COMPUTER SIMULATIONS AND EXPERIMENTAL VERIFICATION OF THE NANOCONDUCTIVITY CONCEPT FOR THE SPACECRAFT ELECTRONICS

Vladimir Saenko, Andrey Tyutnev, Andrey Abrameshin, Gleb Belik

National Research University Higher School of Economics, 20 Myasnitskaya Ulitsa, 101000, Moscow, Russia
Email: vsaenko@hse.ru, *saenko19@gmail.com*

Abstract. The paper develops the concept of the nanoconductivity of insulators as applied to the space technology aimed at creating discharge-free space vehicles and discusses the ways to achieve this. Feasibility analysis of advanced, next generation, discharge-free satellites widely using nanoconducting insulators in spacecraft electronics proves that such a transition is not only necessary but is also practicable. We have performed computer simulations of a multivibrator, which is a typical representative of the digital technology, using the LT Spice software. As any spacecraft dielectric is a potential source of the electrostatic discharges, it is advisable to implement the nanoconductivity concept by replacing high-resistivity insulators with the nanoconducting dielectrics featuring electrical conductivity around 10^{-9} $\Omega^{-1}m^{-1}$.

Keywords: concept of the nanoconductivity of insulators; replacing high-resistivity insulators with the nanoconducting dielectrics; discharge-free space vehicles;

It is believed that the main cause of electrostatic discharges (ESD) on an operational spacecraft is the appearance of the potential difference between its elements. However, until recently experts in all space-faring nations continued to treat the symptoms rather than the decease itself. The decease of modern spacecraft arises from using high-quality insulators featuring very large Maxwell relaxation times reaching hours and even tens of hours. For example, an insulator with an intrinsic conductivity of 10^{-16} $\Omega^{-1}m^{-1}$ and the relative permittivity of 3.0, has the Maxwell relaxation time RC exceeding 73 h. Potentials on big spacecraft may change substantially in less than a second. Thus, in a metal-insulator junction a large potential difference may form in a fraction of a second when the spacecraft undergoes an eclipse exit. To exclude ESD initiation it is necessary to use insulators with RC less than one second. In our case the conductivity should be around 10^{-11} $\Omega^{-1}m^{-1}$. It should be remarked that this value is indeed the minimum one and to be space qualified it should be increased to 10^{-9} $\Omega^{-1}m^{-1}$. This is due to the fact that conductivity of an insulator may suffer appreciable decrease (by some orders of magnitude) as a result of thermal cycling in space. Frederickson [1] attracted attention to this very effect by analyzing flight data from the CRRES technological spacecraft. Our simple reasoning allowed us arriving to the space-qualified magnitude of an insulator conductivity equal to 10^{-9} $\Omega^{-1}m^{-1}$. Later on, we call such insulators “nanoconducting”. [2].

Nevertheless, if we look at NASA HANDBOOK(Tab. 1 on page 18) [3] we find that 6 out of 10 space-qualified dielectrics have RC exceeding 48 h. Their application in spacecraft electronics seems to be ESD risky. The only reason hindering wide application of the nanoconducting dielectrics is the fear that electronics may malfunction in this case.

In this paper, we present computer simulation results together with the experimental testing of the layout which unequivocally show that nanoconducting materials could and even should be used in spacecraft technology. Also, any spacecraft element manufactured from a common dielectric lacking nanoconductivity should be regarded as a delay-action bomb which is bound to lead to an ESD initiation. So, the most direct method of eliminating conditions favoring an ESD occurrence on spacecraft operating on highly elliptical orbits including the geostationary one or in the auroral parts of the Earth’ magnetosphere consists in using nanoconducting dielectrics.

We used computer simulations and experimental testing to study the feasibility of substituting the traditional dielectrics of printed circuits in low-frequency digital devices by nanoconducting composites eliminating space charge accumulation and as a result excluding any possibility of an ESD occurrence.

As a typical example of a digital device, we chose a low-frequency multivibrator, a self-oscillating system generating a square wave (meander). The main idea of a computer modeling was that substituting a traditional dielectric of a printed board by a nanoconducting dielectric is equivalent to the appearance of additional leakage paths. For this reason, some changes would have to be made in the basic electrical diagram of the multivibrator.

Since this substitution reduces the dielectric bulk resistivity of the printed board by several orders of magnitude, one has to introduce a number of additional resistors imitating leakage channels between all nodes of the board. Of course, the calculation should take into account the layout of wires in the printed board.

Figure 1 presents the basic electrical diagram of a multivibrator operating at a frequency of about 700 Hz, while Fig. 2 depicts a fragment of this scheme with additional resistors R5...R19 accounting for the nanoconductivity effects.

