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Article

Cathode Sheath Thickness of a Microhollow Cathode Discharge Plasma In Argon High Gas Pressures

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Abstract. In a glow discharge, the sheath region that is formed around the cathode surface has a decisive effect on the generation of plasmas. In order to investigate the sheath structure in an atmospheric pressure plasma, we developed a microhollow cathode discharge (MHCD) device. The MHCD device had a cathode diameter of 0.5 mm and its length of 2.0 mm. The discharge was operated at a discharge voltage and current of ~220 V and 8 mA, respectively, up to 20 kPa of He-Ar mixtures. We carried out the visible/UV emission spectroscopy, which enabled us to understand the characteristics in the cathode sheath. It was found that two dimensional emission images attributed to Ar^+ ion and neutral atom showed significantly different behavior with increasing gas pressure. By comparing the results obtained by an ionizing sheath theory with experimental ones, the detail of the sheath structure is clarified.

Keywords: Microplasma, electric discharge, sheath, plasma spectroscopy, radical source.

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1. Introduction

According to the Paschen's law that describes the gap distance of electrodes to start the discharge with a reasonable breakdown voltage, the electrode dimension becomes smaller with increasing gas pressure. For instance, at atmospheric discharges the electrode gap should be on the order of 10 μm [1]. To attain the discharge at high pressure, a microhollow cathode discharge (MHCD) is a great deal of interest, because the microplasma with a density above 10^{14} cm^{-3} can readily be produced due to the peculiar geometric configuration. Indeed, Schoenbach *et al* developed the MHCD device and succeeded in the generation of nonequilibrium plasma with a large population of high-energy electrons. This provides a favorable condition for excimer light source [2-4], since a high-density plasma with low temperature is essential to efficiently generate these species. We also fabricated the MHCD with a relatively large reaction volume for application to a microchemical reactor, such as, atomic H and OH radical sources for air purification technology [5-7].

On the other hand, the electron accelerated from the cathode surface (sheath region) to bulk plasma plays an important role to generate and maintain stable plasmas. The sheath theory for a normal glow region in low gas pressure has been well established [8], whereas the research on microplasma has not been sufficiently understood so far. Lazzaroni *et al.* measured the visible emission spectra for argon MHCD plasmas to investigate the sheath structure [9]. By comparing the experimental data with numerical results, they elucidated that the generation of charged particles in the sheath was very important in high-gas pressure discharge. Although they investigated the characteristics of the sheath of Ar microplasma (diameter: 0.25 mm), the cathode length was as short as 0.15 mm, thus the reaction volume was very small.

In this study, in order to clarify the sheath characteristics of the MHCD having a large plasma volume (diameter: 0.5 mm and length: 2 mm), we measured two dimensional emission images of atomic and ionic Ar spectra by using a high resolution spectrometer.

2. Experimental

Figure 1 shows a schematic diagram of the MHCD plasma device. Both cathode and anode electrodes were made of stainless steel, and ceramic disks were used to insulate the electrodes electrically. The cathode disks having an inner hole of D =0.5 mm with a length of L=2.0 mm was prepared. The MHCD assembly was installed in a vacuum chamber and the gas (Ar (80 %)-He (20 %) admixture) with a flow rate of around 0.5 L/min was fed through the cathode opening. As for He atom, atomic spectra and relevant information to derive the plasma parameters are tabulated in [10], and thus we analyzed the He I spectra instead of Ar spectra. The plasma was operated at a discharge sustaining voltage of 220 V, current of 8 mA and gas pressures of 0.5~20 kPa.

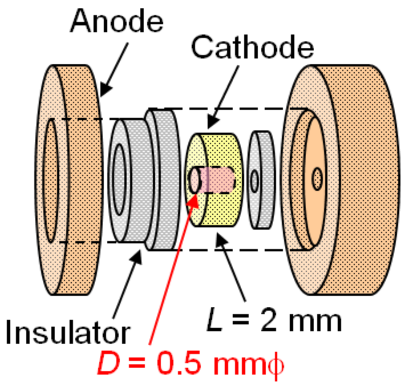

Fig. 1. Schematic of the MHCD assembly.

