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Combined electronic and thermal breakdown Models for polyethylene and polymer laminates

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ABSTRACT

A comprehensive DC dielectric breakdown model has been extended for polyethylene in which specific time and voltage regimes were identified for thermal and electrical failure modes. In addition to electron injection processes, space-charge formation and the associated electric field distribution are critical in determining the conditions for insulator failure. Space charge formation and distribution are governed by electron and hole injection from the electrode as well as charge mobility and trapping. Breakdown fields of 5 MV/cm are predicted through a computational model for polyethylene films in the 5 to 200 μm thickness range and there is weak dependence of breakdown field on thickness. The model is applied to predict the effect of interfaces for multilayer polymer structures that act as barriers.

1. Introduction

The high voltage reliability of polyethylene is important for future DC cable applications. Past studies have explored dielectric breakdown mechanisms including electronic, thermal, electromechanical and partial discharge assuming no space charge [1–5]. Space-charge-limited current arises from local electric field distortion which affects current density [6–8]. Space charge mediated dielectric breakdown has been initiated through pre-stress experiments [9,10]. Moreover, advances in nondestructive measurement techniques such as laser-induced pressure pulse (LIPP), pulsed electro-acoustic (PEA) and thermal pulse methods have made the direct measurement of space charge induced from high electric field possible [11,12]. Space charge from charge injection and transport in low-density polyethylene (LDPE) was observed through the PEA method and analyzed with a trapping/detrapping behaviors of charge carriers [13]. Therefore, the breakdown models of polyethylene should be modified to accommodate space charge effects.

A theoretical breakdown model that predicts not only electronic breakdown but also thermal breakdown was first proposed by Fukuma et al. for polypropylene [14]. This model assumes electron injection at the cathode through Schottky mechanism and charge transport by hopping conduction mechanism through the bulk of the polymer film. Space charge effects on electric field distribution and charge transport are governed by Poisson's equation. Thermal breakdown was expected when elevated local temperature from Joule heating exceeded melting temperature of polypropylene before electric field reached intrinsic breakdown strength. A similar model was applied to LDPE where pressure effects on breakdown strength were also investigated [15]. Although these models have provided general agreement with experiments, the Richardson constant among model parameters showed unrealistically low values of 0.1 $Am^{-2}K^{-2}$. Recently, bipolar charge transport model was proposed for LDPE and their modeling of charge profile and electric field distribution showed good agreement with experiments [16–18]. Bipolar charge transport model assuming constant mobility was also applied to electronic breakdown of LDPE and used to explain thickness dependence of breakdown strength at room temperature [19].

The aim of this work is to develop combined thermal and electronic breakdown models based on bipolar charge transport and charge injection. For the mobility of charge carriers, two kinds of mobility will be addressed including constant mobility and hopping mobility. This model provides not only a prediction of the breakdown strength but also field, time and temperature effects on the space charge dynamics and the resultant electric field evolution during breakdown process. Recently, polymer laminates with high breakdown strength have been demonstrated where the dielectric breakdown fields have doubled over neat polymers [20]. The model is extended to predict the role of added interfaces on the dielectric breakdown strength of polyethylene.

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2. Breakdown model and numerical techniques

Electronic breakdown is initiated by the local electric field enhancement from space charge formation and thermal breakdown occurs from Joule heating by a transient conduction current. Considering that the thickness is much smaller than the width and breadth of the sample, a one-dimensional problem is assumed for thermal breakdown.

$$C_v\frac{\partial T}{\partial t}-\kappa\frac{\partial^2 T}{\partial x^2}=J(x,t)E(x,t) \tag{1}$$

where x is the distance from the cathode in the direction of thickness, T is the local temperature, t the time, C_v the volumetric heat capacity, κ the thermal conductivity, J the transient current density, and E the local electric field. At the breakdown criterion, thermal breakdown occurs when a local temperature in the dielectric attains the melting temperature of LDPE. For impulse thermal breakdown, thermal conduction is ignored, and this assumption has often been used to model breakdown process in polymers [14,15]. However, impulse thermal breakdown is only valid if the time to breakdown is smaller than thermal relaxation time [21]. For a LDPE with thickness of 25 μm the time to breakdown is about 30 s at 25 °C assuming 300 V/s of ramp rate. Meanwhile, the thermal relaxation time (τ_d) is governed by

$$\tau_d=\frac{d^2C_v}{4\kappa} \tag{2}$$

where d is the sample thickness, which yields a thermal relaxation time in the millisecond range. The time to breakdown is much longer than the thermal relaxation time and thermal conduction cannot be ignored and assumption of impulse thermal breakdown is invalid in our case.

