What We Learned and Used in the First Inductively Coupled Plasma, ICP, for Plasma Processing and in Later Development

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The first ICP for Plasma Processing, also called Radio Frequency Induction, RFI, were developed at IBM, East Fishkill, NY, USA. These were extremely efficient at producing high density plasma. This paper will discuss: 1) How to drive the antenna to get high plasma density with low plasma voltage and low capacitively coupled plasma, CCP, losses, 2) Low matching losses, 3) Optimum way (presets) to start an ICP, 4) Frequency effects and 5) Achieving high plasma stability.

1. Introduction

This paper gives some of the information that was learned from the first ICP systems for plasma processing (both etching and deposition) plus knowledge which was gained both at IBM up to 1999 and later from consulting for a number of plasma tool vendors. These consisted of:
3 Plasma tool companies that included inventions,
2 Implantation companies that included an invention and
1 University for bright plasma beams, which included a number of inventions

2. How to Drive the Antenna

In observing ICP system for etching and deposition around the world and in reviewing Journal papers I have observed that many people ground one side of the ICP antenna. Except possibly in some very low rf frequencies, this causes larger than necessary antenna voltages and thus more CCP power losses and lower plasma density. This in turn causes different frequency effects since CCP densities and losses vary with frequency.

To achieve high density, lower plasma voltages and less CCP one should at least drive the antenna symmetrically by grounding the antenna through capacitive impedance. To be symmetric this capacitive impedance should be one half the inductive impedance of the antenna, with the plasma on. If at higher rf frequencies it is desired to have even lower plasma voltage the antenna can be divided into two or more parts and the appropriate capacitive impedance can be added between the sections such that each section is driven symmetrically.

Figure 1 shows driving the antenna through a matching network, with only capacitors and straps, and grounding the antenna though a capacitor. Also shown is the difference in the antenna voltage and the plasma voltage for three cases:

1) The antenna grounded,
2) The antenna grounded through the appropriate capacitor to drive the antenna symmetrically and
3) The antenna split in two with a capacitor between the two sections and a capacitor to ground such that both sections are driven symmetrically.

These latter cases give less than ½ and ¼ of the antenna voltage due to the smaller CCP loses and large plasma density. When the antenna is driven symmetrically there is only a small rf plasma voltage, at the second harmonic.

For each induction frequency there is an optimum insulator thickness, vacuum and/or air spacing between antenna and the plasma. Larger spacing reduces the plasma sheath voltage (inverse with spacing) and CCP losses, but reduces the magnetic coupling thus causing more current to flow in the antenna for a given plasma density (linear with spacing) and thus more coil resistive loss.

In driving rf plasma for producing Ion Beams it is even more important that that the antenna be driven symmetrically. This is because:

1) An energy spread of the ions in an ion beam will reduce the amount of space charge neutralization that is possible and
2) Focusing lenses and mass analysis magnets have chromatic aberrations that interact with the energy spread.

The main reason rf plasma sources are not used to produce ion beams, like in an ion implanters, and focused ion beams is that it was not understood that one should use an ICP or Helicon plasma, with symmetric antenna to produce the plasma.

