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Inductively Coupled RF Discharges Using Helical Antennas†

Yuichi SETSUHARA*, Kunitsugu UEDA**, Jindrich MUSIL***, Tomio ARIYASU**** and Shoji MIYAKE*****

Abstract

Presented in this paper are experimental investigations on the radio-frequency (rf) discharges at 13.56 MHz using helical antennas with different pitches and azimuthal mode numbers. Obvious transition of the discharge has been observed in the plasmas produced using the antenna with an azimuthal mode number of m=±1 in presence of external mirror field > 500 G with rf power > 350 W. The transition of the discharge mode has been accompanied with the significant decrease of the rf circuit current indicating the drastic change of the plasma loading due to the increase in the plasma density.

KEY WORDS: (Inductively Coupled Radio-Frequency Discharge) (Helical Antenna) (Processing Plasma)

1. Introduction

Recently requirements for high-rate and low-pressure processing in microelectronic device fabrication has motivated the development of high-density (10^{12} - 10^{13} cm^{-3}) plasmas generated in low-pressure (≤ 1 Pa) region for materials processing. Inductively coupled radio-frequency (rf) discharges in a low pressure range (≤ 1Pa) may meet future alternatives to conventionally available processing plasmas such as electron cyclotron resonance plasmas and capacitively coupled rf plasmas.

For efficiently coupling the rf power into plasmas generated in external magnetic field, various types of antennas based on slow wave structures have been developed in the frequency region of helicon waves; *e.g.*, helical antennas [1], Boswell type[2], and Nagoya type [3]. Chen has presented the plasma production mechanism based on Landau damping of the helicon waves [4]. On the other hand, the early works on inductively coupled rf discharges in absence of external magnetic field using helical antennas lead to the conclusion that a transition from the E discharge (electrostatic origin) to the H discharge (electromagnetic origin) produces high-density plasmas of the order of 10^{12} cm^{-3}.[5-7] Nevertheless the mechanisms for obtaining the helicon plasmas and the H-discharge plasmas are explained in different manner, both of the high-density rf plasmas are identical from the view point that they are generated in a low pressure range using antennas with helical windings

The present work, therefore, is motivated to investigate the production mechanism of inductively coupled rf discharges using helical antennas with various pitches and azimuthal mode numbers in presence or in absence of the external magnetic field.

2. Experimental

The experimental setup for the rf plasma generation is schematically shown in **Fig. 1**. The discharge tube surrounded with a helical antenna was made of quartz, 190 mm in length and 36 mm in internal diameter, and was connected to the stainless steel chamber which was pumped with a 150-l/s turbomolecular pump. The base pressure was 2.7×10^{-4} Pa and the rf discharge was produced in argon pressures of 10^{-3}-10^{0} Pa. The helical antenna was coupled to the rf power generator operating at 13.56 MHz via a matching network. The rf power was varied between 50 and 500 W, and was measured at the output of the rf generator when an optimum matching condition was achieved; *i.e.* zero reflected power to the generator.

The discharge tube was surrounded with a electromagnetic coil (coil I) to investigate the plasma property in presence of external magnetic field. Another magnetic coil (coil II) at a central position of the cylindrical sputtering target (80 mm long and 60 mm in internal

† Received on Aug. 3, 1993
* Research Associate
** Graduate Student of Osaka Univ.
*** Professor, Institute of Physics, Czech Republic
**** Professor, Kansai University
***** Professor

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diameter) is located for applying this experimental setup to investigations on rf-plasma-assisted DC sputtering deposition (not presented in this paper). The mirror magnetic field with a mirror ratio of 1.05 was generated using both coils. Two types of helical antennas schematically shown in **Fig. 2** were used for the rf plasma generation; (A) a 19-turn coil with a 10-mm pitch, and (B) 190-mm long double half-wavelength antennas with m=±1, where m is the azimuthal mode number.

The electron density was measured using a floating double probe located at the center of the sputtering target; *i.e.* 100 mm from an end of the helical antenna facing to the target. The rf current supplied to the antenna was also measured using a wide band current transformer to investigate the correlation between the plasma loading and the rf power circuit parameter.

