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# Streamer-to-Filamentary Transition and Electron Temperature Measurement in Nanosecond Surface Discharge at High Pressures

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**This paper poses a physical view of streamer-to-filamentary transition process from transition-appearing condition and the trace of electron temperature in the discharge and near afterglow. It was observed that percentage of oxygen in nitrogen and oxygen mixtures plays a significant role during the transition process. In particular, adding 2% of oxygen was sufficient to produce a large shift in the transition point compare to pure nitrogen.**

## I. Introduction

HIGH pressure surface nanosecond pulsed discharge (nSDBD) has been suggested as a tool for the distributed ignition of combustible mixtures in [1–4]. It was shown that the discharge pattern provides a stable repeatable ignition of lean mixtures (f.e.  $ER = 0.3$  CH<sub>4</sub> : O<sub>2</sub> : Ar mixture [1, 3]) up to the pressures  $P = 16$  bar. A recent review of ignition of combustible mixtures by nanosecond discharges [5] points out that the advantages of plasma assisted ignition are demonstrated and proved quantitatively for moderate gas densities,  $N \leq N_{atm}$ , where  $N_{atm}$  is a normal gas density at  $T = 300$  K and atmospheric pressure. A very limited number of scientific groups work on initiation of combustion by nanosecond discharges at high gas densities. Real combustion devices operate at  $P \geq 10 - 20$  bar. Little is known about the development of discharges in combustible mixtures at high pressures. With gas temperature, discharge parameters change only slightly, while the rates of combustion reactions increase exponentially. At the same time with gas density increase, discharge spatial structure rearranges itself to keep the reduced electric field ( $E/N$ ,  $E$  is electric field and  $N$  is a gas density) value high enough for efficient ionization.

With pressure ( $P > 1$  bar) and/or voltage ( $U > 30$  kV) increase, a transition to a new mode of the discharge has been observed, first in air for the negative polarity [1, 6] and later in air and nitrogen for both polarities of the high-voltage pulse [2, 4]. During 1-2 nanoseconds in a single-shot regime, each 4-5 streamers are replaced by a single filament propagating from the high-voltage electrodes with approximately the same velocity as a “new-born” streamer propagating along the non-charged surface of dielectric; current changes from 0.1 per streamer to 1 A per filament; the length of the filaments can reach about 1 cm for 20 ns pulses and gas pressure up to 10 bar. Plasma changes from a plasma typical for streamer discharges, with a relatively low density of electrons, about  $10^{15} \text{ cm}^{-3}$ , to a plasma with the electron density about  $10^{19} \text{ cm}^{-3}$ . The changes in electron density are accompanied with dramatic changes in the discharge spectra: molecular bands of nitrogen typical for low temperature atmospheric pressure plasmas are replaced by a continuum emission and rare atomic and atomic ion lines with a well-defined broadening decreasing in time. A typical time of decay of the electron density is a few tens of nanoseconds, much longer than a typical time of recombination of molecular ions at the given conditions. It should be noted that a similar transition with creating a bright filamentary

