Подход к прогнозированию надежности бортовой аппаратуры спутниковой связи

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Аннотация. *Приведены результаты анализа проблемы оценки надежности средств связи (СС) с учетом воздействия факторов космического пространства на этапах производства. Рассмотрены особенности больших комплексов, как объектов испытаний на надежность. Представлены результаты анализа, показывающие, что нахождение бортовой аппаратуры СС в радиационных поясах Земли может привести к возникновению дефектов в кристаллах полупроводниковых приборов, которые могут стать причиной отказов в работе СС и, соответственно, снижения ее надежности. Приведена методология анализа работоспособности полупроводниковых устройств с учетом характеристик радиационных дефектов в МОП транзисторах. Показано, как при разработке и производстве с использованием методов испытаний можно прогнозировать работоспособность СС.*

Ключевые слова: *надежность, система спутниковой связи, радиационные пояса, ретранслятор, ионизирующее излучение, полупроводник, вероятность безотказной работы.*

An approach to predicting the reliability of on-board satellite communications equipment

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Abstract. *The results of the analysis of the problem of assessing the reliability of satellite communications equipment (CE) are given taking into account the impact of space factors at the production stages. The features of large complexes as objects of reliability tests are considered. The results of the analysis show that the presence of on-board CE in the Earth's radiation belts can lead to defects in the crystals of semiconductor devices, which can cause CE failures and, therefore, reduce its reliability. A methodology for analyzing the operability of MOSFET equipment is given taking into account the characteristics of radiation defects in MOS transistors. It is shown how during the development and production using test methods, it is possible to predict the performance of the CE.*

Keywords: *reliability, satellite communications system, radiation belts, repeater, ionizing radiation, semiconductor, probability of failure-free operation.*

INTRODUCTION

In near-Earth space, as well as in deep space, an artificial Earth satellite is exposed to a number of factors of the space environment, reducing the period of its active existence. One of these factors is radiation belts (Van Allen belts) that encircle the Earth and in which the Earth's magnetic field holds charged particles with high kinetic energy. These belts are divided into internal and external zones. Depending on the location of the radiation belts, there are zones with the highest concentration of high-energy particles (protons, electrons, α-particles with kinetic energy from tens of keV to hundreds of MeV). In the inner zone at an altitude of about 3000 km there is a maximum flux density of high-energy protons (20–800 MeV). The interval between the internal and external zones is in the range from 500 to 15000 km. The presence of equipment, especially semiconductor, in these radiation belts can lead to defects in crystals and, in ultimately, to equipment failures, therefore, when choosing satellites, the heights of the satellites in the Earth's radiation belts or the use of semiconductor elements with increased reliability should be excluded.

FORECASTING RELIABILITY OF SATELLITE COMMUNICATION FACILITIES AT PRODUCTION STAGES

Improving the technical level, quality, reliability and, as a result, competitiveness produced by the domestic industry (including on-board satellite communications equipment) is impossible without restructuring production and, above all, without revising traditional views on the organization of tests regulated by domestic standards, especially concerns on-board satellite communications equipment.

This is due to the fact that already at present the requirements of scientific and technological progress make it necessary to carry out prohibitively large volumes of tests to ensure the required quality and reliability of the on-board communication systems being developed by traditional methods. In addition, in the process of development and production of on-board satellite communication systems according to existing scientific and technical documentation, they undergo various types of tests for the impact of a whole complex of external factors, including space factors. In particular, for airborne systems, the most intense factors affecting the operability of the satellite system equipment are: space vacuum, plasma flows, particle and electromagnetic radiation, micrometeorites, radiation belts, and satellite electrification. These tests are one of the most time-consuming and expensive procedures of a quality and reliability program.

In addition, existing methods for studying the reliability of CE allow only analysis of each of the segments separately (i.e., without taking into account the influence of segments on each other). This is due to the fact that the airborne segment refers to non-renewable products, and the ground segment refers to renewable ones. This approach leads to a significant underestimation of the reliability indicators, which, in turn, entails a rise in the cost of the system, an increase in the terms of its design and a decrease in the quality standards of design.