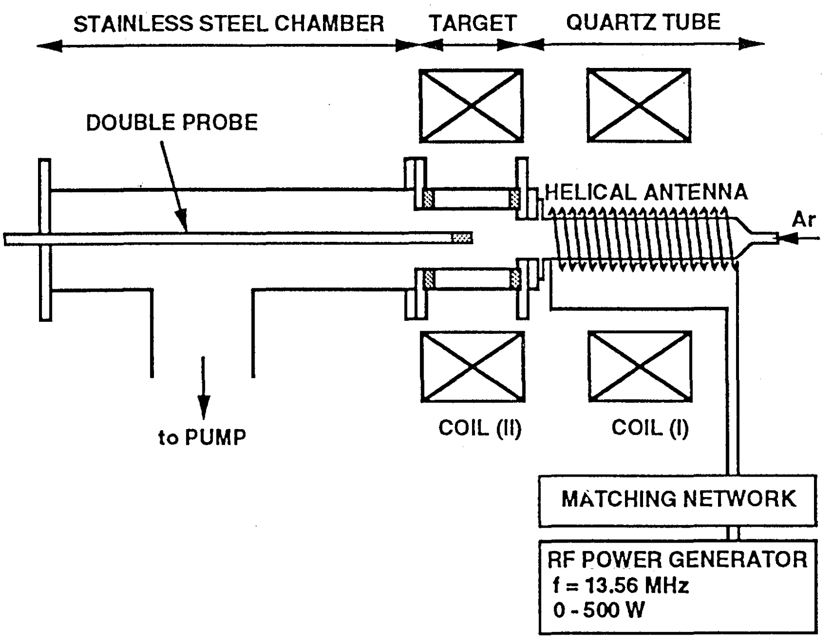

Fig. 1. Schematic of the experimental apparatus.

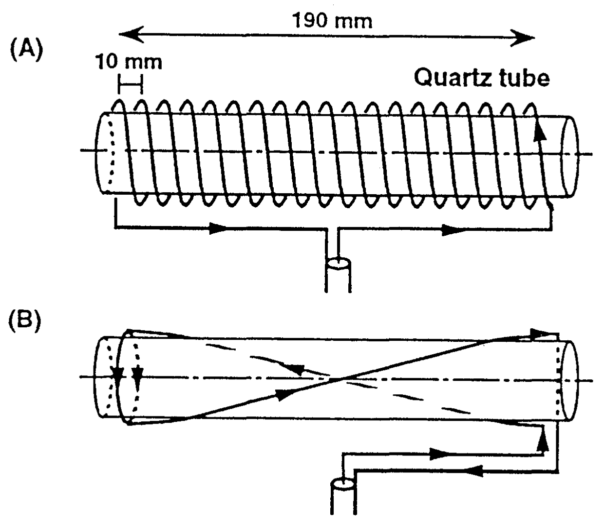

Fig. 2. Antenna configurations.

3. Results and discussion

Figures 3 and 4 show the variation of density with magnetic fields at an argon pressure of 0.1 Pa with 400-W rf power for antennas (A) and (B), respectively. The divergent field configuration was prepared using the magnetic coil (I) illustrated in Fig. 1, and the magnetic fields plotted in Figs. 3 and 4 were measured at the center of the discharge tube. For both antennas, the density was higher in the mirror field configuration than in the divergent. Moreover, explicitly in case for the m=±1 antenna (B) in the mirror field configuration, significant increase in density with increasing magnetic field was observed and appearance of the discharge was drastically changed at magnetic fields >500 G into a bright blue core. Similar appearance of the plasmas has been reported by both Boswell and Shoji that the bright core is due to the Ar II line emission from fully ionized plasma. The magnetic field produced with the coil (II) may improve the radial confinement of the plasma at the probe position diffusing from the discharge tube, however, the drastic change of discharge mode for antenna (B) in the mirror field configuration may be concerned with wave propagation condition and/or end-wall condition.

The changes in the appearance of the plasmas for antennas (A) and (B) are shown illustratively in **Figs. 5** and **6**, respectively, together with the variation of density with various rf power at a 0.1-Pa argon pressure in the 1260-G mirror field. For m=0 antenna (A), at low excitation glow discharge extending throughout the discharge tube was observed. With increasing rf power a localized blue plasma embedded in the glow gradually appeared, however, even with high excitation >600 W the appearance of the plasma was essentially the same and only the brightness of the core region increased with increasing rf power. For m=±1 antenna (B), at low rf power < 200 W glow discharge extending throughout the discharge tube was observed, however, above about 300-W rf power the discharge mode was drastically changed into a bright blue core, and with slightly smaller rf power 200-300 W a localized blue plasma embedded in the glow was observed. Furthermore, at the onset of the bright core plasma the density increased by more than a factor of 7.

