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Comparison study of electromagnetic wave propagation in high and low pressure Ar inductively coupled plasma

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The electromagnetic wave propagation in plasmas has been investigated based on the hypothetical parameters in a number of previous literature, but the results can't mirror the feature of real plasma sources for waves. In this paper, the two-dimension parameters of Ar inductively coupled plasma (ICP) are investigated under high and low pressure by multi-physics coupling analysis method. Meanwhile, the profiles of electron density are diagnosed by the Langmuir probe for comparison with the simulated. The increasing pressure induces the significant increase of oscillation frequency and collision frequency, while a large density gradient causes the more nonuniform distribution. The wave propagation in ICPs is calculated with Z-transform finite-different time-domain method. The curves of attenuation, transmission and reflection coefficient are obtained versus pressure, frequency and power. The low pressure ICP induces the relative more attenuation of wave in the frequency band (1 GHz–6 GHz), while the high pressure ICP is more effective to the frequency band (6 GHz–17 GHz). The increasing power is conductive to the attenuation within limits. The reflection is complicated due to the high degree of wave vector gradient over a wavelength. Moreover, the pseudo secondary wave source is created inside high electron density region of ICP.

1. Introduction

According to a few investigations on the interaction between EM waves and plasma over past decades, it has been demonstrated that the plasma sources could conditionally absorb waves, which depends on the properties of plasma, such as cover-area, thickness, electron density (N_e) and collision frequency (ν_m) distribution [1,2]. A number of researchers have simulated the wave propagation in plasma based on hypothetical distribution of N_e and ν_m, such as uniform [3] or Epstein [4]. However, the results couldn't precisely reflect the impact of real plasma sources on the wave propagation. The planar-coil ICP source has potential advantages over other sources [5], including wider gas pressure range, larger area and higher N_e, which make it more effective to wave attenuation [6]. According to $\nu_m \approx 13.56$ MHz for the pressure (P^*) = 25 mTorr, the ICP can be divided into the two different regimes, low pressure and high pressure. The researches on planar-coil ICP primarily focused on that in low pressure for materials and semiconductor processing, rarely in high pressure.

The experiments [7] proved that the incident waves were intensively attenuated through an all-quartz chamber filled with argon (Ar) ICP. However, the associated mathematical model hasn't been built because the N_e and ν_m distribution of ICP are hardly described by a fixed function. The ICP discharge-process is affected by a number of factors, including RF power, bias voltage, gas species and pressure. According to the results [8], the volume and parameters distribution of ICP were significantly changed from low pressure to high pressure. It is demonstrated by M Andrasch et al. [9] that the N_e profiles of Ar-ICP along the radial direction could be described by a zero-order Bessel function. However, the one-dimension function is not available for multi-dimension model of wave propagation. In addition, the waveform is distorted by time-varying plasma due to the modulation of the amplitude and phase [10]. Therefore, the interaction between wave and ICP are inconclusive, in consideration of the property change of ICP and the corresponding variation of wave vector in different conditions.

In this paper, the two-dimension parameters of high and low pressure Ar-ICP are obtained by multi-physics coupling analysis method. The Ar-ICP discharged at 2/200 Pa are observed in H-mode by the experiments, and the profiles of N_e are diagnosed by

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the Langmuir probe for comparison with the simulation model. The propagation properties of the EM waves in ICP are calculated with Z-transform finite-different time-domain method (ZT-FDTD). The paper is organized as follows. Section 2 describes the geometry and material of ICP. Section 3 presents the multi-physics theory model of the two-dimensional ICP discharge. The two-dimensional parameters distribution is given in Section 4, including the electron oscillation angular frequency (ωpe), N_e, ν_m, the real and imaginary component of wave vector. The detailed ZT-FDTD mode between wave and ICP is building in Section 5. The transmission, reflection and attenuation of the EM waves with ICP at 2/200 Pa are plotted and discussed in Section 6. The conclusions are given in Section 7.

2. Geometry and material

The two-dimensional multi-physical models of ICP, including reactor, inductive coils and plasma region, were set up by COMSOL platforms [11]. The axisymmetric geometry of ICP in simulation was reference to the experimental setup of ICP, as shown in Fig. 1(a) and (b). The ICP source discharged inside chamber bounded by quartz and steel grounded walls. The four-turn coils were placed under the bottom of chamber. The coil antenna coupled the RF power to the plasma across the bottom quartz window, and the EM waves transmitted into chamber across the top quartz window. The Faraday-shield plate, inlet and outlet structures were not considered in the model due to the ignorance of capacitive component [12] and convective flux. The RF source set to 13.56 MHz with the range in 300–700 W and the pressures set to 2/200 Pa. Assumptions of the ICP model were enumerated as follow: I. The convection of electrons due to fluid motion was neglected. II. The electron energy distribution was assumed to be a Maxwellian distribution (EEDF). III. The ions were assumed to be isothermal.

