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A self-consistent global model of solenoidal-type inductively coupled plasma discharges including the effects of radio-frequency bias power

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We developed a self-consistent global simulator of solenoidal-type inductively coupled plasma discharges and observed the effect of the radio-frequency (rf) bias power on the plasma density and the electron temperature. We numerically solved a set of spatially averaged fluid equations for charged particles, neutrals, and radicals. Absorbed power by electrons is determined by using an analytic electron heating model including the anomalous skin effect. To analyze the effects of rf bias power on the plasma properties, our model also combines the electron heating and global transport modules with an rf sheath module in a self-consistent manner. The simulation results are compared with numerical results by using the commercial software package CFD-ACE+ (ESI group) and experimental measurements by using a wave cutoff probe and a single Langmuir probe. © 2011 American Institute of Physics. [doi:10.1063/1.3572264]

I. INTRODUCTION

Inductively coupled plasma (ICP) sources are widely used in semiconductor fabrication processing because a high density plasma with good uniformity is easily obtained under low pressure without an external magnetic field.1–4 Moreover, compared to other reactors (Helicon, ECR, etc.), the ICP reactor can be easily scaled up to accommodate a large wafer size because the system is substantially simpler.5,6 Accordingly, many research groups have been researching the ICP reactor, and it is already being applied to a partial semiconductor manufacturing line.

In the modeling of plasma etching equipment that have radio-frequency (rf) biased on a substrate, the rf sheath must be accurately represented to properly simulate the ambipolar fields, the electron stochastic heating, and a self-bias. Lieberman7,8 derived analytical solutions assuming a sinusoidal current source, and Godyak and Stemberg9,10 have done extensive modeling. Miller and Riley11 presented the unified sheath model, and Panagopoulos and Economou12 obtained an analytic expression for the energy split of the ion energy distributions arriving at the substrates based on the work of Miller and Riley. Edelberg et al.13 determined the ion energy distributions (IEDs) by using a self-consistent dynamic model of the rf sheath by coupling an equivalent circuit model to the fluid equation. Bose et al.14 solved the fluid equation assuming a sinusoidal voltage source including the inertial term in the ion momentum equation. Later, Dai et al.15 proposed a self-consistent fluid model that included all time-dependent terms in the ion fluid equations and assumed the sinusoidal current source.

However, numerically resolving the thin sheath in computer models of the devices requires large computing resources. Therefore, based on the Miller and Riley’s semianalytical solution for rf sheath, Grapperhaus and Kushner16 developed a sheath model that is solved self-consistently within the framework of a two-dimensional hybrid plasma equipment model (HPEM). The sheath model consists of a one-dimensional local model that is implemented at each mesh point at the boundary of the plasma and the walls of the reactor. Although the authors of Ref. 16 combined the transport module with the rf sheath module, only voltage source condition on the substrate is adopted in their model, and they did not fully investigate the effects of rf bias power on the plasma parameters.

In a recent study, the changes of the electron temperature and the plasma density by increasing bias power were observed in planar-type ICP discharges.17 The authors of Ref. 17 explained the changes of the plasma parameters by using the balance between total power absorption and power dissipation. However, the absorbed source and bias powers and the total loss energy at the grounded wall and the substrate should be determined in a self-consistent manner.

Therefore, in this work, we solve a set of spatially averaged global fluid equations for charged particles, neutrals, and radicals.18,19 Absorbed power by electrons is determined by using an analytic electron heating model including the anomalous skin effect.3 Our model combines the electron heating and global transport modules with an rf sheath module in a self-consistent manner based on the recently developed Dai’s model.15 Although the Dai’s model is the self-consistent fluid model, we found that the self-bias under most conditions were obtained in seconds. The simulation results are compared with experimental measurements by using a wave cutoff probe20,21 and a single Langmuir...
We also performed the two-dimensional fluid simulation by using the commercial software package CFD-ACE + (ESI group). 

Unfortunately, in CFD-ACE +, only the sinusoidal voltage source boundary conditions can be applied for rf bias. Assuming the sinusoidal voltage source, we also use a simple circuit model based on the previously developed model. Kim et al. \(^4\) determined the dc self-bias by using a circuit model \(^{25}\) from the plasma parameters. They regarded sheaths on the chamber wall and biased substrate as capacitors, and the capacitors are connected in series through plasma. In their model, the capacitively coupling between antenna and plasma is not considered. In a similar manner, we use an equivalent circuit model and expand their model based on the unified rf sheath model. \(^{11,12}\) The obtained amplitude of applied rf voltage is used for voltage boundary conditions of the two-dimensional fluid model.