One of the main elements of a space communication system that provides signal transmission is a repeater, which significantly affects the overall reliability of CE. The transmitting part of the repeater contains the main components: a local oscillator, a frequency converter and a power amplifier, including those based on semiconductor devices, which on the one hand determines the main electrical characteristics of the transmitter. The power amplifier largely determines the reliability of communication and the design of the satellite payload as a whole. A significant number of repeaters can be located on board of a communication satellite, each of which has its own power amplifier, and in some modern satellites, their number is close to 100.

In ensuring the reliability of large complexes, to which satellite systems can be attributed, there are features explained by the structure of such systems. Indeed, a sudden failure of a satellite in the system can cause the termination of operation for some time of all earth stations operating through this satellite. In a satellite distribution system, a failure of a transmitting station or an airborne relay would lead to a simultaneous cessation of information transmission to hundreds and thousands of stations at once. Failure on a satellite of any one of the trunks, for example, telephone, leads to the termination of the exchange of telephone (telegraph) information between a group of earth stations that operate through this trunk. This forces us to pay special attention to ensuring high reliability indicators of satellite and transmitting stations of distribution systems. The malfunction of one of the earth stations of a telephone network causes the failure of only those communication channels in the formation of which this earth station is involved.

The existing features in ensuring the reliability of satellite systems are inextricably connected with the features of their reliability tests, namely:

- tests for the reliability of large systems, including satellite systems, are carried out, as a rule, simultaneously with tests to assess its compliance with other requirements of the technical specifications;
- for reliability tests, for economic reasons, the products are presented in a single copy and, as a rule, with a reduced composition of the equipment;
- for large on-board CE systems, the use of equipment redundancy is widely practiced, which significantly complicates the testing process;
- widespread use of digital computers and other devices of discrete technology, the normal functioning of which depends not only on the health of the electronic circuit, but also on the correctness (not distortion) of the digital information processed or stored in memory;
- the presence of fundamental difficulties for the unambiguous definition for the onboard CE of the concept of failure, or, more precisely, specific criteria for the operational state of the system as a whole.

An important methodological conclusion follows from the consideration of the features of large complexes that the most suitable method for assessing their reliability according to the test results is the computational experimental method.

This implies the urgent need for forecasting and, ultimately, ensuring the reliability of the developed CE devices at the production stages, taking into account the impact of space factors.

FORECASTING OF CE RELIABILITY WITH ACCOUNT OF SPACE FACTORS

As already mentioned earlier, near the Earth the satellite is exposed to a number of factors in the space environment, reducing the period of its active existence.

In the most difficult conditions, devices, elements and materials located outside the hermetic compartments on the outer surface of the satellite are used. Devices located in pressure containers are mainly exposed to penetrating radiation. In particular, the ionizing radiation of outer space, which is a stream of charged particles (mainly protons and electrons) with low intensity. Since it is not possible to obtain low-intensity radiation of protons and electrons under ground conditions (charged particle accelerators produce a high-intensity flux), gamma-ray sources based on Co-60 and Cs-137 are used for simulation tests. Gamma radiation is most often used to study radiation effects at low dose rates of ionizing radiation. The main parameter is the accumulated absorbed dose $D=Pt$, where P is the dose rate and t is the exposure time.

Transistors with a metal oxide semiconductor structure (MOSFET) are widely used in various devices (logic elements, power amplifiers, etc.). In the case of the use of MOSFETs in the on-board equipment of space systems, their reliability is significantly affected by the ionizing radiation of outer space. The MOSFET test for radiation resistance at low-intensity irradiation is used both abroad [1] and in our country [2]. Since the active MOSFET region is concentrated in the near-surface region of the semiconductor, the usual radiation effects associated with the displacement of atoms (the formation of vacancies and interstitial atoms) do not significantly affect the characteristics of transistors. The main type of MOSFET damage is the creation of defects in the gate oxide film and in the region of the transistor channel. This channel region is the boundary between the SiO_2 oxide film and the semiconductor. Currently, Si is most often used as a semiconductor. As is known, when MOSFETs and integrated circuits are irradiated with low-dose gamma radiation, the charge contribution to the volume of the gate oxide Q_{ot} decreases [3] and the density of surface defects N_{it} at the Si-SiO_2 interface significantly increases [4].

