Influence of radiation defects in a semiconductor structure on the electric field distribution in the air gap of the gas-discharge chamber

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Abstract. We have proposed and analyzed a theoretical model of the influence of a semiconductor structure both without radiation defects and with their presence on the EMI profile in the air gap of the gas-discharge chamber near the surface of the structure. We have carried out mathematical modeling and comparison of the electric field distribution in the gap for the “ideal” structure (without defects) and structures with a single defect at different depths of its occurrence. A transistor was chosen as the semiconductor structure. We have demonstrated a possibility in principle of using the simulated process for diagnosing radiation defects in electronic equipment under space conditions.

1. Introduction
Active exploration of outer space both near-Earth and interplanetary is known to be currently taking place. The effectiveness of this exploration largely depends on the fault-tolerance of the on-board radio-electronic equipment in various types of spacecraft (SC), from nanosatellites to the ISS. One of the most important causes of an increased level of failures and errors in the on-board electronic systems in a spacecraft is cosmic radiation (CR) - the fluxes of elementary particles and atomic nuclei.

The main effects of CR on radio-electronic equipment are due to ionization and nuclear energy losses of particles in sensitive volumes of elements in integrated circuits and discrete semiconductor devices - transistors and diodes. These effects come out through the parametric failures of electronic devices due to the degradation of the characteristics of the semiconductor components as the dose of ionizing radiation accumulates, and short-term interruptions (errors) of the IC under the action of individual high-energy particles. The latter are subdivided into reversible Soft Errors, which are program corrected, and catastrophic failures: SEB breakdown, SEGR dielectric breakdown in MOS [1]. Therefore, the development of new methods of studying the CR effect on the performance of semiconductor structures in radio-electronic equipment is an important task.

A gas discharge is known to take place in a dielectric gap limited by a dielectric sample when placing samples of different nature, such as: biological objects, lubricants, dielectrics into external alternating electromagnetic fields (with frequencies of 10-50 kHz, intensity 100-500 kV/m) in various gaseous environments. The type of discharge is determined by the sample geometry, the magnitude of the field intensity, the pressure and type of gas, the thickness of the gas discharge gap, and the form of
voltage applied to the electrodes. To minimize the effect of a gas discharge on the objects themselves, avalanche, sliding, corona discharges, and less often streamer discharges are used [2,3].

We have proposed to use an avalanche gas discharge occurring in the gas-discharge gap above the surface of a semiconductor transistor to diagnose changes caused by the radiation defects during a long stay in space on board a nanosatellite.

2. **The diagnostics principle of the radiation defects in a semiconductor**

The object of the study can be any semiconductor structure (transistor, diode, microcircuit). To illustrate the principle, in order to simplify it, a homogeneous semiconductor was chosen as an object. With such a choice, the physical nature of the processes taking place does not change. The semiconductor is placed in an electric field of high intensity (see Figure 1). The top electrode is evaporated on an optically transparent dielectric. A CCD camera detecting a glow is located above the transparent electrode. The figure conventionally shows the distribution of the electric field in the gas-discharge gap (using a vector array) and a gas glow.

Figure 1 explains the diagnostics principle of radiation defects. It shows a sequence of implementing the principle.

1. In ground laboratory conditions, the reference distribution of the avalanche discharge glow on the semiconductor surface without the radiation defects is detected.
2. A similar semiconductor sample is exhibited on a nanosatellite in which the radiation defects appear under the action of CR. When a high voltage source is applied, the electric field at the border of the semiconductor and the air-discharge gap is distorted due to the influence of radiation defects. Also the emission capacity of the semiconductor surface layer changes. At points on the semiconductor surface in which the potential of the distorted field exceeds the ignition potential, a gas discharge is initiated. At certain values of an air pressure and the linear size of the gas-discharge gap, the discharge becomes avalanche. The distribution of the discharge glow obtained by the optical system is detected.
3. The obtained luminescence distribution is compared with the reference one and, based on the comparison algorithm, the type of the defect and the magnitude of the dose received are identified.

The main difficulty at this research stage is finding a reliable correlation between the mathematical parameters characterizing the glow and the type of defect, on the one hand, and the accumulated dose of a semiconductor, on the other. The developed method can be used for instant diagnostics of the quality of radiation protection of electronic equipment in situ during the flight of a nanosatellite.
The authors of this paper have obtained a patent for a “Device for a few-angled tomographic diagnostics of induced plasma formations parameters in near-space conditions”. The invention can be used to determine the three-dimensional distribution functions of various parameters of low-temperature plasma induced by a gas discharge around a semiconductor structure under the influence of cosmic radiation. The device comprises a few-angle optical tomography system and consists of a module for collecting and processing initial projection data located on board the nanosatellite and a computation module located on Earth. The distributions of the parameters of a plasma-induced plasma discharge obtained as a result of the operation of a three-dimensional tomograph can provide deeper correlations with the parameters of the radiation defects in comparison with two-dimensional projection data on the plasma glow intensity.

