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A traveling wave driven, inductively coupled large area plasma source

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Abstract

First measurements are reported on an inductively coupled large area (71×61 cm^2) plasma source driven by a 13.56 MHz traveling wave. Launching a traveling wave eliminates standing wave effects to obtain a uniformly-excited processing plasma. The driving coil consists of a series connection of eight parallel rods, embedded in the plasma inside thin quartz tubes for efficient power delivery. The network required to launch a traveling wave through the driving coil is described. Our measurements confirm that a radio frequency traveling wave is launched and that a high density plasma is produced.

Planar coil, inductively coupled plasma systems are known for their capability to generate a high plasma density under low pressure and for their independent control of ion flux and ion-bombarding energy.[1] These properties are favorable for increasing processing speed and minimizing contamination and substrate damage. Plasma reactors suitable for processing 300 mm wafers, cylindrical in shape and driven by a planar spiral coil, have been extensively studied in recent years.[2–7] However, due to the coil configuration and driving network, the plasma generated by these reactors is inherently non-uniform,[8] and scaling to larger sizes for these systems is very difficult.[9] The RF power is coupled through a thick quartz window in these reactors, which hinders effective power coupling. Thicker windows or complicated multiple coil/window configuration must be used for larger reactors. Furthermore, with the increase of processing area, the length of the driving coil becomes comparable to the RF wavelength, and standing wave effects that cause a non-uniform power distribution along the driving coil become intolerable. Lowering the frequency can reduce standing wave effects but can lead to additional problems in obtaining plasma at low pressures.[7] To overcome these difficulties, a novel high density plasma reactor has been developed and characterized in which standing wave effects are eliminated by launching a traveling wave on the antenna coil. This reactor is suitable for large area flat panel and wafer processing. The system design and its theoretical background are described briefly in this letter. The first experimental evidence is presented here confirming that a traveling wave can be launched through the driving coil under plasma-loaded conditions, and that a high plasma density is achievable. We believe this to be the first demonstration of a traveling wave driven RF plasma source. Uniform

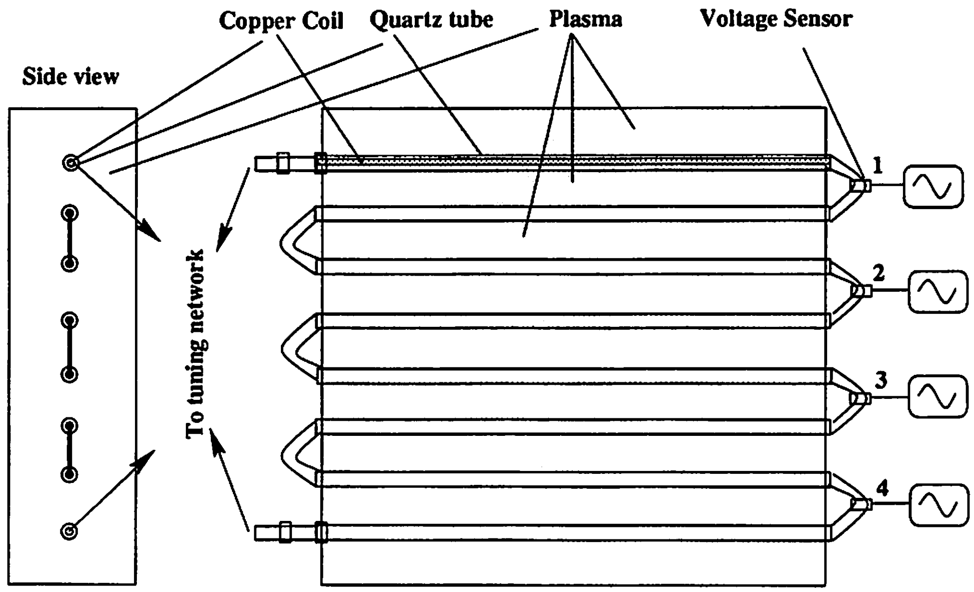

Figure 1: **Antenna coil system. The coil is made of a series of copper tubes, each surrounded by a quartz tube embedded in the plasma. Four voltage sensors are equally spaced along the antenna coil to monitor the voltage distribution.**

excitation of a capillary laser plasma column by a 2.45 GHz traveling wave in a waveguide ring resonator has recently been described.[10]

As shown in Fig. 1, the plasma chamber is a rectangular metal box (71.1 cm $\times$ 61.0 cm$\times$20.3 cm) pierced by a planar line array of eight quartz tubes (25.8 mm o.d, 22 mm i.d, and 80 cm in length) whose centerlines are 7.62 cm apart. The interiors of the tubes are at atmospheric pressure. The rf-excited coil system consists of eight, 6.35 mm o.d. copper tubes threaded through the interiors of the quartz tubes and connected in a series (serpentine) path. The coil-quartz-plasma system can be described as a coaxial transmission line, with the coil (copper tubes inside the quartz tubes) comprising the

