Transient Behaviors of a Radio Frequency Pulse-Modulated Argon Inductively Coupled Plasma in Atmospheric Pressure

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The dynamic behaviors of a radio-frequency pulse-modulated argon inductively coupled plasma (ICP) in atmospheric pressure are investigated experimentally. The experimental observations reveal that, a rapid increase of the coil loading resistance and decrease of the effective coil inductance occurs during the dynamic change of plasma from electrostatic (*E*) to electromagnetic (*H*) mode. As a result, the rf coil current drops abruptly when the load changes from the *E* to *H* mode, thereby decreasing the absorbed power and thus the DC–RF conversion efficiency. A method of enhancing the conversion efficiency by controlling the gate driving frequency is also discussed.

1. Introduction

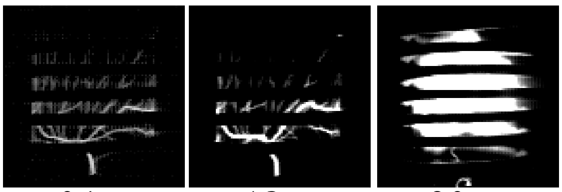
A typical radio frequency (rf) inductively coupled plasma (ICP) can usually be generated by applying rf power in a Pyrex or quartz chamber filled with inert gas such as Ar, He etc. and wound with an induction coil of a few turns. At the initial phase of rf breakdown, an electrostatic discharge (*E* discharge) is generated by the strong electrostatic field (100–200 kV/m) due to high rf voltage on the induction coil for few milliseconds, and then a rapid transition from electrostatic to electromagnetic discharge (*H* discharge) occurs to form the rf induction plasmas [1]. During this mode transition period, induction plasma behaves transient and strongly non-linear [1, 2]. The phase of the rf output voltage to current is changed, the driving frequency is shifted from its resonance one, and the coil current is dropped abruptly during *H* mode. In this article, all these transient and non-linear behaviors of Ar induction plasma in atmospheric pressure are discussed.

2. Experiments

In the present experiments, inverter input DC voltage and current, rf output voltage and current, and rf coil current are measured, and high-speed imaging is performed by using a 'FASTCAM-*ultima* SE' high-speed camera with a frame speed of 13500 fps, to analyze the transient behaviors of Ar induction plasmas. The plasmas are sustained in a Pyrex glass chamber (ϕ = 70 mm, L = 200 mm) by applying a static induction transistor (SIT) inverter power source (rating: 20 kW, 0.2–1.7 MHz) with a driving frequency of 1.12 MHz and rf power of about 3.5 kW. The rf power is modulated with a 100–5000 ms square wave pulse. An L-C matching network is employed to optimize the power coupling. Spark discharge technique [2] is applied to initiate the discharge.

3. Dynamic behavior of induction plasmas

At the initial phase of rf breakdown, streamerlike discharge or *E* discharge [Fig. 1(a)] is generated by the strong electrostatic field (100–200 kV/m) due to high rf voltage on the induction coil. Then the discharge paths connect among the streamers due to the induced electric field (2.5–5 kV/m) to form a ring-shaped discharge or *H* discharge [Fig. 1(b)], and finally, the steady state induction plasma [Fig. 1(c)] develops due to Joule heating with the induced azimuthal current. For detailed analysis of *E*–*H* mode transition, the readers are referred to Ref. 1.



0.4 ms 1.2 ms 8.0 ms

(a) *E* discharge (b) *E-H* transition (c) *H* discharge
Fig.1 High-speed images of Ar induction plasma

The temporal behavior of plasma loading impedance (both real and reactive part), obtained by the rf voltage to current ratio, indicating a dynamic transition from one mode to another is shown in Fig.2.

The resistance in the *E* mode is very small due to a weak coupling of streamerlike discharge and becomes high in the *H* mode due to the growth of the inductive plasma. The reactance, on the other hand, is slightly positive in the *E* mode and decreases as the development of the *H* mode due to plasma reaction by the induction current, which flows in the azimuthal direction but opposite to that of the rf coil current, thereby decreasing the effective coil loading inductance. As a result, the phase of the rf output voltage to current is changed and the driving frequency is shifted from its resonance value during the *H* mode as shown in Fig. 3 and 4(a), respectively. The total load, therefore, becomes slightly capacitive during the *H* mode thereby increasing the switching losses of the SIT inverter elements. As a result, the inverter output power is decreased, thereby decreasing the DC−RF conversion efficiency of the SIT inverter from about 90% to 40% as shown in Fig. 3.