This paper is organized as follows: In Sec. II, the electron heating model, spatially averaged global fluid equations, and rf sheath model are explained. The experimental apparatus is described in Sec. III. Then the numerical and experimental results are presented in Sec. IV. Finally, the conclusion is given in Sec. V.

II. MODEL DESCRIPTIONS

A schematic diagram of the solenoidal-type ICP reactor is shown in Fig. 1. The power absorbed by electrons, including the anomalous skin effect, is calculated by the heating module. The resulting power absorbed by electrons is used to calculate the plasma density and electron temperature in the plasma transport module. The plasma transport module then returns the plasma density and electron temperature to the rf sheath module. Then the sheath voltage drop is obtained from the rf sheath module, which is coupled with the transport module in a self-consistent manner. These processes are repeated until a self-consistent steady state is obtained (see Fig. 2). The detailed models used in this work are described in the following text subsections.

A. Electron heating model

To determine the power absorbed by electrons, we used the previously developed analytic heating model based on collisionless nonlocal electron heating. \(^3\)

Assuming \(\theta\)-symmetry, the wave equation describing the inductive electric field component having only a \(\theta\) component becomes
TABLE I. Gas-phase reactions included in simulations of Ar plasma and their rate coefficients.

<table>
<thead>
<tr>
<th>Reactions</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>ΔE</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron-impact reactions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e + Ar → Ar⁺ + e</td>
<td>2.783 × 10⁻¹⁶</td>
<td>0.3287</td>
<td>140200.0</td>
<td>11.6</td>
<td>26</td>
</tr>
<tr>
<td>e + Ar → Ar⁺ + 2e</td>
<td>5.779 × 10⁻¹⁷</td>
<td>0.6329</td>
<td>186400.0</td>
<td>15.76</td>
<td>27</td>
</tr>
<tr>
<td>e + Ar⁺ → Ar⁺ + 2e</td>
<td>6.225 × 10⁻¹⁴</td>
<td>0.1072</td>
<td>51210.0</td>
<td>4.43</td>
<td>28</td>
</tr>
<tr>
<td>e + Ar⁺ → Ar⁺ + e</td>
<td>2.645 × 10⁻¹⁶</td>
<td>0.2894</td>
<td>8601.0</td>
<td>-11.6</td>
<td>26</td>
</tr>
<tr>
<td>Metastable reactions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ar⁺ + Ar⁺ → Ar⁺ + Ar⁺ + e</td>
<td>1.200 × 10⁻¹⁵</td>
<td>0.0000</td>
<td>0.0</td>
<td></td>
<td>29</td>
</tr>
</tbody>
</table>

The rate coefficients are in the form $k_i = A_i T_e^b \exp(-C_i/T_e)$. The units of $k_i$ are in m¹ s⁻¹ and $T_e$ is in Kelvin.

Cross-section was obtained by detailed balance.

\[
\frac{\partial^2 E_\theta}{\partial r^2} + \frac{1}{r} \frac{\partial E_\theta}{\partial r} - \frac{E_\theta}{r^2} + \frac{\partial^2 E_\theta}{\partial z^2} + \mu_0 \varepsilon_0 \omega^2 E_\theta = -\mu_0 \omega i (J_e + J_p),
\]

where $\mu_0$ is the permeability of free space, $\varepsilon_0$ is the permittivity of free space, $\omega$ is the excitation frequency, and $J_e$ and $J_p$ represent the antenna and plasma current densities, respectively. Assuming that the whole chamber wall is surrounded with a perfect conductor, You et al. obtained the electromagnetic fields by using the mode excitation method, including the anomalous skin effect. Using the obtained analytic electromagnetic fields, a tractable form of the plasma resistance was obtained as a function of various plasma and geometrical parameters.

Then the power absorbed by electrons is given by

\[
P_{\text{abs}} = \frac{R_p}{R_p + R_e} P_{rf},
\]

where $R_p$ is the plasma resistance, $R_e$ is the antenna resistance, and $P_{rf}$ is the rf power supplied at the powered antenna.

**B. Global transport model**

We numerically solve the spatially averaged continuity equation and electron temperature equation based on the Ar plasma chemistry as shown in Table I. The rate coefficients for the electron impact reactions listed in Table I were calculated by assuming that the electron energy distribution function is Maxwellian. The values of the rate coefficients were fit using the Arrhenius form; we chose the fitting parameters such that the match was best for electron temperatures in the range of 1-7 eV.

