Space Charge Behaviour at LDPE Interface under AC Electric Stress

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Abstract. This paper reports on measurements of space charge characteristics in single and two-layer of low-density polyethylene (LDPE) films subjected to an applied voltage with a range of frequencies from dc to 50 Hz. Space charge was measured using the pulsed electroacoustic (PEA) technique.

To measure charge distributions under ac electric fields at different angles, the point-on-wave method has been used. To obtain a good signal to noise ratio under ac conditions, the measured signals were averaged between 1000 and 2000 times.

Experimental results demonstrated that frequency is a significant factor that affects bulk charge formation/distribution. In addition, interfacial charge between polymer and polymer in the two-layer arrangement was influenced by the type of electrode material.

Introduction

In practical insulation system, interfaces have become an interesting research area due to their effect on electrical performance of the whole system. The interfaces in high electrically stressed materials can cause accumulation of space charge, which can lead to unwanted electric field modification. The failure probability at the interface such as cable joints is much higher than cable itself. It is generally recognized that space charge accumulation at the interface plays an important role. Some researches have been done about the accumulated space charge at the interface [1-4] including electrode/polymer, polymer/polymer and silicon-oil/polymer interfaces.

So far, all the work on interfaces has been studied under dc conditions. The investigation of space charge formation at interfaces under ac condition remains a relatively unexplored field. Space charge characteristics in dielectric under ac electric stress is difficult to understand because there are many factors which can affect the results such as varying amplitude of sinusoidal ac voltage, polarity reversal, charge injection/extraction, material degradation, etc. This paper reports on the result of space charge behaviour in LDPE sample under ac electric stress, with an emphasis on the layer interfacial space charge profile under different frequencies.

Experimental details

PEA system. PEA is by far the most widely used technique in the field of space charge measurements. This technique utilizes the interaction between high voltage pulses and charge layers accumulated in the insulating material to produce acoustic pressure waves, which traverse across the material. Detailed reviews on the principle of PEA can be found in [5]. To summarize, acoustic pressure waves are produced when an electrical pulse, applied externally, interacts with charge layers at the electrodes and/or in the material. The acoustic waves, which are proportional to the charge at the layers, are converted into an electrical signal by a piezo-electric transducer, amplified and captured with a digital oscilloscope.

Ac space charge measurement is different from dc space charge measurement as the applied voltage varies with time. Therefore, it is important to correlate space charge measured with the applied ac voltage. This is best achieved with the "point-on-wave" method. The principle of the 'point-on-wave' method [6] is shown in Figure 1. The measurement on a different phase of the ac waveform will yield an output of corresponding magnitude and polarity for the induced charge. The space charge profile is the average of many measurements. To obtain a good signal to noise ratio under ac conditions, the measured signal in this study were averaged between 1000 and 2000 times.

Figure 1 shows the space charge profiles of two-layer LDPE sample at various phases of sine ac waveform, 8 points (every 45°). The significant two phases that may show the presence of charge are 90° and 270° at which the external voltage is the highest. This demonstrates the feasibility of the 'point-on-wave' method of the PEA system.

The spatial resolution of the system is determined by some factors such as pulse width, acoustic speed in the sample, and the sensor thickness. In our system, an electric pulse of 2ns duration and 1kV amplitude is applied to the sample to generate the acoustic signal. The sensor used was a 4µm thick PVDF material. This gives a spatial resolution of about ~4µm, which is considered adequate in this study. Detailed description of the PEA method under ac electric stress can be found in [5, 7].