The MHCD plasmas generated in the cathode opening were observed by a high resolution visible spectrometer with a focal length of 1 m and a grating of 2400 grooves/mm. The detector was a CCD camera with an image intensifier. In this study, we focused on two emission lines: 427.217 nm attributed to neutral Ar ($5p[3/2]_1$-$4s[3/2]_1$) line and 427.752 nm to Ar^+ ion ($4p'^2P_{3/2}$-$4s'^2D_{5/2}$). Moreover, the measurement of the CCD images of Ar and Ar^+ lines were made under an entrance slit of 2.5 mm, which allowed us to observe two dimensional (2D) spatial spectral images (monochromatic 2D image).

3. Results and discussion

3.1. Two-Dimensional Spatial Images

Two-dimensional spatial images of neutral Ar and Ar^+ ion spectra for gas pressures of 4, 8 and 15 kPa are shown in Fig. 2. The spatial distributions of plasma emissions from Ar atom and Ar^+ ion are significantly different at high gas pressures. Figure 3 shows the horizontal cross-section of 2D images for 2, 6, 10 and 15 kPa. With increasing gas pressure, the peak positions of ionic line moves to the cathode surface, while the bright atomic emission remains at the central region. In the periphery of the electrode, the electrons are accelerated toward the cathode center (*virtual anode*) due to the formation of a radial electric field, where considerable fraction of the excitation/ionization occurs. With increasing gas pressure, the collision events also increase, resulting in the intense emission in the outer region.

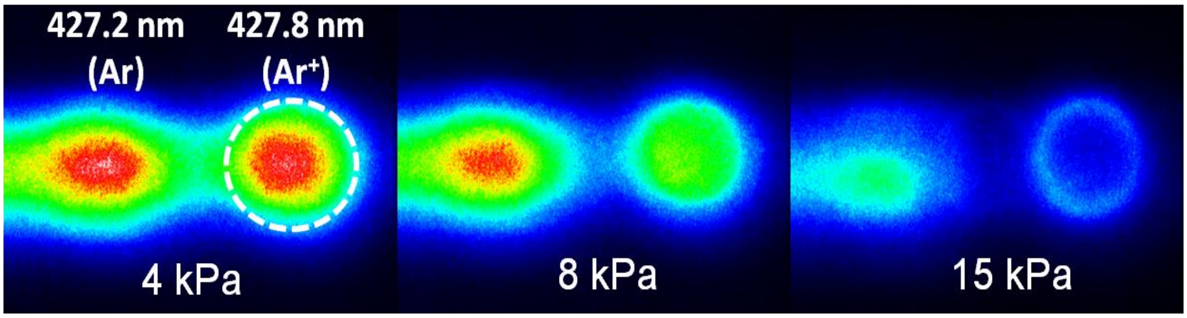

Fig. 2. The CCD images of Ar atom 427.217 nm (left) and Ar^+ ion 427.752 nm (right) lines at 8 mA and Ar-He pressures of 4.0, 8.0 and 15.0 kPa.

