Anode double layer in magnetized radio frequency inductively coupled hydrogen plasma

Deli Tang and Paul K. Chu

Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong

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The formation of the double layer created around the anode in magnetized radio frequency inductively coupled plasma, which is visually apparent because of enhanced light emission from the neutrals excited by energetic electrons, is investigated in detail in this work. The effects of the external magnetic field and anode voltage on the evolution of a cylindrical luminous anode double layer from the anode glow are evaluated in magnetized hydrogen plasmas. The anode glow is initially produced by the additional dc discharge which forms when a cylindrical anode inserted into the plasma diffusion region is positively biased. If the anode voltage is sufficiently high, the anode glow is transformed into an elongated luminous anode double layer in the plasma diffusion region, to which a diverging magnetic field generated by external magnetic coils is coupled. A weakly magnetized plasma is needed for the formation of the anode double layer in our experiments, and there is a magnetic field strength ceiling beyond which the anode double layer disappears. The dependence of the anode double layer structure on the magnetic field strength, anode voltage and the neutral gas pressure is also investigated. © 2003 American Institute of Physics.

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I. INTRODUCTION

The formation of a plasma double layer has been investigated experimentally,1–14 theoretically,15,16 and using computer simulation.17,18 This double layer consists of two space charge layers in close proximity, and may be regarded as spatially localized electric fields that extend many Debye lengths and separate two quasineutral plasmas with different space plasma potentials. The double layer can be formed by employing different methods such as limiting the current in a uniform cross section plasma, constricting the plasma by abruptly changing the cross section, applying a difference in potential between two plasmas, and biasing an anodic electrode immersed in the plasma.6,19–21 The phenomenon has been studied in unmagnetized6 and magnetized plasma5,7 in which an anode electrode is immersed in a basic cathodic plasma and biased to positive voltage. A luminous nearly spherical object ("fireball") will be generated in contact with the anode disk when the anode bias exceeds a certain threshold value in unmagnetized plasma. The effects of an external magnetic field on the evolution of the cylindrical luminous anode double layer ("firerod") from a spherical fireball have been investigated in magnetized plasma in a uniform magnetic field.7 The conical double layer has also been investigated in a nonuniform strong magnetic field with a large anode plate.5 In those experiments, electrons from the cathode were accelerated to sufficient energies that additional discharge occurred in front of the anode and plasma with higher potential and density was created, manifesting itself in fireballs or firerods. The cathode plasma is usually triggered by hot filament discharge at a gas pressure in the range of 0.1–2 mTorr with Ar, Kr, or Xe.

In this article, we describe our investigation of the formation of the anode double layer in weakly magnetized hydrogen plasma. The hydrogen plasma is created by radio frequency (rf) inductively coupled plasma (ICP) discharge and an anode plate is inserted into the cathode plasma diffusion region and biased positively. The effects of the external magnetic field, anode voltage, and neutral gas pressure on the evolution of cylindrical luminous anode double layer from the anode glow are investigated experimentally.

II. EXPERIMENTAL SETUP

A schematic diagram of the magnetized rf inductively coupled plasma discharge apparatus is shown in Fig. 1. The system consists of a plasma discharge chamber (f600 mm × 300 mm) and plasma diffusion chamber (f760 mm × 1030 mm), both made of stainless steel and pumped by a turbo pump and a mechanical pump. The background pressure is about 7×10⁻⁶ Torr. In our study, in order to produce high-density high-uniformity plasmas, four rf planar inductive coils are placed on four planar quartz windows on top of the plasma discharge region and 13.56 MHz rf power (0–2000 W) is coupled to the plasma via four pancake inductive antennas through the quartz windows. The four inductive coils are located symmetrically above the plasma discharge region and connected to a matching box. An axial magnetic field is introduced into the plasma discharge region by external Helmholtz type electromagnetic coils outside the discharge chamber. The axial magnetic field can be adjusted from 0 to 100 G by changing the coil current Ic. The axial
magnetic field $B_s$ is about 6.5 G at $Z = 800$ mm (the center of the discharge chamber) and 1 G at $Z = 0$ mm (above the anode plate) when the magnetic coil current $I_c$ is 0.2 A. A divergent magnetic field is also introduced into the diffusion chamber, shown by the dashed lines in Fig. 1. The magnetic bucket confinement scheme has previously been used to improve the plasma density uniformity in plasma reactors\textsuperscript{22,23} and in double plasma devices.\textsuperscript{11} In this study, the permanent magnets are mounted outside the processing chamber as shown in Fig. 1. Each magnet has a magnetic field of 3 kG at the end. A multipolar cusp magnetic field is produced to confine the plasma and improve the plasma density. A disk electrode (anode) 150 mm in diameter and 50 mm thick is inserted into the plasma diffusion chamber and immersed in the plasma. The anode disk can be adjusted axially and biased positively in the plasma diffusion region.

