Towards Understanding of High Electric Field Phenomena in Polymeric Dielectrics

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***Abstract*—Understanding the response of polymeric insulating materials to high electric fields is not only scientifically challenge but also practically important. Significant amount of effort has been made over the years and it has been found that there are several anomalous phenomena occurred in polymeric dielectrics under high electric fields. In the present paper all these phenomena have been experimentally demonstrated but most importantly we view the observed phenomena originate from the same mechanism therefore have taken a coherent approach. A double injection model has been used to understand the observed phenomena under high fields. Simulations based the model reveal that the presence of bipolar charges is the key to explain these anomalous phenomena.**

Keywords - high fields, solid dielectrics, anomalous phenomena, bipolar charge injection, simulation.

I. INTRODUCTION

Operating at high electric fields for compact and high-performance apparatus and the improvement of reliability and long-term life under severe operation conditions become increasingly important in the competitive market. In such circumstances, it is essential to improve insulating materials based on the fundamental understanding of high field phenomena. Consequently the research in this area has attracted significant attention. There are several anomalous phenomena observed under high electric fields. These phenomena were reported in the literature in separated studies.

In this paper, thesel anomalous phenomena under high dc electric fields were briefly reviewed with examples from the results obtained by the author. Based on strong experimental evidences, a unified model based on a bipolar charge injection has been used to simulate the phenomena. Simulation results showed that all the anomalous phenomena observed can be qualitatively explained, indicating the same physical origin.

II. ANOMALOUS PHENOMENA UNDER HIGH DC FIELDS

The response of polymeric materials to the applied electric field is related to the interaction of dipole and electric charge with the field. When the applied field is increased, the phenomena observed are most likely related to charge injection trapping recombination and transport. They are often surprising and beyond our anticipations.

A. Transient Space Charge Limited Current

When a dc electric field is applied to a dielectric material, there will be a current flowing and this current will decay monotonically over a period of time (polarization current) and finally reach to a steady value (conduction current). However, under a high electric field and in the presence of charge injection and trapping in the bulk of the material, a transient space charge limited current can be observed where a current peak occurs. The transient space charge limited current was a hot topic in 1960s due to its importance to the rapid development in electronics and solid state devices. Theoretical work on the topic was pioneered by Many and Rakavy [1] in 1962. Based on single charge carrier injection, the transient current peak can be used to estimate the mobility of the charge carrier. This transient current peak was subsequently observed in polymeric materials at high fields [2-4]. A typical result is shown in Figure 1.

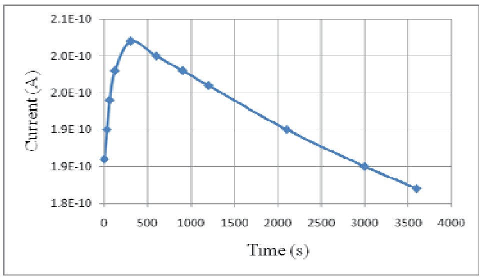


Figure 1 Transient space charge limited current in LDPE (E_{appl}=13.4 kV/mm) at 70°C [2].

B. Depolarisation Current Flowing in the Same Direction as Polarisation Currents

After the removal of the applied dc field, a current, termed as the depolarization current, normally flows in the opposite direction to the polarization current. However under high electric fields it has been observed [2-5] that the depolarization current drops very rapidly and passes through the zero point. After that the current flows in the same direction as the polarization current and decays to zero eventually as shown in Figure 2. So far no theory has been put forward except an over simplified model based on the bipolar charge injection [5].

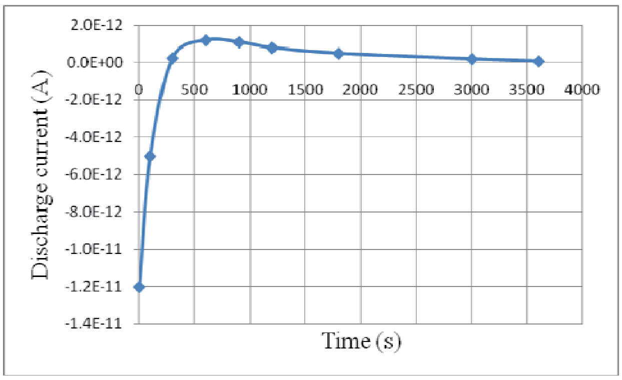


Figure 2 Anomalous discharge current in LDPE (E_{appl}= 26.7 kV/mm) at 70°C [2].

