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Two Dimensional PIC Simulation of VHF Capacitively Coupled Ar Plasma

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A very high frequency capacitively coupled plasma source (100 MHz) was studied using a two-dimensional PIC simulation, and spatial distributions of the plasma parameters were examined at a discharge gap of 25 mm. In the simulation, electromagnetic effects were not taken into account. Electron energy distribution functions were also calculated. It was found that the density and temperature of electrons had a peak value at the center and near the edge of the discharge electrodes, while the plasma potential was fairly uniform.

Key words: *Capacitively coupled plasma, Energy distribution, PIC simulation, Etching*

1. Introduction

Very high frequency capacitively coupled plasma (VHF CCP) sources are widely used for applications such as plasma enhanced chemical vapor deposition (PECVD) and etching because of a high electron density with a low electron temperature. There has been a current tendency that a power generator frequency is increased to obtain high rates of deposition and etching. Recently, VHF plasma sources at excitation frequencies of 100-150 MHz have become popular in etching [1-2]. In fact, when the frequency is increased, the electron density increases, leading to a high etching rate. However, as is well known, electromagnetic effects such as standing wave and skin effects [3] arise at high frequencies, and as a result, the electron density distribution along the discharge electrodes becomes nonuniform [4]. Overzet and Hopkins [5] observed the off-axis radial peak in electron density in the Ar plasma even at a frequency of 13.56 MHz, which was explained by the fluid model simulation [6]. On the other hand, Yamazawa [7] investigated the effect of harmonics on the electron density and reported a center-peaked electron density profile that was caused by a nonlinear electron resonance heating. In addition, Sawada et al [8] observed that the electron density in the VHF Ar plasma at a frequency of 60 MHz had a center-peaked profile. Thus, the study of a spatial distribution of VHF Ar CCPs is an important subject in etching and has been examined by many researchers [2, 8-9].

The Langmuir probe method is a simple and powerful diagnostic tool in a low temperature plasma and is mostly used [5] to measure the plasma parameters such as the density and temperature of electrons. However, there is fear that a Langmuir probe disturbs VHF discharges; spatial distributions of the plasma parameters are deformed by introducing the probe. Therefore, in order to develop a new VHF CCP source for etching, we have studied the characteristics of VHF plasmas by simulation. As is well known, there are three kinds of simulation models to examine the behaviors of a low temperature plasma, that is, fluid model, hybrid model, and particle-in-cell (PIC) model. The fluid model is useful at high pressure while the PIC model is effective at low pressures. The properties of CCPs have been extensively investigated using a two-dimensional (2D) hybrid model [2, 9]. Yang and Kushner [2] explained a shift in the peak electron density toward the center of the plasma source as the power source frequency increased. Bera et al [10] tried to control

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plasma uniformity using two frequency power sources at a combination frequency of 60 and 180 MHz and compared with the simulation by a 2D fluid model including Maxwell equations. They also calculated the electron density profile by a one-dimensional (1D) PIC simulation, where electromagnetic effects were not considered, and found that the electron density became maximum at the center with large contribution of the 180 MHz power source to plasma production and the electron energy distribution deviated from Maxwellian one.

Generally, an electron energy distribution function in VHF plasmas is not Maxwellian at low pressure. In fact, Godyak and Piejak [11] observed that electrons had a bi-Maxwellian distribution. Thus, we need to incorporate a kinetic description of electrons and ions in the simulation for understanding self consistently the plasma characteristics. The best calculation is to use the PIC/Monte Carlo (MC) method [12] because the fundamental equations can be employed without much approximation. In this study, we calculated two dimensional (2D) profiles of the plasma parameters using a 2D Particle-In-Cell with Monte Carlo Collision Module (PIC-MCCM) of PEGASUS Software [13], where electromagnetic effects were not included, that is, we assumed that electrostatic fields were dominant in the VHF discharge.

