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# Simulation of Charge Build Up and Transport in Electron Beam Irradiated Organic Dielectrics: Comparison to Space Charge Measurements.

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**Abstract-** Recently, the Pulsed Electro Acoustic method – PEA – has been adapted to perform space charge measurements in organic dielectrics under electron beam irradiation and during relaxation, considering short-circuit and open-circuit conditions for the insulation. On the other hand, a model has been developed in order to understand the behavior of space charge in spatial conditions. The aim of this paper is to present the numerical model, and to compare simulated results with experimental ones, obtained with the short-circuit PEA and the open PEA, for a PolyTetraFluoroEthylene (PTFE).

## I. INTRODUCTION

Polymeric materials are commonly used in the spacecraft industry as cover parts of satellites. Owing to their insulating properties, such materials store electrical charges generated by the specific space environment conditions. These charges can lead to electrostatic discharges able to affect the spacecraft operation. In order to understand how dielectrics get charged and to prevent violent discharges, the spatial environment conditions are reproduced at lab-scale [1], and PEA set-ups have been implemented to measure the space charge implantation in these irradiation chambers [2]. To complete these studies, models have been adapted to reproduce the space charge behavior of dielectrics during irradiation or for the following relaxation. In the following, we present the experimental results obtained with two PEA configurations on a PolyTetraFluoroEthylene (PTFE) during irradiation and relaxation, and compare the results with simulated ones for each configuration. We discuss model abilities and limits.

## II. EXPERIMENTS

### A. Experimental conditions

PTFE films of 500  $\mu\text{m}$  thickness have been selected for this work. In order to introduce electrons in the bulk of the insulation, the electron beam energy has been fixed at 250 keV which leads to a maximum penetration depth of the order of 370  $\mu\text{m}$ . The irradiation was performed for 30 min with a flux of 50  $\text{pA}/\text{cm}^2$ . Two PEA setups working either with floating potential or under short-circuit conditions have been installed in the chamber and measurements were recorded at the same time under exactly the same irradiation conditions. One face of the sample was metallized and stick to the ground electrode. The upper face was metallized only for short-circuit

measurements. In the open PEA configuration, space charge distribution is probed using a metallic electrode positioned 1 mm above the free surface. This probing electrode is moved away during the irradiation (which is stopped for the time of measurement of 1 min).

### B. Results for open-circuit configuration

As soon as the irradiation starts, a peak of negative charges appears in the bulk and it is centered at around 300  $\mu\text{m}$  (Fig. 1a). A positive peak of induced charges is built up simultaneously at the ground electrode (the irradiated surface is free -without metallization). The peak amplitude grows continuously with the irradiation time. There is no evidence of charge saturation after 30 min.

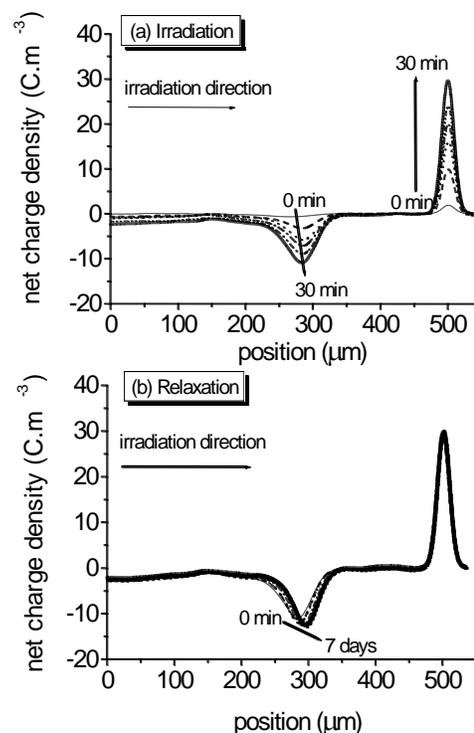


Fig. 1: Charge profile recorded with the open PEA set-up on a 500  $\mu\text{m}$  thick PTFE a) during 30 min irradiation under 250 keV, with a flux of 50  $\text{pA}/\text{cm}^2$ , and b) during 7 days relaxation under vacuum.

