Conductivity Characteristics of XLPE/EPDM Bilayer Dielectrics under Different Interfacial Conditions (Post-print)

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Abstract

This study measured the conduction characteristics of cross-linked polyethylene/ethylene-propylene-diene rubber (XLPE/EPDM) bilayer dielectrics under three contact methods at temperatures of 30-90°C and electric fields of 1-19 kV/mm, and analyzed the influence mechanisms of electric field, interface, and temperature on bilayer dielectric conduction. The results indicate that: as the electric field increases, the field dependence of conductivity for all three bilayer dielectrics increases accordingly; the temperature sensitivity of hot-pressed contact bilayer dielectrics is stronger than that of the other two physical-contact-interface bilayer dielectrics, and temperature exerts a greater influence on chemical interfaces than on physical interfaces. Bilayer dielectric conduction exhibits a polarity phenomenon similar to the PN junction in semiconductor physics, with the polarity effect of hot-pressed contact bilayer dielectrics being opposite to that of the other two bilayer dielectrics. Interfacial state has a significant effect on the conduction characteristics of bilayer dielectrics.

Full Text

Preamble

Research on Conduction Characteristics of Double-layered XLPE/EPDM with Different Interface States

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Abstract

This paper measures the conductivity characteristics of cross-linked polyethylene/ethylene-propylene-diene monomer (XLPE/EPDM) double-layered dielectrics under three interface contact conditions at temperatures ranging from 30°C to 90°C and electric fields from 1 kV/mm to 19 kV/mm. The influence mechanisms of electric field, interface, and temperature on the conduction characteristics of double-layered dielectrics are analyzed. The results show that the electric field dependence of conductivity for all three double-layered dielectrics increases with rising electric field. The temperature sensitivity of conductivity for hot-pressed contact double-layered dielectrics is stronger than that of the other two types with physical interfaces, indicating that temperature exerts a greater influence on chemical interfaces than on physical ones. Additionally, the double-layered dielectric conductivity exhibits a polarity effect similar to PN junctions in semiconductor physics, with the polarity effect of hot-pressed contact double-layered dielectrics being opposite to that of the other two types. These findings demonstrate that interface state significantly affects the conduction characteristics of double-layered dielectrics.

Keywords: Cross-linked polyethylene, Ethylene-propylene-diene monomer, conductivity, temperature, interface

1 Introduction

Cross-linked polyethylene (XLPE) and ethylene-propylene-diene monomer (EPDM) rubber are commonly used as insulation materials for high-voltage DC cable bodies and accessories, respectively, due to their high breakdown strength, strong acid and alkali resistance, excellent oil resistance, superior mechanical properties, and good thermal performance [1-4]. In actual operation, DC cable system failures often occur not in the cable body but at the cable accessories. In high-voltage DC cable accessories, the composite insulation structure composed of XLPE/EPDM rubber is more prone to charge accumulation at the interface than in the bulk material, causing local electric field distortion and making insulation failure more likely. Additionally, under DC voltage, the electric field distribution and insulation design of composite insulation structures are significantly influenced not only by interface conditions and space charge but also by the nonlinear conductivity of the insulation that varies with electric field and temperature. Different dielectric materials exhibit different patterns and mechanisms of conductivity variation with electric field and temperature, complicating electric field calculations for cable accessories and increasing the difficulty of insulation design.

The complexity of electric field distribution inside cable accessories has caused research on accessory insulation materials and insulation structure design to lag far behind that of cable bodies, limiting the development of high-voltage DC cables. The electric field distribution 规律 in composite insulation structures of cable accessories has become a critical issue requiring urgent resolution. Regarding interface charge behavior in double-layer dielectrics, domestic and international scholars have conducted relevant research in recent years. S. Delpino et al. studied space charge accumulation at physical and chemical interfaces in high-voltage DC polymeric insulation systems, finding that physical interfaces accumulate more charge than chemical interfaces and that the interface charge quantity differs for the same interface state when electric field polarity changes [5]. Lü Liang et al. measured space charge distribution at the silicone rubber/EPDM double-layer dielectric interface before and after applying silicone grease, discovering that space charge formation at the double-layer interface is related to charge carrier migration direction, electrode materials, and dielectric materials, and that applying silicone grease effectively reduces space charge accumulation at the interface [6].

