Fast Initiation and Mode Transition of Radio Frequency Induction Plasmas at Atmospheric Pressure Using Tungsten Pin Electrodes Array

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The effects of using an array of tungsten pin electrodes on the ignition dynamics of radio frequency (rf) discharges generated by inductively coupled plasma (ICP) technique at atmospheric pressure are investigated experimentally. The experimental observations reveal that the array of tungsten pin electrodes successfully enhance the initial discharges maintained by the strong electrostatic field with stable and fast ignition, which enables us to sustain efficient rf induction plasmas at atmospheric pressure range.

Keywords: inductively coupled plasma, radio frequency, tungsten electrodes, electrostatic discharge, static induction transistor

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1. Introduction

Atmospheric discharges has been one of the fruitful areas in the recent plasma sciences, since these plasmas have proven to be a very attractive tool both for the thermal treatment of powders and materials synthesis due to their contamination-free (clean) property, high-temperature (typically >10,000 K), and high-reaction activity [1, 2]. These plasma sources are also considered to be one of the effective and attractive tools for destructing the waste materials (radio-active waste, CFC, halogen, PCB etc.) and disposal of harmful gases (CO_2, SF_6 etc.) [3–5]. However, in order to promote these plasma reactors to industrial and environmental issues, it is necessary to generate efficient plasma sources with stable, smooth and fast ignition, which is one of the important criteria of radio frequency discharges, especially at atmospheric pressure range, since a high-voltage initiation is usually required for these types of discharges. Therefore, the research and developments of fast ignition and mode transition, which plays a vital role to sustain efficient radio frequency induction plasmas at atmospheric pressure range, are still to be the subjects of advanced studies.

It has already been established that the typical radio frequency (rf) discharges generated by inductively coupled plasma (ICP) technique are operated in two well-known modes: a capacitively coupled or electrostatic mode (E mode) and inductively coupled or electromagnetic mode (Hmode). From this E–H mode transition dynamics of atmospheric pressure plasmas, it has already been revealed that the development of streamer-like electrostatic discharges (E discharge) at the ignition stage maintained by the electrostatic field plays a very important role for E–H mode transition, thereby developing the ring-shaped electromagnetic discharges (H discharge), which is responsible for sustaining the volumetric induction plasmas maintained by the induced electric field [6–8]. Therefore, the enhancement of the electrostatic discharges (E discharge) at the ignition stage assumes to be a dominant mechanism of fast E–H mode transition and sustainment of efficient high-pressure (one atmosphere or more) radio frequency (MHz range) induction plasmas with stable and fast ignition, especially where the output power of the rf source is limited. With these in mind, in this research, a simple and fast ignition technique, using an array of tungsten pin electrodes along with the conventional ignitor (a typical automobile spark plug in the present case), is employed to enhance the initial discharges, which successfully enables us to sustain efficient rf induction plasmas at atmospheric pressure with a driving frequency of 1.2 MHz and a moderate rf power of about 3 kW.

2. Experiments

In the present experiments, argon plasmas are sustained in a Pyrex glass chamber (inner diameter: 7 cm and length: 20 cm) wound with an induction coil of 7 turns by applying a static induction transistor (SIT) inverter power source (maximum output power: 20 kW and frequency range: 0.5-1.5 MHz). An LC matching network is employed for efficient power coupling, and the discharges are observed by a high-speed camera (*Fastcam-ultima-SE*)

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with a frame rate of 13500 fps. For the description of experimental setup with schematic details, readers are referred to Ref. [7].

Repetitive spark discharge technique using a typical automobile spark plug embedded with a high-voltage transformer circuit is used to initiate the discharge [7, 8]. To enhance the initial electrostatic discharges, in the present experiments, an array of tungsten pin electrodes (total 6) is used along with the conventional ignitor (in this case an automobile spark plug). The tungsten pin electrodes are adjusted to the top flange of the torch chamber distributed evenly along the azimuthal axis with a separation of 60^0 between neighboring pins as shown in Fig. 1. The electrodes consist of solid cylindrical tungsten wire of 3 mm diameter, and the length of each electrode is 50 mm with a 10 mm sharp edge at the bottom (just like a pin).

