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Electron Density Measurements with a Frequency Shift Probe
周波数プローブによる電子密度計測

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This paper reports on a frequency shift (FS) probe applicable to electron density measurements in materials processing plasmas. Resonance frequencies measured in vacuum and plasma directly gave electron density according to a formula. The FS probe could be extended for electron temperature measurements in addition to the density measurements. Modification of probe configuration allowed miniaturization and structure simplification of the probe.

1. Introduction

In general, plasmas have been widely used in manufacturing various devices as well as surface modification in material processing. In an etching process with a high density plasma for an LSI device, improvement of processing repeatability is one of key issues for achievement of precise process control. For this requirement, it is necessary to develop a monitoring tool of the processing plasma to understand phenomena in the plasma and to control the plasma

A Hair-type microwave resonator probe has been reported for electron density measurements[1], and the probes called as hairpin probe[2] have been applied to materials processing plasmas. Since such a probe configuration may disturbs the plasma, we have recently developed a plane-type microwave resonator probe called as Frequency Shift (FS) probe[3] so as to minimize the disturbance to the plasma, and various efforts have been made to improve and extend the probe performance.

In this paper, the FS probe is briefly reviewed, and the recent technology development of the probe is reported, especially for extension to electron temperature measurements and miniaturization of the probe.

2. FS Probe for Electron Density Measurements

The plane-type FS probe enables us to measure an electron density from variation of resonance frequency of the probe head caused by the plasma, and the density measurement is possible under minimum disturbance to the plasma. Furthermore, the probe is applicable to reactive plasmas such as fluorocarbon plasmas since the deposited polymer has little effect on the resonance frequency.

The FS probe composed of plane metal plate with a L-shaped slot antenna which works as a microwave resonator. The resonator is activated by microwave magnetic field supplied with a small loop coupler near a closed end of the slot. Resonance occurs under the condition that the slot length coincides with a quarter wavelength of microwave propagating along the slot, and its resonance frequency was measured with a network analyzer. When the resonance frequency of the FS probe varies from f_0 (GHz) to f_r (GHz) by producing the plasma, the electron density of n_e, (10^{10} cm^{-3}) is given by

$$n_e=(f_r^2 - f_0^2)/0.81 \qquad (1).$$

Note that eq. (1) was derived under no consideration of a sheath formed around the probe. The sheath formation causes underestimation of the formula-derived electron density due to suppression of variation in effective permittivity, however the density underestimation is improved by enlarging a width of the slot[4,5].

3. Extension of FS Probe for Electron Temperature Measurements

When the resonance frequency of the FS probe depends on the sheath, it means that the resonance frequency is given as a function of electron density n_e and electron temperature T_e because thickness of the sheath is proportional to the Debye length. Then, for a measured resonance frequency, there is a specified relationship between n_e and T_e which depends on probe configuration. Therefore, if we measure two resonance frequencies of different two FS probes which have different sheath dependences, an unique solution of n_e and T_e can be obtained.

In our experiments, such a sheath dependence of the resonance frequency was controlled by width of the slot as described in the previous chapter. The control of the sheath dependence is also possible with dielectric plates covering the whole of the slot[6]. Furthermore, two L-shaped slots installed in one FS probe resonate the probe at two different frequencies corresponding to each slot length. Such a multi-resonant probe configuration allows the n_e and T_e measurements with single FS probe whose each slot is covered with different thick quartz. Figure 1 shows an example of measurement results in 2-mTorr 13.56-MHz inductively-coupled Ar plasma by the multi-resonant FS probes with quartz plates of 0.1 mm and 1 mm. . The thick quartz plate gives a decrease in the probe resonance frequency, and suppresses the sheath dependence because the thick quartz plate reduces influences of the sheath on the effective permittivity around the probe. Therefore the different thick quartz plate leads to different sheath dependence enabling the n_e and T_e measurements. The electron density increases with the discharge power similarly to typical features of such a plasma. The electron temperature decreases with an increase in the discharge power probably due to transition from capacitive mode to inductive mode. These values fairly agree with the density measured by a surface wave probe and the temperature measured by a Langmuir probe.

4. Curling Probe –Miniaturization of FS Probe–

In order to make minimization of the conventional FS probe, we have developed a new type of the FS probe called as "Curling Probe" whose size reduce with the following two significant technology as shown in Fig. 2 [7]: modification of the resonator configuration (a) from the L-shaped slot antenna to a spiral slot antenna and (b) from magnetically-coupled excitation to electrically-coupled excitation. The former modification enables miniaturization of the resonator size by half at present, and further miniaturization will be possible by shrinkage of the slot width. For the latter modification, a hole with a diameter larger than the slot width is located in the center of the spiral slot, and a monopole antenna of a microwave-applied rod conductor is located in the hole instead of the small loop coupler. Then a microwave electric field in the hole excites the spiral resonator. Such a configuration significantly simplifies the probe structure, especially for the exciter. Even after the probe modification, the probe clearly resonates and electron density n_e is obtained from Eq. (1) with some corrections derived by comparison with simulation results and consideration of effective permittivity of the heterogeneous medium including inner cylindrical quartz column. In addition to the volume wave

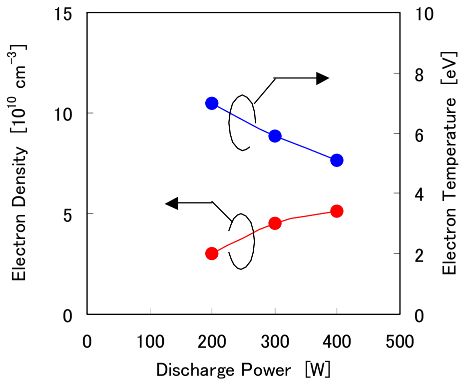

Fig. 1 Power dependence of n_e and T_e measured by multi-resonant FS probe

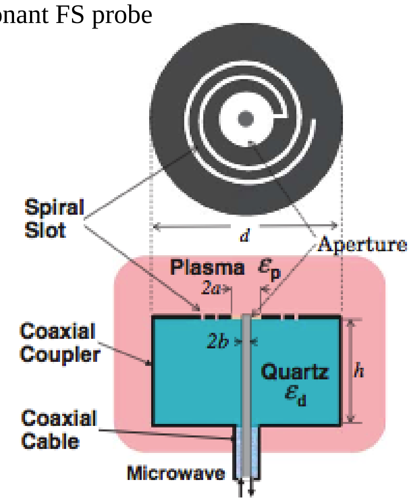

Fig. 2 Structure of Curling Probe

resonance caused by the wave propagating along the slot, surface wave resonance at the boundary at the quartz surface of the center hole.

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