Nonlinear Dynamics of Radio Frequency Plasma Processing Reactors Powered by Multifrequency Sources

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Abstract— **The source frequency has a strong influence on plasma characteristics in RF discharges. Multiple sources at widely different frequencies are often simultaneously used to separately optimize the magnitude and energy of ion fluxes to the substrate. In doing so, the sources are relatively independent of each other. These sources can, however, nonlinearly interact if the frequencies are sufficiently close. The resulting plasma and electrical characteristics can then be significantly different from those due to the sum of the individual sources. In this paper, a plasma equipment model is used to investigate the interaction of multiple frequency sources in capacitively and inductively coupled RF excited plasmas. In capacitively coupled systems, we confirmed that the plasma density increases with increasing frequency but also found that the magnitude of the dc bias and dc sheath voltage decreases. To produce a capacitively coupled discharge having a high plasma density with a large dc bias, we combined low and high frequency sources. The plasma density did increase using the dual frequency system as compared to the single low frequency source. The sources, however, nonlinearly interacted at the grounded wall sheath, thereby shifting both the plasma potential and dc bias. In inductively coupled plasmas (ICP), the frequency of the capacitive substrate bias does not have a significant effect on electron temperature and density. The dc bias and dc sheath voltage at the substrate were, however, found to strongly depend on source frequency. By using additional RF sources at alternate locations in ICP reactors, it was found that the dc bias at the substrate was varied without significantly changing other plasma parameters, such as the substrate sheath potential.**

Index Terms—**Gas discharge devices, nonlinear circuits, plasma material processing applications.**

I. Introduction

IN BOTH inductively coupled and capacitively coupled RF plasma sources for materials processing, the source frequency has a strong influence on the plasma and electrical characteristics. Multiple RF sources at different frequencies are, in fact, often combined to optimize plasma characteristics. For example, commercial capacitively coupled plasma tools often use two RF sources at high and low frequencies to separately optimize the magnitude and energy of the ion fluxes to the wafer.[1] The high frequency source is typically used to control power deposited in the bulk plasma and hence control the magnitude of the ion flux. The low frequency source determines the power into ion acceleration and hence controls the ion energy to the wafer. When the source frequencies in a capacitively coupled discharge are significantly different from each other (e.g., 100 kHz and 13.56 MHz), the resulting plasma characteristics can generally be understood in terms of those due to the individual sources. However, if the source frequencies are close to each other (e.g., 6.78 and 13.56 MHz), they interact through the nonlinear and inhomogeneous plasma medium. This situation often leads to plasma characteristics that are different than those of either of the sources. An investigation of the interaction of the RF sources in these systems is important not only to understand the operation of multifrequency systems, but also because it provides us with insight that can be applied to control plasma characteristics. In this paper, we discuss the dynamics of RF plasmas powered by multiple sources at different but commensurate frequencies. Both capacitively and inductively coupled systems are considered since their plasma environments are typically different, and so their response to RF sources is also different.

Nakano and Makabe theoretically investigated the consequences of frequency on capacitively coupled discharges [1]. Using a fluid simulation, they found that electron and ion densities increased as the source frequency increased from 100 kHz–13.56 MHz [1]. The sheath thickness and ion energy, however, decreased with increasing frequency because of a decrease in the magnitude of the dc bias. Nakano and Makabe also investigated dual frequency capacitively coupled discharges [2], where a high frequency source was used to generate a high plasma density while a low frequency source was used for ion acceleration. When the frequencies were significantly different, the sources operated reasonably independently. The ion flux and the dc bias were, however, observed to change considerably when the source frequencies were brought closer to each other. Meyyapan *et al.* [3] and Vahedi *et al.* [4] also investigated the consequences of source frequency in capacitively coupled discharges using fluid and particle-in-cell codes, respectively. They found that electron

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density scales with the square of radian frequency because of enhanced electron heating at higher frequencies, and that the ion angular distribution incident on the electrodes is narrower at higher frequencies because of there being thinner sheaths. Kim and Manousiouthakis [5], using a fluid simulation, also modeled two frequency excitation of argon RF discharges. They found that the plasma potential and primary (high frequency) dc bias are largely unperturbed by the secondary (low frequency) voltage. Tsai *et al.* [6] experimentally investigated dual frequency (27 MHz/2 MHz) etching of SiO_2 structures in Ar/CO/CF_x plasmas.

In this paper, we report on results from a computational investigation of the interaction of RF sources at different but commensurate frequencies in low pressure plasmas. Our simulation platform consisted of a coupled plasma transport model and a circuit model [7]. We considered Ar and Ar/CF_4 gas mixtures in the capacitively coupled gaseous electronics conference reference cell (GECRC)[10] and a generic inductively coupled plasma (ICP) reactor. In agreement with previous studies [1]–[4], it was found that the plasma density increased with increasing source frequency in the GECRC. The dc bias was, however, more negative at lower frequencies. To investigate the interaction of multifrequency sources, we added a high frequency source (27.12 MHz) to a plasma generated by a low frequency source (13.56 MHz). The plasma density increased with increasing amplitude of the high frequency source as expected. However, the sheaths at different surfaces of the reactor responded differently to the high frequency source due to their nonlinear impedances. The magnitude of the dc bias at the substrate decreased as the voltage of the high frequency source was increased while the average sheath potential was essentially constant.

We also investigated the consequences of changing the RF bias source frequency in an ICP reactor. It was found that ICP reactors respond differently than capacitively coupled sources to changes in the bias frequency. For example, the dc bias and dc sheath voltage depended more strongly on the source frequency than in capacitively coupled sources. The differences in the responses of ICP and capacitively coupled reactors to changes in bias frequency can mainly be attributed to differences in plasma parameters. For example, the plasma density near the RF biased electrode and chamber walls (which provide the return path for RF currents) in ICP reactors is generally different, and so the powered and grounded sheath may respond differently to changes in frequency. Also, plasma generation is essentially decoupled from the RF bias source in ICP's and so changes in bias frequency do not affect current magnitudes as strongly as in capacitively coupled discharge. Due to the nonlinear and inhomogeneous response of sheaths at different locations to sources at different frequencies, there was also a nonlinear interaction of sources in ICP's, and this interaction affected the electrical and plasma characteristics of the discharge.

