

Interfaces roughness effects on charge generation and storage

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ABSTRACT

In this paper, the effects of the roughness of interfaces on the generation and storage of charge between two dielectrics has been investigated. A sandwich structure consisting of two dielectric films of the same nature (crosslink polyethylene XLP1 and XLPE2) was subjected to high DC electric stress for extended periods of time and space charge measurements were taken using the pulsed electroacoustic (PEA) technique. Aluminum and carbon black-loaded polyethylene electrodes were used to investigate the charging behaviour of the electrode/dielectric and dielectric/dielectric interfaces. The time dependence of the space charge distribution was subsequently recorded at room temperature under field (polarization) and short-circuits conditions (depolarization). The experimental results demonstrated that a charge-injected process took place in all cases. However, it was also shown that the sign and the amount of interfacial charge depended drastically on the nature of the interface, the conductivity of the dielectric and the polarity of the electrodes.

Index Terms: Space charge; dielectric interface; smooth interface; roughness of interface; pulsed electro-acoustic technique; effect of electrode materials.

1 INTRODUCTION

THERMOPLASTIC materials are being used more and more in electrical engineering as high voltage insulation. They are highly insulating media and exhibit excellent physical and chemical properties, with the possibility of being processed to comply with complex system geometry. Among them, polyethylene is the most well-known and is widely used as insulation in the power cable industry. Although its formula appears to be very simple, polyethylene is a generic term which is used to refer to insulating materials with very different characteristics, including different base resins (resin type, chemically modified or not, cross-linked or not) and formulations (antioxidants, additives, etc.) [1]. Severe constraints still limit its use in HVDC applications where electrical charges can be injected at the point of electrode/insulation contact or generated within the bulk by the dissociation of species and other electro-chemical reactions. These charges disturb the field distribution and could lead to critical field enhancement, especially when the polarity of the line needs to be inverted [2]. Another important point is the need for junctions and terminations in cable systems. They have been identified as weak points with a probability of failure which is much higher than that of the cable itself due to the presence of dielectric/dielectric and electrode/dielectric

interfaces [3,4].

Regardless of the nature of interfaces, they play a fundamental role in the dynamics of space charge because they have specific electrical properties due to the physical and chemical disorders inherent in their natures. In the case of metal/dielectric interfaces, it is generally considered that charge carriers of both signs can be injected and/or extracted from the point of contact, depending on its nature [5,6]. However, a correct description of the injection of charge from a metal into insulation using the classical laws of injection (Schottky's emissions, for example) has not yet been provided [5,7].

Our objective in this study is to investigate the time-dependent spatial distribution of space charge at metal/dielectric and dielectric/dielectric interfaces using the pulsed electroacoustic (PEA) method. In order to achieve this goal, two main factors of influence have been investigated:

- The behaviour of space charge under positive poling, when the dielectric/dielectric interfaces are rough/rough and smooth/smooth;
- The behaviour of space charge under negative poling, when the dielectric/dielectric interfaces are rough/rough and smooth/smooth.

2 THE MECHANISMS OF INTERFACES

An interface, regardless of its type (metal/dielectric or dielectric/dielectric), plays fundamental roles in the dynamics of space charge. In the case of metal/dielectric interfaces, it is generally considered that the charges can be extracted and injected depending on the metal electrode and the nature of the interfaces [9,10]. In the case of dielectric/dielectric interfaces, theories of electromagnetism [11] predict that charge density is governed by the following equation (Maxwell-Wagner-Sillars):

$$\sigma = (\varepsilon_2 - \varepsilon_1 \frac{\gamma_2}{\gamma_1}) E_2 = (\varepsilon_2 \frac{\gamma_1}{\gamma_2} - \varepsilon_1) E_1$$

where σ , ε and γ represent the conductivities, dielectric constants and electric fields respectively in the media (1) and (2). In our study, the two materials are identical, and therefore the charge density at the interface should be zero (without disturbing the distribution of charge over the internal electric field). However, the interfaces we use are not perfect as they are formed by the contact between two films. This suggests that traps will be introduced, especially because of the weak coupling between films (no chemical bonds). It is these effects that we wish to highlight in the first instance.

