Calculation of The Absorbed Dose of Electron Radiation in Polymer Cases of Microelectronic Devices, Considering the Factor of Its Accumulation

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***Abstract*: A computer simulation of the depth course of the absorbed dose as a function of the electronic irradiation energy of the acting in the range of 30 – 60 keV was performed, and calculations of the dose accumulation factor under these conditions were performed for polyethylene terephthalate, polymethylmethacrylate, polystyrene and low-density polyethylene, as model polymers of microelectronic device housings. It is shown that the electron energy values corresponding to the maximum dose accumulation factor depend on the polymer density.**

The conducted studies allow us to determine with great accuracy the conductivity of plastic cases of microelectronic devices under conditions of electronic irradiation, which is of particular interest to exclude the physical possibility of the occurrence of electrostatic discharges that lead to failures of the onboard electronics of spacecraft.

***Keywords* — Composite dielectric, Computer simulation, conductivity, radio engineering devices, electrization and electrostatic discharge.**

I Introduction

Polymer bodies of microelectronic equipment of spacecraft (SC) operating in near-Earth orbits are exposed to intense effects of electrons and ions of cosmic plasma [1,2]. As a result, an electric charge accumulates in them and radiation charging occurs. Subsequent electrostatic discharges (ESR) can lead to failures in the operation of microelectronic equipment and thereby affect the reliability of the spacecraft operation [3-5].

An accelerated electron moving through matter loses energy in the electromagnetic interaction with the bound electrons of the atomic shells. In this case, the energy that the fast electron loses is used to excite and ionize the atoms and molecules of the substance.

When the primary electron passes through the polymer sample, a large number of secondary electrons are formed as a result of ionization, which, in turn, make a further contribution to the ionization and excitation of polymer molecules. When an accelerated electron passes through a polymer layer of sufficient thickness, its energy decreases. The maximum distance that a fast electron in the polymer travels in the direction of the beam of electrons incident on the sample is called the maximum path. In practice, for electrons, extrapolated runs are usually used as the average value of the runs. The extrapolated path is defined as the thickness of the absorbing layer at which the zero-intensity level is reached when extrapolating the linearly decreasing section of the curve of the electron beam intensity dependence on the thickness of the irradiated polymer.

Electrons, being light charged particles, experience strong scattering as they move through matter. Therefore, the actual path traveled by an electron in a substance can significantly (up to three times) exceed its extrapolated path. As a result, there is a large unevenness in the distribution of the absorbed dose over the thickness of the polymer sample during its electron irradiation (the depth course of the dose), and this significantly complicates the determination of the integral absorbed dose. Errors in determining the amount of absorbed dose can reach 50-60%. This work is devoted to determining the correction that considers the uneven distribution of the dose, which is called the accumulation factor, and allows calculating the absorbed dose when irradiating polymer bodies of microelectronic devices with electrons with much greater accuracy.

The distribution of the absorbed dose over the depth of the polymer sample (the depth course of the dose) is uneven [3,4], but it does not depend much on the nature of the polymer substance. This made it possible, on the basis of the experiments carried out, for example, [3,4,] to propose a number of approximated curves for the distribution of the absorbed dose of electron radiation over the depth of the sample [6-9]. Normalized coordinates were used: the depth of penetration into the sample in units of extrapolated electron path at a given energy was plotted along the abscissa axis, and the absorbed dose at a given depth was plotted along the ordinate axis, normalized to the absorbed dose on the sample surface.

As an example, Figure 1 shows the distribution curve of the absorbed dose of electron radiation with an energy of 65 keV over the depth of the polyethylene terephthalate sample [5].