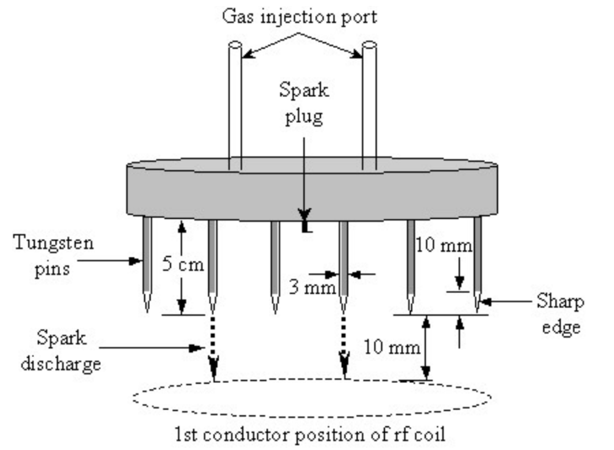

Fig. 1 Adjustment of tungsten pin electrodes on the top flange of the torch chamber to enhance the electrostatic discharges at the ignition stage.

The first conductor position of the rf induction coil is adjusted just 10 mm below the sharp edge of the tungsten pin electrodes.

3. Results and Discussions

The effects of enhancing the initial electrostatic discharges with tungsten pin electrodes are observed by high-speed imaging (with a frame speed of 13500 fps) as well as by analyzing the temporal development of plasma loading impedance.

The high-speed (13500 fps) images of radio frequency (1.2 MHz) argon induction plasmas at atmospheric pressure with and without using the tungsten pin electrodes are compared in Fig.2. Figure 2(a) shows the images without using the tungsten pin electrodes, while 2(b) shows those with using the tungsten pins, where the tungsten pin electrodes position are shown by the arrows. For clear observations, both end view (the first two columns of Fig. 2) and side view (the last two columns of Fig. 2) images are captured. The end view images are taken along the discharge axis and from the bottom of the discharge chamber, while the side view images are taken perpendicular to that of the discharge axis. The high-speed imaging shows that the axial tungsten pins successfully enhance the initial electrostatic discharges at the ignition stage as shown in Fig. 2(b), which is further confirmed by observing the temporal development of plasma loading resistance and described later in Fig. 3. The discharge is initiated by the spark plug used in the system, and the initial streamer-like electrostatic discharge is developed due to the high electrostatic field (about 100 kV/m at atmospheric pressure) produced by the high-voltage in the induction coil [7]. However, the interaction between the sharp edge of the tungsten pin electrodes and that of the high-voltage coil conductor produces the additional spark discharges, which enhances the

