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Ignition and dynamics of high-voltage glow discharge plasma implantation

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Abstract

The self-ignition and dynamics of glow discharge plasma in the pulsed high-voltage plasma immersion ion implantation mode have been investigated. After ignition during the pulse-on period, the glow discharge continues to be sustained for a long period of time after the high-voltage pulse has been turned off as monitored by a Langmuir probe. The glow discharge and ignition lie on the left side of the Paschen curve when *pd* (gas pressure times electrode separation) is adjusted by using different anode to cathode distances utilizing a conducting grounded grid. The increased or constant implantation current I_a reveals that the ion sheath is stable and conforms to the cathode structure as the plasma density increases by one to two orders of magnitude towards the anode. In addition, the duration of the post-pulse-off plasma can be as long as several times of the pulse duration. The ignition time and duration of the plasma depend on the working pressure, applied voltage and pulse duration.

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1. Introduction

Plasmas are commonly ignited by external plasma sources such as inductively or capacitively coupled (ICP or CCP) radio frequency (RF), electron cyclotron resonance (ECR) and hot filament glow discharge. Plasmas can also be generated without an external plasma source by means of self-ignited glow discharge using two electrodes under a range of working pressures. The latter mode of plasma discharge has many advantages such as low hardware cost, small equipment footprint and simple operation. The technique has gradually been accepted in industrial applications since it can be operated in such a way to combine ion implantation and film deposition to increase the efficacy of surface modification. For instance, diamond-like carbon thin films can be more effectively produced on industrial components possessing irregular geometries in methane or acetylene plasmas [1].

Pulsed high-voltage glow discharge plasma implantation differs from conventional plasma immersion ion implantation PIII [2–6] in which the plasma is sustained using external plasma sources. In conventional PIII, the working pressure is typically maintained between 10^{-4} and 10^{-3} Torr and the plasma sheath expands dynamically according to the applied voltage, duration of pulse and plasma density. On the other hand, in pulsed high-voltage glow discharge plasma implantation, the working pressure is usually kept between 10^{-3} and 10^{-1} Torr and the plasma ignition lies on the left side of the Paschen curve (this will be described later). There have been relatively few experimental data related to this technique in the literature. An early study by Matossian and Wei [7] proposed that beam-plasma instability gave rise to plasma discharge, and Khvesyuk and Tsygankov [8] found a near anode plasma and a cathode layer with a thin cathode fall region. More recently, a number of studies involving RF plus

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high-voltage (HV) [9] and seed plasmas [10,11] have shown more uniform ion implantation and earlier ignition of plasma, respectively.

In this work, we systematically investigate the ignition and dynamics of pulsed high-voltage plasma discharge. When a conducting grounded grid is placed at different locations between the cathode and chamber wall, the delayed plasma ignition time and low implantation current reveal that the glow discharge obeys the left Paschen curve. Besides, the plasma parameters depend on the applied voltage, pulse duration and working pressure. Our results show that the plasma not only can be sustained during the pulse-on period but also is maintained for as long as several times of the pulse duration. These new discoveries are expected to offer means to better control the hybrid process of ion implantation and deposition.

2. Experimental

The experiments were conducted in a PIII instrument [12,13]. The vacuum chamber was 1.2 m tall and 1 m in diameter. A stainless steel rod with a diameter of 50 mm and length of 350 mm was used as the cathode. The argon plasma was generated between the cathode and anode without an external plasma source when a high voltage between −5 and −15 kV with the pulse duration of 100–700 μs and repetition rate of 30 Hz was applied to the cathode. To investigate the characteristics and ignition mechanism in high-voltage glow discharge, a conducting grounded grid with different diameters serving as the anode was placed between the cathode and chamber wall. The plasma parameters were measured by an electrostatic Langmuir probe. A single-sided planar circular probe made of copper disk with a diameter of 2 mm was inserted into the vacuum chamber to measure the electron saturation current and plasma density profile. Generally, the electron temperature T_e in most discharge is in the range of 1–5 eV and the plasma potential is on the order of several electron volts [8,14]. The probe was biased to +130 V and the probe signal was monitored across a 100 Ω resistor. The electron density n_e was obtained from the electron saturation current I_{e0} as described in the following relationship [15,16]:

$$n_e = \frac{I_{e0}/(eA)}{[kT_e/(2\pi m_e)]^{1/2}},$$

where e is the electronic charge, A is the area of the probe, k is the Boltzmann's constant and m_e is the electron mass.