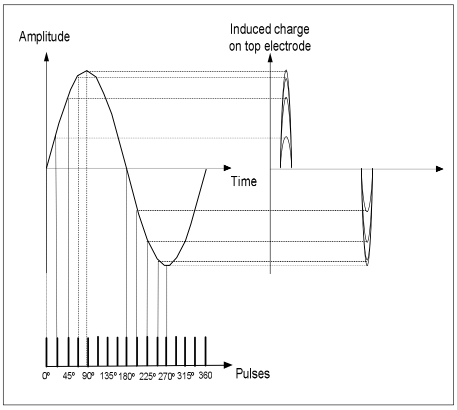

Figure 1: Point-on-wave measurement

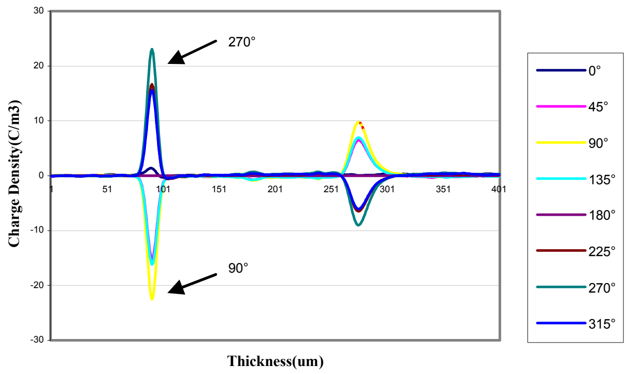

Figure 2: Space charge profile of two-layer LDPE sample

Sample details. Sample used in the present experiment is additive-free low density polyethylene (LDPE) film. LDPE was chosen because of not only its wide application in cable insulation but also its simple chemical structure. Compared to other polymers, additive-free LDPE has few impurities and additives, which could act as ionization center under high electric stress or trapping sites.

The thickness of sample is ~200µm thick (single layer sample is ~180µm thick; two-layer sample consists of two ~100µm thick films).The dispersion influence of material is not considered in this study because it is not significant in thin films. Space charge studies on thick films can be found in [8].

Two materials, aluminum (Al) and Semincon (Sc) were used as electrodes for single and two-layer LDPE. In the case of semicon electrode material, ~100µm thick film was made from semicon pellet by a hot pressing process. The semicon pellet was made of cable grade polyethylene loaded with carbon black to increase conductivity (Borealis LOE592).

A sample structure of interface is shown in Figure 3. Here the two types of interface are named as layer interface and electrode interface.

Experimental protocols. In this experiment, all samples were electrically aged for a duration of 2h. Space charge distributions were measured at 15mins intervals during the ageing period with the voltage applied. Details of experimental protocols are shown in Table 1.

The 'point-on-wave' approach is not necessary for a dc space charge since the applied voltage does not vary with time. In the case of ac space charge, however, equally spaced measurements on a complete sinusoidal wave were taken. After 2h of ageing, space charge distributions under short circuit condition were measured.

Calibration is an important process in the quantitative analysis of space charge in solid dielectrics [9]. Normally, the calibration is carried out at a low applied stress assuming that there is no charge present in the bulk.

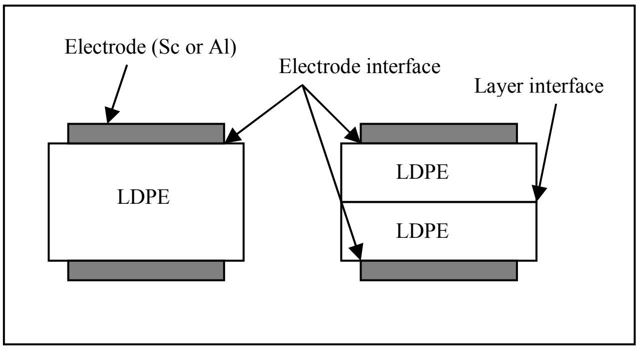

Figure 3: Schematic diagram of sample structure

Sample	layer	Thickness	Stress level	electrode	frequency
A	1	180µm	19.4kVmm^{-1}	Sc(+) Al (-)	DC
B	1	180µm	19.4kVmm^{-1}	Sc(-) Al (+)	DC
C	2	100µm	17.5kVmm^{-1}	Sc(+) Al (-)	DC
D	2	100µm	17.5kVmm^{-1}	Sc(-) Al (+)	DC
E	2	100µm	25kV$_{pk}$mm^{-1}	Sc and Al	1Hz Sine
F	2	100µm	25kV$_{pk}$mm^{-1}	Sc and Al	10Hz Sine
G	2	100µm	25kV$_{pk}$mm^{-1}	Sc and Al	50Hz Sine