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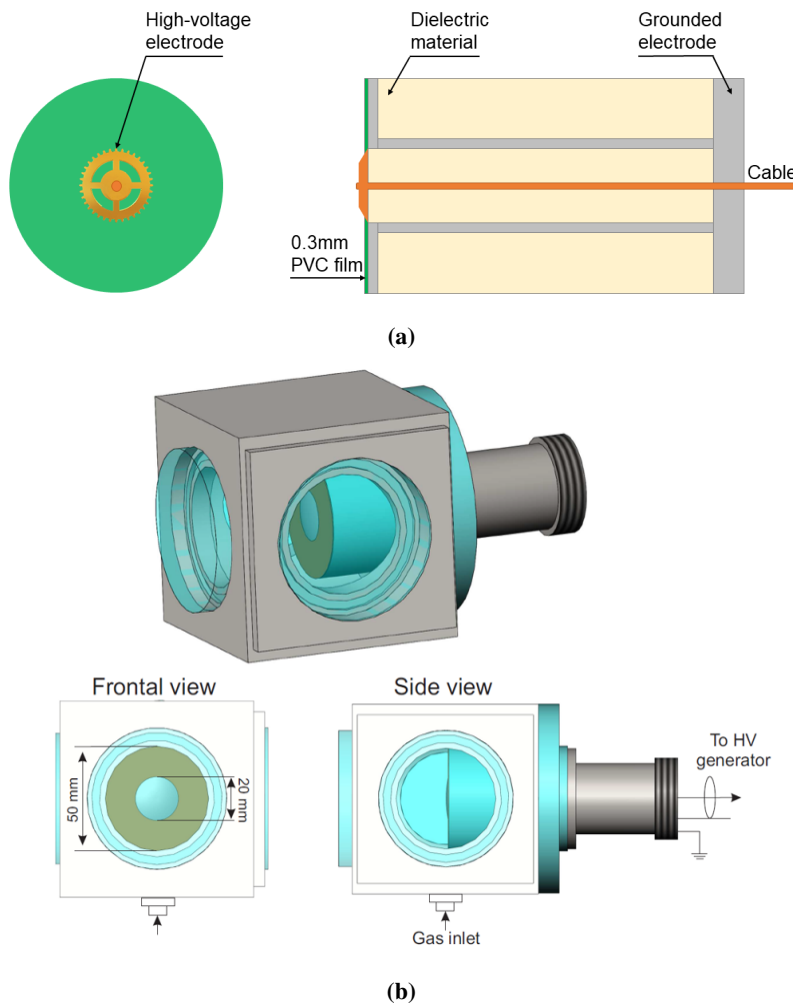
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channel with a diameter tens of microns and elevated electron densities has been observed in a set of papers devoted to study of nanosecond repetitive ( $kHz$  and higher) discharges in pin-to-pin geometry between two open electrodes at small discharges gaps, less than  $1\text{ mm}$  [7–9]

The aim of the present paper is to study streamer-to-filament transition in different gas mixtures and to explain the long plasma decay after turning off the high voltage pulse.

## II. Experimental Setup

A detailed schematic of the electrodes and of the discharge cell geometry used in this work is presented in Fig.1. This configuration is similar to that used in [2]. The electrode systems in a coaxial configuration was developed to satisfy the conditions of experiments in a rapid Compression Machine (RCM) [3]. A metal disk  $20\text{ mm}$  in diameter or a gear wheel of the same diameter to stabilize the position of the filament for optical measurements served as a HV electrode. The internal diameter of the low-voltage (LV) ground electrode was equal to the diameter of the HV electrode, and the external diameter of the LV electrode was  $46\text{ mm}$ .



**Fig. 1** (a) schematic of the system of electrodes; (b) schematic of the high pressure constant volume discharge cell setup.

To change the surface of the dielectric without changing the capacitance of the electrode system, PVC (dielectric permittivity  $3 - 3.5$ )  $d = 0.3\text{ mm}$  thick, or ceramics (MACOR,  $d = 0.5\text{ mm}$ , dielectric permittivity  $5 - 6$ ), were glued to the grounded electrode by Geocel FIXER Mate silicon glue. The electrode system was installed in a constant volume chamber allowing work at pressures  $100\text{ Torr} < P < 12\text{ bar}$ . HV pulses,  $20\text{ ns}$  in duration and  $2\text{ ns}$  rise time, positive

