Development of surface dielectric barrier discharge: electric field measurements

K. Allegraud, O. Guaitella, S.M. Starikovskaia, A. Rousseau

Laboratoire de Physique des Plasmas, Ecole Polytechnique, Palaiseau, France

Abstract: Analysis of available data on electric field measurements in surface dielectric barrier discharges was carried out. Experimental measurements of emission spectra in triggered and non-triggered sinusoidal surface DBD were performed. The obtained results were used for the calculation of electric field value. The comparison of data obtained and the results published by other authors is presented.

Keywords: surface dielectric barrier discharge, nanosecond current pulse, electric field

1. Introduction

The dielectric barrier discharge (DBD) has been extensively investigated for nearly 50 years since it is widely used for different industrial applications, such as ozone production [1-3], intensive UV-light generation [4], plasma gas and surface treatment and so on. There are two basic configurations of DBDs: volume DBD, when the discharge develops mainly in a gas gap between the electrodes, and surface DBD, when the discharge propagates along the surface. The last configuration has been studied recently for air flow control [5].

The main electrical parameters of DBDs, the densities of active species in the discharge and discharge afterglow have been measured and calculated for decades. Nevertheless, experimental information on electric field value in DBD’s microdischarges is rather limited [6-9].

Spatially-temporally resolved nitrogen emission measurements were made in volume single-streamer DBD [6]. The authors calculated electric field in the discharge on the basis of comparison of emission of second positive (N2(^2Σ_u^+) - N2(^2Π_g^+), v’-v”=0-0, λ=337.1 nm) and first negative systems (N2(^2Σ_u^+) - N2(^2Σ_g^+), v’-v”=0-0, λ=391.4 nm) of molecular nitrogen. According to their data, the maximal value of reduced electric field is equal E/N=250Td for sinusoidal alternating voltage, 6.5 kHz frequency, 12 kV peak-to-peak voltage symmetrical DBD volume discharge in synthetic air at atmospheric pressure.

Electric field in surface DBD discharge along the surface of dielectric with ε=16 (BGO crystal) was studied in [7]. One side of BGO crystal (thickness 2.56 mm) was covered by a transparent conductive coating and used as a grounded electrode, and another side had a dielectric mirror coating. High voltage conical electrode was installed on the upper side of BGO crystal, voltage pulse of positive polarity with an amplitude 10 kV initiated the discharge. Pockels effect, that is a change of polarization of the emission under the action of electric field, was used for the electric field measurements. A diode-pumped solid-state laser (λ=532 nm) was used in the experiments. Maximum values of reduced electric field reported by authors do not exceed 100 Td.

Volume and surface DBDs were compared numerically in [8]. The authors [8] claim that reduced electric field in surface discharge under given conditions is not higher than 150 Td.

The surface barrier discharge in coplanar geometry (both electrodes are hidden under the layer of the dielectric) was studied with the help of cross-correlation spectroscopy [9]. The authors were not able to calculate the absolute value of the electric field because of difficulties with spectral calibration, but they obtained 2D time-resolved pictures of the emission of different molecular systems.

Fig.1 Experimental setup, triggered discharge.

Fig.2 General view of the surface DBD for a positive applied voltage (10 kV). ICCD gate is equal to 2 ms.
High values of electric field were obtained in [10], where time-resolved emission spectroscopy of molecular nitrogen was used for measurements of $E/N$ in a nanosecond surface discharge (25 ns and 20 kV pulse) in air at different pressures, from 200 Torr to 1 atm. The value of 780 Td is reported for 1 atm discharge of negative polarity.

Papers [11-12] analyzed behavior of single streamers propagation in surface DBD configuration using fast ICCD imaging. The authors proposed to use 20-nanosecond pulse with an amplitude 10% of peak-to-peak discharge voltage to trigger sinusoidal 50 Hz surface DBD at a given time moment.

The aim of the present work was (i) to measure electric filed value in surface DBD discharge with 50 Hz sinusoidal power; (ii) to compare electric field during positive and negative half-periods of the discharge; (iii) to compare electric field in triggered and non-triggered discharge; (iv) to analyze behavior of the electric field at different distances from the high voltage electrode.

2. Experiments

The experiments were carried out in a N$_2$:O$_2$=95:5 mixture. The discharge was installed in a chamber with a gas flow equal to 500 sccm. Electrode system consisted of two electrodes separated by a 4 mm thick glass plate. The high voltage electrode was 2x3.5 cm, and the grounded electrode was 8x8 cm. High-voltage electrode was connected to a 50 Hz 20 kV peak-to-peak sinusoidal power supply (A2E Technology). For triggered discharge (see Fig. 1), a nanosecond voltage pulse with a 1.5 ns rise time, 8 ns duration, and 1-2 kV amplitude (FID GmBH) has been superimposed on the sinusoidal voltage so that it was in the first quarter of period of the sinusoid. This allowed controllable initiation of the discharge at given time instant. For non-triggered discharge, the sinusoidal power supply was used.

3. Approach to data treatment

It should be pointed out that presently there are two different approaches allowing linking the intensity ratio of two bands of nitrogen and the electric field. The first, theoretical approach is based on knowledge of emission cross-sections for selected molecular bands. Indeed, in quasi-stationary approach, the rates of population by direct electronic impact is equal to rate of depopulation due to emission and quenching. Ratio of rate constants of excitation, $k_\text{e}/k_\text{b}$, depends upon ratio of population of excited levels, $N_2(C^1\Pi_u)$, $v'=0$, and $N_2(B^1\Sigma^+_u)$, $v'=0$. Population of excited species and optical emission are unambiguously related to each other. On the other hand, $k_\text{e}/k_\text{b}$ can be calculated for the given electron energy distribution function (EEDF) using the known cross-sections. More detailed description of this approach can be found in [6,9].

**Fig.3** Emission of molecular nitrogen during the positive half period of applied voltage. Non-triggered discharge. ICCD gate is equal to 2 ms.

**Fig.4** Reduced electric field, comparison of triggered and non-triggered discharge, and of different polarities of the high voltage electrode.

Discharge spectra were recorded with Andor iStar 734 ICCD camera connected to SHAMROCK spectrometer. The discharge image was focused onto the entrance slit of spectrometer. Bands of molecular nitrogen were clearly identified. To estimate electric field value, we measured relative intensity of second positive (N$_2$, C$^1\Pi_u$, $v'=0$ – B$^1\Pi_g$, $v''=0$, $\lambda=337.1$ nm) and first negative (N$_2^+$, B$^2\Sigma^+_u$, $v'=0$ – X$^2\Sigma^-_g$, $v''=0$, $\lambda=391.4$ nm) systems of nitrogen. Part of the experiments was made considering emission of another vibrational transition of second positive (N$_2$, C$^1\Pi_u$, $v'=2$ – B$^1\Pi_g$, $v''=5$, $\lambda=394.3$ nm). Relative calibration of spectral sensitivity of the system at 337.1 and 391.4 nm was made using deuterium lamp (ORIEL 63163).

Different ICCD gates, from 2 ns up to 100 ns, were used in the experiments. Up to 20000 accumulations of the signal were used to reduce signal-to-noise ratio.

To measure emission intensity at different distances from the high-voltage electrode, 3 slit diaphragms 3 mm in width were installed sequentially along the straight side of the high-voltage electrode, at a distance 1.5, 5.5, and 9.5 cm from the electrode.

**Fig.5** Approach to data treatment.
The second, experimental, approach is based on the results of paper [13], where the authors measured ratios of emission $I_{391.4}/I_{394.3}$ and $I_{337.0}/I_{394.3}$ under fixed $E/N$ values in non-sustained discharge in air. The theoretical approach gave $E/N$ values about 40% lower than the experimental one. Later, in [14], the authors of [13] recalculated their data using higher values of rate constants of quenching for molecular nitrogen ion [15]. The authors [14] came to the conclusion that this was the main reason of discrepancy. Finally, papers [13-14] can be considered as an experimental check of the model to calculate $I_{391.4}/I_{394.3}$ dependence upon reduced electric field. As far as our experiments were made in gas mixture not equivalent to air composition, we used the theoretical approach to treat the experimental data obtained in this paper.

4. Results

It was found that both for test experiments in ambient air and for experiments in a N$_2$:O$_2$=95:5 mixture, for triggered and non-triggered discharge, the emission of molecular N$_2$ ion during a positive half-cycle of the discharge (391.4 nm) is significantly stronger than the emission of adjacent N$_2$ band (394.3 nm). This fact, which is clearly illustrated by Fig. 3, proves that the electric field value in the discharge is rather high.

In non-triggered regime, ICCD camera gate was equal to 2 ms, we averaged 4000 accumulations. During one half-period of the discharge, about 10 discharges, each a few tens nanosecond duration, were accumulated. The time to take one spectrum was equal to 25 min. To calculate the electric field on the basis of theoretical considerations, we used EEDF obtained on the basis of solution of Boltzmann equation in two-term approximation calculated with the help of BOLSIG+ code [16]. For electron collisions with O$_2$ and N$_2$, we used the self-consistent sets of cross sections, available in the literature, which allow good agreement between calculations and measurements of transport and rate coefficients in the pure gases. Available in the literature cross sections for O$_2$ [17-18] and N$_2$ [19] were used in the simulation. Emission cross-sections for appropriate transitions of the 2$^1$S and the 1$^2$P systems were taken from [20] and [21], respectively. It should be noted that these data coincide with recommendation of review [22]. Values about 1000 Td have been obtained for positive half-period of the discharge. These values are in rather good correlation with the results given by similar emission technique for nanosecond surface DBD discharge [10] and differs significantly from data obtained using Pockels effect [7].

It is known from ICCD imaging [11] that the emission of surface DBD is bright and filamentary during positive half-period, while during negative half-period the emission is weak and diffuse. The emission of nitrogen ion at 391.4 nm becomes weak in comparison with N$_2$ emission at 394.3 nm, and the electric field drops practically by a factor of 2 (see Fig. 4).

It should be noted that we measured time-averaged spectra assuming that the durations of current pulses are short and that we measure some averaged value, probably the highest possible in the discharge. To have a possibility to synchronize the discharge development and the diagnostic system, it was proposed in [12] to apply an additional HV pulse at the front of the main voltage waveform. To get a spectrum in triggered discharge, the ICCD gate was decreased to 100 ns, so that we registered not more than one microdischarge during a given period. To have a reasonable signal-to-noise ratio, we had to make 10000 accumulations during 1 hour. It was found (see Fig. 5) that the electric field values coincide in triggered and non-triggered discharge. This allows us planning the time-resolved measurements of the electric field behavior.

Dependence of the electric field upon distance from high-voltage electrode was measured during a positive half-period of the non-triggered discharge. ICCD camera gate was equal to 2 ms, 20 000 accumulations were used, and time to take one spectrum was equal 2 hours. In order to check the stability of the discharge, the spectra were

Fig.6 ICCD images of (a) triggered surface DBD discharge, camera gate is 1 ns, and (b) nanosecond surface barrier discharge, camera gate is 0.2 ns [23]. taken in two directions, from 320 to 405 nm, and then immediately from 405 nm to 320 nm. No difference was found between the spectra. It was concluded, that at different distances from the high-voltage electrode, 1.5, 5.5, and 9.5 mm from the high-voltage electrode, the emission
intensity drops significantly, while the electric filed value remains practically constant (see Fig. 5).

Finally, it is interesting to compare qualitatively ICCD pictures obtained with short ICCD gates (1 and 0.2 ns) for sinusoidal 50 Hz dielectric barrier discharge and for 25-ns surface DBD discharge [23] in 1 atm air. As far as camera’s spectral response was 200-800 nm, they were collected mainly emission of second positive system of molecular nitrogen. At atmospheric pressure, quenching by molecular oxygen is strong, and, thus, 0.2-1 ns gates give an “instantaneous” picture of the discharge development. Let us note that in spite of the similar values of the electric fields, the morphology of the discharges seems to be rather different: 50 Hz discharge demonstrates bright emission from the “streamer heads”, similar to development of streamer discharge in 1 atm air gap, while nanosecond surface discharge exhibits strong emission of molecular nitrogen both from the “streamer heads” and from the “channels”, demonstrating a presence of high electric fields behind the discharge front. We believe that comparative analysis of spatio-temporal behavior of the electric field in these two discharges will be of a great interest.

5. Conclusions

Thus, experimental measurements of emission of molecular nitrogen have been performed for triggered and non-triggered surface DBD discharge. It was found that the electric field values in surface DBD can be as high as 700-1100 Td. It was shown that triggering by a short nanosecond pulse with the amplitude of 10% of maximum voltage on HV electrode does not change electric field. With propagation from the HV electrode, the emission intensity decreases, the electric fields remains practically constant.

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References