Stories From China

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A New Estimation Method of Charge Injection at Al (Aluminum)/LDPE (Low-Density Polyethylene) Interface Based on Simultaneous Measurement of Space Charge and Current

Polymeric insulation is widely used as the main insulation of power equipment and electronic devices. When DC voltage is applied on the polymer insulation, space charge may accumulate inside and cause electric field distortion. So, space charge accumulation is important for HVDC insulation materials. The origin of the space charge is considered to be from ionization and charge injection. The space charge accumulation is determined by the charge injection, transportation, extraction, trapping, and other factors. The charge injection rate at the electrode/insulation interface is a key factor that determines the charge accumulation inside insulation material.

Much research on the charge injection at the metal/insulation interface has been done with the steady state conduction current of insulation. And, the results showed that the charge injection at the metal/insulation interface usually follows the Schottky law. However, the steady external current contains both the injection and extraction currents, so the charge injection rate was overrated in these works. Another method is calculating the increasing rate of the space charge inside the insulation. But, no matter for the PEA (pulsed electro-acoustic) or PWP (pressure wave propagation) methods, the obtained space charge distribution is a superposition of the positive and negative charge carriers, and the resolution near the electrode is poor. So, there is an even greater error in this method. Zepeng Lv and his group recently proposed a new method of estimating the charge injection rate with the space charge and conduction current simultaneous measurement. The new method overcomes all the errors previously mentioned in the two methods.

The space charge and conduction current simultaneous measurement system is based on the PEA method. As shown in Figure 1, the ring electrode is used to collect the conduction current, and the center electrode collects the space charge signal. The space charge and conduction current are alternatively obtained by the system with a switch to control. The details of the system can be found in [2].

The double layer sample with a blocking layer is essential for the estimation of the charge injection rate at the metal/insulation interface. The blocking layer should be made by an insulation material with much lower conductivity than the test material. In their study, a 160-μm E-51 epoxy resin (EP) film was used as the block layer for the polyethylene (PE) film. With this blocking layer, the charge injection and transportation in the EP layer are much lower than those in the PE layer and can be neglected. So, it makes a quasi-unipolar condition that only the charge injected from the Al/PE interface influences the space charge of the double-layer sample. And, the extraction current at the Al/PE interface can also be neglected. So, the measured current only contains the displacement current and the injection current, as shown by Equation (1).

$$J(x,t) = J_d(x,t) + J_c(x,t) = \varepsilon \frac{\mathrm{d}E(x,t)}{\mathrm{d}t} + J_i(x,t) + J_e(x,t) \quad (1)$$

The measured space charge and conduction current are as shown in Figure 2. It can be seen that the space charge in the double-layer sample is the sample polarity with the electrode near the PE. The interface charge continuously increases with the decrease of the charge at the cathode. It shows that the

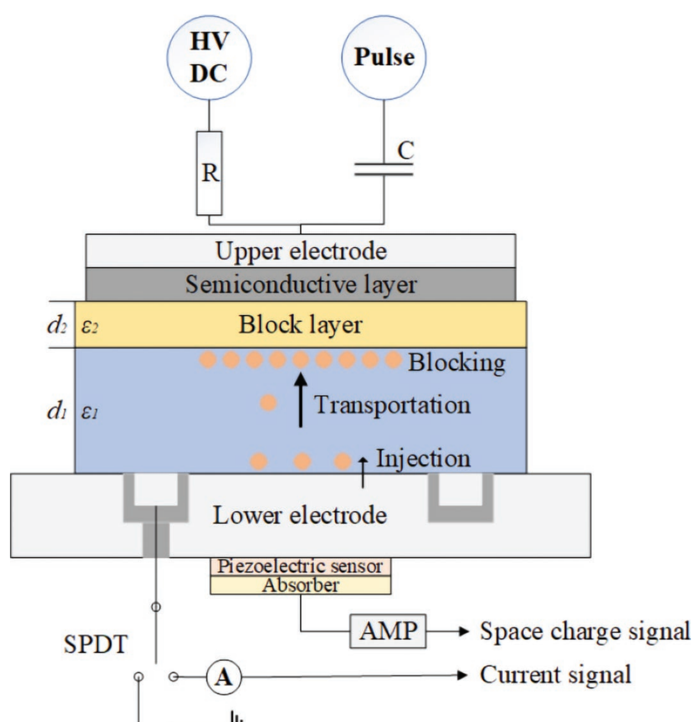

Figure 1. Schematic diagram of the charge movement in a double-layer sample during voltage application [1].

