ANALYSIS OF CHARGE TRANSPORT AND IONISATION EFFECT IN SPACE USED POLYMERS UNDER HIGH ENERGY ELECTRON IRRADIATION

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ABSTRACT

Polymer materials have been tested in the dedicated experimental facility SIRENE (ONERA, Toulouse, France) designed to reproduce the electron energy spectrum met in space in the [0-400 keV] energy range and to perform electric analysis on the materials through dedicated protocols with potential, current and contactless PEA (pulsed-electro acoustic) [CNES patent] measurements. Novel experimental approach shall as well be presented that allowed bringing into evidence the complex response of polymers under irradiation: polarisation and charge differential mobility as well as physical structural changes have been analyzed with these new techniques allowing a better understanding and prediction of charging behaviour and RIC evolution of these polymers under space conditions.

1. INTRODUCTION

Dielectric materials used on spacecraft are submitted to a large spectrum of electron radiation which induce the implantation of charged particles in their all thickness. This charge induce potential gradient which may trigger electrostatic discharges and/or secondary powered arc discharges on different parts of the satellite. Charging effect of space materials is however usually smoothed by ionisation processes due to high energy electron irradiation that enhances significantly the bulk electric conductivity in these materials: we speak about radiation induced conductivity (RIC). It is of high importance to take into account this radiation effect for realistic predictions of spacecraft charging levels met in space environment. Other physical processes, such as polarisation and interfacial effects, might play also a significant role on the charging behaviour of space materials.

Polymers are widely used on spacecraft for thermal, optical, mechanical or electrical application. These materials are very sensitive to radiation dose and their charging behaviour evolves quite swiftly with irradiation duration. A thorough analysis allowed demonstrating that RIC (instantaneous or Delayed) depends not only on radiation dose, but also on total radiation dose, temperature and electric field. The physical mechanisms steering these effects have been identified through a large experimental and parametric study. The attention has especially been focused on Kapton and fluorinated space used polymers. These mechanisms have been implemented in a physical model describing charge transport and ionisation effect, based on solid state physics. This paper presents both the experimental characterisation results as well as numerical output that provided a support on the identification of these physical mechanisms.

2. EXPERIMENTAL SET-UP AND PROTOCOL

2.1. The SIRENE irradiation facility

The experiments have been performed in the unique irradiation test facilities (SIRENE), funded by CNES and installed at ONERA (Toulouse, France) which allows charge characterization under GEO-like electron irradiation spectrum. Fig. 1 shows the electron beam spectral characteristics of the SIRENE facility with an energy spectrum (Kp>5) approaching that of the geostationary charging environment.

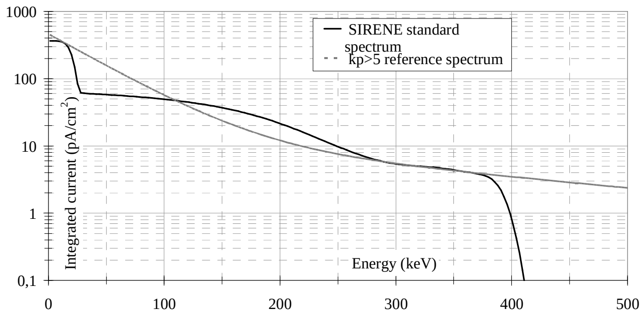

Figure 1 : SIRENE standard spectrum and reference KP>5 spectrum

SIRENE electron spectrum ([20keV, 250pA/cm2] + [0-400keV, 50pA/cm2]) experimental simulation is achieved with the use of two monoenergetic electron beams. In order to get a spacelike electron beam, the 400keV electron beam, passing through complex diffusion foils, is dispersed in energy from 0 to 400keV. The nominal fluxes used for the 20keV monoenergetic beam and the distributed 400 keV one are respectively equal 250pA/cm^2 and 50pA/cm^2 but can be raised respectively up to 1nA/cm^2 and 200pA/cm^2. A pumping system allows experiments at vacuum of around 10^{-6} mbar. The temperature of the sample holder can be controlled in the range of -180°C to 250°C allowing to reproduce the temperature variation of materials on flight. The evolution of charging potential, during and after beam cut-off are monitored using a non-contact electrostatic probe (Kelvin probe TREK 3455ET) coupled with an electrostatic voltmeter (TREK 341B).