The relaxation was followed during 7 days under vacuum (Fig. 1b). A slow movement of the negative peak towards the back electrode is observed. The amplitude of the image charge does not change with time. It means that implanted charges move under the influence of their own electric field but none of them managed to be extracted on such time scale.

### C. Results for short-circuit configuration

In short-circuit conditions, two negative charge peaks are detected in the bulk when the irradiation is initiated (Fig. 2). The first one is in the bulk at about 305  $\mu\text{m}$  from the surface and the second one is near the irradiated surface at about 40  $\mu\text{m}$ . At both sample/electrode interfaces, two positive peaks of induced charges are built up simultaneously (both sides of the sample are metallized).

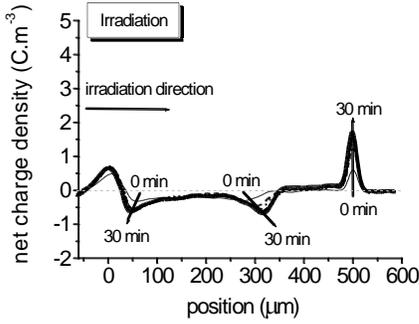


Fig. 2: Charge profile recorded with the short-circuit PEA set-up on a 500  $\mu\text{m}$  thick PTFE during 30 min irradiation under 250 keV, and 50  $\text{pA}\cdot\text{cm}^{-2}$  as flux.

If we compare the amplitude of the signal recorded by both methods, we can see that there is a large difference. Actually the amplitude of the charge density detected with the short-circuit set-up is much smaller than the one recorded with the open PEA equipment. This can be explained by the fact that a large amount of the charges located in the irradiation part can be extracted from the front grounded electrode during the irradiation and also during the measuring period. Electrons implanted in the bulk are driven towards the irradiated surface under the effect of the electric field created by the charges themselves. The same phenomenon could be observed in the non-irradiated part as the field tends to drive the charges in the opposite direction (towards the back electrode). However, the irradiated zone is actually more electrically conductive due to the irradiation (so-called RIC; radiation-induced conductivity). Hence, charges are evacuated essentially through the irradiated region.

## III. SIMULATIONS

### A. Model description

A numerical model developed for the transport of charges in solid dielectrics under electrical stress [3], has been adapted to reproduce the behavior of charges in electron beam irradiated polymers, for the two configurations encountered in the experiments, i.e. ‘open circuit’ and ‘short-circuit’ (Fig. 3). The model features injection of carriers at one or two electrodes, conduction via a constant effective mobility, trapping and detrapping of each carriers into deep traps,

recombination as represented in Fig. 4. The physical hypotheses for the generation of electronic carriers due to the electron beam, i.e. generation of electron/hole pairs, have been taken from Sessler et al [4].

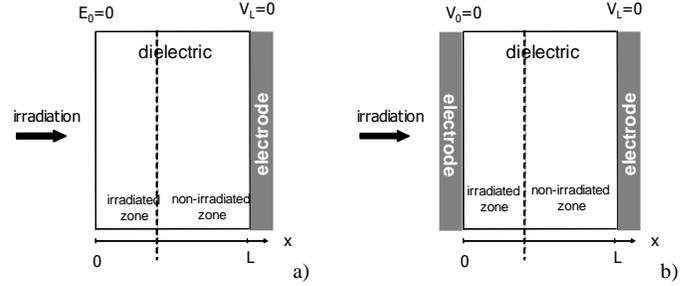


Fig. 3: Representative schemes of the simulated configurations for charge transport in electron beam irradiated polymers for a) a ‘floating potential’ (open circuit), and b) ‘short-circuit’ configuration.

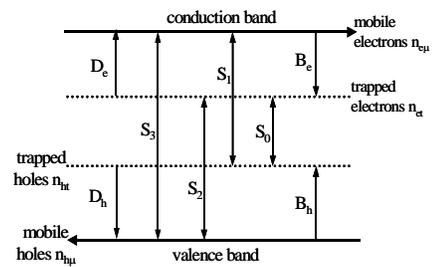


Fig. 4: Schematic representation of the conduction mechanism in a PTFE sample. The values and definition of the parameters are given in Table I.