Table 1. Experimental protocols

Results and discussion

Under dc electric stress. Investigations on dc space charge distribution were done to understand ac space charge dynamics at a similar voltage level. The external voltage applied to the sample was 3.5kV, which is equal to the ac rms value applied to the sample in following section. Space charge measurement was taken at various time during the period of both 'volt-on' and 'volt-off' (short circuit) conditions.

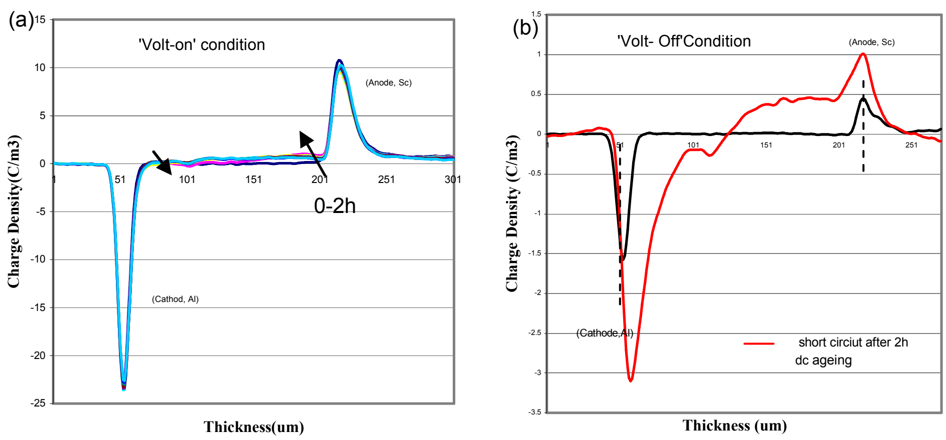

Figure 3: Space charge profiles of sample A

Figure 3(a) shows the 'volt-on' space charge profile during 2h ageing. The homocharge can be seen in the vicinity of both electrode interfaces after 15mins of the testing. There is positive charge accumulated in the bulk of sample as the stressing time becomes longer. It looks like the positive charge from the anode (semicon electrode) can be easily injected into the LDPE sample than the negative charge from the cathode (Aluminium electrode).

The 'volt-off' space charge profiles in Figure 3(b) have unquestionably shown that the space charge occurred in the bulk of the LDPE sample. The dominant positive charges can be seen clearly across the bulk of the LDPE sample.

Figure 4 gives the space charge profiles of sample B which was measured under the reverse polarity. Ageing positive charge is dominant in the sample under 'volt-on'condition. However, the presence of negative charge can be seen clearly after the removal of the applied voltage.

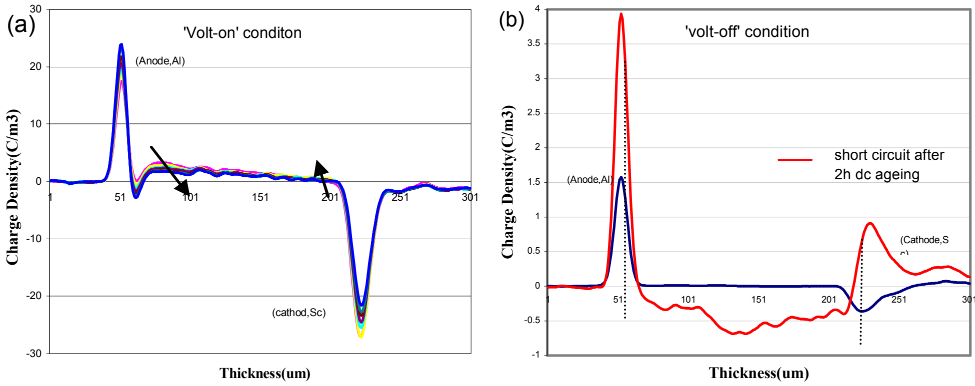

Figure 4: Space charge profiles of sample B

Figure 5 and Figure 6 illustrate the space charge formation for the two-layer structure. In Figure 5(a) 3.5kV applied voltage was applied to the sample, in addition to the increase in amount of negative charge at the layer interface, there is a clear indication of positive charge accumulation in the layer next to the anode.

