DIAGNOSTICS OF RF PLASMAS FOR SEMICONDUCTOR ETCHING

Francis F. Chen and Gaétan Chevalier
Electrical Engineering Department
University of California, Los Angeles, CA 90024-1594

Final Report 1991-92 for MICRO Project 91-021
Industrial Sponsor: Plasma & Materials Technologies, Inc.

ABSTRACT

Commercially available probe diagnostics for rf plasmas are evaluated, and ideas for improvements are suggested and tried. Work reported here includes testing of small inductors used for rf filtering, fabrication of carbon probe tips, and design of new probe circuitry.

1. SCIENTIFIC BACKGROUND

The principal method used to measure plasma plasma properties, such as density and temperature, in discharges used in semiconductor etching and deposition (RIE, ECR, and RFI) has been the Langmuir probe. The difficulties of using this diagnostic in an rf environment are mainly threefold: 1) rf pickup, 2) alteration of the probe by the plasma, and 3) alteration of the plasma by the probe.

Numerous authors have written papers on methods for reducing or canceling out the rf pickup [1-8]. The simplest of these schemes, the addition of a small rf choke, was incorporated by PMT, Inc. in their FastProbe system. This system also helps to solve problems (2) and (3) by pneumatically injecting the probe so rapidly that it is subject to bombardment by plasma ions for only a few tens of milliseconds at a time. The FastProbe also enables an entire density profile to be taken in one shot. This system is commonly available for use by the semiconductor processing industry, but its performance has never been independently assessed. Our aim was to perform such an assessment and to suggest improvements in the probe and circuitry.

Langmuir probes can be used for three types of measurements, and the rf pickup problems are different for each. When biased negatively to collect ion saturation current, a simple low-pass filter anywhere in the system can take out the rf pickup signal. Ion saturation current is insensitive to fluctuations in plasma potential as long as the bias potential is large enough. If the plasma density varies, the ion current follows linearly, and the filtered signal gives the proper average density. When the probe is swept in voltage to get the electron I-V curve, whose slope yields the electron temperature, the rf fluctuations in plasma potential must be canceled out, since the current varies exponentially with potential, and simple averaging will give the wrong result. When the probe is floated to give the plasma potential distribution, a nonlinear region of the I-V curve is used, and rf oscillations will affect the average potential that is measured. Since floating probe measurements (unless the probe is an emitting probe) require a high-impedance load, stray capacitance will affect the measurement by lowering the load impedance. To follow the rf frequency would be extremely difficult, and even following low-frequency fluctuations to study the stability of the plasma requires careful elimination of stray capacitances, usually by capacitance neutralization.

The work reported here is confined to assessing the use of the simplest and most common method for rf rejection, an rf choke located near the probe tip. The inductor should have an impedance at the rf frequency which exceeds the effective output impedance of the plasma, which is roughly the electron temperative (in eV) divided by the ion saturation current. Under typical conditions (2 eV, 0.1 mA), this amounts to 20 kilohms. If the inductive impedance is above, say, 10^5 ohms, the probe tip will follow the potential oscillations of the plasma, and the applied bias voltage will appear at the probe tip as a constant voltage relative to the plasma, as is desired, and not relative to ground. The low-frequency and dc signal, however, will see a small impedance from the choke and will pass without appreciable attenuation. How well this works in practice depends on the details of the implementation.

2. MICROWAVE CALIBRATION

The plasma density n is usually obtained from the ion saturation current I_i by using the formula [9]

$$I_i \;=\; 0.5\, neA\; (KT_e/M)^{1/2}\;, \qquad (1)$$

where A is the probe's surface area, KT_e the electron temperature, and M the ion mass. The factor 0.5 is only an approximation based on more exact theories of ion collection. This factor does not take into account the probe shape or the voltage at which the ion current is considered saturated, but it should be reasonably accurate as long as the probe radius is much larger than the Debye length. To check on this factor, we chose to measure the density independently by microwave interferometry.

Fig. 1 shows the apparatus used. The beam from a 65 GHz Gunn diode source was launched through the plasma from a horn antenna and reflected by an aluminum plate on the far side. The reflected signal, after passing through the plasma twice, is mixed with the incoming signal, giving a detector output that varied from maximum to minimum as the reflector is moved 1/4 wavelength on a micrometer stage. To reduce the loss of signal by beam divergence, the horn and reflector were placed as close as possible to the 5 cm diameter quartz tube housing the discharge. The plasma was operated at a density around $10^{12}\,\mathrm{cm}^{-3}$ in order to keep the phase shift less than 360°. At this density, which is an order of magnitude lower than normal, low-frequency oscillations tended to arise; but by adjusting the magnetic field and the pressure, it was possible to find a quiescent condition with a fairly flat density profile.