The model used to describe the charge transport involves the coupled resolution of the following equations, neglecting the diffusion:

$$j(x, t) = \mu_n E(x, t) \quad \text{transport} \quad (1)$$

$$\frac{\partial E(x, t)}{\partial x} = \frac{\rho(x, t)}{\epsilon \epsilon_0} \quad \text{Poisson} \quad (2)$$

$$\frac{\partial n(x, t)}{\partial t} + \frac{\partial j(x, t)}{\partial x} = s(x, t) \quad \text{continuity} \quad (3)$$

where  $x$  is the distance in the direction perpendicular to the electrodes,  $t$  is the time,  $\mu$  is the carrier mobility,  $n$  is the carrier density,  $E$  is the electric field,  $\rho$  is the net charge density,  $\epsilon$  is the relative permittivity (2.1 for PTFE),  $j$  is the current density.

The term  $s(x, t)$  is the source term, i.e. it encompasses changes in local density by processes other than transport (electron deposition, electron/hole pairs generation, trapping, etc.). The following equations describe the source term of equation (3) for each kind of carriers:

$$s_{e\mu}(x, t) = -\frac{\partial J_0(x, t)}{\partial x} + G(x) - B_e n_{e\mu}(x, t) \left(1 - \frac{n_{et}}{n_{e0et}}\right) + D_e n_{et} - S_1 n_{e\mu} n_{ht} - S_3 n_{e\mu} n_{h\mu} \quad (4)$$

$$s_{et}(x, t) = B_e n_{e\mu}(x, t) \left(1 - \frac{n_{et}}{n_{e0et}}\right) - D_e n_{et} - S_0 n_{et} n_{ht} - S_2 n_{et} n_{h\mu} \quad (5)$$

$$s_{h\mu}(x, t) = G(x) - B_h \cdot n_{h\mu}(x, t) \left(1 - \frac{n_{ht}}{n_{h0ht}}\right) + D_h \cdot n_{ht} \quad (6)$$

$$s_{ht}(x, t) = B_h \cdot n_{h\mu}(x, t) \left(1 - \frac{n_{ht}}{n_{h0ht}}\right) - D_h \cdot n_{ht} \quad (7)$$

where the indexes e and h refer to electrons and holes respectively. The parameters definitions are given in Table I.  $D_e$  and  $D_h$  are the detrapping coefficients, of the form:

$$D_e = v \exp\left(\frac{w_{tre}}{k_B T}\right) \quad (8)$$

where  $k_B$  is the Boltzmann constant and  $v$  the attempt to escape frequency.

$G(x)$  in equations (4) and (6) refers to the electron/hole pair generation, of the form [4]:

$$G(x) = G_0 \cdot D(x) \quad (9)$$

where  $G_0$  is the electron/hole pairs generation coefficient, and  $D(x)$  is the deposited dose, function of the energy of the electron beam, the nature of the material.  $J_0$  in equation (4) refers to the beam current density, function of the position in the dielectric. The corresponding profile along with the deposited dose profile have been calculated using the GEANT 4 software [5], and are given in Fig. 5a) and b) respectively, for the current experimental conditions.

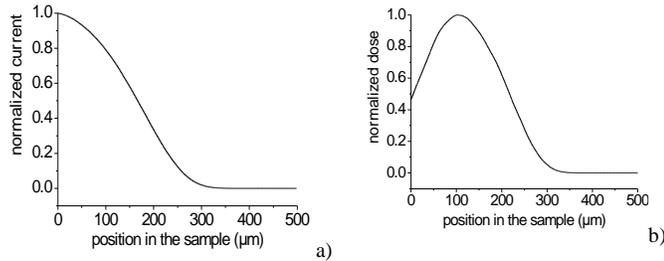


Fig. 5: a) Normalized current density and b) Normalized dose function of the thickness of the sample calculated by GEANT 4 for a 500  $\mu\text{m}$  thick PTFE irradiated by a 250 keV electron beam, 50  $\text{pA}\cdot\text{cm}^{-2}$ .