This irradiation facility allowed a thorough description of RIC dependence with applied parameters (radiation dose rate, total dose, temperature, electric field, …). Recovery and ageing processes have also been analysed through dedicated experimental protocols allowing the optimisation of physics model used for charging prediction in space environment.

2.2.. Experimental protocol

Studying the charging behaviour of space polymer in space environment implies to perform thorough analysis on the ionisation and charge transport processes in representative conditions. Radiation induced conductivity depends on radiation dose, dose rate, temperature and electric field [1-5]. Different experimental procedures have been devised at ONERA for the extraction of RIC and for studying the influence of the different above parameters. The first approach is the potential decay method. For this method, bulk induced conductivity is assessed through the analysis of the surface potential relaxation after charging the sample with low energy electrons (20 keV) up to a given surface potential [5]. During the electric potential relaxation, a 400 keV penetrating ionising electron beam (which does not contribute to material charging) is used to stimulate the potential decay through the activation of radiation induced conductivity. To evaluate bulk conductivity of space materials, the material sample is modelled as a combination of a capacitance and resistance in parallel [6]. RIC can then be extracted from the following equation:

$$\sigma_{RIC}(t)=1/V.[(1-\psi-\beta).J_0.L-\varepsilon.dV/dt] \quad (1)$$

for which V the absolute surface potential, ψ the total electron emission yield, β the leakage surface current coefficient, L the space charge distance to the ground and ε the material permittivity.

Another conventional method is to measure the induced current at the rear face of an irradiated sample. This sample is composed of two electrodes on each side and a potential difference is applied between both electrodes. After annealing of the polarisation current, a 400 keV penetrating ionising electron beam (which does not contribute to material charging) is used to stimulate the leakage current. From this current, we can extract the conductivity from the simple law :

$$\sigma = \frac{I}{V}.\frac{L}{S} \quad (2)$$

for which I is the measured current, V the applied potential difference, L is the thickness, and S the surface area of the sample.

This last method allows recording the conductivity at a constant potential and we are then able to discriminate between electric field effect and radiation dose effect.

3. EXPERIMENTAL RESULTS

3.1. Effect of electric field on RIC

The irradiation experiments allowed demonstrating that RIC of materials is strongly dependent on the applied electric field. Dedicated tests on 25 µm Kapton® with the second above measurement method demonstrated that conductivity rises with the applied electric field when the electric field exceeds a threshold.

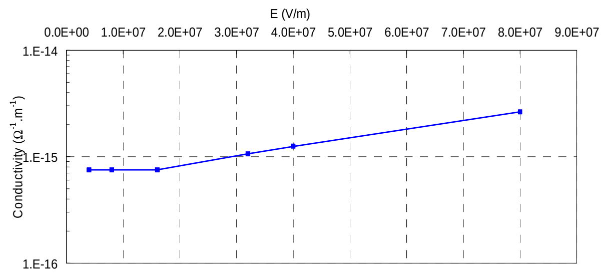

Figure 2 : Evolution of RIC measured by leakage current method on 25 µm Kapton® sample irradiated with 400 keV, 4 pA.cm^{-2} electron beam

These results are in good agreement with the previous results coming out from the potential decay method [5], in regard of the increase of RIC with the electric field. The new result is the saturation of RIC at low electric field. These features have been ascribed to the effect of electric field on geminate recombination. For electric
2) fields below a threshold, electric field is not sufficient to extract electron-hole pairs and reduce recombination rate. Once the electric field exceeds this level, electron-hole pairs can be created and the ionisation effective rate rises up. This behaviour has already been identified by other researchers [7].

