Theoretical study of the dielectric barrier discharge at atmospheric pressure

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Abstract:
In this paper, the progress in the theoretical study of the dielectric barrier discharge is reported. The model of the atmospheric-pressure discharge is discussed. Such effects as the oscillations of the Townsend mode of the discharge, the instability of the Townsend mode with subsequent transition to the filamentary discharge, and the stabilization of the barrier discharge by the photoemission are reviewed.

Keywords: dielectric barrier discharge, DBD, APGD, oscillations, photoemission

1. Introduction

The atmospheric pressure gas discharges is the subject of interest in recent years because of their application in industrial plasma technologies, such as surface treatment or plasma chemistry. The dielectric barrier discharge (DBD) is a low-frequency AC discharge between two plane electrodes covered by a dielectric barrier. This discharge can have either a strongly inhomogeneous (filamentary) form or a homogeneous (glow [1,2] or Townsend [3]) form in dependence on the discharge conditions.

In the present work, we present the model for the theoretical study of the DBD at atmospheric pressure and review the today's problems related to it.

2. Model

The barrier discharge is simulated by continuity equations for electrons, ions and excited particles coupled with the Poisson equation. The model may include a large number of particle types and plasmochemical reactions between them (full model) or only the most important processes (minimal model [4,5]).

The continuity equation for the particles of type k has the following form:

$$\frac{\partial n_k}{\partial t} + \nabla(n_k u_k) = S_k - D_k n_k \qquad (1)$$

Here n_k is the density of particles, u_k is their drift velocity, S_k is the excitation rate and D_k is the destruction frequency.

The velocities of charged and neutral particles are determined as follows:

$$u_{i,e} = -D_{i,e}\frac{\partial n_{i,e}}{\partial x} \pm b_{i,e}E, \qquad u_k = -D_k\frac{\partial n_k}{\partial x} \qquad (2)$$

Here D and b are the particle diffusion coefficient and mobility and E is the electric field.

The field is derived as a gradient of the potential. The latter is obtained from the Poisson equation:

$$\nabla^2 U = 4\pi e(n_i - n_e) \qquad (3)$$

The surface processes (ion-electron emission or particle attachment and detachment) are described by the boundary conditions to the equation (1).

The boundary conditions for electrons and ions have the form:

$$-b_e n_e E - D_e\frac{\partial n_e}{\partial x} = \gamma_{ph} I + \gamma_i b_i n_i E + \gamma_m D_m\left|\frac{\partial N_m}{\partial x}\right| + \sigma_{e0}\nu_{des} - n_e\sqrt{\frac{2T_e}{\pi m_e}} \qquad (4)$$

$$n_i = 0 \qquad (5)$$

Eq. (4) expresses the equivalence of the drift-diffusion flux (left part) and the kinetic flux from (to) the surface (right part). In this equation, γ_i and γ_m are the secondary emission coefficients by ions and metastable atoms, σ is the surface charge density, and ν_{des} is the electron desorption frequency.

For ions, it is enough to assume zero boundary condition (5).

The system of equations at the boundary is fulfilled by the equations for boundary conditions (αrw is the surface charge recombination frequency),

$$\frac{\partial \sigma_{e0}}{\partial t} = n_e\sqrt{\frac{2T_e}{\pi m_e}} - \sigma_{e0}\nu_{des} - \alpha_{rw}\sigma_{e0}\sigma_{i0} \qquad (6)$$

$$\frac{\partial \sigma_{i0}}{\partial t} = b_i n_i E - \alpha_{rw}\sigma_{e0}\sigma_{i0} \qquad (7)$$

The effect of boundary conditions in the description of the discharge is weak. However, different boundary conditions in Townsend discharge (ion-electron emission or desorption of electrons from the surface) may cause different discharge behaviour [5].

The most of researches use one-dimensional (1D) or two-dimensional (2D, cylindrically symmetrical) model. However such problem as the formation of discharge patterns [6] requires three-dimensional (3D) model. Some researches based on the 3D model were performed in [4]; it was shown that two streamers must repulse from each other.

In the current work, the results of 1D and 2D models will be discussed.

3. Oscillations in Townsend discharge

An interesting phenomenon observed in the Townsend discharge is the oscillations of current [3]. The oscillations are not related to the radial structure of the discharge; their origin is the time lag between the ion formation near the anode and the increase of cathode current due to the ion-electron emission [7].