The remaining charge after the removal of the applied voltage is shown in Figure 5(b) measured under short circuit condition. The distribution differs from the results of 'volt-on' in the two-layer and from 'volt-off' in the single layer. It can be seen clearly that negative charges dominate with an extra peak at the layer interface.

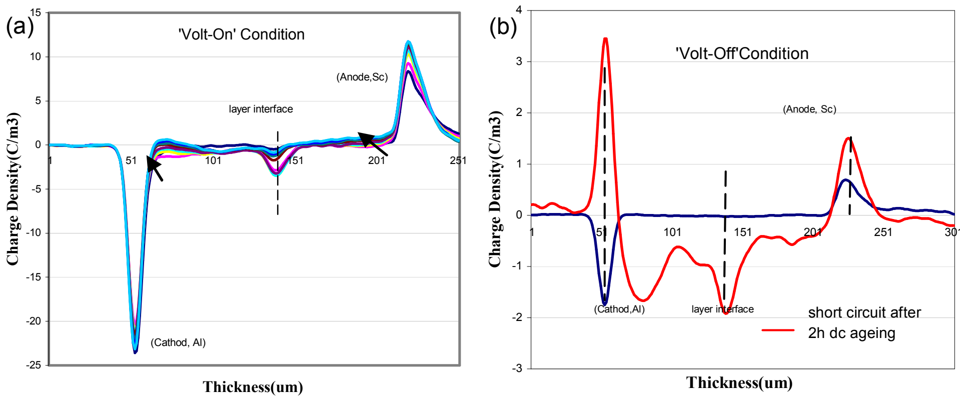

Figure 5: Space charge profiles of sample C

Figure 6 shows the profiles of sample D. Compared with sample C, the polarity of the applied voltage was reversed. In this case, charge at the layer interface is positive, and homocharge can be seen in the vicinity both electrodes. The charge distribution after the removal of the applied voltage is similar to Figure 5(b) in sample C except small amount of positive charge in the layer next to the anode.

Generally, the 'volt-on' space charge measurements from both single and two-layer samples show that positive charges are dominant. However negative charges are the main features after the removal of the applied voltage. This may be attributed to the fact that the use of semicon (Sc) film and silicone oil at the top and bottom electrodes have helped the charge injection into the LDPE sample [3, 10]. The quick disappearance of the positive charge after the removal of the applied voltage may indicate a high mobility of positive charge carries. The layer interface acts as a deep trap for negative charges.