3. Effects of CR on semiconductor structures of radio-electronic equipment

CR is subdivided into:

1. Solar cosmic rays (SCR). They are the flows of protons (98%), helium nuclei (1.5%) which originate during flares on the sun. There are practically no neutrons in the SCR on the Earth orbit since they break up during their trip from the Sun to the Earth. Only the neutrons with energy of more than 150 MeV due to the relativistic time dilatation reach the Earth orbit. SCRs are characterized by an energy range \((10^3 \ldots 10^5)\) eV. The delay of SCR reaching the Earth is from several tens of minutes to several hours, depending on the average energy of the flow. The flow density reaches the values of the \(10^6 \) cm\(^{-2}\) s\(^{-1}\).

2. Galactic cosmic rays (GCR). They are proton fluxes (95%), helium nuclei (4%), heavy nuclei (0.5%), electrons, and positrons. Particles with relatively low energy are assumed to come from our galaxy, while ultrahigh-energy particles are of extragalactic origin. The angular distribution of GCR is almost isotropic. GCRs are characterized by an energy range \((10^6 \ldots 10^{20})\) eV. Due to the decay, the neutron component of the cosmic rays is practically absent in their composition. The flux density is about 1 cm\(^{-2}\) s\(^{-1}\).

3. Emissions of the Earth radiation belts. They are mainly a proton flux (95%). The flux density is about \(10^3 \) cm\(^{-2}\) s\(^{-1}\). Energy range \((10^3 \ldots 10^5)\) eV.

The distribution and concentration of radiation defects in a semiconductor substantially depend on the mass of the bombarding particles. When irradiated with light ions, individual point defects appear along the trajectory of the ion. When irradiated with heavy ions, a large three-dimensional region is formed from a microscopic point of view around the ion track containing some point defects of very high concentration. This region becomes amorphous since its ordered structure is lost. At ion irradiation, elastic shocks with atoms of the structure occur which lead to the formation of a Frenkel pair, as well as inelastic, primarily exciting the electron shell of an atom and leading to ionization [5]. Such a mechanism takes place both in dielectrics and semiconductors. In metals, the energy transferred by the electron to the electron shell of an atom during a collision eventually converts into a thermal energy. If the energy possessed by a primary atom displaced in an internode, exceeds approximately 100 eV, then such an atom, in its turn, when moving can generate Frenkel pairs near its trajectory. The result of the collision cascade is the formation of defective disordered regions — radiation clusters with a characteristic linear size of the order of \((10^6 \ldots 10^5)\) cm. The concentration of the components of Frenkel pairs in a cluster can reach \((10^{21} \ldots 10^{22})\) cm\(^{-3}\) [6].

The concentration of excessive electron-hole pairs resulting from radiation-induced ionization can be estimated by the formula [6]:

\[
\Delta n = \Delta p = \frac{w \epsilon \tau}{e},
\]

where \(w\) is the radiation dose intensity, \(\epsilon\) - conversion efficiency depending on the type of particles and their energy spectrum, \(\tau\) - nonequilibrium charge carrier life span, \(e\) - elementary charge.

4. Theoretical model

If a slowly varying (compared to the characteristic time of the gas-discharge processes) electric field is applied to a capacitor in which the transistor under study is located, the uniform field in the gas-
discharge gap above the transistor surface is distorted due to the inside presence of the impurity zones of a certain geometry with a certain bulk charge density.

Under the influence of cosmic radiation, radiation defects accumulate in the semiconductor volume which are characterized by their own geometry and the bulk charge density. Accordingly, both the potential and the electric field intensity on the semiconductor surface are distorted in comparison with those of the non-irradiated transistor. Due to the inhomogeneity of the potential distribution over the semiconductor surface, at some points the potential exceeds the ignition potential, a gas discharge is initiated and an avalanche is formed. Therefore, the “information” about the presence of a radiation defect in a semiconductor is “transmitted” to a gas discharge, the glow of which summarizes the information on the presence and concentration of radiation defects in the structure.

To simplify a task, the p type semiconductor is provided instead of the transistor. Figure 2 (a) shows a calculated 2D model of a semiconductor with a dielectric constant \( \varepsilon \) and bulk charge density \( \rho_1 \), in which there is a cylindrical defect with the bulk charge density \( \rho_2 \). Due to ionization processes \( \rho_2 > \rho_1 \). The defect is located at a depth \( h \) from the semiconductor surface and has a radius \( R \).