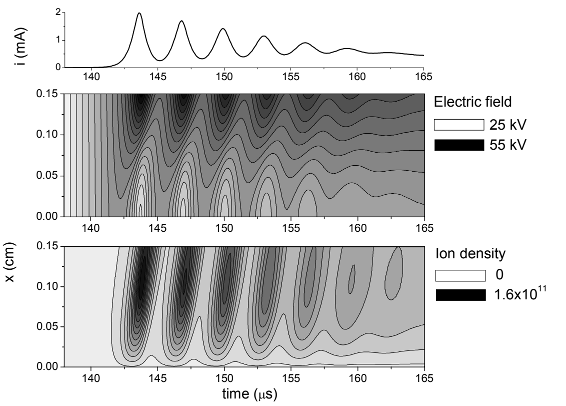

Fig. 1. Oscillations in Townsend discharge in N_2.

Besides the ion-electron emission, the origin of oscillations may be the effect of the space charge. The space charge of ions distorts the electric field and changes the multiplication coefficient for electrons. In this case, the electric field and particle densities have the the form of waves in space and time (see Fig. 1). The period of oscillations is also determined by the time of ion movement from the anode to the cathode.

The oscillations in the Townsend DBD can be described in terms of the analytical model. In [4], a self-consistent nonlinear theory of oscillations in Townsend discharge is developed. It was shown that the oscillations must be strongly nonlinear, and the current must have a series of peaks (the period of peaks is determined by the voltage growth rate and the ion velocity).

4. Townsend discharge instability and streamer formation

The most of experimental studies of the DBD in nitrogen show that only the Townsend discharge is radially stable when the voltage or frequency increases, the DBD becomes filamentary.

The origins of this instability can be investigated, when the discharge conditions are close to the transition from

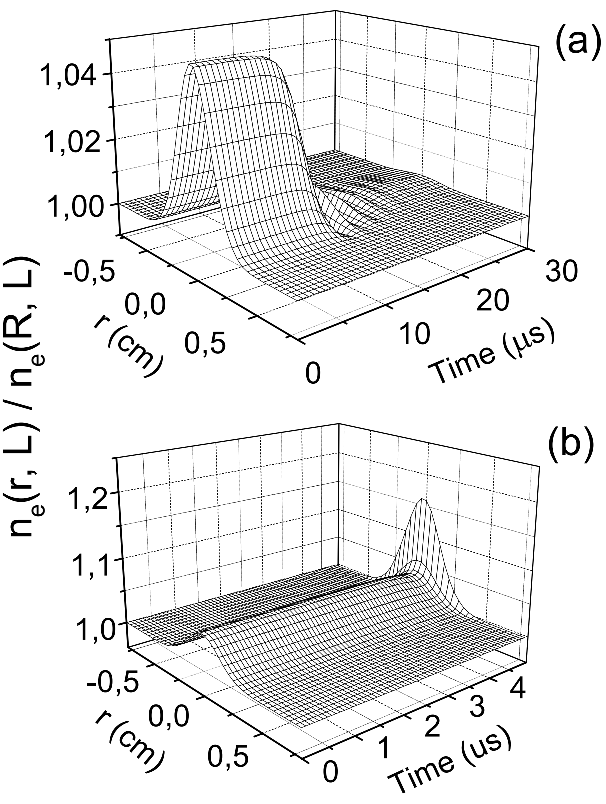

Fig. 2. Evolution of a 5% perturbation in the Townsend discharge (the electron density at the anode normalized to the undisturbed value). (a) stable discharge, (b) unstable discharge.

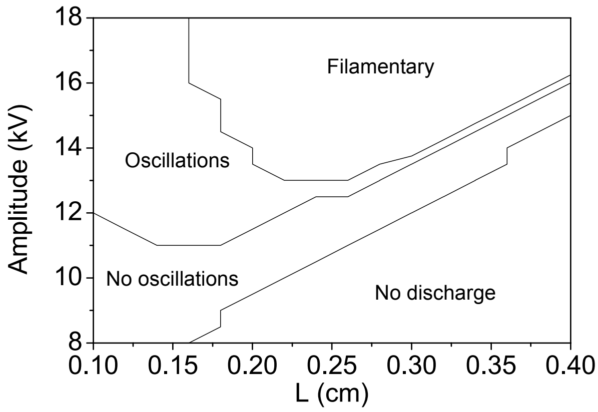

Fig. 3. Different discharge modes in N_2, f=7 kHz.

Townsend to filamentary discharge. In the experimental work [8] the space-time profile of the discharge radiation intensity was obtained. It was shown that there is a relatively long Townsend “prebreakdown” phase with subsequent streamer formation at the anode. Therefore, the mechanism of streamer formation is the instability of the Townsend discharge instead of the avalanche-to-streamer transition.

In the theoretical study [5], a radial perturbation of the electron surface density is introduced in the Townsend discharge and its behaviour with time is studied (Fig. 2). It is shown that in stable Townsend discharge this perturbation decreases with time, whereas in unstable regions (for instance, when the voltage amplitude is increased) the perturbation grows. The growth of the perturbation is followed by the local increase of the electric field with subsequent streamer formation. The formation of the streamer from the initial perturbation was demonstrated in [9].