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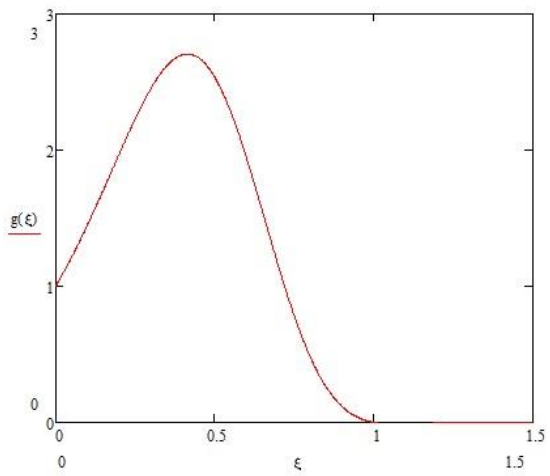

Figure 1. The distribution curve of the absorbed dose of electron radiation over the depth of the polyethylene terephthalate sample. The electron energy is 65 keV [9]

For electrons with an energy of 40 keV, Monte Carlo calculations of the dose depth curves were performed [7,8], which refine the above-mentioned approximation curves. As a result, the following formula was obtained:

$$g(\xi) = exp(3{,}677 \cdot \xi^{0{,}972} - 4{,}978 \cdot \xi^{3{,}069}) \cdot cos(\frac{\pi \cdot \xi}{2}) \quad (1)$$

Here $\xi = x/l_m$, where x - is the coordinate in the direction of the normal deep into the polymer sample, l_m - is the extrapolated electron path at a given electron energy. The expression (1) is universal, changing slightly with varying electron energy and the average atomic number of the polymer, and can be used for a number of polymers with a density from 0.9 to 1.4 g·cm^3.

The graphs shown above show that the depth course of the dose across the sample is highly uneven. The curve passes through the maximum and then drops to zero. The increase in the absorbed dose with depth in the initial part of the curve is explained by the fact that the interaction cross-section, the ionization density, and, accordingly, the absorbed dose increase as the electron loses its energy in collisions with the medium molecules. However, the total number of primary electrons passing through the polymer sample decreases with increasing depth, which leads to a decrease in the absorbed dose with increasing depth. The competition of the above factors explains the presence of a maximum on the curve of the deep course of the dose.

To calculate the absorbed dose rate of electron irradiation, the following expression is used:

$$R_e = \frac{I_0}{q}\frac{dE}{dx} \quad (2)$$

Where I_0 - the density of the electron flux incident per unit surface area of the material, A·m^{-2} , q - is the electron charge.

The absorbed dose is related to the dose rate by the expression $D_e = R_e t$ and is calculated by the expression:

$$D_e = \frac{I_0}{q}\frac{dE}{dx}t \quad (3)$$

In expressions (2) and (3), it is customary to introduce a significant correction for the unevenness of the deep course of the dose.

II Calculations of the Absorbed Dose Accumulation Factor

Since expressions (2) and (3), one of the multipliers, contain the average stopping power of the material $\frac{dE}{dx}$ that is logical for a sample with a thickness of L enter the average correction for the depth course of the dose, called the dose accumulation factor and considering (1) equal to:

$$K = (1/L)\int_0^L (exp(3{,}677 \cdot [x/l_m]^{0{,}972} - 4{,}978 \cdot [x/l_m]^{3{,}069}) \cdot cos(\frac{\pi \cdot x}{2l_m}))dx \quad (4)$$

Note that the expression (4) is valid for the case when the extrapolated path of an electron l_m determined by its energy, is equal to or greater than the thickness of the sample L (in the direction of the normal to the surface):

$$l_m \geq L$$

At the same time, when the sample thickness L is greater than the extrapolated electron path l_m, and $l_m \leq L$, all accelerated electrons are retained by the sample, and the dose accumulation factor will be:

$$K = (1/l_m)\int_0^{l_m} (exp(3{,}677 \cdot [x/l_m]^{0{,}972} - 4{,}978 \cdot [x/l_m]^{3{,}069}) \cdot cos(\frac{\pi \cdot x}{2l_m}))dx = 1.546 \quad (5)$$

At the same time, the polymer layer with $\xi > 1$(where x is greater l_m), where the electrons do not penetrate, it is considered blocking with zero absorbed dose.

