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Numerical Investigation of the Dynamic of Electrons Implanted in a Polymeric Material

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Abstract— This paper focuses on studying the effect induced by the dynamics of radiation charges on the behavior of the electric field within an irradiated polymeric material. Utilizing a simulation model based on the numerical resolution of transport equations, the evolution of implanted charges under various DC electric fields is examined over time. The main analyzed parameter is the depth of the implanted charges within the material. The results obtained demonstrate that when the implanted charges are deeply positioned, they lead to an intensification of the local electric field over a wide area within the material. Moreover, their dynamic response to an applied electric field causes an additional intensification of the local field by approximately 25%. Furthermore, these charges tend to accumulate increasingly as they penetrate deeper into the bulk of the material.

Keywords—Electric field, irradiation, polymers, simulation, space charge.

I. INTRODUCTION

Due to their lightweight and non-corrosive properties, polymers are currently the materials of choice in the design of equipment operating in space (satellites, space shuttles, etc.). Despite the technical and economic advantages they offer, polymers have a significant drawback related to their tendency to accumulate electrical charges within their bulk. This characteristic renders their behavior unpredictable, particularly in the demanding and variable environments of space where they are subjected to various types of radiation. To address this challenge, numerous researchers worldwide are focused on comprehending the effects of radiation on polymers from both structural and morphological perspectives [1] particularly concerning the behavior of space charges under such constraints. For instance, experiments involving controlled implantation of electronic charges into polymers, followed by monitoring their evolution within the material volume over time and under varying conditions using the PEA technique, have been conducted [2].

Additionally, various simulation models have been implemented to describe the behavior of space charges in irradiated polymers [3]. Intensive efforts have been made to enhance the reliability of these models by considering various parameters that influence the conduction process, such as trapping/detrapping, charge recombination, and charge injection... [4]. This approach enables the study of space charge dynamics in a realistic situation and allows to align well the computed data with experimental observations. Nevertheless, presence of the simultaneous effects of the various considered parameters renders interpreting the results challenging. It appears that a detailed description of the effect induced by each parameter and linking each observed

phenomenon to its direct origin is necessary. Consequently, given that simulations may facilitate this, there is an interest in understanding separately the effects of different parameters influencing space charge accumulation in polymers, particularly in irradiated ones.

The work proposed here aims to explore a basic model for describing charge transport to examine the space charge behavior within an irradiated polymer, considering the variable energies of radiation rays. It is demonstrated that higher radiation energy results in charges being located deeper within the material [5]. Thus, our study focuses on investigating the effect of radiation energy by varying the depths of the radiation-induced charges when selecting initial conditions before applying the DC electric field. Knowing the crucial effect of the temperature parameter on space charge generation and its dynamics within the dielectric, with the aim of focusing solely on the effect of radiation energy (considered through the location of implanted charges), it is important at first to prevent the creation of other types of electrical charges that could influence the results (such as the temperature dependent injection process, the electric field dependent recombination phenomenon, etc.). The simulation is conducted in such a way that only the impact of radiation-induced charges is considered, without any influence from other charged species.

This paper aims to elucidate the effects of different initial positions of the radiation-induced charges (correlated to radiation energy) on their dynamics within the irradiated polymeric material under DC electric fields. Additionally, we aim to demonstrate the influence of radiation energy on the local electric field distribution and its evolution over time, as this parameter is crucial in defining the reliability and capabilities of the dielectric material

II. NUMERICAL METHOD

The simulation involves numerically solving the Poisson, continuity, and current equations using the Finite Differences Method

$$\partial F(x, t)/\partial x = \rho(x, t)/\varepsilon \quad (1)$$

$$\partial J(x, t)/\partial x = \partial \rho(x, t)/\partial t \quad (2)$$

$$J(x, t) = \mu \rho(x, t) F(x, t) \quad (3)$$

In the provided context, ε represents the material permittivity, while μ denotes the charge mobility which is

considered as a constant. Additionally, ρ , F , and J correspond to the charge density, the local electric field, and the conduction current, respectively.