2. Description of the model

The PIC/MC method is based on a kinetic description of charge particle motions in phase space. Charged particles move in the self-consistent electric field that is obtained by solving the Poisson equation. The Monte Carlo method is used to calculate collisions including excitation and ionization. The PIC method has been described in detail by Birdsall [14], Turner [15], and Verboncoeur [12]. In the PIC-MCCM of PEGASUS Software, electrons and ions are modeled as a large number of representative particles that are referred to as simulated particles (superparticles). A motion of the individual superparticle is subject to the Newton's law in the electric field. Various kinds of collisions are also taken into account using Monte Carlo collision method. Macroscopic quantities of the electron and ion densities, mean energy, particle flux are obtained by statistical calculations using velocities and positions of all the superparticles. Here, we assume that there are two kinds of charged particles in the plasma for saving the computation time: electrons and Ar^+ ions. Figure 1 is a schematic of our CCP source simulated (380 × 40 mm^2), where a Cartesian coordinate is used and a symmetric plane at the center between two discharge electrodes is assumed. A power source frequency was 100 MHz, where external circuit was not included. The gas used was Ar and the pressure was varied from 20 to 100 mTorr. The initial conditions for superparticles were: the density=3 × 10^5 m^{-3} for electrons (10^{15} m^{-3}) and ions (10^{15} m^{-3}).

3. Simulation Results and Discussion

Since a VHF CCP source provides a high electron density plasma with a low electron temperature, it has been popular for etching. On the other hand, the self-bias voltage formed on the power electrode that is indispensable for etching is much lower than that at a power source frequency of 13.56 MHz. Therefore, recently dual-frequency power sources have been employed for etching. In this study, we performed the simulations at a single power source frequency as a first step for developing a large-area VHF CCP source. At first, we calculated the time history of the self-bias voltage V_{dc} at a pressure of 40 mTorr. Figure 2 shows that V_{dc} saturates to – 3.3 V that is very low for etching, as expected.

We calculated a two-dimensional (2D) map of the plasma parameters. The results at 30 mTorr are shown in Figs. 3-5, where the

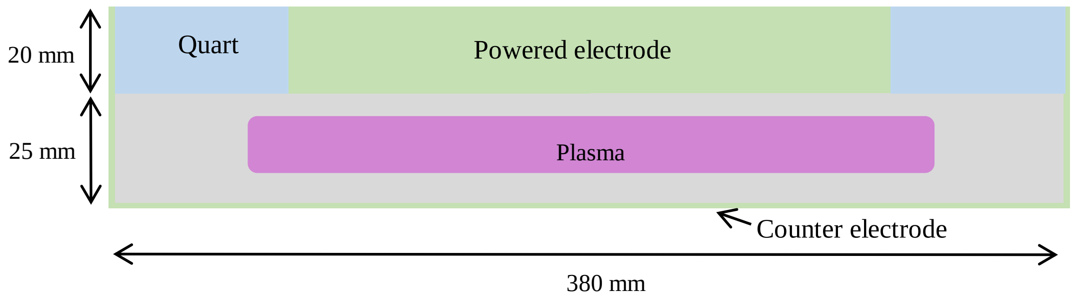


Fig.1 Schematic of the VHF CCP source.

amplitude is 30 V. Figure 3 shows that the electron density n_e amounts to 3.6×10^{16} m^{-3}. Note that n_e peaks at x= 75 and 190 mm, that is, the electron density peaks both near the edge of the discharge electrodes and the chamber center. Bera et al [16] simulated a VHF-CCP at a frequency of 180 MHz using the 2D fluid model coupled with Maxwell equations and found the two-peak profile at a narrow gap of 17.8 mm at a pressure of 100 mTorr. They also reported that as the gap distance was increased, the electron density profile became to a center-peaked profile. In addition, Sawada et al [8] carried out the experiments on a VHF-CCP at power source frequencies of 60 and 106 MHz and compared with the simulations taking into account of Maxwell equations. They pointed out that higher harmonics of a power source frequency affected the electron density profile. As already described, here we did not solve Maxwell equations, so we can conclude that the two-peak profile may be due to other effects.

