MULTIPLE FREQUENCY ANALYSIS OF CAPACITIVELY COUPLED RF PLASMA

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ABSTRACT

Homogeneous Hydrogen plasma discharge driven by two sinusoidal current sources has been analyzed. Two RF sources, operating at 27.12MHz and 1.94MHz respectively, are generally coupled to each other through the plasma medium. We assumed time independent and collisionless ion motion that gave us the analytic expressions for discharge parameters as a function of frequency, current and voltage. As a consequence, we have proposed that for conventional CCRF plasma generated by driving one electrode with a single RF power source can be improved by finding the optimal characteristics for the discharge operation or by introducing a secondary RF source. The ratio of main RF source power to secondary RF source power can be controlled for plasma density and plasma uniformity.

1. INTRODUCTION

Plasma processing is a must for manufacturing VLSI – Very Large Scale Integrated and ULSI-Ultra Large Scale Integrated circuits. Plasma density distribution is a crucial parameter in several applications as well as density itself. High density plasma sources are widely used in semiconductor manufacturing and are typically operated at higher densities and lower pressures in order to obtain higher etch rates and better ion anisotropy at the target[1]. The knowledge of the energy distributions of the ions hitting the substrate surface and the knowledge of how to control number density are vital for understanding and further developing the techniques for surface modifications. Therefore, plasma uniformity is important for industrial applications such as etching 300 mm wafers or for uniform deposition. Many applications require knowing an axial or longitudinal local plasma number density distribution. This local plasma density distribution estimation can be achieved by computational modeling of plasma system responses under different conditions. Surface modification[2,3] is an other application which growing very rapidly for last decades. There are still some common problems need to be solved for generating better plasma processing techniques. These problems can be sorted as the independent control of the ion flux and ion energy bombardment, number density level and homogeneity. Meanwhile eliminating the notch of local side wall as well as enhancement of etching selectivity needs to be studied harder[4,5,6]. In order to overcome such problems, we need to optimize the magnitude and energy of the ion fluxes to the wafer, separately. That's why most of the commercial capacitively coupled plasma systems were driven by two RF sources.

Kim et al[1] proposed an analytic expressions obtained for discharge parameters such as the plasma density, the plasma potential, and the powers dissipated by electrons and ions. Kim expressed the parameters; plasma density, plasma potential and dissipated power as function of effective frequency, effective current and voltage under the assumptions of time-independent and collisionless ion motion and inertialess electrons.

Rauf and Kuchner[4] reported higher source frequencies led to larger displacement currents, more electron heating and higher electron densities. They also noted that multiple RF bias sources interacted with each other through the nonlinear plasma medium 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. For Ar plasma, they noticed that 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, and electrons diffuse radially more rapidly, the discharge becomes more symmetric at higher frequencies, and the magnitude of the dc bias decreases.

Halil et al[7] proposed an investigation on a study of a dual-mode microwave/radio frequency plasma system. They reported that Ar^+, N_2^+ and N_1^+ ions show structured Ion Electron Distribution Function- IEDFs at the rf-powered electrode in the single- and dual-frequency modes, while a single peak was observed in the continuous MW plasma. Their most critical report is the MW/RF plasma presents substantially higher ion flux and plasma density, and a the sheath thickness, d, is found to be very small compared with the RF case, due to the higher n_s.

Lee et al[8] investigated the IEDF on the powered electrode in a symmetric single and double frequency driven CCRF discharges in Argon with PIC/MCC simulations. They reported that the IEDF shape and spread on the cathode could be controlled by the low frequency voltage in a dual frequency capacitive discharge. The density of plasma decreases, the sheath width, the plasma potential and the self-bias voltage increase with growth of the low frequency voltage in the dual frequency capacitive discharge. One of the conclusion they made is the width of IEDF increase by growing the low frequency voltage for dual frequency case.

2. THEORY

Either for VLSI/ULSI circuits or for any kind of polymer based biomaterial processing, we need to know the energies ions and number density profile. We know that the high frequency source is typically used to control power deposited in the bulk plasma and hence control the magnitude of the ion flux and the low frequency source determines the power into ion acceleration and hence controls the ion energy to the wafer[9].

Following is an ion arriving at the electrode travels through the sheath with a distribution of energies. It is a result of the time varying electric field in the sheath and the ions' response to the electric field. The shape of IEDF is determined by the ratio of the ion transit time (ion τ) to the RF period (rf τ) is given by Kawamura[10]

$$\frac{\tau_{ion}}{\tau_{rf}} = \frac{3s\omega}{2\pi}\left(\frac{M}{2eV_s}\right)^{1/2} \qquad 1$$

Where s is the time-averaged sheath thickness, ω is the RF frequency, M is the ion mass, V is the time-averaged sheath potential, and e is the elementary charge. If this ratio $\frac{\tau_{ion}}{\tau_{rf}} >> 1$, then the energy of the ions will depend on the phase of the RF cycle, otherwise, $\frac{\tau_{ion}}{\tau_{rf}} << 1$, ions can can no longer respond to the instantaneous electric field and the ion energy will depend on the time-averaged sheath potential[10].

