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Radio frequency inductive discharge source design for large area processing

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Abstract - This paper examines planar radio frequency (RF) inductively coupled discharges for plasma processing of large area substrates. Concerns associated with increasing the size of spiral antennas are addressed through consideration of alternative antenna designs. A single straight antenna element is considered as a building block for rectangular antennas, and the interaction between neighboring straight antenna elements is addressed. It is shown that a discharge can be sustained with a single straight antenna element, and that in antenna designs that split the current through separate parallel paths, the path lengths must be equal for power to be evenly distributed. Further, we report evidence of destructive field interference (and associated poorer performance) for closely spaced parallel antenna elements with oppositely directed currents

Introduction There is currently a demand for plasma processing equipment for large-area substrates driven by needs for the microelectronics industry and flat panel displays. Reactors in operation in commercial fabs today process silicon wafers 150-200 mm (6-8") in diameter, but this size will to increase to 300 mm (12") in the next few years. In the case of flat panel displays, substrates may be even larger with dimensions greater than 500 mm on a side. Increasing reactor size for uniform processing of larger substrates is not a simple matter of making everything larger, and reactor development presents several major challenges. Some of these challenges, as they apply to the specific example of planar inductively coupled plasma (ICP) sources, are the topic of this paper.

Planar ICPs[1] are a natural choice (helicon, electron cyclotron resonance and helical resonators are other candidates) for processing of large area substrates. In commercial reactors in use for etching 150 mm and 200 mm diameter wafers, current at 13.56 MHz is driven through a flat spiral antenna separated from the process chamber by a flat quartz window. This creates an "image" current in the plasma resulting in inductive coupling of power. Because of its lack of external dc magnetic field and flexible antenna design, the ICP presents an attractive alternative for uniform processing of large area substrates. Straightforward scaling of this configuration for larger substrates involves increasing the outer diameter of the spiral antenna as well as the diameter of the quartz window.

There are several problems specific to increasing window and antenna size, in addition to other problems associated with scale-up such as gas delivery and substrate handling. An increase in window area requires an accompanying increase in window thickness to maintain structural integrity. The separation between the antenna and the plasma is also increased, with the result that a higher antenna current is required to couple a given amount of power into the discharge. At the same time, going along with an increase in size of a spiral antenna is an increase in inductance. The problem arises because these two effects significantly increase the voltage requirements for the antenna, and therefore increase the degree of capacitive coupling to the discharge, possibly changing its character significantly in undesired ways.

In this paper, we explore some of the issues associated with discharge scale-up and introduce some alternatives to the conventional ICP design that have some advantages for large area discharges. To address the issue of antenna inductance, we introduce lower inductance alternatives to the spiral designs. Results of extensive characterization of power coupling to the plasma will be discussed, particularly in the context of optimization of antenna design.

The standard spiral shape of ICP antennas poses some problems as reactor size is increased for processing of large area substrates. Power is coupled to the plasma locally in a region adjacent to current carrying antenna elements. For the spiral antenna, energy is deposited in a ring-shaped region, which, when combined with diffusion, can produce a uniform plasma. However, as substrate size is increased, in order to produce a uniform plasma a larger antenna area is necessary. This requires more turns and a larger diameter for the spiral, both of which increase the inductance and therefore the voltage requirements for the antenna. Higher antenna voltages may be a problem because of higher voltage ratings required for matching network components and because of the associated capacitive coupling of power to the plasma. If one end of the antenna is grounded, capacitive coupling will occur preferentially at the high voltage end, possibly resulting in process nonuniformities. It is therefore desirable to develop alternatives to the spiral antenna design that cover large areas but with lower inductance, minimizing undesired effects of capacitive coupling.

