A New Method for Monitoring Electron Temperature in Si Plasma Etching

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This paper proposes a new method for monitoring the electron temperature in silicon plasma etching. The method is based on the maximum charging voltage that can be established by a local charge build-up at the bottom of a capillary having a high aspect ratio. The method is demonstrated for inductively coupled plasma (ICP) in argon by using a quartz chip containing an array of 400 µm-long, 20 µm-diameter capillaries. The maximum charging voltage is linearly related to the electron temperature. The charging voltage, however, is lower than the theoretical sheath voltage by 4.3 V over electron temperatures from 2.2 to 4.0 eV. From numerical simulations, this voltage difference is due to the potential barrier against ion movement in the capillary. Therefore, the voltage difference is independent of the electron temperature and this method can be used for relative measurement of electron temperature.

1. Introduction

Plasmas used for silicon etching processes must be reproducible and controllable. When performing low-temperature plasma etching and deposition in commercial reactors, the plasma characteristics immediately above the wafer must be monitored. This is especially true for the electron temperature, because it is directly related to plasma chemistry. Measurement tools for commercial silicon plasma etching processes should be simple, compact, and contamination-free, and they must have a long life cycle. The Langmuir probe has been widely used to measure electron temperatures in research and commercial reactors.[1] However, this probe is unsuitable for monitoring the properties of commercial plasma reactors, because it has a short-lived metal tip that can be a source of metallic contamination in a reactive gas.[2]

In this paper, we propose a new method for measuring the electron temperature in plasmas by using a small dielectric chip with an array of capillaries. The method is based on the maximum charging voltage that can be established at the bottom of a capillary due to the local-charge build-up effect.[3),4] This monitoring chip, which is placed on the reactor wall, remains free from contamination, corrosion by reactive gases, and spatial disturbance.

First, we explain the concept of our method for measuring the electron temperature in plasmas by using a dielectric chip with a capillary-array mounted on a reactor wall.[4] When plasma interacts with a wall surface having a small dielectric chip with a fine trench pattern, positive charges build up at the bottom of the trench. This occurs because the difference in directionality between ions and electrons incident on the surface wall forms a negative potential barrier near the trench entrance. Although ions pass through the barrier and accumulate at the bottom, most electrons incident on the surface do not reach the bottom because they cannot pass the negative potential barrier. As a result, the balance between the electron flux and the ion flux at the bottom results in a positively charged trench. The positive charge at the bottom reduces the height of the negative potential barrier, thereby enabling electrons to reach the bottom. If the trench aspect ratio is increased, the charging voltage at the bottom increases until it reaches the saturation voltage because the positive charge at the bottom cannot make electrons reach the bottom and also cannot suppress the movement of ions to the bottom. As a result, the floating potential at the bottom almost equals the plasma potential in the collision-less sheath. In other words, the charging voltage, *Vchg*, almost equals the potential drop within the sheath, *Vs*. It is known that in a collisionless sheath, the potential drop has a linear relationship with the electron temperature,[5] *Te*, as given by:

$$Vs = Te \ln \sqrt{\frac{M}{2\pi m}} \quad (1)$$

where M and m are, respectively, the ion mass and electron mass. Therefore, we can obtain the temperature by dividing the charging voltage, *Vchg*, by the following factor:

$$\ln \sqrt{M/2\pi m}$$

2. Experiment

We measured electron temperatures in a high-density, inductively coupled plasma (ICP) in argon at a low pressure by using a quartz chip with a capillary array on a dielectric wall surface. We then compared the results with the values obtained from a Langmuir probe. **Figure 1** shows our experimental setup.[4] An ICP source driven at 3.4 MHz was observed in the pressure range between 2 and 30 mTorr in Ar. We placed two 25 mm-diameter silicon chips on an electrode covered by a quartz plate. One chip was uncovered, and the other was completely covered by a 25 mm-diameter quartz chip with a capillary array. The capillary array was 0.4 mm long, 20 µm in diameter, and had an aspect ratio of 20. We kept the ion saturation current in the chip constant at different pressure levels. The charging voltage was observed using two high-voltage probes (Tektro P6009) to measure the potential difference between the chips. The current through the capillaries was observed using a current probe (Tektro 503A) while applying various DC bias voltages. We used a compensated, movable Langmuir probe[6] in the ICP source to measure the electron density and the electron temperature without disturbing the plasma.

