SUBMICROSECOND ATMOSPHERIC ELECTRIC DISCHARGE FROM THE NON-UNIFORM ELECTRODE (TIP) TOWARDS THE PLANE ELECTRODE

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Abstract:

This paper deals with the results of a numerical simulation of the fast atmospheric pressure discharge in a strongly non-uniform configuration of a tip-to-plane diode filled with a nitrogen and oxygen mixture. The simulation is based on the advanced hydrodynamic plasma discharge accounting also gas photoionization. It was shown that, in the absence of photoionization, discharge develops similarly to the case with photoionization, except the case of reversed voltage polarity. The theoretical results correspond to the existing experimental data for the spatial discharge structure and the current/voltage discharge characteristics.

Key words: plasma, numerical simulation, atmospheric discharges.

Introduction

Various gas-filled diodes are widely used in modern electro-technical devices. The tip-to-plane electrodes system represents probably the most common design of a gas diode unit with a strongly non-uniform configuration of an electric field. Namely, they are used as spark-gap high-voltage switches (Shaefer et al, 1990) as well as the main component of technological devices for the discharge plasma surface treatment (Akishev et al, 2001). Therefore, major theoretical problems of discharge development in such a system are intensively investigated by using various theoretical simulation approaches (Eichwald et al, 2011).

The discharges in gas-filled diodes are attractive due to the non-trivial switching characteristics and the low-temperature plasma parameters. Among the switching parameters, the breakdown formation time and the corresponding voltage amplitude are the most important. The plasma parameters, e.g. its spatial structure or its plasma-chemical composition are also of great importance, especially w.r.t. time-dependent studies. While the switching characteristics can be easily measured experimentally, the measurement of plasma parameters is much more complicated. That is the main reason to perform a theoretical simulation of gas discharge.

At present, we have a rather extensive base of experimental studies of this type of discharge, including those performed with picosecond and subnanosecond time resolutions, as well as with time synchronization of measured signals. As part of the series of experimental studies done by groups of Russian and Chinese researchers (Shao et al, 2013), a comparison can be made with the results of actual theoretical studies.

In this paper, we use a two-moment "liquid" discharge plasma model (Gogolides & Sawin, 1992) implemented in the Plasma module of COMSOL Multiphysics 5.2 software. It allows modeling the time-dependent discharge propagation from the metal non-uniform electrode (tip) towards the second electrode (plane) accounting for all necessary plasma-chemical reactions. The main aim here is to simulate nanosecond gas discharge and accurately obtain the spatial discharge structure evolution.The introduction is an introductory part of the article.

Experimental setup

The experimental setup is represented in Figure 1. The triggering pulse from 1 provides a signal that the voltage pulse generator 2 transforms into a negative polarity voltage pulse with the amplitude values in the range of $U_0 \approx$ 27-30 kV with the rise time $t_f \approx$ 200 ns. The

cathode here is a thin needle with a diameter of 0.4 mm having the tip curvature radius of 0.1 mm (medical syringe needle), while the anode is a simple plane electrode made of aluminum foil. The distance between the electrodes is equal to $d = 9$ mm. The nitrogen at 1 atm pressure with small (~2 %) oxygen admixture is used as the operating gas.