C. Space charge paket

Following the significant development in charge mapping techniques, space charge packet has been observed in many occasions in polymeric materials under high electric fields [6-8]. It can be loosely defined as a pulse of net charge that propagates across the material under the influence of electric field while maintaining its shape. In reality, it may broaden its shape during travelling as shown in Figure where a dc voltage of 7 kV was applied across 100 µm thick low density polyethylene at room temperature. Charge packet has been termed as an unexpected phenomenon and usually formed under high electric field and propagates through the material from one electrode to the other. In many cases, positive charge packet was reported although negative charge packet was also observed.

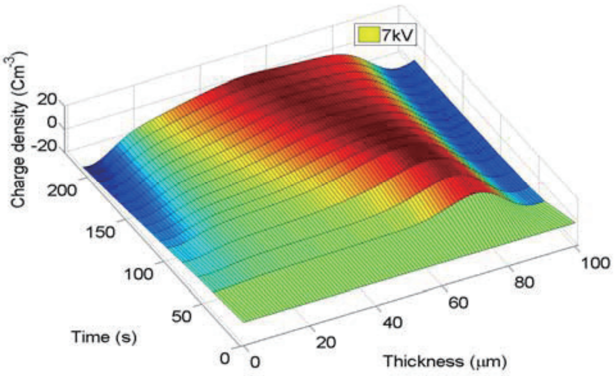


Figure 3 A charge packet travelling across LDPE film.

D. *Cross-over Surface Potential Decay*

Corona charging and surface potential decay were studied extensively in 1970's as it provides a useful tool to monitor charge movement in the insulating materials and characterize their properties. In 1967, surface potential cross-over phenomenon was firstly reported by Ieda et al [9], i.e. initially the surface potential of a sample charged to high-potential decays more rapidly than one charged to a lower potential. Figure 4 shows a typical example of the surface potential decay cross-over. Most of the theories addressed the time evolution of the surface potential in terms of surface conduction [10], charge injection [11–13], and polarization [14]. It is worthy to point out that the fast potential decay occurs only when the electric field across the sample exceeds a certain value. The existing theories and models were all based on the single charge injection and various unrealistic assumptions were made such as partial injection and time dependent injection.

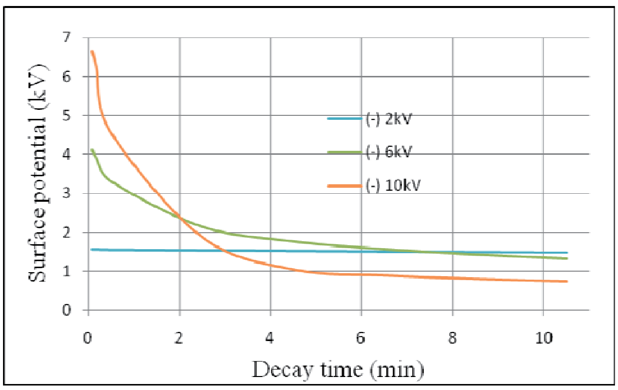


Figure 4 Surface potential decay of 50µm LDPE samples after being corona charged at different voltages.

E. *Cross-over in Space Charge Decay*

With the recent progress in space charge measurement techniques, it is possible to observe charge evolution within the bulk of the insulating material. After the volts on measurement, it is also possible to observe charge decay in the sample. Generally, the total charge in the sample decay monotonically with time. It has been recently observed that the charge decay becomes fast in the sample stressed at high electric fields than that stressed at lower stress as shown in Figure 5 [15].