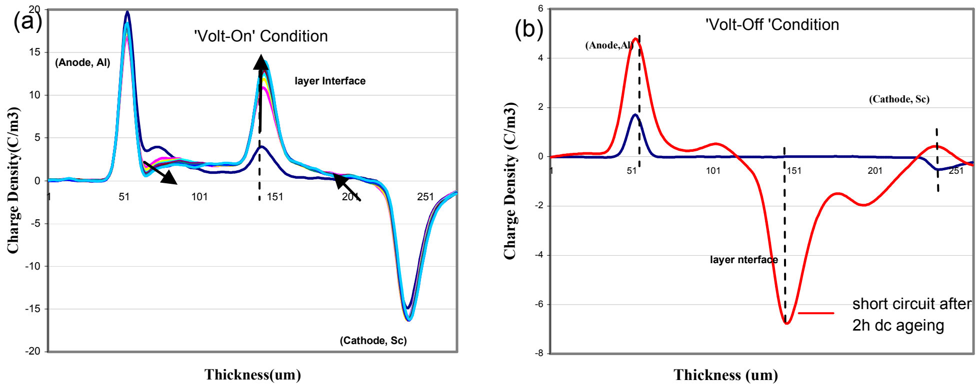

Figure 6: Space charge profiles of sample D

Under ac electric stress. In this part of experiments, the threshold voltage for space charge formation in thin LDPE film was measured by changing the amplitude of applied voltage and stressing time. The ac voltage level (peak-peak) nearly 5kV, 8kV, 10kV and the stressing time of 1h and 2h were tested several times. It has been found that the space charge has only occurred in the set of experiment when the ac voltage level was set to 10kV (peak-peak) and stressing time was 2h.

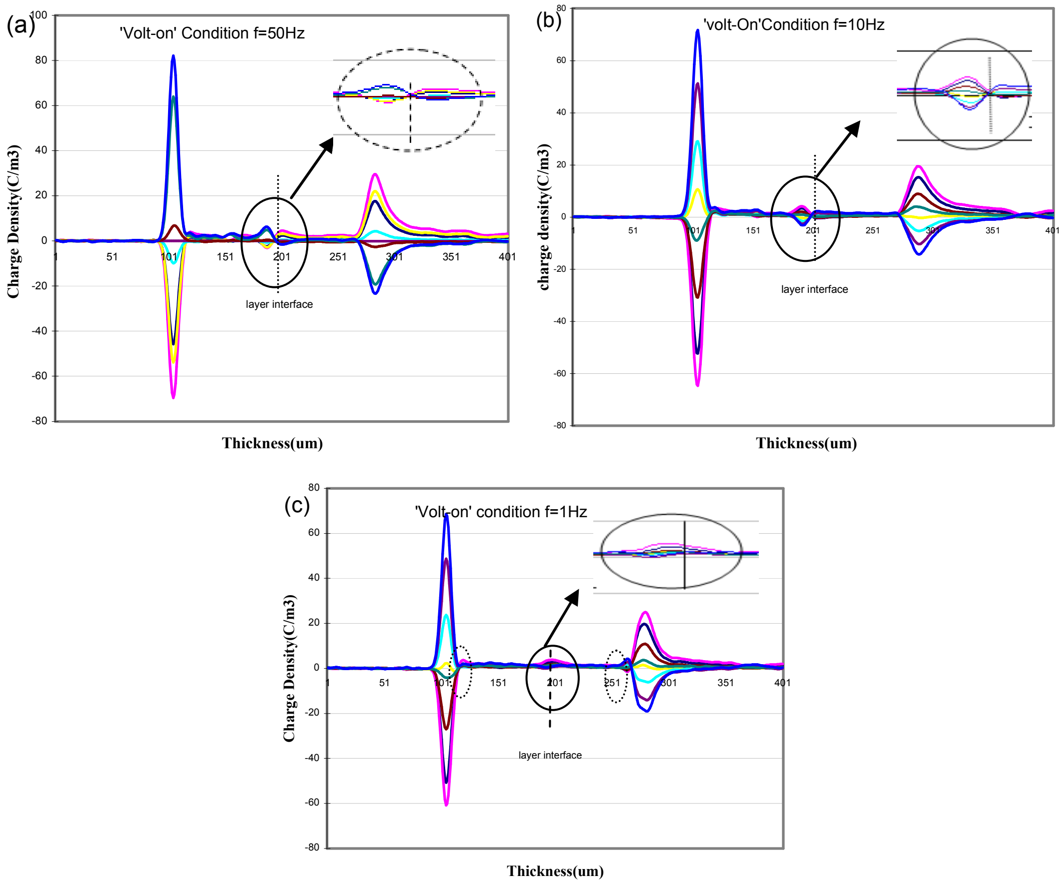

Figure 7: 'volt-on' charge profiles of ac sample E, F and G

Figure 8 shows the space charge phenomena occurred across two-layer LDPE samples under different frequencies after 2h electric stressing. The results in Figure 7(a) have clearly indicated the mixture of accumulated positive and negative charges in the sample. When referred to enlargement results at the layer interface in Figure 7(a) (b) (c), it could be found that there are more charges at the layer interface than in the bulk of sample. It is also clear that charge distributions at the samples E, F and G layer interfaces are different.

