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Comparison between Single and Double Langmuir Probe Techniques for Analysis of Inductively Coupled Plasmas

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Comparison between Single and Double Langmuir Probe Techniques for Analysis of Inductively Coupled Plasmas.

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Abstract

In this study, the plasma density and electron temperature of Inductively Coupled Plasmas were determined by three types of Langmuir probes: a double probe, a single probe with RF choke and a single probe with RF choke and compensating electrode. The results obtained by the double probe offered the most reliable results for both plasma parameters. The single probe with compensating electrode has a similar precision as the single probe with only a RF choke, but its accuracy is better. For the investigated argon plasmas, the electron temperature increases with coil power and decreases with pressure, while the cathode power does not influence very much. The plasma density increases mainly with coil power, and to a lesser extent also with pressure and cathode power.

I. Introduction

Inductively Coupled Plasma etching is becoming an increasingly important technique in integrated circuit and microstructure fabrication [1-3]. For most applications, RF current passes through a planar coil, inducing a RF electric field to create the plasma. At the same time, power is applied to the electrode on which the wafer sits, to control the ion bombardment [4,5]. Recently, these plasmas have been analysed with Langmuir probes [6,7]. This analysis is relatively difficult, as the theories developed for analysis of the current versus bias voltage (I-V) curves of the probe, are based on the assumption that there is no magnetic field in the plasma. Another factor which turns the probe construction and the I-V curve analysis more difficult, is the presence of the RF electric fields. If a single probe is not well RF compensated, the I-V curve will be distorted and the values obtained for the electron temperature will be overestimated [8]. There are several ways to decrease the influence of the RF induced currents on the measured I-V curve. A first one is through active compensation, known as the driven probe technique, where a small RF component is superimposed on the DC voltage applied to the probe [9].

A simpler approach is to use an RF choke, which is in general composed of a blocking inductor which has a very high impedance at the operating RF frequency [10,11]. There exist several variations on this approach. One particularly interesting technique introduces an extra capacitor in parallel to the plasma sheath formed between the plasma and the probe tip. The impedance between plasma and probe tip is decreased resulting in less distortion of the collected characteristic probe curve. Another disadvantage of the single probe is that it may drain so much current from the discharge that it disturbs the plasma. To avoid this situation, one can use the double probe technique [12-14]: two Langmuir probes immersed in the plasma in

such a way that the electron current collected by one of the probe is limited by the positive ion current collected by the other. The current collected by the double probe is typically 20 times less than the current collected by the single probe.
The external circuit of the double probe floats together with the plasma potential, making the RF interference much less significant. A disadvantage of the double probe technique is that it does not determine the floating and plasma potentials of the plasma.
In this paper, a single probe with RF choke, a single probe with RF choke and compensating electrode and a double probe were used to analyse inductively coupled plasmas. Using these results, the precision and the accuracy of the measurements were evaluated and the electron temperature and plasma densities of different plasmas were determined.

II. Experimental

A. Plasma etch equipment

A home-built reactive ion etching system was modified by placing a 5 turn coil above a 1 cm thick pirex plate on top of the reactor. The original reactor has been described as system 2 in reference 15. The wafer sits on a 6 inch diameter aluminium electrode, which we shall call the cathode from now on. Power can be applied independently to the coil and to the cathode at 13.56 MHz. A special matching network has been developed to transfer the power from generator to coil without much reflection.

B. Used Langmuir probes

In order to determine the plasma densities and the electron temperature, three different types of Langmuir probes were used: a single probe with only a traditional RF choke [16], a single probe with RF choke and compensating electrode [10] and a double probe [13]. A schematic view of the three probes is shown in figure 1.
The probe tips are all made of tungsten and have a diameter of 0.2 mm. For the single probes, 4 mm of the tungsten wire is exposed to the plasma, for the double probe, 8 mm is exposed and the distance between the two tips is 4 mm.
The tips of the single probes were connected to a RF choke (at the choke's plasma end terminal) to provide RF compensation.
These RF chokes consist of a series of two small shielded inductors in parallel with a variable capacitance. The capicitance is tuned to obtain a maximum impedance of about 200 KΩ at 13.56 MHz.
The other terminal of the choke (its circuitry end terminal) is connected to the core conductor of a coaxial cable. RF choke and coaxial cable are protected by a 13 mm outer diameter, 30 cm long pyrex tube.