For investigation of the effects of the magnetic field configuration on the plasma mode transition for antenna (B), we performed a series of experiments at a 0.14-Pa argon pressure with a 400-W rf power where the ratio of the magnetic field strength at the probe to that at the antenna was varied from 0 to 1 while the magnetic field strength at the antenna was kept nearly constant at 1100 G. **Figure 7** shows the variation of the electron density as a function of the ratio of the magnetic field strength at the probe to that at the antenna. As a result, the mode

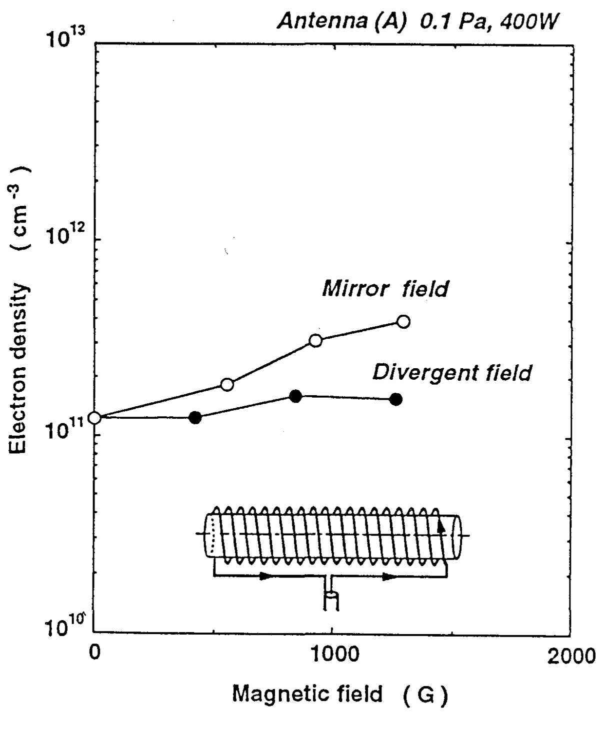

Fig.3. Density vs magnetic field for antenna (A) in mirror and divergent fields.

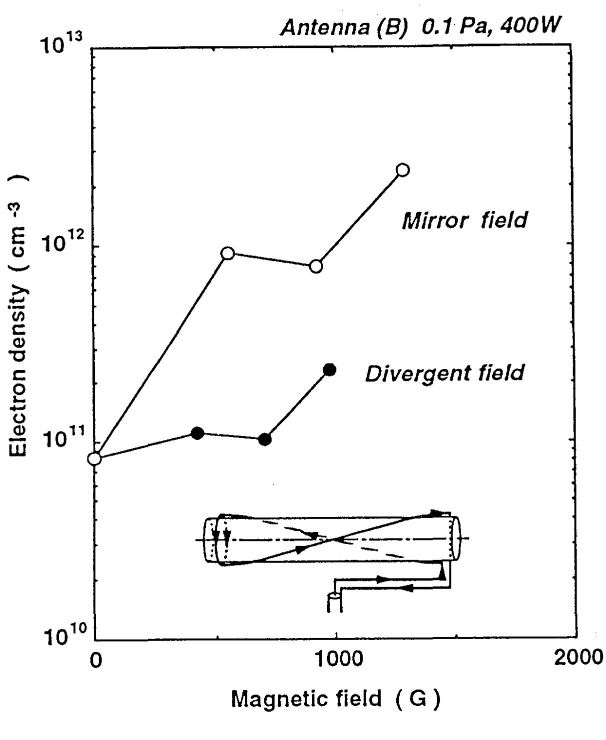

Fig. 4. Density vs magnetic field for antenna (B) in mirror and divergent fields.