3 MATERIALS AND EXPERIMENTAL METHODS

3.1 SPECIMEN CHARACTERISTICS

Peelings of cross-linked polyethylene of the series described in [8] were used for this study. They were peeled from a medium voltage (63/90 kV) cable with 14 mm thick insulation using a lathe equipped with a specially designed knife for optimum surface smoothness. The peelings had a nominal width of 8 mm and a thickness of 150 μm . A thermal treatment was carried out at a temperature of 50 $^{\circ}\text{C}$ in order to get rid of the by-products of the cross-linking reactions. Investigations were made of the surfaces of the peelings, as they might affect the measurements. As a result of the cutting procedure, the surfaces were not as smooth as they would have been if a compression-moulded specimen had been used. Measurements using an atomic force microscope (AFM) indicated that the two surfaces of the peelings were rough to varying extents. The typical and maximum peak-to-trough heights were measured and the RMS roughness estimated as is indicated in Table 1. It was verified that the difference in surface roughness between the two dielectrics affected charge storage at field values of <40 kV/mm. A full characterisation of the physical, chemical and electrical characteristics of the samples can be found in [8].

Table 1: Atomic force microscopy measurements of the roughness of the peeling surfaces

PEELING SURFACE	TYPICAL PEAK TO TROUGH HEIGHT (μM)	MAXIMUM PEAK TO TROUGH HEIGHT (μM)	RMS ROUGHNESS (NM)
SMOOTHER	~ 0.3	~ 1	~ 150
Matt	~ 1	~ 2	~ 350

3.2 EXPERIMENTAL SET-UP

In this study, we used a conventional PEA set-up, where combinations of flat specimens are sandwiched between a thick aluminum electrode in contact with a piezoelectric sensor and a semi-conductive (SC) electrode (carbon black- load polyethylene film) to which is applied the voltage pulse of the PEA and the DC voltage for poling the specimen being tested. Measurements were performed at room temperature. The sensitivity and the spatial resolution of the measurements were of the order of 0.1 C/m^3 and $10 \mu\text{m}$ respectively. When performing an experiment on a sandwich structure formed by the association between two dielectric films, particular attention was paid to the transmission of acoustic waves at the interface by ensuring close contact between the two layers in order to avoid acoustic reflection.

3.3 MEASUREMENT PROTOCOL

The influence of the nature of the dielectric/dielectric interface on the build-up of charge was investigated using samples with symmetrical electrode systems.

The Al/XLPE/SC structure corresponds to the usual PEA

measurement configuration. A 31 kV/mm field was applied to the samples for 60 min. PEA measurements were performed during polarization and under short-circuit conditions where the charge accumulation would be more clearly evident, taking into account the small space charge density (of the order of 1 C.m^{-3}) and the high value of the capacitive charge during the application of voltage. At this field level, a charge injection is known to dominate the charge accumulation in XLPE when by-products of the cross-linking reaction have been eliminated (hetero charge is usually observed in XLPE in the presence of by-products, compared to homo charge after thermal treatment; see [10] for an example). Moreover, space charge accumulation within a sample always results from a three-step process, which consists of charge generation, transport and extraction. Therefore, we chose a relatively short poling time of 60 min in order to reduce charge transport. Under such conditions, the accumulated charge is thought to provide us with a picture of the charge injection processes.

4 RESULTS AND DISCUSSION

4.1 Measurement of a sandwich structure under positive poling

Space charge profiles in a field of ± 33 kV/mm during polarization and under short-circuit conditions are shown in Figure 1 for two kinds of interface: smooth and rough.

