1. Introduction

Atmospheric pressure dielectric barrier discharges (DBD)\(^1\) are used in the industry for in-line plasma treatment of fabrics or large area substrates. The utilization of different types of DBD for these applications has been made with different success. The main problem of moving substrates in DBD stands is the inhomogeneity of DBD at atmospheric pressure (formation of plasma microchannels). This results in inhomogeneous treatment of the substrates and unintentional pin-holing of the substrates at high power densities necessary for rapid treatment. This disadvantage is not presented at atmospheric pressure glow discharge (APGD), but on the other hand the glow regime of this discharge is sensitive to the gas impurities and the discharge power.

The diffuse surface coplanar barrier discharge (DSCBD) plasma is generated in thin layer above the surface of dielectric. The plasma microchannels are oriented parallel to dielectric surface. Due to small distance between electrodes the microchannel part of the discharge can be suppressed in order to increase the homogeneity of the treatment and suppress the pin-hole effects. Furthermore, the plasma microchannels of DSCBD move rapidly along the surface, which improves the homogeneity of the treatment\(^2,3\).

For better utilization of the DSCBD for industrial purposes\(^4,5\) the influence of the outer physical conditions on the discharge parameters has to be studied. In this paper the influence of electrode temperature and total input power is presented. Using spatially resolved spectroscopy spatial profiles of vibrational and rotational temperature calculated from the second positive system of nitrogen was determined and correlated with profile of intensity of the second positive system of nitrogen. Time-space maps of integrated intensities of second positive system of nitrogen (SPS – 377.1 nm) and first negative system of nitrogen (FNS – 391.5 nm) were also estimated.

2. Experimental setup

The scheme of experimental setup is shown in Fig. 1. It consisted of coplanar discharge cell with discharge chamber and cooling/heating unit, power supply unit and diagnostic instruments.

The discharge cell (see also Fig. 1 – bottom) was composed of two brass electrodes overlaid by dielectric plate (96 % Al\(_2\)O\(_3\) with the thickness of 0.5 mm). The electrodes had form of semi-circle. Gap between electrodes had length of 30 mm and width of 0.7 ± 0.1 mm in all cases. This coplanar electrode system was dipped in insulating oil bath. The grounded electrode was controllably heated/cooled using cascade of Peltier cells attached eventually to external cooler. The electrode system consisted of only one electrode pair, contrary to large area DCSBD.

The open space below the dielectric (in Fig. 1 – bottom) was covered with cylindrical discharge chamber. The diameter of the chamber was 30 mm and its height was 30 mm. The chamber enables us to control the discharge atmosphere. In this work 99.996 % pure nitrogen was flown through the chamber with constant rate of 3 slpm controlled with Vögtlin Instruments red-y GCR mass flow meter. The emission spectra and discharge pictures were taken through the quartz window on the chamber.

The discharge was powered by LIFETECH high voltage power supply unit with sinusoidal output of 35 kHz frequency. The voltage amplitude was changed in the range 12
to 18 kV. This corresponds to discharge power of 16 to 42 W. TTL triggering signal for time resolved spectroscopy was taken from the power supply frequency generator.

Electrical parameters were measured by LeCroy WaveRunner 6100A digital storage oscilloscope (1 GHz / 5 GSa). Input voltage was measured by Tektronix P6015A high voltage probe (1000:1). The discharge current was measured using HP 1160A (10:1) probe by the voltage drop on the 330 Ω resistor placed in the circuit. Dissipated discharge power was then calculated from the time evolution of input voltage and discharge current.

Optical emission spectra were recorded with Horiba Jobin-Yvon FHR 1000 monochromator equipped with two gratings (2400 gr mm⁻¹ and 3600 gr mm⁻¹). The optical signal was detected by Symphony CCD camera and i-Spectrum ICCD camera that was externally synchronized by TTL signal. Both of them were cooled by means of cascaded Peltier cells.

The discharge emission pattern was projected by quartz lens on the adjustable slit. The light passing through the slit was guided by the quartz optical fiber to the monochromator. The 1D spatial profile of discharge emission was obtained by moving the slit in direction across the electrode gap. The optical resolution in the direction of scanning was set to 1 mm, and the optical signal was gathered from the total area of approx. 5 mm² of the discharge in all cases.

3. Experimental results and discussion

3.1. Visual appearance of the discharge and the electrical parameters

The visual appearance of the discharge is presented in Fig. 2 (top). The distinct pictures show discharge operated at different conditions. The horizontal axis represents increase of the temperature of grounded electrode from 10 °C to 80 °C. The vertical axis represents increase of input voltage amplitude from 12 kV to 17 kV.

The planar structure of the discharge pattern can be recognized, both on the discharge pictures and on the corresponding intensity profiles of the SPS given in Fig. 2 (bottom). The first region is formed by microchannels – filaments crossing the gap in-between of the electrodes (the distance of ~1 mm to 1 mm on the intensity profile). The second region is represented by the bright violet areas above the edge of electrodes. These bright areas propagate above the electrodes with increasing input voltage (power). The outer edge of this region can be recognized on the intensity profile as well (at the distance of ~5 mm). Third region, that is most clearly visible for the pictures with input voltage of 15 kV, appears as the diffuse blue light that is extended up to the outer edge of the electrodes. There is a slight asymmetry of the luminosity towards powered electrode, which is visible both in the discharge pattern and on the intensity profile.

It can be seen that electrode temperature influences, even in very narrow range, the discharge pattern and the corresponding intensity profiles. Most pronounced is the change of the second region above the powered electrode. The equilibrium temperature of the powered electrode was in the range of 40 °C to 50 °C (measured after several tens of minutes of discharge operation).

3.2. Rotational and vibrational temperature spatial profiles

The spatial profiles of rotational and vibrational temperature are useful characteristics for deducing the effects of plasma treatment of materials in DCSBD. The distribution of vibrational temperature (comparing with the intensity profiles) can give us the information about the “active area” involved in plasma treatment and the efficiency of this treatment. The distribution and the absolute values of the rotational temperature is on the other hand very important parameter in the case of plasma treatment of temperature sensitive materials. The rotational temperature of SPS can be used as a measure of the neutral gas temperature, thus the rotational temperature profile can be used for the estimation of the temperature stress of treated materials.

The evolution of spatial profiles of rotational temperature, with respect to the input power as well as the electrode temperature, is given in Fig. 3. For the estimation of rotational temperature rotational lines R₁ (22–21) to R₁ (17–16) of fully
resolved rotational spectrum of second positive system of nitrogen C $^3\Pi_u \rightarrow B^3\Pi_g$ (band 0–0 at 337.1 nm) were used.

In the filamentary region of the discharge the rotational temperature raises up to 600 K, whereas the rotational temperature in the second region of the discharge, the bright one, has substantially lower values around 350 K. The rotational temperature increases proportionally with the input voltage.

The estimated error of the rotational temperature is about 50 K for the 12 kV and about 20 K for the rest of the profiles. This was caused by low signal to noise ratio for the signal of the discharge operated at 12 kV.

The changes of the rotational temperature profile due to electrode heating/cooling are apparent too (Fig. 3, bottom). It can be observed, that the rotational temperature of the filamentary region is the highest in case of electrode temperature of 10 °C. Rotational temperature above electrodes increase with increasing electrode temperature, as can be expected.

The evolution of spatial profiles of vibrational temperature, with respect to the input power as well as the electrode temperature is given in Fig. 4. The vibrational temperature was estimated from the bands of SPS ($\Delta v = -2$, heads 0–2, 1–3, 2–4 starting at 380 nm).

The vibrational temperature of the filamentary region of the discharge peaks at approx. 3000 K. In the second region of the discharge there is still high vibrational temperature with the values about 2800 K. Thus, it can be seen that the DCSBD creates highly non-equilibrium plasma with low rotational and high vibrational temperature and high emission intensity in UV region. The estimated error of the vibrational temperature is about 200 K.

These results are in good agreement with our observation, that the results of plasma treatment of materials above the luminous (second) region are better than above the filamentary (first) region.

In Fig. 5 the time-space map of the SPS is given. This map represents the accumulated time and space distributed luminosity of the SPS over thousands of discharge periods, representing the average exposure of the treated samples during the potential plasma treatment.

The results are qualitatively in agreement with cross-correlation spectroscopy measurements of Hoder et al.\textsuperscript{1}, carried on one-filament coplanar discharge with pin-to-pin electrode configuration. The luminous regions can be distinguished above the anode in both semi-periods of the dis-
show the significant influence of the input voltage and electrode temperature on the plasma parameters of coplanar barrier discharge, especially in the spatial distribution of the intensities and temperatures. The time-space maps of the SPS intensities were also obtained. The results are in agreement with the DSCBD plasma treatment experiments.

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J. Čech*, a, P. Sřahel*, Z. Navrátil†, and M. Černák* (aDept. of Physical Electronics, F. of Science, Masaryk University, Brno, Czech Republic, bDept. of Experimental Physics, Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia): Space and Time Resolved Optical Emission Spectroscopy of Diffuse Coplanar Barrier Discharge in Nitrogen

In this work we have studied the influence of electrode temperature and input power on plasma properties of the surface diffuse coplanar barrier discharge. Properties of the discharge can be affected by outer conditions and discharge configuration and better understanding of these effects can lead to optimization of the discharge parameters for industrial applications. The discharge was operated in nitrogen at atmospheric pressure. The power input and electrode temperatures were changed and plasma parameters were studied by the means of time and space resolved optical emission spectroscopy. These measurements gave us time and space distribution of discharge luminosity (e.g. intensity of second positive system of nitrogen) and spatial profiles of rotational and vibrational temperatures.

4. Conclusion

Experimental apparatus for the space and time resolved spectroscopy of DSCBD was successfully developed. The spatial profiles of intensities of SPS and the rotational and vibrational temperatures of SPS were obtained. The results