Most of the aforementioned research has investigated double-layer dielectrics through space charge analysis, with relatively few studies on conductivity characteristic variations. Conductivity changes can reveal dynamic transport characteristics of charge carriers in samples and evaluate microscopic property changes inside dielectrics under DC electric fields. Moreover, since the electric field at cable accessory insulation under DC voltage is determined by conductivity, it is necessary to study how conductivity of double-layer dielectrics varies under different electric fields and temperatures. This paper focuses on XLPE/EPDM double-layer dielectrics in high-voltage DC cable accessories, preparing double-layer dielectrics with three different contact methods: direct contact, silicone grease contact, and hot-pressed contact. The conductivity characteristics of samples under various electric fields and temperatures were measured to investigate the effects of temperature, electric field, and interface state on the conduction properties of double-layer dielectrics.

2.1 Sample Preparation

The XLPE and EPDM samples used in this study are commercial insulation materials specifically for high-voltage DC cables and accessories. The raw material for preparing XLPE sheet samples was cross-linked polyethylene pellets provided by a cable insulation material manufacturer. To eliminate interfaces between pellets, the XLPE pellets were first melt-mixed in a torque rheometer at 110°C for 5 minutes. The mixed material was then placed in a plate vulcanizing machine for hot-press cross-linking. After preheating the plate vulcanizer to 110°C, the material was placed inside and gradually pressurized to a final pressure of 20 MPa. The temperature was then increased to 180°C and maintained at this temperature and pressure for 15 minutes to ensure complete cross-linking. Finally, while maintaining 20 MPa pressure, the sample was cooled to room temperature at a rate of 1°C/min, producing XLPE samples with a thickness of approximately 80 m. The EPDM sheet samples, with a thickness of about 410 m, were provided by a cable accessory manufacturer.

Direct-contact double-layer samples were prepared by tightly pressing XLPE and EPDM sheets together at room temperature without additional treatment. Silicone-grease-contact double-layer samples required applying silicone grease to the contact surfaces between XLPE and EPDM. Hot-pressed-contact double-layer samples were prepared by pressing XLPE and EPDM sheets together at 110°C and 5-10 MPa, then gradually cooling to room temperature while maintaining pressure. To reduce the influence of cross-linking byproducts and eliminate residual stress from the pressing process, samples were preconditioned before experiments: prepared samples were short-circuited in a vacuum oven at 60°C for 24 hours with a vacuum degree of 10 ^{2} Pa, then cooled to room temperature at 0.1°C/min.

2.2 High-Field Conductivity Experiment

The conductivity measurements in this study employed a self-developed high-field conductivity measurement system, as shown in [Figure 1: see original paper]. The system consists of a high-voltage DC power supply, temperature control system, high-precision ammeter, and three-electrode current measurement system. The high-voltage DC power supply outputs voltages from 0 to 10 kV with a ripple factor less than 1%. The temperature controller maintains precision of ±0.1°C. The ammeter uses a Keithley 6517A electrometer with minimum measurement precision of 0.75×10 ^{1} A. The electrode system employs a three-electrode structure with a guard ring to eliminate the influence of surface leakage current on measurement results.