Charge injection and space charge formation in dielectric materials are closely related with the electronic breakdown. Space charge dynamics plays an important part in breakdown process because it governs the local electric field. It has been experimentally demonstrated that under high DC electric field the charge injection and space charge formation occurs in polyethylene [13,22–24]. In the breakdown model, it is assumed that injected charges from electrodes produce space charge within bulk and its electric field enhancement determines the breakdown. Breakdown occurs when local electric field within the bulk reaches intrinsic breakdown strength of polyethylene. The intrinsic breakdown strength of polyethylene is determined based on the literature and set to 680 MV/m [25].

The theoretical breakdown field based on electronic and thermal models can be determined if the electric field and the temperature in the insulator is numerically calculated for each time and each position. For every time step, the local temperature is compared with the melting point and the local electric field is compared with intrinsic breakdown strength. Dielectric breakdown occurs when either of the two criteria is reached. Both electric field and temperature are evaluated from charge injection and charge transport through Poisson's equation and Joule heating.

Charge generation and transport models are described by injection, transport, trapping and recombination of bipolar charges to predict space charge evolution in polyethylene [17,18]. Charge carriers are injected at the interface of electrode/dielectric according to the Schottky process. The two kinds of carriers can be either trapped or mobile within the dielectric. Under an externally applied electric field, mobile electrons in the conduction band (or holes in the valence band) drift with an effective mobility that is governed by trapping and detrapping in shallow traps. Deep trapping is described as a single traps level in which electrons or holes have insufficient energy for detrapping. The recombination process between the electron-hole pairs are also taken into account. After recombination, the carrier in the trap is released and thus trapping is feasible again.

Table 1
Parameters in the simulation of breakdown strength using constant mobility.

Parameters	Value	Unit	Reference
Barrier height for injection			
w_{ei}	1.15	eV	[27]
w_{hi}	1.14	eV	[27]
Mobility			
μ_e	9.0×10^{-15}	$m^2V^{-1}s^{-1}$	[28]
μ_h	1.5×10^{-16}	$m^2V^{-1}s^{-1}$	[28]
Trap density			
N_{0et}	100	Cm^{-3}	[27]
N_{0ht}	10	Cm^{-3}	[27]
Trapping coefficients			
B_e	7×10^{-3}	s^{-1}	[27]
B_h	7×10^{-5}	s^{-1}	[27]
Recombination coefficients			
S_0	4×10^{-3}	$m^3C^{-1}s^{-1}$	[27]
S_1	4×10^{-3}	$m^3C^{-1}s^{-1}$	[27]
S_2	4×10^{-3}	$m^3C^{-1}s^{-1}$	[27]
S_3	0	$m^3C^{-1}s^{-1}$	[27]

Initially no mobile charges are assumed within the dielectric. Dipolar polarization has been ignored considering the non-polar nature of polyethylene.

Assuming one-dimensional problem along the thickness, the current densities at the cathode ($x=0$) and the anode ($x=$d) from the Schottky mechanism is governed by

$$J_e(0,t)=AT^2\exp\left(\frac{-w_{ei}}{k_BT}\right)\exp\left(\frac{e}{k_BT}\sqrt{\frac{eE(0,t)}{4\pi\varepsilon}}\right),$$
$$J_h(d,t)=AT^2\exp\left(\frac{-w_{hi}}{k_BT}\right)\exp\left(\frac{e}{k_BT}\sqrt{\frac{eE(d,t)}{4\pi\varepsilon}}\right), \tag{3}$$

where J_e(0,t) and J_h(d,t) are the fluxes of electrons and holes at cathode and anode respectively, A is the Richardson constant, T the temperature, k_B the Boltzmann constant, $E(0,t)$ and $E(d,t)$ the electric fields at the cathode and the anode, ε the permittivity of the dielectric, e the elementary electron charge, w_{ei} and w_{hi} the potential barriers for electrons and holes. Assuming no extraction barriers at electrodes, extraction current densities for electrons at the anode and holes at the cathode are described by

$$J_e(d,t)=\mu_e n_{em}(d,t)E(d,t),$$
$$J_h(0,t)=\mu_h n_{hm}(0,t)E(0,t), \tag{4}$$

where n_{em} and n_{hm} are charge densities for mobile electrons and holes, and μ_e and μ_h are the effective mobility for the electron and the hole.

The behavior of charge carriers within dielectrics as a function of time and distance are governed by three fundamental equations:

Poisson's equation

$$\frac{\partial E(x,t)}{\partial x}=\frac{\rho(x,t)}{\in}, \tag{5}$$

Transport equation

$$J(x,t)=\mu n(x,t)E(x,t), \tag{6}$$

Continuity equation

$$\frac{\partial n(x,t)}{\partial t}+\frac{\partial J(x,t)}{\partial x}=s, \tag{7}$$

where E is the electric field, ρ the net charge density, n the charge density for each carrier, and s is the source term. The source term defines variations in local charge density due to trapping and recombination processes. For each charge type, mobile or trapped,