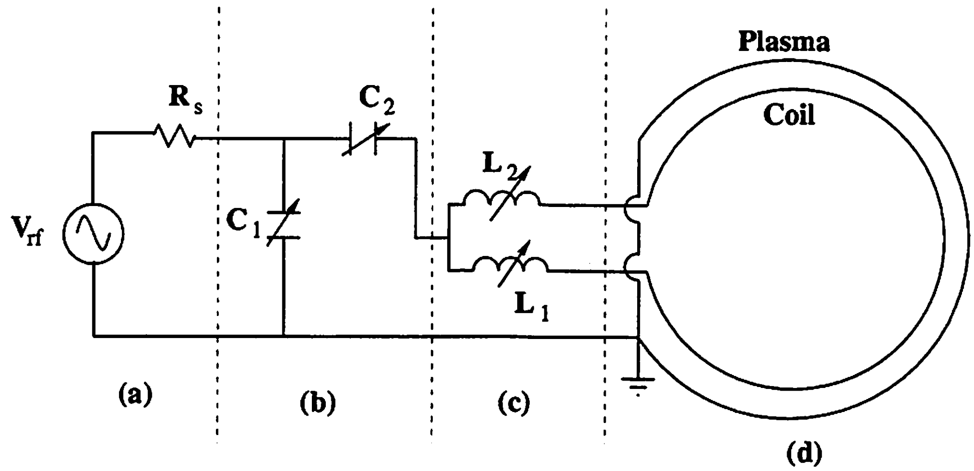

Figure 2: **The circuit schematic of the system, with the tuning network shown to launch a traveling wave along the antenna coil. L_1 and L_2 are two identical variable inductors. (a) RF power generator; (b) matching network; (c) tuning network; (d) antenna coil.**

inner conductor and the plasma surrounding the quartz tubes comprising a lossy outer conductor. The rf currents induced in the plasma flow along and outside the quartz tubes.

As shown in Fig. 2, a three-port two-element lossless tuning network (c) is required in order to launch a traveling wave on the coil (d). The tuning network elements are either variable inductors, as shown in the figure, or variable capacitors (each in series with a fixed inductor), as in our experimental tuning network. Each end of the coil is connected to one of the inductors, and the other ends of both inductors are driven by the output of a two-port matching network (b) of the usual design appropriate to inductive antennas.[11] The input of the matching network is driven by the rf power supply (a).

We have evaluated the equivalent circuit parameters of the antenna/plasma transmission line for our system under various plasma conditions using a volume-averaged discharge model.[12] For example, in argon at 5 mTorr and a density of 10^{11} cm^{-3} at the plasma-sheath edge, we obtain a characteristic admittance $Y_0 = G_0 + jB_0 \approx 0.015 + j0.00043$ S and a complex propagation constant $\gamma = \alpha + j\beta \approx 0.013 + j0.47$ m^{-1}.

The condition to launch a pure traveling wave along the line can be determined by solving the transmission line equations along with Kirchoff's laws for the circuit shown in Fig. 2, to obtain the reactances

$$X_1 = \omega L_1 = \frac{-G_0 \exp(-\alpha l) + (B_0 \sin \beta l + G_0 \cos \beta l)}{(B_0^2 + G_0^2) \sin \beta l}$$

$$X_2 = \omega L_2 = \frac{-G_0 \exp(\alpha l) - (B_0 \sin \beta l - G_0 \cos \beta l)}{(B_0^2 + G_0^2) \sin \beta l}$$

where l is the length of the antenna coil. We have designed the adjustable range of our tuning network (c) to cover the possible plasma operating conditions according to the above equations. The tuning network in figure 2 is symmetrical with respect to the wave traveling direction. In other words, an anti-clockwise traveling wave is as good as a clockwise one ($X_1' = X_2$ and $X_2' = X_1$). Let us also note that for a lossless line ($\alpha \equiv 0$, $B_0 \equiv 0$) we obtain $X_1 = X_2$. This indicates a degeneracy; i.e., both a clockwise and anticlockwise traveling wave are launched. Hence using this tuning network a single traveling wave (clockwise or anticlockwise) can only be launched on a lossy line.