3. Multi-physics theory model of ICP

The sinusoidal external current $\mathbf{J}_e$ in the inductive coils creates a “time-varying” magnetic field around the surrounding, and the power is transferred to the plasma electrons by collisional dissipation or collisionless heating process. The magnetic vector potential **A** is calculated in the frequency domain by D'alembert's equation [13], from plasma electric conductivity σ_P:

$$\sigma_P = \frac{N_e e^2}{m_e(\nu_m + j\omega)} \tag{1}$$

where ω is the angular frequency of the electric source,e is the electron charge and m_e is the electron mass. The ν_m is calculated from $\nu_m = \sigma_k N\sqrt{8kT_e/\pi m_e}$, where k is the Boltzmann constant, N is the number of neutral background species density, σ_k is the collision cross section and T_e is electron temperature. The magnetic field creates an azimuthally symmetric electric field E_θ and associated induced current J_θ in the chamber. For $E_\theta, J_\theta \propto r$, the absorbed power density P_{abs} decays sharply near the axis, resulting in a single-turn ring-shaped plasma current. The N_e and mean electron energy density N_ε are computed by solving the electron drift-diffusion equations [14,15] (2) and (3).

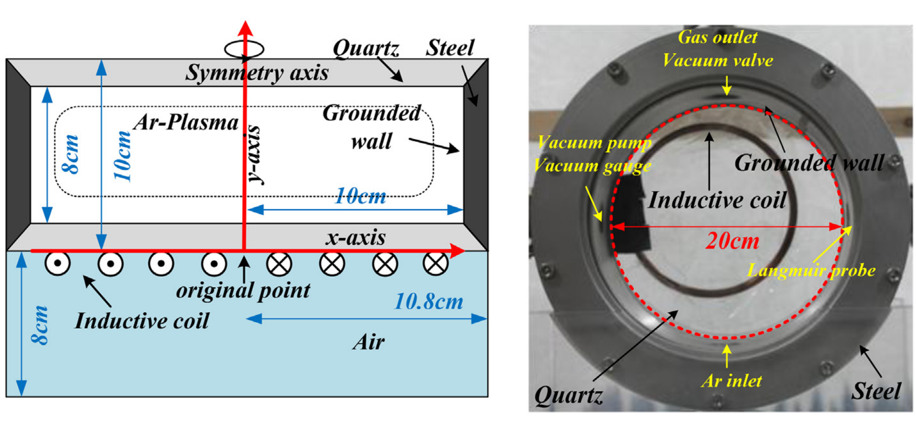
$$\frac{\partial N_e}{\partial t} + \nabla \Gamma_e = R_e \tag{2}$$

$$\frac{\partial N_\varepsilon}{\partial t} + \nabla \cdot \Gamma_\varepsilon + \mathbf{E} \cdot \Gamma_e = R_\varepsilon \tag{3}$$

where **E** is the electric field, R_ε is the energy loss due to inelastic collisions and R_e is the electron source. The electron flux vector Γ_e and electron energy flux Γ_ε are defined as:

$$\Gamma_{e/\varepsilon} = -\left(\mu_{e/\varepsilon} \cdot \mathbf{E}\right) N_{e/\varepsilon} - \nabla\left(D_{e/\varepsilon} N_{e/\varepsilon}\right) \tag{4}$$

where $\mu_{e/\varepsilon}$ is electron/energy mobility, $D_{e/\varepsilon}$ is electron/energy diffusivity. The R_e in Eq. (2) is determined from the plasma chemistry rate coefficients which are computed by each electron impact reaction based on cross section data. Simple Ar chemistry is chosen from Ref. [16], including the excited state of argon Ar (4s). The electron-impact rate coefficients of reactions are calculated by the electron cross sections data imported from Ref. [17]. The R_ε is computed by summing the energy loss due to inelastic collisions over all reactions. The non-electron species transport is obtained by the mixture-averaged diffusion model [18] according to the mass fraction of each species. The space charge density is obtained by using the charge conservation based on all type of plasma chemistry reactions.



(a) COMSOL model (b) experimental setup

Fig. 1. Schematic of the inductively coupled plasma source.