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Bipolar model for electrical breakdown in polyethylene materials under dc high electrical fields

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ABSTRACT

In this paper, we have applied our bipolar transport model for studying the charge dynamics in the insulating polyethylene materials, from nano to micro -scales and under dc high applied field. We have also applied the model for studying the electrical breakdown phenomenon for these mentioned scales. The principal results are dedicated to the evolution of the external current in low density polyethylene samples. Under notable dc high applied field, the electrical pre-breakdown phenomenon is indicated by an abrupt increase that occurs during the steady state of the external current.

Introduction

The synthetic insulating material such as low density polyethylene (LDPE) becomes more suitable for insulating cable that is integrated in high voltage applications [1–3]. However, several previous works indicate that the application of a strong dc electrical stress to the LDPE material leads to the acceleration of the aging process and consequently can affect drastically the functional behavior of the sample [4–13]. Under high dc applied voltages, the degradation of the LDPE insulating can induce the establishment of the electrical breakdown of the material [9,14]. A relationship between the space charge accumulation and the electrical breakdown in the insulation material has been discussed previously [11,12]. Unfortunately, the corresponding mechanisms of the electrical breakdown phenomenon remain unclear. To contribute to the resolution of this phenomenon, we have applied, to this problem, our recent transient-steady model that is established initially for bipolar charge transport in the LDPE materials [15]. In this setting, we inform that majority of previous theoretical models are based on statistical aspects to study the breakdown phenomenon in the insulating materials [14,16]. In fact, these statistical approaches are used in the analysis of lifetime data and in problems related to modeling of failure processes and aging. Among these approaches, the weibull distribution is considered as the most widely used lifetime distribution model in analyzing the electrical breakdown characteristics of different polymers [14]. We noted that this probabilistic approach uses some parameters such as scale and shape parameters without physical meaning.

Concerning our approach, our theoretical formulation is based on physical transport equations in order to study the charge dynamic evolution, in time and space, for both transient and steady regimes. This procedure allows us to obtain several physical instantaneous variables such as the space charge densities, the electric field distributions as well as the conduction and the external current densities. In addition, our resolution strategy is based on the best choices of the high precise numerical resolution methods that we have applied adequately for each physical equation, as we will explain in the following section. Besides, under dc high applied field, the suitable choice of the parameters of the model allows us to obtain pertinent results corresponding to the electrical breakdown phenomenon. In fact, the principal result is attributed to the aspect of the cross over in the current from stability to instability.

Our model results show two different aspects of bipolar charge transport under low and high dc applied voltages. In fact, under low dc applied voltage, the external current profile reveals the appearance of space charge limited current aspect that shows the

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increase of the current during the transit time of the bipolar charges following by its decreases until the establishment of the steady state. For high dc applied voltage, the evolution of the external current shows that the current tends to its steady state without decreasing [3,17]. This latter aspect indicates the space charge limited current for injection high regime [17]. Under this regime, our principal results show the apparition of the space charge packet phenomenon during the transient stage of the bipolar charge transport in the LDPE sample. The generated charge packets induced the distortion of the interfacial electric field and then the intensification of the bipolar charge injection for which the dynamic remains largely dominated by the mobile charges.

Besides, our results show that the electrical pre-breakdown phenomenon is marked by an abrupt increase of the external current evolution during the steady state. This obtained phenomenon is also reported in previous literature based on statistical models [14]. In fact, this previous literature presents only the aspect of the abrupt increase evolution.

Principally, we are interested in our results by the evolution of the external current for different thicknesses of LDPE materials, ranging from nano to micro-scales. From the external current profiles, the electrical breakdown field and the breakdown time are determined. The effects of the temperature of the sample as well as the carrier mobility are also investigated in this paper.

