Dynamics of E-H Mode Transition in High–Pressure RF Inductively Coupled Plasmas

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***Abstract*—Capacitive (E) to inductive (H) mode transition dynamics in radio frequency (RF) argon inductively coupled plasmas (ICPs) with up to atmospheric pressure is studied experimentally. High-speed imaging (13500 fps) is performed to investigate the transition dynamics, and to estimate the characteristic time scale of E-H mode transition. The effect of diatomic gas inclusion (here N_2) on the E-H mode transition dynamics is also discussed.**

***Index Terms*—E-H mode transition dynamics, high-speed imaging, inductively coupled plasma.**

RECENTLY, attention has been renewed on the investigation of E-H mode transition dynamics, and many theoretical and experimental works have been done, but mainly for low-pressure (mtorr range) discharges [1]–[3], because of simple and easy ignition, generation, and diagnostics of low-pressure ICPs. But, the starting of atmospheric plasma torches is hard, and a high-voltage initiation is usually required [4]. In this paper, we investigate the mode transition dynamics of high-pressure (up to 1 atm) RF (1.2 MHz) ICPs to understand the difference of E-H mode transition dynamics between high- and low-pressure ICPs [1]–[3], and estimate the transition time using high-speed imaging. We also discuss the effect of N_2 gas inclusion on the transition dynamics, and comment on the easy ignition procedure of high-pressure, and diatomic mixed-gas plasmas.

The plasmas were sustained in a cylindrical Pyrex glass chamber with an internal diameter of 70 mm and length of 200 mm. A static induction transistor (SIT) inverter power source with a maximum power rating of 20 kW and frequency range of 0.5–1.5 MHz is employed for plasma generation. The Ar and Ar-N_2 gas pressure is maintained at 100 and 50 kPa, respectively. An L-C matching network is employed to optimize the power coupling. The side-view plasma images were take by the "FASTCAM *ultima* SE" high-speed camera, with a frame speed of 13 500 fps, setting perpendicularly to the discharge axis. The top-view images were taken with the same speed by setting a mirror 45° inclined to that of the top flange of the discharge chamber to understand the dynamics clearly.

The high-speed images of Ar plasma in atmospheric pressure are depicted in Fig. 1. The instantaneous power, calculated from the time varying RF intput voltage and current, are shown beneath the respective images. The time behaviors of the formation of E discharge, E-H mode transition and the development of H discharge are observed clearly from the images. The characteristic mode transition time, which corresponds to the duration of E discharge, is estimated about 500 μs in the present case.

The physical mechanisms of E-H mode transition dynamics can briefly be described as follows: at the initial phase of RF breakdown, strong axial electrostatic field (100 kV/m in the present case) gives enough energy to the electrons for increased ionization. The newly formed electrons together with the primary ones repeat this process and produce more free electrons. Therefore, cumulative ionizations take place along the direction of the electrostatic field, thereby developing the multiple streamerlike discharge paths (E discharge) at the top and very close to the inner surface of the discharge chamber [Fig. 1(a) and (b)].

The induced electric field, on the other hand, promotes diffusive and/or convective drift motion for electrons in the azimuthal direction. These energetic electrons produce ionization and make electrically conducting bridges between the neighboring streamers by the diffusive and/or convective process, and transform the streamers into the ring-shaped azimuthal discharge (H discharge) [Fig. 1(c)]. In the primary stage of H mode, still some streamers exist even after transforming it into the ring-shaped plasma, as shown in Fig. 1(c). But these streamers disappear as soon as the azimuthal flux is induced by the electrically conductive ring, thereby flowing the azimuthal RF current and injecting the Joule power into the ring-shaped plasma to form the volumetric H discharge [Fig. 1(d)–(f)] due to Joule heating.

Fig. 2 shows the comparison of E-H transition dynamics between Ar and Ar-N_2 (10% N_2) plasmas at a pressure of 50 kPa. The starting of E discharge, formation of ring shaped plasma, and hence the mode transition and development of H discharge occurs delayed in the case of Ar-N_2 plasma than pure Ar plasma, because plasma losses become high by adding N_2 on pure Ar plasma due to high-power consumption for the dissociation of N_2 molecules, and due to the strong diffusive and/or convective energy loss with high enthalpy nitrogen gas content. Therefore, it is seen that Ar-N_2 plasmas require higher mode transition and steady state power than pure Ar plasmas (Fig. 2). As a result, the mode transition time for Ar-N_2 plasma (about 1300 μs in the present case) is much higher than that of pure Ar plasma (about 500 μs in the present case).

It is observed that, unlike low-pressure plasma [1], both the E and H discharges are developed near the inner surface of the discharge vessel because of the stronger electrostatic and electromagnetic field near the torch surface than the center of the chamber. Finally, since the E-H mode transition and the ring-shaped discharge plays a vital role to form the volumetric