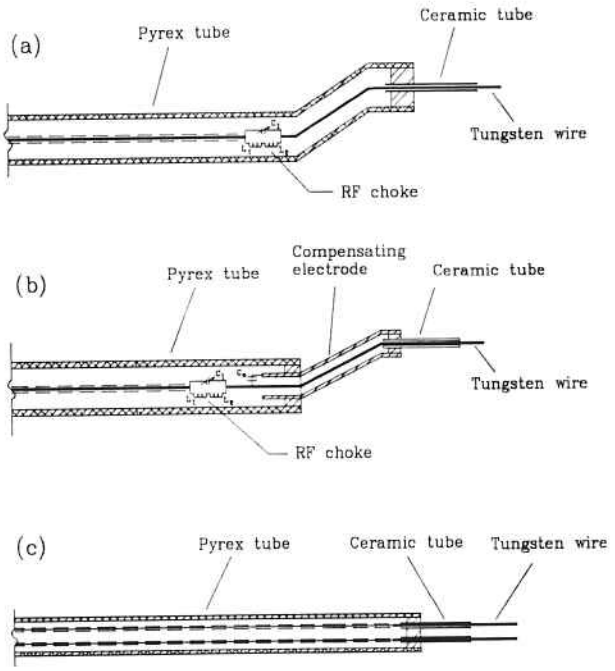

Fig. 1: Schematic view of the used Langmuir probes: (a) single probe with RF choke, (b) single probe with RF choke and compensating electrode, (c) double probe.

For one of the single probes, a 6.35 mm outer diameter 30 mm long stainless steel tube is placed near the probe tip and connected via a capacitor of 0.33 μF to the plasma end terminal of the RF choke. In this way the RF compensating electrode is accomplished,

which improves the characteristics of the RF choke. As both tips of the double probe are floating with respect of the discharge circuit, the use of RF choke is less necessary and, in this work, it is not used. The tungsten wires are directly connected to the core wires of two coaxial cables, which are protected by a 13 mm outer diameter, 30 cm long pyrex tube.

C. Langmuir probe data treatment

The collected current was measured over a resistor. The value of this resistor must be changeable as the collected current from the double probe is a factor of about 20 less than the current collected from the single probes. This voltage was digitalized by a 12 bit A/D converter and collected in computer tables as a function of the probe input voltage (also digitalized by a similar A/D converter). The data in these tables were then used to calculate the plasma density and the electron temperature. To increase the signal to noise level, a numerical Butterworth filter was used mainly when both cathode and coil were powered.

For the single probes, the electron temperature was determined from the part of the semi-logarithmic electron current versus probe bias voltage ($\ln(I_e)$ - V) curve, near the region of the floating potential. In this region, the collected electrons have higher energies and their trajectories are therefore less affected by the magnetic field, generated by the coil current [17]. The ion densities were determined using the method of Laframboise, since the assumptions of collisionless, stationary and non-magnetised plasma and absence of negative ions, are nearly satisfied [18].

When using the double probe, the electron temperature was determined by the logarithmic plot method as described in reference 12. The plasma density was obtained by adjusting the I-V curve using the method of Peterson and Talbot [13], in a similar way as Brockhaus et.al. did [14].

For each process analysis, three I-V curves were measured by the probes. Each curve was analysed and the plasma parameters determined, as described above. From these three measurement results, the average value and the standard deviation were determined.

III. Results and Discussion.

In order to be able to compare the results obtained by the three probes, we treat in this paper only the electron temperature and the plasma density, because the double probe does not determine the plasma and floating potentials.

Table I shows the average percentual standard deviation of the calculated results of the electron temperature and the plasma density. The double probe has a much better reproducibility than both single probes, mainly for the determination of the electron temperature. The 1 sigma value for the electron temperature determined by the single probes is nearly 10%, which means that the 3 sigma value, often used as the relative error value, is more than 25% ! This means that the uncertainty of these results is very high: the results of the electron temperatures must be evaluated with great caution. The double probe has a much better reproducibility: the three sigma value is only 6%, which is compatible with the reproducibility of most semiconductor processes.

Figure 2 shows the electron temperatures as a function of cathode and coil power for a constant pressure of 50 mTorr, obtained by the three different probes.

