1D PHYSICAL MODEL OF CHARGE DISTRIBUTION AND TRANSPORT IN DIELECTRIC MATERIALS UNDER SPACE RADIATIONS

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ABSTRACT

In this paper, we discuss about our current development of a 1D physical and numerical model for the description of charge transport and ionization processes of irradiated space used polymers (here Teflon® FEP and Kapton® HN). It extends the previous simple circuit model (0D physical and numerical model) and relies on solid state physics. This model aims at predicting the charging behavior of space used dielectric materials under space radiation conditions. Validation of this model is carried out through crossed comparisons with the experimental data on surface potentials, conductivity and bulk charge distribution. This paper presents the 1D physical model coupled with numerical results under different irradiation conditions on several materials. The interest of this 1D model is to obtain more realistic predictions of dielectric charging behavior, which will be demonstrated in this paper.

1. INTRODUCTION

In space, dielectrics and especially polymers are commonly used in satellites for their good physical, optical and mechanical properties. Under the irradiation of high energy charged particles, these materials tend to get highly charged. The charging behavior of polymer materials under representative space conditions is very specific: the high energy incident particles (electrons and protons) can ionize the materials which will induce significant changes in their levels of conductivity. We speak about Radiation Induced Conductivity (RIC) which has already been described in [1]. Because materials have different electrical properties, charge transport is different from one material to the other leading to significant discrepancies on their charging profile (fig. 1, from [1]). Some materials can get highly charged which may lead to strong potential differences with the neighbor conductive element. It can then lead to the occurrence of possible electrostatic discharges and therefore potential electromagnetic disturbances or system degradations.

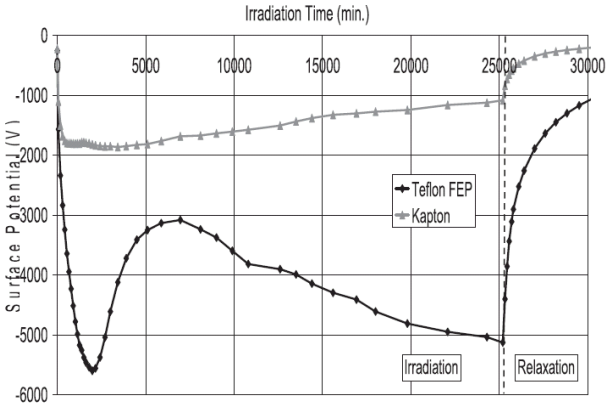

Figure 1. Evolution of surface charging potential measured on space used polymers under GEO-like electron irradiation (Kp > 5) – irradiation conditions: [20 keV, 250 pA/cm²] + [0-400 keV, 50 pA/cm²]. From [1].

2. OVERALL APPROACH OF THE STUDY

This study is split into two objectives. The first one is to develop a 1D physical and numerical model for the prediction of electrical behavior in dielectric materials under representative space radiations. Besides, this should help us better understand charging and ionizing behavior in dielectric materials. The second objective involves the1D model validation by analyzing and comparing both numerical and experimental results. Experimental results are obtained at ONERA though dedicated facilities, such as the SIRENE experiment which is able to reproduce geostationary like electron irradiation spectrum. The SIRENE experiment is fully detailed in [2] and in [3].

The experimental set-up is the following. A 127 µm thick sample of Teflon, whose back face is aluminum metalized, is irradiated with a double mono-energetic beam. One beam is of low energy (20 keV, 250 pA/cm²) and is used to charge the polymer. The other beam is of high energy (400 keV, 50 pA/cm²) in order to study the RIC. Surface potential and bulk charge densities measurements are monitored experimentally using a

Kelvin probe and a Pulsed Electro-acoustic (PEA) system.

With 1D numerical simulation we are able to assess both surface potential and bulk charge densities as a function of irradiation and relaxation time. Hence, we can compare these parameters directly to experimental results. The approach of this study is to understand the physical processes steering the specific behavior observed on dielectric materials submitted to long-term electron irradiation: for this purpose, the method lies on the analysis of the effect of all physical parameters (trapping, recombination, generation, mobility) and external parameters (electron flux and energy) on charge transport in dielectrics.