Abel inversion is a following step for determining local plasma number density distribution after microwave interferometer measurements. Microwave interferometer gives us an integration value over observation path as given below in figure 1.

3. EXPERIMENTAL SETUP

MWI setup which its details were represented at our previous presentation that it is basically a kind serrodyne type interferometer operating at 8-18GHz range. Discharge system consists of two parallel-plate electrodes of equal area, with a diameter of 140 mm, which are separated by a 5 cm gap given at our second presentation. The discharge is confined between the electrodes using a cylindrical quartz tube, with a wall thickness of 5 mm. The quartz tube window both shields the discharge from the grounded chamber walls and creates a pressure differential between the inside and outside of the tube so the discharge happens inside the quartz tube. Outside the tube, the pressure is too low for plasma discharge. The plasma is nearly symmetric resulting in a large sheath voltage (> 100 V) on both the powered and grounded electrode, and also a very low DC bias.

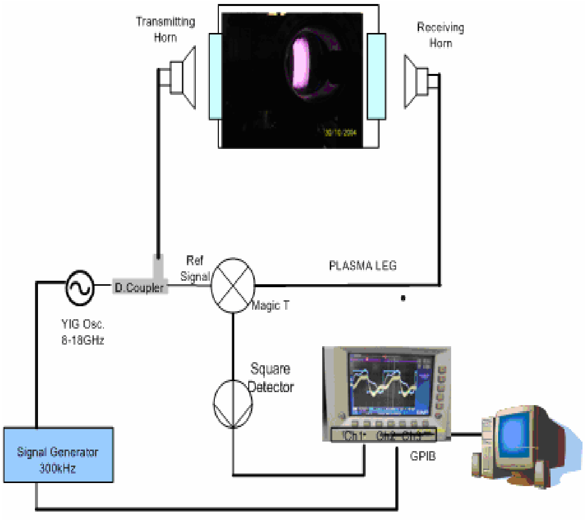

Figure 1. Shematics of Heterodyne Interferometer.

Horn antennas were placed such that both transmitter and receiver antennas were in alignment through the center. Their heights were also variable through the z direction. By varying antenna heights, we have collected 6 data for each pressure and each power level up to 5cm height from the center line. Since the experimental system does not allow us to make measurements at the edge of electrode, we assumed that at the boundary which is glass density is zero and the previous point which is 6 cm a reasonable data is assumed based on the experimental results.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 represents axial electron density variation for single frequency application. Main Frequency is 27.12MHz and secondary source frequency is 1.94MHz. While the primary source power is kept at 160Watts constant, secondary power is varied between 0 Watt to 30 watts. As seen from the figure2 that number is decreasing parallel to the increased ratio of secondary power to primary power.

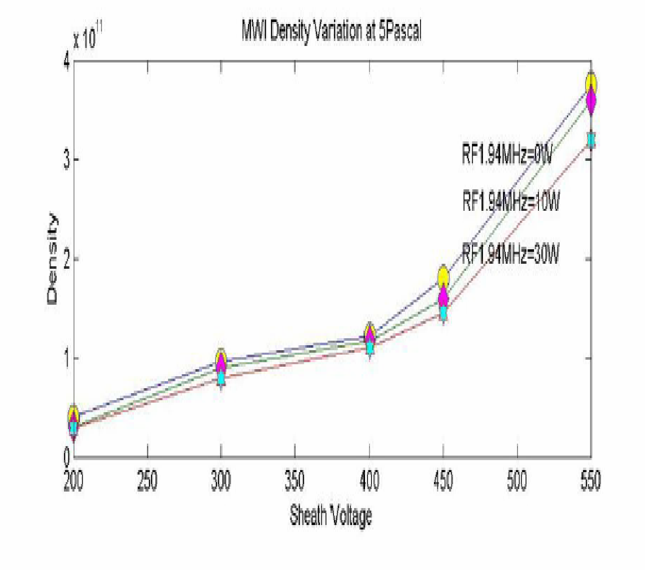

Figure 2. Density Variation with secondary RF power at 5 Pascal.

Figure 3 gives us axial number density variation for single of main source power is 500Watts. Figure 4 represents axial electron density variation for dual frequency application. There is an additional rf power source operating at frequency of 1.94 MHz. 30 Watts of 1.94 MHz power has been applied to the main electrode combined with 27.12 MHz 500 W power. Density decreases from centre to the edge of electrodes. It is seen that pressure dependence sequence is the same as single frequency case with a small difference less than 1%. The plasma density in a conventional single frequency CCP source can be increased by increasing the applied power and plasma density decreases with growth of the low frequency voltage in dual frequency capacitive discharge[11]. The increase of low frequency power to high frequency power $P_{1.94MHz}/P_{27MHz}$ leads to the decrease in plasma density with subsequent increase of sheath width until the discharge collapses[12]. Secondary frequency power to main frequency power ratio is 30/40=0.75 at figure 4. Applied secondary power decreases plasma number density by about 40%. This deviation was about 1% in the case of main frequency power of 500Watts.

