Ultrafast imaging and spectroscopy of low pressure N_2 streamer discharge.

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In this contribution we report on the spatial and temporal evolution of nanosecond discharge emission. ICCD images of the streamer formation and propagation in a volume DBD geometry were captured with time resolution of 50 ps by employing technique of kinetics series with progressive increase of the ICCD gatewidth. We show that during initial phase an avalanche slowly builds up in the anode region with subsequent formation of cathode direct streamer with an estimated average propagation speed reaching $5\times10^6\pm0.5$ m/s.
Spectra of this phase were acquired with different spatial and temporal resolution. In particular spatially resolved spectra with 100ps effective gating enable to evidence the distincitive spectral characteristics of the different phases.

1. Introduction

A streamer is a frequent form of transient discharge which develops from an electron avalanche in an overvolted gap. The most important characteristics of such streamers are very high propagation velocity, a small streamer channel radius, and high density and mean energy of free electrons occurring in the streamer head. All these facts make laboratory streamers extremely difficult to observe with sufficient spatial (μm) and temporal (ps) resolutions [1–3].
Optical emission produced by streamers is determined by the spatial distribution of various species within the streamer channel that were excited to radiative states by streamer head electrons. Radial distributions produced by streamer electrons are strongly non-uniform because the maximum electric field of a propagating streamer occurs on the axis of the streamer and rate constants of the excitation, dissociation and ionization processes exponentially depend on the E/N. Radial non-uniformity of excited species have to be considered when using diagnostics with limited spatial and temporal resolutions or when comparing experimental results with numerical simulations [1–3].
In this contribution, evolution of optical emission produced by developing streamer filament in the DBD gap of 5mm was inspected by employing ultrafast ICCD diagnostic at 50torr in pure N_2. Due to the enhanced stability of the streamer discharge triggered by short nanoseconds high voltage pulse with sharp rise time of the order of few nanoseconds and by employing technique of kinetic series with a variable width of ICCD intensifier gate, we have been able to achieve effective temporal resolution of tens of picoseconds. Such an enhanced temporal resolution allows resolving various phases of the streamer channel evolution, either through averaged ICCD images or ICCD emission spectra.

2. Experimental Setup

A single triggered streamer DBD reactor consists of a pair of MACOR® glass-ceramic disks with embedded circular flat metallic electrodes (diameter of upper/lower metallic electrode 2/10 mm, thickness of both dielectric layers 0.5 mm) placed in a stainless-steel chamber [1]. The gap between both ceramic discs was fixed at 5 mm.
The chamber is equipped with quartz windows for optical diagnostics, gas feed input/output ports and a high voltage (HV) interface. The chamber was fed with nitrogen of high purity purity nitrogen (grade 5.0 purity 99.999%) through a MKS mass-flow controller (with a fixed flow of $\Phi = 0.1$ slm). The pressure was regulated by using a needle valve backed by an oil-free diaphragm vacuum pump (KNF Laboport) and measured by a piezo gauge.
The streamer discharge was powered by a home-made High Voltage pulse power supply composed of charging DC circuit and a Behlke solid state switch generating repetitive positive HV pulses (u_P up to 10 kV, ~100 ns long, repetition rate $f_P = 100Hz$).
Images and spectra were acquired by means of an imaging spectrometer (Acton SP300i) equipped with a fast gated ICCD Princeton Instruments model PIMAX 4. An UV quartz lenses telescope was used to collect the emission from the discharge gap. Fast kinetics technique with fixed or variable gate (with steps down to 20 ps) was used to collect fast streamer event with spatial resolution of 12μm.

3. ICCD images

Figure 1 shows DBD electrode geometry with inserted ICCD image (accumulated image of 200 micro-discharge events occurring in pure nitrogen, taken with an ICCD gate of 5 ns). Dashed lines represent the region of interest selected for studying the propagation of streamer discharge and its optical emission. We selected areas close to the dielectric surfaces with embedded electrodes and the center of the gap (2.5 mm far from both electrodes).

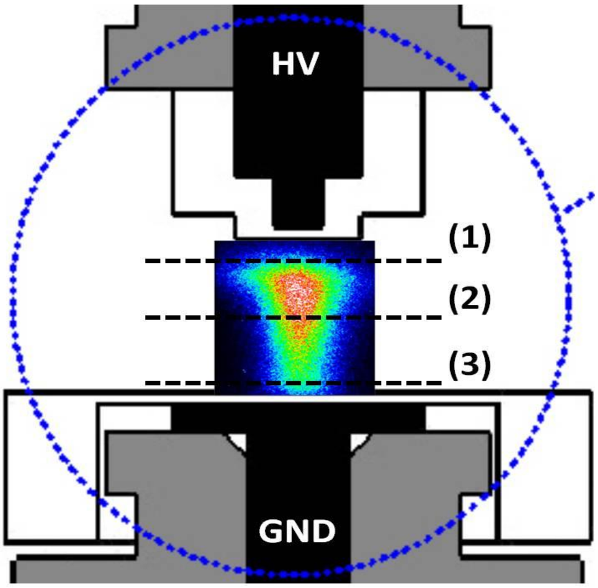

Figure 1. Schematic of the DBD discharge electrodes with inserted integral ICCD image of the discharge event. The discharge region is imaged on the spectrometer entrance slit by means of a quartz telescope.