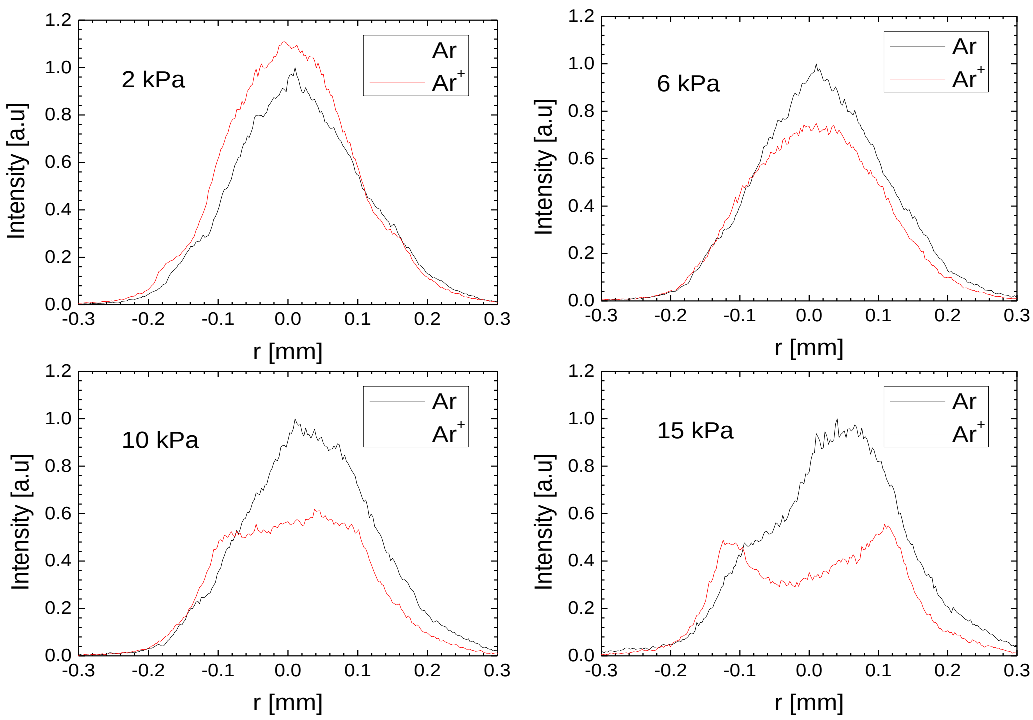

Fig. 3 Emission intensity distribution of Ar and Ar^+ lines at a discharge current of 8 mA for various Ar-He gas pressures.

3.2. Numerical Calculation of the Sheath Thickness

The evaluation of sheath thickness by a numerical calculation was performed [8, 9]. First, we assume that electron-ion recombination is not a significant in the sheath, and thus we neglect the recombination process in the charged particles balance. Indeed, there are substantial differences in the thermal velocity of electrons and ions in the sheath. Considering that the electron density is quite low, this assumption should be justified too. Figure 4 shows a schematic for the numerical calculation. The cathode in 1D cylindrical geometry has an infinite length in depth and its radius of *R*. The sheath width is set to be the value of *d*. Here, we adopted the model that includes the ionizing effect in the sheath (ionizing sheath model) due to electron impact ionization (ionization coefficient: α), which is opposite to that by well-known Child-law. Taking into account the charge continuity and secondary emission of electron due to ion bombardment into the cathode surface (emission coefficient: γ), the following equation can be obtained,

$$\int_{R-d}^{R} \alpha(r)\, dr = \ln\left(\frac{1-\zeta}{\gamma} + 1\right), \tag{1}$$

where ζ is the fraction of the ion current entering the sheath to the values at the cathode surface. The value of ζ=0 corresponds to the typical regime of the cathode fall in a DC discharge tube. The coefficient $\alpha(r)$ can be given by [11],

$$\frac{\alpha}{p} = A\beta \exp\left(-\frac{B\beta p}{E}\right) \tag{2}$$

where p is the gas pressure, the electric field E and the factor $\beta = 300/T\,[\mathrm{K}]$ is the value according to gas temperature T. For the cathode voltage V_C of 220 V, the secondary emission coefficient is γ=0.07 [12]. The coefficients of A and B are determined experimentally and tabulated in Ref. 8. Moreover, assuming the high-voltage matrix approximation, the Poisson's equation gives the electric field, $E(r)$, in cylindrical geometry as follows

$$E(r) = E_0 \frac{R}{2Rd - d^2}\left(r - \frac{(R-d)^2}{r}\right), \tag{3}$$

where E_0 is the field at R.