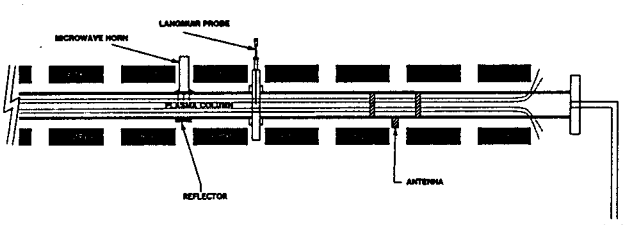

Figure 1: Experimental setup

The discharge was pulsed, and the detector output was read before and during the pulse. The corresponding curves of interferometer signal vs. reflector position are shown in Fig. 2. Since no automatic peak-sensing circuitry was used, the shapes of the curves can be seen. They are not pure sine waves, and the distortion is different with and without plasma. We have fit the curves to sine waves plus the lowest harmonics. By adjusting the magnitudes and phases of the harmonics, we could fit the data points with the curves shown. Both cases can be fit by adding about 20% second harmonic and a few percent third harmonic, but with different phases relative to the fundamental. If the second harmonic is present in the input signal, it would be possible in principle to get density measurements at two frequencies simultaneously, but unfortunately the phase shift of the second harmonic did not yield a value that was in reasonable agreement with the fundamental.

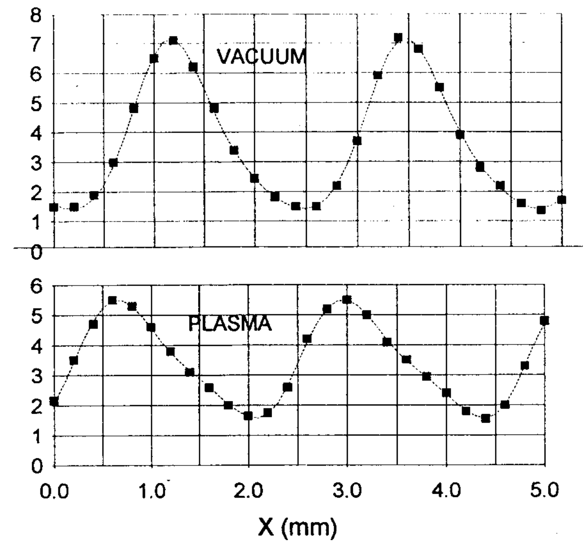

Figure 2: Microwave interferometer signals with and without plasma. The lines give Fourier fits to the data. The 2nd and 3rd harmonic contents are 20.3% and 2.6% in the vacuum case, and 23.1% and 1.1% in the plasma case.

The phase shift of the fundamental alone, obtained from the fit, was then used to calculate the density by comparing it with that calculated using the measured density profile. Comparing with the measured probe current, we found that a value of 0.7 should be used in Eq. (1) instead of 0.5. The probe and interferometer were located in adjacent ports 12 cm apart. The axial density variation in that distance should be less than a few percent; and in any case, the correction is opposite in sigh from what would be expected from an axial density gradient. The electron temperature was assumed from previous measurements to be 3 ± 0.5 eV. The probe tip was 0.5 mm in diameter and about 1 mm long. Its area could be measured only to within 5% because of the jaggedness of the ceramic shield that defines the collection area. The probe was assumed to collect ions from both the sides of the tip and the end. No correction was made for the width of the microwave beam, which encompassed regions where the density was lower than in the flat, central region. Thus, we believe that the value of 0.7 can be trusted to within about 10%.

3. TUNED PROBES

In this section, the effectiveness of a simple, commercially available rf inductor is investigated. Our probes are mounted on 6.4 mm diam. stainless steel shafts with a 1.6 mm diam. alumina tube extending out the end about 4 cm. A tungsten rod 0.5 mm in diameter protrudes past the end of the tube by 1 to 1.5 mm to form the probe tip. Just inside the stainless shield, as close to the tip as possible, a cylindrical rf choke is spotwelded to the tungsten tip, and the other end is soldered to a copper wire which passes through the vacuum seal to the probe circuitry. The inductors are of the Minired (MR), Microred (MCR), and Nanored (NR) series manufactured by Lenox Fugle Electronics, Inc.