An ICCD camera was used to obtain a sequence of instant images of the discharge dynamics (depicted in Figure 2). The images from an ICCD camera are an integral picture of the glow of non-stationary discharge, which, to a certain extent, can be compared with the distribution of the discharge plasma at a given point in time. Based on this comparison of experimental and theoretical data can be done in the present work.
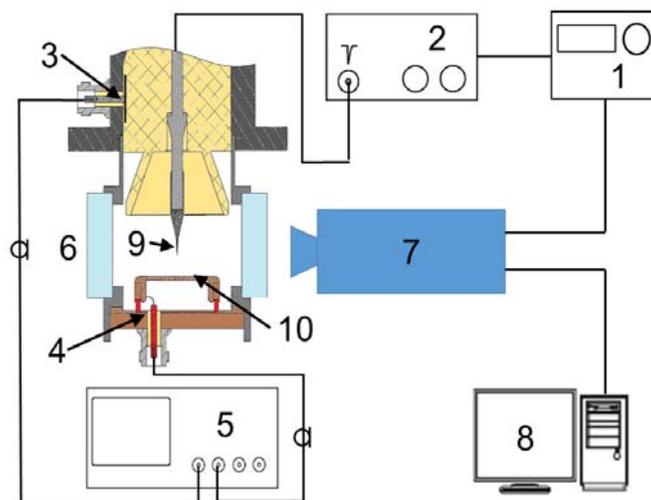
Figure 1 – The experimental setup: 1 – triggering pulse generator, 2 – pulsed voltage source, 3 – capacitive voltage divider, 4 – current shunt resistor, 5 – storage oscilloscope, 6 – output window, 7 – ICCD camera, 8 – personal computer, 9 – metal tip cathode, 10 - plane anode electrode
Рис. 1 – Схема эксперимента: 1 – запускающий генератор, 2 – импульсный источник напряжения, 3 – емкостный делитель напряжения, 4 – токовый шунт, 5 – цифровой запоминающий осциллограф, 6 – выходное окно, 7 – скоростная камера, 8 – компьютер, 9 – острийный катод, 10 – плоский анод
Слика 1 – Поставка експеримента: 1 – генератор окидног импулса, 2 – пулсни извор напона, 3 – капацитивни разделник напона, 4 – шант отпорник, 5 – меморијски осцилоскоп, 6 – заштитни прозор, 7 – камера ИЦЦД, 8 – лични рачунар, 9 – катода – метални врх, 10 – анода – обична плочаста електрод

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a) 71-74 ns   b) 74-77ns   c) 77-80 ns
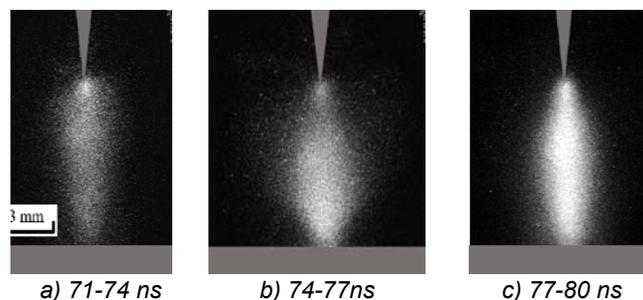
Figure 2 – Instant photographs from the ICCD-camera (grey areas depict the electrodes)
Рис. 2 – Мгновенные фотографии свечения, полученные скоростной камерой
(области, отмеченные серым цветом обозначают электроды)
Слика 2 – Инстант фотографије добијене камером ИЦЦД (сиве зоне
представљају електроде)

Theoretical model

For the simplicity reasons, a real three-dimensional diode in the model is substituted by a two-dimensional axisymmetric structure (Figure **3**).

The gas discharge model is based on the two-moment "liquid" model where the movement of charged particles is covered by the drift-diffusion approximation (Gogolides & Sawin, 1992). Since the discharge characteristic time is short, the model implements only three important plasma-chemical reactions: electron impact ionization $e + N_2 \rightarrow 2e + N_2^+$, molecular nitrogen dissociation $e + N_2 \rightarrow e + 2N$ and photoionization $h\nu + N_2 \rightarrow e + N_2^+$.