Finally, we obtain the relation between the gas pressure and sheath thickness,

$$\ln\left(\frac{1-\zeta}{\gamma} + 1\right) = \int_{R-d}^{R} A\beta p \exp\left[-\frac{B\beta p}{2V_c}\left(d(2R-d) + 2(R-d)^2 \ln\frac{R-d}{R}\right)\frac{1}{r - \frac{(R-d)^2}{r}}\right] dr \tag{4}$$

By numerically solving this equation, we determine the sheath thickness in terms of the gas pressure. Figure 5(a) shows the sheath thickness calculated for various ζs at T_g=700 K. As clearly seen, the sheath width becomes thinner with increasing gas pressure, indicating that the mean free path for the electron impact ionization is short, while the weak *d*-dependence on the value of ζ is obtained. On the other hand, Fig. 5(b) shows the temperature dependence on the sheath thickness for ζ=0.0, in which the experimental results are also plotted. At the gas temperature of 700 K, a good agreement between the experiment and calculation is obtained. An analysis of emission spectroscopy also gives a justification of this temperature. The detail of the measurement to determine the plasma parameters is described in Ref. 5. Hence, it is found that the ionization event in the sheath and the increase of the gas temperature significantly influence the decreasing of sheath thickness.

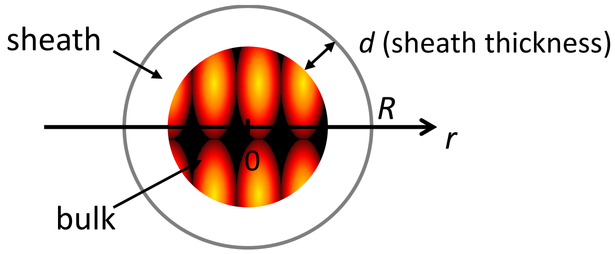

Fig. 4. The geometric configuration for the numerical calculation.

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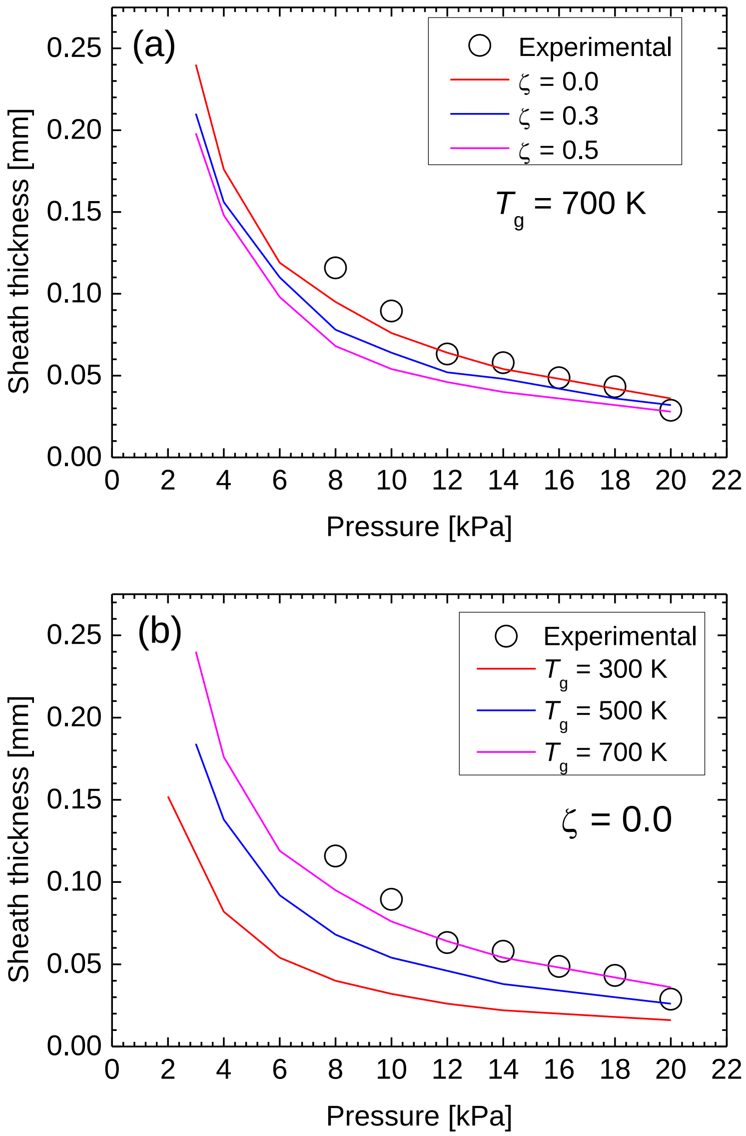