3. Results and discussions

Figure 2 shows the observed charging voltage, which is the difference between the floating potentials of the silicon chips, as a function of electron temperature as measured by the Langmuir probe and the corresponding pressure. The figure also shows the potential drop in the sheath as a function of electron temperature as calculated from Eq (1). The observed charging voltage varied almost linearly from 6.6 to 14.9 V with the electron temperature. The charging voltage and the sheath potential drop showed similar linear relationships with the electron temperature. However, the charging voltages were lower than the theoretical sheath voltages by 4.3 V. **Figure 3** shows the current through the capillary array as a function of the bias voltage at the covered Si chip. The plasma potential was estimated from the electron temperature and the floating potential at the uncovered Si chip using Eq (1). The

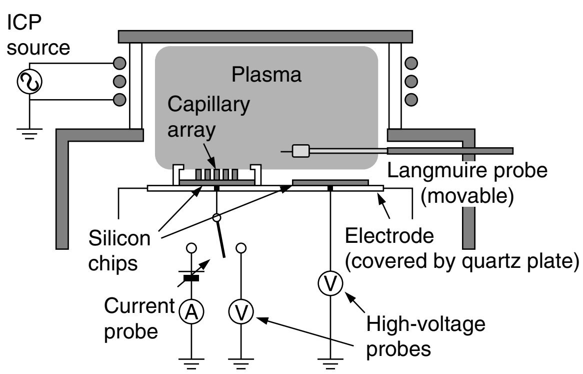

Figure 1
Experimental setup.

zero-crossing point of the curve was equal to the observed floating potential at the bottom of the capillary array. When the bottom reaches the saturation voltage, the electron current balances the ion current; however, under the balanced condition, there is still a flow of electrons to the bottom. This indicates that the electrons can reach the bottom even when the aspect ratio is very high, and this flow may cause the difference between the measured charging voltage and the theoretical sheath voltage.

We numerically estimated the surface potential distribution by tracing the trajectory of ions and electrons incident on a capillary to investigate the magnitude of the charging voltage at the bottom of the silicon chip and its relationship with the sheath potential drop. **Figure 4 (a)** shows the model we used. Here, we assume that the capillary is completely dielectric and that the constant boundary condition is provided at 10 µm above the top of the capillary surface and at the bottom of the capillary: respectively, øtop and øbottom. A positive ion, Ar^+, and an electron at the plasma-sheath boundary are assumed to have an isotropic Maxwellian velocity distribution with, respectively, temperatures Tp and Te. Ions are accelerated and electrons decelerated without collisions by a sheath potential that is perpendicular to the capillary surface. **Figure 4 (b)** shows a flowchart of the calculations. An axis-symmetric, 3-dimensional coordinate system is used for the capillary. To solve Poisson's equation, we calculate the potential distribution, ø (r, z), using a finite element method[7] taking into account the accumulated charge at the top and inside of the capillary and the constant boundary conditions at øtop and