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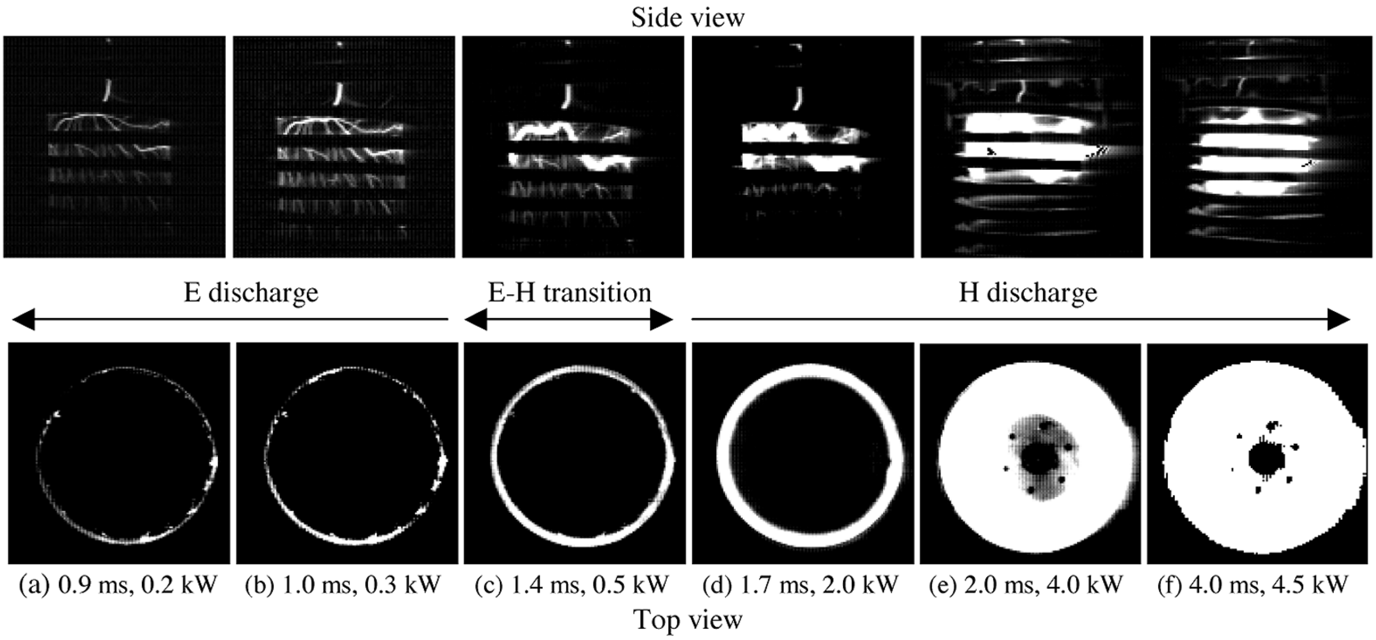

Fig. 1. Observation of E-H mode transition in atmospheric pressure argon plasma. Timing and corresponding RF power are indicated below the respective image.

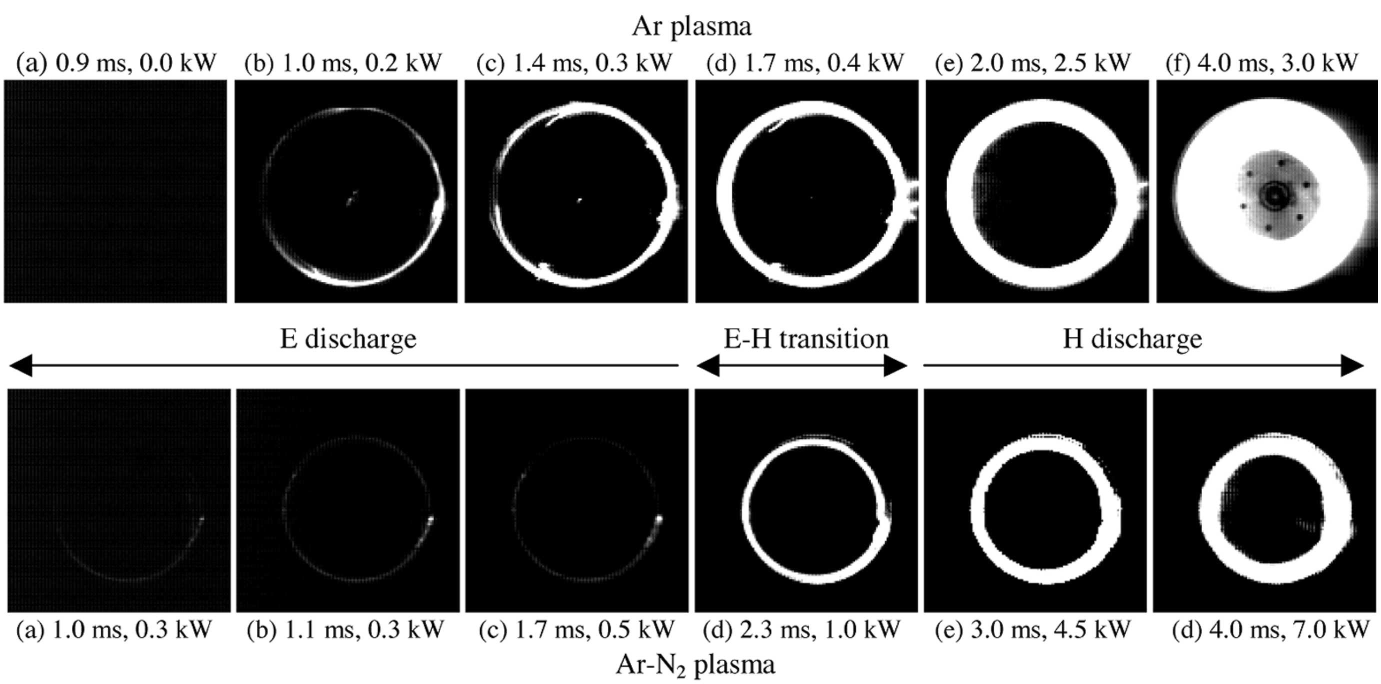

Fig. 2. Comparison of E-H mode transition dynamics between pure Ar and Ar-N_2 plasmas with 10% N_2 in a pressure of 50 kPa.

plasmas, one can employ a few number of ignitors (say typical automobile spark plug) inside the discharge chamber along the azimuthal axis, which can assist connecting among the streamers to form the ring-shaped discharge in high-pressure and diatomic mixed-gas plasmas.

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