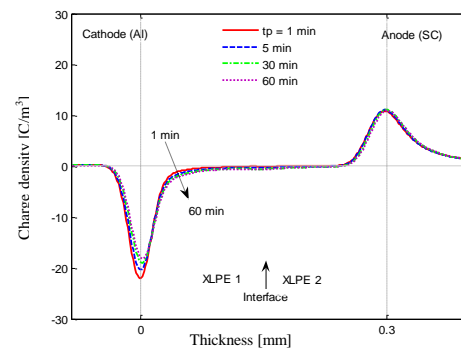
Smooth-smooth interface

Al cathode/rough interface – smooth surface – smooth interface – rough interface/SC anode.

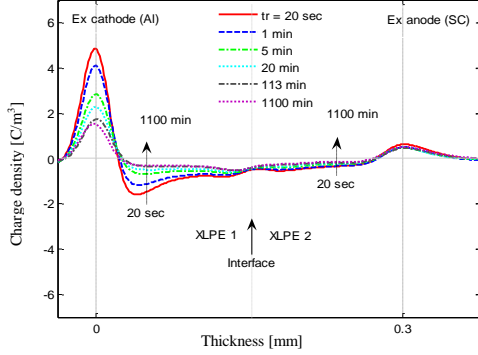
The polarization and, more clearly, depolarization profiles (Figure 1b) indicate that space charge built up in the two layers of XLPE. Based on the amount of charge accumulated in the sample, we can judge that an Al cathode can inject a large amount of electrons.

In contrast, there is no evidence of a positive injection at the SC/XLPE interface. We noted that the SC anode was not strongly injecting. It is believed that the injected electrons are thrown towards the opposite electrode at high speed and meet the injected holes near the anode, where they are recombined with the holes.

At the dielectric interface XLPE1/XLPE2, the PEA system revealed a weak negative charge. Space charge decayed faster in the XLPE1 layer next to the Al electrode (ex-cathode) than in the XLPE2 layer, and the amount of space charge in the first XLPE1 layer was much greater than in the XLPE2 layer.



(a) Charge profile during polarization, where t_p is the time of polarization



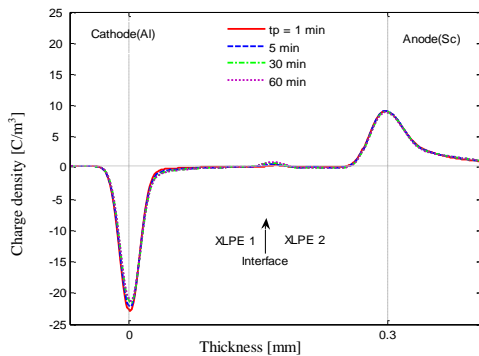
(b) Charge profile during depolarization at $t=60$ min, where t_r is the time after the sample has short-circuited

Figure 1. Space charge distribution within a sandwich of XLPE1 and XLPE2 with a negative charge at the dielectric/dielectric interface subjected to a field of -33 kV/mm at $T=25^\circ\text{C}$

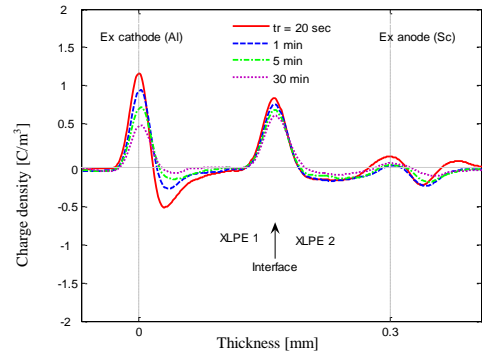
Rough-rough interface

In the case of a rough-rough interface, bipolar injection was clearly revealed for both polarization and depolarization. The behavior of the charges in the bulk of the two layers is best illustrated in the phase of depolarization.