3. PHYSICAL AND NUMERICAL MODEL OF CHARGE TRANSPORT

In this section, the 1D physical model is described. The objective is to show that the circuit model has some limitations and cannot predict sufficiently well the charging and ionizing behavior of a polymer under the irradiation of high energy particles. Therefore, a new approach is necessary which lead to the present 1D physical and numerical model.

The circuit model, detailed in [4] and [1], does not describe well enough charge transport in dielectric materials. Its main limitations come from the absence of dimension. Indeed, dose distribution is considered as uniform and constant throughout the material, charge barycenter displacements are time and space independent and interfaces phenomena such as secondary electron emission or surface leakage current are inexistent. In addition, conduction currents - that strongly steer surface potentials and charge densities - are absent in the charge transport equations.

Therefore, in this new approach, we add one dimension in our equations, meaning that the deposited dose and the generation rate g are now non-uniform (depth-dependent). In these conditions, the simple RC circuit model is no longer valid. The conduction current computed from a simple resistance R is now described by a transport current taking into account the convection and the diffusion of the charges in the material. While the capacitance C is replaced by the Poisson equation that computes the potential and electric field maps as a function of the charges densities inside the material. The computation of the electric potential in the material is done as follows:

$$-\Delta V(x) = \frac{\rho(x)}{\varepsilon} \quad (4.6)$$

$$(\partial_x V)(0) - \frac{\varepsilon_0}{\varepsilon}\frac{1}{V} = 0 \quad (4.7)$$

$$V(d) = 0 \quad (4.8)$$

Equation (4.6) is the Poisson equation, equation (4.7) is a Robin boundary condition (that mimics the electric field behavior in vacuum) and equation (4.8) is a Dirichlet boundary condition (that mimics a metal interface). In equation (4.6), $\boldsymbol{\varepsilon}$ is the relative dielectric permittivity, $\boldsymbol{\rho}$ the charge density - with $\boldsymbol{\rho = -n + p - n_t + p_t}$ - and $\boldsymbol{V}$ the potential. In equation (4.7), $\boldsymbol{\varepsilon_0}$ is the vacuum permittivity. In equation (4.8), $\boldsymbol{d}$ represents the material length. Charge densities for electrons and holes can be evaluated from the generation rate, trapping, de-trapping and recombination rate, diffusion currents, conduction currents and incident electrons current with the following equations:

$$\frac{\partial n}{dt} = g(x) - \frac{div(j_0)}{e} - D_n\Delta n - \mu_n E\nabla n - \mu_n div(E)n - \alpha_1 n p_t - \alpha_2 np - \frac{n}{\tau_n} + \frac{n_t}{\tau_{n_t}} \quad (4.9)$$

$$\frac{\partial n_t}{dt} = -\alpha_3 n_t p + \frac{n}{\tau_n} - \frac{n_t}{\tau_{n_t}} \quad (4.10)$$

$$\frac{\partial p}{dt} = g(x) + D_p\Delta p - \mu_p E\nabla p - \mu_p div(E)p - \alpha_3 p n_t - \alpha_2 np - \frac{p}{\tau_p} + \frac{p_t}{\tau_{p_t}} \quad (4.11)$$

$$\frac{\partial p_t}{dt} = -\alpha_1 n p_t + \frac{p}{\tau_p} - \frac{p_t}{\tau_{p_t}} \quad (4.12)$$

Equations (4.9) to (4.12) represent respectively the free electrons, trapped electrons, free holes and trapped holes time derivative function. These functions are dependent of several terms: g which is the generation rate of free electrons and holes; $div(j_0)$ is the incident electrons implantation current in the material; $\mu_n E\nabla n - \mu_n div(E)n$ and $\mu_p E\nabla p - \mu_p div(E)p$ are the convection terms that represents the conduction currents for free electrons and free holes; $D_n\Delta n$ and $D_p\Delta p$ are the diffusion currents for free electrons and free holes, where D_n and D_p are the diffusion coefficients; $\alpha_1 n p_t$, $\alpha_2 np$ and $\alpha_3 p n_t$ are the recombination terms where the α_i (i∈[1;3]) relate to the recombination coefficients. τ_n, τ_{n_t}, τ_p and τ_{p_t} are respectively the trapping

characteristic time and the de-trapping characteristic time for electrons and holes.

