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Low-temperature radiation-induced conductivity of polystyrene under the action of low-energy electrons

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Received August 19, 2022
Revised November 2, 2022
Accepted November 2, 2022

A technique has been developed and, for the first time, sufficiently complete data on the radiation-induced conductivity (RIC) of polystyrene (PS) at a temperature of 79 K, close to the boiling point of liquid nitrogen (77 K). RIC has been studied under pulsed and continuous exposure to electrons with an energy of 50 keV. It is shown that the RIC of PS at a temperature of 79 K, as well as at room temperature, determined by the sum of two components: prompt and delayed. Both components at 79 K are much smaller than at 298 K. The total signal falls off by a factor of 40, while the delayed component falls off by a factor of almost 200, and the prompt component dominant in the RIC signal. The possibility of the occurrence of electrostatic discharges (ESD) in PS with decreasing temperature was studied. It has been shown that PS, which is capable of resisting the occurrence of ESD at room temperature, at 79 K passes into the category of materials in which ESD is possible.

Keywords: electron radiation, radiation-induced conductivity, polystyrene, low temperatures, electrification.

DOI: 10.21883/TP.2023.01.55446.207-22

Introduction

By now, there are almost no published results of investigations of the radiation-induced conductivity (RIC) in polymers at low temperatures. Experimental data on the low-temperature RIC in polymers under an impact of 1 ms pulses of accelerated electrons are reported in monograph [1]. In addition, a number of studies are published [2–5] on RIC of some organic liquids (Chernogolovka). Unfortunately, no systematic studies of RIC in polymers of the space equipment at low temperature have been performed. However, this data is very important for the estimate of electrifiability of dielectric materials in the near-Earth space plasma, as well as in plasma of other planets (for example, the Jupiter) having their own magnetosphere. Indeed, in [6] the estimation methods to determine maximum electric field when exposing polymer films to electron beams are considered in details. It follows from the mentioned study, that the maximum electric field that can be created in a polymer plate (or film) under exposure to an electron beam is directly proportional to the current density of the electrons incident on the plate surface and inversely proportional to the conductivity of material of this plate. This fact leads to the conclusion that a polymer material identified as non-electrifying at a room temperature, becomes well electrifying at a low temperature, when its RIC is significantly (for polystyrene (PS) — by 40 times) decreased. The subject of this study is the technique to investigate RIC in polymers at low temperatures, experimental study of RIC in PS, and carrying out estimate calculations of maximum electric fields in this material under exposure to low-energy electron radiation, which will allow determining the possibility of electrostatic discharges. The PS was selected as a model polymer with well-known properties to work out the technique of low-temperature investigations. Subsequently the investigation of polymers for space applications is planned.

1. Experiment description

An ELA-50/5 electron-gun is used as the experimental equipment to measure RIC in polymers at low temperatures. This plant allows irradiating the sample under study by a beam of electrons in pulsed or continuous mode. The electron energy can be controlled in the range from 1 to 50 keV. Block diagram of the measuring low-temperature cell and measuring system of the plant is shown in Fig. 1.

The polymer sample under study with evaporated aluminum electrodes is placed in a copper measuring cell. The sample is cooled by thermal conduction through a copper rod that connects the measuring cell to a Dewar flask with liquid nitrogen. The measuring cell and the thermal conduction rod is protected from external heat flows by a screen vacuum thermal insulation, which is used to ensure thermal mode of spacecraft multi-layer insulation. Above the sample a holder is installed with replaceable film of polyethylene-terephthalate (PETP) with a thickness of 5 μm with evaporated 100 nm-thick aluminum layers on both sides to reduce heating of the sample by the cathode of the electron gun. We have experimentally determined that such PETP film decreases a dose rate radiation in the measured sample by 1.35 times, which has been taken into consideration in the processing of the experimental data.