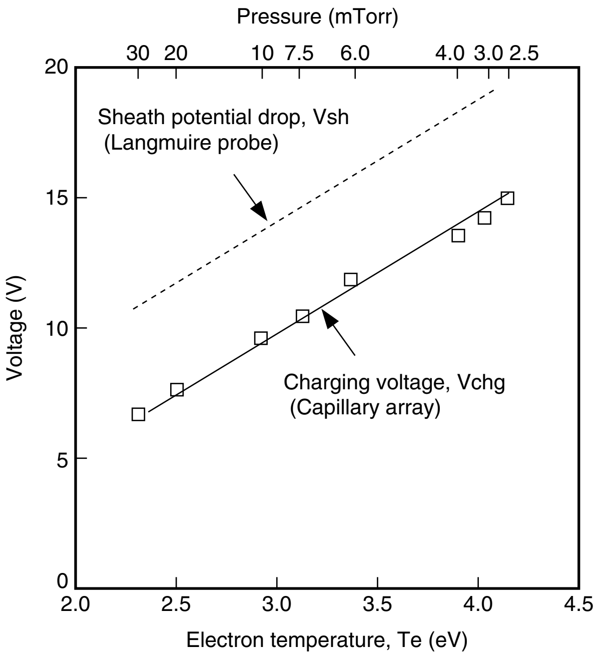

Figure 2
Charging voltage and sheath potential drop as functions of electron temperature. The ion saturation current density was constant at 5.4 mA/cm^2. The electron densities ranged from 1.8×10^{11} to 2.4×10^{11} cm^{-3}.

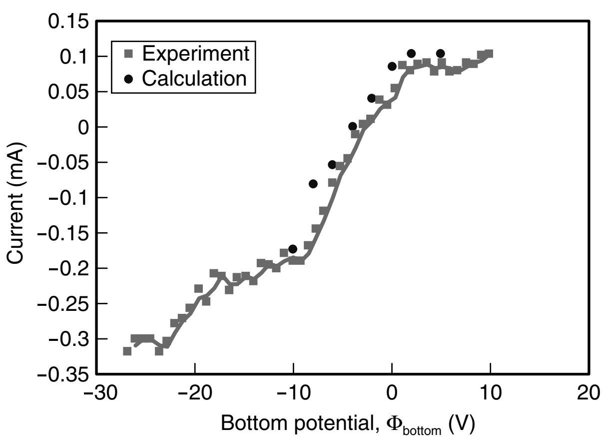

Figure 3
Experimental and calculated currents through the capillary array of the quartz chip as functions of the bias voltage at the Si chip. Electron temperature, Te, was 3.0 eV.

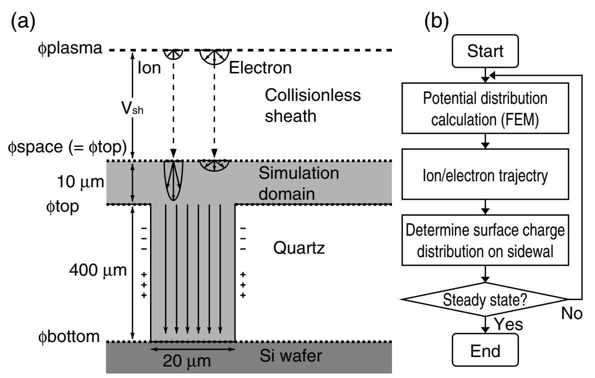

Figure 4
(a) Calculation model, (b) flowchart of the calculations.

øbottom. The accumulated surface charge distribution is calculated, without considering the surface conduction current, by tracing the trajectory of the ions and electrons under potential ø (r, z). The simulations are repeated until the ion flux equals the electron flux at every point in the capillary inner side-wall. As shown in Figure 3, the calculated values of the current roughly agree with the measured values for a Te of 3 eV and an electron density, Ne, of 1×10^{11} cm^{-3}.

Figure 5 shows the 2-D spatial distribution of potential in the capillary and the potential distribution along the center of the capillary for a Te of 3 eV, Tp of 293 K, and a plasma potential of 0 V. The bottom potential is 0 V, which is equal to the plasma potential in Figure 5. We found that not only a potential barrier (A) against electrons but also a potential barrier (B) against ions form as a result of positive charges accumulating on the upper section of the sidewall. We also found that the potential at the peak of barrier (B) is nearly equal to the plasma potential. **Figure 6** shows the angle distribution of ions and electrons. In Figure 6 (a), ions at the entrance of the capillary have a more anisotropic directionality than the electrons. On the other hand, as shown in Figure 6 (b), electrons at the peak of barrier (B) have a more anisotropic directionality. Therefore, the electrons can reach the bottom more easily than the ions; hence, there is a slight voltage difference between the peaks of barriers (A) and (B). The potential barrier against ions, which originates from their angular distribution, is independent of the electron temperatures; therefore, this method can be used for relative measurement of electron temperatures.