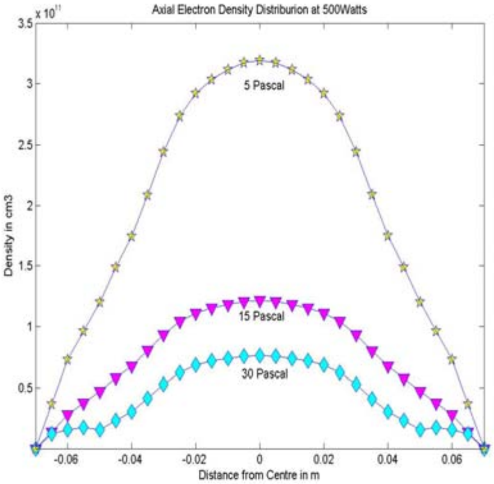

Figure 3 Single Frequency Low Power density variation.

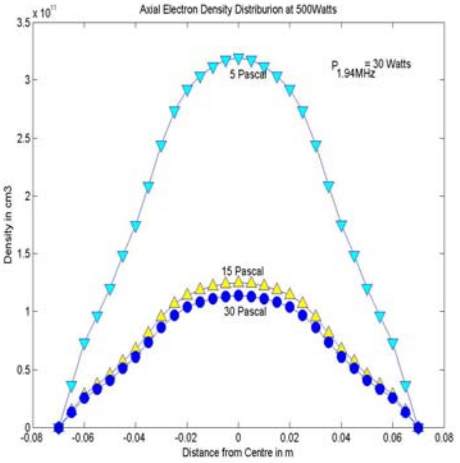

Figure 4. Dual Frequency Response $P_{2MHz}/P_{27MHz}<0.06$

Plasma density decreases as the pressure goes up from 5 Pascal to 30 Pascal. In capacitive discharges, the electrons are Boltzmann electrons and the electron density can be written as in equation 3.

$$n_e(y) = n_0 e^{\frac{e\varphi(y)}{T_e}} \qquad 2$$

From equation 2 the normalized potential with respect to electron temperature can be pull out and spatial potential profile can be obtained. The spatial potential profile for

40 W power at 5 Pascal is represented in figure 5. Since MWI method is noninvasive method and does not give info about electron temperature but we can obtain the potential drop from center to the boundary edge by using above formula. It is approximately two electron temperature[12,13,14] for single frequency which is sharper than comparable secondary source application. While the ions diffuse to the main electrodes there are diffusion losses to the side boundaries usually neglected in modeling of capacitive discharges.

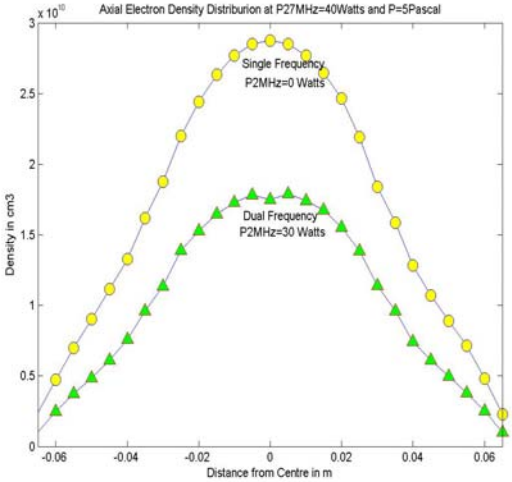

Figure 4. Dual and Single Frequency Response $P_{2MHz}/P_{27MHz} = 0.75$

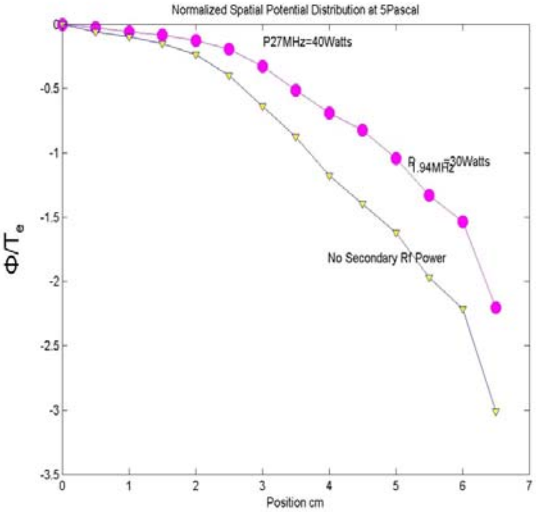

Figure 5 Normalized plasma potential distribution

Conclusion:

In a quartz tube confined capacitively coupled hydrogen plasma discharge system, the plasma density is measured spatially using microwave interferometer method with Abel inversion technique for different powers and pressures. The normalized potential profile is obtained with the assumption of the Boltzmann electrons indicates that the potential drop is almost two electron temperature from center to the boundary which is neglected usually CCP modeling. The density goes up as the pressure goes down is a result of stochastic heating mechanism that is dominant at low pressures. As the power goes up the density goes up linearly that confirms the global modeling of power dependence for CCP[15]**.** If the secondary rf power is comparable to the primary power source, the plasma density goes down as a result of subsequent increase of sheath width until the discharge collapses.

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