To investigate the effects of the anode disk voltage and the external magnetic field on the characteristics of the plasma double layer in magnetized plasma discharge, the plasma parameters were monitored by an electrostatic Langmuir probe. A cylindrical tungsten probe 10 mm long and 0.2 mm in diameter was swept across the plasma double layer along the axial and longitudinal directions to determine the electron temperature, plasma potential, and ion density profile. These dimensions are larger than all Debye lengths involved and small enough to prevent disturbance to the double layer structures.\textsuperscript{8}

III. EXPERIMENTAL RESULTS

A stable anode double layer is generated by applying positive voltage to a large anode plate immersed in the plasma diffusion region where a diverging magnetic field is sustained by the external magnetic coils. RF power (1000 W) is fed to the plasma discharge region via the inductive coils. The plasma discharge is ignited and enhanced by the external magnetic field introduced into the discharge and diffusion regions.\textsuperscript{24} The evolution of the anode glow sheath into a luminous anode double layer is illustrated in Fig. 2. The neutral gas pressure $p$ is $5 \times 10^{-4}$ Torr and the external magnetic coil current $I_c$ is 0.8 A. A series of photographs are taken at various anode voltages in the magnetized hydrogen plasma to monitor the evolution of the double layer. When a positive anode voltage is applied, plasma electrons are drawn from the plasma discharge and diffusion regions to the anode plate. At low anode bias voltage, a thin anode sheath forms around the anode disk, but when the anode voltage is sufficiently high and the drop in potential in the sheath exceeds the background gas ionization potential (15.4 eV for hydrogen), the electrons drawn from the plasma will have enough energy to ionize the gas molecules and atoms and a new plasma is produced around the disk. Consequently, anode glow discharge occurs between the anode plate and cathode plasma. In our experiments, the luminous anode glow sheath is visually apparent when the anode bias voltage $V_a$ is equal to or larger than 30 V and the diameter of the anode glow sheath increases with the anode bias voltage. A glow column forms below the disk and intensifies when the anode voltage is further increased. If the rate of ionization within the sheath is high enough, part of the anode sheath moves away from the anode disk and forms a strong luminous magnetized double layer above the anode disk. Our results show the existence of a critical voltage $V_{on}$ and the luminous anode double layer will appear when the anode voltage $V_a$ reaches the critical value $V_{on}$.

This phenomenon can be observed at different neutral gas pressures, but the critical voltage changes with the gas fluxes. The critical voltage $V_{on}$ versus the neutral gas pressure $p$ relationship is exhibited in Fig. 3. Here, the magnetic coil current is about 0.8 A and the axial magnetic field strength above the anode disk is about 4 G. It can be observed that the critical voltage decreases with higher neutral gas pressure, and the higher the gas flux, the lower the critical voltage. The critical voltage diminishes from about 120 to less than 70 V when the neutral gas pressure increases from $5 \times 10^{-4}$ to $9 \times 10^{-4}$ Torr. In our experiments, the anode double layer has a conical shape and its interface is not very distinct at low gas pressure ($5 \times 10^{-4}$ Torr), but at higher gas pressure, the anode double layer manifests itself as a well demarcated cylindrical luminous column from the cathode plasma.

After the double layer has been created, a further increase in the anode voltage increases the height of the luminous column as well as the anode current. When the anode
voltage is gradually decreased, the height of anode double layer and anode current are both reduced. However, the double layer does not vanish until the anode voltage reaches a certain value $V_{\text{off}}$ when the anode voltage is less than critical voltage $V_{\text{on}}$. When the anode voltage reaches critical value $V_{\text{off}}$, anode current $I_a$ drops suddenly and the anode double layer disappears. This phenomenon can be observed from the $I-V$ curve of the anode current–voltage characteristics depicted in Fig. 4. When the anode is biased positively, the electron saturation current increases with the anode voltage. However, when the anode voltage reaches critical value $V_{\text{on}}$, the anode current jumps abruptly and a cylindrical luminous column is created in front of the anode disk. Here the critical value is about $V_{\text{on}}=73$ V. If the anode voltage is increased further, the thickness of the anode double layer increases slightly before the anode double layer becomes unstable and expands radially while the height of the luminous column decreases when $V_a>90$ V. When the anode voltage is reduced to $V_{\text{off}}=55$ V, the anode current drops sharply and the luminous anode double layer is extinguished. The hysteresis of the anode current–voltage characteristics is illustrated in Fig. 4.

