Plasmoid Formation and Multiple Steady States in a Low Pressure, Inductively Coupled Electronegative Plasma

Demeter J. Economou, Richard S. Wise, and Alison A. Kubota

***Abstract*— Hysteresis and multiple steady states have been observed in a low pressure inductively coupled plasma in chlorine gas. A bowl-shaped bright structure with sharply delineated edges (plasmoid) was found to form under the planar coil. A different plasma state with rather diffuse emission of lower intensity was also observed under the same operating conditions.**

***Index Terms*— Chlorine plasma, inductively coupled plasma (ICP), plasma etching.**

HIGH density plasmas are currently in wide use in the microelectronics industry due to their inherent advantages of quasi-independent control of ion bombardment flux and energy, better ion directionality, and the potential for better uniformity as compared to their low density counterparts. Instabilities, multiplicities, and hysteresis have been observed in both low density and high density plasmas. Such phenomena are important not only from the scientific but also from the practical point of view because they may occur for operating conditions in the range typically used for manufacturing. Process instabilities, drifts, and irreproducibilities may then result.

Luminous bodies formed in a gas discharge which are embedded in a less luminous background have been termed plasmoids. Wood reported on plasmoid formation in RF discharges in the late 1920's [1]. More recently, plasmoid formation and multiple states in a low density capacitively coupled chlorine plasma were reported by Aydil and Economou [2]. Multiplicities in electron cyclotron resonance (ECR) argon plasmas have been reported by Aydil *et al.* [3]. Stittsworth and Wendt [4] observed azimuthal striations in an inductively coupled plasma (ICP) in argon with a planar coil.

In this paper we present an image of a plasmoid formed in an inductively coupled plasma in chlorine and show hysteresis associated with the plasmoid. A similar structure was observed by Miller and Hebner [5] in a chlorine discharge sustained in a gaseous electronics conference (GEC) reference cell modified for inductive plasma operation [6].

Experiments were performed in a reactor which is a scaled-up version of the GEC-ICP reference cell. A quartz window was suspended 7.62 cm above the 33 cm-diameter grounded bottom electrode. This electrode was chilled with a water-glycol mixture. A planar (stove top) three-turn coil, approximately 20 cm in diameter, was placed directly above the quartz window. For the results shown below, the inductive power was 100 W, and the ultra high purity chlorine flow rate was 20 sccm.

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Fig. 1 shows a side view of a plasmoid formed at 5 mtorr. The image was taken with a charge-coupled device (CCD) camera and computer enhanced. A bowl-shaped bright structure with well delineated edges is observed. The upper edge of the plasmoid is directly against the quartz window while the lower edges of the plasmoid are well separated from the grounded bottom electrode. The plasmoid was centered with respect to the reactor axis. The (spectrally unresolved) light intensity appeared highest a small distance under the coils and decreased continually toward the bottom electrode.

The plasmoid was one of two plasma states that were observed under otherwise identical conditions for a certain range of operating parameters. The other plasma state appeared with rather diffuse emission without well-defined edges. Fig. 2 shows hysteresis in the Cl-atom emission at 837.6 nm as a function of pressure. The emission was collected from the midplane between the grounded bottom electrode and the quartz window, and 3 cm off the reactor axis, where the peak emission was found to occur. A plasmoid was formed at a pressure of 5 mtorr. As the pressure was increased, the plasmoid was sustained until a pressure of between 25 and 30 mtorr was reached. The plasmoid then disappeared spontaneously giving place to the other more uniform plasma state. As the pressure was subsequently lowered, this other plasma state was sustained until a pressure of between 5 and 10 mtorr was reached. At that point the plasmoid was again formed spontaneously.

Plasmoid formation may be associated with the existence of double layers inside the plasma [7]. It has been shown that there is a range of plasma electronegativity for which an internal double layer forms that separates an ion-ion plasma core from an electron-ion plasma periphery [8], [9]. The edges of the plasmoid may be where the internal double layer is located. For higher pressures, the plasma electronegativity increases to the point that the electron-ion periphery is squeezed out of the plasma and the double layer disappears. For low enough pressures, the plasma should turn into electropositive-like (due to the high degree of Cl dissociation) and the plasmoid should again disappear. Unfortunately, with the present matching network, the plasma could not be sustained below a few mtorr. It should be noted that the plasmoid could not be made to form in less electronegative discharges. For example no plasmoid could be obtained for argon additions to chlorine greater than 40% by volume.