Both the double probe and the single probe with compensating electrode show the same trends: the electron temperature increases mainly with coil power in the 0 W to 50 W range. Once a certain level has been reached, the electron temperature levels off - it remains approximately constant in the 50 W to 150 W power range. The effect of the cathode power is less outspoken: when at least 50 W coil power is applied, the electron temperature increases with cathode power, mainly in the 0 W to 50 W region, after which it levels off, in a similar way as it does as a function of coil power. If no coil power

Table I - Standard deviation for electron temperature and plasma density measurements for argon plasma at p=50 mTorr

	σ_{Te} / Te (%)	σ_{Ni} / Ni (%)
probe with choke	8.8	6.1
probe with choke and electrode	9.2	6.0
double probe	2.0	3.2

is applied, the electron temperature decreases with cathode power, a phenomenon which will be commented in more detail later in this paper. The single probe with choke shows nearly no trend at all: however, one should not forget that the reproducibility of the obtained results is ± 27%. This means that the variations for the processes with 50 W or more cathode power are all within this uncertainty range. The only conclusion one may draw is that increasing the cathode power from 0 W to 50 W increases the electron temperature, compatible with the results of the other probes.

These results show that, when applying an inductively coupled plasma, a single probe with RF choke is not a good instrument to determine the electron temperature.

Comparison of the absolute values of the different probes, shows that the results obtained with the double probe are always lower than with the single probes. This is caused by the influence of the RF component on the probe sheath [8,17,19], which causes a slight distortion of the I-V curve, resulting in an overestimation of the electron temperature. As the double probe circuit floats together with the plasma, the measurement is much less influenced by this RF interference. Therefore, we believe that the values of the electron temperatures obtained by the double probe are more exact than the others. The double probe is the preferred instrument for measuring electron temperature when using inductively coupled plasmas.

Figure 3 shows the plasma densities as a function of both cathode and coil power, for a constant pressure of 50 mTorr. This figure shows that the general trends are similar for all the probes: the plasma densities increase very strongly with coil power, while the cathode power has little effect.

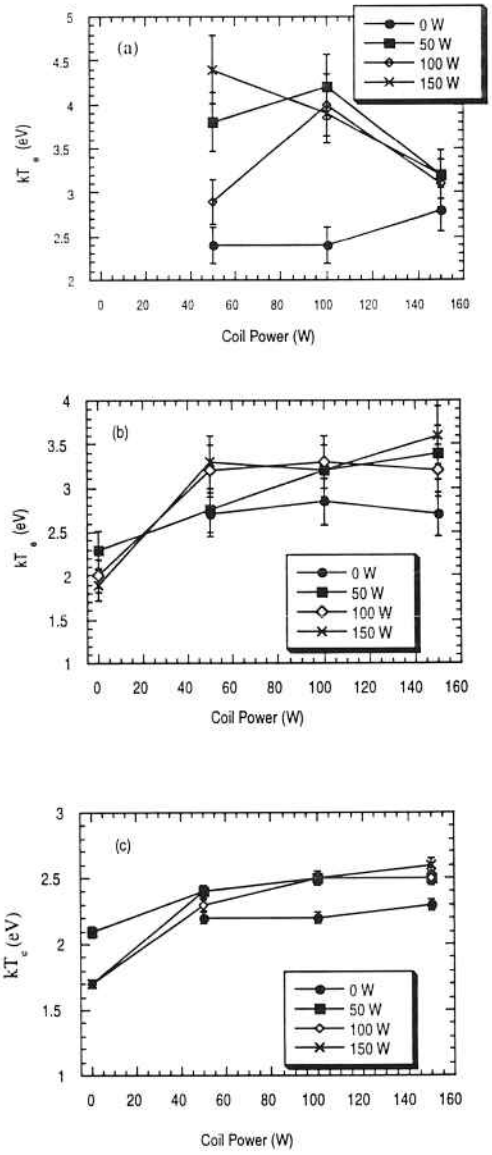

Fig. 2: Electron temperature as a function of coil and cathode (inset) power for 50 mTorr Ar plasmas measured with (a) single probe with choke, (b) single probe with choke and compensating electrode, (c) double probe. The error bars represent the 1 sigma value.

An unexpected result, confirmed by the three probe measurements, is the fact that for 100 W coil power process, the plasma density is highest when no cathode power is applied.

As the three probes obtained the same result, we believe that this behaviour is really happening, although we are not able to explain it.

The values obtained by the three methods are within a 10% error indicating that for these measurements, the three probes can be used.