Before the plasma source was constructed, an experimental model system was developed and tested thoroughly to verify the possibility of launching a traveling wave through the driving coil. It included an aluminum chamber with an inner dimension similar to that of the real system, a tuning network and a matching network. In the model system, eight sections of coaxial cables in series were used to simulate the antenna coil in the real plasma system. The outer shields of the cables were broken, and eight resistors were placed in series with the shields. These resistors were varied to simulate different resistive loadings of the real plasma. We constructed the model system to resemble the real plasma system in its impedance characteristics. Since the coaxial cable used had a 50 Ω characteristic impedance, we were able to connect a Bird Model 43 power meter at various locations along the "antenna coil" to determine the traveling wave direction and power. In addition, eight voltage sensors were connected to each section to verify the launching of the traveling wave. Under all conditions tested, we were able to launch a traveling wave through the model system, and found that the launching of traveling waves indicated by the Bird power meter was compatible to the voltage sensor measurements. The experimental results agreed well with the theoretical predication.[13]

The plasma source is driven by a 2.5 kW, 13.56 MHz RF power supply through the matching and tuning networks. Operating conditions of 100–1500 W of supplied power and 1–100 mTorr of argon pressure were investigated. For all of these conditions, we were able to launch pure traveling waves through the driving coil, while adjusting the matching network capacitors C_1 and C_2 to achieve a reflected power to the power supply of less than 1%.

The achievement of launching a traveling wave is identified using four voltage sensors equally spaced along the antenna coil as shown in Fig. 1. The principle of the measurement is very simple: a traveling wave means that the voltage amplitude should be the same along the transmission line. Since the RF wavelength in our system is 11–15 meters, depending on the plasma conditions, and since the total length of the transmission line of our system is 8.1 meters, four voltage sensors are enough to reveal the standing wave ratio. The voltage sensors are cylindrical in shape, and capacitively couple the antenna coil voltage to the measuring circuit. The signals picked up by the voltage sensors are immediately converted into DC signals by four HP M12DM RF probes which convert 1 Vrms to 1 Vdc.

Since real-time voltage monitoring is a key factor to obtain a traveling wave for various plasma conditions and to facilitate the tuning network and matching network adjustments, a multiplexer circuit was constructed to display the four spatially separated DC signals in one time-multiplexed oscilloscope channel.

Figure 3 shows an oscilloscope display of the voltages at the four equally spaced locations along the coil (see Fig. 1). The input power to the system is 500 W and the gas pressure is 18 mTorr. As shown in the Fig. 3(a), the voltages picked up by the voltage sensors at different locations of the driving coil are very different, which indicates that a wave with a high standing wave ratio was formed along the coil. By adjusting the tuning network, this difference decreased (b), and at the optimal condition (c), all the voltages were identical, indicating that a traveling wave has been launched. Further adjusting the tuning network made the operating point (d) depart from the optimal condition, but opposite to those shown in figures (a) and (b), i.e., the voltage is higher in locations 1 and 4 (see Fig.1). This display suggests how a standing wave will cause a non-uniform power dissipation along a driving coil when a plasma system is scaled to sizes comparable to or larger than an rf wavelength, and how a traveling wave may be obtained by using a

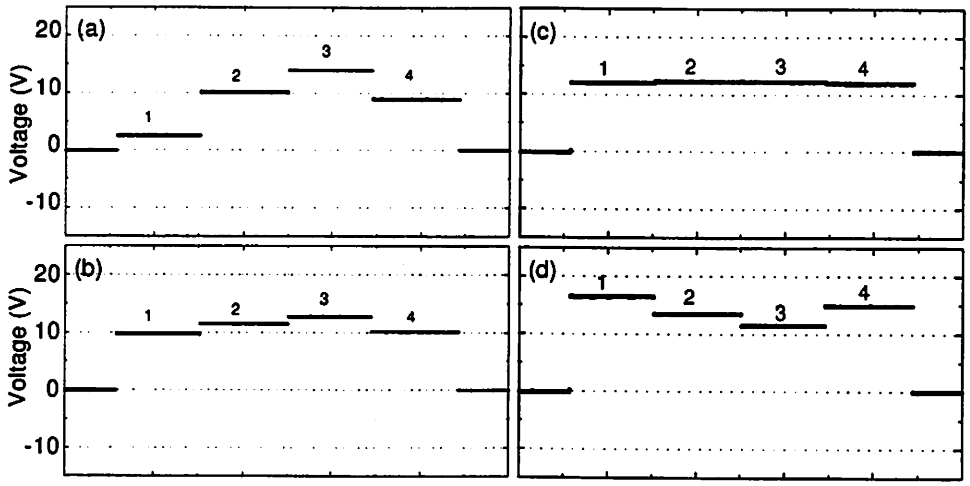

Figure 3: **Oscillocope traces showing the voltages on the four sensors. Each segment of the signal comes from one voltage sensor. (a) Voltages from the four sensors are very different, indicating a high standing wave ratio along the coil; (b) as the tuning network is adjusted, the voltage signals become comparable; (c) voltages from the four sensors are equal, indicating that a traveling wave has been launched; (d) over tuned condition.**

simple tuning network.