This study is based on an experimental research involving the electron beam irradiation of a $150\mu\text{m}$ thick XLPE film. It has been demonstrated that Gaussian distributions of electrons are located at varying depths within the material bulk, depending on the energy of the radiation [2]. This characteristic is incorporated into the model by introducing a Gaussian distribution of electrons at different positions within the thickness of the material at $t=0$. When the dielectric material is submitted to the action of an external electric field, the radiation charges evolve within the thickness of the material under the combined effect of both external applied electric field and the internal field due to its presence. The contact at both electrodes is assumed to be of ohmic natures.

TABLE I. SET OF THE MODEL PARAMETERS

Parameter	Value
Relative permittivity (ϵ/ϵ_0)	2
Charge mobility	$10^{-13} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$
σ parameter of the Gaussian distribution of electrons	12.4

III. RESULTS AND DISCUSSION

Under DC electric fields of 40 , 70 and 100 MV/m , the evolution of the space charges, the electric field distribution and the conduction current are calculated during the first 10 seconds of the transient period.

In this study, the influence of various applied electric fields is emphasized, showing a trend towards the uniformity of the local field with increasing external field strength, alongside the thickness of the material. It is observed that relative variations in the local electric field are more pronounced for lower applied electric fields compared to stronger fields. Therefore, this paper explores the dynamics of the implanted electrons and their induced effects on the local electric field for different initial positions of the radiation's charges within the thickness (at 30 , 75 , and $105\mu\text{m}$), assuming the irradiated material is subjected to a moderate electric field of 40MV/m .

A. Effect of the implanted electrons location on the space charge behavior

Figure 1 depicts the dynamics of electrons implanted at various depths within the material thickness under an applied electric field of 40MV/m . It is observed that electrons implanted deeply into the material require more time to be extracted from the bulk by the electric field effect. By the final time of 10 seconds , a noticeable accumulation of space charge is observed within the irradiated material. This accumulation becomes more pronounced with increasing radiation energies, as previously discussed in [2], especially when the implanted electrons are deeply located within the material. When quantifying the charge accumulation at $t = 10\text{seconds}$ through integration of the charge distribution function, a nearly linear increase in accumulated charges is observed, particularly as the implanted electrons are deeply positioned within the material (Table 2).

