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as a manuscript

Afanasyeva Margarita Aleksandrovna

Development of discharge-free semiconductor devices with plastic cases for the spacecraft electronics.

Dissertation summary
for the purpose of obtaining academic degree
Doctor of Philosophy in Engineering

Academic supervisor:
Doctor of Technical Sciences,
professor, Russian Government award winner,
Saenko Vladimir Stepanovich

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Relevance of the topic

The use of serial production electronic components in the space industry has arisen since the creation of small spacecraft. The serious development in the field of creating materials for integrated microcircuit cases (ICs) of improved design, increased reliability and other important indicators led to the widespread use of plastic IC cases, which led to the rejection of sealed / ceramic cases. The suitability and possibility of using the former for military and aerospace applications have been studied in detail. Unlike sealed /ceramic, plastic case is cheaper, more affordable and has greater mechanical stability. Nevertheless, the lack of data on long-term reliability studies in space conditions raises concerns about the possibility of their reliable use.

Spacecraft operating in geostationary and highly elliptical orbits is subject to the effects of electrostatic discharges (ESD) on their surface resulting from the accumulation of static charges on dielectric sheathing materials (mainly polymeric), which are actively in contact with the external environment due to electron flows generated as a result of geomagnetic disturbances.

It is ESD that is by far the most negative manifestation of the electrification of the spacecraft. Despite the efforts made by scientists, a significant number of failures on the spacecraft operating in the geostationary orbit, highly elliptical orbits and in the auroral regions of near-Earth space are caused precisely by the electrification of the spacecraft and the accompanying ESD.

The occurrence of ESD is caused by the time of the potential's equalization of conductive spacecraft dielectric elements. It should be noted here that the elements of such a "pair" can be the dielectric substrate and the conductors of the printed circuit board. A radical way to eliminate the possibility of ESD is to increase the required conductivity of the spacecraft dielectric elements.

As the most effective way to reduce the likelihood of the ESD formation it should be noted the solution of the problem by applying such polymeric materials on the spacecraft outer surface that would have high radiation electrical conductivity (EC). The high polymer EC contributes to the intensive drain from the polymer

volume of an excessive amount of charge carriers onto its surface, as well as to a decrease in the magnitude of the electric field arising in this material when it is irradiated. Due to this property, electric potentials equalization is carried out on the polymer material surface and, accordingly, in its volume, which significantly reduces the likelihood of ESD.

Over the past 20 years, domestic and foreign researchers have done lots of work on the synthesis of such materials and their modifications in the right direction. These studies are primarily associated with significant difficulties in predicting the behavior of the EC dependence of the materials under study on the dose rate, absorbed dose, temperature, and other external factors. In this regard, detailed forecasting for each polymer under study individually or its modification of the behavior of EC over time, taking into account the influence of external factors, becomes the subject of independent scientific work.

In this regard, it seems to be extremely important to develop a methodology for EC predicting polymers as a function of time and external conditions of irradiation using computer simulation and experimental confirmation of the resulting model, followed by an assessment based on this technique of considered polymer material effective using on the spacecraft outer surface.

To solve this problem, it is necessary to select a dielectric with a lower electrical conductivity due to its intrinsic conductivity, to model it using by optimal software product in order to know how its characteristics will change over the course of the experiment and confirm the results in practice. Studies of such a dielectric use as a protective material for space applications will provide an opportunity to increase the spacecraft's resistance to the influence of electrification factors, thereby contributing to an increase in the spacecraft's active life, which determines the relevance of the topic of this work.

The Dissertation purpose is to increase the stability of on-board electronic equipment to the effects of electrification by developing a method for creating discharge-free semiconductor devices in polymer cases for the spacecraft electronics and implementing on its basis an engineering method for choosing the bulk conductivity of a case’s dielectric to exclude the physical possibility of ESR

type “charged volume of a semiconductor device polymer case – chip crystal”.

To successfully achieve the research target, based on published literature data review and analysis, the following dissertation research tasks are set:

1. To approximate a real semiconductor device to a spherically symmetric shape and to develop a physical model for the space charge accumulation in the semiconductor device polymer case with a uniform injection of electrons.

2. Based on the analytical expressions obtained when solving the physical model system of equations, to create a program in MatCad for calculating the maximum electric field in the dielectric of the semiconductor device plastic case (without field amplification on inhomogeneities).

