National Research University Higher School of Economics

as a manuscript

Zhadov Aleksei Dmitrievich

Studying the serviceability life of the polyimide flexible printed circuits for space-used electronics

Dissertation summary

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Tyutnev Andrei Pavlovich

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Relevance of the research topic

One of the most important problems for the long-term operation of spacecraft (SC) for many years is the phenomenon of electrification and its accompanying electrostatic discharges (ESD), which are the most common cause of malfunctions and failures of on-board electronics. During operation, the spacecraft is exposed to the flow of ions and electrons of the cosmic plasma resulting in the accumulation of charge on the surface or inside the SC, that is, an electric potential occurs. The most dangerous zones near the Earth are highly elliptical and geostationary (GEO) orbits characterized by intense movement of high-energy particles. The situation is further complicated by the rapid development of electronic components, which are becoming more complex and functional making them more vulnerable to environmental factors, in particular to ESD.

Despite several decades of studying the phenomenon of electrification and related phenomena, the availability of different approaches and technologies, ESD is still the main cause of failures of high-orbit SC.

This is so since modern SC have a complex heterogeneous design and many different dielectric materials on its outer surface. Accordingly, there emerges a potential difference between the individual sections of the non-conducting surface, in other words, there is a differential charge of the spacecraft. Since the potentials do not level up quickly enough, this leads to a discharge.

One of the solutions to the problem of SC electrification is the use of special dielectric polymers. The peculiarity of these polymers is their increased radiation electrical conductivity (RIC), which controls the accumulation of bulk charges inside them. The higher the RIC, the lower the accumulated charge, which means that the probability of ESD is lower. However, the presence of this property should not affect

other dielectric characteristics, so that the performance of the electronic components of the SC is not impaired.

The polyimides were selected as the most promising for use in the space industry. This is due, for example, to their high radiation resistance ~~of polyimide~~ and the operating temperature reaching 420 K. In addition, in the polyimides under consideration (in particular, Kapton ® or Kapton-H ® of DuPont Corporation or its Russian-made analogue PM1), the RIC increases with the absorbed dose of ionizing radiation and persists in a vacuum at a significant level for a long time. This sharply distinguishes polyimide from other polymers whose RIC decreases with the absorbed dose of ionizing radiation.

We plan to study these polyimides for use as flexible printed circuit boards (PCB), that is interconnect systems, which are currently the most relevant and in demand.

Thus, this dissertation, devoted to the development of a methodology for predicting the durability of polyimide substrates of flexible PCB for near-Earth high-orbit SC and interplanetary missions in the solar system, is undoubtedly relevant.

Object of research – flexible printed circuit boards for space applications.

Subject of the study – prediction of the durability of polyimide substrates of flexible PCB for high-orbit spacecraft and interplanetary missions in the solar system.

Research goals and objectives are to study the durability of polyimide substrates of flexible printed circuit boards of radio electronic equipment for space applications and to develop a methodology for predicting their operation life for near-Earth high-orbit spacecraft and interplanetary missions.

To achieve this goal, the following objectives were formulated and set:

1. Perform a critical review and analysis of the literature data on the use of polyimide as a material for flexible printed circuit boards for space application. Identify the main manufacturing technology of such boards.
2. To develop an original method for studying the radiation induced conductivity of polyimide under the action of electron radiation in a vacuum in a small-signal regime for a wide time range (from 20 ms to 30 s).
3. According to the classical and developed methodologies, conduct a comprehensive study of radiation- induced conductivity, considering the features of its growth with the time of irradiation, which determine the durability of flexible printed circuit boards based on polyimide.
4. To create a physical semi-empirical model of the kinetics of the electrical conductivity of polyimide when it is irradiated with electrons in a vacuum which correctly describes the experimental data.
5. To develop a physical semi-empirical model of the increase in the radiation-induced conductivity of polyimide irradiated by electrons in vacuum.
6. To determine the criterion and based on the developed models, to elaborate an engineering methodology for predicting the durability of polyimide substrates of flexible printed circuit boards for space applications in full-scale operating conditions, including the interplanetary missions.