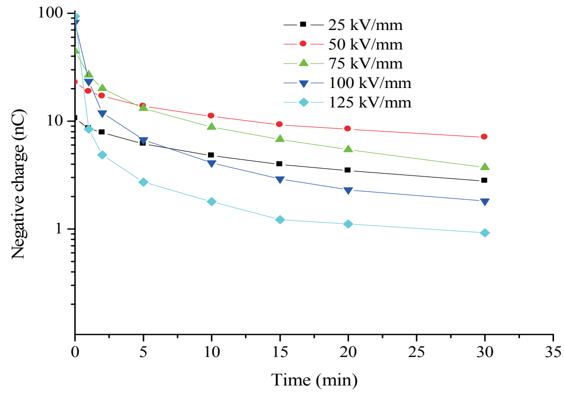
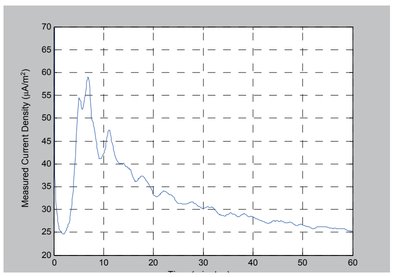


Figure 5 Charge decay after the removal of the applied electric fields (t_p=60 min) [15].

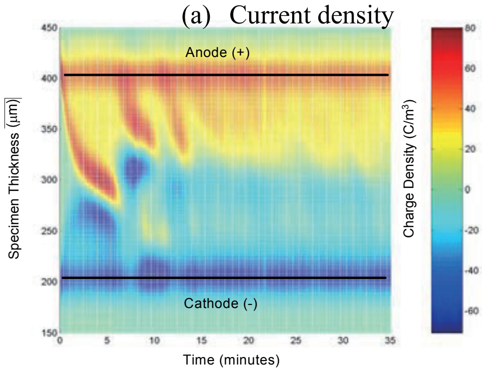
This phenomenon is very similar to that described in the above section. Space charge profiles associated with Figure 5 clearly show charge injection from both electrodes.

III. NEW EVIDENCES FO BIPOLAR CHARGE INJECTION

By using the newly developed space charge measurement technique it becomes possible to observe charge formation and dynamics in polymeric materials. New evidences of bipolar charge injection have been obtained, especially at high electric fields. Figure 6 illustrates transient current and space charge distribution measured simultaneously in cross-linked polyethylene sample [16].



(a) Current density



(b) Space charge density

Figure 6 Current density and space charge density colour contour graph for the first 35 minutes in fresh (E_{appl}=100 kV/mm).

Instead of a single peak there are multi-current peaks. From Figure 6 (b) it is clear that bipolar charge injection has taken place and charge recombination occurs in the bulk of the sample. This is often referred as charge packets. By comparing the current and space charge dynamics, it is evident that bipolar charge injection and recombination are responsible for the current peaks observed.

By using pulse excitation and transient space charge measurement it is possible to estimate charge carrier velocity associated with charge packet [17]. Figure 7 shows an observed hole velocity versus the applied dc electric field [18]. Similar trend has been proposed [19]

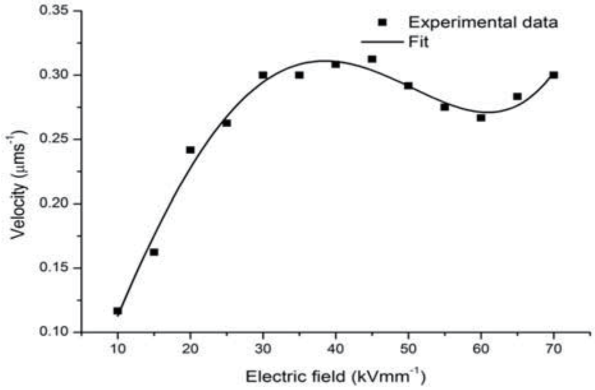
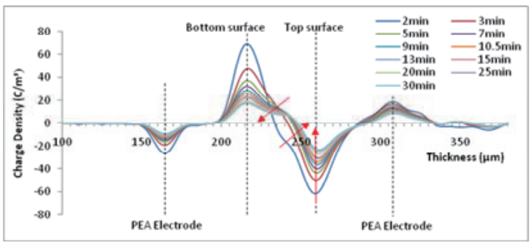
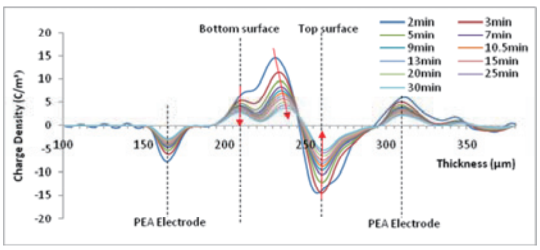