With this new set of equations, we are now able to describe bulk and interfaces phenomena. Besides, experimental data showed the creation of a double charge layer close to the surface which results from the differences between electrons and holes behavior in polymers; this double charge layer can act as a macro-dipole and strongly steer the surface potential behavior. However, this phenomenon cannot be explained with a 0D approach. That is why a 1D study is necessary over a 0D model if we want to better apprehend charge transport and ionization processes in a polymer under the irradiation of high energy charged particles.

4. EXPERIMENTAL AND NUMERICAL RESULTS

Teflon® FEP and Kapton® HN are both polymers and dielectrics. However, each one of them shows very specific charging behavior. When irradiated with electrons, Teflon® FEP surface potential shows three phases when Kapton® HN only shows two (fig. 1). In addition, due to its specific potential levels Teflon® FEP is more likely to trigger electrical discharges and lead to electromagnetic disturbances than Kapton® HN. That is why it is preferable to use dielectrics such as Kapton® HN than polymers like Teflon® FEP in satellites.

In this section we will present both experimental and numerical results of surface potential for Teflon® FEP (fig. 3) and Kapton® HN (fig. 4). In order to study surface charging and effects of radiations on conductivity (RIC), irradiation conditions for Teflon® FEP are the followings: one mono-energetic beam of 20 keV with a flux of 250 pA/cm² and one mono-energetic beam of 400 keV with a flux of 50 pA/cm². For Kapton® HN irradiation conditions are different: we irradiate the polymer with the SIRENE spectrum (fig. 2, from [1]) to illustrate the capability of the physical model and validate this model in different configurations.

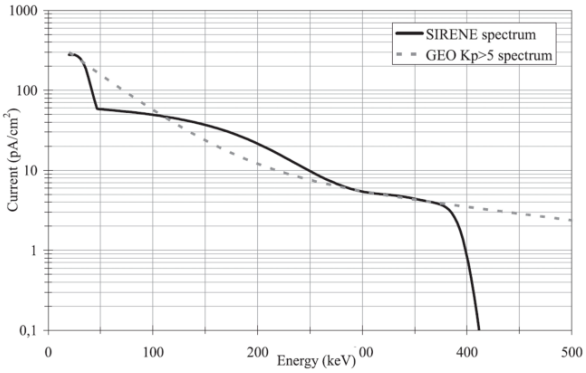

Figure 2. SIRENE standard spectrum and reference Kp > 5 spectrum. From [1].

As mentioned above we observe three phases in the surface potential behavior of Teflon® FEP (fig. 3). The first phase is characterized with a quasi-constant increase in the absolute surface potential, followed by a decrease in phase 2 and by another increase – although much smoother – in phase 3. The 20 keV electron beam acts as a charging beam and is responsible for the **first phase** where surface potential increases with time: electrons are all deposited within the first micrometers around the surface material. The explanation underlying this phenomenon is due to electrons fast-trapping, preventing them from leaving the surface and reaching the bulk. In the **second phase** we observe that surface potential decreases. This could mean two things: either electrons are leaving the surface material into the bulk or holes are reaching the surface from the bulk. Numerical analyses showed that the second hypothesis is the right one. Indeed, the 400 keV electron beam induces global ionization throughout the material generating free electron-hole pairs. Because holes have a longer lifetime than electrons they are able to drift from the bulk towards the surface whereas electrons stay trapped at the surface. Holes conduction will then attenuate the surface potential created by the electron implantation during phase 1. In the **third phase** we observe an increase of surface potential which is regulated through recombination processes. Indeed, as the irradiation goes on, more and more free/trapped electrons and holes are generated in the material. Therefore, during phase three recombination processes play a major role in charge transport preventing free holes generated in the bulk from drifting to the surface as they recombine before reaching it.

On fig. 3 we observe that all three phases are in good agreement between numerical and experimental results. However, some discrepancies can be observed that

reveal two things about our 1D model. Either our physical description of charge transport is incomplete or the implemented Teflon® FEP parameters such as gap energy, electrons and holes mobility, trapping time – de-trapping time – of charges and recombination coefficients are inadequate and need to be modified.