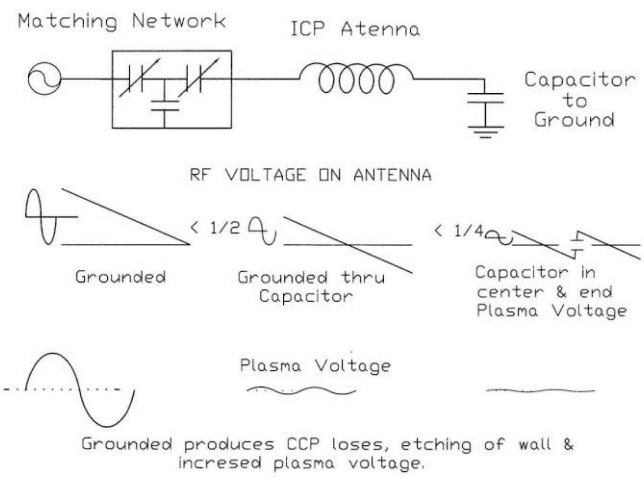

Fig 1 Driving an ICP, Antenna Voltages and Plasma Voltages

3. Low Matching Network Losses

To run dominantly in the inductive mode the matching network and antenna must be capable of producing more current, at a given power, than the ICP threshold current for the antenna. This is equivalent to a minimum V/cm needed to maintain the plasma. Since the antenna is inductive the matching network can be made up of only low loss capacitive elements and the connecting straps. The antenna and all the leads/ straps should have large enough cross sectional perimeter and thickness to have low matching losses. These losses can be less than 5% to 10% of the input power. Shown in fig 1 is a tee match, which the author prefers because in an auto match it matches fast. The 1st series variable capacitor can have a smaller current capability. The parallel capacitor can be made up of a number of ceramic capacitors in parallel so as to be able to easily handle the current capability. Thus only the 2nd series variable cap needs to handle large current and it can also have a ceramic cap in parallel with it.

The 1st 13.56 MHz ICP etching system at IBM was so efficient that once the matching network for the antenna was tuned for the plasma, the ICP power could be turned off and the inductive plasma would run solely by powering the wafer bias electrode. That is the rf power to this electrode drives a plasma voltage which in turn would drive sufficient current in the ICP antenna/matching network to produce the inductive plasma. For low loss both resistive and CCP the antenna should have a small inductance (see function dependences below).

If your chosen matching network is not sufficient to drive current larger than the ICP threshold current, a ceramic capacitor can be added in parallel with the input to the antenna such that most of the rf antenna reactive current flows through this capacitor and the matching network supplies mainly the real current.

4. Functional Dependencies

The follow functional dependencies are from calculations using "OERSTED" (*integrated engineering*). These give the antenna currents and voltages:

$$I \,\alpha\, 1/(F^{0.27} L^{2/3}) \sim \text{constant} \qquad (1)$$

$$V \,\alpha\, F^{0.7} L^{1/3} \sim F^{1/2}, \qquad (2)$$

were L = inductance, F= frequency and one generally increases L as F deceases.

5. Optimum presets for starting an ICP

Optimum matching network presets for starting an ICP for ashing, etching and deposition and a procedure for determining them is given in US Patent Application 2002/0067133 A1

The optimum preset for starting an ICP is to set the preset to be matched to a very low powered CCP. To do this: 1) Turn on the ICP, 2) Turn down the power so that only the CCP is lit (a few watts) and 3) Then set the presets to that condition.

Then when the ICP power is turned on, the match immediately turns on the CCP and all the additional power causes the coil current to exceed the threshold current, which lights the ICP, then tunes the match to the ICP condition.

6. Frequency Effects

If done properly to achieve low matching losses and low CCP losses then there is little frequency effects on the plasma density certainly from 400 KHz to about 27 MHz, unless the skin depth exceeds the radius or plasma depth. Below 13.56 MHz there is a slight confinement of the plasma by the rf magnetic field from the antenna.

An ICP is efficient only if the skin depth, δ, is small compared the to the radius or plasma depth.

δ is a function of $(\text{pressure}/\omega)^{1/2}$ and $(1/Ne)^{1/2}$,

where ω is the radian frequency and N_e is the electron density. So if the plasma is electronegative and /or the pressure is high, one may want to use a high frequency.

The ICP's are used extensively in ashing and etching of silicon and metals as well as for deposition of oxides. At IBM we developed an ICP for etching which has a magnetic filter to produce a cold plasma, Te <1 eV, above the wafer. This system had a 1 sigma uniformity of < 1%. It was tested for silicon gate etch and had much higher than normal selectivity.

Attempts have been made to use ICP at 13.56 MHz to etch oxide; however, These ICP have the property of producing too much gas cracking. We had tested higher frequency of 40 MHz, however, with normal antennas where most of the antenna CCP current goes to the walls and the bias electrode, these produce hot plasmas both over the wafer and at the wall sheaths.

I have also done designs for antenna driven systems from 80 to 200 MHz. In these 80-200 MHz designs most of the rf current that flows from the antenna to the plasma is returned to a different part of the antenna. These, I believe, can have high plasma density with reduced gas cracking, particularly if the plasma is colder over the wafer, as is possible with a magnetic filter.

7. Plasma Stability

Lastly ICP, including those with negative ions, can be made stable by abandoning the criteria of nearly zero reflect power, with a phase such that when the plasma density decreases the system moves closer to being matched. Note that there are two criteria here, both the reflected power and the phase. The reflected power of 5-10 % is sufficient for achieving this stability. It is a nice addition that this also makes the process more stable and repeatable. For more information see US Patent 5,866,985

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