This method allowed to obtain the regions of stability for the barrier discharge. Fig. 3 shows the regions of stability for the discharge in nitrogen (frequency 7 kHz). It is seen from the figure that, as the voltage or the discharge gap width increases, the discharge oscillations occur due to the space charge effects, and then the discharge becomes unstable (filamentary).

The effect of radial instability explained why the barrier discharge with high-permittivity barriers is less stable than the discharge with low-permittivity barriers [10]. The local increase of the surface charge density increases the electric field. The more is the permittivity of the barrier, the higher is the electric field and the earlier is the streamer formation.

5. Effect of photoemission

The photoprocesses in DBD are rarely included in the model because of their nonlocal nature. However they may be the origin of glow discharge stability in He, N_2 and other gases.

The work [11] studies the effect of photoemission in N_2. The photoemission is caused by UV radiation by singlet states [11]. The modeling starts from a narrow initial avalanche and finishes in the afterglow phase.

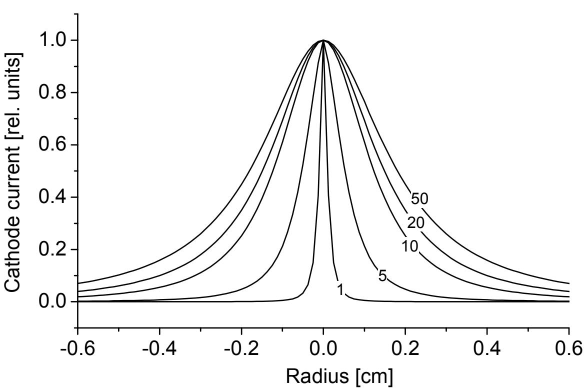

Fig. 4. Current density at the cathode in the Townsend phase of the discharge.

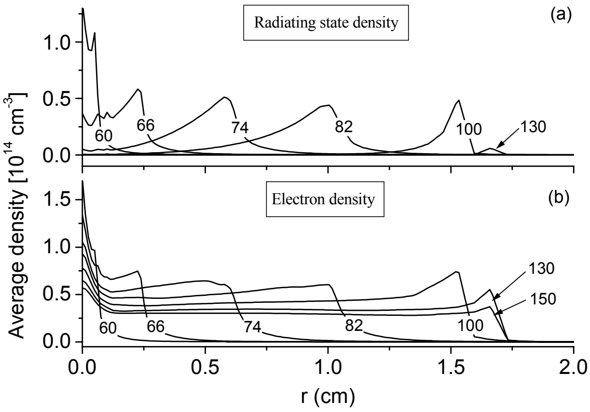

Fig. 5. Radiating state density (a) and electron density (b) in the phase of radial expansion.

It is shown that in Townsend phase of the discharge, the photoemission causes an essential widening of an initial avalanche (Fig. 4). After the electron density at the anode reaches critical value, a streamer is formed in the center of the discharge. In this phase, the photoemission expands the discharge in radial direction (the phase of radial expansion (Fig. 5).

In Fig. 5, another interesting effect can be seen. The radiation of a discharge in the phase of radial expansion must have the form of a ring whose radius increases with time.

The radial expansion due to the photoemission may be the origin of a stable atmospheric pressure glow discharge (APGD) observed in experiments [11].

6. Self-organization effects in the DBD

In this section, several interesting effects are briefly described, which are still not described by the present theory.

The first self-organization effect is the formation of the patterns in the filamentary discharge [12]. The triangular patterns are the most often observed, however the authors of [12] observed also rectangular patterns, bands and other patterns.

The proper description of the pattern formation in the dielectric barrier discharge requires 3D model. Qualitatively the patterns are formed because the discharge remembers the position of the previous microdischarge due to the residual surface charge, and the filaments interact with each other. It was recently shown [4] that two filaments are repulsing.

Recently, it was observed that sometimes the filament in the discharge is not uniform along the axial direction [13]. That is, the filament becomes stratified. The nature of the stratification is still unclear. Similar phenomenon was observed and theoretically described at lower pressures (tens of Torr) in Ar [14]. It was shown that the constriction of the glow discharge must be followed by the appearance of striations.

7. Conclusion

The results of the 1D and 2D modeling of the dielectric barrier discharge at atmospheric pressure are reviewed. The theory gives the explanation for several phenomena occurring in the DBD.

The oscillations in the Townsend discharge are because of a time lag between the ion production near the anode and electron production on a cathode.

The transition from the Townsend to the filamentary state because of radial instabilities is studied. The Townsend discharge is stable relative to radial perturbations, whereas these perturbations grow in glow mode and cause the transition to the filamentary state.

The atmospheric pressure glow discharge may be stable because the photoemission expands the discharge in a radial direction.

Several phenomena, such as pattern formation in a DBD, require 3D model.

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