Beside charging by incident electrons and related effects, we have considered the possibility that charges be generated by injection at the electrodes. This has been accounted for by considering a modified-Schottky law of the form:

$$j_{inj}(L, t) = AT^2 \exp\left(\frac{-w_a}{k_B T}\right) \left\{ \exp\left(\frac{e}{k_B T} \sqrt{\frac{e \cdot E(L, t)}{4\pi\epsilon\epsilon_0}}\right) - 1 \right\} \quad (10)$$

The same equation holds at  $x=0$  for the short circuit configuration.  $A$  is the Richardson constant and  $w_a$  is the injection barrier (cf. Table I). The nature of injected carriers depends on the sign of the field at the electrode.

Simulations results presented in the following have been obtained with the optimized parameters given in Table I. It is to note that the adaptation of the parameters in order to best fit the experiments has been done manually, meaning a long lasting work. The irradiation conditions and the material features are those described in section II.

Table I: Final optimized parameters used for all simulations

Parameter	Value	Units
<b>Mobilities</b>		
$\mu_e$ electrons	$3 \cdot 10^{-14}$	$\text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$
$\mu_h$ holes	$8 \cdot 10^{-16}$	$\text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$
<b>Trapping coefficients</b>		
$B_e$ electrons	$10^{-1}$	$\text{s}^{-1}$
$B_h$ holes	$10^{-2}$	$\text{s}^{-1}$
<b>Trap densities</b>		
$n_{e0et}$ electrons	100	$\text{C} \cdot \text{m}^{-3}$
$n_{h0ht}$ holes	100	$\text{C} \cdot \text{m}^{-3}$
<b>Recombination coefficients</b>		
$S_0$ trapped electron/trapped hole	$4 \cdot 10^{-3}$	$\text{m}^3 \cdot \text{C}^{-1} \cdot \text{s}^{-1}$
$S_1$ mobile electron/trapped hole	0	$\text{m}^3 \cdot \text{C}^{-1} \cdot \text{s}^{-1}$
$S_2$ trapped electron/mobile hole	0	$\text{m}^3 \cdot \text{C}^{-1} \cdot \text{s}^{-1}$
$S_3$ mobile electron/mobile hole	0	$\text{m}^3 \cdot \text{C}^{-1} \cdot \text{s}^{-1}$
<b>Injection barrier heights</b>		
$w_e$ electrons	1.15	eV
$w_h$ holes	1.35	eV
<b>Detrapping barrier heights</b>		
$w_{tre}$ electrons	1.17	eV
$w_{trh}$ holes	1.05	eV
<b>Electron/hole pair generation coefficient</b>		
$G_0$	$2 \cdot 10^{-1}$	$\text{C} \cdot \text{m}^{-3} \cdot \text{s}^{-1}$

### B. Results for open-circuit configuration

In the case of open circuit configuration (Fig. 3a), charges can only be injected and extracted at the right electrode (ground), the sign of the injected carriers being dependent upon the electric field. The irradiation comes from the left side ( $x=0$ ). A post-treatment of the simulated results enables us to add the image charge induced by the internal charge inside the dielectric on the electrodes and to smooth the profiles in an equivalent way as the PEA method does. In this configuration, image charges can only be seen at the ground electrode. The model parameters are given in Table I, except for the recombination coefficient  $S_0$  which has been set to zero in order to obtain a better comparison between the experiment and the simulation profiles.

**B.1 Irradiation:** Simulated results obtained for the optimized parameters are given in Fig. 6.a for the irradiation. A negative charge peak appears quickly inside the bulk and increases with the irradiation time. The peak maximum is detected at 280  $\mu\text{m}$  after 30 min of irradiation. No charges are observed next to the irradiation face (left electrode), and beyond 400  $\mu\text{m}$ . The simulated profiles are consistent with the experimental ones (Fig. 1.a), as the model only takes into account mono-energetic electrons. During irradiation, positive charges are produced (due to the electron/hole generation process). However they do not appear as net charge since they are compensated by negative carriers produced by the generation process and by deposition of charges from the incident beam. The net charge is effectively null from  $x=0$  to 200  $\mu\text{m}$ .