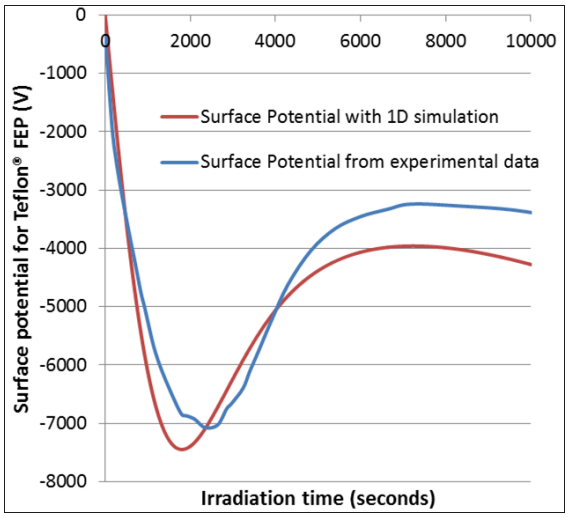

Figure 3. Evolution of experimental and numerical surface potential under two mono-energetic electron beam – irradiation conditions: [20 keV, 250 pA/cm²] + [400 keV, 50 pA/cm²].

For Kapton® HN we observe two phases in the surface potential behavior (fig. 4). In the first phase the potential increases along with the irradiation time and in the second phase it slowly decreases. In Kapton® HN holes lifetime is very small: holes get very fast trapped. Besides, electrons and holes de-trapping times are small compared to Teflon® FEP's. As a result, charge transport in Kapton® HN is very different from Teflon® FEP. During **phase one** the implanted electrons contribute to the surface potential increase. However, as the irradiation goes on, trap levels get more and more filled by electrons and holes resulting in an increase of the de-trapping rate. Therefore, Kapton® HN conductivity tends to increase with irradiation time which leads to holes migrating from the bulk to the surface and electrons leaving the surface towards the bulk. As a consequence holes current overcomes the electrons implantation current explaining why surface potential decreases during **phase two**.

As it is the case for Teflon® FEP there are some discrepancies between numerical and experimental results. As mentioned before, these may be the result of either inadequate implemented parameters or lack of physical description.

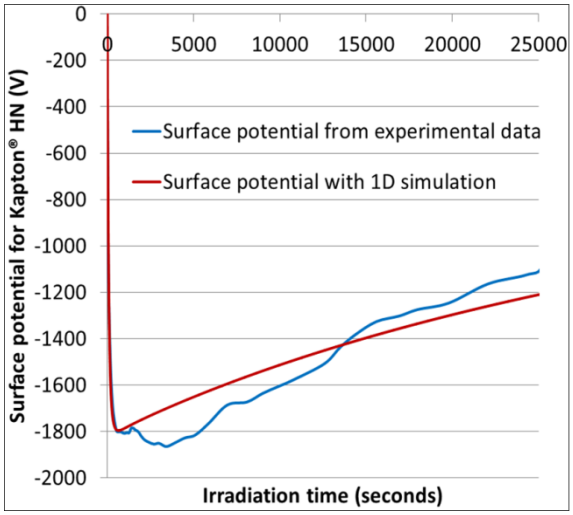

Figure 4. Evolution of experimental and numerical surface potential under SIRENE spectrum.

5. CONCLUSION AND OUTLOOKS

In this paper we presented the development of a 1D physical and numerical model for the description of charge transport and ionization processes in irradiated space used polymers. The previous physical circuit model did not describe well enough charge transport in polymers as the deposited dose was considered uniform (i.e. depth-independent) throughout the material. Therefore, multi-energetic simulations would have been irrelevant as the deposited dose is actually depth-dependent.

In this study we presented two materials, both being polymers, but each with very specific charging behavior. Teflon® FEP charge transport seems mainly steered by free holes and recombination processes while Kapton® HN charge transport is steered by trap-filling followed with de-trapping. For both materials numerical results were in good agreement with experimental results proving that our 1D model is relatively well representative of charge transport in dielectric polymers. However, further investigations need to be done to improve the physical description of charge transport. For instance, generation of electron-hole pairs is temperature-dependent and field-dependent whereas it is temperature-independent and field-independent in the current 1D model; besides our understanding of trap levels is still limited as we assumed only one trap level in the model.

Therefore, further experiments and numerical simulations will be performed in order to fully validate the model and characterize the intrinsic parameters of Teflon® FEP and Kapton® HN. The validation of the model will be a great step for understanding charge transport, which will help us predict charging behaviors.

6. REFERENCES

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