3. For an adequate electric field gain calculation at the crystal vertices and edges of a parallelepiped-shaped device, to perform experimental studies of the air breakdown strength when using the upper electrode with different radii of curvature (from 10 mm to 20 microns). To confirm the obtained experimental dependence theoretically and to use it in the engineering method to calculate the maximum electric field in the actual semiconductor device construction.

4. To develop a new maximum electric field criterion applicable to the semiconductor devices configuration in plastic cases, upon reaching which the ESR can flow from the polymer volume to the semiconductor device crystal.

5. Based on the studies, to create an engineering method for selecting the bulk conductivity of the dielectric to exclude the ESD physical possibility of "charged volume of a semiconductor device polymer case – chip crystal" type applicable to semiconductor devices of various designs and sizes.

The degree of research topic elaboration

Prior to this work, when designing the spacecraft two criteria were used for the electric field magnitude in the volume of the dielectric element. The first criterion is that ESR from the dielectric volume is possible when the electric field exceeds 2.10^7 V/m. The second criterion (used mainly for on-board electronics printed circuit boards) - ESD is possible with an accumulated total electron fluence is about 2.10^{10} el./cm^2 in 10 hours.

Research methods

The following theoretical, experimental, and computational research methods were used to solve the tasks of the dissertation:

1. Physical modeling method with its spherical approximation that allowed to obtain analytical expressions for the maximum electric field in a polymer dielectric layer with finite conductivity, in which high-energy electrons are injected uniformly in its volume.

2. For an adequate calculation of the electric field gain on the vertices and edges of the chip crystal (having the form of a parallelepiped), during the conducted works, experimental studies of the breakdown field in air were performed when using an upper electrode with different radius of curvature (from 10mm to 20 microns). The obtained experimental dependence was theoretically confirmed and used for engineering method of calculating the maximum electric field in the semiconductor device real design.

3. Based on analytical expressions obtained when solving the physical model system of equations, a program for calculating the maximum electric field in the plastic case dielectric of a semiconductor device (without amplifying the field on inhomogeneities) was created (Mathcad software). The calculation method obtained in this way became the basis of an engineering method for selecting the bulk conductivity of the chip case dielectric to exclude the physical possibility of "charged volume of a semiconductor device polymer case – chip crystal" ESR.

Author's personal contribution of the problem development

In the dissertation, the main idea of the work belongs to the author. This idea is to create a spherical model of the chip and to obtain an analytical solution to this problem. The result of the calculation is the electric field maximum value, which will be created by the electron radiation uniform in volume - at the first stage. Experimental work carried out by the author determines the field gain at the edges and vertices of the chip crystal. Based on these works performed by the author an engineering method was implemented to determine the electrical conductivity of the plastic of the chip case, which eliminates the physical possibility of electrostatic

discharges (ESD) of the “charged volume of a semiconductor device polymer case – chip crystal” type.

Based on the research, the author of the dissertation formulated and substantiated the third criterion number, which is determined by the maximum possible electric field at the plastic – chip interface. If this field is exceeded, ESD is possible. This third criterion number was discussed at the international conference SCTC-2018 in Japan (Kobe) and, likely, will be included in the reference materials intended for the creators of electronics for space technology.

The author of the dissertation conducted an analysis of the results, formulated conclusions on the thesis.

The main results of the study

1. A published literature critical review and analysis of spacecraft electrification was carried out. The main factors leading to the ESD emergence both with external and internal electrification of the spacecraft are identified. The measures taken to eliminate the ESD possibility on the spacecraft are considered. The conclusion about the measures insufficiency to protect the spacecraft from the damaging factors of internal electrification is made and the goal and objective of this study are set.

2. The real semiconductor device is approximated to a spherically symmetric shape and a physical model for the space charge accumulation in the semiconductor device polymer case is developed with electron injection uniform in volume.

3. Based on the analytical expressions obtained when solving the physical model system of equations, a MatCad program had been created for the maximum electric field calculating in the dielectric plastic case of the real construction (without field amplification on inhomogeneities).

4. For an adequate electric field gain calculation at the crystal vertices and edges of a parallelepiped-shaped device, experimental studies of the air breakdown strength were performed using the upper electrode with different curvature radii (from 10 mm to 20 μm). The obtained experimental dependence was theoretically

confirmed and used in the engineering method to calculate the maximum electric field in the actual design of semiconductor device.