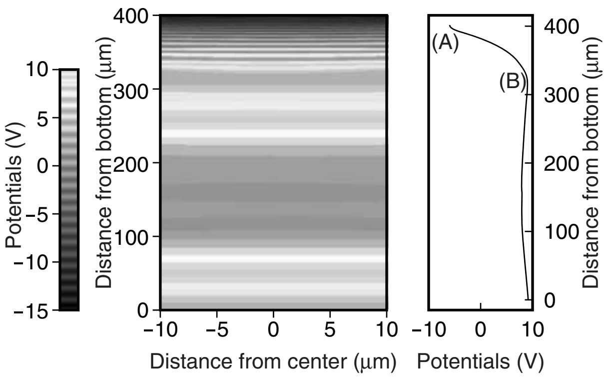

Figure 5
Spatial potential distribution in the capillary and the potential distribution along the capillary center at an electron temperature of 3 eV, ion temperature of 293 K, and plasma potential of 0 V. The bottom potential is 0.0 V.

4. Conclusions

We have developed a method for measuring the electron temperature in inductively coupled plasmas in argon by using a small quartz chip with

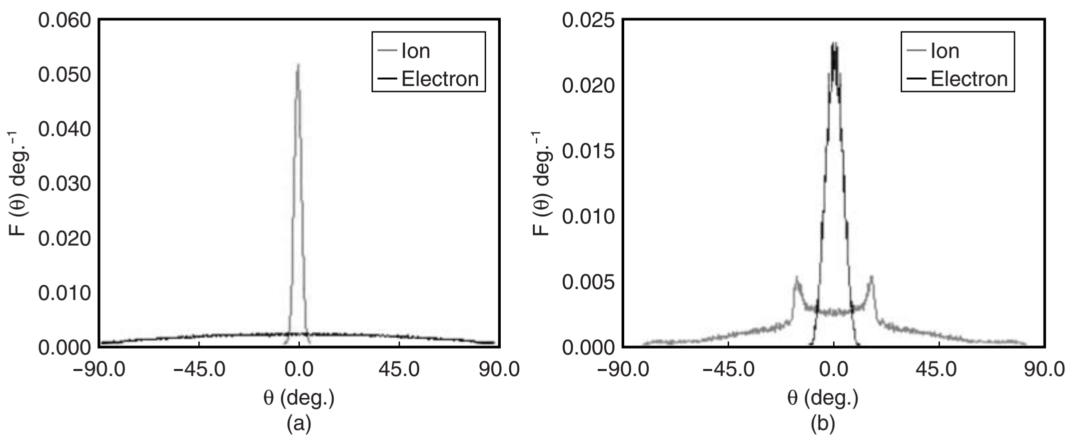

Figure 6
Ion and electron angle distribution. (a) Distribution at the capillary entrance, (b) distribution at the peak of barrier (B) in Figure 5. Direction of $\theta = 0$ is toward the bottom.

a capillary array. The results were compared with those obtained using a Langmuir probe. The charging voltage, however, was lower than the sheath voltage. We numerically estimated the potential distribution by tracing the trajectory of ions and electrons incident on a capillary to investigate the magnitude of the charging voltage at the capillary bottom. We found that a potential barrier against ions formed in the capillary, causing electrons to have an anisotropic directionality. As a result, there is a constant difference between the sheath voltage and the charging voltage. This method can be used for relative measurement of electron temperature.

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