The governing equations of the spatially averaged global model are as follows:

\[
\frac{\partial n_i}{\partial t} = \sum_{j,k} k_{ij} n_j n_k + \sum_{i,k} k_{ij} n_i n_k + Q_{\text{inlet}} - n_i \left( \sum_{j,k} k_{ij} n_j n_k + \sum_{i,k} k_{ij} n_i n_k \right) - n_i y_i' - Q_{\text{pump}},
\]

\[
\frac{\partial}{\partial t} \left( \frac{3}{2} n_e T_e \right) = \frac{P_{\text{abs}}}{\Omega} - E_e - \frac{1}{\Omega} \int \left( \nabla \cdot Q_e + e E \cdot \Gamma_e \right) d\tau.
\]

where $n_i$ is the density of species $i$ particle, $k_{ij}$ is the electron impact rate coefficient of species $i$ generation by electron collision with species $j$ and $k_{ij}$ is the rate coefficient of species i generation by reactions between species $j$ and $k$. $Q_{\text{inlet}}$ and $Q_{\text{pump}}$ are the source and loss terms by gas inlet and pumping out, respectively. $n_e$ is the electron density, $T_e$ is the electron temperature, $\Omega$ is the volume of the chamber, and $E_e$ is the collisional energy loss term.

The loss speed of the ions at the plasma-sheath boundary is assumed to be the Bohm velocity, and, thus the loss frequency of the $i$th ion species becomes $v_i' = S_e \sqrt{T_e/M_i}/\Omega$. Here, $S_e$ is the effective area for particle loss and $M_i$ is the ion mass. Assuming the ambipolar diffusion, the loss frequency of the escaping electron into the wall is given by $v_e^w = S_e \sqrt{T_e/M_i}/\Omega$.

Equation (4) is the spatially averaged electron temperature equation. The equation and the loss energy $e v_e^w$ into the wall can be directly derived from integrating the below electron temperature equation over space.

where $n_e^w$, $T_e^w$, $P_{\text{abs}}^w$, and $E_e^w$ are the local electron density, the local electron temperature, the local power absorption, and the local collisional energy loss term, respectively. $Q_e$ is the electron energy flux, $E$ is the electric field, and $\Gamma_e$ is the electron flux. If Eq. (5) is divided by the volume of the chamber and integrated over space, we have

\[
\frac{\partial}{\partial t} \left( \frac{3}{2} n_e T_e \right) = \frac{P_{\text{abs}}}{\Omega} - E_e - \frac{1}{\Omega} \int \left( \nabla \cdot Q_e + e E \cdot \Gamma_e \right) d\tau.
\]

Assuming the isothermal thin sheath and the force balance condition of massless electron, the third term on the right-hand side of Eq. (6) can be rewritten as

\[
\frac{1}{\Omega} \int \left( \nabla \cdot Q_e + e E \cdot \Gamma_e \right) d\tau \equiv \frac{S_e}{\Omega} \frac{5}{2} \Gamma_{e,w} T_{e,w} + e \frac{S_e}{\Omega} \Gamma_{e,w} V_{\text{sh}} \equiv n_e v_{e,1} v_{e}',
\]

where $V_{\text{sh}}$ is the sheath potential drop, and $\Gamma_{e,w}$ and $T_{e,w}$ are the electron flux and electron temperature at the wall, respectively. Thus we can define the loss energy into the wall as $e v_{e,1} = V_{\text{sh}} + 2.5 T_e$. 

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If the bias power is applied to the substrate, \( \varepsilon_{e,1} \) can be given by

\[
\varepsilon_{e,1} \cong \frac{1}{n_e k_B} \left( \int_{\text{wall}}^{\text{edge}} -e \frac{\partial V}{\partial z} \Gamma_e \, dz \right) + 2.5 T_e. \tag{8}
\]

Here we assume that the sheath is uniform in radial direction. Thus the sheath potential drop can be obtained by integrating the first term on the right-hand side of Eq. (8) from the sheath edge to the wall. To simplify the analysis, we assume that the electron current density is uniform within the thin sheath. Finally, we have

\[
V_{sh} = \begin{cases} V_p & \text{at the chamber wall}, \\ V_p - \langle V_s \rangle & \text{at the substrate}. \end{cases}
\]

Here \( \langle V_s \rangle \) is the time averaged voltage on the substrate. \( \langle V_s \rangle \) is obtained from the rf sheath module that is coupled with the transport module in a self-consistent manner.