5. The third criterion was proposed, tested at an international conference (Kobe, Japan) that described in the IEEE Transactions on Plasma Science journal. It determines the ESD possibility of flowing from the volume of a polymer dielectric into a chip of a device with a maximum electric field of 2.10^6 V/m.

6. An engineering method has been developed for choosing the bulk conductivity of the case dielectric to exclude the physical possibility of "charged volume of a semiconductor device polymer case – chip crystal" ESD. This engineering method is applicable to semiconductor devices of various designs and sizes.

The **scientific novelty** of the results is as follows:

1. A physical model of the space charge accumulation in electronic components plastic cases with a uniform volume of electron injection is proposed for the case of a spherically symmetrical crystal and case shape. The proposed model differs from others. For an adequate calculation of the electric field gain on the vertices and edges of the chip crystal (having the form of a parallelepiped), during the conducted works, experimental studies of the breakdown field in air were performed when using an upper electrode with different radius of curvature (from 10mm to 20 microns).

2. A new criterion for the electric field value in the volume of a polymer dielectric that is proposed as the limit value 2×10^6 V/m, above which an electrostatic discharge generates from the volume of this dielectric into the chip crystal of a semiconductor device. This criterion was first proposed and tested at the leading international SC electrification conference (15 Spacecraft Charging Technology Conference, 2018, Kobe, Japan) and described in IEEE Transactions on Plasma Science journal.

Provisions to be protected

1. A physical model of the space charge accumulation in the polymer case of a semiconductor device with a uniform injection of electrons in volume.

2. The program for calculating the maximum electric field in the plastic case dielectric.

3. A new, fifth criterion that determines the ESD possibility flowing from the volume of a polymer dielectric into the chip with a maximum electric field of 2.10^6 V/m, intended for use in the design of spacecraft on-board equipment.

4. Engineering method for selecting the dielectric for selecting the bulk conductivity of the chip case dielectric to exclude the physical possibility of "charged volume of a semiconductor device polymer case – chip crystal" ESD. Engineering method is applicable to semiconductor devices of various designs and sizes.

The dissertation results reliability is confirmed by:

• numerical simulation on modern electrodynamic calculation packages;

• the results obtained are consistent with fundamental physical principles;

• conducting experimental research.

Work approbation

The work results were presented at the following Russian and International conferences:

1. Afanasyeva M. A. Radiation Electrification: A Real Threat to the Reliability of Spacecraft // In: Innovative, Information and Communication Technologies: Materials of the international scientific-practical conference, 2014 / Publishing editor: I.A. Ivanov; main editor: S.U.Uvaysov; science editor: A.N. Tikhonov. M. : NRU HSE, 2014. P. 457-459.

2. Afanasyeva M. A., Technical equipment protective methods from the electrostatic discharges // Interuniversity scientific and technical conference of students, graduate students and young specialists named after E.V. Armensky, 2016, Moscow, Russia.

3. Afanasyeva M. A., Measures to combat the damaging factors of the spacecraft electrification in near-Earth orbits // Proceedings of the III All-Russian Scientific and Technical Conference "Technologies, Measurements and Tests in the Field of Electromagnetic Compatibility", 18-20 April 2016, Moscow, Russia.

4. Afanasyeva M. A., Electrostatic materials behavior in a charging space environment // Proceedings of the XIII International Scientific and Practical Conference "Innovative, Information and Communication Technologies" (INFO-2016), 1-10 October 2016, Sochi, Russia.

5. Afanasyeva M. A., Smirnov D.D., Improving the resistance to the ESD occurrence of spacecraft radioengineering elements containing dielectrics // Proceedings of the IV All-Russian Scientific and Technical Conference "Technologies, Measurements and Tests in the Field of Electromagnetic Compatibility", 28-29 March 2017, г. Moscow, Russia.

6. Afanasyeva M, The increased resistance of the spacecraft electronic elements containing dielectrics to the emergence of ESD. // Moscow Workshop on Electronic and Networking Technologies (MWENT-2018). 14-16 March 2018, Moscow, Russia.

7. Afanasyeva M. A., Agapov I.I., Meshkov A.V., Simulation of plastic cases electron loading of semiconductor devices in the process of internal spacecraft electrification. // Proceedings of the V All-Russian Scientific and Technical Conference "Technologies, Measurements and Tests in the Field of Electromagnetic Compatibility", 28-29 March 2018, Moscow, Russia.