Due to the drift of holes under the action of the field in the direction of the lower electrode and their subsequent accumulation there, in the semiconductor itself a bulk charge density \( \rho_1 \) appears, which in this model is assumed to be constant. The effect of the surface charge of holes on the electric field in the gap due to its insignificance can be neglected.

The external electric field in the absence of a defect can be considered homogeneous. The resulting potential of the disturbed field in each of the 1, 2, 3 areas indicated in figure 2 with the corresponding numbers in the circle will be determined by virtue of the superposition:

\[
\phi = \phi_0 + \phi_i, \tag{1}
\]

where \( \phi_i \) is the potential of the secondary field in the \( i \) region, \( i = 1, 2, 3 \); \( \phi_0 \) is the potential of an external, “unperturbed” field determined by the formula:

\[
\phi_0 = -E_0(s + d - y) = -E_0(s + d - r \cos \alpha), \tag{2}
\]

where \( s \) is the transparent dielectric thickness, \( d \) - gas discharge gap thickness. The potential of the lower metal electrode is taken as a zero potential 1.

The formulation and solution of the 2D problem is carried out in the polar coordinates \((r, \alpha)\). The center of coordinates coincides with the center of the radiation defect, while the polar angle \( \alpha \) is read clockwise from the \( y \) axis. The distribution of the potential of the secondary field in media 1 and 2 is determined by the Poisson equation, while in medium (3) by the Laplace equation. Let us write the system of the corresponding equations:

\[
\begin{cases}
\Delta \phi_1 = - \frac{\rho_1}{\varepsilon_0 \varepsilon_1}, \\
\Delta \phi_2 = - \frac{\rho_2}{\varepsilon_0 \varepsilon_1}, \\
\Delta \phi_3 = 0
\end{cases} \tag{3}
\]

We will write the boundary conditions for this system. The first type of boundary conditions occurs at the interfaces of media 1 and 2, 2 and 3 and is due to the continuity of the function \( \phi \):

\[
\begin{align*}
\phi_1 \bigg|_{r=R} &= \phi_2 \bigg|_{r=R}, \\
\phi_2 \bigg|_{r=0, \alpha} &= \phi_3 \bigg|_{r=0, \alpha}
\end{align*} \tag{4}
\]

The second type of boundary conditions occurs at the origin and at infinity due to the finiteness of the potential:
The third type of boundary conditions arises at the interfaces of media 1 and 2, 2 and 3 and is caused by the continuity of the normal component of the electric induction vector $D$:

$$
\left \{ \begin{array}{l}
\frac{\partial \phi_1}{\partial r} \bigg|_{r=0} = 0 \\
\phi_1 \bigg|_{r=\infty} = 0
\end{array} \right.
$$

(5)

The Laplace operator is known to be recorded in the polar coordinate system as [7]:

$$
\Delta = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2}
$$

We look for the solution of system (3) in general [7]:

$$
\left \{ \begin{array}{l}
\phi_1, \phi_2 = C_0 + \sum_{n=1}^\infty r^n (A_n \cos n\alpha + B_n \sin n\alpha) \\
\phi_3 = C_0 + \sum_{n=1}^\infty r^{-n} (A_n \cos n\alpha + B_n \sin n\alpha)
\end{array} \right.
$$

After applying the boundary conditions (4) - (6), formulas (1) and (2), and the well-known relation $\varphi = -\nabla E$ for the boundaries of regions 2 and 3, we will obtain the distribution of the resulting electric field:

$$
E = E_0 \sqrt{1 + \frac{\rho - 2\rho (Y^2 - X^2)}{Y^2 - X^2}}
$$

(7)

where $\rho$, $Y$, $X$ are the relative values determined by the following formulas:

$$
\rho = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}, Y = \frac{h}{R}, X = \frac{x}{R}.
$$

The value $\rho$ characterizes the effect on the field in the gas-discharge gap of the difference between the volume charges of the defect and the main semiconductor; $Y$ is the relative depth of localization of the defect expressed in units of its linear size; $X$ is the relative coordinate along the semiconductor surface expressed in units of the linear size of the defect.

To describe the process of the electron avalanche in a gas discharge, it is important not only the magnitude of the electric field, defined by expression (7), but also the projection of the vector on the normal to the surface of the semiconductor. However, such a study remained outside the scope of this article.

Figure 2 (b) shows a dependency graph of the electric field normalized by an external field in a gas-discharge gap $\frac{E}{E_0}$ from relative coordinate on the semiconductor surface $X$ at different depths of the defect $Y$ and at different values $\rho$ (curve 1: $Y = 1$, $\rho = 0.2$; curve 2: $Y = 3$, $\rho = 0.2$; curve 3: $Y = 3$, $\rho = -0.2$; curve 4: $Y = 1$, $\rho = -0.2$).

