Time-resolved electric field measurements in 1-5 atm nanosecond surface dielectric barrier discharge.

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Abstract: Surface nanosecond dielectric barrier discharge in air has been studied in a pressure range 1-5 atm in coaxial geometry of electrodes. High-voltage pulses of 11 kV amplitude in a cable, 30 ns duration and 3 Hz repetitive frequency were used to initiate the discharge. Emission profiles of molecular bands of the first negative and second positive systems of molecular nitrogen have been measured, dependence of electric filed value versus pressure and distance from the high-voltage electrode has been analyzed.

Keywords: high pressure, surface nanosecond discharge, electric field

1. Introduction

The dielectric barrier discharge (DBD) has been extensively investigated for nearly 50 years since it is widely used for different applications such as ozone production [1-3], intensive UV-light generation [4], plasma gas and surface treatment, air flow control [5] and so on. Nevertheless, experimental information on electric field value in DBD microdischarges is rather limited [6-8]. Spatially and temporally resolved nitrogen emission measurements were made in volume single-streamer DBD [6]. The electric field in surface DBD discharge in atmospheric air along the surface of dielectric with \( \varepsilon = 16 \) (BGO crystal) was studied in [7]. Experiments [8] demonstrate presence of a high electric field in 50 Hz DBD surface discharge. The surface barrier discharge in coplanar geometry in synthetic air at atmospheric pressure was studied with the help of cross-correlation spectroscopy [9].

High values of electric field were obtained in [10], where measurements of E/N were performed in a nanosecond surface discharge (25 ns and 20 kV pulse) in air at different pressures, from 200 Torr to 1 atm. Still the question about E/N value at surface DBDs remains open.

2. Experimental setup

The coaxial electrode system is schematically given at Fig. 1. High voltage pulse was applied to the central coaxial electrode which is connected to a disk aluminium electrode. The electrode was 50 \( \mu \)m in thickness and 20 mm in diameter. The discharge was initiated from the edge of the high-voltage electrode. The aluminium foil electrode covered the 0.4 mm PVC dielectric layer under which the low-voltage electrode was located. Low-voltage electrode was made from aluminium, its inner diameter equals to the outer diameter of the high-voltage foil electrode, and its outer diameter was equal to 46 mm.

Figure 1. Scheme of the experimental setup and electrode system. High voltage pulse parameters in a cable connecting the discharge cell and the HV generator.

High voltage pulses were produced by FID Technology HV generator. They were delivered to the electrode system through the coaxial HV cable of the 25 m length and 50 Ohm wave resistance. In the middle of the cable a back current shunt was installed to perform the electrical measurements of
the energy input in the discharge. The shunt was composed of 20 x 3.2 Ohm resistances, soldered into the break of the cable shield. The shunt has dividing coefficient of 318 and it was connected to the LeCroy WaveRunner 400 MHz oscilloscope.

Figure 2. Spectra of emission of 0-0 transitions of the second positive (left) system of molecular nitrogen and first negative (right) system of molecular nitrogen ion. Grey squares give the spectral region registered in the experiments.

Typical shape of the pulse is presented in Fig. 1. In all of the experiments carried out HV amplitude was set up between 6 and 12 kV what corresponds to the energy stored in the single pulse from 35 to 70 mJ. Pulse duration was constant within all of the experiments and was equal to 28 ns.

Electrode system described was installed inside a high pressure stainless steel chamber which could be either evacuated up to the pressure of \(6 \times 10^{-2}\) Torr or filled in with synthetic air up to the pressure of 5 atm. Chamber was connected to rotational pump and to the cylinder with synthetic air. In each experiment the chamber was evacuated up to the pressure less than \(5 \times 10^{1}\) Torr and then filled up with the air up to the pressure of interest. Low pressures (less than 10 Tor) were measured by Pfeiffer capacitive vacuum gauge, high pressures (more than 1 bar) were measured by SCM capacitive manometer. Synthetic air (80% N\(_2\), 20% O\(_2\), impurities did not exceed 3 ppm) was used for the experiments.

3. Emission measurements

Two molecular bands with significantly different cross-sections and thresholds of excitation by an electron impact, namely 0-0 vibrational transitions of the second positive (337.1 nm) system of molecular nitrogen and of the first negative (391.4 nm) system of molecular nitrogen ion were used for the analysis of the electric field behaviour.

The emission was focused to the entrance slit of monochromator by UV lens. Nanosecond photomultiplier tube (PMT) RTC XP2020 was installed on the output slit of the monochromator. In the experiments the TRIAX 320 scanning monochromator was used (2400 mm\(^{-1}\) grating, 1.3 nm/mm dispersion). PMT signal was registered by Le Croy WaveRunner 400 MHz oscilloscope with input impedance of 50 Ohm. Time resolution of the system was about 2 ns. Broad-band glass filter was used to reduce emission intensity in UV spectrum range (at the wavelength of 337.1 nm) to perform the measurements of both molecular bands at similar PMT voltages.

Figure 3. Energy input in the discharge vs pressure, negative polarity of HV pulse.

The ring plastic diaphragm was installed 3 mm away of the dielectric layer of the electrode system. It allowed us registration of emission only from a narrow area of the dielectric surface, i.e. to obtain field measurements along the radius of electrode system. 4 diaphragms were used in the experiments. Diameters of the diaphragms were 20, 26, 32, 38 mm and width of each diaphragm was 2 mm.

The entrance slit of the monochromator was set up to the value of 2.54 mm for registration of N\(_2\) second positive system emission and 1.31 mm for registering of N\(_2\) first negative system emission. For the second positive system, we registered all the rotational structure, as it is indicated in Fig.2, and for the first negative system of molecular nitrogen ion we cut the data at low wavelengths to avoid the overlapping with the spectrum of 3-6 vibrational transition of the second positive system of molecular nitrogen. The last fact caused the error not more than
5-10% in determination of the total intensity of emission of the first negative system of molecular ion.

For relative intensity calibration of the optical system an ORIEL 3000 deuterium lamp was used. Power of the lamp was 30 W, supply current was equal to 30 mA. Several different PMT supply voltages were used to check the signal PMT linearity and to reduce a possible error in the calibration coefficient.

4. Results

The energy input into discharge, calculated on the basis of a difference between incident and reflected current pulses, is given by Fig.3. It is clearly seen that the energy input at 5 atm is two times lower than at 1 atm at the same amplitude of the high-voltage pulse. At fixed gas pressure, equal to 1 atm, increase of high voltage amplitude from 6 to 11 kV leads to increase in deposited energy from 5 to 22 mJ at a negative polarity of a high-voltage pulse.

It should also be mentioned that for all the pressures considered, a nanosecond ICCD imaging of the second positive system emission, simultaneous (within an ICCD gate equal to 0.5 ns) start and propagation of streamers in radial direction [10,12] is observed. There is relatively long time period (at least about 5-7 ns), when bright emission of the second positive system is observed both in the heads of these “streamers” and in their channels, similar to the picture of the development of a fast ionization wave at low pressures.

Measurement of ratio of intensities of emission at 391.4 and 337.1 nm gives the following results: for different distances from the HV electrode, for different pressures and voltage amplitude we observed (a) elevated values (peak) of reduced electric field during first 5 ns of the discharge development; (b) relatively high values of reduced electric field (hundreds of Td) behind the front, during approximately 20 ns.

With pressure, the peak ratio of emission intensity in the discharge gap drops significantly (see Fig. 4), changing from 0.07 at 1 atm to 0.035 at 4 atm. It should be noted that there is no change of the emission ratio at the edge of the high-voltage electrode.

Fig. 5 represents spatial distribution of peak of reduced electric field for 1 atm pressure. The E/N values were recalculated from 391.4/337.1 emission ratio in analogy with [8] neglecting the possible role of three-body quenching of N₂ ion [13]. The minimal value of the electric field is observed at the edge of the electrode, while for the other distances the ratio remains practically constant and equal to 500–600 Td.
Fig. 6 illustrates time-resolved behaviour of the electric field for 3 atm pressure at 3 mm from the high-voltage electrode, but a similar trend was observed for all other regimes.

5. Conclusions
Measurements of electric field in nanosecond pulsed DBD surface discharge of negative polarity in synthetic air in the pressure range of 1-5 atm has been performed. It was demonstrated that in the front of the discharge the electric field is rather high (500 Td and higher), then it decreases during a few nanoseconds but the absolute values remain still high (hundreds of Td) during the discharge.

6. Acknowledgements
This work was partially supported by ANR (RAMPE Project) and EOARD AFOSR, grant FA8655-09-1-3077. Work of P.N. Sagulenko has been supported by Student International Fellowship, Ecole Polytechnique Palaiseau.

References