Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 697-699



# Advanced Langmuir Probes for RF Discharge Plasmas

Masaki Hirayama[1,2] and Tadahiro Ohmi[1]

[1]Department of Electronics, Faculty of Engineering, Tohoku University, Aza-Aoba, Aramaki, Aobaku, Sendai 980, Japan
[2]Laboratory for Microelectronics, Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980, Japan

Langmuir probes for 200 MHz discharge plasmas were developed. Two types of RF filters were used in the probe circuit to increase the probe-ground impedance. One is a $\lambda/4$ length semi-rigid coaxial cable circuitry shorted at one end, and the other is a LC filter. Even if the probe body is located physically close to a ground, sufficiently large probe-ground impedance can be kept. A mesh probe was developed to directly observe the waveforms of the instantaneous plasma potential by an oscilloscope. The oscillating plasma potential was measured for several kinds of gases.

## 1. INTRODUCTION

RF discharge plasmas have been widely used for several years and their significance are going to increase in the field of manufacturing processes of integrated circuits. In order to achieve high performance plasma processing, the several plasma parameters must be entirely under the control and therefore, must be precisely measured. The use of Langmuir probe is the oldest and experimentally simplest technique. While the traditional Langmuir probe is applicable to DC discharge plasmas, these use in RF discharge plasmas have the fatal problems of RF interference.

The perturbing effects of RF interference have been reported in numerous papers.[1-4] In RF discharge plasmas, the plasma potential fluctuates with time at the plasma excitation frequency, causing the probe potential to also fluctuate. The amplitude and phase of the probe potential are generally unknown and different from those of the plasma potential. They are influenced by not only the fluctuation of the plasma potential but also the impedance between the probe and the ground. Since the instantaneous probe current is a function of the voltage between the plasma and probe, it also fluctuates with time. Thus the time-averaged I-V characteristics of the traditional Langmuir probe are distorted by the non-linear nature of the probe sheath. In order to suppress the RF interference, the probe potential must be forced to completely follow the instantaneous plasma potential.

A general approach for suppressing the RF interference is to enlarge the ratio of the probe-ground impedance to the probe sheath impedance. That is to say, the probe-ground impedance should be increased and the probe sheath impedance should be decreased. The probe sheath impedance can be reduced by shunting the probe sheath with an large electrode[5-9] or by using an emissive probe.[11] The use of RF (LC) filters is general for increasing the probe-ground impedance. These filters are tuned for being maximized at the fundamental frequency of the RF discharge excitation and in some cases at the second harmonic frequency also. Godyak et al. developed an excellent Langmuir probe for 13.56MHz.[9] They minimized the RF coupling between the probe and ground by inserting three microminiature LC filters in series into a glass tube and enlarged the sheath capacitance by using a loop probe as a reference probe.

The chain of the LC filters has usually sufficiently large impedance as compared with the probe sheath impedance. In case that the probe body is located physically close to the ground (chamber wall etc.), the probe-ground impedance intolerably decreases with a stray capacitance between the lead wire which connects the probe tip and the LC filters and the ground ($C_p$). It is desirable to locate the LC filters as close as possible to the probe tip to decrease $C_p$. However the glass tube, the outside diameter of which should be larger than 7 mm, must disturb the plasma.

In this paper, we describe the probe to work in 200 MHz discharges. Even if the probe body is located physically close to the ground, sufficiently large probe-ground impedance can be kept.

The RF components of the oscillating plasma potential are also important parameters for the plasma processing. Moreover, the amplitude of each order harmonics is essential so as to evaluate the reliability of the probe measurement. A mesh probe was developed to directly observe the waveforms of the instantaneous plasma potential by an oscilloscope. The oscillating plasma potential was measured for several kinds of gases.

## 2. MESH PROBE

Figure 1 shows the mesh probe developed to observe the waveforms of the plasma potential. For forcing the probe potential to follow the plasma potential, the probe sheath impedance should be decreased, and the probe–ground impedance should be increased.

The probe electrode is a 14 mm × 18 mm aluminum mesh composed by 200 μm diameter wires arranged at 4 mm intervals. The surface area is relatively large for decreasing the probe sheath impedance. A semi-rigid coaxial cable (2.19 mm in diameter and 296 mm in length) forms the probe body. A 2 GHz bandwidth digitizing oscilloscope is connected to one end of the semi-rigid coaxial cable via a coaxial cable (634 mm in length) and a feedthrough. In order to increase the probe impedance, a 2 KΩ resistor is connected between the mesh electrode and the semi-rigid coaxial cable. The characteristic impedance of the semi-rigid coaxial cable, feed through, and coaxial cable is 50Ω. The input impedance of oscilloscope is also 50 Ω. Therefore, the probe circuit functions as a 50:2050 = 1:41 resistive voltage divider. However the resistor has intolerable parasitic capacitance (≈ 0.07 pF) and inductance. The frequency dependencies of the division ratio and the phase were carefully calibrated. The measured data of the oscillating plasma potential were transferred to the computer, and 512 points FFT (fast Fourier transform) were carried out. After the rectifications for the amplitudes and the phases, IFFT (inverse fast Fourier transform) were carried out.