Fig. 5. Pressure dependence of the sheath thickness for (a) T_g=700 K, (b) ζ=0.0.

4. Conclusion

In order to examine the sheath structure for Ar MHCD plasmas, we carried out the emission spectroscopy. The 2D images of the Ar ionic and atomic lines were measured for various gas pressures. With increasing gas pressure, the sheath thickness became thinner. This trend can be reproduced by the numerical calculation based on the sheath theory that considers the effect of the generation of plasma ions in the sheath. The detailed analysis clarified that the reduction of the sheath thickness was caused by the ionization process and the rise of gas temperature in the sheath region.

References

[1] Y. P. Raizer, *Gas Discharge Physics*. Berlin: Springer, 1991.
[2] K. H. Schoenbach, A. El-Habachi, W. Shi, and M. Ciocca, "High-pressure hollow cathode discharges," *Plasma Source Science and Technology*, vol. 6, no. 4, pp. 468-477, 1997.
[3] R. H. Stark and K. H. Schoenback, "Direct current high-pressure glow discharges," *Journal of Applied Physics*, vol. 85, no. 4, pp. 2075-2080, 1999.

[4] K. H. Schoenbach, A. El-Habachi, M. M. Moselhy, W. Shi, and R. Stark, “Microhollow cathode discharge excimer lamps,” *Physics of Plasma*, vol. 7, no. 5, pp. 2186-2191, 2000.
[5] S. Namba, T. Yamasaki, Y. Hane, D. Fukuhara, K. Kozue, and K. Takiyama, “Emission spectroscopy of a microhollow cathode discharge plasma in helium-water gas mixtures,” *Journal of Applied Physics*, vol. 110, no. 7, 2011.
[6] T. Yamasaki, S. Namba, K. Takiyama, and H. Nojima, “Effect of cathode length on electrical characteristics of a microhollow cathode discharge in helium,” *Japanese Journal of Applied Physics*, vol. 51, no. 6, pp. 066001-006601-5, 2012.
[7] T. Yamasaki, S. Namba, K. Takiyama, and H. Nojima, “Pressure dependences of gas temperature and electron density in microhollow cathode discharges in He and He+H2O gases,” Japanese Journal of Applied Physics, vol. 51, no. 12, pp. 126101-1261010-5, 2012.
[8] M. A. Lieberman and A. J. Lichtenberg, *Principle of Plasma Discharges and Materials Processing*. John Wiley & Sons, 2005.
[9] C. Lazzaroni, P. Chabert, A. Rousseau, and N. Sadeghi, “The excitation structure in a micro-hollow cathode discharge in the normal regime at medium argon pressure,” Journal of Physics D: Applied Physics, vol. 43, no. 12, 2010.
[10] H. R. Griem, Plasma Spectroscopy. New York: McGraw-Hill, 1964.
[11] J. D. Cobine, Gaseous Conductors. New York: Dover, 1958.
[12] J. P. Boeuf, L. C. Pitchford, and K. H. Schoenbach, “Predicted properties of microhollow cathode discharges in xenon,” Applied Physics Letters, vol. 86, no. 7, pp. 071501-071501, 2005.