Scientific novelty

1. An original method has been developed for studying the radiation- induced conductivity of polyimide under electron irradiation in vacuum in a small-signal regime for a wide time interval (from 20 ms to 30 s). The method differs from the existing ones by using a combination of pulsed and continuous electron irradiations to achieve the required effect ~~value~~ in the absence of recombination of charge carriers in a polyimide sample.

2. A physical semi-empirical model of the kinetics of the electrical conductivity of polyimide under electron irradiation in vacuum has been developed, which differs from the existing ones by the two-exponential distribution of traps.
3. A physical semi-empirical model of the polyimide RIC growth when it under electron irradiation in vacuum in the range of absorbed doses (1-30) MGy has been created. The model explains the increase in the RIC of polyimide by an increase in the concentration of jump centers created during its irradiation.

Application significance lies in the development of an engineering technique for predicting the durability of polyimide substrates of flexible printed circuit boards for space applications under full-scale operating conditions for high-orbit spacecraft and interplanetary missions in the solar system. The developed prediction method is based on the proposed physical models of the kinetics and the growth of the RIC of polyimide irradiated with electrons in vacuum.

Research methods

The experimental methods of pulsed and stationary radiolysis were used, based on a source of low-energy electrons with computer registration of radiation currents in the study of the RIC. To perform calculations based on the created physical semi-empirical model, modeling was performed using modern MatLab / MathCad calculation packages. The simulation results correspond to the experimental results obtained and to the fundamental physical principles.

Provisions to be protected:

1. An original method for studying the electrical conductivity of polyimide under the action of electron radiation in vacuum in a small-signal regime for a wide time range (from 20 ms to 30 s).
2. The results of a comprehensive study of the radiation electrical conductivity of polyimide from various manufacturers, considering the features of its growth with the time of irradiation, which determine the durability of flexible printed

circuit boards based on polyimide. The experiment time was 3600 seconds at an electron radiation dose rate of 190 Gy/s.

3. A physical semi-empirical model of the electrical conductivity kinetics of polyimide with a two-exponential distribution of traps over the band gap when it is irradiated with electrons in a vacuum.
4. Physical semi-empirical model of the increase in the electrical conductivity of polyimide when it is irradiated with electrons in vacuum in the range of absorbed doses (1-30) MGy.
5. Engineering methodology for predicting the durability of polyimide substrates of flexible printed circuit boards for space applications under full-scale operating conditions for high-orbit spacecraft and interplanetary missions in the solar system.

Compliance with the specialty passport

The purpose of the research and the scientific task is to study the durability of polyimide substrates of flexible printed circuit boards of radio-electronic equipment for space applications and to develop a methodology for predicting the duration of their operation for high-orbit spacecraft and contributes to the following research areas of the specialty "Electronics, Radio Engineering and Telecommunications", listed in the passport of this specialization of the Higher School of Economics "Engineering Sciences and Applied Mathematics": research of new processes and phenomena that allow increasing the efficiency of radio engineering, electronic and telecommunications devices and systems.

Approbation of the derived results

The main results of the thesis were reported at the following all-Russian and international conferences:

1. «Analysis of signal integrity in a microstrip transmission line on a substrate of the nanoconducting dielectric», 2018 Moscow Workshop on Electronic and Networking Technologies (MWENT), 14-16 March 2018, Moscow, Russia.
2. «Radiation-induced Conductivity in Kapton-like Polymers Featuring Conductivity Rising with Accumulating Dose», The 15th Spacecraft Charging Technology Conference, 25-29 June 2018, Kobe, Japan.
3. «*Sravnitel'nye issledovaniia radiatsionnoi elektroprovodnosti otechestvennogo poliimida PM1 i Kaptona*» [Comparative studies of radiation electrical conductivity of domestic polyimide PM1 and Kapton], XX Interuniversity Scientific School of Young Specialists «Concentrated energy flows in Space technology, Electronics, Ecology and Medicine», 25-26 November 2019, Moscow, Russia (In Russian).
4. «Teoreticheskii analiz radiatsionnoi elektroprovodnosti v polimerakh» [Theoretical analysis of radiation- induced conductivity in polymers], XXI Interuniversity Scientific School of Young Specialists «Concentrated energy flows in Space technology, Electronics, Ecology and Medicine», 23-24 November 2019, Moscow, Russia (In Russian).