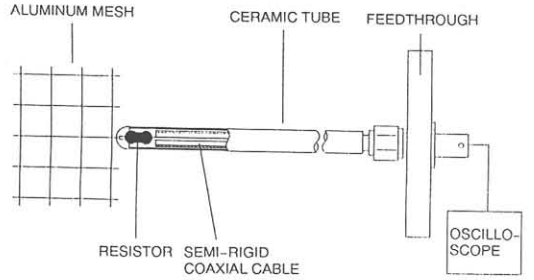


Fig.1 Schematic diagram of the mesh probe

Figure 2(a) and (b) show waveforms of the plasma potential measured by the mesh probe in a conventional parallel plate plasma excitation equipment. In Ar plasma, the waveform involves not only fundamental component but significant large higher harmonics as well. The higher harmonics are caused by non-linear characteristics of the sheaths in front of the excitation and grounded electrodes. On the other hand, in $NF_3$ plasma, the waveform looks like just sinusoidal. This is because the $NF_3$ plasma has only a few electrons relative to negative ions.

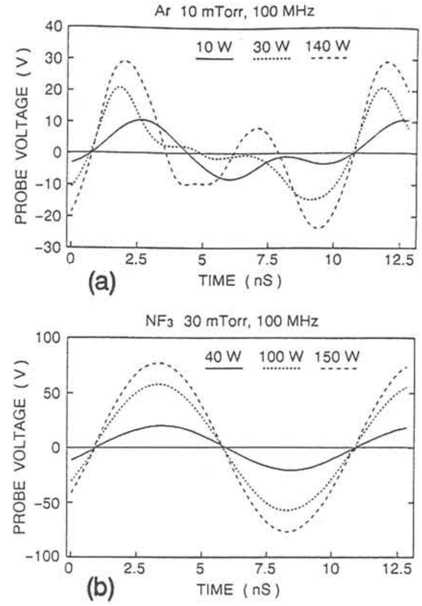


Fig.2 Waveforms of the plasma potential measured by the mesh probe for Ar(a) and $NF_3$(b) discharges.

## 3. LANGMUIR PROBE WITH λ/4 FILTER

Figure 3 shows schematic diagram of the Langmuir probe for 200 MHz RF discharges. Figure 4 shows the equivalent circuit of it. A 3 mm length of 100 μm diameter tungsten wire forms the probe tip. A ceramic tube around the probe tip prevents electrical contact between the probe tip and any conductive sputtered material on the probe body. An aluminum tube is connected to the tungsten wire via a 1000 pF capacitor to decrease the probe sheath impedance.

For enhancing the probe–ground impedance, not only the LC filters but also the RF filter of a λ/4 length semi-rigid coaxial cable circuitry shorted at one end is connected between the probe tip and the LC filters. To achieve large LC filter impedance, we employed microminiature inductors with a self-resonance frequency of 200 MHz and 400 MHz. The semi-rigid coaxial cable (2.19 mm in diameter and 154 mm in length) is terminated with four 1000 pF tip capacitors.

The typical probe sheath impedance is about 100 Ω at 200 MHz. The probe–ground impedance must be larger than about 1.1 KΩ at the fundamental frequency in order to measure the plasma potential within an accuracy of 0.1V. The chain of LC filters has sufficiently large impedance of the order of 20 KΩ for the fundamental frequency. However the stray capacitance $C_p$ intolerably decreases the probe–ground impedance. Therefore the λ/4 filter (6.8 KΩ for the fundamental frequency) is connected between the probe tip and the LC filters to increase the probe–ground impedance.

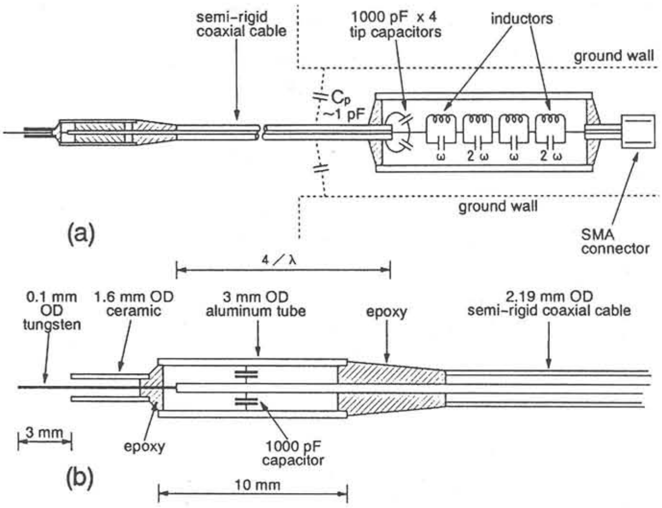


Fig.3 A schematic diagram of the Langmuir probe with the λ/4 filter:(a)the entire probe, and (b) details of the probe tip area.