The ionization effect, in which excess electron-hole pairs are created in silicon and in oxide, in which charges on oxide traps change the threshold voltage of the MOSFET. However, with low-intensity irradiation, this charge is neutralized in the oxide trap and its contribution to the change in the MOSFET characteristics decreases. This can be seen in Fig. 1 [3], which shows the change in the contribution of the defect charge in the oxide volume to the threshold voltage of the MOSFET ΔU_{ot} at different dose rates P. Thus, the main contribution to the degradation of the MOSFET parameters is made by surface defects at the Si-SiO_2 interface.

An analysis of low-intensity gamma-ray irradiation of MOSFETs for the first time showed that the formation of surface defects at the Si-SiO_2 interface occurs in two stages [5]. At the first stage, surface defect formation occurs on the side of the oxide, which saturates over time. At the second stage, the main role is played by "hot" electrons, which are an integral part of Compton electrons [6]. These processes of surface defect formation are separated by time, which can be observed in Fig. 2, where N_{it} is the density of surface defects at a dose D, and $N_{it.s.}$ is the maximum density of surface defects during saturation of the defect formation process. As you can see, the first stage is a "dose" effect, and the second stage depends on time (and, accordingly, on dose rate P). Thus, the second stage depends on the time of formation of Compton electrons. This circumstance is important for predicting the performance of MOSFETs in the fields of low-intensity radiation from outer space. As shown in Fig. 2, surface defect formation at the first "dose" stage may not lead to failure. Then the failure will occur in the second stage, but after a longer period.

Thus, when the dose rate P decreases, the two stages of surface defect formation occur at different times, which leads to an underestimated reliability assessment, due to the uncertainty of the influence of the 2nd stage. Therefore, in the future, it is necessary to develop a model of the 2nd stage of surface defect formation, which allows one to reliably predict the reliability of satellite communication systems with prolonged low-intensity exposure to outer space factors.

It should be noted that radiation tests are usually carried out at dose rates of more than 1.0 rad/s. Therefore, both stages

Figure 1
Decrease in the contribution of charge in oxide traps to the MOSFET threshold voltage with a decrease in the dose rate of ionizing radiation

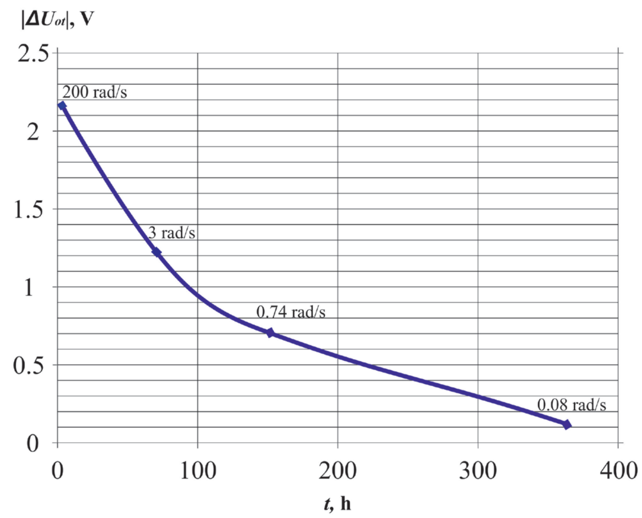


Figure 2
Dose dependences of relative changes in surface densities defects with gamma radiation dose rates of 1.0 rad/s (1) and 0.1 rad/s (2)