Measuring cell is equipped with a copper-constantan thermocouple to control the sample temperature. The rate

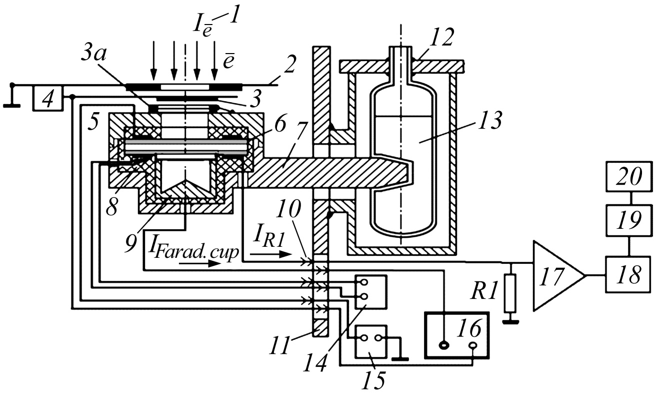

Figure 1. Block diagram of the low-temperature cell and the measuring system to measure RIC in polymers at low temperatures: *1* — electron beam, pulsed or continuous mode; *2* — collimator; *3* — shutter to interrupt the electron beam and to measure it; *3a* — replaceable PETP film coated with aluminum on both sides in a holder serves to ensure the required thermal mode, film thickness is 5 μm; *4* — electromechanical system of damper control; *5* — copper body of the measuring cell with a constant-voltage current lead to the sample *6*; *7* — copper cooling rod; *8* — copper-constantan thermocouple; *9* — Faraday cup to control the beam current during long-term measurements; *10* — vacuum current lead; *11* — opening cover of the vacuum chamber; *12* — Dewar flask body; *13* — liquid nitrogen; *14* — thermocouple e.m.f. meter; *15* — High voltage source connected to the top electrode of the sample; *16* — Tektronix 3012B double-beam oscilloscope; *R1* — bank of resistors from 100 Ω to 200 kΩ; *17* — differential amplifier with a power supply unit and a gain from 0.1 to 100; *18* — L-CARD 14-440 14-bit ADC; *19* — personal computer with special SW to record performed measurements; *20* — printer to print out prepared graphs of RIC measurements as a function of time. The thermal protection of the cell with sample made of the thermal insulation material of the space aircraft is not shown for clarity.

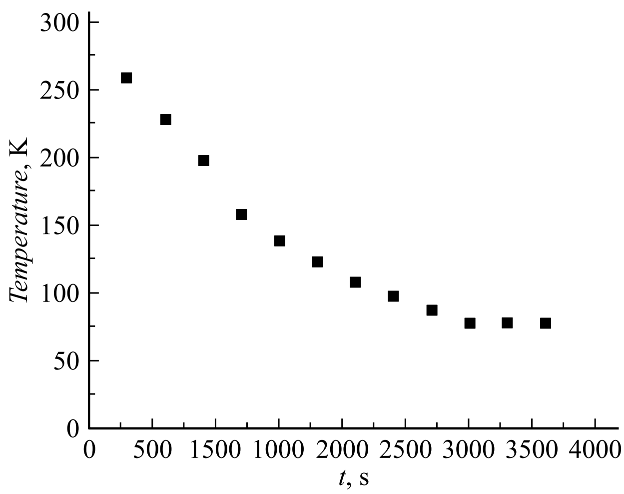

Figure 2. Decrease in sample temperature vs time after the Dewar flask is filled with liquid nitrogen.

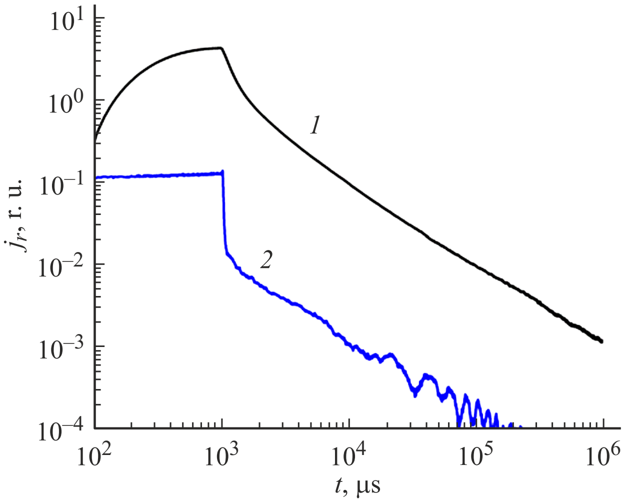

Figure 3. Signal of radiation-induced current through the PS sample irradiated by 1 ms pulse at a temperature of 298 (*1*) and 79 K (*2*).