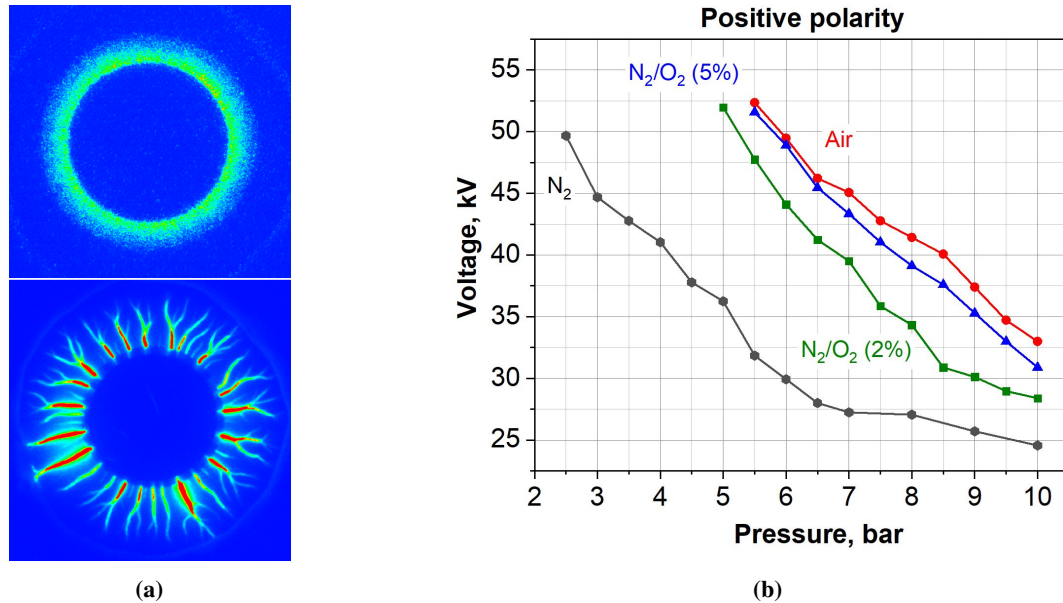
or negative polarity, 10 – 50 kV in amplitude on the HV electrode were delivered by the coaxial 30 m long 50  $\Omega$  cable from the FPG20–03PM or FPG20–03PN pulser (FID Technology). A calibrated custom-made back current shunt installed in the center of the cable allowed measurements of current and voltage waveforms ICCD images in the wavelength range 300 – 800 nm were taken by a Pi-Max4 Princeton Instruments ICCD camera. A broad-band filter was used to remove the second diffraction order. Optical spectra, 480 – 620 nm, were recorded by an ACTON spectrometer (SP-2500, 1200 l/mm grating) coupled with the ICCD camera.

Before the experiment, the discharge cell was pumped down to  $10^{-2}$  Torr. N<sub>2</sub> and O<sub>2</sub> (Air Liquide) with < 100 ppm of impurities were used to prepare the mixtures. All the experiments were carried out in a single shot regime.

### III. Results and Discussion

#### A. Streamer-to-filament transition

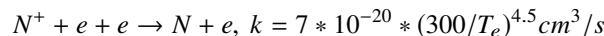
The transition from streamer to filamentary discharge was studied with the help of ICCD imaging. The curves of a transition were obtained for different percentage of O<sub>2</sub> in N<sub>2</sub> : O<sub>2</sub> mixtures. Synthetic air, pure nitrogen and mixtures of nitrogen with 5 and 2% of O<sub>2</sub> were studied. The point was considered as a transition point if during first 13 ns of the discharge at least 3 to 5 filaments appeared along the edge of the high-voltage electrode (typically this means that in the next 1 – 2 ns all the edge of the electrode will be covered with a regular “grid” of radially propagated filaments). Fig.2 presents the ICCD images of two modes discharge and the transition curves.



**Fig. 2** (a) ICCD images of streamer (top) and filamentary (bottom) sNDBD discharges in air; the ICCD gate is 20 ns. (b) Voltage and pressure map indicating the regions of streamer discharge (below the curves) and filamentary discharge (above the curve).

From Fig.2 (b), it can be seen that the pressure and voltage of the transition point strongly depend on the oxygen concentration in N<sub>2</sub> : O<sub>2</sub> mixtures. For instance, at the pressure  $P = 6$  bar, in pure nitrogen the transition occurs when the voltage reaches up to 30kV while in N<sub>2</sub> : O<sub>2</sub>(2%) mixtures, the transition required voltage increases nearly 50% up to 44 kV. And then the continuous increase of oxygen does not significantly affect the transition condition any more when the percentage of oxygen is larger than 5%.