Four samples each of chokes of six different nominal inductances and three different size series were purchased. The resonant frequencies and maximum impedances were measured *in situ* in the same probe mount. The nominal inductances and resonant frequencies bear little relation to the measured results, which depend on the environment in which the chokes are mounted. Fig. 3 shows the frequency and impedance data for the Minired series vs. nominal inductance. For some inductances all four samples were measured to give an idea of the sample-to-sample variation. It is seen that the resonant frequency decreases with increasing inductance, as expected; but there is such a large sample-to-sample variation that the inductors should be hand-picked, especially at the lower inductances. The impedance values varied from 200 K to less than 80 K, so that an off-the-shelf inductor will not be effective at lower plasma densities.

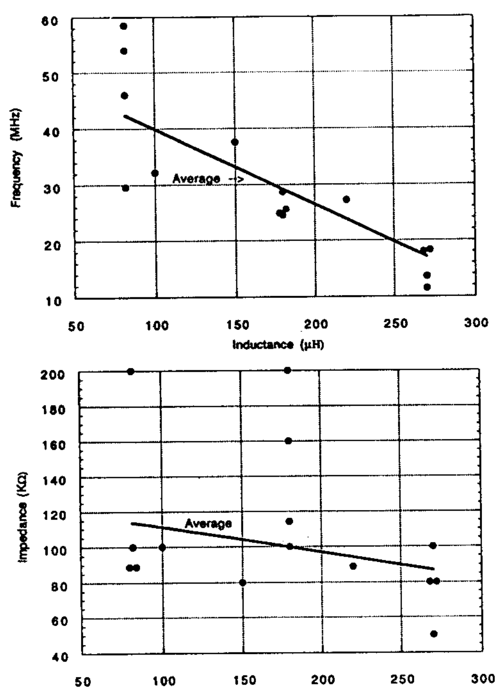

Figure 3: Performance of Minired series inductors vs. nominal inductance: (a) self-resonant frequency; (b) maximum impedance.

Data for the Microred and Nanored series are omitted to save space. For these, the resonant frequencies were more consistent, and the scatter in the impedances seemed also somewhat smaller. However, the absolute value of the impedance, around 50-60 K, is so low that the probe tip will not float with the rf at plasma densities much below $10^{12}\,\mathrm{cm}^{-3}$.

We would not advise putting the chokes closer to the probe tip, in the unshielded ceramic section, where they can have capacitive pickup from potential fluctuations in the p plasma. The small inside diameter of the ceramic shield would furthermore necessitate using Picored series inductors, which have such a small Q that they are hardly effective.

We have also taken probe characteristics with and without the rf chokes, to see how much the rf fluctuations actually change the electron temperatures obtained from the I-V curve. This was done in a helicon discharge, where the rf electric fields are relatively small, and where there is a relatively large population of fast electrons accelerated by the helicon waves. The results can be expected to be different in RIE discharges, where the oscillating electrostatic fields are much larger. Analysis of the results cannot be given here.

4. CARBON PROBES

It was necessary to bias the probes to -200 V in order to repel the primary electrons and collect saturation ion current. The high incident ion energies cause sputtering of the probe tip. Continued operation at densities above $10^{13}\ \mathrm{cm}^{-3}$, even in pulsed discharge, eroded the tungsten probe tips so that the effective area charged with time. We have found that carbon probes are more stable against sputtering. A convenient source of carbon is ordinary pencil lead, available in 0.5 and 0.3 mm diameters. The conductivity is quite low and is higher with the harder grades of pencil lead.

We have devised a method of mounting the fragile carbon tips so that they are protected against breaking. A schematic is shown in Fig. 4. First, a hypodermic needle, complete with plastic end holder, is filled with conducting epoxy, using the syringe that normally comes with it. An 0.3 mm diam. piece of pencil lead, which can be obtained only in grade HB, is inserted into the epoxy and nestled into the plastic needle holder. An alumina tube, .062″ od by .031″ id, is then slipped over the hypodermic needle so that the carbon tip protrudes by about 1.5 m, and the end of the needle is recessed by about 1 mm to act as a centering device. This prevents the probe tip from contact with any conducting coating that can be deposited on the ceramic. The stainless steel needle is magnetic, but we do not expect the field from this to perturb the probe measurements.