Kinetic series of ICCD images were obtained using fixed delay with respect to the discharge trigger and varying the gatewidth with the step of about 50 ps. Figure 2 captures the three phases of the streamer evolution (avalanche build-up, avalanche-to-streamer transition and streamer arrival to cathode) occurring during first 2 ns . The integral of the total discharge emission, obtained by integrating a 10 pixel wide strip (about 120 μm) of streamer images at positions shown in figure 1, is repoted in the right side of figure 2. The collected image corresponding to the onset of the emission, indicated by a red arrow on the graph, is shown on the left side. The event propagates with a smaller velocity across the first half of the gap, and then significantly accelerates across the second half. The estimated average propagation speed during the streamer phase reaches $5\times10^6\pm0.5$ m/s.

On the left side averaged images of 200 events are reported at the time corresponding to plasma emission onset occurring at the HV, Middle of the gap and GND electrode positions.

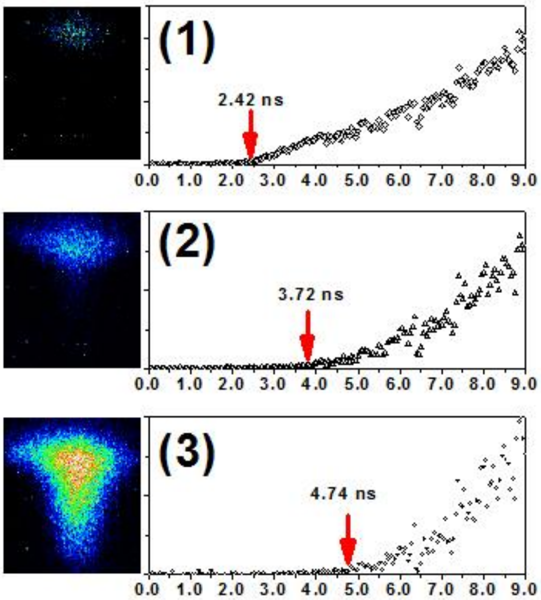

Figure 2 Streamer event evolution captured through three ICCD images (left) and temporal evolution of emission (right) integrated along (1), (2) and (3) positions. Onset of emission indicated by red arrows.

5. ICCD spectra

Spatially and temporally resolved emission spectra were collected for different spectral regions with different time resolution. Kinetic series (1000 accumulated events) of spatially integrated emission over the entire streamer discharge gap, taken with a fixed gate of 3 ns and a time step of 3ns is reported in figure 3. Band emission from various N_2 SPS transitions and the N_2^+ FNS (0,0) can be clearly identified. The temporal evolution of the N_2 SPS and N_2^+ FNS systems occurs on two different time scales.

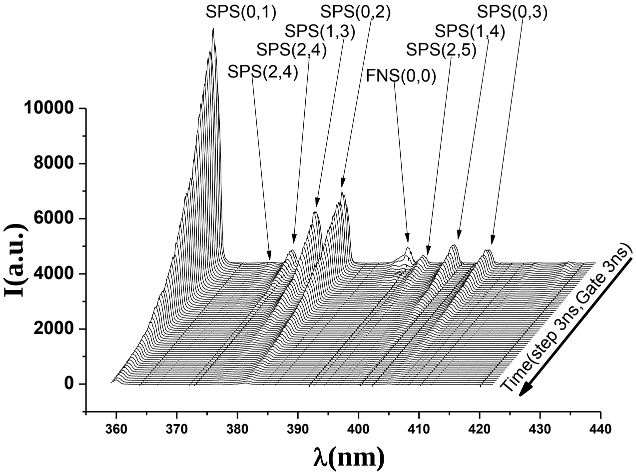

Figure 3. Kinetics series with a fixed gate of 3 ns and a time step of 3ns. FNS and SPS emission integrated on all the gap.

While emission from FNS system is almost completely undetectable after 40 ns the SPS emission from the stronger band heads is still present at the end of the series i.e. 180 ns.

The luminosities of the FNS and SPS are determined by direct electron impact excitation processes. In weakly ionized non-equilibrium plasmas, being the mean electron energy of a few eV, only a small fraction of electrons are above the threshold for excitation processes (18.7 eV and 11.0 eV for FNS and SPS respectively). A higher threshold energy is consistent with a stronger rate constant dependence on E/N [3–5]. Consequently, the FNS band spatio-temporal distribution tracks the development of E/N while the SPS emission is related to the convolution of the electric field and the electron density. Knowing the ratio of FNS and SPS emissions the E/N could be estimated [4].

In order to highlight such ultrafast processes, streamer head emission must be studied with high temporal resolution. For example, possible way how to perform such task is employing ICCD kinetics series fixed intensifier ON time with respect to high-voltage pulse and varying intensifier's gate width by steps of 50ps.

A typical result of a spatially integrated spectra over the entire discharge gap in the first 650 ps of the streamer propagation is reported in figure 4. By making a subtraction of the subsequent spectra in kinetic series (acquired with sufficient statistics) we succeeded obtaining spectra with time resolution down to 50 ps.

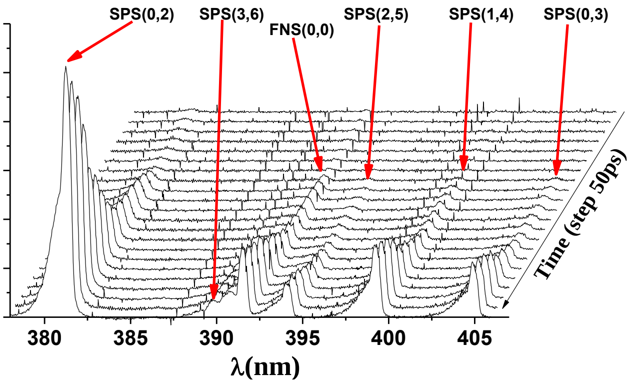

Figure 4. Kinetic series of the full binning o the emission from streamer in the first 625 ps of the discharge with variable gate, difference from gate to gate of 50 ps.

In order to understand the evolution of the streamer parameters, nevertheless, spatially resolved measurements are required. Figure 5 reports the emission spectra taken in an effective gate of 100 ps after the plasma emission onset shown in figure 2 for the three different position.

The localized light spot at the anode shown at the top left side of Fig. 2 marks the end of the avalanche build-up phase. Soon after, the accumulated space charge causes a cathode-directed ionizing wave. At the back of the ionizing wave, electrons drift toward the anode, generating a glow near the anode. Two active zones of the discharge with different properties are formed. Near the cathode, a high electric field is present, while the density of electrons is maximal at the anode [4]. Due to the charge accumulation on the electrode dielectric surfaces, the increase of the electric field radial component causes a local broadening of the discharge channel at the surfaces. Finally in the volume in about 10 ns, the axial electric field is reduced due to accumulation of charge carriers on the dielectrics. This picture is clearly seen on the spectra in figure 3-5, with the variation of the FNS and SPS relative intensities, in time (figure 3,4) and in space (figure 5).

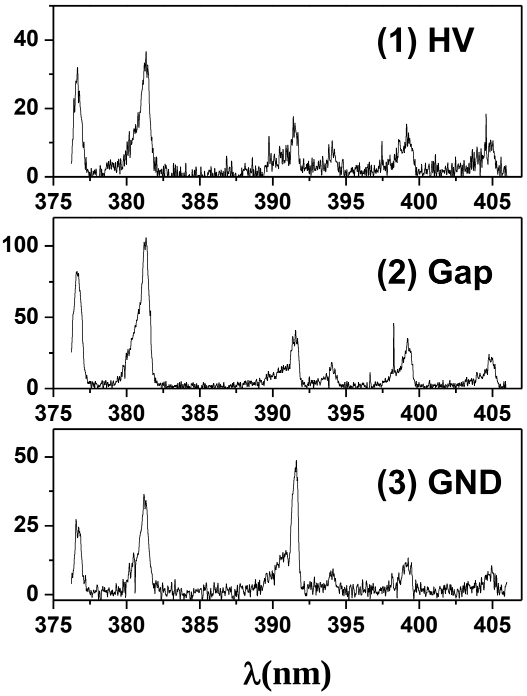

Figure 5. Emission Spectra at the spatial position indicated in figure 1. The effective gate was opened for about 100ps after the onset of the plasma emission.

6. Conclusions

We have succeeded with tracking the volume DBD streamer discharge evolution by employing technique of ICCD kinetics series with time resolution down to 20 ps. We show that the initial phase is characterised by slow avalanche build-up which is immediately followed by a fast cathode directed streamer evolving between the surfaces of the DBD electrodes. This was clearly evidenced through high temporal resolution kinetics series with a progressive increase of the gatewidth of the ICCD's intensifier.

An estimated average propagation speed during the fast streamer phase reaches as much as $5\times10^6\pm0.5$ m/s. UV emission spectra of this phase were acquired with different spatial and temporal resolution. In particular, spatially resolved spectra of N_2(SPS) and N_2^+(FNS) systems acquired with a 100 ps effective ICCD gate enable evidencing fast variation of the streamer head parameters.

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