The model used in this study is described in Section II. The results from our study for capacitively coupled Ar and Ar/CF_4 discharges are discussed in Section III, and those for inductively coupled plasmas are treated in Section IV. Section V contains concluding remarks.

II. Description of the Model

The computational tool we used in this investigation consisted of a circuit model imbedded in the hybrid plasma equipment model (HPEM) [7]. Since the integrated model has been previously described in detail, only a brief explanation is included here. The HPEM is a two-dimensional (2-D) hybrid code in which a kinetic Monte Carlo simulation is used for electron energy transport while the species densities are determined using a fluid model [9], [10]. To model inductively coupled systems, Maxwell equations are also solved to obtain the inductive electromagnetic fields. The HPEM is coupled to an extensive database of electron impact cross-sections and ion transport coefficients.

The circuit module (CM) of the HPEM addresses the interaction of RF plasmas with their external circuitry. This interaction is mainly through sheaths that form at electrodes and surfaces. The CM takes advantage of this interaction and uses ion fluxes, electron density, and electron temperature from the plasma transport modules of the HPEM to construct a simple circuit representation of the plasma reactor consisting of sheaths and resistors (to approximate the bulk plasma). The sheaths are treated as nonlinear circuit elements whose dynamics are governed by Riley's sheath model [11]. In the CM, the equivalent circuit for the plasma reactor is connected to the external circuitry, and the resulting circuit equations are solved using implicit time integration until all currents and voltages attain steady state conditions.

The plasma transport modules and the CM are iteratively coupled in the HPEM. After each HPEM iteration, the CM uses the intermediate results from the plasma transport modules to compute voltages (dc, fundamental, and harmonics) at all electrodes and reactor surfaces. These values are passed on to the plasma transport modules, where they are used as boundary conditions during the solution of Poisson's equation. This procedure is repeated until both the plasma and circuit quantities attain quasisteady state conditions. The model has been previously validated against experimental data for the systems of interest [7], [12].

III. Capacitively Coupled Discharges

In capacitively coupled discharges, the same RF source generates the plasma and creates a dc bias to balance current to the electrodes. The coupling of multiple RF sources is, therefore, expected to be strong in these devices. In this section, we describe the consequences of source frequency on plasma and electrical characteristics in the capacitively coupled GECRC, and the manner in which RF sources of different frequencies interact with each other. The choice of reactor was influenced by the fact that the model has been validated against experiments in the GECRC under similar conditions [7], [12]. The geometry of the GECRC is shown in Fig. 1(a) along with the electron density in Ar at 100 mtorr gas pressure, 100 V (13.56 MHz) applied voltage amplitude and 10 sccm gas flow. The electrodes have a radius of 5.1 cm and are spaced 2.26 cm apart. The gas is injected through a showerhead in the top electrode and flows out through a pump port at the bottom of the reactor. Unless stated otherwise, all

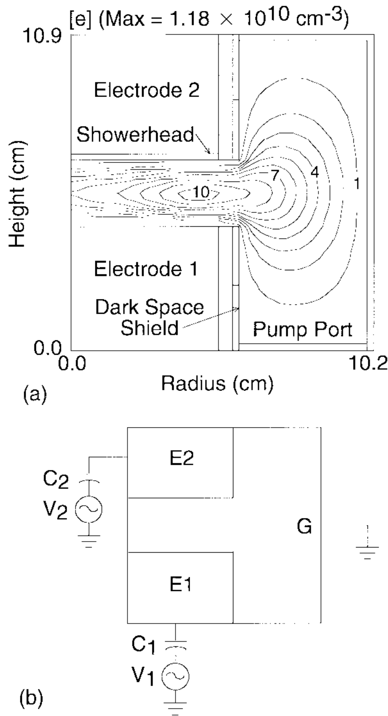

Fig. 1. Schematics of the GEC reference cell used in this study. (a) Electron density in an Ar discharge at 100 mtorr and 100 V (13.56 MHz) applied to electrode E1. (b) Electrical connections to the GECRC.

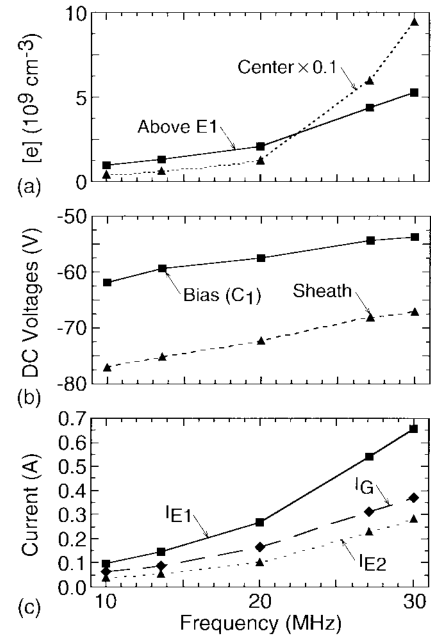

Fig. 2. Consequences of RF source frequency ($V_1 = 100$ V) on: (a) electron density at the sheath edge above electrode E1 and between the electrodes (on axis), (b) dc bias on capacitor C_1, dc sheath voltage at electrode E1, and (c) first harmonic of currents flowing through the electrodes (E1 and E2) and walls (G).

simulations were done at 100 mtorr gas pressure and 10 sccm gas flow. A schematic of the reactor with the external circuitry is shown in Fig. 1(b). The blocking capacitors C_1 and C_2 are both 0.6 nF. Current flowing through the grounded dark space shields is included in the wall current.