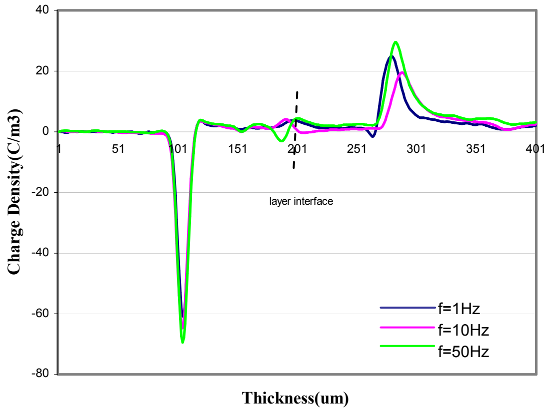

Figure 8. Space charge profile of ac-sample on the phase of 90°

Both positive and negative charges have been observed clearly adjacent to the layer interface in Figure 7(a) and (b) which are under 50Hz and 10Hz. A big difference occurred less than 1Hz in Figure 7(c), only positive charges appeared at the sample layer interface. These three graphs are under same experiment protocols so the pink line in Figure 7 can be considered as a reference line to assist in observing the behaviours of injection charge. Charge polarity that the pink line represents is the same polarity as the semicon electrode. It seems that charges just arrive at the layer interface and fail to pass through the interface at 50Hz in Figure 7(a). At 10Hz charges seem to have traversed the layer interface as shown in Figure 7(b). However, they monopolize the layer interface at 1Hz. The same behaviour can be seen in Figure 8, and the space charge profiles of ac samples E, F and G correspond to $25kV_{pk}$/mm ac electric stress at phase 90°.

Charge distributions for samples E, F and G under ‘volt-off’ condition have been taken before and after 2h stressing as shown in Figure 9, there was a shape difference between the charge distribution in those two situations. Initial results show no bulk charge but the induced charge on the electrodes due to the pulse voltage.

After 2h ac stressing, space charge distributions after the removal of the applied voltage show difference, depending on ac frequency. Similar to the dc results, negative charges are dominant. At 10Hz and 50Hz, negative charge occurs mainly at the layer interface with the presence of small amount of positive charge adjacent to the electrodes. At 1Hz, negative charge presents across bulk of the sample. When frequency further decreases, the amount of negative charge seems to increase slightly.

In the ac electrical stress study, it is also believed that semicon electrode can easily inject charge into the sample and pass through the layer.

Frequency effect on space charge formation has been investigated before[7, 10, 11]. In the present study, it has been found that frequency effects charge distribution.

At lower frequency injected charges have enough time to pass through the electrode interface of the sample before the voltage change polarity. Some injected charges arrive at the layer interface and will be trapped there, and some can travel further, which accumulated and built quite big magnitude adjacent to the layer interface and some indeed pass through the bulk of sample. As this process keeps on repeating, more charges are able to be injected inside the sample and mainly trapped in between the sample interface.

The results show significant difference in space charge profile between ‘volt-on’ and ‘volt-off’ for two-layer samples.

Under most the ‘volt-off’ conditions, the dominant type of charge trapped inside the LDPE sample is negative charge. On the contrary, for ‘volt-on’ condition, the positive charges are the dominant accumulated charges across the sample. This can be explained in terms of the difference in mobility of these two types of charges.