Figure 4 shows that the electron temperature T_e also has a peak value at x=75 and 190 mm and T_e is around 2 eV. Note that T_e near the discharge electrodes is around 3 eV that is a little higher than T_e at the center. The CCP is produced by electron impact ionization, so T_e near the electrodes becomes higher. In this study, the power source frequency is 100 MHz, so VHF effect will be higher, leading to a low electron temperature. There have been many reports on spatial distributions of the electron density of VHF-CCPs, that is, researchers have mostly focused on the electron density profile. Spatial distributions of the electron temperature, especially those near the discharge electrodes, are also important because it is closely related to the sheath formation on the substrate.

Figure 5 shows that the plasma potential V_s is around 32 V and fairy uniform over the discharge electrodes. Looking carefully at V_s close to the discharge electrodes, it is not uniform, and the thickness of the sheath formed on the grounded electrode is not uniform, suggesting that it will not easy to control energy distribution functions of charged particles by dual-frequency technology [2].

Energy distribution functions of charged particles play an important role in etching as well as plasma production. We calculated the energy distribution functions of electrons (EEDF) and ions (IEDF) at different monitoring positions denoted by P_i. As seen in Fig. 6(a), electrons have a Maxwellian distribution function in the low energy region. In fact, we confirmed that semi-log plots of the EEDFs fit to a straight line in the energy region of (0-15) eV and high energetic electrons are truncated, that is, the obtained EEDF looks a Druyvesteyn-like distribution function. Experimentally, Godyak and Piejak [11] observed the bi-Maxwellian and Druyvesteyn distribution functions at low and high pressures, respectively, at a frequency of 13.56 MHz. Abdel-Fattah and Sugai [17] also measured EEDFs for different power source frequencies ranging from 13.56 to 60 MHz and reported that the EEDFs became a Druyvesteyn distribution function below 30 MHz and a bi-Maxwellian distribution function above 30 MHz. In this simulation, the VHF plasma was generated at 40 mTorr at 100 MHz, but the bi-Maxwellian distribution function was not obtained, so we can conclude that the effect of stochastic heating [3] on the plasma generation is negligible small. Figure 6 also indicates that the electron density is lower and electron temperature is higher at a monitoring position of P_1 (inside the ion sheath) which agrees with the results of Figs. 3 and 4. On the other hand, ions were cold except at P_1 where ions are accelerated by the sheath potential.

As aforementioned, we have found a two-peak profile of the electron density in the VHF electrostatic discharge by the PIC simulation. As is well known, the PIC simulation is more accurate than the fluid model simulation because of fewer assumptions for modeling. To understand the two-peak profile, we need to examine the parametric dependences of the 2D map such as the pressure and gap dependences. This will be discussed in future.

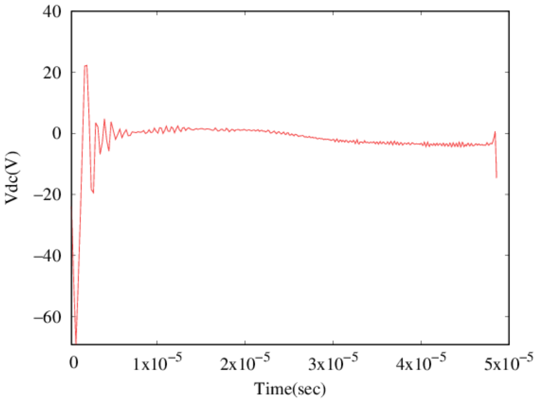


Fig.2 Time history of the self-bias voltage, V_{dc}, on the powered electrode at a pressure of 40 mTorr, where the amplitude is 30 V

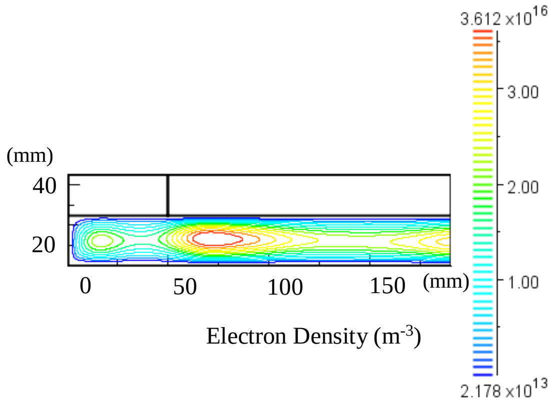


Fig.3 2D map of the electron density n_e at a pressure of 40 mTorr, where the amplitude is 30 V.