We first discuss the consequences of RF source frequency on the plasma and electrical characteristics in an Ar discharge. Electrode E2 is grounded ($V_2 = 0$ V) and electrode E1 is powered ($V_1 = 100$ V). Typical sheath currents and voltages are shown in [7, Figs. 3 and 4] for 13.56 MHz. The electron density at the sheath edge above electrode E1 and in the center of the discharge gap (on axis), the dc bias on capacitor C_1, the dc sheath voltage at electrode E1, and first harmonic of currents through the electrodes and the grounded reactor walls are shown in Fig. 2 as a function of source frequency. (The dc sheath voltage is the cycle average of the time dependent sheath potential.) The sheath currents are nonlinear and produce higher harmonics which scale with frequency in the same manner as the first harmonic. The second and third harmonics are approximately 45 and 20% of the first harmonic. The dc voltage on capacitor C_2 is negligible. The electron density at the sheath edge and in the gap increase with increasing frequency while the dc bias and sheath voltage decrease in magnitude (less negative).

The dependence of electron density on frequency shown here is well described in Lieberman and Lichtenberg's treatment of the inhomogeneous capacitively coupled discharge model [13]. Briefly, as the frequency is increased, the displacement current through the sheaths, $I_{disp} \propto dE/dt \approx \omega E$, increases for otherwise similar conditions. Since the current through the sheaths increases, more ohmic and stochastic heating takes place and the electron density rises. The same argument explains the increase of sheath currents as the frequency is raised; higher frequency produces more displacement current. The variation of the dc bias as a function of frequency is more intricately linked to the nature of the gas. Using qualitative arguments based on Lieberman and Lichtenberg's model [13]

$$K_{iz}(T_e)T_e^{-1/2} \propto 1/d \tag{1}$$

where K_{iz} is the rate coefficient for ionization, T_e is the electron temperature, and d is the width of the bulk plasma (d = gap length − sheath widths). As the frequency is increased, the electron density increases leading to smaller sheath widths and a larger d. Under the conditions considered in Ar, $K_{iz} \propto T_e^n$ where $n > 0.5$, so the electron temperature decreases with an increase in frequency. In our 2-D simulation, the electron temperature in the interelectrode region (obtained from the Monte Carlo simulation module of the HPEM) did indeed decrease from approximately 2.5 to 1.5 eV as the frequency was increased from 13.56 to 30 MHz. The lower electron temperature at higher frequencies means that electron momentum transfer collision frequency (ν_m) is lower and the diffusion coefficient is larger. As a consequence, electrons diffuse radially more rapidly, the discharge becomes more symmetric at higher frequencies, and the magnitude of the dc bias decreases. This trend can be observed by comparing the electron density at 13.56 MHz (shown in Fig. 1) with that at 30.0 MHz (Fig. 3). The sheath voltage at the grounded wall was not significantly affected by the source frequency because the sheath admittance and current changed in a similar fashion. Since the dc sheath voltage at electrode E1 is the sum of the

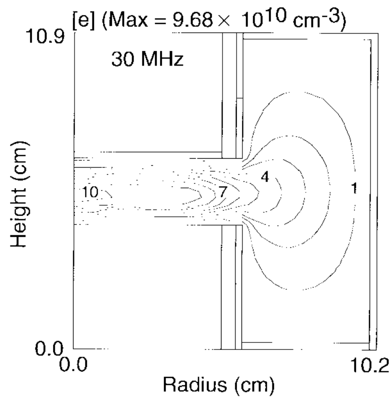

Fig. 3. Electron density for an Ar discharge in the GEC reference cell at 100 mtorr and 100 V at 30 MHz applied to electrode E1. The higher frequency produces a more confined plasma and less negative dc bias.

dc bias and dc sheath voltage at grounded wall, its amplitude decreased as the dc bias decreased.

The shift of electron density peak toward the axis with increasing frequency also explains why the electron density in the center of the discharge rises faster as a function of frequency than the spatially-averaged electron density above electrode E1 [Fig. 2(a)]. In the above arguments about the dependence of dc bias on frequency, many factors sensitively depend on the nature of the gas as manifested in the electron temperature dependence of K_{iz} and ν_m. Not surprisingly, therefore, the dependence of the dc bias on frequency was found to be different for other gas mixtures, such as Ar/CF_4, as discussed below.

If this capacitively coupled reactor was intended for ion energy dependent etching, such as for silicon dioxide, one would ideally like to have a high ion density and a large negative dc sheath voltage. The results shown in Fig. 2 indicate that use of a single source at any frequency may compromise one of these conditions. An alternate option might be to use multiple sources at different frequencies; a high frequency source for generating the plasma and a low frequency source to generate a large sheath voltage at the substrate. This strategy has been employed in commercial plasma reactors and it has also been theoretically investigated [2]. We reconsider the problem here, however, to investigate the interaction of the two RF sources when their frequencies are commensurate. In this study, a low frequency (13.56 MHz) and high frequency (27.12 MHz) sources are connected to electrodes E1 and E2, respectively.

The electron density at the sheath edge above electrode E1 and in the center of the discharge gap (on axis), the dc bias on capacitors C_1 and C_2 and dc sheath voltages at the two electrodes are shown in Fig. 4 as a function of the amplitude of the 27.12 MHz source (V_2). The amplitude of the 13.56 MHz source is $V_1 = 100$ V. The addition of the high frequency source increases the sheath displacement currents, which lead to more ohmic and stochastic heating, resulting in higher electron densities. The magnitude of the dc bias for the 27.12 MHz source and the dc sheath voltage scale with V_2, becoming more negative at larger amplitude.