C. Rf sheath model

To determine the bias voltage from the plasma parameters, in this work, we use not only the Dai’s model but also a circuit model as shown in Fig. 3.

We assume that the time averaged power flowing from the rf bias power into the discharge is totally absorbed within the sheath region because the impedance of the bulk plasma is quite small comparing the sheath impedance for the high-density and low-pressure plasmas. Therefore, the rf bias power to the substrate can be calculated from the time dependent voltage and current wave forms as

\[
P'_{\text{bias}} = \frac{1}{\tau} \int_0^\tau V_s(t) I_s(t) \, dt, \tag{9}
\]

where \( \tau = 2\pi/\omega \) is the rf cycle and \( I_s(t) \) is the current on the substrate. Until \( P'_{\text{bias}} \) becomes equal to the applied rf bias power of \( P_{\text{bias}} \) within the margin of error, the amplitude of applied rf current or voltage is determined by Eq. (9) with an iterative process. The obtained amplitude of applied rf voltage is also used for voltage boundary conditions of a two-dimensional fluid model.

1. Current control model (Model I)

The one-dimensional spatiotemporal variations of ion density, electron density, ion velocity, and electric potential are described by the ion continuity equation, the Boltzmann relation, the momentum equation, and the Poisson’s equation, respectively: \(^{15}\)

\[
\frac{\partial n_i}{\partial t} + \frac{\partial (n_i u_i)}{\partial x} = 0, \tag{10}
\]

\[
\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x} = -e \frac{\partial V}{M_i} \frac{\partial V}{\partial x}, \tag{11}
\]

\[
n_e = n_s \exp \left( \frac{e V}{T_e} \right), \tag{12}
\]

\[
\frac{\partial^2 V}{\partial x^2} = -\frac{e}{\varepsilon_0}(n_i - n_e), \tag{13}
\]

where \( u_i \) is the velocity of ion species, \( e \) is the elementary charge, \( V \) is the potential, and \( n_s = n_0 \exp(eV_1/T_e) \). Here, \( V_1 = -T_e/2e \) denotes the potential drop in the presheath, and \( n_0 \) is the plasma density. \(^{25}\)

Assuming a sinusoidal current source at the electrode, a current balance can be written as \( J_i + J_e + J_d = J_0 \sin(2\pi ft) \), where \( J_i \) and \( J_e \) are the conduction current densities of the ion and electron, respectively. \(^{12,13,15}\) The displacement current density, \( J_d \), can be derived as

\[
J_d \equiv \frac{C_s(t) \, dV_s(t)}{A} - \frac{V_s(t) \, dC_s(t)}{A}, \tag{14}
\]

where \( C_s(t) \) is the sheath capacitance and \( A \) is the surface area of the substrate. \(^{15}\) The current balance is coupled to the sheath model through the electrode potential and the sheath thickness. By solving the current balance equation with the fourth order Runge–Kutta method, we obtain the potential drop across the sheath. Using the obtained potential \( V_s(t) \), we then solve the fluid equations and the Poisson’s equation by using a finite difference method with an iterative process.

Assuming that the current at the electrode from the rf bias supply is sinusoidal, Eq. (9) can be rewritten as

---

FIG. 3. Schematic diagram of equivalent circuit for rf sheath model.
where

\[ P_{\text{bias}} = \frac{1}{\tau} \int_0^t V_s(t) I_{\text{max}} \sin(o t) \, dt \]

is the amplitude of applied rf bias current.

### 2. Voltage control model (Model II)

As mentioned in the preceding text, numerically resolving the thin sheath in computer models of the devices requires large computing resources. To reduce the computing resources and compare the our results with the two-dimensional fluid model, we also use a simple circuit model based on the previously developed model.\(^4\),\(^11\),\(^25\) The schematic diagram of an equivalent circuit is described in Fig. 3. Based on the previously developed rf sheath model, the following circuit relations can be obtained.