The photoionization model we implement is based on the assumption (Kulikovsky, 1995) that the major contribution to the photoionization rate is produced by the radiation in the spectral range 980-1025 Å, where the radiation absorption by nitrogen N_2 can be omitted. The wavelength of 1025 Å is the natural threshold for the molecular oxygen photoionization reaction. Below 980 Å, the radiation is strongly absorbed by nitrogen providing insignificant contribution to the production of photoelectrons. Taking into account the fine structure of the oxygen absorption spectrum, in the integral over the wavelength range 980-1025 Å in the general expression for the rate of photoionization was calculated and adopted for further computations.
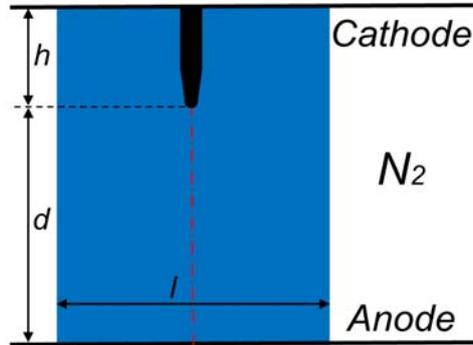
Figure 3 – The computational domain configuration (h = 1.6 mm, l = 4 mm, d = 9 mm)
Рис. 3 – Счётная область пространства (h = 1.6 мм, l = 4 мм, d = 9 мм)
Слика 3 – Конфигурација области израчунавања (h = 1,6 mm, l = 4 mm, d = 9 mm)

We also draw the attention to the importance of taking into account the molecular nitrogen dissociation reaction as the main factor leading to electron energy losses (Cosby, 1993). Other plasma-chemical reactions typical to nitrogen, e.g. involving ions of atomic nitrogen, are omitted due to their smaller contribution to the fast discharge development. For the same reasons, we also exclude different kinds of neutral excited species. The electron component is described by the following equations system:

$$\begin{cases} \dfrac{\partial n_e}{\partial t} + \nabla \cdot \mathbf{\Gamma}_e = R_e \\[2mm] \dfrac{\partial n_\varepsilon}{\partial t} + \nabla \cdot \mathbf{\Gamma}_\varepsilon + \mathbf{E} \cdot \mathbf{\Gamma}_e = R_\varepsilon \end{cases} \qquad (1)$$

where n_e is the electron number density, n_ε is the electron energy density, t is the time variable, and $\mathbf{E}$ is the electric field strength. The source coefficients R_e and R_ε are defined by

$$\begin{aligned} R_e &= k_{ion}\left(\overline{\varepsilon}\right) n_n n_e + S_{ph}, \\ R_\varepsilon &= k_{ion}\left(\overline{\varepsilon}\right) n_n n_e + k_{diss}\left(\overline{\varepsilon}\right) n_n n_e, \end{aligned} \qquad (2)$$

where $k_{ion}(\overline{\varepsilon})$ is the ionization rate as a function on the mean electron energy, $\overline{\varepsilon} = n_\varepsilon / n_e$, n_n is the total neutral number density, $k_{diss}(\overline{\varepsilon})$ is the dissociation rate coefficient, and S_{ph} is the photoionization rate.

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The ion component is described by

$$\frac{\partial n_i}{\partial t} + \nabla \cdot \mathbf{\Gamma}_i = R_e \qquad (3)$$

where n_i is the N_2^+ number density.

The electron, the electron energy and the ion density fluxes $\mathbf{\Gamma}_e$, $\mathbf{\Gamma}_\varepsilon$ and $\mathbf{\Gamma}_i$ respectively, are given by the expressions

$$\mathbf{\Gamma}_e = -n_e \mu_e \mathbf{E} - D_e \nabla n_e$$
$$\mathbf{\Gamma}_\varepsilon = -\frac{5}{3} n_\varepsilon \mu_e \mathbf{E} - \frac{5}{3} D_e \nabla n_\varepsilon \qquad (4)$$
$$\mathbf{\Gamma}_i = -n_i \mu_i \mathbf{E} - D_i \nabla n_i$$

where μ_e and μ_i are the electron and ion mobilities, and D_e and D_i are the electron and ion diffusivities.

The electric field is accounted self-consistently in the model by implementing the Poisson's equation:

$$\varepsilon_0 \nabla \cdot \mathbf{E} = -q\left(n_i - n_e\right) \qquad (5)$$

where, q is the elementary charge, and ε_0 is the electrical constant.