The dc sheath voltage at electrode E1 is little affected by currents from the 27.12 MHz source because its sheath

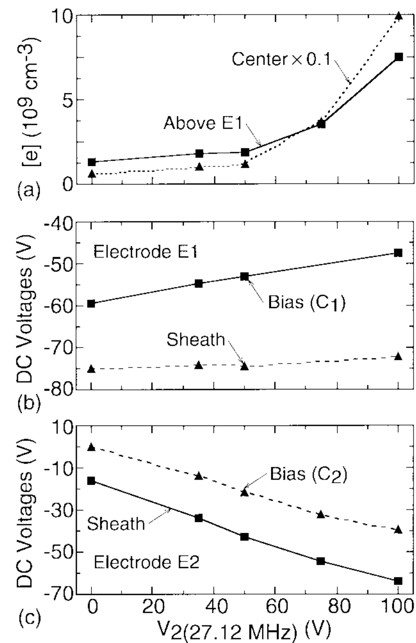

Fig. 4. Effect of 27.12 MHz source amplitude applied to electrode E2 on (a) electron density at the sheath edge above electrode E1 and between the electrodes (on axis), (b) dc bias on capacitor C_1, dc sheath voltage at electrode E1, and (c) dc bias on capacitor C_2 and dc sheath voltage at electrode E2. A 100 V, 13.56 MHz RF source is connected to electrode E1.

impedance is larger at lower frequencies [14] and the 13.56 MHz current is proportionally larger at electrode E1. The decrease in the magnitude of the dc bias for the 13.56 MHz source at E1 resulting from the contributions of the 27.12 MHz source is, however, surprising. To explain this scaling, the sheath currents and voltages due to separate sources and their combination are shown in Fig. 5 for $V_1 = V_2 = 100$ V. When used separately, the 13.56 MHz source is connected to electrode E1 and the 27.12 MHz source is connected to electrode E2. The addition of the 27.12 MHz source at electrode E2 significantly changes the current through electrode E1 [Fig. 5(a)] because electrode E1 is part of the return path of the larger current generated by the 27.12 MHz source. Since the sheath impedance is larger at lower frequencies [12], the sheath voltage at electrode E1 [Fig. 5(c)] is mainly governed by the 13.56 MHz current component even with the 27.12 MHz source present. The 13.56 MHz current component at electrode E2 is only a small fraction of the total current entering the plasma through electrode E1, with the remainder returning through the grounded sheaths. The 27.12 MHz current component is larger at electrode E2 since the 27.12 MHz source is connected there. The sheath voltage at electrode E2 is, therefore, mainly governed by the 27.12 MHz source with only a small perturbation due to the addition of the 13.56 MHz source [Fig. 5(d)].

The situation at the grounded wall sheath is, however, different. As shown in Fig. 5(e), the maximum sheath voltage drop at the walls is roughly the same when either the 13.56 or 27.12 MHz source is used. When both sources are used, current from both sources returns to ground through the wall sheaths resulting in a doubling of the wall sheath voltage. The dc bias on capacitor C_1 [Fig. 4(b)] can be thought of as the difference

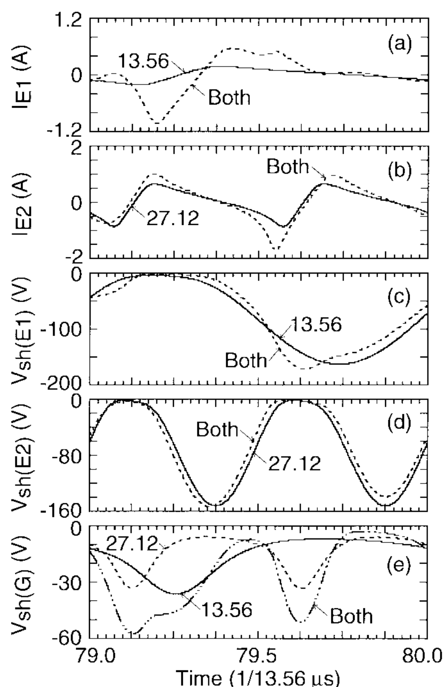

Fig. 5. Currents through the sheaths and sheath voltages as a function of time. (a) Current through electrode E1, (b) current through electrode E2, (c) sheath voltage for electrode E1, (d) sheath voltage for electrode E2, and (e) sheath voltage at the grounded surface. Results are shown for only the 13.56 MHz source at electrode E1 (13.56), only the 27.12 MHz source at electrode E2 (27.12), and both sources simultaneously connected (both). The gas pressure is 100 mtorr, $V_1 = 100$ V and $V_2 = 100$ V.

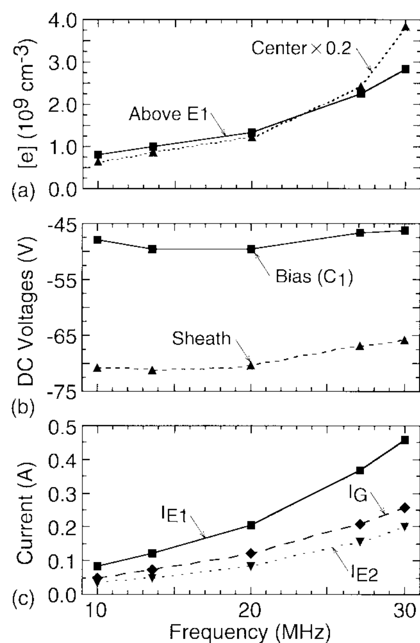

Fig. 6. Consequences of the RF source frequency ($V_1 = 100$ V) for an Ar/CF_4 $= 80/20$ discharge on: (a) electron density at the sheath edge above electrode E1 and between the electrodes (on axis), (b) dc bias on capacitor C_1, dc sheath voltage at electrode E1, and (c) first harmonic of currents flowing through the electrodes (E1 and E2) and walls (G).

between the dc voltage drop for the sheath at electrode E1 and the grounded wall sheath. Since the dc voltage amplitude at the grounded wall sheath increases significantly (from 15.8 to 24.7 V) due to the current from the 27.12 MHz source while the dc voltage at electrode E1 sheath changed little (72.2 V as opposed to 75.2 V), the magnitude of the dc voltage on capacitor C_1 decreases.

In general, all sheaths in a plasma reactor will respond differently to the addition of new RF sources because of the differences in the electron density, electron temperature and ion flux at their boundaries and their inherent nonlinearity (change of impedance with current amplitude). Because of the nonuniform and nonlinear response of the sheaths, RF sources at multiple frequencies will sometimes interact in an unpredictable manner. The interactions are generally strongest near surfaces where sources are not connected, (e.g., grounded wall in the problem considered here) and these interactions affect the electrical and plasma characteristics of the discharge.