A similar phenomenon is observed when the gas flux is varied while the anode voltage and magnetic field strength are kept constant. The anode current varies with the gas flux $Q$, and the $I_a$ vs $Q$ relationship of the anode disk in magnetized plasma is illustrated in Fig. 5. In our experiments, the pumping rate is fixed and the gas pressure changes with the gas flux. The neutral gas pressure is about $6.3\times10^{-4}$ Torr when the gas flux is 34 sccm. The anode voltage $V_a$ is 80 V and the external magnetic coil current is 0.8 A. The neutral gas pressure is about $6.3\times10^{-4}$ Torr when the gas flux is 34 sccm. It is observed that the anode current increases gradually with the gas flux. When the gas flux reaches a critical value of $Q_{\text{on}}=32.2$ sccm, the anode current increases suddenly and the luminous anode double layer is created at the same time. If the gas flux is further increased, the anode double layer will increase. However, the anode double layer does not disappear when the gas flux is reduced gradually, even below the critical value $Q_{\text{on}}$. When the gas flux reaches $Q_{\text{off}}=25.5$ sccm, the anode current drops precipitously and the luminous anode double layer vanishes. Our results indicate that the current-gas flux (or the current-gas pressure) characteristics of the anode also exhibit hysteresis at higher anode voltage in magnetized plasma. When the external magnetic field strength is varied by adjusting the magnetic coil current and the anode voltage and gas flux are kept constant, the anode current will also change. The $I_a$ vs $I_c$ relationship of the anode disk in magnetized plasma is shown in Fig. 6. Here, the anode voltage $V_a$ is 70 V and the gas flux is 52 sccm ($p=9\times10^{-4}$ Torr). When the magnetic coil current is increased from a low value of $I_c=0.3$ A, the anode current diminishes gradually and reaches saturation. When the magnetic coil current reaches a critical current $I_{c\text{ on}}$, the anode current increases suddenly and the luminous anode double layer forms simultaneously. Further increase of the coil current will, however, result in a reduction of anode current. The thickness of the anode double layer increases until coil current $I_c=1$ A, and then it begins to decrease, become less distinct gradually, and disappear at about $I_c=2.5$ A. If the coil current is decreased, the anode double layer will appear again and the above phenomenon can be repeated until coil current $I_c=0.8$ A. When the coil current is reduced from $I_c=0.8$ A, the anode current will increase first and subse-
quently decrease. If the coil current is further reduced and reaches a certain value of \( I_{c_{\text{off}}} \), the anode current will drop suddenly and the anode double layer will disappear. The above results indicate that different hysteresis characteristics exist in the current and magnetic field strength of the anode.

The hysteresis of the anode plate current can be observed when adjusting the anode voltage, gas flux and magnetic field strength in the above experiments. Meanwhile, the thickness of the anode double layer can be affected not only by the anode voltage and gas flux but also by the external magnetic field. When we reduce the above three parameters from their onset values \( (V_{\text{on}}, Q_{\text{on}}, I_{c_{\text{on}}}) \), the luminous anode double layer will drop gradually and finally disappear at their cut-off values \( (V_{\text{off}}, Q_{\text{off}}, I_{c_{\text{off}}}) \). This phenomenon can be seen in the photographs of the anode double layer with different external magnetic fields in Fig. 7. Here, anode voltage \( V_a \) is 70 V and the gas flux is 52 sccm. The cylindrical luminous column drops gradually with a reduction of external magnetic field.

The axial plasma potential profile of the anode double layer is obtained using a Langmuir probe. The axial plasma potential of a typical anode double layer is displayed in Fig. 8. Anode voltage \( V_a \) is 70 V and the neutral gas pressure \( P \) is \( 9 \times 10^{-4} \) Torr. In this case, the thickness of the anode double layer is about 250 mm. The boundary of the plasma luminous column consists of a double layer and the drop in potential \((\sim 22 \text{ V})\) between the anode and the cathode plasma is larger than the hydrogen ionization potential \((\sim 15.4 \text{ V})\).

In our experiments, a well demarcated cylindrical luminous column exhibits an one-dimensional double layer structure at higher gas pressure \((9 \times 10^{-4} \text{ Torr})\). However, a magnetized three-dimensional double layers of conical shape can form at low gas pressure \((5 \times 10^{-4} \text{ Torr})\). The thickness of the double layer appears to diminish with an increase in gas pressure whereas the drop in potential remains roughly constant. The axial expansion and sharpening of the double layer with higher gas pressure can be attributed to an increase of the ionization probability. The Langmuir probe measurements indicate that the ion density in the double layer is higher than that in the cathode plasma without changing the rf power, gas pressure and magnetic field strength when only the anode plate is biased. One reason is that the enhancement of ambipolar diffusion will result in an increase of ion losses in the volume plasma to the chamber wall when the anode is positively biased whereas energetic electrons that pass through the double layer will produce new ionization which will increase the ion density in the plasma column.