This is compatible with the fact that the reproducibility for the determination of the plasma density is better than for the electron temperature, for both single probes, as shown in Table I. The highest plasma densities obtained in this system are of the order of 10^{12} electrons per cm^3. For the evaluated pressure level of 50 mTorr, this is a really high density plasma, showing that in this system, the power is coupled very efficiently into the plasma.

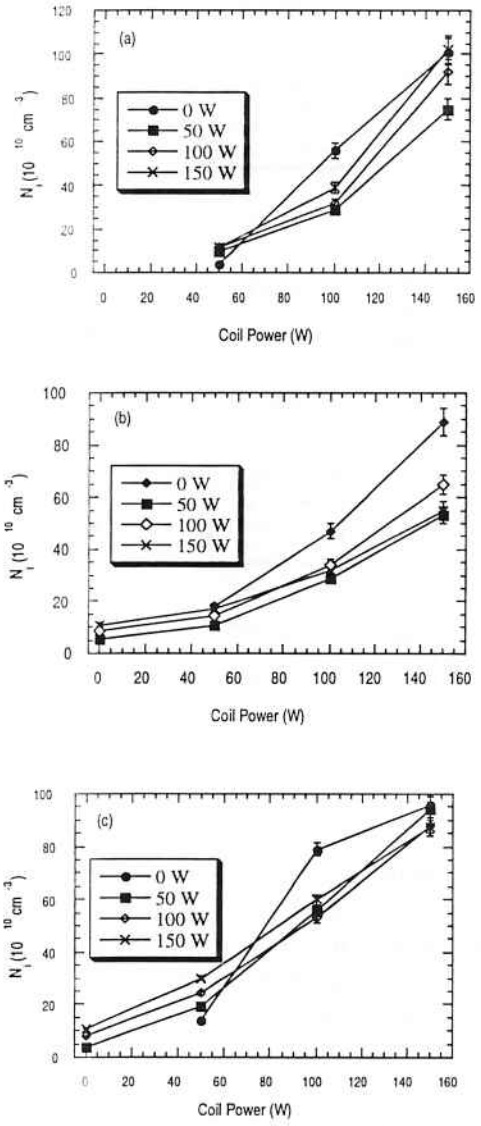

Fig. 3: Plasma density as a function of coil and cathode (inset) power for 50 mTorr Ar plasmas measured with (a) single probe with choke, (b) single probe with choke and compensating electrode, (c) double probe. The error bars represent the 1 sigma value.

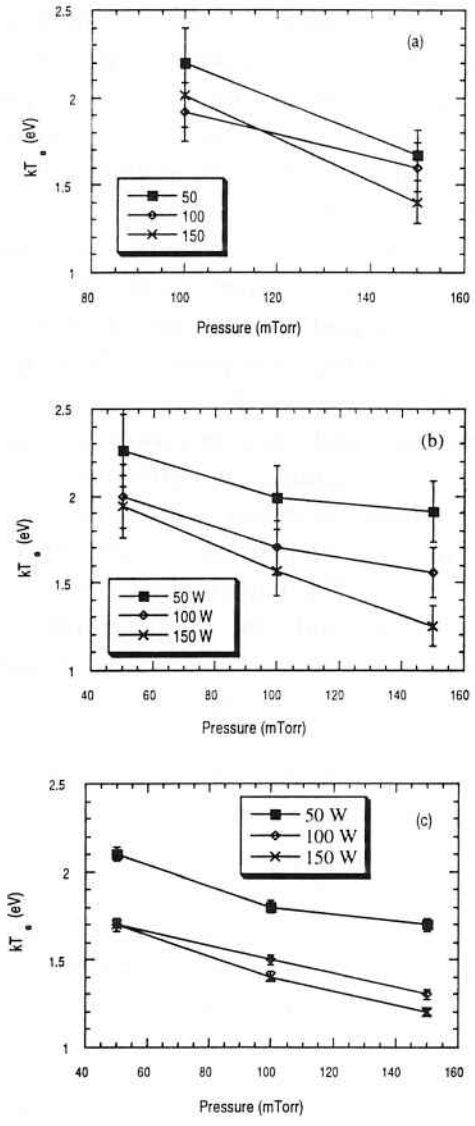

Fig. 4: Electron temperature as a function of argon pressure and cathode power, measured with (a) single probe with choke, (b) single probe with choke and compensating electrode, (c) double probe. The error bars represent the 1 sigma value.

Figure 4 shows the influence of the pressure and the cathode power , with no power to the coil, on the electron temperature, as measured with the three probes.