When packaging microelectronic devices, complex polymer composite materials are used. However, the mechanism of action of ionizing radiation on different polymers is the same – ionization of atoms and molecules of the medium. Therefore, we used a number of polymers with different densities as model materials for polymer housings: polyethylene terephthalate (PETF) with a density of d = 1.39 g/cm^3, polymethylmethacrylate (PMMA) with a density of d = 1.19 g/cm^3, polystyrene (PS) with a density of d = 1.05 g/cm^3, and low-density polyethylene (LDPE) with d = 0.92 g/cm^3. For them, computer simulation of the depth course of the absorbed dose depending on the energy of the acting electrons in the range of 30 – 60 keV was performed, and calculations of the factors of dose accumulation K under these conditions were performed. In all cases, the same polymer film thickness of 15 microns was used. Calculations were made for cases when the extrapolated electron path in the polymer was equal to the film thickness and exceeded it:

$$l_m \geq L$$

Extrapolated mileage values не l_m they were taken from the work [1].

The SciLab package of applied mathematical programs was used for modeling and corresponding calculations.

Figure 2 shows the curves showing how the function for the PET film, which characterizes the depth course of the absorbed dose, changes for different electron irradiation energies E. We

see that when moving away from the surface into the depth of the film, it first increases, reaches a maximum value at a certain depth, and then falls to zero (if the film thickness is equal to the value of the extrapolated electron path at a given energy. The greater this energy, the greater the extrapolated range compared to the film thickness, and therefore a smaller part of the dose depth curve will be reflected in the graph in the range of 15 microns.

In Fig. 3. It is shown how the dose accumulation factor K calculated by expression (4) changes in PETF when the electron energy E changes. From the energy of 33 keV, at which the extrapolated path is equal to the thickness of the PET film (l_m = L), with an increase in E and, respectively, l_m , The K factor increases and passes through the maximum at 44 keV, reaching a value of 2.13. Further, with increasing energy, it decreases.

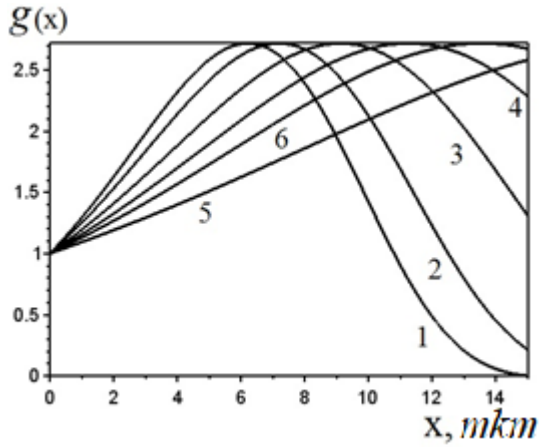

Figure 2. The depth course of the absorbed dose in a PET film with a thickness of 15 microns for different electron irradiation energies E: 1-33 keV; 2-35 keV; 3-40 keV; 4-45 keV; 5-50 keV; 6-60 keV.

A similar pattern was observed for PMMA, PS, and LDPE. The nature of the change in the dose accumulation factor with a change in the energy of the accelerated electrons did not change.

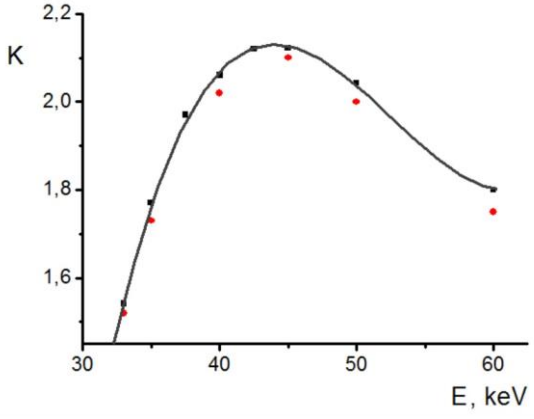

Figure 3. Dependence of the dose accumulation factor K in PET on the electron energy E: ■ calculation by expression (7); ●- experimental data.

Note that in all cases, the maximum value of the dose accumulation factor was the same and was Km = 2.13. However, the energies at which the maximum value of K was reached were different for different polymers.