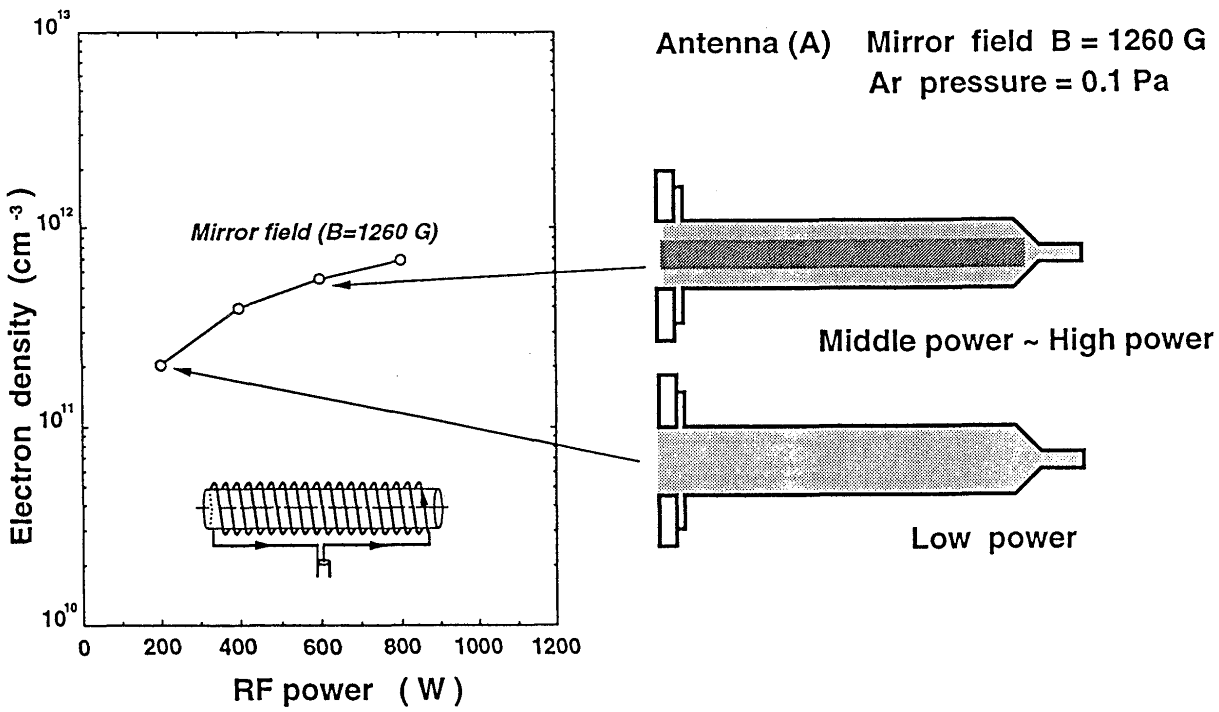

Fig. 5. Density vs magnetic field for antenna (A) in mirror field.

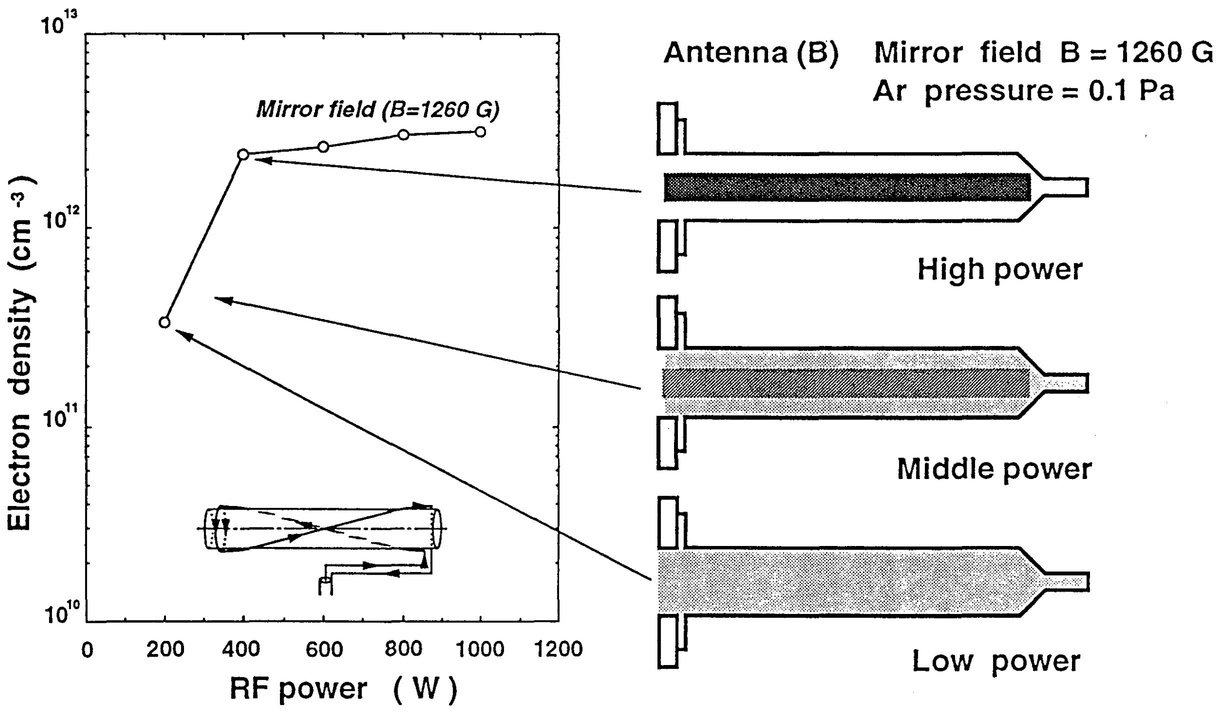

Fig. 6. Density vs magnetic field for antenna (B) in mirror field.