TABLE II. CHARGE ACCUMULATION FOR VARIOUS DEEPHTS OF IMPLANTED ELECTRONS

Implanted electrons location (μm)	30	75	105
Accumulated charge (μC)	871	442	187

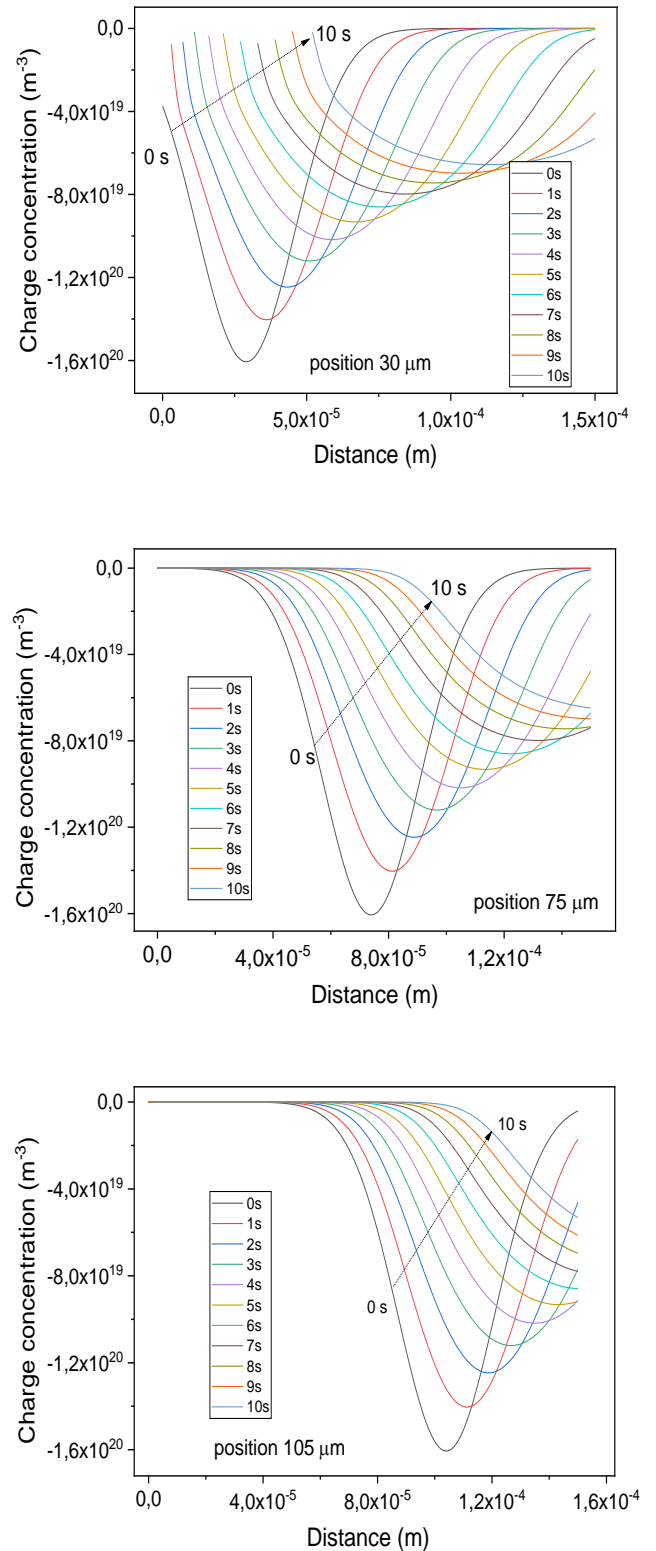


Fig. 1. Impact of the implanted electrons' position on the space charge behavior

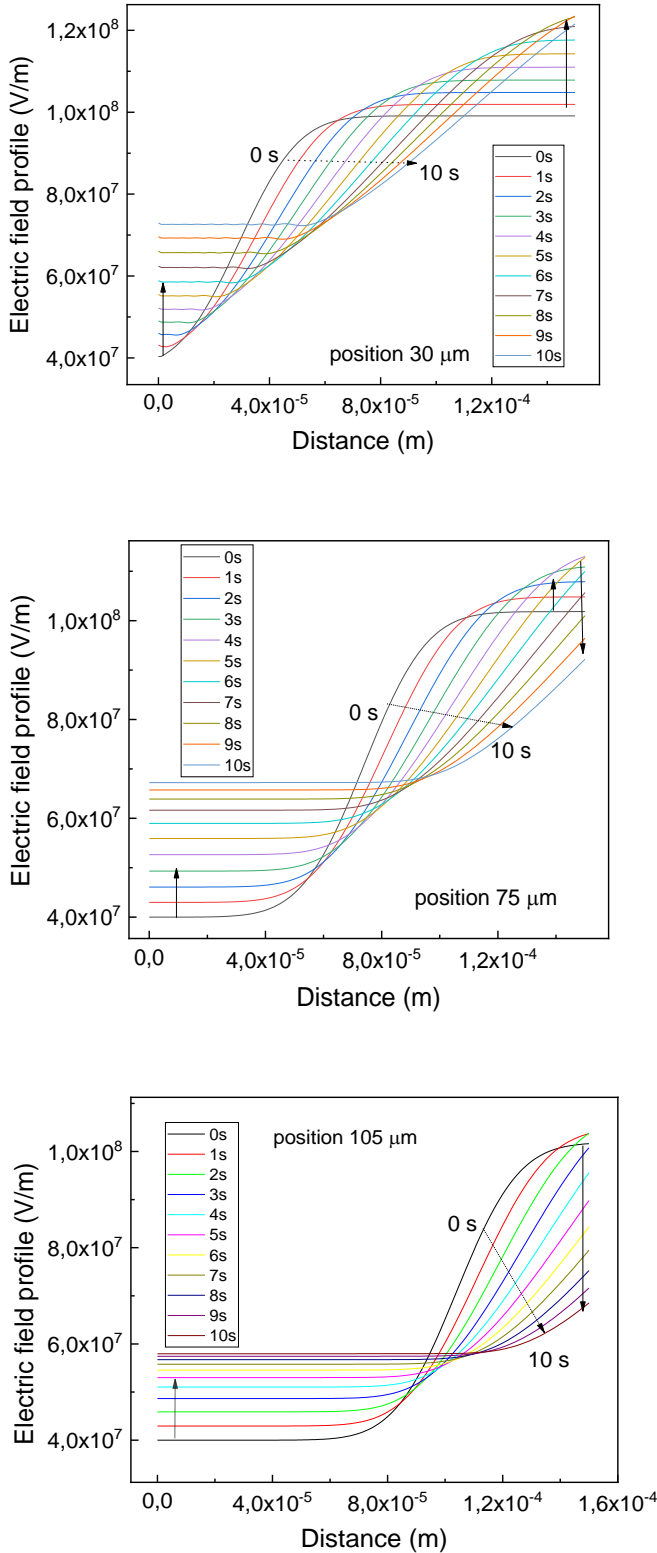


Fig. 2. Effect of the implanted electrons position on the local electric field behavior

B. Effect of the implanted electrons location on the local electric field distribution

Figures 2(a), 2(b), and 2(c) illustrate the behavior of the local electric field for various depths of electrons implanted

within the material's bulk. It's important to note that the intensification of the local electric field due to the presence of implanted electrons is evident from $t=0$, and this intensification is consistent across all cases. Specifically, in comparison to the applied field of $40MV/m$, the intensified electric field reaches $100MV/m$. However, a significant distinction among the three considered cases is observed regarding the extent of this enhancement of the local electric field. At $t=0$, for the three locations of the implanted charges (at depths of 30 , 75 , and $105\mu m$), the local field attains its maximum value ($100MV/m$) within distances of 100 , 50 , and $15\mu m$, respectively

The evolution of the electric field within the irradiated material under the influence of the external DC field (from $t=0$ to $t=10$ seconds) can be primarily characterized by three

distinct regions: The zone near the cathode (considered the deepest within the thickness in relation to the radiation direction), the middle region, and the zone near the anode, which represents the superficial region. Firstly, the local field near the cathode experiences continuous augmentation regardless of the initial position of the electrons. In this zone, the electric field increases from $40MV/m$ to 72 , 68 , and $59MV/m$ for initial electron positions of 30 , 75 and $105\mu m$, respectively. Secondly, in the middle region of the sample, the local field demonstrates a continuous decrease when the implanted electrons are positioned at $30\mu m$, while it tends to remain relatively unchanged when the electrons are placed at 75 and $105\mu m$.