There are two work hypothesis: (i) the electron density decay is due to almost complete dissociation in the afterglow and so a sharp change of the main ion: recombination of atomic ions in the following process [10]



$T_e$  is the electron temperature, takes tens of nanoseconds; (ii) production of equilibrium plasma in early afterglow.

In the last case, the density of ions and electrons will be defined by Saha equation, and the decay of the electron density will correlate to the decrease of the electron temperature of plasma in the afterglow.

### B. Time-resolved electron temperature measurement in negative polarity

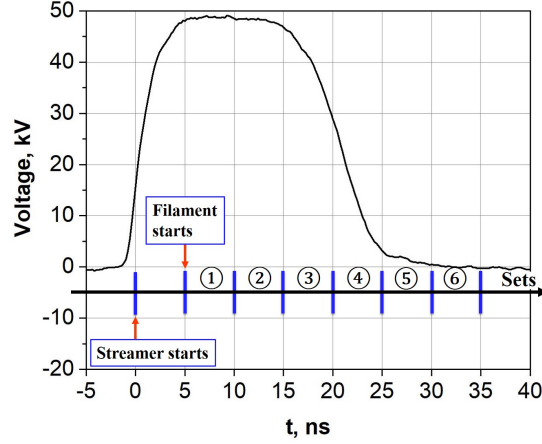


Fig. 3 High voltage pulse in discharge corresponding with experimental sets

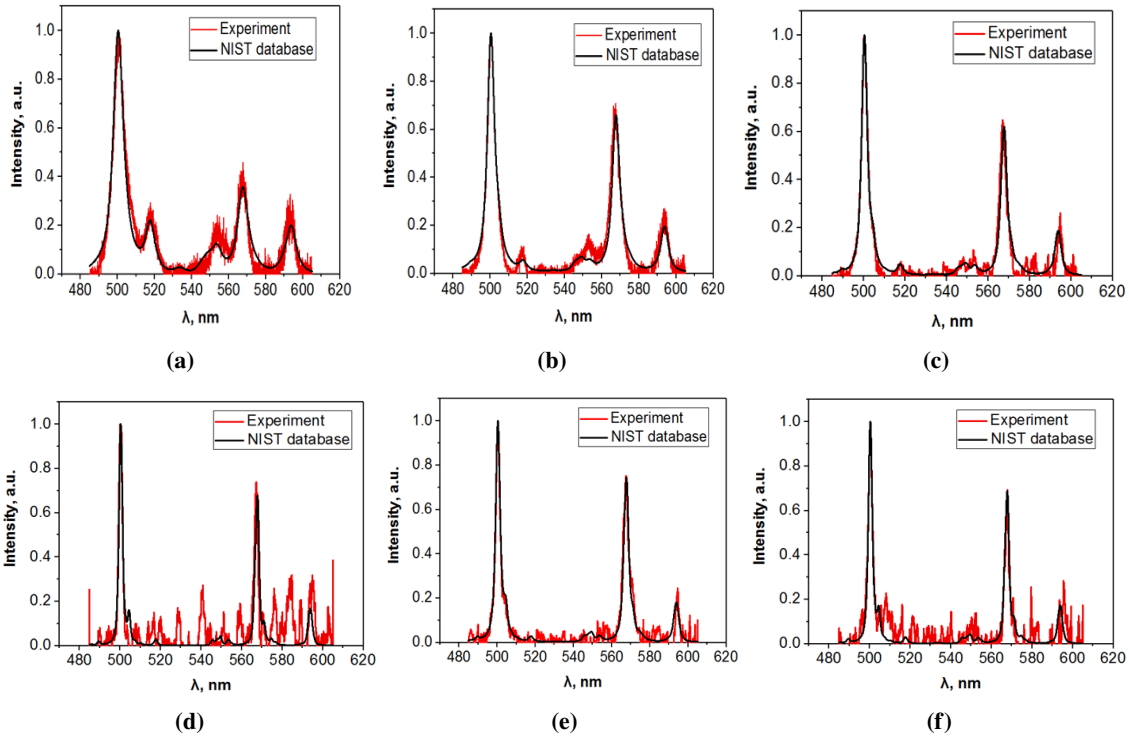


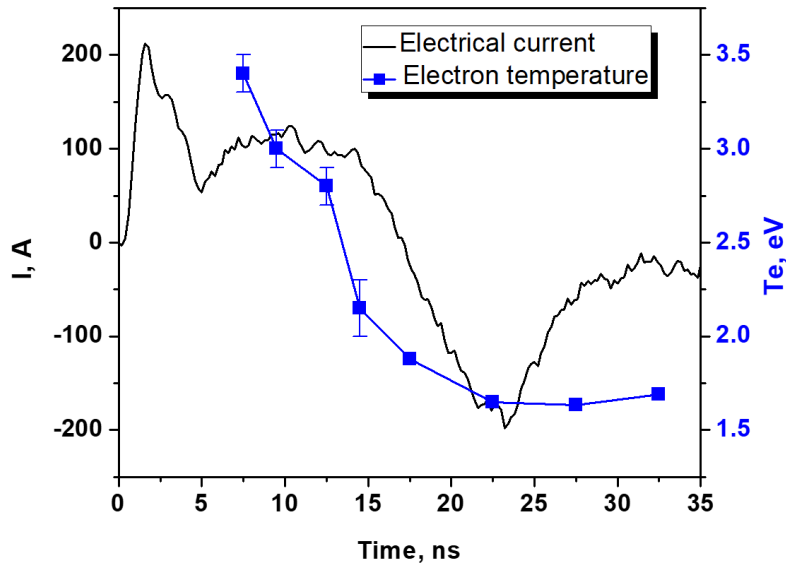
Fig. 4 Experimental N<sup>+</sup> emission (red curves) and NIST-based extrapolation (black curves). The time instants for the frames are 5-10, 10-15, 15-20, 20-25, 25-30 and 30-35 ns after the discharge start; the streamer-to-filament transition happens within the interval 0-5 ns.

Electron temperature  $T_e$  in discharge and near afterglow was measured on the basis of the Boltzmann plot for N<sup>+</sup> ions in the spectral range 485 – 605 nm. The experiments were carried out in pure nitrogen at  $P = 6.8$  bar and the input

voltage in discharge is 48 kV of positive polarity. The optical emission signal was accumulated over the gate interval equal to 5 ns. The delay relative to the discharge start was changed to get the time-resolved data. The discharge pulse duration is 20 ns. The streamer-to-filament transition happens 5 ns after the rising edge of the discharge pulse, shown in Fig.3.

After subtracting the ICCD background and the background from the cw emission, the data were modeled using NIST database [11] for atomic species ( $N^+$ ). Obtained optical emission signals and corresponding modeling based on NIST database are presented in Fig.4, in which (a)(b)(c) were taken from filamentary discharge region while (d)(e)(f) indicate the results of afterglow area.

The results on the electron temperature in the discharge and near afterglow are presented in Fig.5. The main conclusion is that the  $T_e$  is high in the discharge, almost 3.5 eV; it drops down to about 1.5 eV in early afterglow, due to high ratio of quenching and recombination effects, staying at this value for at least 20 ns.



**Fig. 5 Typical waveforms of electric current and electron temperature as functions of time.**

In the future, we will continue to measure the dynamics of the electron temperature at different polarities and in different mixtures; to provide an accurate synchronization with electric current with the aim to describe the decay of the electron temperature, and as a consequence the decay of the electron density in near afterglow of the nanosecond surface dielectric barrier discharge at high pressures.

#### IV. Conclusion

This paper gives an experimental view of physics of filamentary discharge by measuring the streamer-to-filament transition happening condition and electron temperature during discharge and near afterglow region. Dramatic effects of oxygen in transition were detected and the sharp decay of electron temperature as well.

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