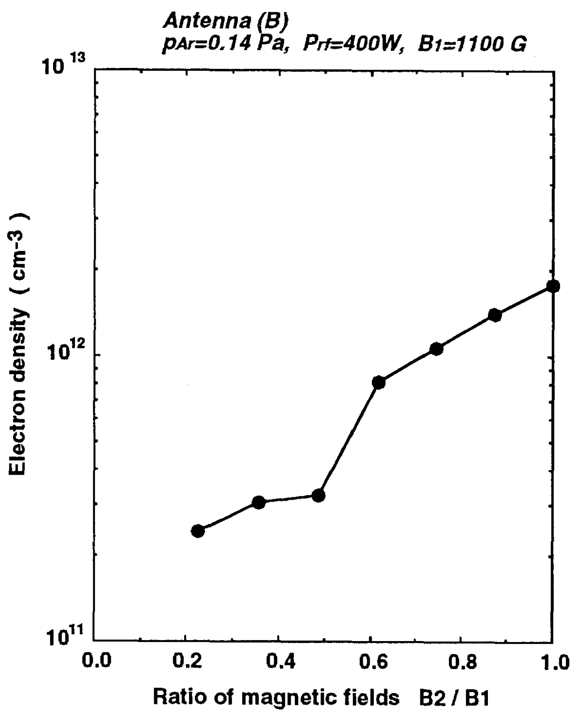

Fig.7. Variation of the electron density (N_e) as a function of the ratio of the magnetic field strength at the probe to that at the antenna (B_2/B_1).

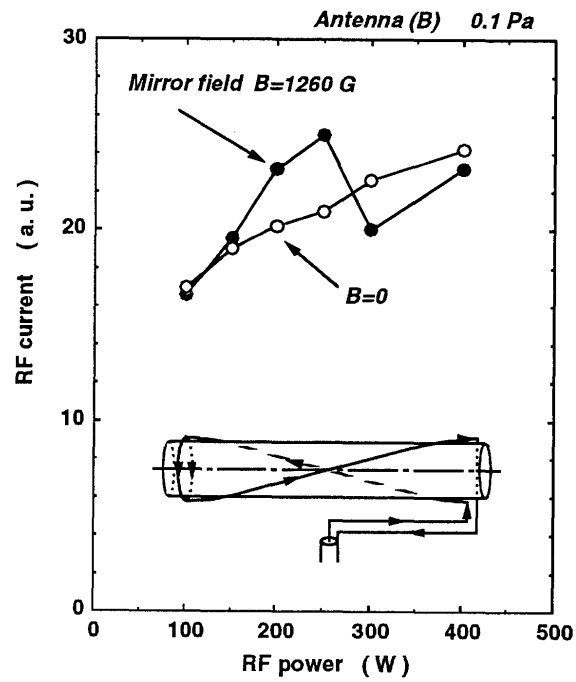

Fig.8. The rf current supplied to the antenna (B) as a function of rf power.

transition was observed when the ratio exceeded approximately 0.5. This result may indicate that the onset of the mode transition requires a certain length of the plasma region exceeding the critical magnetic field strength in order to match the slow wave structure of the antenna with the wave length of the rf radiation in the plasma. This consideration, however, needs further investigations on the wave propagation measurements.

The change of the rf resonance circuit current at the transition of the discharge for the antenna (B) was also observed by measuring the rf current supplied to the antenna. **Figure 8** shows the rf current as a function of rf power. The current was measured in the experiment where the plasmas were generated at a 0.1-Pa argon pressure in a 1260-G mirror field and in absence of the external magnetic field. In absence of the external magnetic field the rf current increased almost linearly with increasing rf power because the increase in the loading of the antenna was very small due to the less significant increase in plasma density (<10 % in 100-600 W rf power). On the other hand, in the mirror field the rf current dropped significantly at the transition of the discharge due to the significant increase in the loading. Furthermore, the reason for less significant increase in density with increasing rf power in >400-W region (see Fig. 6) can be due to the reduction of the quality factor of the rf resonance circuit with increasing loading of the antenna.

4. Summary

Significant increase in density with increasing magnetic field and rf power is observed at the onset of the bright localized plasma explicitly in case for the m=±1 antenna in mirror magnetic field configuration. The transition of the discharge mode results in the significant decrease of the rf circuit current indicating the drastic increase of the plasma loading due to the considerable increase in the plasma density.

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