The photoionization rate S_{ph} is implemented in the "differential" formulation i.e. based on the numerical solution of the Helmholtz equations set (Bourdon et al, 2007).

$$\nabla^2 S_{ph} - \Lambda_{ph}^{-2} S_{ph} = -G_{ph} R_e \qquad (6)$$

Here, Λ_{ph} is the effective photon path length, G_{ph} is the coefficient of the conversion of the ionization rate R_e into photon radiation. The percent of oxygen admixture was set to 2 % (15 Torrs in the equivalent partial pressure units).

We use uniform plasma number density not exceeding 10^3 cm^{-3} and the zero electric field and the photoionization rate S_{ph} as the initial conditions. The boundary conditions are given in terms of generalized expressions for the particle and the electron energy density fluxes on the solid electrode walls (Kozhevnikov et al, 2015)

$$\mathbf{\Gamma}_e \cdot \boldsymbol{n} = \frac{1}{4} n_e \bar{v}_e - \gamma \left(\mathbf{\Gamma}_i \cdot \boldsymbol{n} \right) + \mu_e n_e \left(\boldsymbol{E} \cdot \boldsymbol{n} \right),$$

$$\mathbf{\Gamma}_i \cdot \boldsymbol{n} = \frac{1}{4} n_i \bar{v}_i + \mu_i n_i \left(\boldsymbol{E} \cdot \boldsymbol{n} \right), \tag{7}$$

$$\mathbf{\Gamma}_\varepsilon \cdot \boldsymbol{n} = \frac{1}{2} n_\varepsilon \bar{v}_e - \bar{\varepsilon} \cdot \gamma \left(\mathbf{\Gamma}_i \cdot \boldsymbol{n} \right),$$

where $\boldsymbol{n}$ is the normal vector to the wall surface, $\bar{v}_e$ and $\bar{v}_i$ are the electron and ion thermal velocities, respectively, and $\gamma = 0.1$ is the secondary electron emission coefficient of the ion-wall interaction in nitrogen.

The simulation also accounts the contribution of the field emission (autoelectronic emission) from the cathode surface due to the increase of an electrostatic field near the emission centers formed by the metallic surface roughness. This electron flux is given in terms of a convenient Fowler-Nordheim expression (Kozyrev et al, 1987).

The complete discharge plasma system of equations (1)−(4) is solved in the COMSOL Multiphysics software with Plasma Module implementing the above two-moment model DC-discharge physics. Prior to this, the ionization rates and the electron mobility were calculated using the BOLSIG+ solver (Hagelaar & Pitchford, 2005) except the dissociation rate coefficient that was taken from another source (Cosby, 1993).

We compare the simulation results according to two discharge models. In the first one (I), photoionization was not included, while the second model (II) implements all enlisted elementary processes. The following simulation results of the calculations are the refinement of the preliminary computations of a similar discharge type presented in the conference paper (Kozhevnikov et al, 2018). The effects of oxygen molar fraction increasing in nitrogen (more than 2%) and gas diode parameters variations on the gas discharge dynamics have not been studied focusing on the configurations close to the experimental one.

Results of the simulation

The comparison of the voltage - time profiles is shown in Figure 4 (switching characteristics) for both discharge models. We assume the breakdown formation to be a time point having the maximum voltage at the discharge gap.The breakdown occurs at $t_{breakdown} \approx 92$ ns ($U_{breakdown} \approx 12$ kV) for both simulation regimes (with photoionization and

without it). The presence of photoionization just slightly reduces the breakdown voltage value by no more than 50 V. Such difference is negligibly small, so we can assume that the switching characteristics of two modes are practically identical.
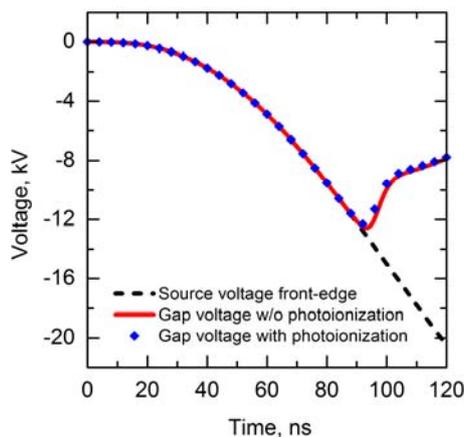
Figure 4 – Discharge voltage- time profiles
Рис. 4 – Коммутационные характеристики разряда
Слика 4 – Профили пражњења напон–време

The discharge evolution is demonstrated in the sequence of the static images in Figure 5. In both cases, the discharge initiation occurs approximately at the time point of t = 50 ns. The movement of the plasma channel begins with the expansion of the initial cathode formation in both spatial directions. After that, approximately from the time point of t = 80 ns, the formation of a plasma tip on the spherical plasma cloud surface occurs. This tip is the main channel of the discharge which slightly expands in the radial direction during the motion. The formation of the initial spherical distribution is associated with the intense losses of the electron energy in the electron impact N_2 dissociation reaction. After the electric field exceeds the Lozansky-Firsov criterion threshold value, the rapid ionization wave development starts from the 0.5-1.0 mm spherical layer surface. The process ends with the discharge gap switching stage at the time point of the gap intersection with the ionization wave channel (t = 90 ns). The gap voltage drop and the corresponding significant increase of the total discharge current accompanies this.

The comparison of calculations with photoionization and without it shows that the effect of the latter on the development of gas discharge is insignificant if the electron impact dissociation reaction of molecular

nitrogen is included in the model. Also, the quantitative characteristics of the plasma do not change. The significant increase of the oxygen partial pressure in the photoionization model, and hence the fraction of oxygen in gas mixture will probably lead to a visible change in the spatial discharge structure, but also the simulation will require a more accurate plasma-chemical reaction set. Nevertheless, one of this paper's aims is to investigate the influence of a minor electro-negative mixture to the discharge formation and evolution.
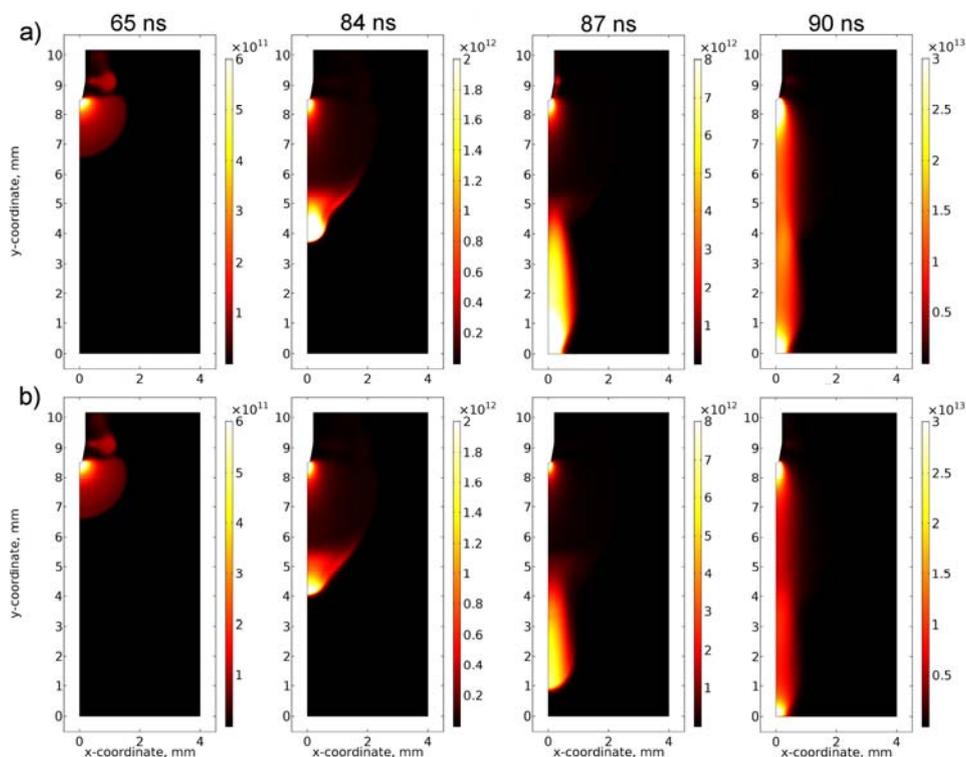
Figure 5 – Spatial distribution of the electron number density (scale in cm^{-3}) for gas discharge a) without and b) with the photo-ionization process for the same time points
Рис. 5 – Пространственные распределения концентрации электронов (в единицах в куб.см.) в газовом разряде а) без и b) с учётом процесса фотоионизации в одинаковые моменты времени
Слика 5 – Просторна дистрибуција густине броја електрона (скала у ст$^{-3}$) за пражњење гаса: а) без процеса фотојонизацијеза исте временске тачке и б) са процесом фотојонизације за исте временске тачке

Additionally, the parameters of runaway electrons have been calculated in order to discover their influence on the discharge dynamics. The calculations were based on the "hybrid" theoretical approach, involving the principles of physical kinetics described earlier (Kozyrev et al, 2016). The results show that the runaway electron current passing through the anode is too small compared to the full discharge current, so the influence of the runaway electrons on the discharge is negligible. Such conclusions are connected with the long rise time (more than 100 ns) of the operating voltage pulse.

Conclusion

The simulation of the gas-filled diode breakdown in the tip-to-plane electrodes configuration shows good agreement with the existing experimental data. The current theoretical study shows that gas photoionization insignificantly affects the discharge spatial structure for the positive polarity of the anode voltage. It was also shown that, in gas mixtures containing a valuable amount of nitrogen, the electron impact dissociation plays an important role in the formation of the spatially-inhomogeneous discharge structure.

Our theoretical study of gas discharges of submicrosecond duration substantially complements the existing experimental base. The obtained information about the time-spatial discharge structure allows studying the generation of runaway electrons and X-rays under the atmospheric pressure. This opens up broad prospects for the creation of high voltage power supplies for UV and VUV excilamps as well as for the application in the fields of industrial X-ray radiography.

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СУБМИКРОСЕКУНДНЫЙ РАЗРЯД АТМОСФЕРНОГО ДАВЛЕНИЯ С НЕОДНОРОДНОГО ЭЛЕКТРОДА (ОСТРИЯ) В НАПРАВЛЕНИИ ПЛОСКОГО ЭЛЕКТРОДА

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Резюме:

В данной работе рассматриваются результаты численного моделирования быстрого разряда при атмосферном давлении в сильно неоднородной конфигурации диода «острие-плоскость», заполненного смесью азота и кислорода. Моделирование основано на современной гидродинамической модели разрядной плазмы, учитывающей также фотоионизацию газа. Было показано, что при отсутствии фотоионизации разряд развивается аналогично случаю с фотоионизацией (за исключением случая обратной полярности приложенного напряжения). Теоретические результаты соответствуют существующим экспериментальным данным для структуры пространственного разряда и для временных характеристик тока / напряжения разряда.

Ключевые слова: плазма, численное моделирование, атмосферные разряды.

ПРАЖЊЕЊЕ У НАНОСЕКУНДАМА ПРИ АТМОСФЕРСКОМ ПРИТИСКУ ОД НЕУНИФОРМНЕ ЕЛЕКТРОДЕ (ВРХ) ПРЕМА РАВНОЈ ЕЛЕКТРОДИ

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Сажетак:

У раду се разматрају резултати нумеричке симулације брзог пражњења при атмосферском притиску у високо нехомогеној конфигурацији диоде типа врх–раван напуњене смешом азота и кисеоника. Симулација се заснива на савременом хидродинамичком моделу пражњења плазме, који такође узима у обзир фотојонизацију гаса. Показано је да се, у одсуству фотојонизујућег пражњења, он развија слично као и код фотојонизације, са изузетком напона инверзне поларизације. Теоријски резултати су конзистентни са постојећим експерименталним подацима за просторну структуру пражњења и за карактеристике пражњења напона/струје.

Кључне речи: плазма, нумеричка симулација, атмосферска пражњења.