Figure 7 Dependence of hole velocity on the applied electric field.

Figure 8 shows some features of charge distribution in LDPE samples after being corona charged at 8 kV for different times [20 – 21]. It is clear that both positive and negative charges are present in the bulk of the sample. When the charging time is extended from 2 minutes to 10 minutes significant positive charge injection can be observed as shown in Figure 8 (b). Different decay rate is evident which can be attributed to dynamics of these bipolar charges (trapping, transport and recombination) in the material are responsible for the surface potential decay.



(a) t_c = 2 minutes



(b) t_c = 10 minutes

Figure 8 Space charge distribution in 50µm sample corona charged at 8 kV for (a) 2 minutes and (b) 10 minutes.

IV. NEW MODEL AND SIMULATION

To understand these observed anomalous phenomena, it is crucial to remember that almost in all the cases, bipolar charges are involved. By exploring the models in literature, it is noticed that the bipolar charge injection model proposed in [22] has a potential to simulate all these anomalous phenomena. In addition, the bipolar charge injection model has been used extensively to simulate charge transport, trapping and recombination under dc voltage. The simulation results for space charge dynamics in LDPE show a good match with experimental results [13].

A. *Bipolar Charge Injection Model*

The model [22] aims to effectively describe the bipolar transport and space charge phenomena in solid dielectrics under high dc stress. The bipolar transport is being described as a conduction process governed by an effective mobility. This feature distinguishes the model from the others. In effect, charge carriers are injected from the electrodes, electrons from the cathode and holes from the anode. Injection occurs based on the *Schottky* mechanism whereby overcoming a potential barrier W at the interfaces.

$$J_S = AT^2 \exp\left(-\frac{W - \sqrt{\frac{e^3 E}{4\pi\varepsilon_r\varepsilon_0}}}{kT}\right) \quad (1)$$

where A is a constant related to the material, T the temperature, k the Boltzmann constant, e the electron charge, E the electric field at the interface, ε_r the relative permittivity of the material and ε_0 the permittivity of vacuum.

After penetrating into the material, the carriers, under the influence of the applied field, will drift across the material characterized by an effective mobility. Throughout its motions, some carriers are trapped in the localized states i.e. deep trap centres and therefore, the total amount of charges moving across reduces. However, no extraction barrier is introduced in the model and on the other hand; they are prone to recombine with their opposite species (electrons with holes).

Charge transportation in solid dielectrics is essentially governed by a set of basic equations. They describe the behaviour of charge carriers in the system through a time and space dependent total flux *j(x,t)* and by neglecting diffusion [22]:

Transport equation:

$$j_C(x,t) = \mu n(x,t) E(x,t) \quad (2)$$

Continuity equation:

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

Poisson's equation:

$$\frac{\partial E(x,t)}{\partial x} = \frac{\rho(x,t)}{\varepsilon} \quad (4)$$

where µ is the mobility of carriers, n the density of mobile species, E the electric field, j the current density, x the spatial coordinate, t the time, s the source term, ε the dielectric permittivity and ρ the net charge density.

B. Simulation Results

Using the above model space charge dynamics in the bulk of the material under dc voltages can be calculated [23]. In addition, it is also possible to calculate the current density J and its relationship with time. Figure 9 illustrates initial simulation results of current density under various applied electric fields. It is clear that a current peak appears. Similar to the experimental results, the peak shifts towards the shorter time when the applied electric field increases.