This study measured the high-field conductivity of direct-contact, silicone-grease-contact, and hot-pressed-contact XLPE/EPDM double-layer samples at 30°C, 50°C, 70°C, and 90°C. Quasi-steady-state current density and conductivity were calculated using current values measured at 600 s. At each temperature point, polarization currents were measured sequentially from low to high applied electric fields, with measurement fields of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 15, 17, and 19 kV/mm. After each measurement, samples were short-circuited for 120 s to eliminate effects from previous voltage applications on subsequent measurements. For each contact method, conductivity characteristics were measured under both positive polarity fields (-/XLPE/EPDM/+) and negative polarity fields (-/EPDM/XLPE/+) to investigate the influence of field polarity on double-layer dielectric conductivity. To ensure samples reached the specified temperature before current measurement, they were stabilized for 30 minutes at each temperature point before measurements began.

3 Experimental Results and Analysis

In existing research on conduction mechanisms of polymer insulation materials, space charge limited current theory is commonly used to describe current characteristics at high electric fields [7-8]. Therefore, experimental results are plotted in double logarithmic coordinates as lg J ~ lg E and lg ~ lg E. [Figure 2: see original paper] through [Figure 4: see original paper] show the quasi-steady-state current density and conductivity of the three contact-type double-layer dielectrics as functions of electric field at different temperatures. The current density and conductivity trends are similar for all three double-layer samples, increasing exponentially with temperature and showing piecewise linear relationships with electric field in double logarithmic coordinates. Among the three double-layer dielectrics, direct-contact samples exhibit the highest conductivity, while hot-pressed-contact samples show the lowest conductivity across the measured temperature range. Only at 90°C under -/XLPE/EPDM/+ polarity does the silicone-grease-contact double-layer dielectric show the minimum conductivity among the three types.

As electric field strength increases and temperature rises, the quasi-steady-state current and conductivity of double-layer samples under different polarity fields become unequal, indicating a polarity effect. For direct-contact and silicone-grease-contact double-layer samples, current density and conductivity are greater under -/EPDM/XLPE/+ polarity than under -/XLPE/EPDM/+ polarity. For hot-pressed-contact double-layer samples, the opposite trend is observed.

Piecewise linear fitting of the current density curves yields slopes and threshold fields summarized in . Under different field polarities and contact methods, the slope of lg J ~ lg E increases with electric field, with the low-field current density J slope being smaller than the high-field J slope, indicating a change in conduction mechanism within the measurement range. The slope of current density versus electric field can characterize the electric field dependence of dielectric conductivity. As electric field increases, the electric field dependence of conductivity for all three double-layer dielectrics increases accordingly. At 50°C, direct-contact double-layer dielectrics show the strongest electric field dependence at high fields. When temperature exceeds 50°C, silicone-grease-contact double-layer dielectrics exhibit the strongest electric field dependence.

At a measurement temperature of 30°C, the slope of the first current density segment J is approximately 1, meaning current density is proportional to applied electric field, consistent with Ohm’ s law. This indicates the sample is in the Ohmic region, where charge carriers participating in conduction are primarily thermal equilibrium carriers. The slope of the second current density segment J ranges from 1.71 to 2.33, placing the double-layer dielectric in the non-Ohmic region where current variation is influenced by trap distribution, carrier number, migration, and recombination. At higher measurement temperatures (>30°C), the J slope is generally greater than 1, while the J slope varies significantly with contact method and temperature, ranging from 1.92 to 2.34.

4 Discussion

At the microscopic level, dielectric conduction characteristics represent charge carrier transport processes, which are influenced by carrier generation, migration, trapping, de-trapping, and recombination behaviors. When measurement temperature and electric field change, carrier density, kinetic energy, and migration barriers within the dielectric vary accordingly, affecting carrier transport. For double-layer dielectrics, the presence of interfaces causes carriers injected from electrodes to migrate and accumulate near the interface. The microscopic structure and potential energy distribution near the interface greatly influence carrier migration and recombination behaviors at the interface. Multiple factors affect carrier transport in double-layer dielectrics, all influenced by applied electric field, temperature, and interface state.