This profile confirm the presence of negative charge which has accumulated in the layer next to the Ex cathode, as well as followed by a large amount of positive charge close to the dielectric interface. Moreover, it can be seen that a small amount of negative charge is present in the layer next to the Ex anode. The presence of positive charge at the dielectric interface may be interpreted according to two assumptions: first, during positive poling, the rough interface between the two polyethylene layers is as a preferential site for charge trapping and behaves as a barrier, preventing the transportation of positive charge. Second, the holes are trapped at the dielectric interface XLPE1/XLPE2 because the XLPE2 layer which is in contact with the anode is more conductive than the XLPE1 layer, meaning that the holes spreading from the anode become blocked at the dielectric interface.



(a) Charge profile during polarization, where t_p is the time of polarization



(b) Charge profile during depolarization at $t=60$ min, where t_r is the time after the sample has short short-circuited

Figure 2. Space charge distribution within a sandwich of XLPE1 and XLPE2 with a negative charge at the dielectric/dielectric interface subjected to a field of -33 kV/mm at $T=25^\circ\text{C}$

4.2 Measurement of a sandwich structure during negative poling

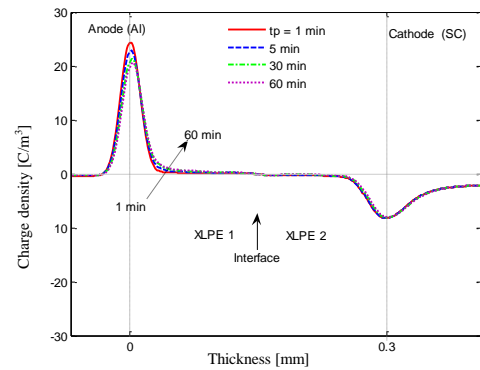
When the polarity of the electrodes is reversed, i.e. Al becomes the anode and SC becomes the cathode, the charge dynamics also become different, as shown in Figure.2.3

Smooth-smooth interface

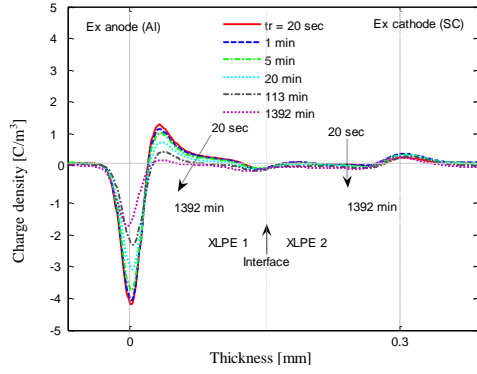
The amount of positive charge increases slightly as the duration of the voltage application increases. The positive charge injection process can clearly be seen when the applied voltage is removed (Figure 3b).

There was a small amount of positive charge present in the bulk, with the maximum amount of charge present adjacent to the anode. However, there was a very weak amount of negative charge present at the dielectric interface which is somewhat surprising, considering that the SC cathode is strongly injecting the electrons. It is believed that positive charge carriers may be able to cross the interface, but that they will be recombined with the large amount of electrons spreading from the SC electrode.

The physical smooth-smooth interface is not seen as preferential for charge trapping.



(a) Charge profile during polarization, where t_p is the time of polarization

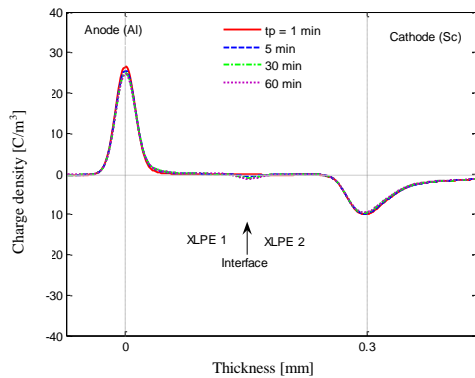


(b) Charge profile during depolarization at $t = 60$ min, where t_r is the time after the sample has short-circuited.