8. Vladimir Saenko, Andrey Tyutnev, Margarita Afanasyeva and Andrey Abrameshin, Spacecraft Inner Charging Simulation of the Electronics Devices Plastic Cases, The 15th Spacecraft Charging Technology Conference, 25-29 June 2018, Kobe, Japan

9. Margarita Afanasyeva, Ilya Agapov, Experimental determination of the electric field gain coefficient on the top of the spherical electrode on air // 2019 International Seminar on Electron Devices Design and Production (SED), 24-26 апреля 2019, Prague, Czech Republic.

List of publications

The main dissertation provisions are presented in the works published by the author in leading peer-reviewed scientific journals indexed in Scopus:

1. Afanasyeva M. Experimental Determination of the Electric Field Gain Coefficient on the Top of the Spherical Electrode on Air, in: 2019 International Seminar on Electron Devices Design and Production (SED). IEEE, 2019.

2. Afanasyeva M. The increased resistance of the spacecraft electronic elements containing dielectrics to the emergence of ESD, in: 2018 Moscow Workshop on Electronic and Networking Technologies (MWENT). Proceedings. M.: IEEE, 2018.

3. V.S. Saenko, A.P. Tyutnev, M.A. Afanasyeva, A.E. Abrameshin. Spacecraft Internal Charging Simulation of the Electronics Device Plastic Cases // IEEE Transactions on Plasma Science. 2019. Vol. 47. No. 8. P. 3648-3652. doi

4. A.P. Tyutnev, V.S. Saenko, Aleshkevich A., M. A. Afanasyeva. The Nature of Plateau on Time-of-Flight Curves in Molecularly Doped Polymers // Polymer Science - Series A. 2017. Vol. 59. No. 4. P. 575-578. Doi

Another publications

1. Ihsanov R.Sh., Afanasyeva M. A., Saenko V.S., Tutnev A.P. Experimental and theoretical studies of polymers radiation-induced conductivity used in electrovacuum thermal spacecraft insulation // Atomic science and technology Issues, Series: Physics of electronic equipment radiation effects, 2016. V. 2. P. 26-31.

2. Afanasyeva M. A. Polyimides for the protection of spacecraft equipment //Book.: Innovative Information Technologies: Materials of the International scientific–practical conference. Part 2 / Ed. by S. U. Uvaysov. Part 2. M. : HSE, 2014. P. 417-420.

3. Afanasyeva M. A. Polyimides in the spacecraft equipment // Interuniversity scientific and technical conference of HSE students, graduate students and young specialists. Conference proceedings / main editors.: Tikhonov A.N., Azarov V.N,, Aristova U.V., Karasev M.V., Leokhin U.L., Lvov B.G., Titkova N.S., Moscow, MIEM HSE, 2014. P. 209-210.

Contents

The dissertation includes an introduction, four chapters and conclusion.

Chapter 1 provides a review and critical analysis of the published literature data on the electrification of near-Earth high-orbit spacecraft. This review covers the main causes of electrostatic discharges depending on the spacecraft location as well as the nature of electrification. The main occurrence criteria and methods of dealing with the external and internal electrification damaging factors are described.

In **Chapter 2**, a physical model of the space charge accumulation in electronic components plastic cases is developed. The physical model developing objective was divided into 2 stages. At the first stage it was needed to approximate the chip design to a spherical shape in order to obtain a simple analytical solution for the electric field magnitude that occurs when the chip is irradiated with an isotropic electron flux. Then the partial differential equation needed to be written and solved.

Chapter 3 describes the experimental determination of the amplification factor of the electric field gain in the polymer material volume, in the presence of inhomogeneities in the form of chip crystal tops and edges. The chapter also provides the calculation of electric field in dielectrics of spacecraft radio-technical products. Mentioned calculation becomes the basis for the “Electric fields calculating Program for dielectrics of spacecraft radio electronic products” that was developed for purposes of conducted works.

In **Chapter 4**, a new criterion for the electric field value is developed, at which the ESD is possible in the volume of a spacecraft dielectric in the presence of inhomogeneities in it. An engineering method for choosing the bulk conductivity of a dielectric is presented, developed based on the simulation and its experimental confirmation.

In the conclusion of the dissertation, the results of the research, recommendations, prospects for further development of the topic are presented.