The influence of the pressure is very clear: increasing the pressure decreases the electron temperature. This is expected as the collision frequency increases with increasing pressure, resulting in less energy gain of the electrons between each collision. The electron temperature decreases with increasing cathode power for these processes without any coil power. This unexpected phenomenon will be commented later on. The values obtained with the double probe are once again lower than those obtained with the single probes, compatible with our explanations above.

Figure 5 shows the influence of the pressure and the cathode power, with no power applied to the coil, on the plasma density, as measured with the three probes. These results show that the plasma density increases with both pressure and cathode power, as can be expected: the number of collisions to form free electrons increases with pressure and more power is consumed to generate these free electrons. The values obtained from the double probe and the single probe with compensating electrode are very compatible, indicating that both probes are suitable to be used for this type of measurements. The single probe with only RF choke gives lower densities, by approximately a factor of 2. We are not able to explain this large difference for these results. Combining the results of the plasma densities with the electron temperatures, one can formulate an hypothesis why the electron temperature decreases with increasing cathode power. The main mechanism to generate a free electron is a collision between a highly energetic electron and a neutral, a molecule in general. After the collision, the new electron has a low energy and the original electron also decreases its energy. Therefore it is possible that for the higher cathode power (and zero coil power) levels, one obtains a plasma with more free electrons but with an average electron energy lower than for the plasmas with lower power levels..

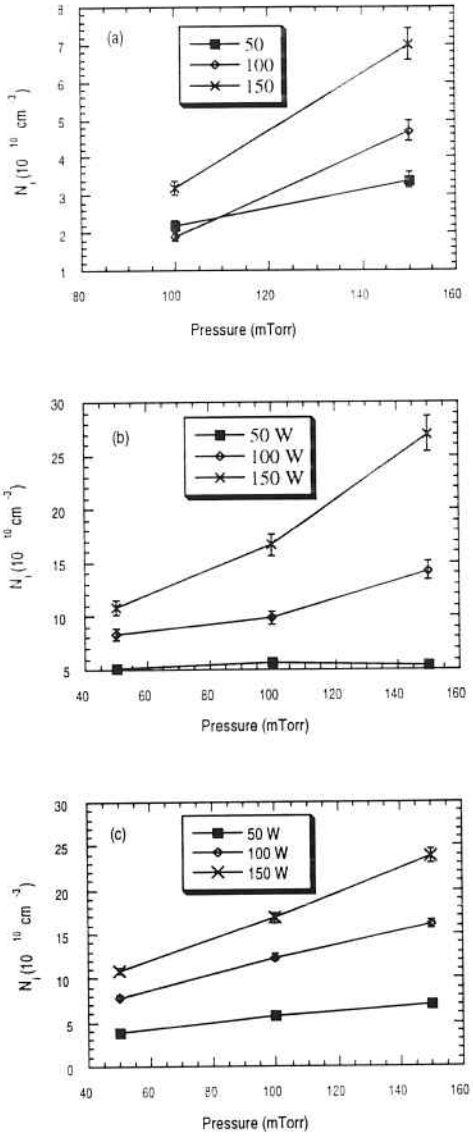

Fig. 5: Plasma density as a function of argon pressure and cathode power, measured with (a) single probe with choke, (b) single probe with choke and compensating electrode, (c) double probe. The error bars represent the 1 sigma value.

Conclusions

The electron temperature and the plasma density of several Inductively Coupled Plasmas were determined by three different types of Langmuir probes: a single probe with RF choke, a single probe with RF choke and compensating electrode and a double

probe. The precision of the measurements is good for the double probes, but relatively bad for the single probes, mainly for the determination of the electron temperatures. The accuracy of the determination of the electron temperature obtained with the double probe also is better than the one obtained with a single probe, as the RF component influences much less the double probe than the single probes. Therefore, to determine the electron temperature of Inductively Coupled Plasmas, a double probe should be used.

When determining the plasmas densities, the precision increases for the single probes and decreases slightly for the double probe, although it still is a factor of 2 better than for the single probes. Comparing the results obtained with the three probes, one may conclude that the accuracy obtained with the double probe and the single probe with compensating electrode is very good.

This paper also shows that for the investigated Inductively Coupled Plasmas, the electron temperature increase with coil power, mainly in the 0 W to 50 W range, and decreases with pressure, while the cathode power influences less this plasma parameter. The plasma density increases mainly with coil power, and to a lesser extent also with cathode power and pressure.

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