of temperature decrease of the measured sample is shown in Fig. 2. As can be seen from the figure, temperature of the measured sample reaches a steady-state value of 78 K within 50 min. The RIC measurement experiments were carried out after an hour after pouring liquid nitrogen into the Dewar flask.

Fig. 3 shows RIC in PS at pulsed irradiation with a duration of 1 ms at 79 and 298 K. A significant decrease (by 40 times) in the total signal of the radiation-induced current through the PS sample at temperature decrease can be seen.

2. RIC simulation

The theoretical description and simulation of RIC we have used the Rose–Fowler–Vaisberg (RFV) model [1]:

$$\begin{cases} \frac{dN(t)}{dt} = g_0 - k_r N_0(t) N(t), \\ \frac{\partial \rho(E,t)}{\partial t} = k_c N_0(t)\left[\frac{M_0}{E_1}\exp\left(-\frac{E}{E_1}\right) - \rho(E,t)\right] - \\ -\nu_0 \exp\left(-\frac{E}{kT}\right)\rho(E,t), \\ N(t) = N_0(t) + \int\limits_0^\infty \rho(E,t)\,dE, \end{cases}$$

$$\gamma_r = e\mu_0 N_0(t),$$

where $N(t)$ — total concentration of the mobile charge carriers (holes in the case of PS); g_0 — volume generation rate of charge carriers; k_r — volume recombination coefficient of charge carriers; k_c — rate constant of charge carrier capture by traps; M_0 — total concentration of initial traps exponentially distributed over energy; $\rho(E,t)$ — energy distribution density of captured charge carriers; ν_0 — frequency factor for the thermal release of captured electrons from traps; E_1 — parameter of the exponential distribution of traps over energy; γ_r — RIC in polymer; e — elementary charge; μ_0 — charge carrier mobility.

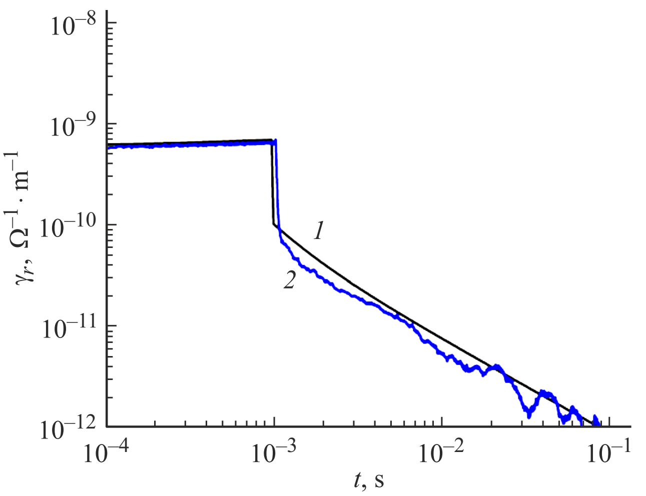

Figure 4. RIC in PS exposed to radiation of 1 ms pulse at 79 K as a result of simulation (*1*) using the Rose–Fowler–Vaisberg (RFV) model and as a result of measurement (*2*). The electron radiation dose power — $1.3 \cdot 10^5$ Gy/s.