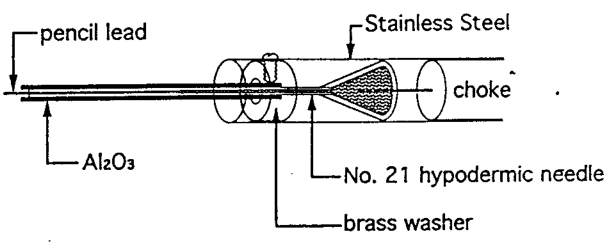

Figure 4: Schematic of carbon probe.

5. OPTICALLY COUPLED PROBE CIRCUIT

The current measuring resistor in a probe circuit can be placed either on the ground side or the hot side of the voltage generator supplying the probe bias. If it is on the ground side, it is properly terminated to the oscilloscope or other detector; but the power supply has so much stray capacitance to ground that all but the lowest frequency currents are likely to reach ground before seeing the resistor. If the resistor is on the hot side, the power supply is properly grounded, but the resistor is floating, and the voltage across it must be read differentially. This is risky in an rf environment, because the rf pickup can be different on the two sides of the resistor, due to different stray capacitances.

To alleviate these problems, we have built a circuit with a 50 ohm measurement resistor and differential op-amp inside the probe shaft, within 2 cm of the rf choke filter. The circuit is designed for ion currents only; floating potential measurements will require capacitance neutralization. The amplifier stage is floating at the probe bias potential of −200 volts, and the power for the op-amp is optically coupled to the driver stage through an LED. A separate lead is required for the output stage because it is on the ground side. Schematics of the circuit and the component layout are shown in Fig. 5. The circuit itself is rather straightforward, but the choice and placement of components was critical. The entire circuit is fit inside the 0.25″ od probe shaft; the op-amp had to be taken out of its case and filed down to fit. First tests of the circuit showed a large amount of rf pickup. It will require several trial versions before a reliable system is developed.

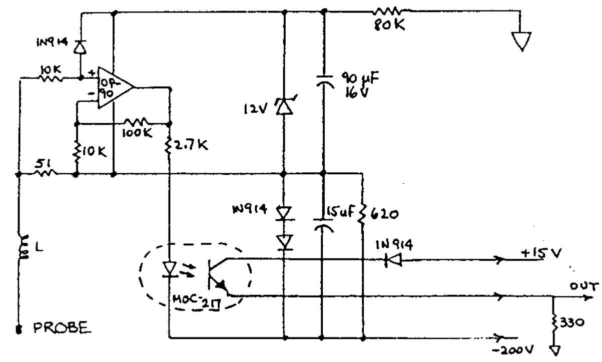

Figure 5: Schematic of miniature probe circuit

6. PERSONNEL

In addition to the authors, four students contributed to the work of the group. Max Light and David Blackwell are graduate students working on their Master's degrees. Johannes Hsieh is a Wisconsin student working at UCLA as part of our collaboration with the Wisconsin Engineering Research Center on Plasma-Aided Manufacturing. Scott Hsu, who built the probe circuit, is an undergraduate student doing extracurricular work on plasma physics.

REFERENCES

[1] N. St. J. Braithwaite, N.M.P. Benjamin, and J.E. Allen, *J. Phys. E: Sci. Instrum.* **20**, 1046 (1987).

[2] A. Cantin and R.R.J. Gagné, *Appl. Phys. Lett.* **30**, 316 (1977).

[3] V.A. Godyak, in *Plasma-Surface Interactions and Processing of Materials,* O. Auciello et al., eds., Kluwer, Netherlands, pp. 95-134 (1990).

[4] V.A. Godyak and R.B. Piejak, *J. Appl. Phys.* **68**, 3157 (1990).

[5] A.P. Paranjpe, J.P. McVittie, and S.A. Self, *J. Appl. Phys.* **67**, 6718 (1990).

[6] S.E. Savas and K.G. Donohoe, *Rev. Sci. Instrum.* **60**, 3391 (1989).

[7] E.Y. Wang, N. Hershkowitz, T. Intrator, and C. Forest, *Rev. Sci. Instrum.* **57**, 2425 (1986).

[8] J.L. Wilson, J.B.O. Caughman II, P.L. Nguyen, and D.N. Ruzic, *J. Vac. Sci. Technol.* **A7**, 972 (1989).

[9] F.F. Chen, "Electric Probes", in *Plasma Diagnostic Techniques*, R.H. Huddlestone and S.L. Leonard, eds., Acad. Press, N.Y., Chap. 4 (1965).