Hydrodynamic modelling of microdischarges in asymmetric barrier discharges in argon

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Microdischarges in dielectric barrier discharges in argon have been analysed by means of hydrodynamic modelling. The results of the calculations show qualitative agreement with experimental observations. It is found that the discharge characteristics depend sensitively on the applied voltage. At applied voltages slightly above the burning voltage, period multiplication phenomena occur and two different discharge modes are obtained similar to those found in the experimental investigations. In particular, the temporal evolution of the surface charge density and the spatiotemporal variation of the electron density are examined to explain the distinct discharge events.

1. Introduction

Dielectric barrier discharges (DBD) are widely used in many technical applications like high power lasers and plasma display panels, for the modification of surfaces, the synthesis of ozone and exhaust treatment. Therefore, the profound understanding and the optimization of such discharges is of high interest. Particularly, the stability and reproducibility of the plasma is crucial for its industrial application. The existence of phenomena like period multiplication and transitions to chaotic states in atmospheric-pressure glow discharges as well as in DBD is well known from experimental [1, 2] and theoretical [3, 4] investigations. Recently, the unstable occurrence of two different discharge modes have been observed in experimental studies of asymmetric argon barrier discharges at atmospheric pressure, where only the grounded electrode is covered by a dielectric and the powered electrode is driven by a sinusoidal voltage at 60 kHz [5]. The first mode occurs only at applied voltage amplitudes slightly above the burning voltage and is characterized by a classical microdischarge with a strong current peak and a straight channel. Striated structures appear during the second mode which is characterized by multiple weaker current peaks. A typical picture of the observed striations is represented in Fig. 1.

In order to support the experimental investigations, theoretical studies of the spatiotemporal evolution of atmospheric-pressure argon microdischarges in an asymmetric DBD configuration have been performed. Results on the temporal variation of discharge voltage and current are discussed for a wide range of applied voltages and an analysis of the spatiotemporal discharge behaviour is given in the present contribution.

2. Model of the DBD

The theoretical analysis has been performed by means of a self-consistent hydrodynamic model comprising the continuity equations

\[
\partial_t n_s + \nabla \cdot \Gamma_s = S_s \quad (1)
\]

for the particle densities \(n_s\) of all considered species ‘s’, the electron energy balance equation

\[
\partial_t w_e + \nabla \cdot Q_e = -e_0 E \cdot \Gamma_e + \tilde{S}_e \quad (2)
\]

determining the spatiotemporal evolution of the electron energy density \(w_e\) and Poisson’s equation providing the electric potential \(\Phi\) and the electric field \(E = -\nabla \Phi\) according to

\[
-\Delta \Phi = \frac{1}{\varepsilon_0} \sum_s q_s n_s. \quad (3)
\]

The particle fluxes and the electron energy flux

![Fig. 1: Striations in asymmetric argon barrier discharges at atmospheric pressure.](image-url)
are given in drift-diffusion approximation by

\[
\Gamma_s = -\nabla (D_s n_s) + \text{sgn}(q_s) b_s E n_s \quad (4)
\]
\[
Q_e = -\nabla (\bar{D}_e n_e) - \bar{b}_e E n_e . \quad (5)
\]

Here, \( \varepsilon_0 \), \( q_s \), \( D_s \) and \( b_s \) denote the vacuum permittivity, particle charge, diffusion coefficient and mobility of the species ‘s’, respectively. \( \bar{D}_e \) and \( \bar{b}_e \) in equation (5) are the diffusion coefficient and mobility for energy transport of the electrons. To achieve an adequate description of the atmospheric pressure argon plasma, atomic and molecular argon ions as well as 7 excited atomic and 4 excited molecular argon states have been taken into account. All transport coefficients of the electrons are treated in dependence on the mean electron energy as described in [6]. The respective transport coefficients for ions depend on the reduced electric field and those for the metastable atoms are assumed to be constant. The source terms \( S_s \) and \( \bar{S}_s \) of the balance equations (1) and (2) represent the gain and loss of particles and energy due to reactive processes. The reaction kinetic model takes into account about 70 electron energy due to reactive processes. The reaction kinetic model takes into account about 70 electron energy due to reactive processes.

\[
\partial_t \sigma = \sum_s q_s \Gamma_s \cdot n \quad (8)
\]

which includes the assumption that the surface charge density does not diffuse along the surface.

Boundary conditions for the balance equations of particle and electron energy at both electrodes are derived by taking into account the partial reflection of particles as well as emission of secondary electrons due to ion bombardment. The secondary electron emission coefficients at the metal and the dielectric surface are set to 0.06 and 0.02, respectively.

The numerical solution of the governing equations has been performed by means of a semi-implicit time-stepping scheme similar to that detailed in [7]. The balance equations of the charge carriers have been solved by the Scharfetter-Gummel finite-difference method. The central-difference method has been used for the spatial discretization of Poisson’s equation and the balance equations of the neutral particles.