3.2. Analysis of delayed RIC

Fig. 3 presents an experiment in which the 400 keV irradiation was switched off after a given duration while the electric field remained constant. This measurement first proves that the measured current is not due to polarisation effect (since the measured current is mainly steered by irradiation). We can notice as well that the leakage current prevails for a long period of time after the irradiation was cut off : this is due to the delayed conductivity (DRIC). Ionisation effect keeps up for a long period of time due to electrons and holes detrapping. We can notice as well an initial steep drop of DRIC after irradiation shut down followed by a slow decay. This characteristics has been modelled as well with the simple circuit model developed at ONERA [5] and is explained by a first rapid trapping of free charges followed by a continuous detrapping during relaxation.

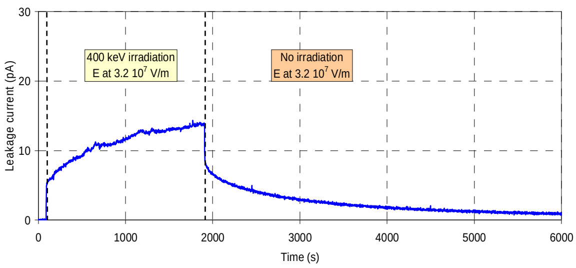

Figure 3 : Evolution of leakage current measured on 25 µm Kapton(R) irradiated at 400 keV, 4 pA.cm^{-2} with an applied electric field of 3.2 10^{7} V/m

Following the first initial drop, we have observed that the relaxation kinetics of DRIC measured with the leakage current method is lower than the one measured with the potential decay method. In this last method, the electric field varies during relaxation which seems to enhance the DRIC relaxation. This observation suggests that DRIC is electric field dependent, which could be explained by Poole-Frenkel or Schottky effect.

3.3. Effect of electrode on RIC measurement

Comparison between RIC values measured with the leakage method and potential decay method revealed that the first method leads to lower values (factor of 2) in comparison with the potential decay method. These differences might indeed be due to the influence of metallization applied for the first method that hinders on electron injection in the material : Schottky effect (electron injection at the interface) might therefore play a noticeable role on RIC and charge transport processes. Further experimental studies are planned to confirm these first assumptions.

4. NUMERICAL ANALYSIS

A dedicated physical and numerical model, called circuit model, has been developed at ONERA to describe the evolution of surface potential and RIC of space used materials irradiated with high energy electrons and representative charging conditions. This model is based on former studies and models devised by Rose [8] and Fowler [9].

Two levels of localized traps have been implemented in this model: one deep trap for which detrapping should be very low but should act as recombination centres if filled with electrons; a second trap corresponding to middle energy depth and for which detrapping is easier. Shallower traps are supposed to get in thermal equilibrium with the extended state. Mobility for free charges is therefore an average mobility taking into account this thermal equilibrium process. We assume as well that a free charge recombines with a localized charge with opposite sign. Based on the above assumptions and introducing charge detrapping process in the model, the equations describing the circuit RIC model are:

$$\frac{dn}{dt} = g(E,T) - \alpha_1 n(p_{t1} + p_{t2}) - \frac{n}{\tau_{n1}} - \frac{n}{\tau_{n2}} + \frac{n_t}{\tau_{nt1}} + \frac{n_{t2}}{\tau_{nt2}} \quad (3)$$

$$\frac{dp}{dt} = g(E,T) - \alpha_2 (n_{t1} + n_{t2})p - \frac{p}{\tau_{p1}} - \frac{p}{\tau_{p2}} + \frac{p_t}{\tau_{pt1}} + \frac{p_{t2}}{\tau_{pt2}} \quad (4)$$

