Journal of Electrostatics 81 (2016) 71–75

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Dielectric barrier discharge in needle-to-plane configuration: Model of surface charge relaxation

Oleg Emelyanov, Mikhail Shemet*

Peter the Great St.Petersburg Polytechnic University, Polytechnicheskaya st. 29, St. Petersburg 195251, Russia

ARTICLE INFO

Article history:
Received 20 February 2016
Received in revised form
31 March 2016
Accepted 1 April 2016
Available online 10 April 2016

Keywords:
Charge measurement
Dielectric films
Electric breakdown
Relaxation processes
Surface charging

ABSTRACT

Relaxation process of surface charge owing to dielectric barrier discharge (DBD) in "needle – air gap – polyethylene terephthalate film – plane" configuration is considered. Experimental data of the surface charge relaxation (SCR) are obtained by means of the rotating capacitive probe. Taking into account Gaussian radial distribution of accumulated charge density, effective surface and volume electrical conductivities of a barrier dielectric, phenomenological model of SCR for any dielectric thickness is proposed and exact solutions are obtained. The adequacy of the model is confirmed by the numerical computation. There is a good agreement between the experimental results and the model calculations.

1. Introduction

Charge accumulation and relaxation in dielectrics are the complex processes that depend on many external factors and dielectric intrinsic properties. Observation of the charge evolution and polarization distributions allows one to draw conclusions about charge transport in dielectrics that plays an important role in electronic devices and electrical insulation systems [1–6]. This topic is too broad to be treated in one paper and we can only slightly touch on the main reasons of charge behavior in dielectrics. Generally, the space charge evolution can be represented by the following simplified system of equations:

$$\begin{cases} \dfrac{\partial \rho_i}{\partial t} + div[(\gamma_i + n_i q_i \mu_i)\cdot E] = G_i + R_i + D_i \Delta(n_i q_i) & (1) \\ \rho = \sum_i \rho_i = \sum_i n_i q_i & (2) \\ \Delta\varphi = -\dfrac{\rho}{\varepsilon\varepsilon_0} & (3) \end{cases}$$

where ρ is space charge density equals the sum of all i-sort charge carriers (electrons, holes, ions) with concentrations n_i and charges q_i; D_i are their diffusion coefficients; γ_i are electrical conductivities; μ_i are effective drift mobilities; $\boldsymbol{E}$, φ are electrical strength and potential respectively; Δ denotes the Laplacian operator; ε and ε_0 are relative dielectric and vacuum permittivities. Generation sources G_i and recombination sinks R_i of the charge carriers are determined by different processes such as injection, trapping or detrapping in dielectric, surface recharging, UV ionization, chemical reactions, etc. [3,7–9]. The continuity Equations (1) are coupled to Poisson's Equation (3) via the charge density (2).

Dielectric samples usually are charged with electron beams, corona, thermal or electrical/tribo contact methods, UV radiation, dielectric barrier discharge (DBD), etc. [1,2,7,10–14]. During the corona charging process the energy of charged particles is around of few electron-volts such that charge penetration depth into dielectric medium is negligible [4,15]. Initially, the main part of the total charge is captured by dielectric surface traps. The following surface charge relaxation (SCR) depends on the surface and volume charge transport processes including the surface recombination caused by atmospheric ions [16–19]. In some cases the surface or volume ion diffusion processes can play an important role for SCR [20]. In experimental investigations one can usually measure the surface potential decay (SPD) that depends on surface charge density, electrical field, and dielectric parameters. In the case of relatively low electrical fields (<10–20 MV/m) one has observed the ohmic behavior of the volume electrical conductivity that provides an exponential kinetics of SCR (or SPD) [8,21]. At higher

* Corresponding author.
E-mail address: mvshemet@gmail.com (M. Shemet).

http://dx.doi.org/10.1016/j.elstat.2016.04.001
0304-3886/

fields there are some nonlinear patterns of relaxation kinetics such as well-known cross-over phenomenon [7,22] or field-dependent electrical conductivity (due to Poul-Frenkel or Shottky mechanisms) [3,21,23]. At first, the cross-over behavior of SPD was explained on the base of the field dependent mobility and the trapping process in dielectric volume [8]. Subsequently, it has been shown that this phenomenon is caused by double injection from dielectric surfaces [24]. The trap energy distribution in disordered dielectrics can lead to dispersive transport process that provides nonexponential kinetics of the dielectric's current [25,26]. Assuming that polarization depends on dielectric response function [27] the SPD can be explained by dipolar polarization process [28]. However, in some cases, the complicity of the offered models based on the dispersive transport, the polarization, or the detrapping leads to similar results of SPD kinetics [1]. The primary question here is recognition of the main physical reasons of the observed SPD experimental results. Nevertheless the nature of the transport processes in dielectrics is still the matter of debate.