Many of the effects of frequency and nonlinear interaction sensitively depend on the nature of the gas. To demonstrate the extent of this dependence, we investigated similar issues as above for an Ar/CF_4 $= 80/20$ gas mixture. The consequences of source frequency on the electron density at the sheath edge above electrode E1 and between the electrodes (on axis), the dc bias on capacitor C_1, dc sheath voltage at electrode E1, and first harmonic of the sheath currents through the electrodes and walls are shown in Fig. 6 for 100 mtorr gas pressure and $V_1 = 100$ V. The electron density and sheath currents increase as a function of frequency because of the larger sheath displacement currents, which lead to more ohmic and stochastic heating. The dc bias and sheath voltage, however, have a nonmonotonic dependence on the source frequency, although the variation is small, demonstrating that the dc bias is sensitive to the nature of the gas. When CF_4 is added to Ar, volumetric sinks of electrons (i.e., attachment and dissociative recombination) are introduced and the electrons are primarily confined between the electrodes even at low frequencies. Although ν_m decreases with increasing source frequency and the electrons spread out more in the interelectrode region, the change in electron density profile is not significant enough to appreciably modify the dc bias.

The consequences of the nonlinear interaction of a 13.56 MHz source ($V_1 = 100$ V) with a source at 27.12 MHz (V_2) are shown in Fig. 7 for the Ar/CF_4 discharge. The sources are connected in the same manner as for the Ar discharge. The electron densities at the sheath edge above electrode E1 and between the electrodes [Fig. 7(a)] increase with increasing amplitude of the 27.12 MHz source due to the increase in the sheath displacement currents that leads to more ohmic and stochastic heating. The magnitudes of the dc bias on capacitor C_2 and dc sheath voltage at electrode E2 [Fig. 7(c)] scale with V_2. The magnitude of the dc bias on capacitor C_1 [Fig. 7(b)], however, decreases as the contribution from the 27.12 MHz source is increased due to the nonlinear and nonuniform response of the wall and electrode sheaths (in a similar manner as described earlier for the Ar discharge). In contrast to the argon discharge, the magnitude of the sheath voltage increases at E1 while the dc bias becomes less negative, a consequence of the 27.12 MHz current flowing through the sheath.

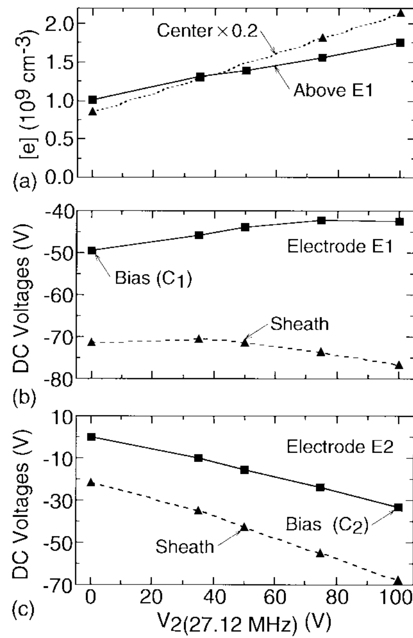

Fig. 7. Effect of 27.12 MHz source amplitude applied to electrode E2 for an $Ar/CF_4 = 80/20$ discharge on: (a) electron density at the sheath edge above electrode E1 and between the electrodes (on axis), (b) dc bias on capacitor C_1, dc sheath voltage at electrode E1, and (c) dc bias on capacitor C_2 and dc sheath voltage at electrode E2. A 100 V, 13.56 MHz RF source is connected to electrode E1.

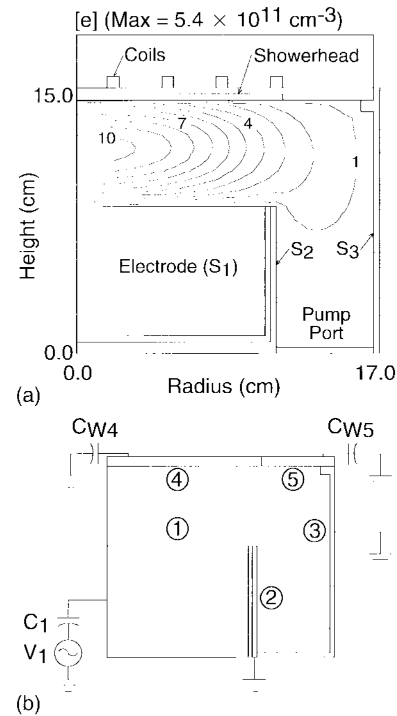

Fig. 8. Schematics of the ICP reactor used in this study. (a) Electron density in an Ar discharge at 20 mtorr, 500 W inductive power and 100 V (13.56 MHz) applied to electrode E1. (b) Electrical connections. The labels denote 1—substrate, 2—grounded dark space shield, 3—grounded wall, 4—portion of the dielectric window, and 5—portion of the dielectric window.

IV. Inductively Coupled Plasmas

In this section, we investigate the consequences of RF bias source frequency on plasma and electrical characteristics and coupling of multifrequency RF sources in inductively coupled plasmas. We consider only the consequences of the RF bias sources since the coupling between the ICP source and the RF bias source is generally weak, and so chose conditions where capacitive coupling from the coils can be ignored. ICP reactors provide a very different plasma environment from capacitively coupled discharges. The plasma in ICP reactors is generated by an external source (the current in the ICP coils) and the channels for RF source coupling through the bulk plasma parameters are generally limited due to the high plasma density. Since the chamber height is usually larger in ICP reactors compared to RIE reactors because of uniformity considerations, the plasma characteristics near the powered electrode can be different from those at the walls through which most of the RF return current flows. The sheaths at these surfaces, therefore, respond differently to changes in source frequency and this affects global characteristics such as the dc bias.

The generic ICP reactor geometry used here is shown in Fig. 8(a). A four-turn antenna sits on top of a dielectric window. Gas is injected into the chamber through a showerhead below the dielectric window and flows out through the pump port at the bottom of the reactor. The wafer sits on top of an electrode (S_1) that will be RF-biased and which is surrounded by a grounded dark space shield (S_2). The circuit representation of this reactor is shown in Fig. 8(b). The surfaces S_2 and S_3 are part of the grounded walls. When we later study the interaction of RF sources, a second source will be connected to S_3. The displacement current flowing through the dielectric window (surfaces four and five) is taken into account by representing the window by equivalent capacitors, $C_{W4} = 195$ pF and $C_{W5} = 183$ pF. The blocking capacitor $C_1 = 30$ nF.