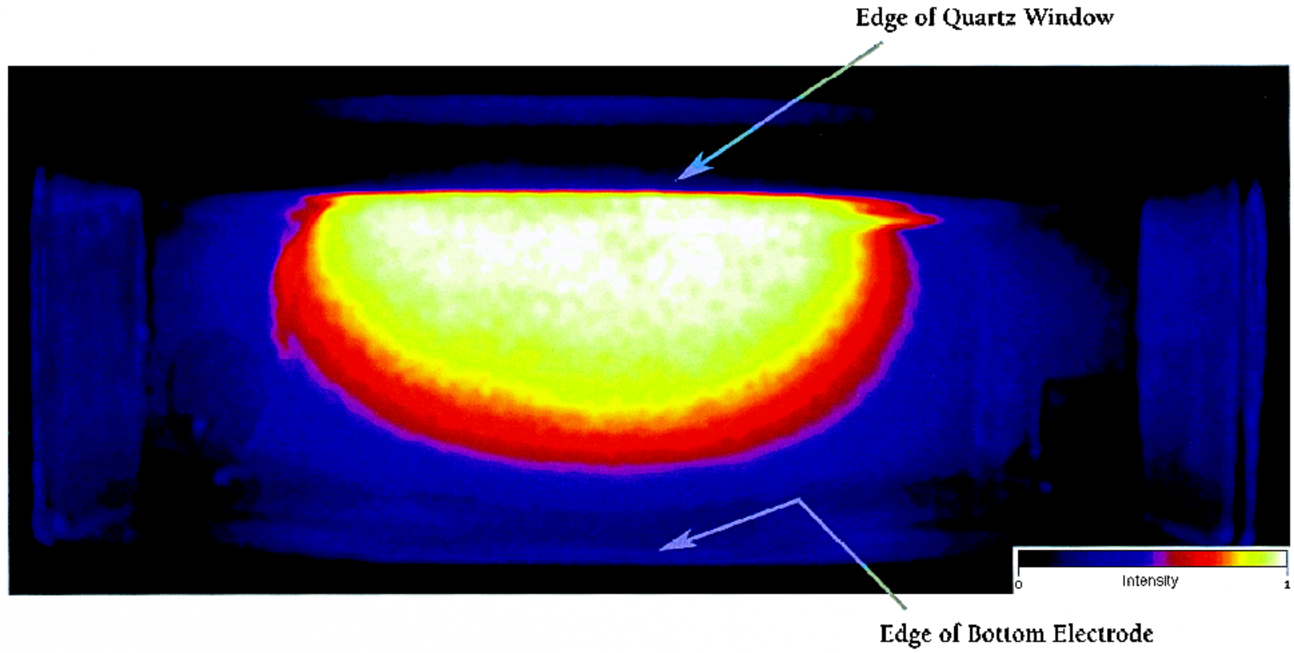

Fig. 1. Side view of a plasmoid formed at 5 mtorr. The bright structure is against the quartz window at the top and is well separated from the grounded bottom electrode. The spacing between the bottom electrode and the quartz window is 7.62 cm.

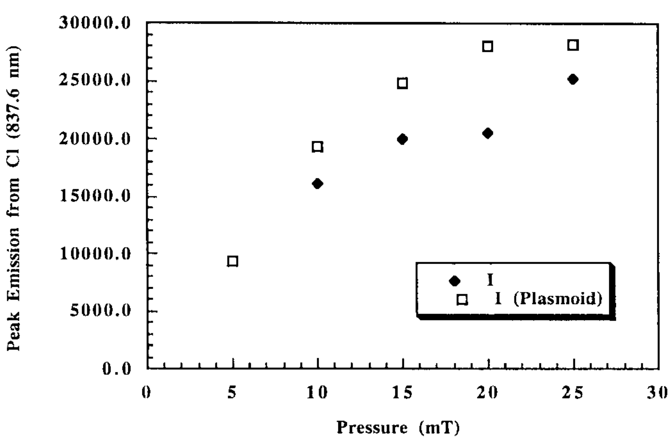

Fig. 2. Hysteresis in the Cl emission at 837.6 nm as a function of pressure in a chlorine plasma. Emission was obtained from the midplane between the quartz window and the bottom electrode and 3 cm off the reactor axis where the peak emission occurred. The filled diamonds were obtained with a conventional (diffuse) plasma, the empty squares with a plasmoid present.

Nevertheless, the effect of the matching network should not be neglected. For example, Taillet [10] suggested that plasmoids can form in plasmas containing negative ions as a result of resonance between the inductive plasma and capacitive sheaths. Although the plasma sustained in our reactor was definitely inductive, capacitive coupling from the coils can't be ruled out (there was no Faraday cage to shield the capacitive fields). If plasmoid formation is the result of a resonance condition, the matching network should be playing a role.

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