**IV. DISCUSSION**

The evolution of a luminous anode glow sheath into a cylindrical anode double layer can be achieved in radio frequency inductively coupled magnetized hydrogen plasma. When a positively biased anode is immersed in the plasma, ionization and excitation of neutral gas molecules and atoms within the sheath around the anode plate become important. As the anode voltage is increased, the anode sheath becomes visible. When ionization resulting from energetic electrons can maintain the plasma in the high potential region of the anode sheath, the anode sheath will evolve into a stable anode double layer in the diverging magnetic field region. In our experiments, a small magnetic field is still necessary for
the formation of a stable anode double layer. The magnetic field may not only enhance cathode plasma production but also confine the ions within the double layer structure. The stable double layer relies on a balance of ions between the plasmas determined by the ionization of neutral gas species by energetic electrons that are accelerated into the double layer and by ion losses via the double layer boundary. When the anode double layer is created, the thickness will increase with higher anode voltage. Although collisional ionization is essential for the production of the double layer, the double layer potential is not limited by the ionization potential. In fact, it will increase with the anode voltage until the glow discharge becomes unstable. Therefore, the high double layer potential will enhance collisional ionization and prolong the double layer along the magnetic field direction. When the gas flux is increased, the ionization rate increases and a lower anode voltage can still maintain a sufficient rate of ionization to form the double layer. The onset value of the anode voltage must drop with an increase in gas flux and neutral gas pressure.

The anode plate current hysteresis observed by adjusting the anode voltage, gas flux, and magnetic field strength indicates that the anode discharge may have nonlinear dynamics. The nonlinear characteristic of the anode discharge current is due to the occurrence of the anode double layer, which results in a sharp increase of the anode current. This means that the genesis of the anode double layer is the origin of the nonlinear variation of the anode current. The double layer consists of two space charge layers with different plasma potential in close proximity. A kinetic energy gradient of the electrons is created by their local acceleration towards the positively biased electrode. The electrons are rapidly collected by the biased anode electrode, in front of which a plasma enriched with positive ions appears. Its presence develops electrostatic forces whose magnitude increases with the anode voltage. An increase of the electric field will result in an increase in the electron kinetic energy. Taking into consideration the energy dependence of the ionization cross section function, the net positive space charge will be increased due to enhancement in the ionization rate. Therefore, the anode sheath expands and the plasma potential increases with the anode voltage. When the anode voltage achieves the critical value of $V_{\text{on}}$, the anode glow sheath is transformed into a plasma double layers and a nonlinear ionization growth occurs in the double layer. Consequently, nonlinear variation in the anode current is observed at the $V_{\text{on}}$ and $V_{\text{off}}$ as shown in Fig. 4. The similar hysteresis in the $I_a-Q$ characteristic is also due to the nonlinear ionization growth when the gas flux is increased to the critical value. Here, the nonlinear ionization is not due to the increase in the electron kinetic energy, but rather to the probability of ionization at increased gas pressure caused by the change in gas flux. The ionization rate will increase with the gas pressure. Nonlinear variation of the ionization rate occurs when the double layer appears and disappears by when the gas flux is changed. When the external magnetic field strength is introduced, the electrons are magnetized. The anode current decreases due to the electrons being confined by the increased magnetic field, whereas the collisional ionization rate of electrons and neutrals is increased because of an increase in gyromotion of electrons under the external magnetic field. The nonlinear ionization trend is thus due to a collisional ionization avalanche of electrons and neutrals when the external magnetic field reaches a critical value.

The anode double layer observed from the aforementioned photographs also exhibits hysteresis. The magnetic field strength in our experiments is lower than that used in other similar experiments, maybe due to the larger anode plate used in our experiments. The axial magnetic field strength is about 4–20 G in the double layer at $I_\text{c}=0.8$ A whereas the ion gyro radius is about 5–25 cm. Hence, since the double layer is thicker than 15 cm, it is reasonable to expect that the magnetic field will have some influence on side ion loss. When a larger diameter disk is used, the anode double layer can form at lower magnetic field strength. However, there still exists an upper limit on the magnetic field beyond which the anode double layer cannot be maintained. This is partly due to electrons that are confined by the diverging high magnetic field that cannot enter the anode region. This results in the reduction of the anode current as well as the rate of collisional ionization and eventually the anode double layer disappears, although the high magnetic field can enhance the confinement of ions and reduce ion loss from the cylindrical side.

V. CONCLUSION

The luminous cylindrical anode double layer was studied in low magnetized hydrogen plasma at low gas pressure when an anode disk is immersed in the plasma diffusion region. Critical onset values ($V_{\text{on}}, Q_{\text{on}}, I_{\text{c on}}$) are necessary for evolution of the anode glow sheath into the anode double layer. After the anode double layer is created, the plasma column can be maintained until and a little beyond the cutoff values ($V_{\text{off}}, Q_{\text{off}}, I_{\text{c off}}$). Our results show that the dimensions of the plasma column and double layer structure can be varied by adjusting the anode voltage, gas flux and magnetic field strength in radio frequency inductively coupled hydrogen plasma.

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