The current flowing through the surfaces and sheath voltages are shown in Fig. 9 for 500 W inductive power deposition, 20 mtorr Ar, and 100 V amplitude (10.0 MHz) applied to the substrate. The current entering through the powered electrode (I_1) mainly exits through the dark space shield (I_2) and grounded walls (I_3). The displacement currents through the dielectric window (I_4, I_5) are, however, nonnegligible and represent 10's of percent of the total. The electron density at the sheath edge of the powered electrode ($\sim 4 \times 10^{10}$ cm^{-3}) is much larger than that at the grounded walls ($\sim 3 \times 10^9$ cm^{-3}). As a result, the current carrying capacity of the substrate, albeit with a smaller area, is larger than that for the walls and of the window. The system thereby generates a positive bias on the substrate (29 V). The low plasma density at the walls and positive bias on the substrate produce large sheath impedances and sheath voltages at the grounded walls compared to the powered electrode (V_1). At the window, the voltage primarily drops across the dielectric and so the sheath voltages (V_4, V_5) are small.

The electron density in the center of the discharge, first harmonic of current through the substrate (I_1), dc bias on capacitor C_1 and dc sheath voltage at the substrate (S_1) are shown in Fig. 10 as a function of RF bias frequency for

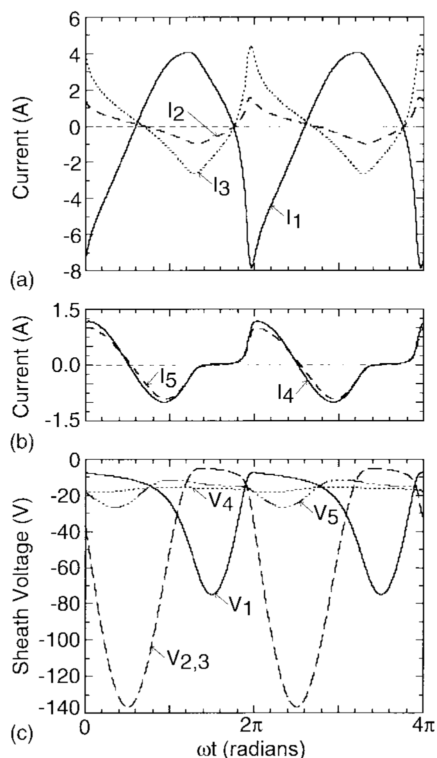

Fig. 9. Electrical characteristics in the ICP reactor with Ar (20 mtorr) at 500 W inductive power deposition and 100 V at 10 MHz applied to the substrate. (a) Sheath currents $I_{1,2,3}$, (b) sheath currents $I_{4,5}$, and (c) sheath voltages. The subscripts refer to the surfaces noted in Fig. 8(b).

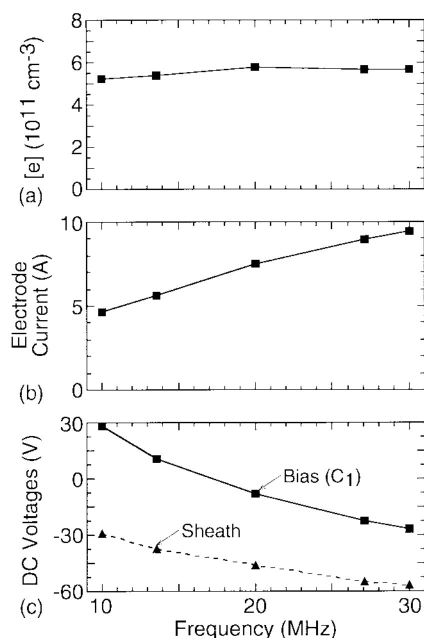

Fig. 10. Effect of RF bias source frequency (100 V amplitude) on (a) electron density in the center of the chamber, (b) first harmonic of the current collected by the substrate, and (c) dc bias on capacitor C_1 and dc sheath voltage at the substrate. Results are for 500 W inductive power deposition and 20 mtorr gas pressure. The bulk plasma properties are not perturbed by the RF bias, however redistribution of the currents in the reactor change the dc bias from positive to negative.

20 mtorr Ar, 500 W inductive power deposition and 100 V bias. Since plasma generation is dominated by the inductive power deposition, the electron density in the center of the discharge [Fig. 10(a)] does not change by more than 10% as the RF bias frequency is varied between 10–30 MHz. Since the sheath displacement current is proportional to frequency, the first harmonic of current flowing through the biased substrate [Fig. 10(b)] increases with frequency. Recall that for the capacitively coupled discharge, the dc bias changed by only 8 V (-62 to -54 V) as the source frequency was varied between 10–30 MHz. This scaling was attributed, in part, to changes in the bulk plasma electron temperature which produced more confinement of the plasma. In contrast to the capacitively coupled system, the dc bias for the ICP system strongly depends on the RF bias source frequency becoming more negative with increasing frequency. At low frequencies, the dc bias is positive, indicating that the current carrying capacity of the substrate (S_1) is greater than the other surfaces. This condition results from the large impedance of S_4 and S_5 (the window segments) due to their small capacitance, and the large impedance of S_2 and S_3 (the grounded segments) due to the low plasma density at their sheath edges. To balance currents through the surfaces, a positive dc substrate bias is produced. The plasma density and electron temperature do not change significantly enough as a function of the RF bias frequency to account for the observed change in dc bias. This conclusion was, in fact, verified by solving the circuit equations for a 10 MHz source while using presheath plasma parameters obtained with the 30 MHz source. The resulting dc bias was 23 V, which is close to the self-consistent results for 10 MHz (29 V).