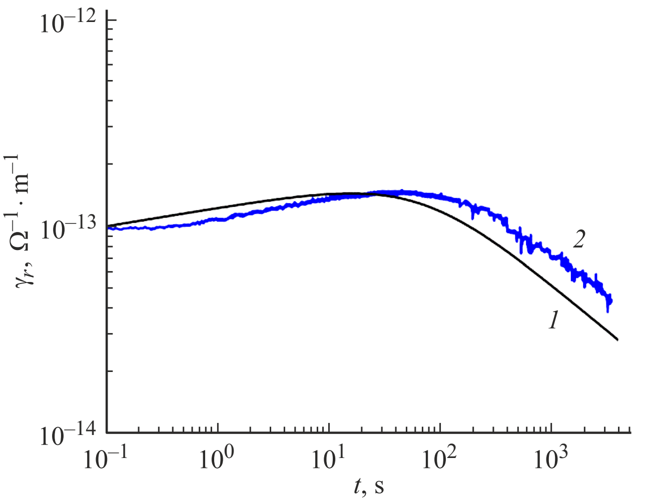

Figure 5. Comparison between calculated (*1*) and experimental (*2*) measurements of RIC in PS for continuous irradiation at 79 K. The electron radiation dose rate power — 13 Gy/s.

Earlier, in [7] we have found that at a room temperature for PS the following parameters are valid for the RFV model: dispersion parameter $\alpha = kT/E_1 = 0.35$, frequency factor $\nu_0 = 8 \cdot 10^6\,s^{-1}$. The dispersion parameter for the required temperature can be obtained from the following relationship: $\alpha(79\,K) = \alpha(298\,K) \cdot 79/298 \approx 0.09$. The frequency factor was obtained by the trial-and- probe method based on results of the numerical calculation $(4 \cdot 10^3\,s^{-1})$. Other parameters of the RFV model are temperature-independent.

The value of j_r is reduced to the value of RIC in accordance with the method described in [8]:

$$\gamma_r(t) = \frac{j_r(t)}{F_0},$$

where $\gamma_r(t)$ — RIC equal to the sum of delayed and prompt components; j_r — current density obtained from experiment, F_0 — field strength in the irradiated sample.

Fig. 4 shows RIC curves for irradiation by 1 ms pulse obtained experimentally and with the help of simulation with appropriate parameters. Fig. 5 shows RIC curves for continuous exposure to radiation.

As can be seen in Fig. 4 and 5, the RFV model adequately describes RIC at low temperatures, which opens the possibility of its use in the calculations to investigate the possibility of electrostatic discharge (ESD) in polymers for space applications using the method described in [9].

3. The possibility of ESD emergence

As it is found from our experiments, RIC in PS at a temperature of 79 K is significantly lower than that at a room temperature. In addition, it is known that the sum charge accumulated by a dielectric material is less, the higher is the radiation-induced conductivity of this dielectric material due to the less relaxation time of the injected charge. Based on this, a conclusion can be made that at low temperatures the probability of critical charge concentration accumulation in a dielectric material is higher, which can result in electrostatic discharges. Let us estimate this possibility.

For this purpose, let us make use of the differential equation for the dependence of electric field strength in the irradiated part of dielectric material on time, that arises as a result of the radiation-induced electrfication (see [9]):

$$\frac{dF}{dt} = \frac{h - R}{h\varepsilon\varepsilon_0}\left\{i_0 - \left[F(t)(\gamma_D + \gamma_R(t))\right]\right\},$$

where F —electric field strength in the irradiated part of polymer, $[V{\cdot}m^{-1}]$; t — time of the exposure to radiation, [s]; i_0 — electron flux density incident on the film surface, $[A{\cdot}m^{-2}]$; $\varepsilon_0 = 8.85 \cdot 10^{-12}\,F{\cdot}m^{-1}$ — vacuum permittivity; ε — relative electric constant of polymer dielectric material; γ_D — dark conductivity in polymer; γ_R — radiation-induced conductivity in polymer (in its irradiated part); R — maximum electron range; h — polymer thickness. Numerical calculations of the change in field strength over time using Mathcad software.

Taking into account the fact that the dark conductivity at a room temperature is several orders of magnitude less than the radiation-induced conductivity (about $10^{-16}\,\Omega^{-1}m^{-1}$) and activation-dependent on temperature, the dark conductivity term can be considered negligible (taken equal to zero).