Computer simulations used the LTspice software intended to analyze electronic devices. These resistors could be changed in a wide range from hundreds of kΩ to hundreds of MΩ and served to interconnect all nodes including the ground node.

It is important to find a true correlation between values of the added resistors and the bulk conductivity of the board dielectric. Let us make an assessment.

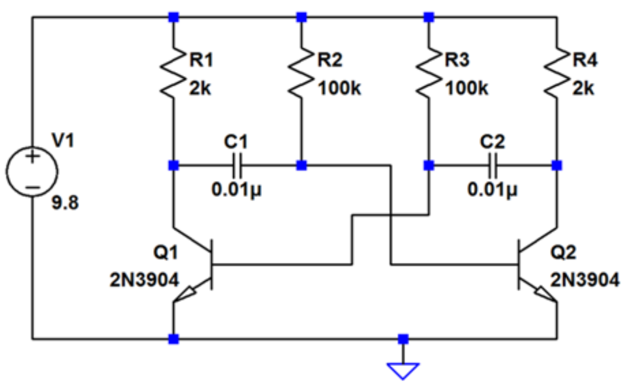

Figure 1. Basic multivibrator electric diagram.

Dielectric's capacitance may be easily computed from the formula :

$$C = \varepsilon_0 \cdot \varepsilon \cdot \frac{S}{d}, \qquad (1)$$

where $\varepsilon_0 = 8{,}85 \cdot 10^{-12}$ F·m^{-1} is the dielectric constant;

ε – dielectric relative permittivity (assumed equal to 4);

d – dielectric thickness, m;

S – overlapping area of two printed conductors.

Dielectrics resistance is given by

$$R = \frac{d}{\gamma S}, \qquad (2)$$

where γ is the dielectric bulk conductivity.

Combining (1) and (2), we have:

$$R = \frac{\varepsilon_0 \cdot \varepsilon}{\gamma \cdot C} \qquad (3)$$

In present-day printed boards the above mentioned capacitance constitutes roughly a few pF. For assessment, let us assume it to be safely 10 pF. Then, for $\gamma = 5 \cdot 10^{-9}\ \Omega^{-1}\cdot\mathrm{m}^{-1}$ we find

$$R = \frac{\varepsilon_0 \cdot \varepsilon}{\gamma \cdot C} = \frac{8{,}85 \cdot 10^{-12} \cdot 4{,}0}{5 \cdot 10^{-9} \cdot 10^{-11}} = 0{,}71 \cdot 10^{9}\,\Omega \qquad (4).$$

As our simulations show, for this leakage resistance, there are no changes in multivibrator characteristics. Moreover, they do not change even for a much higher value of the conductivity.

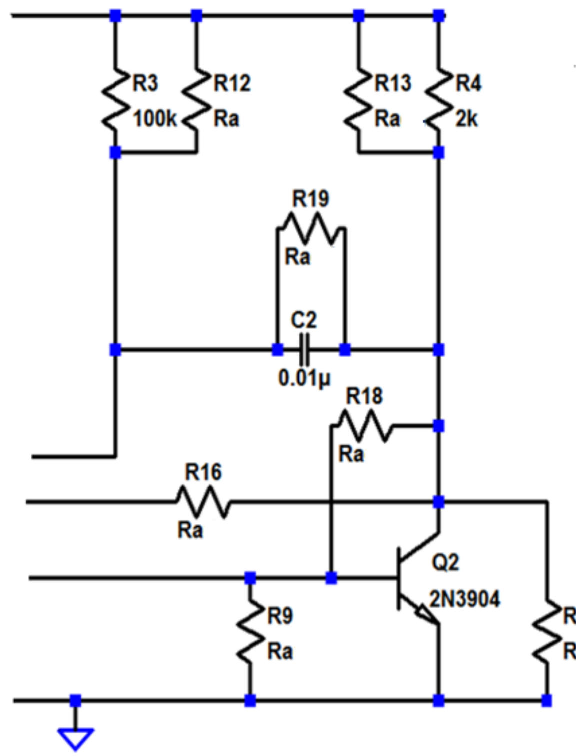

Figure 2. Fragment of the multivibrator circuit with additional resistors with value of Ra

Indeed, as Fig. 3 shows that the critical value of the leakage resistor below which the meander period starts to change is 20 MΩ. According to Eq. (3), we have $\gamma = 1.55 \cdot 10^{-7}$ $\Omega^{-1}\cdot\mathrm{m}^{-1}$, which exceeds the recommended value of $\gamma = 5 \cdot 10^{-9}$ $\Omega^{-1}\cdot\mathrm{m}^{-1}$ by almost two orders of magnitude. Thus, an application of printed boards with nanoconducting dielectrics secures the timely leakage of charge introduced into the board as a result of the internal charging.