**B.2 Relaxation:** During relaxation, the negative charges accumulated during the irradiation shift towards the ground electrode (Fig. 6.b). During this process the magnitude of the peak tends to be growing. At the end of the relaxation, the peak maximum is at about 300  $\mu\text{m}$  from the irradiated side. No charges are detected next to the irradiation electrode. After

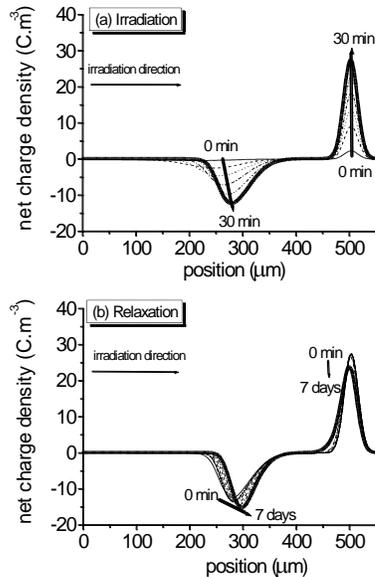


Fig. 6: Simulated space charge profiles for a 500  $\mu\text{m}$  thick PTFE in open-circuit configuration **a**) during 30 min of irradiation with a 250 keV electron beam and **b**) for the following relaxation during 7 days.

7 days of relaxation, the simulated results show a small quantity of positive charges close to the ground electrode. These charges have been injected from the ground electrode under the effect of the implanted charge-induced field.

### C. Results for short-circuit configuration

The simulated charge profiles obtained with the optimized parameters of Table I are given in Fig. 7 for irradiation in the short-circuit configuration as shown in Fig. 3.b. In this case, charges can be injected and extracted at both electrodes. As previously, the image charges on both electrodes have been added.

Two negative charge peaks are observed during irradiation. The first peak is detected at  $\sim 40 \mu\text{m}$  from the irradiation face. It increases with the irradiation time and shifts towards the left electrode. The second peak is observed at  $250 \mu\text{m}$  at the beginning of the irradiation. It also increases with irradiation time and shifts towards the right electrode (from  $250$  to  $290 \mu\text{m}$ ). Between these peaks, the net charge is nearly zero. The negative charges, deposited by the electron beam or generated by electron/hole pair, are drifted by the implanted charges-induced field (Fig. 8) towards the irradiated surface or the back electrode, depending on their position inside the bulk. As to positive charges, the field tends to stabilize them between  $100$  and  $250 \mu\text{m}$ , giving rise to a quasi-zero net charge density.

Simulated results are in good agreement with experimental ones for the 'short-circuit PEA' configuration (Fig. 2). The model is able to reproduce the dynamic of space charge for this case and many features related to the charge profiles, particularly the appearance of a double peak. Only the density of charge seems overestimated in the simulation. However, the optimization of the parameters has been done mainly qualitatively, not quantitatively.

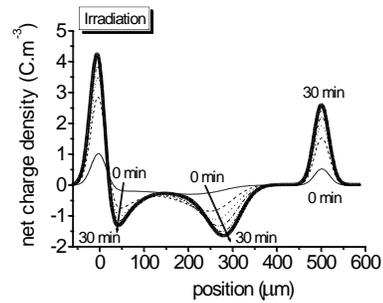


Fig. 7: Simulated space charge profiles for a 500  $\mu\text{m}$  thick PTFE in short-circuit configuration during 30 min irradiation with a 250 keV electron beam.

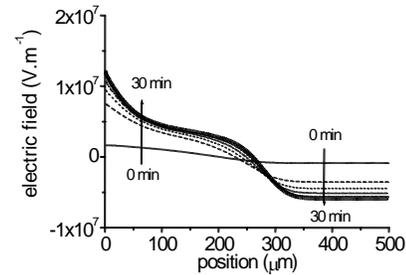


Fig. 8: Simulated electric field profiles during irradiation in short-circuit configuration. Image charges have not been added prior to field computation.

## CONCLUSION

A numerical model has been implemented in order to reproduce original space charge measurements in space environment. The comparison between the experiment and the simulation leads to a good agreement for both configurations, i.e. the open PEA and the short-circuit PEA configurations. This is however a preliminary work, and more studies need to be done in order to further develop the model for different polymeric materials encountered on satellites, and to understand the impact of the recombination on simulated space charge profiles.

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