\[
C_s \frac{\partial}{\partial t} (V_p - V_s) + I_s + C_b \frac{\partial}{\partial t} (V_H - V_s) = 0, \tag{15} 
\]

\[
C_w \frac{\partial V_p}{\partial t} + I_w + C_s \frac{\partial}{\partial t} (V_p - V_s) + I_s = 0, \tag{16} 
\]

\[
\frac{\partial \tilde{V}_s}{\partial t} = \frac{\partial V_p}{\partial t} - \omega_p (\tilde{V}_s - V_s), \tag{17} 
\]

\[
\frac{\partial V_w}{\partial t} = \frac{\partial V_p}{\partial t} - \omega_p \tilde{V}_w, \tag{18} 
\]

where \( \tilde{V}_s \) and \( \tilde{V}_w \) are damped potential at the substrate and chamber wall, respectively. \( C_s \) and \( C_w \) are the sheath capacitance on the substrate and chamber wall, respectively, \( C_b \) is the blocking capacitance, and \( \omega_p = \sqrt{2e n_i/(\epsilon_0 M_i)} \). The sheath capacitance \( C_s \) is related to voltage drop across the sheath as

\[
\frac{\partial E}{\partial V_s} = \frac{e n_i T_e}{\epsilon_0 E} \left\{ M^2 \frac{V_s}{V_s} \left[ \sqrt{1 - \frac{2V_s}{M^2 T_e}} - 1 \right] + \frac{1}{T_e} \exp \left( \frac{V_s}{T_e} \right) \right\}. \tag{19} 
\]

Here, \( V_s = V_s(0 V_w) - V_p \), \( \tilde{V}_s = V_s(0 V_w) - V_p \), \( M \) is the Mach number, and the electric field is

\[
E = \left\{ \begin{array}{l}
\frac{2e n_i T_e}{\epsilon_0} \left\{ M^2 V_s \left[ \sqrt{1 - \frac{2V_s}{M^2 T_e}} - 1 \right] \right. \\
+ \left. \left[ \exp \left( \frac{V_s}{T_e} \right) - 1 \right] \right\} \right. \right)^{1/2}, 
\]

where the electric field at the sheath-pre sheath boundary is

\[ E_s = -T_e \log(e)/\lambda_i, \tag{11},\tag{12} \]

\( \epsilon \) is the ratio of the electron Debye length to the ion mean free path. The total current \( I \) to the sheath can be given by

\[ I = A (J_1 + J_e) - C_s \frac{\partial V_s}{\partial t}, \]

and \( C_s = A \epsilon_0 \partial E/\partial V_s \). Here,

\[
\frac{\partial E}{\partial V_s} = \frac{e n_i T_e}{\epsilon_0} \frac{M^2 V_s}{V_s} \left\{ 1 - \sqrt{1 - \frac{2V_s}{M^2 T_e}} - \frac{V_s}{M^2 T_e} \left[ \sqrt{1 - \frac{2V_s}{M^2 T_e}} - 1 \right] \right\} \tag{21} 
\]

Assuming that the voltage at the electrode from the rf bias supply is sinusoidal, Eq. (9) can be rewritten as

\[
P_{\text{bias}} = \frac{1}{\tau} \int_0^t V_{\text{max}} \sin(o t) I_s(t) \, dt, \]

where \( V_{\text{max}} \) is the amplitude of applied rf bias voltage.

### III. EXPERIMENT

To validate our model, the experiments were performed at an ICP reactor of Surface Technology Systems (STS) as shown in Fig. 1. The single-turn antenna coil (radius: 0.1905 m, width: 0.001 m height: 0.05 m) is wound around the dielectric tube of which radius and height are 0.172 and 0.165 m, respectively. The Ar gas of 10 sccm is fed from the mass flow controller (MFC), the pressure is 20 mTorr, and the rf source power at 13.56 MHz was supplied to a rf antenna via L-type matching network.

In the present study, we used the cutoff probe for the precise measurement of the electron density.\(^20\) It is well known that plasma density can be measured by using the cutoff probe within 2% of uncertainty.\(^21\) The cutoff probe consisted of two tips as shown in Fig. 1. One was a microwave radiating antenna connected to the radiating port of a network analyzer through a 50 \( \Omega \) coaxial cable, and the other was a detecting antenna connected to the receiving port of the network analyzer. The cutoff probe was mounted on a top plate center, and the plasma density was measured at the five different positions from 0.05 to 0.125 m in axial direction. The averaged values of the five points for the measured electron density were used to compare the simulation results.

To acquire the electron temperature and the electron energy probability functions (EPPFs), the rf compensated single Langmuir probe (SLP2000) were used. The SLP was also mounted on a top plate center; we measured the electron temperature and EPPFs in axial direction.

### IV. RESULTS

In Sec. II, we described the self-consistent global model, which consists of the heating module, plasma transport module, and rf sheath module. The simulation results are compared with not only experimental measurements by using the cutoff probe and the SLP but also two-dimensional numerical results by using the CFD-ACE +.