3. Results

3.1. Voltage-current characteristics

Model calculations have been performed for applied voltage amplitudes \( \Phi_0 \) between 2 and 4 kV. Figure 3 shows the temporal evolution of the applied voltage \( \Phi_g(t) = \Phi_0 \sin(\omega t) \), the gap voltage \( \Phi_g(t) = \Phi_a(t) - \Phi(d, t) \) and the discharge current at \( \Phi_0 = 2, 2.5 \) and \( 3 \) kV.

Two different discharge modes at applied voltage amplitudes slightly above the burning voltage (\( \Phi_0 < 3 \) kV) and only one discharge mode at higher applied voltages (\( \Phi_0 \geq 3 \) kV) are predicted by the model calculations in accordance with experimental observations [5]. However, the burning voltage of the theoretical model is about two
times higher than that found in the experimental investigations. This issue might result from the assumption of a spatially one-dimensional geometry and uncertainties in the reaction kinetic model.

At \( \Phi_0 = 2 \) kV non-striated microdischarges associated with a significant single current peak occur every fourth period in the arrangement with metallic cathode and dielectric-covered anode (M-D+) as well as in that with metallic anode and dielectric cathode (M+D-). The subsequent striated microdischarges are characterized by a sequence of two or three weaker current peaks. At \( \Phi_0 = 2.5 \) kV non-striated microdischarges appear in the M+D- arrangement only, and at \( \Phi_0 = 3 \) kV striated structures always result.

The absolute values of the maximum current peaks during every period of the temporal evolution in dependence on the applied voltage are displayed in Fig. 4. For \( \Phi_0 < 3 \) kV the maximum current peak is not the same in every period, as indicated by more than one peak value for the respective voltage amplitude. The occurrence of more than one current peak value is caused by period multiplication phenomena similar to those observed in symmetric DBD in argon at different frequencies and applied voltages [4]. Four peak values indicate that one current period is four times longer than the external voltage period \( T \), i.e., exactly the same discharge happens every fourth period. At \( \Phi_0 = 2.75 \) kV a chaotic state exists which does not show any periodic state. The decrease of the maximum current peak values at increasing applied voltage is caused by higher surface charge densities and consequently higher memory voltages.

In order to clarify the complex voltage-current characteristics at \( \Phi_0 = 2.5 \) kV (cf. Fig. 3), the temporal evolution of the corresponding gap and memory voltage and the surface charge density is shown in Fig. 5. For the first discharge event around \( t/T = 1 \), the gap voltage is at its largest positive peak. Hence, the gas breakdown is relatively strong and the resulting peak value of the current pulse is large. Consequently, the surface charge density at the dielectric increases strongly in conjunction with the memory voltage. Since the memory voltage remains at a high level until the absolute value of the gap voltage raises.
again due to the high charge carrier population in the plasma, the subsequent microdischarges are comparatively weak. After four periods at $t/T \approx 5$ the memory voltage reaches its smallest peak value. The charge carrier production during this discharge event is comparatively low, and the electron density drops before the next discharge ignites, as illustrated in the following section.

### 3.2. Spatiotemporal discharge behaviour

The spatiotemporal distribution of the electron density and the corresponding temporal variation of the discharge current during a striated and the succeeding non-striated microdischarge at $\Phi_0 = 2.5$ kV is represented in Fig. 6. Figure 6a points out that the electron density remains locally high just before the striated microdischarges ignites. This behaviour is the same for all discharge events exhibiting multiple current peaks. As a consequence, the charge carrier production during the striated discharges is mainly driven by indirect ionization processes of excited argon atoms. Due to the repeated reignition, the positive column is not homogeneous. In contrast to that, the electron density decreases strongly in the whole discharge region before the succeeding non-striated microdischarge ignites as shown in Fig 6b. Thus, the charge carrier production is predominantly caused by direct electron-impact ionization of ground state atoms.

### 4. Conclusion

The occurrence of different microdischarge modes in asymmetric dielectric barrier discharges in argon at atmospheric pressure has been analysed by means of hydrodynamic modelling. Striated and non-striated microdischarges have been predicted at different applied voltages in accordance with experimental observations.

The analysis of the dependence of the voltage-current characteristics on the applied voltage has revealed that periodic doubling phenomena occur at applied voltages lower than a certain limit. This might be the reason for the discharge instabilities observed in experiments. The examination of the spatiotemporal variation of the electron density has pointed out that the distinct discharge characteristics of the two discharge modes are caused by different mechanisms affecting the charge carrier production.

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**Fig. 6:** Electron density and discharge current during a striated (a) and non-striated (b) microdischarge.

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**References**