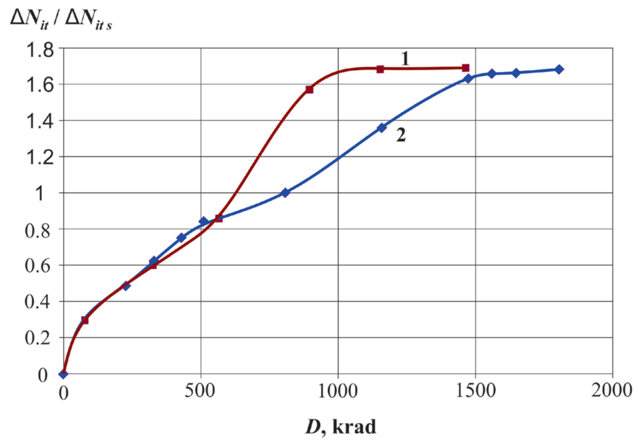


Figure 3
Change in the density of surface defects N_{it} at the SiO_2 interface in MOSFETs fabricated using 100 nm technology

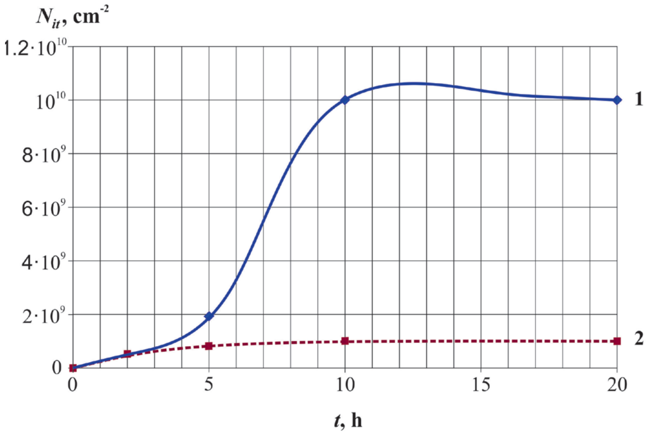


Figure 4
Changing the time for switching a logical element (inverter) from "zero" to "unit"

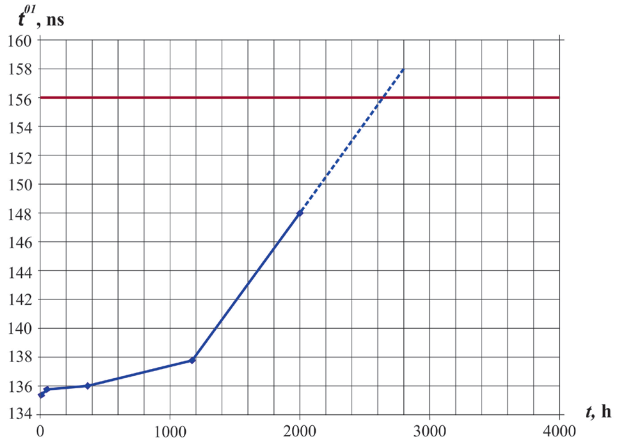
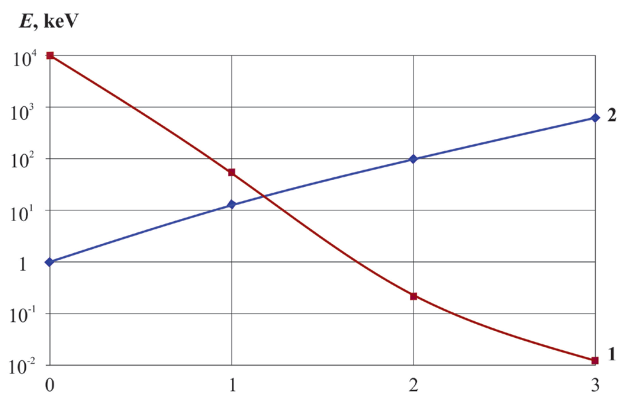


Figure 5
Area Numbers of radiation effects in a MOSFET when exposed to protons in outer space (curve 1) and in simulation experiment (curve 2)



of defect formation almost "merge" into one curve, as can be seen in Fig. 2 at a dose rate of P=1.0 rad/s. At dose rates of P=0.1 rad/s and less, the discrepancy of dependence becomes significant.