CFD-ACE + is suitable for modeling a variety of coupled physical phenomena, such as fluid dynamics, electrodynamics, heat, and complex chemical reactions. The governing equations used for the plasma simulation are the Navier Stokes and continuum equations for gas flow and heat transfer, nonequilibrium plasma transport, and species transport, and the Poisson equation for electrostatic field. Two-dimensional simulations were performed for Ar plasma (see Table I) under the same operating conditions and reactor geometry as used in the experiments.

Figure 4 shows the dependence of plasma densities on the bias power for various ICP source powers. Although there is a difference in the absolute values, as the bias power increases, we can see that the numerically solved plasma densities are in a good agreement with the measured results. Here, data numerically solved by using the two-dimensional fluid model were averaged in the same manner as with the experiments. Our results, both simulation and experience agree well with the previous report\(^17\) that observed plasma
The dependence of the electron temperature on the bias power at various ICP source powers was solved and presented in Fig. 6. As shown in Fig. 6, the electron temperature decreases little with the source and increases with the bias powers; this is consistent with the previous report of Ref. 17. Our experiments show a slight increase of the electron temperature with bias and source powers as presented in Table II and Fig. 7. Although increase of the electron temperature with source powers is in contradiction to the simulation results, the difference between the results can be negligible within the margin of error. However, as the bias power increases further (>100 W), the electron temperature decreases drastically. This is due to the fact that dominant...
electron heating mechanism of plasma changes from the inductive heating of ICP source power to capacitive heating of bias power while increasing bias power. This change of heating mechanism with bias power is well exhibited in the EEPF evolution from Maxwellian distribution of ICP discharge to bi-Maxwellian distribution of CCP discharge (Fig. 7).30 Because this electron heating mode transition is of kinetic phenomena in the plasma physics, our model based on the continuum assumption cannot capture this drastic change of the electron temperature with bias power. It is believed that this heating mode change can be easily observed when the capacitive coupling between two antennas (ICP antennas and bias chuck), that is, high voltage (power) and small distance between antennas. This might be a reason why this drastic change of the electron temperature cannot be measured in the previous report17 with low voltage (power) and long distance between these antennas compared with our experiment.

![Graph](image1)

![Graph](image2)

![Graph](image3)

![Graph](image4)

**FIG. 5.** Dependence of the dc self-bias on the bias power for various ICP source powers; (a) 500 W, (b) 600 W, (c) 700 W, and (d) 800 W. The ■ is experimental data measured by a cutoff probe, the ○ is numerically solved data by using the two-dimensional fluid model, and solid and dashed lines are obtained values from Models I and II, respectively.

**FIG. 6.** Dependence of the electron temperature on the bias power for various ICP source powers. Solid and dashed lines are obtained values from Models I and II, respectively.

**TABLE II.** Measured electron temperatures for various ICP source and bias powers (the reliable electron temperature measurements cannot be performed at the bias power of 300 W because of the insufficient rf compensation of Langmuir probe).

<table>
<thead>
<tr>
<th>Source power (W)</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias power (W)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.78</td>
<td>2.84</td>
<td>2.86</td>
<td>2.92</td>
</tr>
<tr>
<td>100</td>
<td>2.93</td>
<td>2.93</td>
<td>3.04</td>
<td>2.94</td>
</tr>
<tr>
<td>200</td>
<td>0.81</td>
<td>1.02</td>
<td>1.52</td>
<td>1.36</td>
</tr>
<tr>
<td>300</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

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V. CONCLUSIONS

We developed a self-consistent global simulator of solenoidal-type ICP discharges and observed the effect of the rf bias power on the plasma density. We numerically solve a set of spatially averaged fluid equations for charged particles, neutrals, and radicals. Absorbed power by electrons is determined by using an analytic electron heating model including the anomalous skin effect. To analyze the effects of rf bias power on the plasma properties, our model also combines the electron heating and global transport module with an rf sheath module in a self-consistent manner.

To validate our model, experiments were performed in inductively coupled argon plasmas. The simulation results are also compared using the commercial software package CFD-ACE+. We observe that the numerical results are in a good agreement with the experimental results, and dependence of the electron density on the bias power cannot be negligible.

In our work, we assumed that the time averaged power flowing from the rf bias power into the discharge is totally absorbed within the sheath region. However, power flowing from the rf bias power into the discharge could not be negligible under the other conditions. Therefore we will develop a model including the stochastic and ohmic heating effect. This is under active study and will be reported later.

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