The previous results of the surface charge accumulation due to DBD in the needle-to-plane system show that the charge density distribution has a shape close to Gaussian and the maximum value of the charge-induced field in dielectric samples is in the range of 5–10 MV/m [29]. Therefore, in the first approximation, we can assume the field independence of the electrical conductivity. For thin dielectric layers this leads to exponential behavior of SPD which has been observed in Refs. [8,21]. Also there are some models and technical standards [17,30,31] that use the field-independent effective bulk γ_V or near-surface layer γ_S electrical conductivities for dielectric property characterization. In these circumstances, we can reduce the continuity equation (1) for surface charge density σ_S to the following simple form:

$$\frac{\partial \sigma_S}{\partial t} + \gamma_V \cdot \boldsymbol{E}_V + \gamma_S \cdot \boldsymbol{E}_S = 0, \tag{4}$$

where subscripts 'V' and 'S' denote the volume and surface processes respectively. In this equation the γ_S is a volume conductivity of effective thin surface layer d at that the usual designation of surface conductivity is $\chi = \gamma_S/d$. Based on the above considerations we present a SCR model that takes into account Gaussian surface charge density distribution, effective surface and volume electrical conductivities, and dielectric barrier characteristics. To our knowledge, there has been no work on SCR under these conditions. In the Section 2 the mathematical model is described and exact solutions are obtained. The verification of the proposed model is performed by the numerical simulation in Comsol Multyphysics software. In the Section 3 we discuss the experimental results of the relaxation process of surface charge due to DBD in the needle-to-plane electrode system with polyethylene terephthalate (PET) film barrier. There we show a good agreement between the experimental results and the proposed model calculations. The main conclusions are given in the last section.

2. Mathematical model of the surface charge relaxation

2.1. Mathematical model

Let us consider a system with a dielectric layer and a bottom ground electrode in the air as it is shown in Fig. 1.

The thickness and the relative dielectric permittivity of the dielectric layer are d and ε respectively. There is an accumulated charge owing to DBD on the dielectric surface. As noted above, the previous investigations [29] have shown that the experimentally determined radial distribution of the surface charge density can be approximated by Gauss's law:

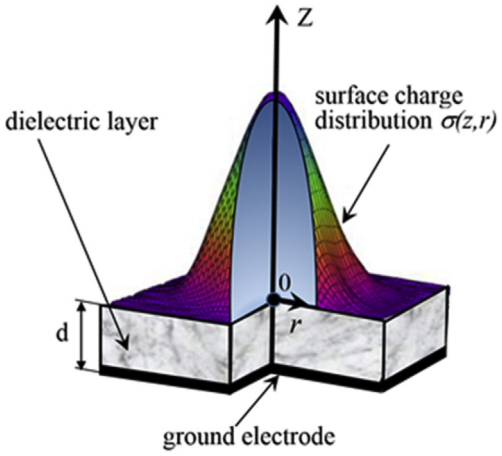

Fig. 1. Surface charge on polymer layer in cylindrical coordinates *(r,z)*.

$$\sigma(r) = \sigma_{max} \cdot \exp\left[-(r/r_0)^2\right]. \tag{5}$$

Further relaxation of the surface charge depends on the volume γ and surface χ electrical conductivities of the dielectric layer. In this axisymmetric case, the electric potential $\varphi(r,z,t)$ satisfies the Laplace equation in cylindrical coordinate system (r,z) as:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \varphi_i}{\partial r}\right) + \frac{\partial^2 \varphi_i}{\partial z^2} = 0, \tag{6}$$

where $i = 1,2$ corresponds to the dielectric and the air respectively.

The boundary conditions at $z = 0$ are as follows:

$$\begin{cases} \varphi_1 = \varphi_2 \\ \varepsilon\varepsilon_0 \dfrac{\partial \varphi_1}{\partial z} - \varepsilon_0 \dfrac{\partial \varphi_2}{\partial z} = \sigma_S(r,t) \\ \varphi_1 \to 0, \varphi_2 \to 0 \quad as \quad r \to \infty \end{cases} \tag{7}$$

Here $\sigma_s(r,t)$ is the radial distribution of the surface charge density.

Along the z-axis we have the following boundary conditions:

$$\varphi_1 = 0 \text{ at } z = -d, \varphi_2 \to 0 \quad as \quad z \to \infty. \tag{8}$$

Taking into account the continuity equation (4) we can get the following kinetic equation for SCR due to the volume γ and surface χ conductivities:

$$\chi\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \varphi_1}{\partial r}\right)\right]_{z=0} - \gamma\left(\frac{\partial \varphi_1}{\partial z}\right)_{z=0} = \frac{\partial \sigma_S(r,t)}{\partial t} \tag{9}$$

with the initial condition in accordance to (5):

$$\sigma_S(r,0) = \sigma(r). \tag{10}$$

Using the inverse Hankel transform [32], the electric potential can be expressed as:

$$\varphi(r,z,t) = \int_0^\infty \Phi(\lambda,z,t)\lambda J_0(\lambda r)\mathrm{d}\lambda, \tag{11}$$

where $J_0(\lambda r)$ being the first kind Bessel function of the zeroth order, λ is a path of integration.

The Hankel transform of (11) gives: