Spectroscopic investigations of high-pressure microhollow cathode discharges

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1 Introduction

Microhollow cathode discharges are high-pressure, non-equilibrium discharges in a planar geometry with a hollow cathode and an arbitrary shaped opposite anode, both with an axial borehole. Electrode and insulator dimensions are in the 100µm range. The large concentration of high-energetic electrons combined with the high gas density favours excimer formation [1]. Excimer radiation is based on the formation of excited molecular complexes (excimers) and the transition from a bound excimer state to a repulsive ground state. The advantage of excimer sources is their high VUV- and UV efficiency that reaches values up to 40%, when operated under optimum conditions.

The basic requirement for the production of excimer radiation is the availability of high-energetic electrons, which can efficiently excite the gas atoms. Dependent on the working gas electron energies of more than 10 eV are necessary to form the metastable states, the precursors of the excimer. The second parameter is the high gas pressure, as the formation of excimers is a three body collision process. Optimum gas pressures are typically one atmosphere or higher. Both criteria can be fulfilled simultaneously only in a non thermal-plasma.

The optimisation of the discharge conditions however requires a detailed knowledge of the plasma properties itself. Electron density and temperature control, both control excitation and plasma chemistry reactions. Gas temperature plays a major role, too, as a significant energy loss process limiting efficiency of excimer radiation generation.

Most of the actual spectroscopic investigations [2, 3] have been focused on the ultraviolet or vacuum ultraviolet range for direct detection of the excimer. In our experiments we concentrated to investigate characteristics of the microhollow cathode discharges from the near UV to the near infrared (300-850nm), in order to measure the basic plasma parameters using standard plasma diagnostic techniques, like stark broadening for electron density and the relative line intensity method for electron temperature. In addition, the heavy particle temperature was measured by analysing the vibrational-rotational structures of the second positive system of nitrogen.

2 Experimental

2.1 Experimental Setup

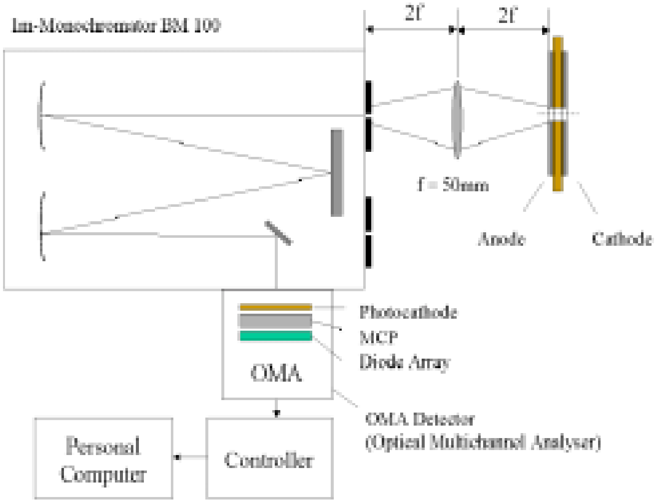

Figure 1: Experimental setup for spectroscopic measurements together with the schematics of the microhollow cathode geometry

The electrode system, shown in Fig. 1, consists of 100µm thick molybdenum foils separated by an alumina insulator of 250µm thickness. The hollow cathode is formed by a laser drilled aperture of the cathode having 100µm in diameter. The discharge was mainly operated in argon. For diagnostic purpose hydrogen was added to measure Stark broadening of the Balmer H_{α}- and H_{β}-lines and nitrogen to determine the gas temperature. The discharges were operated d.c. at currents up to 15mA and a forward voltage drop of approximately 200V in argon. In the pulsed mode the discharge is able to carry up to 32mA with a pulse length from 1-100µs.

The diagnostic system for spectroscopy consists of a 1m-monochromator, model BM100 equipped with 1200l/mm grating having a blaze angle of 500nm. The spectral lines were detected by a Princeton Instruments OMA (Optical Multichannel Analyser: Model 1420UV) mounted in the focal plane of the instrument. Most precise resolution was achieved setting the aperture of the entrance slit to 20µm, which allowed a minimum apparatus profile (approximately Lorentzian shape) of the spectroscopic system of 0.043nm width.

The radiation emitted from the anode borehole was depicted 1:1 onto the entrance slit of the monochromator by a 50mm lens. The detection of light emitted form the anode opening allows to determine the plasma parameters in the cavity of the microhollow cathode discharge.

2.2 Electron Density Measurement

The electron density obtained from Stark broadening of the Balmer H_{β}-line of a microhollow cathode discharge in argon is shown in Fig. 2. Using the Stark width of the H_{β}-line electron densities down to a density of $3*10^{14}cm^{-3}$ were measured with the described spectroscopic system. Actual data from literature [4] were used to determine the theoretical width.

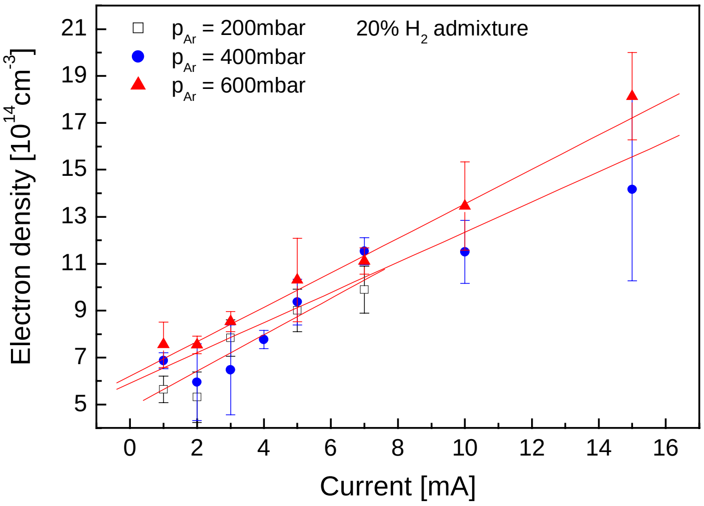

Figure 2: Electron density measured from Stark broadening of the Balmer H_{β}-line in d.c. operation for different argon pressures of 200, 400 and 600mbar and a 20% admixture of hydrogen as function of discharge current

As shown in Fig. 2 the electron density was measured d.c. currents up to 15mA and gas pressures from 200-600mbar. Electron densities increased from $5*10^{14}cm^{-3}$ at low current (≤ 1mA) up to $1.9*10^{15}cm^{-3}$ at 15mA. A slight tendency for an increase of electron density with gas pressure seemed to be visible but it is not sure, because the increase is still within the error bars. Error bars themselves were calculated from statistical fluctuations of the discharge and its radiation, and from the uncertainties obtained in the line fit process. The width was adjusted to the apparatus profile. At higher pressure than 600mbar the signal to noise ratio for the H_{β} line was not sufficient to determine the FHWM of the line.

2.3 Electron Temperature

The second parameter controlling the excitation and ionisation processes within the microhollow cathode plasma is the electron temperature. If one assumes a Maxwellian electron energy distribution function and at least partial local thermal equilibrium conditions for the investigated lines, one can get the electron temperature from comparing line intensities in a Boltzmann plot [5]. In a Boltzmann plot the logarithm of the line intensities of numerous Ar I and Ar II lines is plotted against the energy difference to an arbitrary chosen reference energy level.

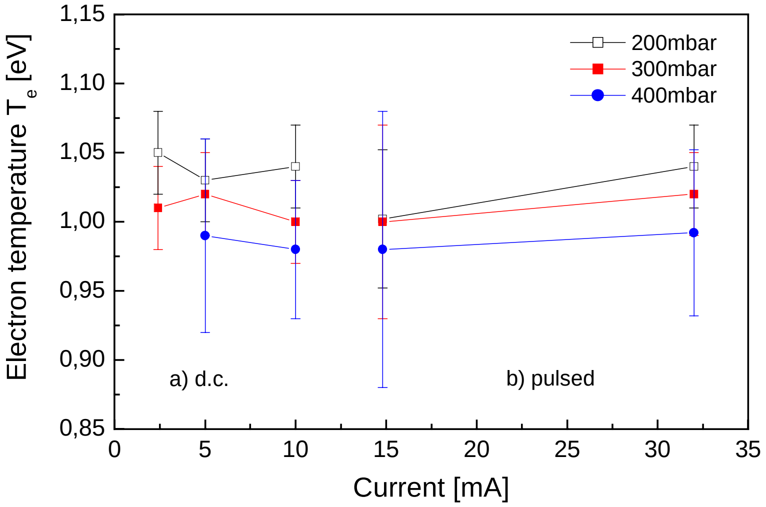

Figure 3: Electron temperature measured by a Boltzmann plot of Ar I and Ar II lines in d.c. and pulsed operation for different argon pressures of 200, 300 and 400mbar as function of discharge current; in pulsed operation pulse length of 5µs with a repetition rate of 2kHz has been used.

The electron temperature plotted versus the discharge current from 2 to 32mA is shown in Fig. 3 with numbers of about 1eV for the complete current range in d.c. and pulsed operation. An increase in pressure of the working gas leads to a slight decrease in electron temperature. It decreased from about 1.04 eV at 200mbar to 0.98 eV at 400 mbar. At higher pressure Ar II emission is too weak to be measured. Temperature determination from Ar I lines only lead to large errors due to the low energy difference between the upper levels of the lines.

2.4 Gas Temperature

The gas temperature in the microhollow cathode discharge was measured by comparing the vibrational and rotational bands of the 2nd positive system of nitrogen, the $C^3\Pi_g$-$B^3\Pi_u$ transition. The 0-0 band at 337.1nm and the 0-2 band at 381.5nm were measured and compared with calculated spectra [6].

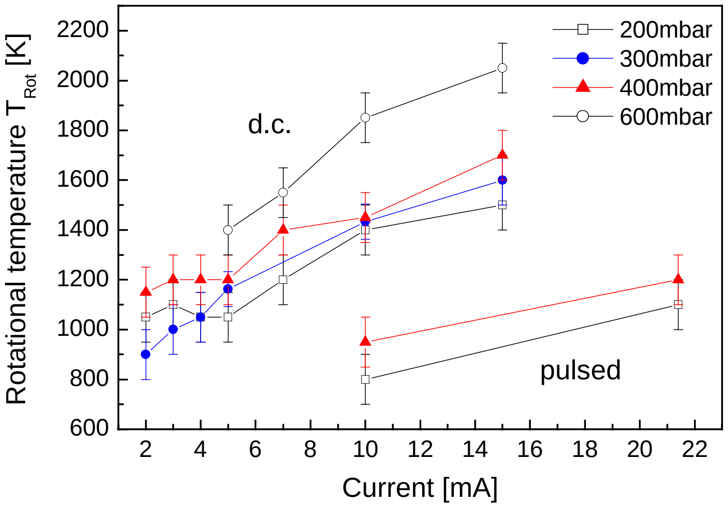

Figure 3: Rotational temperature obtained from 0-0 transition of the 2nd positive system of nitrogen at 337.1nm in d.c. and pulsed operation for different argon pressures of 200, 300, 400 and 600mbar as function of discharge current; in pulsed operation pulse length of 5µs with a repetition rate of 2kHz has been used.

The gas temperature in the cavity of the microhollow cathode has been measured with pure nitrogen only due to stability problems. Since the forward voltage drop with 360 V is 1.5 times larger than in argon, gas temperatures in pure argon should be much lower. In nitrogen gas temperatures were found d.c. ranging from 900K (2mA, 300mbar) up to 2000K (15mA, 600mbar). Between 200 and 400mbar the gas temperature did not depend strongly on gas pressure. The variations are within the errors bars, leading to maximum temperatures of 1650K (15mA, 400mbar). For a gas pressure of 600mbar the temperature was found to be significantly higher.
By pulsed operation the gas temperature was found to be much lower for the same discharge current, which is quite understandable because the total energy input in the discharge is limited due to the duty cycle of 0.02. At 10mA discharge current the gas temperature was reduced from 1350K in d.c. mode to about 900K in pulsed.

3 Conclusion and Summary

In our experiments the electron density and electron temperature were measured using Stark Broadening of the hydrogen Balmer line and comparing line intensities in a Boltzmann plot. Until now no other measurements of these plasma parameters were found from other authors. Furthermore the gas temperature was determined in pure nitrogen. The values measured agree quite well with the value in [7], which has been obtained in air at a current of 10mA a forward voltage drop of 380 V.

With respect to the optimum plasma conditions for excimer formation and the requirement of an increase of efficiency the following can be summarized: As known from simulations made for barrier discharges [8] electron density should be kept below $10^{15}cm^{-3}$ to avoid quenching of the excimer states by electron collisions. Since a large amount of excimer radiation however comes from the surface around the cathode opening, where the electron density is much lower, the increase of efficiency with rising current found in experiment [1] can be explained.

Operation in the pulsed mode seems to be the most promising way to increase efficiency due to reduced energy loss in heating of the gas, which is assumed as one of the main loss processes in the microhollow cathode discharge.

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References

[1] A. El-Habachi and K.H. Schoenbach, Appl. Phys. Lett 72 (1), pp. 22-24, 1998

[2] A. El-Habachi and K.H. Schoenbach, Appl. Phys. Lett 73 (7), pp. 885-887, 1998

[3] K.H. Schoenbach, A. El-Habachi, M.M. Moselhy, W. Shi and R.H. Stark, Physics of Plasmas 7 (5), pp. 2186-2191, 2000

[4] M. A. Gigosos, V. Cardenoso, J. Phys. B: At Mol. Opt. Phys. 29, pp. 4795-4838, 1996

[5] H.R. Griem, McGraw-Hill Book Company, New York, 1964

[6] C. Western, private communication, 2000

[7] M. Laroussi, R. Block, F. Leipold and K.H. Schoenbach, Symp. Proc. of the 14th International Symposium on Plasma Chemistry, Prague, Czech Republic, 2.-5. August, pp. 945-950, 1999

[8] B. Eliasson and U. Kogelschatz, IEEE Trans. on Plasma Science 19 (2), pp. 309-323, 1991