$$\frac{dn_{t1}}{dt} = \frac{n}{\tau_{n1}} - \frac{n_{t1}}{\tau_{nt_1}} - \alpha_2 p n_{t1} \quad (5)$$

$$\frac{dn_{t2}}{dt} = \frac{n}{\tau_{n2}} - \frac{n_{t2}}{\tau_{nt2}} - \alpha_2 p n_{t2} \quad (6)$$

$$\frac{dp_{t1}}{dt} = \frac{p}{\tau_{p1}} - \frac{p_{t1}}{\tau_{pt}} - \alpha_1 n p_{t1} \quad (7)$$

$$\frac{dp_{t2}}{dt} = \frac{p}{\tau_{p2}} - \frac{p_{t2}}{\tau_{pt2}} - \alpha_1 n p_{t2} \quad (8)$$

for which g(E,T) is the electron / hole pairs generation rate which varies with the applied electric field and temperature (according to the Onsager theory [geminate recombination]), α_1 and α_2 are the recombination rates, n, n_{t1} and n_{t2} are densities of free and trapped electrons, p, p_{t1} et p_{t2} are densities of free and trapped holes, τ_{n1}, τ_{n2}, τ_{p1} and τ_{p2} are trapping time for free electrons and holes, τn_{t1}, τn_{t2}, τp_{t1} and τp_{t2} detrapping time for trapped electrons and holes. In this model, the effect of temperature on detrapping time has been taken into account through a conventional Arrhenuis law that reflects the fact that detrapping kinetics is enhanced with the increasing temperature :

$$\tau_t = \tau_{t0}.\exp\left(-\frac{E_a}{k.T}\right) \quad (9)$$

We can then assess densities of free electrons and holes that are used in (10) for surface potential assessment:

$$\frac{dV}{dt} = \frac{Lj(1-\eta-\beta) - e(\mu_n n + \mu_p p)V}{\varepsilon} \quad (10)$$

in which L is the sample thickness, J the incident flux of low energy implanted electrons (20 keV), η the secondary electron emission yield, β is the surface leakage parameter, V the surface potential, e the elementary charge and ε the material permittivity.

This circuit model has been validated on 127 µm thick Kapton® irradiated under GEO like electron irradiation at different temperature levels. Fig. 4 presents the evolution of surface potential on this material at 100 K and 293 K. These results are in good agreement with the experimental results with the following trends :

- a shift of the surface potential to lower values with the decreasing temperature,
- a decline of RIC increase during irradiation when temperature drops down,
- a decline of potential relaxation kinetics with temperature.

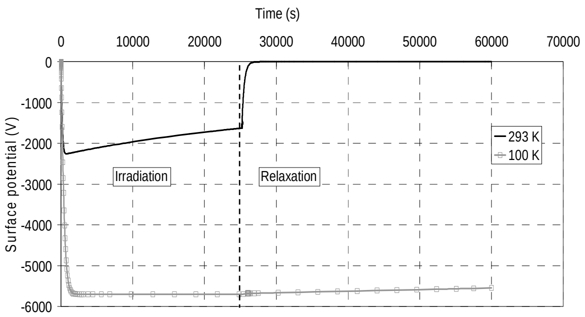

Figure 4 : Evolution of surface potential, assessed numerically, on 127µm thick Kapton® irradiated under GEO like electron irradiation at two different temperature levels (100 K and 293 K)

5. CONCLUSION

This paper demonstrates the specific behaviour of space polymers and their conduction processes under high energy electron irradiation. Radiation induced conductivity is indeed steered by several physical processes in competition and is therefore dependent upon radiation dose rate, total received radiation dose, electric field and temperature. These different effects have been brought into evidence at ONERA through dedicated experimental procedures. They have been implemented as well in a physical and numerical model that allows understanding and predicting the charging behaviour of space dielectrics in representative space radiation conditions. This model has been validated with the large experimental database available at ONERA.

6. ACKNOWLEDGMENTS

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