Results of the estimate of electric field strength under conditions of magnetospheric substorm ($i_0 = 10^{-5}\,A{\cdot}m^{-2}$), when the radiation-induced electrification is the most intensive, are shown for $R = 0.5h$ (maximum electron path is equal to half thickness of the PS sample) in Fig. 6.

Note, that as a result of in-situ testing on the SCATHA satellite launched by NASA to study the radiation-induced

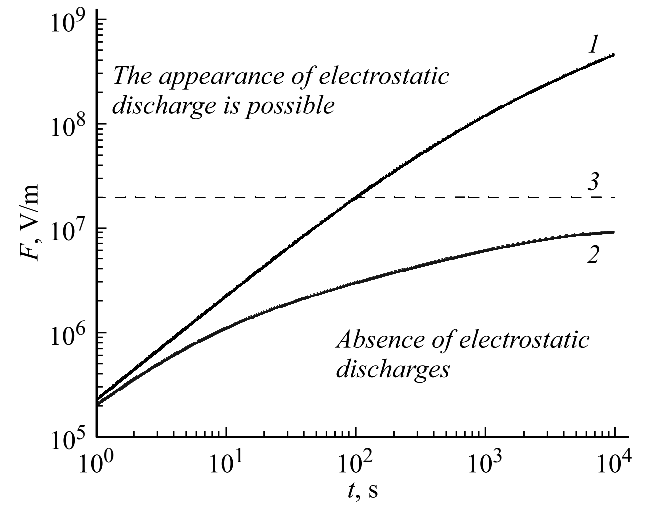

Figure 6. Calculated field strength in PS as a function of radiation exposure time at 79 (*1*) and 298 K (*2*). Dashed line (*3*) shows the level of field strength where electrostatic discharges take place. Beam current density $i_0 = 10^{-5}\,A\cdot m^{-2}$.

electrification it was found that ESDs take place when the electric field in the dielectric material body achieves $2 \cdot 10^7$ V/m. This level is referred to in the NASA reference book as a criterion [10], and it is the level that is taken by us as a start of discharging.

As can be seen from Fig. 6, the electrifiability of PS at low temperatures is increased significantly: at 79 K electrostatic discharges should be observed in contrast to the room temperature, which stresses the importance of this study for materials used in the space equipment.

Conclusion

Radiation-induced conductivity is investigated in pulsed (1 ms) and continuous mode of irradiation at a temperature of 79 K. It is shown, that with a decrease in temperature down to the specified level, the RIC still composed of two components (as at a room temperature): prompt and delayed. The most significant effect the temperature lowering has on the delayed component. This component, being measured $100\,\mu$s after the end of radiation pulse, decreases by almost 100 times. At the same time, the total RIC signal at both pulsed and continuous impact decreases by 40 times. It is known [11], that to calculate RIC in polymers, it is customary to use the following relationship: $\gamma_r = AR^{\Delta}$, where R — radiation dose, A — experimentally determined RIC coefficient (an individual value for each polymer, as well as the power exponent of $0.5 \le \Delta \le 1.0$. It is found in the works that A decreases by 40 times, while the power exponent Δ increases from a value of 0.75 at a room temperature up to a limit value of 1.0 at 79 K. The current-voltage curve of the radiation-induced current in the electric field range of $(5 \cdot 10^6 - 5 \cdot 10^7$ V/m) keeps its superlinear behavior, which takes place at a room temperature and follows the expression of $i_r = E$, where $\delta = 1.6$.

We have used the RFV model for theoretical description and simulation of RIC at 79 K, as in the case of its successful application to describe RIC in PS at a room temperature [7]. Based upon the data presented in the study, the use of this model is fully justified for the case of low temperature as well.

Acknowledgments

The authors would like to thank the Fundamental Research Program of the National Research University Higher School of Economics.

Conflict of interest

The authors declare that they have no conflict of interest.

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