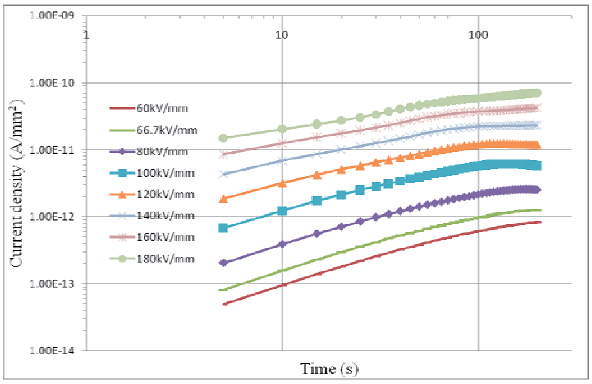


Figure 9 Transient space charge currents obtained from the bipolar charge model.

Once the applied electric field is removed, the discharge current can also be calculated. The discharge current flowing in the opposite direction decays monotonically. However, when the applied electric field increases, the discharge current decreases very rapidly and cross the zero. It flows in the same direction as the charging current before decaying to the zero as shown in Figure 10.

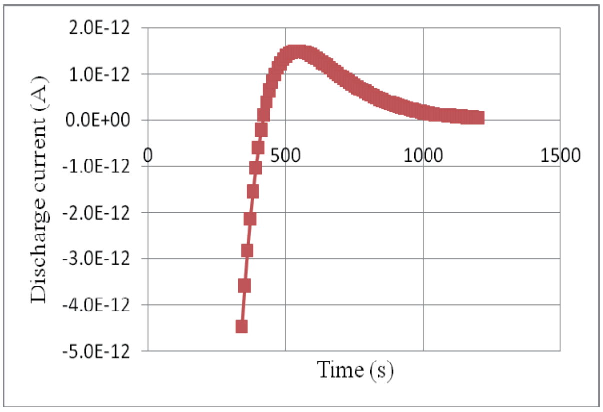


Figure 10 Discharge current obtained from the bipolar charge injection.

Based on the velocity result versus the applied field (Figure 7), the formation and movement of charge packet can also be simulated using the bipolar charge model described above. A typical result is shown in Figure 11. It has to be stressed that the characteristics of velocity versus the field shown in Figure 7 is necessary to produce charge packet.

The related space charge decay is shown in Figure 12. It has been found that for the same length of voltage application time, the injected charges travel further with increasing applied electric field. The amount of the injected charges also increases rapidly with the applied electric field.

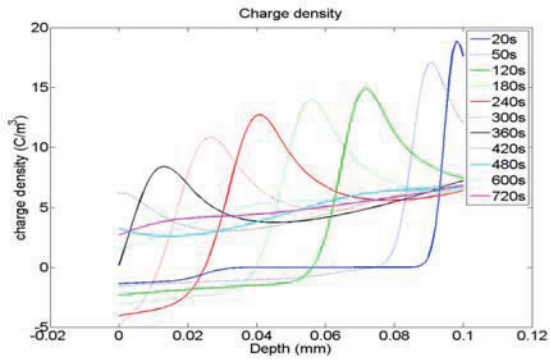


Figure 11 Simulated charge packet travelling across LDPE at 5 kV.

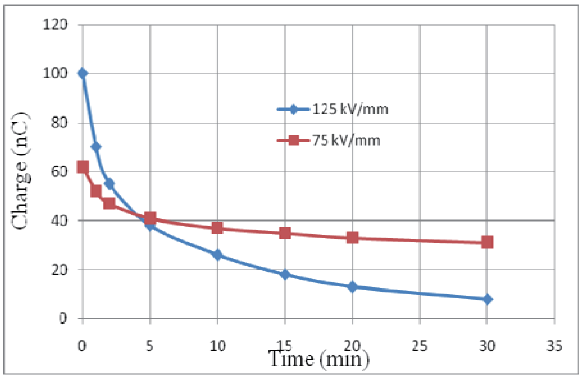


Figure 12 Space charge decay after the removal of the electric fields.