The analysis showed that the electron energy values corresponding to the maximum dose accumulation factor depend on the density of the polymers. The higher the density of the polymer, the greater the energy value. This is clearly seen in Fig. 4. There is a linear relationship, which is well explained from the physical point of view. Indeed, the inhibitory capacity of a substance, which determines the absorbed dose, is approximately proportional to the density d and weakly depends on the nature of this substance.

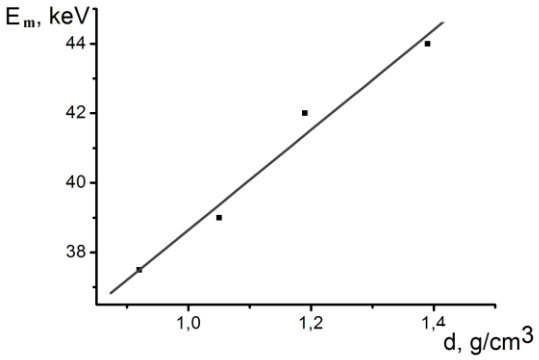

Figure 4. The dependence of the electron energy corresponding to the maximum dose accumulation factor on the density of polymers.

III Experimental Verification of the Results of Calculating the Dose Accumulation Factor

For experimental verification of the simulation results, the radiation radiation conductivity of PETF was measured during its pulsed irradiation at the same electron energies as the calculated ones. We took advantage of the fact that with pulsed irradiation in the low-signal mode, when the irradiation time is very short and the recombination of charge carriers can be neglected, the radiation conductivity is proportional to the absorbed dose rate.

We measured the radiation conductivity of PET at the installation [2] with an electron beam from an electron gun with a voltage of 30-60 keV falling on a polymer sample located inside a vacuum chamber (vacuum 2 * 10^{-5} mm Hg) at room temperature. The block diagram of the installation is shown in Fig. 5, the measurement method is described in detail in [2].

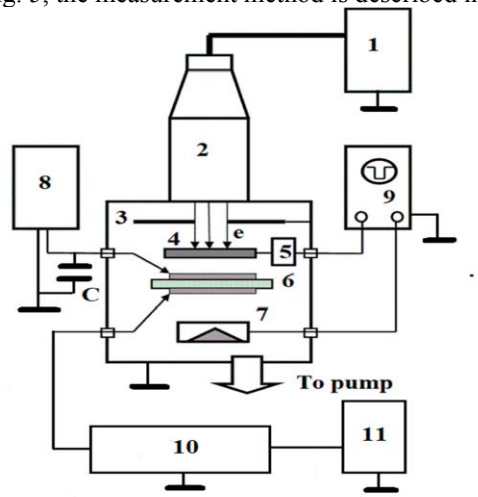

Fig. 5. The experimental setup for measuring radiation-induced conductivity

of the polymer and of studies using time-of-flight techniques: 1—high-voltage source; 2—electron gun; 3— collimator electron beam; 4—metal valve; 5—damper control system; 6—the sample with A evaporated electrodes; 7—Faraday Cup; 8—a DC power supply with a cumulative capacity C and electronic control circuit voltage: 9—dual beam oscilloscope Tektronix 3012B with a bandwidth of 300 MHz; 10-electronic unit for measuring the radiation-induced conductivity of the analog signal, amplification and analog-to-digital conversion and final transmission to the printer.

With an increase in the electron energy, the inhibitory capacity of the irradiated substance and, accordingly, the power of the absorbed dose decreases. In order to be able to compare the measured values of the radiation conductivity of PETF at different electron energies, it is necessary that their surface dose rates are the same. During the experiment, we achieved this by a corresponding increase in the current density of the electron beam (radiation current).

If, for example, during the transition from the experiment to measure the RE at 35 keV, when [9] the braking capacity $\frac{dE}{dx}$ was $8.094 \cdot 106$ eV·cm^2·g^{-1} at 40 keV $\frac{dE}{dx} = 7.3252 \cdot 10^6$ eV·cm^2·g^{-1} and, consequently, decreased by 1.105 times, then exactly the same with $3.185 \cdot 10^{-7}$ A·cm^{-2} to $3.519 \cdot 10^{-7}$ A·cm^{-2} in the experiment, we increased the density of radiation power.