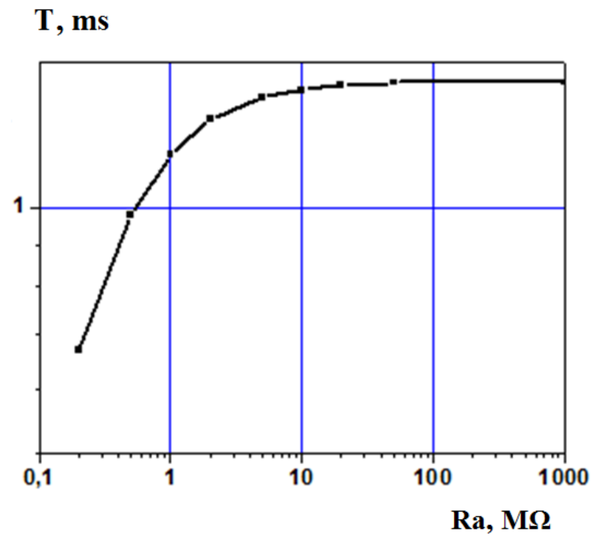

Figure 3. The dependence of the oscillation period from Ra

In fact, we have two orders of magnitude to spare so that one can speak with confidence of ESD-free spacecraft operation equipped with such printed boards. It should also be noted that even in the extreme case of the dielectric conductivity $\gamma = 1 \cdot 5 \cdot 10^{-7}$ $\Omega^{-1} \cdot m^{-1}$ accompanied with a noticeable change of the multivibrator frequency, its application is still possible once due corrections to the multivibrator nominal values have been made at the design stage.

For validation of the above computer simulations, we have prepared a multivibrator mock-up in a skeleton mode (Fig. 4). This was intended to be grouted by a model dielectric with $\gamma = 5 \cdot 10^{-9}$ $\Omega^{-1} \cdot m^{-1}$.

The model dielectric (MD) was a suspension of graphite conductive filler (carbon black) P-803 in P2 paraffin having the specified bulk conductivity. For this purpose, we used 300 ml chemical glass equipped with a magnetic stirrer and a heater. First, 100 g of P2 paraffin was put into the glass and melted, then the stirrer was put on and the technical carbon powder was added gradually during 30 s in portions of 5 g. After 1h, a sample has been taken and its conductivity measured. Depending on the measurement results, further portions of either paraffin or powder have been added to the glass and the whole procedure repeated until the specified value of conductivity $\gamma = 5 \cdot 10^{-9}$ $\Omega^{-1} \cdot m^{-1}$ has been reached (Fig. 5). This value corresponded to the powder mass concentration of 6.5 %.

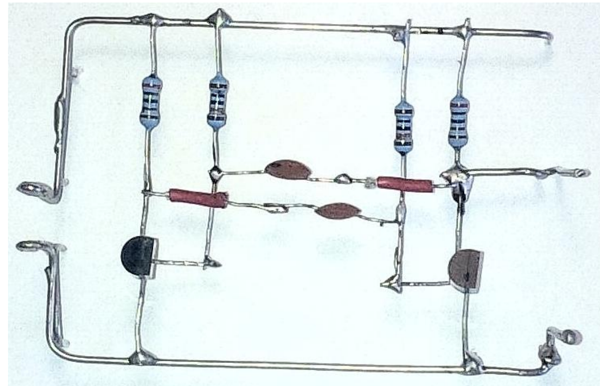

Figure 4. The multivibrator skeleton- mode mock-up

Then, the prepared mock-up was placed into laboratory oven to be heated to 80^0 C and grouted.

Figure 5. Sample with model dielectric for conductivity measurements

Experimental work fully validated computer simulations. We saw no effect of grouting on the multivibrator characteristics.

To be sure that there was no ESDs in MD under electron irradiation, test samples have been prepared which are shown on Fig. 6. These were irradiated in vacuum by 50-keV electrons with a beam density 10^{-4} A/m^2. The sample on the left was prepared from pure paraffin, while four others had conductivity values as follows: $5 \cdot 10^{-9}$, 10^{-9}, $5 \cdot 10^{-10}$ and 10^{-10} $\Omega^{-1}\cdot m^{-1}$.

Under these irradiation conditions, we observed ESDs (with one or two in a second) only in the first sample made of pure paraffin. There were no ESD in four other samples.