5. Numerical simulation

The fundamental system of equations for the numerical simulation of processes in a transistor in the diffusion-drift approximation consists of the Poisson equation, the continuity equations for electrons and holes, and the Boltzmann kinetic equation. The latter, in the indicated approximation, splits into two equations expressing the densities of the currents of electrons and holes [8]:

$$
\left \{ \begin{array}{l}
\frac{\partial \phi_1}{\partial r} \bigg|_{r=0} = 0 \\
\phi_1 \bigg|_{r=\infty} = 0
\end{array} \right.
$$
\[
\Delta \varphi = \frac{e}{\varepsilon_0} (n - p + N_a - N_d)
\]
\[
\frac{\partial n}{\partial t} = \frac{1}{e} \operatorname{div} j_n - RG_s
\]
\[
\frac{\partial p}{\partial t} = \frac{1}{e} \operatorname{div} j_p - RG_p
\]

where \( n, p, N_a, N_d \) are the concentrations of the free electrons, holes, ionized acceptors and donors, respectively; \( j_n \) and \( j_p \) are the current density of electrons and holes, respectively. The latter are determined by the expression:

\[
\begin{align*}
\vec{j_n} &= e(D_n \nabla n - n \mu_n \nabla \varphi) \\
\vec{j_p} &= -e(D_p \nabla p + p \mu_p \nabla \varphi)
\end{align*}
\]

where \( D_n, D_p, \mu_n, \mu_p \) are the diffusion and mobility coefficients of the electrons and holes, respectively.

Figure 2. (a) the calculated model; (b) the graph of the distribution of the electric field in the gap.

At high concentrations of free charge carriers which arises in the presence of radiation defects, Auger recombination takes place [9]:

\[
\left\{ \begin{array}{l}
(RG)_s = G_s - R_s \\
(RG)_p = G_p - R_p
\end{array} \right.
\]

The numerical simulation of the electric field distortion in the presence of the radiation defects in the transistor was carried out using the finite-element method with a triangular grid in COMSOL Multiphysics software version 5.4. Geometrically, the model for a numerical simulation corresponds to the model for theoretical consideration (see Figure 2) with the only difference of two areas of the n-type semiconductor being introduced into the numerical model. To set the boundary conditions and correctly solve the system of differential equations for modeling, the air region around the transistor is being set.

Figure 3 (a) shows the potential distribution between the capacitor plates, and arrows show the electric field intensity vector for cases of different depth of defects in the transistor, and the case when the defect is absent. The simulation was carried out with the value of the bulk density of charges in the defect 1000 times greater than the bulk charge density in the semiconductor (5 mC/m³). It can be seen that as the defect approaches the transistor surface, its effect on the initial field increases which is reflected in the distortion of the potential contours and, accordingly, the magnitude and direction of the electric field intensity vector.

Figure 3 (b) shows the distribution of the intensity vector modulus along the length of the transistor at the boundary points with the gas-discharge gap. The field on the axis of symmetry has a minimum which is consistent with the theoretical consideration (see Figure 2, curve 1) with \( \rho < 1 \). However, the
nature of the further change in the intensity modulus with the distance from the axis is different from monotonic, and an additional maximum and minimum occurs. This is due to the redistribution of charge carriers in a semiconductor under the influence of an applied field, which was not taken into account when theoretically considering.

Figure 3. (a) a npn-transistor design model for a numerical simulation; (b) a potential distribution between the metal electrodes (the arrows indicate the intensity vector) and graphs of the distribution of the intensity vector magnitude across the surface of the transistor for different depths and without defect.

6. Conclusion
In this paper, we have proposed and studied, both theoretically and numerically, a model of the effect of the radiation defect in the transistor on the distribution profile of the electric field in a gas-discharge gap. A theoretical formula was obtained that allows us to build a normalized graph of this distribution. The result of numerical modeling refines the profile view when accounting for the redistribution of charges in a semiconductor due to diffusion, drift, recombination, and carrier generation. The values of the magnitude of the electric field intensity vector in the gas-discharge gap change by a value of the order of units — tens of percent, up to two times at the maximum possible value of the bulk charge density of the defect. Such a variation in the value of the field leads to different emissions from the transistor surface and, consequently, to the different trajectories of the development of an avalanche discharge in a gas. Therefore, it is possible to draw a conclusion about the presence and concentration of radiation defects in semiconductor structures by comparing the pattern of distribution of the glow of the gas discharge with a certain reference picture corresponding to the absence of the defects.
7. References

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