Antenna Experiments In considering alternative antenna designs to determine the minimal antenna elements that could be used as building blocks for more complicated designs covering a large area, straight conductor segments were investigated as possible induction antennas. Antenna designs covering rectangular areas, suitable for processing of rectangular substrates, such as flat panel displays, may be easily constructed from these straight segments. Examples are illustrated in Fig. 1, including serpentine, ladder and loop configurations. A question also arises as to the magnitude of the interaction of the fields due to neighboring antenna elements. In comparing the serpentine and ladder geometries, for example, it is noted that for the ladder, currents in neighboring parallel elements run in the same direction, while in the serpentine case they run in opposite directions, raising the possibility of destructive interference of the fields. Experiments addressed (a) whether a single straight antenna element is sufficient to generate a discharge, and if so, (b) what constraints exist for pairs of parallel antenna elements with currents running in the same or opposite direction, and finally (c) the feasibility of the antenna designs shown in Fig 1.

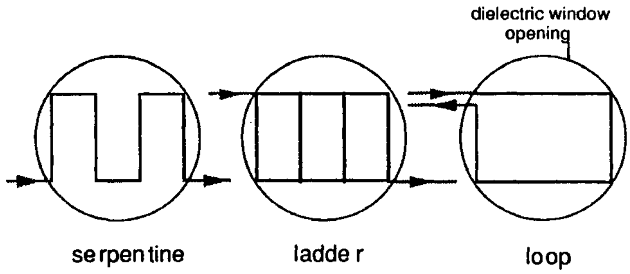

Figure 1. RF induction antenna designs for rectangular substrates. The "loop" design on the right is closest to the conventional spiral geometry, and has a higher inductance than the "serpentine" and "ladder" configurations.

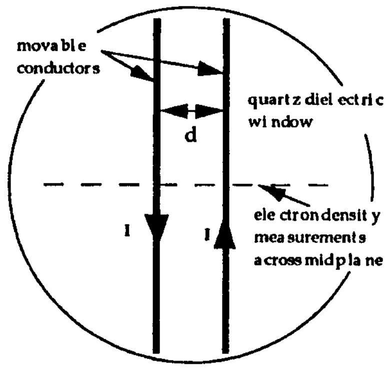

Figure 2. Configuration for dual conductor induction antenna with currents flowing in opposite directions.

Experimental Setup Experiments involving one or two straight antenna segments were conducted in a cylindrical stainless steel vacuum chamber with a 30 cm inner diameter. A circular quartz window 1 cm thick with an exposed diameter of 20 cm located at one end of the chamber separates the antenna from the plasma. Antenna segments are 18 cm in length, and two segments could be accommodated with a separation, d, between them of up to 7 cm, as shown in Fig. 2. Discharges were generated in argon to test antennas. Langmuir probes[2] were used to measure plasma properties as a function of spatial position along a chord at the midplane running perpendicular to the antenna segments.

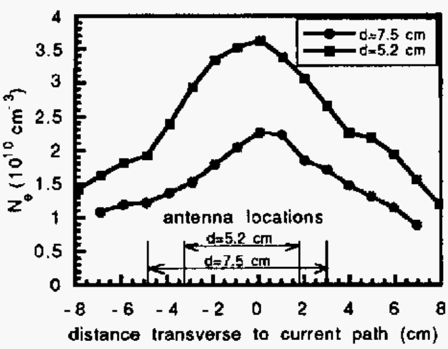

Figure 3. Electron density, N_e, spatial profiles for antennas with two parallel straight conductors with currents in opposite directions. Spacing between conductors is d=5.2 cm and d=7.5 cm.

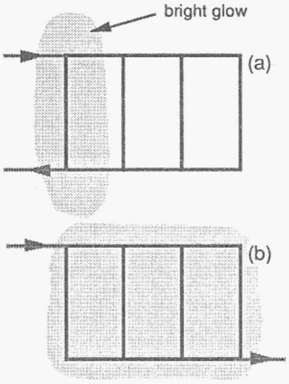

Figure 4. Schematic representation of plasma glow for "ladder" antenna with (a) asymmetric and (b) symmetric current feeds. Equal path lengths are necessary for parallel current feeds.

