-irradiation ranges, in which the degradation of the average holding current for control and investigated thyristors proceeds in different ways, namely:

2.1. For $D_\gamma \approx 1\cdot 10^1 \ldots 1\cdot 10^2$ mSv there is a decrease in $I_h(D_\gamma)$ for control Si devices. It may be manifestation of the "low-dose effect" of γ-irradiation thyristors, manufactured on Si. For SiGe devices, there is an increase in the holding current, therefore, the "low dose effect" is not manifested.

2.2. Range $D_\gamma \approx 1\cdot 10^2 \ldots 1\cdot 10^4$ mSv can be considered as an area of unstable operation of the control thyristors in the radiation field. Perhaps it is more accurate to call it the "degradation noise area" of $I_h(D_\gamma)$. Devices made with SiGe are sufficiently more stable.

2.3. For $D_\gamma \geq 1\cdot 10^4$ mSv there is an expected increase in $I_h(D_\gamma)$ for thyristors, fabricated in Si. SiGe devices continue to be more stable. Thus, from a qualitative point of view, the use of isovalent doping with germanium increases the radiation resistance of low-power thyristors

3. For $D_\gamma \approx 1\cdot 10^1 \ldots 1\cdot 10^4$ mSv use of SiGe makes it possible to increase the average interval radiation resistance of thyristors by approximately 7 %, and in the range of $D_\gamma \approx 1\cdot 10^4 \ldots 1\cdot 10^6$ mSv ≈ up to 12 %.

4. The greater the nonlinearity of the processes that take place in a discrete device at certain values of Dγ, the more difficult it is to increase its radiation resistance using isovalent doping by Ge (low and high doses for $I_h(D_\gamma)$). At the same time, ensuring radiation resistance for a sample of devices does not exclude failures of individual thyristors.

5. The leakage current (I leakage) and holding current ($I_h$) of the control Si thyristor are more correlated, than for the SiGe thyristors. The model of the process has to be considered.

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