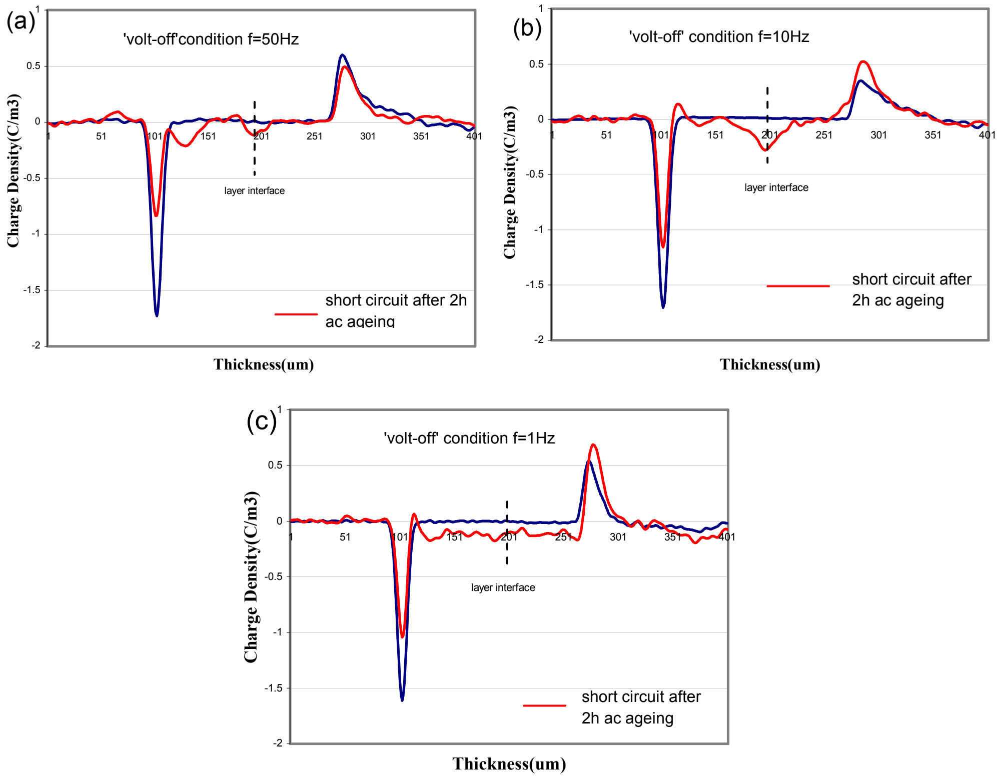

Figure 9: Short circuit charge profiles of ac-sample

During 'volt-on' condition, the mobility of positive charges is faster than negative charge. With this feature, both electrodes under ac stress have easily injected more positive charge into sample, making it become the dominant type of charge under this condition. Positive charges will not intend to stay inside the sample after the removal of the applied voltage due to their high mobility. They will disappear rapidly in this condition. That is why only negative charge could be recorded under 'volt-off' condition.

Increasing the applied ac electric stress increases the amount of charge trapped in the sample. Increasing the ageing time has the same effect. We believe charge injection, trapping, and combination in the bulk caused by ac applied voltage together with the characteristics of the interfaces are accountable, for the features observed. Space charge behaviours under ad conditions are more complicated and more research is required.

Conclusion

The space charge behavior in LDPE sample containing interface under dc and ac electric stress has been reported. Sc and Al were used as electrodes and different frequencies were tested. Following conclusions may be drawn:

The charge distribution in the bulk of sample under dc stress strongly depends on the electrode materials. The semicon electrode can inject charge into the bulk sample easily no matter positive charge or electrons. The dominant charge at the layer interface after short circuit is negative.

Frequency plays an important role in determining the space charge dynamics. At lower frequency, more charge can traverse the layer interface. The dominant charge at the layer interface is positive charge during 'volt-on' condition and negative charge become dominant during 'volt-off' condition.

The positive charge seems to have a high mobility compared with negative charge. Semicon electrode and the lower frequency are two important factors to determine the charge injection and distribution under ac electric stress.

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