In the experiments under consideration, as the radiation electrical conductivity, the surface dose rate of radiation conductivity PETF, and the corresponding K = 1 (see Fig. 1), the radiation-pulse electrical conductivity of PET was used at an energy of 8 MeV and under the same conditions as in the above-mentioned experiments for 30-60 keV. Indeed, calculations based on expression (4) for an energy of 8 MeV using $\frac{dE}{dx}$ = 1.8047 MeV·cm^2·g^{-1} they give the value K =1.00157, which is only 0.15% higher than 1. Figure 6 shows how the curve corresponding to the energy of 8 MeV is spread along the abscissa axis in comparison with the curve corresponding to 60 keV.

The value of the radiation-induced conductivity PETF for the energy of 8 MeV at a pulse time of 2.5 microseconds was taken from [3]: $\gamma_P^0 = 5.156 \cdot 10^{-11}$ ohm^{-1}·m^{-1}. Thus, for the radiation-induced conductivity of PETF at 35-60 keV, we have:

$$\gamma_P = A \cdot K_{mes} \cdot R_e$$

A for radiation-induced A for PET at 8 MeV: $\gamma_P^0 = A \cdot R_e$,

Where from $K_{mes} = \frac{\gamma_P}{\gamma_P^0}$.

The results of the experiment shown in Fig. 6. A comparison of these results, plotted in circles, with the values of the dose accumulation factor obtained as a result of modeling, shows that the maximum error between the calculated and experimental points does not exceed 3%. Thus, the results indicate the adequacy of the calculated model of the dose accumulation factor, and its values obtained from the experiment.

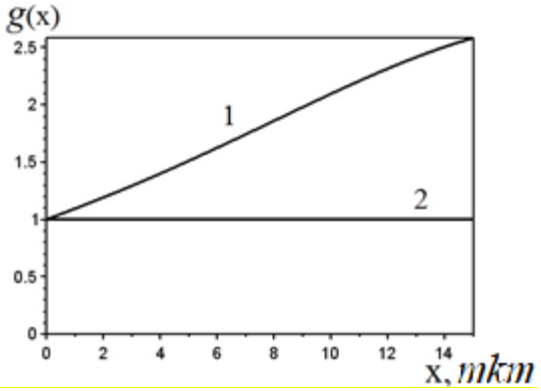

Figure 6. The depth course of the absorbed dose in a PET film with a thickness of 15 microns for electron irradiation energies E: 1-60 keV; 2-8 MeV.

Indirectly, the correspondence between the simulation results and the experimental data is confirmed by the linear dependence of the electron energy corresponding to the maximum dose accumulation factor for different polymers on their density.

The conducted studies allow us to determine with great accuracy the value of the absorbed dose accumulation factor, which in turn allows us to calculate the absorbed dose and, accordingly, the conductivity of any polymer materials, including plastic cases of microelectronic devices under electron irradiation. The latter determines the flow and equalization of the electric charge accumulated in the polymer dielectric during radiation loading, which is of particular interest to exclude the physical possibility of the occurrence of electrostatic discharges that lead to failures of the onboard electronics of spacecraft.

IV Conclusion

Performed computer modeling of the deep stroke of the absorbed dose, depending on the electronic irradiation energy in the range of 30 to 60 Kev, and calculations of factors of dose accumulation for polyethylene with a density of d = 1.39 g/cm^3, polymethylmethacrylate with a density of d = 1.19 g/cm^3 polystyrene with a density of d = 1.05 g/cm^3 and low density polyethylene with d = 0.92 g/cm^3. It is shown that the electron energy values corresponding to the maximum dose accumulation factor linear depend on the polymer density.

The conducted studies allow us to determine with great accuracy the conductivity of plastic cases of microelectronic devices under conditions of electronic irradiation, which is of particular interest to exclude the physical possibility of the occurrence of electrostatic discharges that lead to failures of the onboard electronics of spacecraft.

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