Figure 6. Samples for test on the resistance to ESD occurrence

In addition to computer simulations and testing of the multivibrator with an operating frequency 700 Hz, we performed a similar work with the multivibrator operating at much higher frequency of 37 MHz based on the SN74S124 microchip. The same results have been confirmed, so that nanoconductivity did not interfere with the operation of the device.

Next, we performed an experiment with the PC network card measuring a data transfer rate through a typical printed circuit. For this purpose, we used two PCs exchanging data at the high rate of 100 Mbit/s (Ethernet technology in IEEE 802.3u Fast Ethernet local network). These PCs were connected with a twisted pair of wires 2 m long (cable category 5). For this investigation, the network card was connected to the PCI slot of one of the computers.

First, the information transmission parameters have been registered between two network cards using iperf program software operating through the command line in connection with the interface add-in written in the Java-iperf language. Afterwards, a layer of the protective resin has been removed from one of the cards and this has been covered with a 3mm-thick layer of the nanoconducting dielectric as shown on Fig. 7.

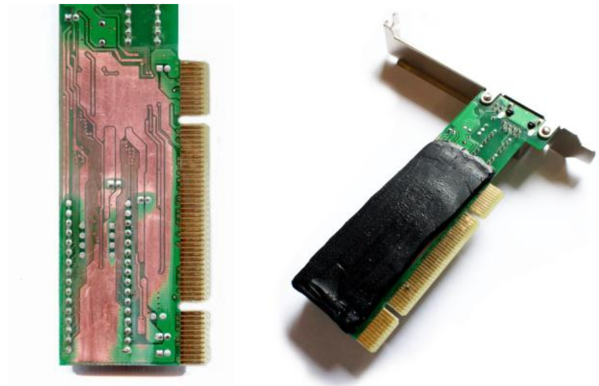

Figure 7. The network card without a layer of protective resin on the left and covered with a layer of nanoconductive dielectric on the right

Again, as a result of more than 50 sessions of data transmission and reception, it has been confirmed that the nanoconducting layer 3mm thick had no effect on either the transmission rate or the quality of the signal (Fig. 8). For five consecutive sessions of data transmission, the maximum transmission rate proved to be the same as for the original network cards as well as for those with a layer of nanoconducting dielectric. The printed board with the nanoconducting dielectric has been the subject of the patent for invention [4].

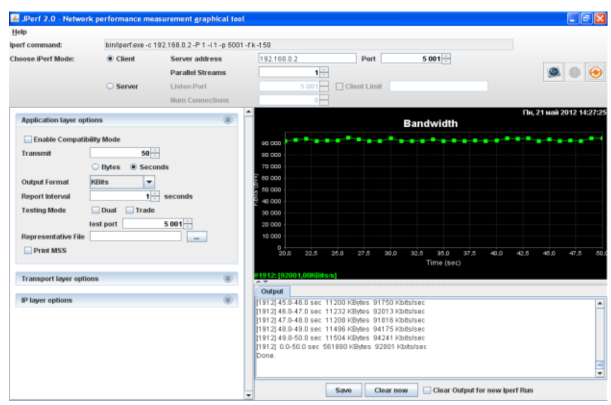

Figure 8. General view of the customer iperf program after completion of the measurements

CONCLUSIONS

We have proposed a new approach to the problem of eliminating ESD on board a satellite. For this purpose, one should use dielectrics with low RC values arising from their enhanced conductivity ($\gamma = 5 \cdot 10^{-9}$ $\Omega^{-1} \cdot m^{-1}$) which we call as nanoconducting. In this case, initiation of an ESD is impossible since the potential difference between any points of the spacecraft would be too low to trigger off a discharge.

Computer simulations and mock-up testing proved this approach most convincingly. We are sure that if such an approach is used as a tool to protect a spacecraft against ESD-related risks and if there are no common dielectrics on it (including plastic cases of semiconductor devices and integrated microcircuits), the ESD-free spacecraft design will become possible in the nearest future.

REFERENCES

1. Frederickson, A. R. (1996). Upsets Related to Spacecraft Charging. IEEE Transactions on Nuclear science, 43(2), 426-441.
2. Pozidaev E.D., Saenko V.S., Tyutnev A.P., et. al. (2003). Upgrading Spacecraft Tolerance against the Damaging Effects of the Spacecraft Charging. Cosmonautics and rocket engineering. 30(1), 32-35 (in Russian).
3. NASA-HDBK-4002, February 17, 1999
4. Patent RU 2497319 C2, Printed circuit board for onboard avionics spacecraft/ Abrameshin A.E., Belik G.A., Vostrikov A.V. & Saenko V. S. Effective date for property rights: 28.02.2013, Date of publication: 27.10.2013, Bull.30.