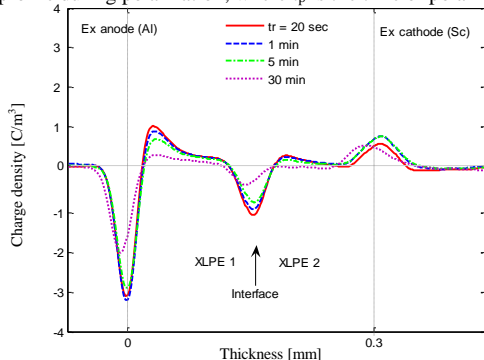
Figure 3. Space charge distribution within a sandwich of XLPE1 and XLPE2 with a negative charge at the dielectric/dielectric interface subjected to a field of -33 kV/mm at $T=25^\circ\text{C}$

Rough-rough interface

In the case of negative poling voltage, Figure 4a shows that a positive charge appears in the XLPE1 layer next to the anode. Figure 4a also shows the dynamics of the charge at the dielectric interface XLPE1/XLPE2. The growth of this interfacial charge is faster than that of the charge in the XLPE1 layer near to the Al anode. This means that not all of the charges that move towards the electrodes and towards the dielectric interface can be transferred. In other words, the dielectric/dielectric interface has properties that allow it to block the electrons, but not the holes. It is believed that these negative charges are a part of those injected from the cathode. The amount of both positive and negative charge increases slightly as the duration of the voltage application increases.



(a) Charge profile during polarization, where t_p is the time of polarization



(b) Charge profile during depolarization at $t = 60$ min, where t_r is the time after the sample has short-circuited.

Figure 4. Space charge distribution within a sandwich of XLPE1 and XLPE2 with a negative charge at the dielectric/dielectric interface subjected to a field of -33 kV/mm at $T=25^\circ\text{C}$

Charge relaxation followed when the sample was short-circuited after 60 min of polarization. Figure 4b reveals a large amount of positive charge next to the Al electrode and a small amount of positive charge in the vicinity of the SC electrode. These positive charges are due to a charge injection from the Al anode that was hidden under polarization by the surface charges. At the dielectric interface XLPE1/XLPE2, the PEA detected a large amount of negative charge. The rate of decay of the space charge within the sample was much faster.

With a negative poling voltage, the rough-rough interface between the two polyethylene layers acted as a trap for the electrons but not for the holes, and behaved as a barrier, preventing charge transport.

In all of the tests, when the physical interface was a smooth-smooth interface, PEA revealed a very weak negative charge, and when the physical interface was a rough-rough interface the PEA method detected a large amount of negative space charge at the dielectric interface. The magnitude of the charge at the interface increased as the duration of the voltage application increased, and the polarity of the space charge at the dielectric interface XLPE1/XLPE2 was the same as that of the applied voltage.

IV. DISCUSSION

One can see a remarkable difference in terms of space charge between a smooth/smooth interface and a rough/rough interface, meaning that space charge is strongly affected by the roughness of a dielectric interface.

These preliminary results illustrate the complexity of the problem. They show, moreover, the importance of the preparation of surfaces (polishing and cleaning) this is because the correct preparations can limit the formation of charge at the dielectric interface.

CONCLUSION

In this article, we studied the effects of an electrode/polymer interface and a polymer/polymer interface on the phenomenon of space charge in XLPE. Based on these results, we can draw the following conclusions:

The charges which accumulate in the dielectric interface depend on the nature of the electrodes and the state of the interface (smooth or rough);

The charge at the dielectric interface should have the same polarity as the polarity of the electrode which is in contact with the layer with the highest conductivity;

A smooth/smooth physical interface “between two dielectrics” does not seem to present a barrier to charge transportation.

We conclude that the accumulation of space charge at a dielectric interface can be eliminated if we use only a smooth/smooth interface.

This finding will be important in the development of DC XLPE power cables, especially for the joints and terminations in cable systems.

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