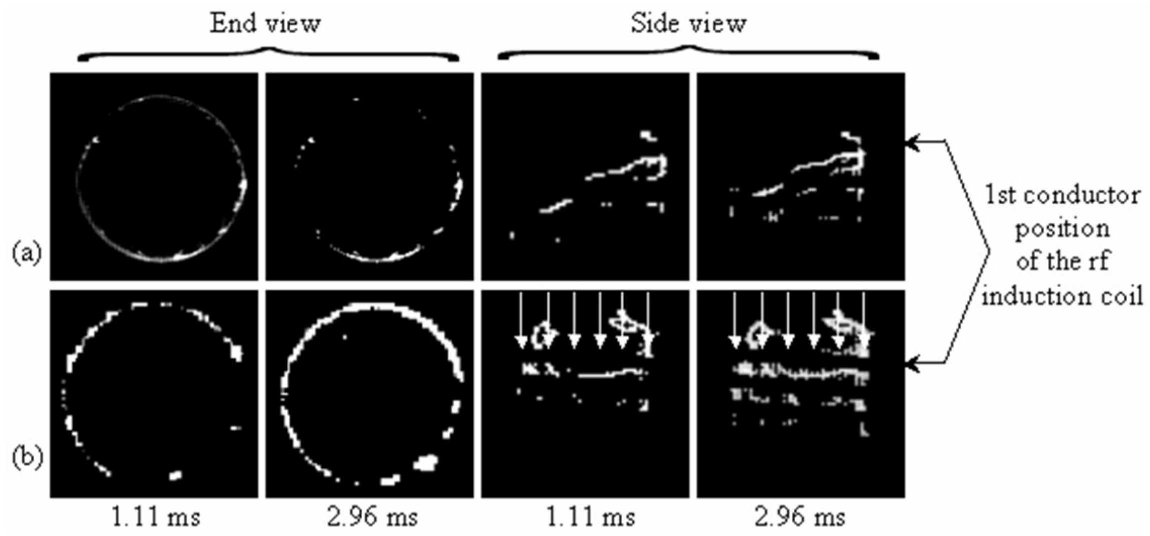

Fig. 2 High-speed (13500 fps) images of argon induction plasma without tungsten electrodes (a), and with tungsten electrodes (b).

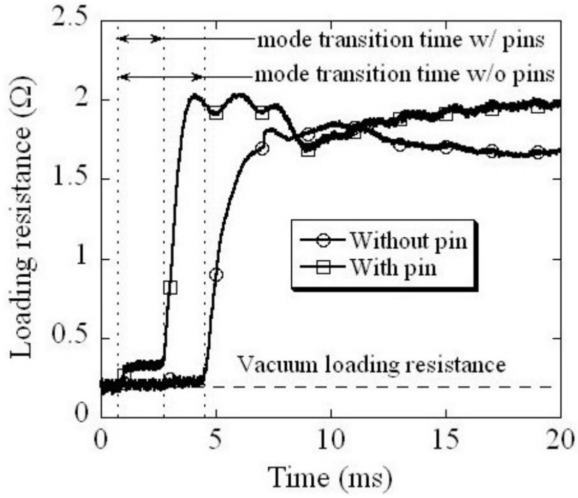

Fig. 3 Temporal development of high-frequency loading resistance of argon induction plasmas at atmospheric pressure with and without using the tungsten pin electrodes.

electrostatic discharges at the ignition stage as shown in Fig. 2(b). This is clearly observed in the side view images of Fig. 2(b) where it is seen some streamer-like discharges between the first coil conductor and that of the tungsten electrodes regions, which are absent in the images without using the tungsten pins as shown in Fig. 2(a). These enhanced electrostatic discharges confirm the fast mode transition developing the ring-shaped electromagnetic discharges as well as the volumetric induction plasmas with the Joule heating [6–8]. To understand the fast mode transition more precisely with quantitative analysis, we investigate the high-frequency plasma loading impedance at the ignition phase, which is discussed in the following paragraph.

The temporal developments of plasma loading impedances (real part only) of argon plasmas at atmospheric pressure with and without using the tungsten pin electrodes are depicted in Fig. 3. The loading resistance, $R_L = R_C + R_P$, where R_C and R_P are the coil resistance and the resistance introduced by the plasma, respectively. As a result, from Fig.3, it is seen that the loading resistance at the ignition stage is higher with the axial tungsten pins than without using the tungsten pin electrodes, since the use of tungsten pin electrodes enhance the initial electrostatic discharges at the ignition stage as shown in Fig. 2(b). It is also observed that the effects of axial tungsten pin electrodes reduce the E–H mode transition time (which corresponds to the duration of E discharge) [6–8], with fast and stable ignition, from about 4 ms down to 2 ms, which enable us to sustain efficient radio frequency (rf) inductively coupled plasma (ICP) at atmospheric pressure range.

4. Conclusions

It is concluded that the array of tungsten pin electrodes successfully enhances the initial electrostatic discharges at the ignition stage with stable and fast ignition, which enables us to sustain efficient radio frequency induction plasmas at atmospheric pressure. This technique is very much helpful for the initiation and generation of atmospheric plasmas, especially where the output power of the rf source is limited.

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