The technology of modern MOSFETs is developing to reduce the thickness of the gate oxide. This leads to the fact that the density of surface defects (interface traps) at the Si-SiO_2 interface formed on the oxide side should decrease. Tests of test MOSFETs manufactured using the 100 nm technology, where the oxide film thickness is $d_{ox} \approx 15$ nm [7], confirm this conclusion. Using the method of subthreshold currents [8] (the same as in [5]), we obtained a change in the density of surface defects in the MOSFET channel. The calculation results are presented in Fig. 3, where the curve 1 is the experimental dependence and the curve 2 is the approximation dependence of the first stage. As can be seen, at the first stage (dashed curve 2), the change in the density of surface defects is much lower than in the case of MOSFETs with an oxide film thickness of 60 nm at [5]. Thus, the main contribution to the change in the density of surface defects at the Si-SiO_2 interface is made by the process of the second stage, caused by the flux of "hot" electrons.

A change in the density of surface defects leads to a decrease in the slope of the MOSFET, and this is reflected in the amplifying characteristics of the devices and in the speed of the logic elements. Fig. 4 shows the prediction of a change in the speed of the CMOS inverter when switching from a logical "zero" to "unit" (t^{01}). As you can see, the main decrease in speed occurs at the second stage of surface defect formation (dotted line). The red line shows the failure level of the switch.

Two stages of the formation of surface defects in bipolar transistors upon low-intensity irradiation with gamma rays were noted in [9]. This effect is associated with the recombination of charge carriers in the near-surface region of the base.

ANALYSIS OF THE RESULTS

As mentioned earlier, in space, a whole spectrum of protons and electrons acts on the MOSFET. In the first radiation belt (near the Earth), proton fluxes prevail. In ground conditions, radiation tests use Co-60 or Cs-137 isotopic sources. A comparison of the effects of protons with a wide spectrum and the spectrum of an isotope installation is shown in Fig. 5. Fig. 5 shows areas of radiation effects in MOSFET under the influence of protons (curve 1) of Earth's radiation belt and simulating gamma radiation (curve 2): 0-1 – displacement effect silicon atoms (the formation of defects in silicon) in the MOSFET, 1-2 – effect of "hot" electrons near the Si-SiO_2 interface, 2-3 – ionization effect (the formation of electron-hole pairs). As you can see, "hot" electrons occupy a middle position in the spectra of cosmic protons and simulating gamma radiation.

The region of defect formation in the bulk of the semiconductor (silicon) is shown in Fig. 5 on the left side of the diagram. Defects formed in the silicon volume do not significantly affect the performance of MOSFETs manufactured according to planar technology, since transistors and other elements are placed in a narrow silicon layer under a silicon oxide film.

CONCLUSION

Based on the analysis of the problem of assessing the reliability of CE at the stages of production, the features of large complexes as objects of reliability tests have been established. It is shown that the presence of on-board equipment under the influence of cosmic space factors can lead to defects in the crystals of semiconductor devices and, ultimately, to failure of the CE equipment.

The obtained experimental data show that under prolonged low-intensity exposure to outer space radiation, two stages of surface defect formation in semiconductor planar transistors take place. Comparison of the dependences of the density of surface defects on time at different dose rates of gamma radiation shows that with an increase in the dose rate, two stages of surface defect formation become difficult to distinguish on a linear time scale. With a decrease in dose rate *P*, two stages of surface defect formation occur at different times, which leads to an underestimated reliability assessment, due to the uncertainty of the influence of the 2nd stage. Therefore, in the future, it is necessary to develop a model of the 2nd stage of surface defect formation, which allows one to reliably predict the reliability of satellite communication systems with prolonged low-intensity exposure to cosmic radiation.

The introduction of test methods into the development and production of CE devices allows revealing latent defects and realizing the improvement of acceptance testing methods by introducing tests for the complex effect of outer space factors equivalent in effectiveness to the actual operating conditions.

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