4.1 Charge Transport in Double-Layer Dielectrics

The charge transport schematic is shown in [Figure 5: see original paper]. Under DC electric fields, according to Maxwell-Wagner polarization theory [9], double-layer dielectrics generate polarization charges at the interface. At low electric fields where no significant carrier injection occurs at the electrode/dielectric interface, charge carriers participating in conduction are primarily thermal equilibrium carriers. The electric field generated by polarization charges at the double-layer interface causes the internal electric field to distribute according to the dielectric conductivity, ensuring current continuity between the two dielectrics. At high electric fields, both electrode/dielectric interfaces inject carriers of different polarities. Injected carriers migrate through the dielectric bulk. Compared to movement within the bulk, the transition of carriers from one dielectric to another through the interface is often more difficult due to differences in microscopic structure, imperfect contact, and surface states. Consequently, carriers accumulate extensively at the interface, which can be viewed as a trap region or recombination center. Near the interface, carriers of different polarities have high density, significantly increasing the probability of recombination or trapping, thereby reducing the number of carriers participating in conduction. Accumulated carriers of different polarities at the interface substantially enhance the local electric field, promoting carrier transition from one dielectric to another. Meanwhile, injection and accumulation of like-polarity carriers reduce the electric field within the dielectric bulk, thereby decreasing carrier injection at the electrodes. Thus, the interface in double-layer dielectrics plays a regulatory role in current.

4.2 Temperature Sensitivity of Double-Layer Dielectric Conductivity

Temperature exerts an exponential influence on both carrier injection and migration in dielectrics. As temperature increases, electrons gain greater thermal kinetic energy, making it easier to overcome barriers and enter the dielectric from electrodes or transition between dielectrics through contact interfaces, thereby increasing the number of carriers participating in conduction. For carriers transporting via hopping conduction mechanisms, hopping distance increases with temperature, meaning carrier mobility increases. Overall, temperature elevation promotes carrier transport behavior and increases dielectric conductivity.

For double-layer dielectrics, conductivity also shows an exponential relationship with temperature. Conductivity values at different conduction regions were selected and plotted against temperature, as shown in [Figure 6: see original paper] through [Figure 8: see original paper]. Direct-contact double-layer samples show an exponential relationship between conductivity and temperature across the 30-90°C range, while silicone-grease-contact and hot-pressed-contact samples exhibit this relationship in the 50-90°C range. The relationship between polymer conductivity and temperature follows a form similar to the Arrhenius equation [10]:

= Ae^(- /kT)

where A is a constant, is activation energy, T is absolute temperature, and k is Boltzmann’ s constant. Activation energy characterizes the temperature sensitivity of dielectric conductivity; larger activation energy indicates more dramatic conductivity variation with temperature.

The Arrhenius equation coefficients for different samples are listed in . Direct-contact double-layer samples have activation energies of 0.87-1.14 eV, with weaker temperature sensitivity under -/XLPE/EPDM/+ polarity than under -/EPDM/XLPE/+ polarity. Silicone-grease-contact double-layer samples show activation energies of 0.93-1.14 eV, with noticeable differences between polarities only at 19 kV/mm, where temperature sensitivity is stronger under -/XLPE/EPDM/+ polarity. Hot-pressed-contact double-layer samples have activation energies of 1.08-1.32 eV, with stronger temperature sensitivity under -/XLPE/EPDM/+ polarity. Comparing the three double-layer dielectrics, hot-pressed-contact samples exhibit the strongest temperature sensitivity, meaning their conductivity is most significantly affected by temperature.

The difference in temperature sensitivity among the three double-layer dielectrics with different contact states primarily depends on how temperature affects interfaces with different contact conditions. The interface of hot-pressed-contact double-layer dielectrics involves chemical contact between the two materials with tight bonding, whereas direct-contact and silicone-grease-contact interfaces involve only physical contact with air and silicone grease effects, respectively. Therefore, temperature influences chemical interfaces more strongly than physical interfaces. The temperature sensitivity of direct-contact and hot-pressed-contact double-layer dielectrics is affected by field polarity, while silicone-grease-contact double-layer dielectrics show no obvious polarity effect on temperature sensitivity at low fields. This may be related to the introduction of silicone grease at the interface, whose apparent activation energy polarity is influenced by multiple factors and shows no clear pattern at low fields. However, silicone-grease-contact interfaces exhibit more obvious polarity effects at high fields, likely because more carriers participate in conduction at high fields, making temperature effects more pronounced.

