Micrometer-scale very-high-frequency (VHF) plasma generation supported by thermoelectrons

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ABSTRACT
With a simple and effective method, a micrometer-scale very-high-frequency (VHF) plasma (thermoelectron-enhanced micrometer-scale plasma; TEMP) has been generated in a fine capillary, in which the inner diameter was approximately 25 μm. The excitation temperature of Ar TEMP has also been measured by the optical emission spectroscopy.

[1] INTRODUCTION
Recently, micrometer-scale plasma has attracted much interest. The miniaturization of plasma can be carried out in a small space with low energy and low cost. Applications of the plasma are found in various fields, such as analytical instruments (e.g., mass spectroscopy) [1], light sources [2,3] and materials processing [4-6].

For micrometer-scale plasma generation, it is very important to fabricate a micrometer-scale space (gap). Initially, we fabricated a micrometer-scale gap and generated micrometer-scale plasma using the scanning probe microscopy (SPM) technique [7]. Then, for easier generation, we also developed coplanar film electrodes on a substrate by lithography. Next, we generated a micrometer-scale direct-current (d.c.) plasma using these electrodes and confirmed the high density of micrometer-scale d.c. plasma experimentally [5]. Micrometer-scale d.c. plasma has been applied to materials processing successfully, and a novel processing tool composed of many plasma processing devices on a substrate, named the plasma chip, has been proposed [5,6]. However, micrometer-scale d.c. plasma has a short lifetime. Therefore, the development of radio-frequency (r.f.) or very-high-frequency (VHF) micrometer-scale plasma is highly anticipated for many applications.

Recently, micrometer-scale VHF plasma has been generated under atmospheric-pressure Ar gas using a novel technique [8]. One of the key issues in generating VHF microscale
plasma is the manner in which to supply electrons for plasma sustenance. A simple and effective method using thermoelectrons emitted from an inserted probe has been proposed.

In this study, even small plasma, the diameter of which is almost 25 μm, has been generated. In addition, we have also measured the temperature of this plasma by the optical emission spectroscopy.

III) EXPERIMENTAL
(A) Thermoelectron-enhanced micrometer-scale plasma generation

Figures 1 and 2 present a schematic diagram and an image of a micrometer-scale plasma torch, respectively. A micrometer-scale inductively-coupled plasma (ICP) generator, composed of a fine glass tube, a coil and an inserted tungsten wire, which was grounded, was employed. Supplying VHF (450 MHz) power to the coil also yields thermoelectrons, emitted from the heated tungsten wire and sustaining the micrometer-scale VHF plasma in stable condition. This micrometer-scale plasma is thus termed as thermoelectron-enhanced micrometer-scale plasma (TEMP).

To fabricate capillary, a micropipette puller (Sutter Instrument Corp., P-2000) was employed. The material was quartz, in which the inner and outer diameter were 0.5 and 1 mm respectively; the puller can pull quartz with a CO₂ laser. The top of the capillary was polished with a grinding machine for a micropipette. The five-turn coil of 1 mm inner diameter was made of 0.5-mm-diameter copper wire. For easier plasma generation, a high-voltage d.c. power source (15 kV, 0.5 s) was also employed to input electrons. Ar gas at 10 atm was injected and controlled with a flowmeter. The main generation steps are summarized in Table I.

![Fig.1 A schematic diagram of a TEMP generator.](image-url)
(B) Measurement of excitation temperature of Ar

As the first step of the measurement of TEMP, the dependence of Ar excitation temperature on the environment pressure was measured. The TEMP was generated in a 500-μm-inner diameter quartz tube with a 100-μm-diameter tungsten wire inserted to the second turn of the coil, which was the same coil as used in the above-mentioned generation (A). A torch was placed in the vacuum chamber for changing the environment pressure. The environment pressures ranged from 50 Torr to 760 Torr. The applied power and the Ar flow were fixed as 7 W and $1.16 \times 10^2$ mol/min, respectively.

The temperatures were estimated by performing optical emission spectroscopy in the area between the fourth and the fifth coil. We measured the intensity of the Ar peak from 425 nm to 435 nm. On the basis of these relative intensities, the temperature could be estimated [9]. A spectroscope with a CCD (charge coupled device) detector (Acton Research Corporation) and 100-μm-diameter optical fiber were employed.
RESULTS AND DISCUSSION

(A) Thermoelectron-enhanced micrometer-scale plasma (TEMP) generation

TEMP was generated in a fine capillary. For example, figs.3 and 4 show a setting consisting of a coil and a quartz capillary (about 25-μm inner diameter), and TEMP generation (25W, Ar - 6 x 10^{-6} mol/min), respectively. The electrode, inserted from the left side to the second turn of the coil, to provide thermoelectrons support, was a 10-μm-diameter tungsten wire. TEMP was confirmed to exist at the edge of the inserted wire and was almost 700 μm long (Fig.3). Without the inserted wire, the plasma could not be generated even with 30 W applied power. Moreover, this generation requires preheating of the tungsten wire. Therefore, the inserted hot wire played an important role which might indicate that the thermoelectrons contributed in the sustenance of TEMP.

The generation was very stable and continued for at least 30 minutes. After generation, no distinct surface change, such as melting or sputtering, could be found on the tungsten wire. Moreover, we did not observe any tungsten’s peaks for optical emission spectroscopy.

Using thermoelectrons is very effective for generating micrometer-scale plasma. For example, a tungsten circle (in case of the temperature 2400 K, radius = 5 μm) located at the edge of the inserted wire can supply thermoelectrons, which are approximately 20% of the ionization quantum needed for sustaining the cylinder-type plasma (in case of the radius = 5 μm, and the length = 50 μm) with a 10^{-4} ionization rate at the center.

Fig. 3 Setting for TEMP generation (coil, capillary, and inserted tungsten wire).
(B) Measurement of excitation temperature of Ar

Figure 5 presents the estimated temperature (excitation temperature) of Ar as a function of environment pressure. It is seen that, except for the result at 50 Torr, the lower the environment pressure, the lower the temperature; this is probably because the residence in the coil area becomes increasingly shorter. We suppose that between 100 and 50 Torr the plasma might start to change from arc type to glow type and thus might take a higher excitation temperature.

These measurements are still preliminary ones. However, the apparatus can set the optical fiber with a very precise (nanometer-scale) control by using a piezoelectric-inertial motor and a piezoscanner, from below 10 Torr to an atmospheric-pressure environment. Therefore, the measurement of smaller TEMP, such as that shown in (A), is currently in progress.

Fig. 5 Excitation temperature of Ar-TEMP as a function of environment pressure.
[IV] CONCLUSION

We have generated TEMP in a fine capillary (inner diameter 25 μm). This method, using thermoelectrons emitted from a heated wire, is very simple and effective. Moreover, the duration time and stability might be sufficient for some applications, such as surface analysis and materials processing. Moreover, the temperature dependence of TEMP on the environment pressure has been measured and a marked change corresponding to the transition from arc-type plasma to glow-type plasma has been found. In addition to the measurement of TEMP in a fine capillary, the design of a highly efficient coil and its application are currently in progress.

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REFERENCES