The most significant impact on the local electric fields, stemming from the space charge evolution due to different initial positions, is observed in the zone near the anode. Specifically, the electric field near the anode evolves as follows: it experiences a continual increase over the ten-second period when the implanted electrons are located at $30\mu m$, it increases initially then decreases when they are positioned at $75\mu m$, and it decreases steadily if they are placed at $105\mu m$. When quantifying the intensification of the local electric field due to the dynamics of the space charge, an additional enhancement of 25% is observed when the radiation's electrons are positioned at $30\mu m$ (extending up to 80% of the dielectric thickness). Additionally, there is an additional intensification of 10% when the implanted electrons are placed at $75\mu m$ (representing 50% of the thickness).

IV. CONCLUSION

The primary objective of this work was to investigate the effects induced by radiation energy, manifested through various locations of radiation charges, on the space charge behavior within irradiated polymeric materials. The specific and overarching goal of this research was to track the evolution of solely implanted charges and comprehend their effects in the absence of any other charged species.

The findings reveal that as the radiation charges penetrate deeper into the material:

- ✓ Their presence, particularly at $t=0$, results in an enhancement of the local electric field across a wide zone of the material's thickness.
- ✓ The intensification of the electric field near the anode is notably pronounced.

✓ they are more accumulated into the material

In future studies, to enable comparison with experimental data, this simulation will be extended to incorporate various processes such as trapping and charge recombination. Additionally, it is crucial to investigate the modifications induced by radiation on the material's properties and incorporate these findings into the model. This holistic approach will provide a comprehensive understanding of the complex interactions between radiation, charge dynamics, and material properties in irradiated polymeric materials.

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