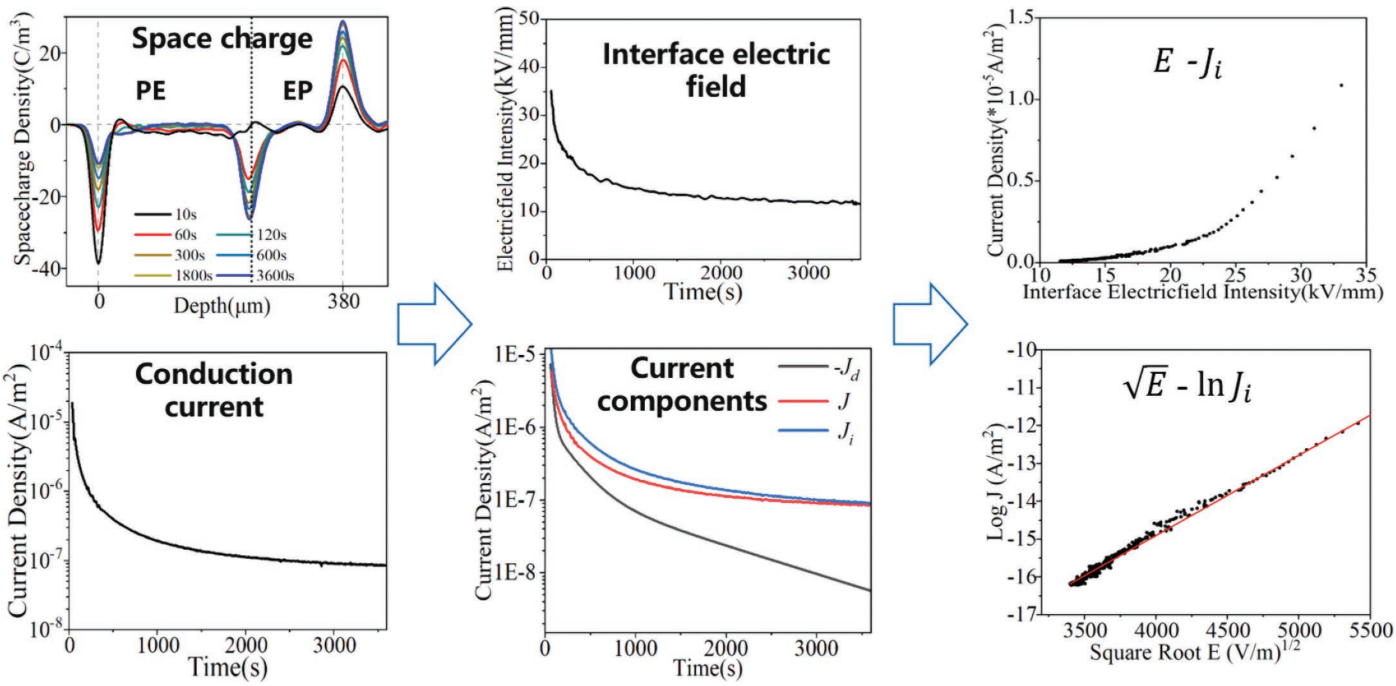

Figure 2. The procedure of estimating the charge injection at the Al/polyethylene interface.

charges injected from the cathode to PE and transports to the PE/EP interface. In this period, the conduction current continuously decrease. This is because the injection current decreases with the reduction of the cathode electric field, and the displacement current decreases with the decreased reduction rate of the cathode electric field.

With the space charge distribution, the cathode electric field can be obtained according to the method mentioned in the supplementary material of [1]. The reason for using the new method is that the electric field directly calculated by the Poisson's equation has a big error due to Gaussian-like extension of the surface charge at electrodes. With the calculated electrode electric field, the displacement current and the injection current then can be calculated. With the electrode electric field E and the pure injection current J_i, the relationship between them can be analyzed. It is found that $\sqrt{E}$ and $\ln J_i$ fit the linear relationship better, suggesting that the charge injection follows the trend of the Schottky theory [Equation (2)] or Poole-Frankel effect [Equation (3)].

$$J_s = AT^2 e^{-\frac{\phi_s}{kT}} e^{\frac{\sqrt{\frac{e^3 E}{4\pi\varepsilon_0\varepsilon_r}}}{kT}} \tag{2}$$

$$J_f = A'T^2 e^{-\frac{\phi_f}{kT}} e^{\frac{\sqrt{\frac{e^3 E}{\pi\varepsilon_0\varepsilon_r}}}{kT}} \tag{3}$$

The difference of the two theories in mathematic is that the coefficients of the $\sqrt{E}$ are different: the Schottky coefficient β_s is one-half of the Frankel coefficient β_f. As for LDPE, the theoretical values are about $4 \cdot 10^{-24}$ and $8 \cdot 10^{-24}$, respectively, for the Schottky or Poole-Frankel effect. Twelve tests for both polarities with different average electric field are repeated. The fitting results indicated that the charge injection at the Al/PE interface follows the Poole-Frankel effect rather than the Schottky theory. This is a challenge for the long and widely accepted Schottky theory. It raises an important question about whether the charge injection at Al/polymer is determined by the metal or polymer chains. The Schottky effect considers the charge injection process as the charge is leaving the metal interface with the acceleration of the electric field, whereas the Poole-Frankel effect considers the charge injection process as the charge is activated by the electric field to the conduction or valence bend to become free charge. So far there is no further evidence to distinguish the two effects. It still needs further research to verify.

The new method of estimating the charge injection at the metal/insulation interface has several advantages: (1) it removes the error caused by the overlapping of positive and negative charge in the space charge measurement; (2) it removes the error caused by the combination of the injection current and extraction current; and (3) it is easy to distinguish the positive and negative charge injection by changing the polarity of the voltage source.

References

[1] Z. Lv, J. Peng, Y. Ma, B. Wang, C. Zhang, J. Yao, K. Wu, and Y. Cheng, "Estimation of charge injection at Al/LDPE interface based on space charge and external current measurement," *Appl. Phys. Lett.*, vol. 123, article 17292, 2023.

[2] Z. Lv, Y. Ma, C. Zhang, J. Peng, K. Wu, and L. A. Dissado, "The simultaneous evolution of space charge and conduction current in LDPE," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 28, no. 2, pp. 616–624, 2021.