The author's personal contribution consists in the formulation and setting of research tasks and their solution, preparation, implementation, calculation and analysis of experimental and theoretical data, modification and use of program code for various calculations, preparation and visualization of graphic material, preparation of the text of articles and presentation of research results at Russian and international conferences and publications.

Credibility of the results obtained in the dissertation research is confirmed:

- numerical modeling on modern calculation packages MatLab, MathCad.
- compliance of the obtained results with the fundamental physical principles.

- compliance of experimental results and calculations with the proposed physical semi-empirical models.

Status of the problem

At present, the kinetics of charge carrier transport using pulsed and continuous irradiation cannot be described by standard multiple capture models for polyimides and some other polymers, especially the characteristic sharp increase in electrical conductivity at high radiation doses.

List of articles on the dissertation topic.

The main provisions on the topic of the dissertation are set out in the articles [1-5] indexed in Scopus, while the journal [2] is in the quartile Q2, [3-4] - in the quartile Q1, [5] - in the quartile Q3.

1. A. D. Zhadov "Analysis of signal integrity in a microstrip transmission line on a substrate of the nanoconducting dielectric," 2018 Moscow Workshop on Electronic and Networking Technologies (MWENT), Moscow, Russia, 2018, pp. 1-4, doi: 10.1109/MWENT.2018.8337214.
2. A. Tyutnev, V. Saenko, A. Zhadov and E. Pozhidaev "Radiation-Induced Conductivity in Kapton-Like Polymers Featuring Conductivity Rising With an Accumulating Dose," in IEEE Transactions on Plasma Science, vol. 47, no. 8, pp. 3739-3745, Aug. 2019, doi: 10.1109/TPS.2019.2901000.
3. Tyutnev, A.; Saenko, V.; Zhadov, A.; Pozhidaev, E. Time-Resolved Radiation-Induced Conductivity of Polyimide and Its Description Using the Multiple Trapping Formalism. Polymers 2019, 11, 2061.
4. Tyutnev, A.P.; Saenko, V.S.; Zhadov, A.D.; Abrameshin, D.A. Theoretical Analysis of the Radiation-Induced Conductivity in Polymers Exposed to Pulsed and Continuous Electron Beams. Polymers 2020, 12, 628.

5. Tyutnev, A.P., Saenko, V.S., Zhadov, A.D. et al. Electron Transport in Polyethyleneterephthalate. Polym. Sci. Ser. A 62, 300–306 (2020).

Conclusions

- An original method has been developed for studying the radiation- induced conductivity of polyimide under electron irradiation in vacuum in a small-signal regime for a wide time range (from 20 ms to 30 s). The method differs from the existing ones by using a combination of pulsed and continuous electron irradiations to achieve the required response value in the absence of recombination of charge carriers in a polyimide sample.

- According to the developed methodology, a comprehensive study of the radiation electrical conductivity of polyimide from various manufacturers was carried out, considering the features of its growth with the time of irradiation, which determines the durability of the polyimide flexible printed circuit boards. The experimental time was 3600 seconds at an electron radiation dose rate of 190 Gy/s.

- A physical semi-empirical model of the kinetics of the RIC of polyimide under electron irradiation in vacuum has been developed, which differs from the existing ones by the two-exponential distribution of traps.

- A physical semi-empirical model of the increase in the RIC of polyimide when it is irradiated with electrons in vacuum in the range of absorbed doses (1-30) MGy has been developed.

- A criterion has been defined, and an engineering method has been developed for predicting the durability of polyimide substrates of flexible printed circuit boards for space applications under field operating conditions. As a criterion, the value of the acceptable resistance of 10^7 Ω for a polyimide film with a thickness of 25 microns with an area of 10^{-4} m^2 has been determined. This value has a margin

factor of 10 in relation to the value of 10^6 Ω, specified by GOST 23752-79 for printed circuit boards.