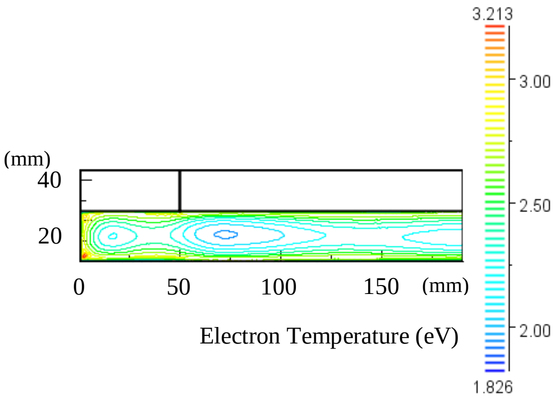


Fig.4 2D map of the electron temperature T_e at a pressure of 40 mTorr, where the amplitude is 30 V .

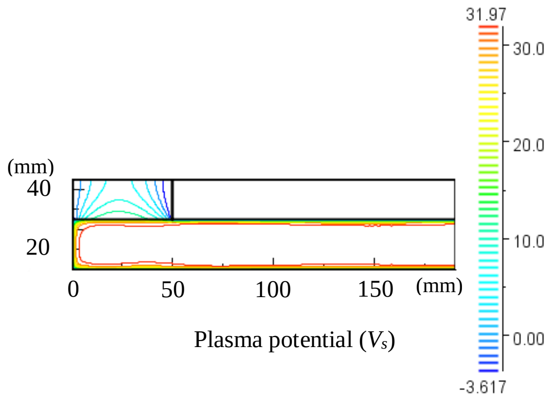
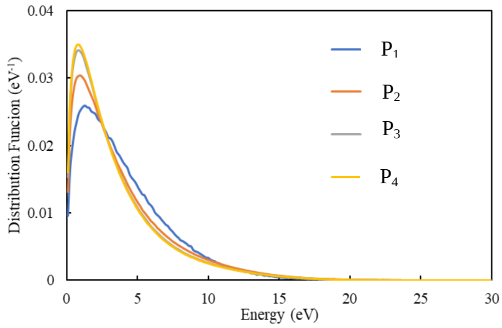
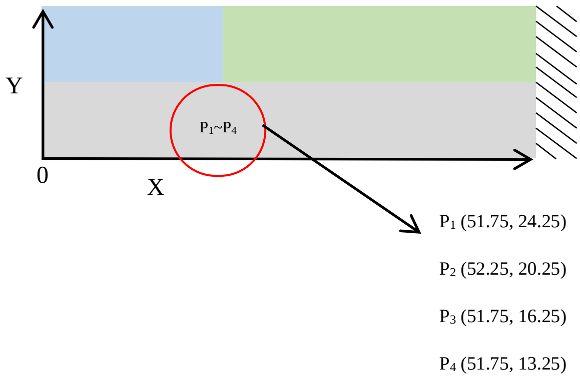


Fig.5 2D map of the plasma potential V_s at a pressure of 40 mTorr, where the amplitude is 30 V.



(a)



(b)

Fig. 6 Energy distributions: (a) EEDFs for different monitoring positions at a pressure of 30 mTorr, where the amplitude is 30 V and (b) the monitoring positions of electron energy distributions

4. Conclusion

We calculated the characteristics of the VHF Ar plasma (100 MHz) at a pressure of 40 mTorr using the PIC-MCCM of PEGASUS Software, where we assumed that the plasma is produced by electrostatic fields. We found the following results:

(1) The self-bias voltage is as low as a few volts.

(2) The 2D maps of the electron density and electron temperature show that they peak both near the center and the edge of the discharge electrodes, while the plasma potential is fairly uniform.

(3) The electron energy distribution function is similar to the Druyvesteyn-like one.

We conclude that the above-mentioned results will be useful for designing a VHF plasma source for large-area etching. The simulation using the dual-frequency power sources will be our future study.

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