To shed light on why the dc bias and the dc sheath voltage at the substrate [Fig. 10(c)] become more negative as the RF bias frequency is increased, sheath currents and voltages for a 30 MHz RF bias are shown in Fig. 11. These currents should be compared with those for a 10 MHz bias shown in Fig. 9. The dc bias (voltage on capacitor C_1) is the difference between the dc voltage across the powered electrode sheath (V_1) and the grounded wall sheath ($V_{2,3}$). At 10 MHz, the impedance of the sheath at the grounded walls is larger than the impedance of the powered sheath due to the smaller plasma density near the wall. Consequently, $|V_{2,3}| > |V_1|$ and the dc bias is positive. As the frequency is increased to 30 MHz, the capacitive impedance of the sheaths decreases. Near the grounded surfaces, S_2 and S_3, the plasma density is small ($\sim 3 \times 10^9$ cm^{-3}) and so most of the current is carried by the sheath displacement current. An increase in frequency therefore significantly decreases the total sheath impedance at the walls. On the other hand, the plasma density near the powered electrode is large ($\sim 4 \times 10^{10}$ cm^{-3}) and most of the current is carried by conduction, which is little affected by frequency. The effect of source frequency on the impedance of the sheath at the powered substrate was therefore proportionally smaller. Since the sheath impedances changed nonuniformly, $|V_{2,3}| < |V_1|$ at 30 MHz and the dc bias became negative. The strong dependence of the dc bias on RF bias source frequency is, therefore, due to the different (i.e., nonlinear) manner in which the powered electrode sheath and

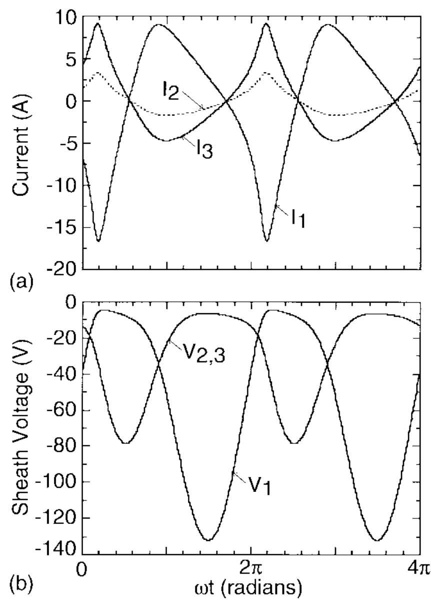

Fig. 11. Electrical characteristics in the ICP reactor with Ar (20 mtorr) at 500 W inductive power deposition and 100 V at 30 MHz applied to the substrate. (a) Sheath currents $I_{1,2,3}$ and (b) sheath voltages. The subscripts refer to the surfaces noted in Fig. 8(b).

the grounded wall sheaths responded to the additional current produced at the higher frequency.

When ICP reactors are used for ion energy dependent etching, it is often desirable to have a large negative dc voltage across the sheath at the wafer to accelerate ions to high energies. In our results thus far, the dc bias is positive at low frequencies (particularly at 13.56 MHz) and so the dc sheath voltage at the substrate is low. This result is largely a consequence of the specific geometry that was used. The placement of the coils is such that the electron density peaks on-axis (Fig. 8) and is low near the walls. The current collecting capability of the substrate is therefore proportionally larger. For there to be a negative bias (at 13.56 MHz) the current collecting capability of the walls should be larger than the substrate. This can be accomplished by powering only the outer two ICP coils. As shown in Fig. 12, the peak in electron density shifts off-axis. As a result, the presheath electron density increased at the walls thereby decreasing their sheath impedance, increasing their current collection capability. The end result was a decrease in the dc bias from 10.8 to −21.9 V and a decrease in the dc sheath voltage at the substrate from −37.3 to −54.1 V. With more current being collected by the grounded walls in the unbiased configuration, the effective area of the walls is increased to the degree that the area ratio changed from less than one to greater than one. The RF bias source does not have a strong impact on the bulk plasma density and temperature, which are primarily determined by the inductive power deposition. The dc bias, which is generally attributed only to the RF bias, is seen to be a global characteristic of the discharge. Redistribution of currents by changing the spatial inductive power deposition can modify the dc bias, as demonstrated above.

The interaction of the inductive source and the RF bias is usually weak in ICP reactors. To investigate how RF sources

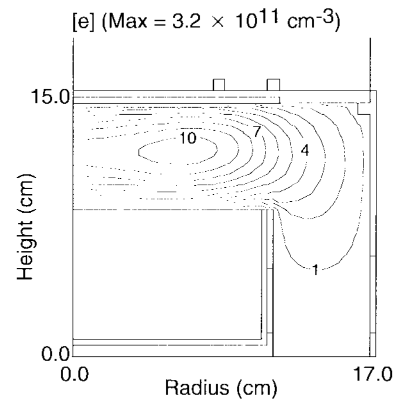

Fig. 12. Electron density in the ICP reactor powered with only two coils for Ar (20 mtorr) with 500 W inductive power deposition and 100 V (13.56 MHz) bias on the substrate.

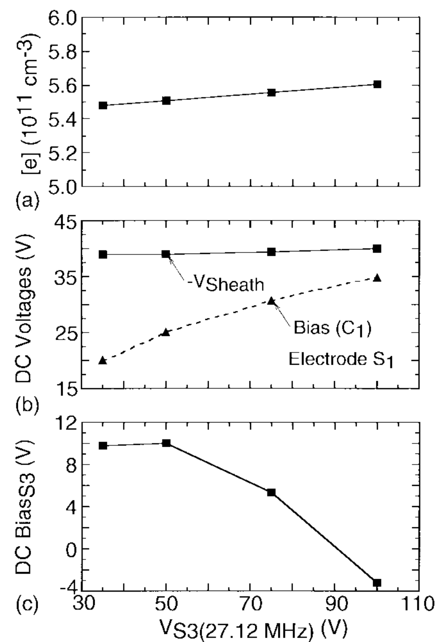

Fig. 13. Effect of the amplitude of the 27.12 MHz source applied to surface S_3 on: (a) electron density in the center of the chamber, (b) dc bias on capacitor C_1 connected to the substrate, dc sheath voltage at the substrate, and (c) dc bias on capacitor C_3 connected to surface S_3. Although the plasma density is not perturbed the voltage source at S_3, the reapportionment of current through the reactor does change the dc bias on the substrate.