Considering the new evidence of bipolar charge injection during the corona charging and decay processes (Figure 8), the bipolar charge injection model can also be applied to explain the surface potential decay with some modifications. This deviates significantly away from the previous surface potential decay models. Additionally, a tunneling process has been proposed to account for charge injection from the top surface while the conventional Schottky injection is used for the bottom surface.

The charge transport in the bulk of the sample is determined by the electric field. The electric field in the sample at any time consists of contributions from three components, i.e. space charge ρ(x, t), surface charge density at the top $\sigma_1(t)$ and the induced surface charge density at the bottom electrode $\sigma_2(t)$. Let us assume the field components are represented by $E_\rho(t)$, $E_{\sigma 1}(t)$ and $E_{\sigma 2}(t)$ respectively. The surface potential across the sample can be calculated by integrating the total electric field:

$$V_0(t) = \int_0^d [E_\rho(t) + E_{\sigma_1}(t) + E_{\sigma_2}(t)]dx \qquad (5)$$

In addition, the total charge in the system at any time must in balance, i.e.

$$\sigma_1(t)S + \sigma_2(t)S + \int_0^d \rho(x,t)S\,dx = 0 \qquad (6)$$

where S is the surface area where charges are present.

Clearly, $\sigma_1(t)$, $\sigma_2(t)$ and ρ(x, t) are not independent quantities. Based on the modified model, it is possible to calculate ρ(x,

t) during the corona charging until a predefined charging time $t=t_0$. The quantities $V_0(t_0)$ and $\rho(x, t_0)$ are the initial condition for surface potential decay. This allows one to determine $\sigma_1(t_0)$ and $\sigma_2(t_0)$ using the above two equations.

Once these initial four quantities are determined, one can calculate new space charge distribution $\rho(x, t_0+\Delta t)$ based on the proposed model and the two surface density $\sigma_1(t_0+\Delta t)$ and $\sigma_2(t_0+\Delta t)$ using the FN tunneling and Schottky injection respectively. In addition, as the system is an open circuit, the injected charge must satisfy the following condition:

Maxwell's equation for the total current:

$$J(t) = j_C(x,t) + \varepsilon \frac{\partial E(x,t)}{\partial t} = 0 \qquad (7)$$

The surface potential at time $t=t_0+\Delta t$ can finally be computed using equation (5). Repeating the process the relationship between the surface potential and time can be calculated. Our initial simulation work shows it is possible to achieve surface potential cross-over providing the initial surface potential and space charge distribution are set right as shown in Figure 13.

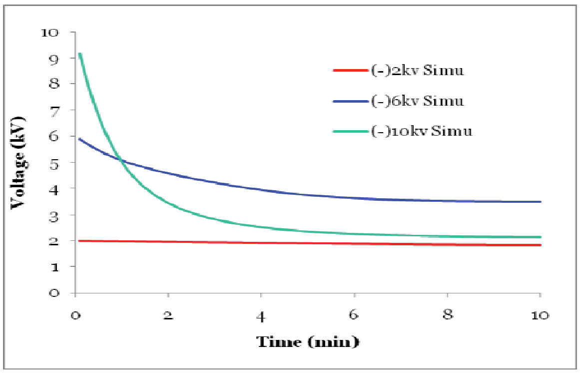


Figure 13 Initial simulation showing cross-over of surface potential decay.

From the above results it can be seen that the bipolar charge injection model shows a good qualitative agreement with all the anomalous phenomena observed at high dc fields. This suggests that they come from the same origin in terms of physical mechanism.

V. Conclusions

New experimental evidences obtained using the space charge mapping techniques clearly indicate that bipolar charge injection, trapping, recombination and transport are responsible for the observed anomalous phenomena at high electric fields. Simulations based on the bipolar charge injection model can reveal all features observed in anomalous phenomena. This suggests that all these observed phenomena have the same origin in terms of physical mechanisms. We are currently working on the details of the model such as parameters selection so it can be applied to all the simulations. The changes in these parameters may be related to material degradation under high electric fields.

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