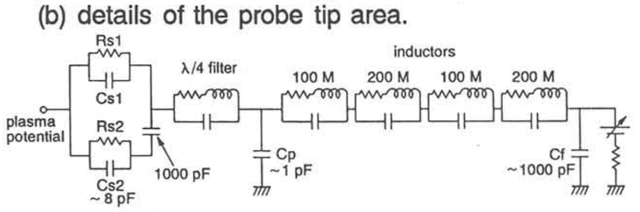


Fig.4 Equivalent circuit for the sheath, probe, and measurement system.

While the λ/4 filter has large impedance for odd order harmonics, it has only small impedance for even order harmonics. Therefore, this probe is applicable to the plasmas that have little higher order harmonics in the oscillation of the plasma potential such as $NF_3$ and $SF_6$ plasmas.

On the other hand, the probe shown in Fig. 5 is applicable to the plasmas that involve large higher harmonics as well such as Ar and $H_2$ plasmas. The probe body is formed by λ/4 and λ/8 filters. This probe has large probe–ground impedances for the fundamental frequency(ω), 2ω, 3ω, 5ω, 7ω,⋯.

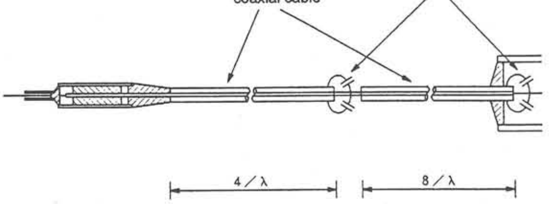


Fig.5 A schematic diagram of the Langmuir probe with the λ/4 and λ/8 filters.

Figure 6 shows the difference of the I–V characteristics between the conventional Langmuir probe, which was not designed for measurements in RF discharges, and the advanced one shown in Fig. 5 in 200 MHz Ar discharge. The evaluated value of the plasma potential from the IV curve of the conventional Langmuir probe is about 24 V smaller than that of the advanced one.

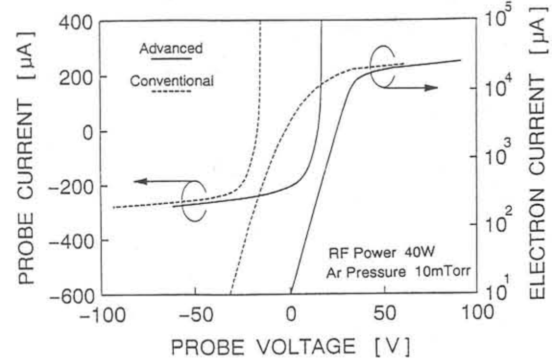


Fig.6 *I–V* characteristics of the conventional (----) and advanced (—) Langmuir probe in Ar discharges.

## 4. CONCLUSIONS

Mesh probe was developed to directly observe the waveforms of the instantaneous plasma potential by an oscilloscope. The oscillating plasma potential was measured for several kinds of gases. While Ar plasmas have large higher order harmonics, $NF_3$ plasmas have little higher order harmonics.

A Langmuir probe for 200 MHz discharges was developed. The LC filters have sufficiently large impedance of the order of 20 KΩ. However the probe–ground impedance decreases with the stray capacitance between the probe body and the ground. Therefore we used a λ/4 or λ/8 filter between the probe tip and the LC filters. Even if the probe body is located physically close to the ground, sufficiently large probe–ground impedance can be kept.

## ACKNOWLEDGMENT

This study was carried out at the Superclean Room of the Laboratory for Microelectronics, Research Institute of Electrical Communication, Tohoku University.

## REFERENCES

1) A. Garscadden and K. G. Emeleus, Proc. Phys. Soc. 79(1962) 535.
2) A. Boschi and F. Magisrelli, Nuovo Cimento 24(1963) 487.
3) Y. M. Kagan and V. I. Perel, Sov. Phys. Usp. 6(1964) 767.
4) E. Eser, R. E. Ogilvie, and K. A. Taylor, J. Vac. Sci. Technol. 15(1978) 199.
5) T. I. Cox, V. G. I. Deschmukh, D. A. Hope, N. St. J. Braithwaite, and N. M. P. Benjamin, J. Phys. D: Appl. Phys. 20(1987) 820.
6) A. P. Paranjpe, J. P. MacVittie, and S. S. Self, J. Appl. Phys. 67(1990) 6718.
7) V. A. Godyak and R. B. Piejak, J. Appl. Phys. 68(1990) 3157.
8) G. Dilecce, M. Capitelli, and S. De benedictis, J. Appl. Phys. 69(1991) 121.
9) V. A. Godyak, R. B. Piejak, and B. M. Alexandrovich, Plasma Sources Sci. Technol. 1(1992) 36.
10) N. Hershkowitz and M. H. Cho, J. Vac. Sci. Technol. A6(1988) 2054.
11) E. R. Mosburg, R. C. Kerns, and J. R. Abelson, J. Appl. Phys. 54(1983) 4916.