at different frequencies interact with each other, we instead connected a second RF bias to the wall segment S_3. Although ICP reactors are usually not operated in this configuration, the results are revealing about the interaction of RF sources. For the results shown in Fig. 13, we connected a 13.56 MHz source ($V_1 = 100$ V) to the powered substrate and an additional 27.12 MHz (amplitude V_{S3}) RF source at S_3 with a 30 nF blocking capacitor. The electron density in the center of the reactor, dc sheath voltage at the substrate and dc bias on the two blocking capacitors are shown in Fig. 13 as a function of the amplitude of the 27.12 MHz source. Since the 27.12 MHz source does not produce any appreciable electron heating, there is not a significant change in the bulk electron density [Fig. 13(a)]. The dc biases, however, do depend on the current contribution

TABLE I
CURRENT AT 13.56 AND 27.12 MHz, DC SHEATH VOLTAGE AT THE SUBSTRATE (S_1) AND WALLS (S_2 AND S_3), AND DC BIAS ON THE CAPACITORS. THE SUBSTRATE HAS A 100 V (13.56 MHz) BIAS, S_2 IS GROUNDED, AND S_3 IS BIASED AT 27.12 MHz WITH VOLTAGE AMPLITUDE V_{S3}

V_{S3} = 35 V			V_{S3} = 100 V		
urrent (A)	dc Sheath Voltage (V)	dc bias on Capacitor (V)	Current (A)	dc Sheath Voltage (V)	dc bias on Capacitor (V)
(13.56 MHz)	–39.27	19.9	5.06 (13.56 MHz)	–40.44	34.6
(27.12 MHz)			2.62 (27.12 MHz)		
(13.56 MHz)	–60.60	–	0.92 (13.56 MHz)	–76.39	–
(27.12 MHz)			1.21 (27.12 MHz)		
(13.56 MHz)	–49.61	9.8	2.62 (13.56 MHz)	–78.62	-3.6
(27.12 MHz)			5.03 (27.12 MHz)		

from the 27.12 MHz source. The substrate bias becomes more positive while that for the higher frequency source becomes more negative. The dc sheath voltage at the electrode is not affected by the high frequency source.

To explain these scalings, the RF current amplitudes at 13.56 and 27.12 MHz, dc sheath voltages at the substrate and wall surfaces and dc bias on capacitors are shown in Table I for $V_{S3} = 35$ V and $V_{S3} = 100$ V. As V_{S3} is increased, the component of current at 27.12 MHz through the sheath at S_3 increases and eventually becomes larger than the 13.56 MHz component. The dc sheath voltage at S_3 is therefore sensitive to the additional current from the 27.12 MHz source. At the substrate (S_1), the 13.56 MHz current is always larger than the 27.12 MHz component because the 13.56 MHz source is connected there. Since the sheath impedance is larger at lower frequencies, the dc sheath voltage at the electrode is primarily determined by the 13.56 MHz source, and it does not change appreciably due to the additional current from the 27.12 MHz supply. On the other hand, the currents at 13.56 and 27.12 MHz are commensurate at both extremes of V_{S3} at the grounded surface S_2, though as V_{S3} is increased, the 27.12 MHz component increases relative to the lower frequency, thereby increasing the dc sheath voltage amplitude. The dc bias on capacitor C_1 can be thought of as the difference in the dc voltage across the powered electrode sheath and the sheath at S_2. Since the dc voltage for the substrate sheath does not change significantly as V_{S3} is increased and the dc sheath voltage amplitude at S_2 decreases, the dc bias on capacitor C_1 increases. In a manner similar to the capacitively coupled discharge, source interaction is strongest at surfaces where sources are not connected. The inhomogeneous response of different sheaths to the additional RF sources changes the electrical characteristics of the discharge.

V. CONCLUDING REMARKS

The consequences of RF bias frequency on the electrical and plasma characteristics of RF plasma processing reactors, and the nonlinear interaction of RF sources at different frequencies have been discussed for capacitively and inductively coupled plasmas. In the capacitively coupled GECRC, higher source frequencies led to larger displacement currents, more electron heating and higher electron densities. The dc bias also varied with the frequency, but the effect was weak and depended on the electron transport coefficients and net ionization rates of the specific gas mixtures used. Under the conditions investigated, multiple RF bias sources were found to interact with each other through the nonlinear plasma medium. This interaction was mainly due to the fact that the sheaths adjacent to the powered electrode and grounded walls have different impedances due to the different plasma properties at their boundaries, and so responded differently to the current from the additional source at a different frequency. For argon in the GECRC, the nonlinear source interaction caused the dc bias on the lower frequency driven substrate to become more positive as the voltage of the second source at higher frequency was increased.

In contrast to the capacitively coupled discharges, the dc bias was observed to depend strongly on the RF bias frequency in ICP's. This scaling was attributed to the nonuniform variation of the impedances of the powered electrode and grounded wall sheaths as a function of frequency. Since the inductive coil current generates the plasma in ICP reactors, the plasma density varied little with RF bias frequency. As a result, incremental changes in sheath impedances depend largely on the change in frequency and the plasma characteristics at the sheath edge. For example, an increase in frequency will produce a larger relative change in current through a sheath whose adjacent plasma density is low (and hence is dominated by displacement current) compared to a sheath whose adjacent plasma density is large (and is dominated by conduction current). Under these conditions the interaction between RF sources at different frequencies can be strong even in ICP reactors.

Many of the nonlinear interaction effects can be minimized (or enhanced) by selecting the RF source frequencies to be farther from (or closer to) each other. For example, if the source frequencies are very different in a dual frequency capacitively coupled discharge, the sheath voltage at the grounded wall will be primarily governed by the low frequency source.

The dc bias at the powered electrode (with the low frequency supply) will not be strongly perturbed by the high frequency source. Since the nonlinear interactions can be strong when the frequencies are commensurate, they should be taken into account when multifrequency discharges are designed.

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Mark J. Kushner (S'74–M'79–SM'89–F'91), for a photograph and biography, see p. 5 of the February 1999 issue of this TRANSACTIONS.