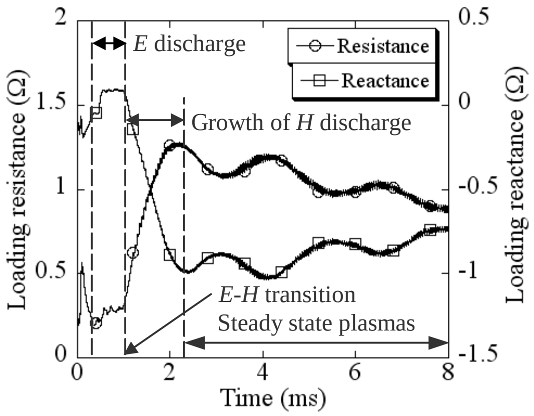


Fig. 2 Temporal plasma loading impedance

The DC−RF conversion efficiency of the SIT inverter power source can be enhanced by applying the immittance conversion circuit [3], which helps to inject a higher power to the plasma than the typical resonance circuit. In this experiment, we use another simple method by controlling the gate driving frequency, changing it from 1120 to 1250 kHz starting at about 40 ms when the *E* mode has been transferred to *H* mode. However, the experimental conditions other than the frequency control remain unchanged. The temporal change of the gate driving frequency and the DC−RF conversion efficiency are shown in Fig. 4(a) and (b), respectively. Fig. 4(b) shows that the rf power is doubled from about 3.5 kW to 7 kW, thereby enhancing the DC−RF conversion efficiency from about 40% to 85% by bringing the driving frequency close to resonance one. This is because by controlling the driving frequency close to resonance value, the losses mainly coming from the switching are considered to become low, thereby increasing the absorbed power and thus the DC−RF conversion efficiency of the SIT inverter power source.

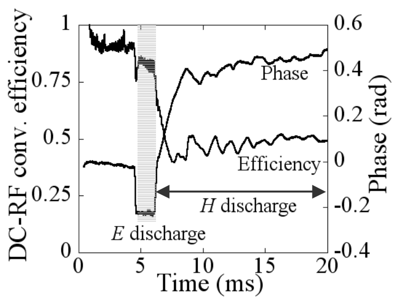


Fig. 3 Time behavior of phase and DC-RF conversion efficiency

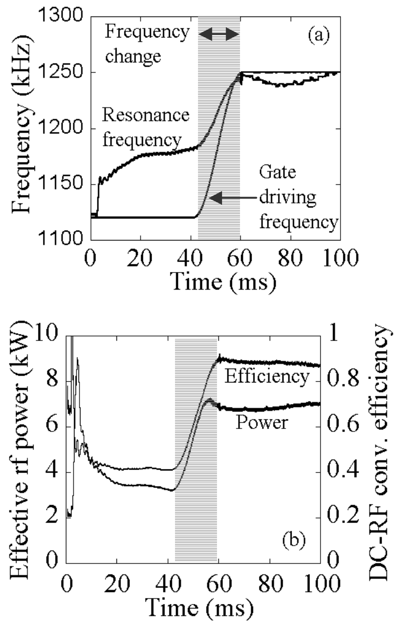


Fig. 4 The evolution of the driving and resonance frequency (a), and the DC-RF conversion efficiency of the SIT inverter (b) when the driving frequency is varied as shown in figure (a)

4. Conclusion

The transient behaviors of a radio frequency argon inductively coupled plasma in atmospheric pressure are investigated experimentally. The experimental observations reveal that, a rapid increase of the effective coil loading resistance and decrease of the inductance occurs during the dynamic change of plasma from electrostatic to electromagnetic mode. As a result, the rf coil current drops abruptly, thereby decreasing the absorbed power and thus the DC−RF conversion efficiency (Fig.3). However, the conversion efficiency can be enhanced from about 40% to 85% by performing the frequency control [Fig. 4(b)].

5. References

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