We estimated the fraction of power lost in the tuning and matching networks and the antenna coil.[14] We measured the antenna sensor voltage with plasma loading at the traveling wave condition to be $V_t = 12.5$ V and the power delivered to the system to be P_T=500 W. We then extinguished the discharge by bringing the reactor chamber to atmospheric pressure. The tuning and matching networks and the power supply were readjusted to bring the voltage back to V_t at the traveling wave condition. At this point, the net power (forward minus reflected) delivered into the system was measured to be $P_T^0 = 113$ W. The net power absorbed by the discharge was therefore evaluated as $P_{abs} = P_T - P_T^0 = 387$ W. The fraction of power lost in the tuning and matching networks and the antenna coil is then estimated to be 22.6%.

The measurements of the plasma densities under various operating conditions were made with Langmuir probes. The probes were biased from -35 to 35 V to obtain the complete $I - V$ characteristics. The variation of the ion saturation current with voltage was then used to calculate the plasma densities based on orbital ion motion model for Langmuir probes.[15,16]

Figure 4(a) shows a plot of plasma density vs. input power (forward minus reflected, including losses in the matching and tuning networks and driving coil) as measured by a Langmuir probe for our system at an argon pressure of 1.4 mTorr. Figure 4(b) shows ion density vs. pressure at an input power of 500 W. As shown in the figure, plasma densities that are comparable to those generated by other high density inductive sources have been achieved. Our computer simulations and simulations reported elsewhere[17,18] indicated that over a processing area equal to 360×465 mm^2 a nonuniformity of less than 3.5% may be achieved over a wide range of plasma operating conditions if a traveling wave is used to drive the antenna coil. We leave the topic regarding detailed uniformity investigation to another paper. We believe that by eliminating the standing wave effect as the plasma system is scaled to large sizes, the approach presented in this letter is suitable for most RF driven systems with coil length comparable to or larger than the RF wavelength.

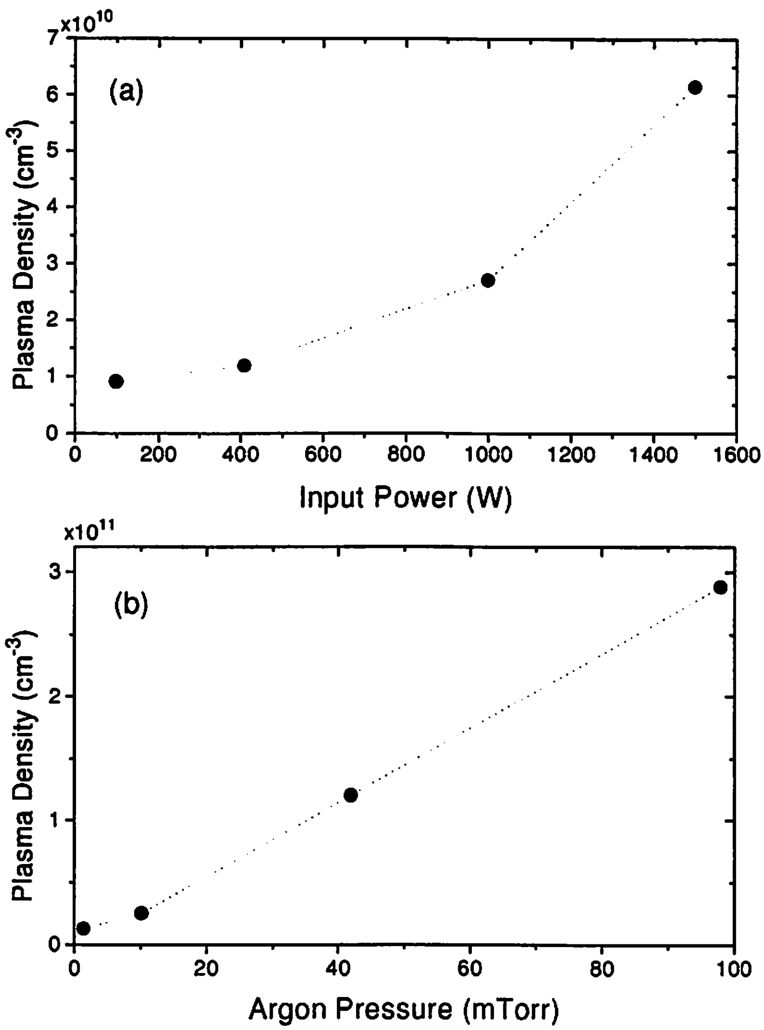

Figure 4: **Langmuir probe measurement of (a) plasma density vs. input power at 1.4 mTorr argon pressure and (b) plasma density vs. argon pressure at 500 W input power.**

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