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Development of high-temperature and high-density plasma source by a cascade arc discharge

カスケードアーク放電による高温高密度プラズマ源の開発

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In order to realize a novel vacuum-atmosphere interface without large differential pumps, a robust cascade arc discharge source was constructed and tested for a long time operation. By modifying the test plasma by direct current discharge (TPD) device, we can successfully generate a plasma window with a high-gas pressure ratio (1/407) between discharge and expansion section at a discharge current of 20 A. Analysis of visible spectra revealed that a stationary argon plasma having a temperature of 1 eV and density of 1.4×10^{17} cm^{-3} was produced in the arc channel.

1. Introduction

Thermal plasmas having high gas/plasma viscosities can significantly suppress the gas flow rate in an arc discharge channel, and thus the cascade arc channel (*plasma window*) has a potential as an interface to isolate vacuum and atmosphere without a large differential pumping [1]. Therefore, various applications have been expected, i.e., (1) welding, cutting and fine processing by electron beam [2], (2) creation of new material and nano-processing by ion etching/implantation and (3) observation of biological living cell by x-ray [3]. In fact, Hershcovitch *et al* extracted the electron beam into air through the plasma window and demonstrated the welding of stainless steel in atmosphere [2]. They purchased the cascade arc apparatus developed by the Tech. Univ. Eindhoven group [4]. Unfortunately, no modification of the cascade arc has been done.

As arc plasma source for plasma windows, we have focused on the TPD (Test Plasma by Direct current discharge) [5]. This device is one of the cascade arc discharges and can readily generate stationary high-density plasma (~5 eV, ~10^{14} cm^{-3}) [6]. In this study, by modifying the TPD electrodes, the thermal arc plasma source with 1 eV, ≧10^{17} cm^{-3} under atmospheric Ar gas was developed.

2. Experimental Setup

The modified TPD device had a length of 30 cm and a inner-hole diameter of 3 mm. The cathode electrode was a needle shaped CeW rod (3.2 mmϕ) and the anode was tungsten. The intermediate electrodes (10 plates, floating) were made of molybdenum. The anode and intermediate electrode were water cooled to prevent their surfaces from being damaged. The argon was fed into the discharge section with a flow rate of 3.3 L/min. The discharge current was up to I_d=20 A. The plasmas produced expanded into a vacuum chamber (expansion section) which was exhausted by mechanical booster and rotary pumps. The plasma was initiated in a glow discharge mode (I_d=1 A, V_d=1 kV), and then the cathode was self-heated up to the working temperature, resulting in the transition to the cascade arc discharge (V_d ~150 V).

Plasma parameters are measured by visible spectrometers (f=50 cm, 150 grooves/mm and f=1 m, 2400 grooves /mm). The detectors are CCD cameras for both measurements. The observation is performed from the end port.

3. Results and discussion

Figure 1 shows the dependence of gas pressure in the discharge section on the current. Before the plasma initiation, the pressure was kept to be P_d~330 mbar. At I_d=20 A, it increased by ~3.6 times (1180 mbar). Considering that the pressures of the expansion section were P_e= 2.9 mbar, the ratios of the pressure in discharge section to that of expansion region is ~1/407. This steep pressure gradient is caused by the plasma plugging effect and choking of supersonic gas flow. Assuming that the initial gas temperature is 300 K, the simple

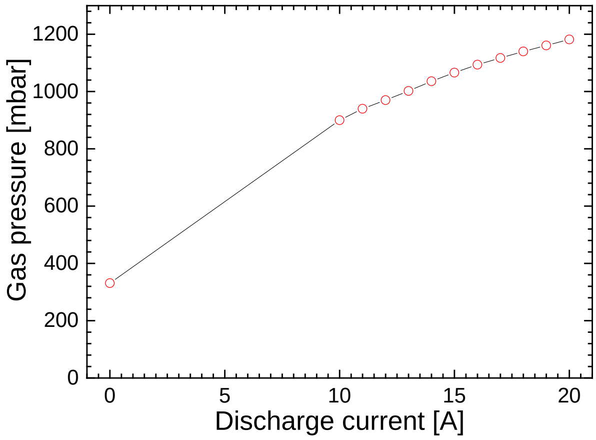

Fig. 1. Dependence of discharge pressure on current.

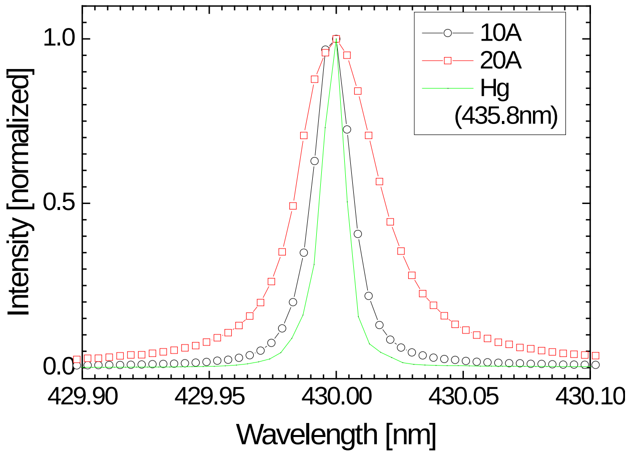

Fig. 2. Spectra of Ar I 4*s*-5*p* transition (λ=430 nm) at 10 A and 20 A discharges. For reference , the Hg spectrum is also plotted.

estimation yields the average gas temperature of 1,100 K inside the arc channel.

With increasing discharge current, intense emission (continuum and line spectra) can be observed in the arc channel. Although we cannot perfectly assume the continuum emission as a blackbody [7], the intensity peak appears ~450 nm. The Wien displacement law implies the radiation temperature of 6500 K [8].

In order to determine the electron temperature, we observed population densities of highly-lying levels attributed to Ar atom. Because the Rydberg states follow the Boltzmann distribution in a partially local thermal equilibrium (p-LTE), electron temperature can be obtained from the Boltzmann plot, yielding $T_e = 0.9^{+0.6}_{-0.2}$ eV and $1.0^{+0.7}_{-0.2}$ eV at I_d =10 and 20 A, respectively.

For atmospheric pressure plasmas, spectral line shape is broadened by various effects [9,10]. In particular, the Stark broadening dominates in the dense plasmas with the electron density of above 10^{15} cm^{-3}. The cascade arc discharge can efficiently generate high density plasmas, so that we derived the plasma density by measuring Ar I 4*s*-5*p* transition (λ=430 nm). Figure 2 shows the emission spectra for I_d =10 and 20 A. For reference, the instrumental profile obtained by a low-pressure Hg lamp of 435.8 nm is also plotted. As clearly seen, the line width becomes broader with increasing discharge current. The broadened shape observed can be described by a Voigt profile, which is a convolution of Gaussian and Lorentzian shapes. Since the Stark broadening effect accounts for the Lorentzian profile, we determined the Lorentzian width by a deconvolution procedure [11]. As a result, the Stark width shows that the electron density are $(4.1 \pm 0.5) \times 10^{16}$ and $(1.4 \pm 0.5) \times 10^{17}$cm^{-3} I_d =10 and 20 A, respectively.

4. Summary

In order to demonstrate the high performance plasma window, we modified the TPD apparatus. The plasma channel had a 30 cm in length and an opening of 3 mmϕ. Emission spectroscopy was carried out to determine the plasma parameters. Spectral analysis showed that the plasma had the electron temperature of ~1 eV and density of $1.4{\times}10^{17}$ cm^{-3} at a discharge current of 20 A.

Acknowledgments

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