Hypothesis and model equations

Hypothesis

In this section, we present the main hypothesis for the formulation of our model. In fact, we consider an additive-free low density polyethylene film sandwiched between two electrodes, under dc applied voltage. A contact insulator-electrode is supposed to be perfect. Our theoretical approach is based on the bipolar charges generated by injection mechanism, the transport process, the trapping as well as the recombination of positive and negative charge carriers (Fig. 1). For the LDPE film, we assume that the width and breadth are much larger than the thickness. For this latter supposition, we can admit that the problem is unidirectional and then all physical mechanisms act mainly in the direction of the sample thickness [17]. We suppose that the initial local net space charge density is neglected. The charge generation is assumed to be controlled by Schottky law at the electrode-dielectric interface, for both electrons and holes injected. This assumption is also adopted in previous work [17] when the thermo-electronic effects are considered during the injection process and when the applied

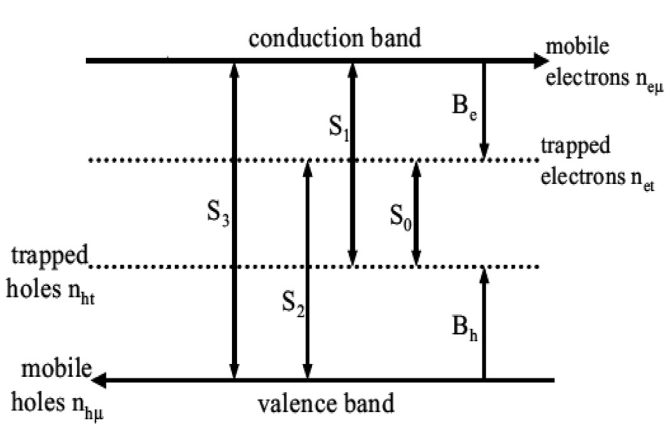

Fig. 1. Representation of the conduction mechanism of the model.

electric field values are less than 10^9 V/m [3,14,16]. The polyethylene sample is considered under uniform room temperature and the carriers are supposed having an effective constant mobility. In order to describe the long-lasting of space charge in the deep trapping in polyethylene, we have introduced a unique average level of deep traps for electrons and holes. Indeed, two types of traps, shallow and deep, are described in the LDPE materials [18,19]. The deep traps are associated to the chemical defects while the shallow traps are related to the physical conformational of the LDPE chains. In fact, the shallow traps, having a very short residence time (10^{-12}s), are supposed to contribute only to the conduction process. The deep traps are assumed to contribute only to the accumulation of charges in the bulk of the sample.

Theoretical equations

The model of charge transport is composed by the coupled equations of Poisson's, the continuity and the transport. Based on the hypothesis of unidirectional problem, formulated in the previous section, the coupled equations are one-dimensional and then they are supposed depending only on the ‘*x*’ coordinate. These equations are adopted by some previous works in order to study the bipolar charge transport in the LDPE material [12,13,15,17]. Although the LDPE insulating material is composed of crystalline and amorphous phases that are nested, some previous works show that this material is characterized by a chemical homogeneity [20].

For this reason, all physical proprieties such as permittivity in Poisson's equation are giving in average values [15,21].

Poisson's equation, the initial and the boundary conditions are given as follows:

$$\frac{\partial^2 V(x,t)}{\partial x^2} + \frac{\rho(x,t)}{\varepsilon} = 0 \quad 0 < x < D \tag{1}$$

$$\overrightarrow{\boldsymbol{grad}}(V(x,t)) = -\overrightarrow{\boldsymbol{E}}(x,t) \tag{2}$$

where *E(x,t)* is the local electric field, *V(x,t)* is the local scalar electric potential. In fact, the local electric field *E(x,t)* is composed by the dc applied field and the field of the space charges generated in the LDPE material. *ρ(x,t)* is the net volume charge density composed of trapped and mobile electrons and holes. Because the problem is unidirectional along x axis, the density ρ depends only on ‘*x*’ coordinate.

The initial condition for free additive polyethylene film is:

$$\rho(x,0) \approx 0 \tag{3}$$

The boundary conditions are written as follows:

$$\Delta V = V_C - V_A \tag{4}$$

$$V(0, t > 0) = V_C \tag{5}$$

$$V(D, t > 0) = V_A \tag{6}$$

$$\int_0^D E dx = \Delta V \tag{7}$$

where V_C and V_A, respectively, are the potentials at the cathode and at the anode and D is the dielectric thickness. The continuity equation, with trapping and recombination term sources, and the transport equation are given as follows: