NANOSECOND HIGH-VOLTAGE GAS DISCHARGE DEVELOPMENT: ELECTRON ENERGY BRANCING AND GAS EXCITATION

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Abstract

Spatio-temporal evolution of electric and spectral parameters of plasma created by high-voltage periodic pulsed discharge has been studied. Discharge characteristics for positive and negative polarity of high-voltage pulse were investigated. Longitudinal component of electric field and electron density at every time moment at different distances from high-voltage electrode were obtained from excessive discharge measurements. On the other hand, electric field was derived from relative time-resolved emission of second positive and first negative systems of molecular nitrogen. Comparison of electric field values determined by different methods leads to the conclusion of non-local and non-stationary character of the electron energy distribution function during discharge development.

Introduction

Fast ionization wave (FIW) is a type of discharge which is realized at multiple overvoltage and characterized by high propagation velocities ($10^4 - 10^5$ cm/s), high uniformity and repeatability on the pulse repetition mode [1, 2]. The considerable difference of FIW parameters at different polarity of the high voltage pulse are found and explained by many researchers [1, 3]. However due to the fact that in general integral values, such as current, wave velocity, amplitude attenuation along the length were measured in experiments there was no possibility to explain the difference in FIW development by differences in elementary processes at different polarity.

In this study with the use of both electrical and spectroscopy diagnostic we seek to describe the differences in development of FIWs of negative and positive polarity, using nitrogen as an example. The dynamics of charge per unit length and spatial-temporal distribution of emission produced by $C^3\Pi_u$, $\nu = 0 \rightarrow B^3\Pi_u$, $\nu'' = 0$ and $B^2\Sigma^+_g$, $\nu' = 0 \rightarrow X^2\Sigma^+_g$, $\nu'' = 0$ are measured. Spatial-temporal distributions of electric field and electron concentration are derived on the basis of the data on charge dynamics per unit length. Rates of $N_2(C^3\Pi_u$, $\nu=0)$ and $N_2^*(B^2\Sigma^+_g$, $\nu=0)$ electronic level population are obtained with the use of measured emission intensities.
Experiment

Discharge was initiated in a tube of quartz, 17.5 mm inner diameter, 21.5 mm outer diameter and 600 mm length. The discharge tube was surrounded with a cylindrical metallic shield of 60 mm inner diameter. Pulse of 13.5 kV amplitude, 25 ns duration at half-height and 6 ns rise time was supplied from a high voltage generator with a repetition frequency of 40 Hz. The dynamics of excessive charge along the discharge tube length was measured by a calibrated capacitive gauge (capacitance of the output arm of the divider is 330 pF) movable along the discharge device length, beginning from the high-voltage electrode to a distance of \( L = 45 \) cm towards the low-voltage electrode at a length interval of 3 mm. Emission was recorded by the optical system comprising monochromator MD 12A (aperture ratio is 1:3; a grating with slit density of 1200 slit/mm; operating range is 200–500 nm, reverse linear dispersion is 2.4 nm/mm) and high current photomultiplier 11F1U F7S (the range of photocathode spectral sensitivity is 250–600 nm). Emission of both studied transitions was measured with a step of 5 cm along the discharge tube length, beginning from 1.5 cm from the high-voltage electrode. Coaxial photocell with transport time of 500 ps was used to determine time correlation between electric and optical signal. Signals were recorded by oscilloscope Tektronix TDS-380. Temporal resolution of diagnostic system was less than 1 ns and was determined by the oscilloscope frequency bandwidth.

Dynamics of charge, electric field and electron concentration

Figure 1 illustrates temporal dependencies of reduced electric field and electron concentration in section \( x = 13 \) cm from the high-voltage electrode at different polarities of the voltage pulse. It is clearly seen that temporal dependency of electric field in FIW of negative polarity is characterized by two maxima. The first of about 400 V/(cm Torr) corresponds to the precursor propagation (indicated with letter P in the figure), the second, \( \sim 120 \) V/(cm Torr) \( \sim \) to the main wave (indicated with letter M in the figure). Field behind the FIW front is about 80 V/(cm Torr). In about 3 ms electron concentration in the precursor reaches values of \( \sim 10^{12} \) cm\(^{-3}\), in the main wave it increases in approximately three times else in the same time.

The reduced electric field in the front of positive polarity wave reaches 1kV/(cm Torr), which is approximately three times higher than the field in the precursor of the negative wave and significantly higher than the electron runaway threshold. However, behind the front the reduced electric field in the positive wave (\( \sim 40 \) V/(cm Torr)) is approximately two times lower than in the negative wave. It should be noted here that in the case of negative polarity two main processes are responsible for ionization wave propagation from the high voltage electrode. They are ionization by fast electrons and photoinization, like to the propagation of anode-directed streamer. In the case of positive polarity the crucial process is photoinization, and this difference should be reflected in the dynamics of electric field.
Figure 1: Reduced electric field (curves 1-2) and electron concentration (curves 3-4) for FW of negative polarity (curves 1,3) and positive polarity (curve 2,4) in section / = 13 cm.

Population of Electron Excited States in Ionization Wave of Different Polarities

Emission of second positive \((C^2Π_u, \nu' = 0 \to B^3Π_g, \nu'' = 0)\) and first negative \((B^2Σ^+_g, \nu' = 0 \to X^2Σ^+_g, \nu'' = 0)\) systems of molecular nitrogen was recorded simultaneously with electrodynamic parameters over every 5 cm along the discharge gap length. It is seen (figure 2) that the dynamics of emission qualitatively correlates with the dynamics of the field and electron concentration.

At negative polarity the two waves of the first negative system emission which are caused by propagation of the precursor and main wave are clearly distinguished. The rapid growth of emission takes place in the precursor; emission intensity value remains practically constant behind the precursor front. Propagation of the main wave causes a new growth of emission intensity. On the contrary, emission intensity of second positive system monotonically increases beginning from precursor arrival at the section and finishing by the time approximately corresponding to the high voltage pulse "time off". Therewith, arrival of the main wave causes essential increase in the emission growth rate, which is clearly seen in figure 2. Let note that at negative polarity the electric field in both the precursor and the main wave is sufficiently high to effectively excite both the levels. The emission intensity in the main wave increases approximately in two three times in comparison with emission intensity in the precursor.

At positive polarity the dynamics of the second positive system emission demonstrates the presence of two waves - incident and reflected, which is fully in compliance with the dynamics of the electric field. The emission intensity increases up to the rear edge of the high-voltage pulse, therewith, the rate of emission growth significantly increases in the reflected wave. Emission intensity of first negative system increases for approximately 5 ns nearby the front of the incident wave where the electric field is high enough. The emission wave associated with the reflected wave is minor, which is explained by the weak field in the reflected wave. Really, in weak fields of reflected wave the electric field and the electron density seem to be sufficient for population of the \(N_2(C^2Π_u, \nu = 0)\) level, while
Figure 2: Emission intensity: a) the second positive and b) first negative systems of nitrogen. 1) Pulse polarity is negative. 2) Pulse polarity is positive.

Excitation of high-energy $N_n^+_2 (B^2 \Sigma^+_u, \nu=0)$ state is less effective.

Electric Field and EEDF Dynamics Analysis

The electron energy distribution function (EEDF) behind the breakdown front forms as a result of competition between two oppositely directed electron fluxes along the energy axis. One of them is due to the relaxation of high-energy electrons produced in the front where electric field is very high; it is downward directed along the energy axis. It is clear that in the case of positive polarity the influence of this flux should be more pronounced because of preferable electron motion downstream from the front. Inside the plasma, another electron flux arises due to the presence of electric field and heating of electrons behind the front: it is directed from low to high energies, which is typical for gas discharges. The time required for the EEDF to relax to a quasisteady function is governed by the time scales of both mentioned fluxes. The spatially nonlocal processes that increase the mean electron energy ahead of the front should also have a significant effect on the shape of the EEDF.

Electric field obtained from electrical measurements does not carry any information about electron energy distribution. At the same time the rate of excitation of the given electronic level reflects behaviour of electron density, electric field and electron energy.
distribution $f(ε, x, t)$. Owing to the essential difference in cross sections of excitation by direct electron impact, the reduced electric field dependencies of these levels rate constants essentially vary in wide range of electric fields, which makes it possible to calculate the electric field, using the electron energy distribution and known from experiment emission intensities of $(C^3Π_u, \nu' = 0 \rightarrow B^3Π_g, \nu'' = 0)$ and $(B^3Σ^+_g, \nu' = 0 \rightarrow X^3Σ^+_g, \nu'' = 0)$ transitions.

So, we can compare electric field behaviour in two cases: electric field $E_ε(x, t)$ calculated on the basis of spectral data and electric field $E_p(x, t)$ obtained from electrical measurements. Deviation of $E_ε(x, t)$ from $E_p(x, t)$ will give us estimation for overpopulation of $N^+_p(B^3Σ^+_g, \nu = 0)$ level. In fact, the increase of $E_ε(x, t)$ in comparison with $E_p(x, t)$ means that $Y_ε(x, t)/Y_p(x, t)$ decreases in comparison with this value in equilibrium conditions. As far as constant rate of $N^+_p(C^3Π_u, x = 0)$ level population flattens with electric field, it implies that $Y_p(x, t)$ increases and reflects preferable excitation of high-energy levels.

Figure 3 shows the dynamics of electric field obtained in two ways: from spectroscopy and from measurements of charge per unit length described in the previous section.

Figure 3: Dynamics of electric field measured in two waves with the use of a capacitive gauge and the spectroscopic method (bold curve). a) – pulse polarity is negative, b) – pulse polarity is positive.

An essential overestimate (up to ten times) of the electric field obtained by the spectroscopic method relative to the obtained by measurements of the dynamics of charge per unit length is typical for the positive polarity wave. This feature can likely be explained
by essential EEDF non-locality and non-stationarity behind the wave front. Let consider possible factors that determine the non-locality and non-stationarity of electron energy distribution in case of positive polarity pulse.

Thus, spatial-temporal dynamics of electron density, longitudinal electric field and emission of different spectral bands has been investigated experimentally in nanosecond discharge in molecular nitrogen at a pressure of 5 Torr and high-voltage pulse amplitude of 13.5 kV for both polarities of the pulse. Such distinguishing features as precursor development in the case of negative polarity or strongly pronounced reverse wave in the case of positive polarity were studied in detail.

It was demonstrated that in general behaviour of electric field, electron density and emission intensity is in good correlation with our previous results: electric field has strong and narrow maximum; peak values of the field are very high; major excitation of electron levels takes place behind the front of the fast ionization wave in residual fields. At the same time considerable difference between measured values for different polarity has been observed. The most remarkable result is that the peak electric field value in the positive polarity breakdown is few times higher than in the negative polarity one. This leads to significant distinctions both in electron density and emission intensity.

Comparison of electric field behaviour obtained from electric measurements $E$, and calculated from emission intensity of second positive and first negative systems of molecular nitrogen $E_I$, has demonstrated that for positive polarity electric field $E_I$ value is by the order of magnitude greater than $E$, value. It means that very strong overpopulation of high electron levels (such as $N_2^*$($\Pi_{\Sigma^+}^*$, $v=0$) state of nitrogen ion) is observed in comparison with calculated within the framework of the local approach.

To conclude, comparison of discharge development at various polarities of the high voltage pulse has shown that differences in the development are the result of two causes: near by electrode effects which shows up in start delay and availability of the precursor in FIW of negative polarity and essential non-locality and non-stationarity of breakdown, which are caused by electrons produced. Such electrons after the wave front enrich the high energy part of EEDF, resulting in a noticeable increase of the rate of the high electron levels population, which is especially pronounced in the positive polarity breakdown.

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References