Results Discharges were easily sustained with antennas consisting of a single straight segment or two parallel segments with currents running in the *same* direction. This result supports the assertion that a single straight antenna element can be considered as a building block for more complicated antenna configurations, but does not address the possibility of interference between fields produced by neighboring antenna segments with currents in *opposite* directions, as in the serpentine antenna geometry.

Spatial profiles of electron density as determined by Langmuir probe measurements are shown in Figure 3, demonstrating the destructive interference associated with antenna currents in opposing directions. Electron density is shown for two antenna configurations, with argon pressure of 10 mTorr and peak antenna current of 52 A for both configurations. In both cases, a pair of straight parallel antenna elements carry current in *opposite* directions, but the separation d between the pair elements is different for the two cases, d=7.5 cm for one case, and d=5.2 cm for the other. Both the peak electron density ($N_e=2.2\times10^{10}$) and discharge power (300W) are lower for the closer spacing than for the larger spacing ($N_e=3.5\times10^{10}$, 355W). The difference between the two cases is attributed to the destructive interference of the rf electromagnetic fields produced by the neighboring opposing currents, and has some important implications for antenna design. In fact, we were unable to sustain a discharge when the antenna elements were placed yet closer at d=3 cm and driven with opposing currents, although a discharge was easily produced for this configuration when the currents were in the same direction. A simple rule of thumb consistent with these results for parallel antenna elements with *oppositely* directed currents is that if the separation between the two conductors is less than twice the dielectric window thickness plus skin depth for field penetration, significant interference will take place. Since skin depths are typically on the order of 1-2 cm, a separation of about 7-10 cm is dictated, entirely manageable for a reactor designed for large area substrates.

Large Area Antennas In addition to investigations of antenna segments described above, several configurations for large area antennas were also studied. Argon discharges were generated with each of the three rectangular antenna configurations, serpentine, ladder and loop, shown in Fig. 1. Discharges generated with the large antennas were also confined in a cylindrical vacuum vessel with a circular flat quartz window between the antenna and the plasma. For these experiments, an aluminum chamber with an inner diameter of 42 cm and window opening of 35 cm was used. Outer dimensions of the rectangular antennas are 20 cm by 30 cm. The spacing between parallel segments of the antenna were thus a minimum of 10 cm, so interference between neighboring conductors is expected to be minimal.

Discharges were readily generated over a wide range of operating conditions with the serpentine, ladder and loop antenna configurations. Lower antenna voltages were required for the serpentine and ladder antennas than for the loop antenna for a given antenna current or discharge power, consistent with their lower inductance design. The ladder configuration seemed to give the lowest inductance, to the extent that additional series inductance had to be added in order to attain an acceptable impedance match to the power supply using the same matching network as for the other antennas.

Symmetric current feeds The ladder antenna was the only one investigated for which the antenna current was split between several paths. The importance of choosing a design so that the current paths have equal lengths was demonstrated in a simple experiment illustrated in Fig. 4. In one case the external current leads were connected at one end of the antenna, and in the other the external leads were connected symmetrically, at diagonally opposite corners of the rectangle. In the case of the asymmetrically placed leads, a glow was observed only at the end of the antenna, where clearly the current had chosen the path of least resistance. When all parallel current paths have equal length, however, there is no preferred path and a much more uniform glow is achieved.

Summary Many low inductance antenna designs are possible for generating inductively coupled discharges for materials processing of large area substrates. This flexiblity in antenna design creates new opportunities for scaling up reactor size while maintaining process uniformity. Two practical constraints on antenna designs have been demonstrated. When parallel neighboring antenna segments carry currents in opposite directions, a spacing of about 10 cm or greater between the two segments must exist in order to maintain a discharge and efficiently couple power to the plasma. Finally, a separate requirement is that when current is split between two or more current paths, the parallel path lengths must be equal in order to distribute current equally among the paths.

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