4.3 Influence of Interface State on Double-Layer Dielectric Conductivity

Charge injection, extraction, recombination, and accumulation behaviors at both electrode/dielectric and XLPE/EPDM contact interfaces affect double-layer dielectric conductivity. For metal/dielectric contacts that are truly perfect and without surface state effects, three contact types exist based on work function differences: neutral contact, blocking contact, and Ohmic contact [11-12]. When work functions are equal, electrons show no net directional flow between materials, dielectric conduction and valence bands remain unbent, forming a neutral contact. When metal work function exceeds dielectric work function, electrons must overcome a barrier to enter the dielectric conduction band, forming a blocking contact for electrons. When metal work function is smaller than dielectric work function, electrons flow from metal to dielectric, forming an Ohmic contact.

For the copper electrodes, XLPE, and EPDM materials studied here, we assume copper has the smallest work function, EPDM is intermediate, and XLPE has the largest work function—a plausible assumption. According to contact band theory, both copper/XLPE and copper/EPDM contacts are Ohmic contacts for electrons, meaning electrodes always tend to inject electrons into the dielectrics. For XLPE/EPDM contact, since both are dielectrics with non-fixed Fermi levels that shift with electron and hole concentrations, contact between XLPE and EPDM always tends to inject electrons from EPDM into XLPE and holes from XLPE into EPDM. Charge flow occurs at the contact interface, changing both dielectrics' Fermi levels until they align. Referencing heterojunction PN junction energy diagrams, the XLPE/EPDM contact energy diagram can be drawn as shown in [Figure 9: see original paper].

For the XLPE/EPDM interface, assuming perfect contact without surface state effects, electrons more easily flow from EPDM to XLPE and holes from XLPE to EPDM due to work function differences. When the applied field polarity is -/EPDM/XLPE/+, the electric field lowers the barrier, providing higher space-charge-limited current. When polarity is -/XLPE/EPDM/+, electrons from XLPE flowing to EPDM encounter restrictions from electrons within the barrier region. The barrier can be considered a depletion layer of free carriers, meaning impedance inside the barrier exceeds that outside. Interface current density becomes smaller than dielectric bulk current, making the conduction electrode-limited. Current density is thus smaller than under -/EPDM/XLPE/+ polarity, similar to PN junctions where current densities differ significantly under forward and reverse bias, exhibiting polarity effects.

5 Conclusions

This paper primarily investigates XLPE/EPDM double-layer conduction behavior under different temperatures and electric fields. By analyzing the effects of electric field, temperature, and interface on double-layer dielectric conductivity, the following conclusions are drawn:

1. In double logarithmic coordinates, double-layer dielectric conductivity shows a piecewise linear relationship with electric field. As electric field increases, the electric field dependence of conductivity for all three double-layer dielectrics increases accordingly.
2. Double-layer sample conductivity increases exponentially with temperature, following a relationship similar to the Arrhenius equation. The temperature sensitivity of hot-pressed-contact double-layer dielectric conductivity is stronger than that of the other two physical-interface double-layer dielectrics, indicating temperature affects chemical interfaces more strongly than physical interfaces.
3. For double-layer dielectrics with different contact states, conductivity differs under different electric field polarities, with differences gradually increasing as temperature and electric field rise. This polarity effect, similar to PN junctions, likely results from work function differences between XLPE and EPDM. The polarity effect of hot-pressed-contact double-layer dielectric conductivity is opposite to that of the other two types.

Note: Figure translations are in progress. See original paper for figures.

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