3. Results and discussion

Glow discharge is the result of breakdown of the gas under high voltage and a plasma can be produced under certain conditions. Experimental results of the relationship between the cathode bias and the time-dependent discharge current show that at low cathode voltages of −5 and −7.5 kV, there is a delay time in the breakdown discharge and initiation at around 60 and 20 μs, respectively. After a certain time period, the current reaches a saturation level and remains quasi-constant until the end of the voltage pulse for all the applied cathode biases. The quasi-constant values of the discharge current reveal that the plasma sheath is steady during the high-voltage pulse. It should be noted that a small increase in the cathode bias can result in a rapid increase in the discharge current. According to Child–Langmuir law, the current density J on the target is proportional to the applied voltage $V_a^{3/2}$. In our case, the recorded discharge currents indicates that $J \propto V_a^n$ where $n > 2$ and the results are in agreement with our previous work [17].

A conducting grounded grid with holes of 2 mm × 2 mm is inserted between the cathode and chamber wall to study the plasma discharge properties. The grid serves as an auxiliary anode to partially shield the potential in the cathode and chamber wall. Fig. 1 plots the time-dependent current curves obtained for different cathode to grid distances under −10 kV cathode bias and 18 sccm argon flow rate. It can be observed that the smaller distance between the grid and the cathode lowers the discharge current and delays the plasma ignition time. It indicates that smaller values of pd (pressure times electrode separation) result in more difficult breakdown of the gas and a later ignition time. This behavior obeys the left side of the ordinary Paschen curve.

Fig. 2 presents the electron density n_e and delay time t_d of the electron signal detected by the probe along a horizontal discharge axis with different pulse durations, −10 kV cathode bias and 18 sccm argon flow rate. The maximum electron density has been recorded; where $X > 10$ cm, it is in-phase with the applied voltage and where $X < 10$ cm, it is the delayed electron signal. An intense discharge region can be observed at about 10 cm from the cathode surface toward the anode. The plasma density exhibits a relatively constant value in the region until the density decreases near the chamber wall. The plasma sheath is proportional to the duration of the applied

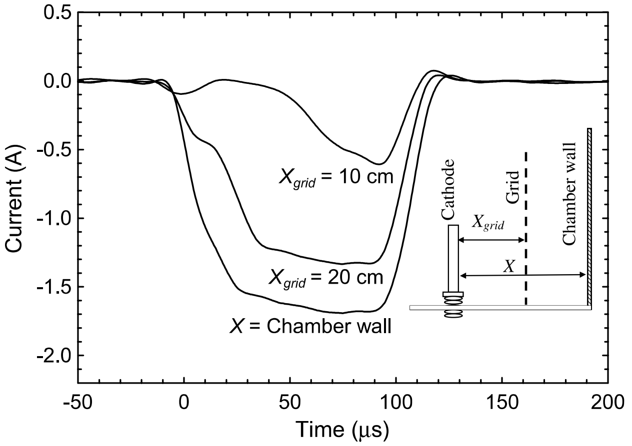

Fig. 1. Influence of conducting grounded grid on the discharge current at different grid-to-cathode distances at −10 kV and at argon flow rate of 18 sccm.

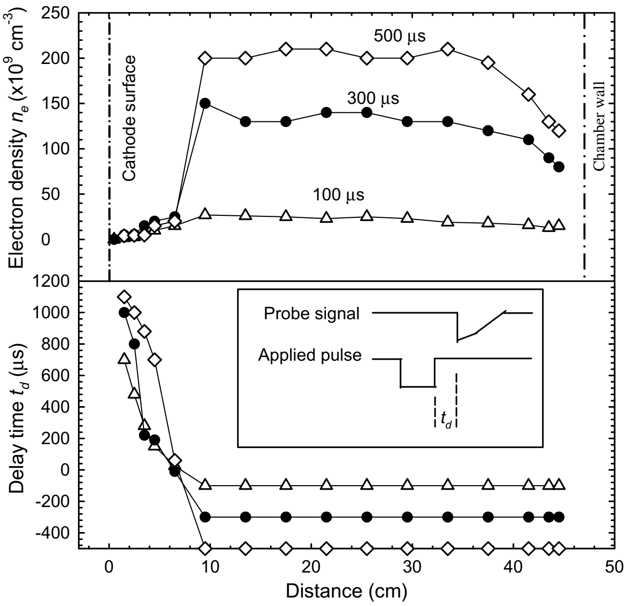

Fig. 2. Electron density and delay time of electron signal along the horizontal axis of the discharge at different pulse durations at −10 kV and argon flow rate of 18 sccm.

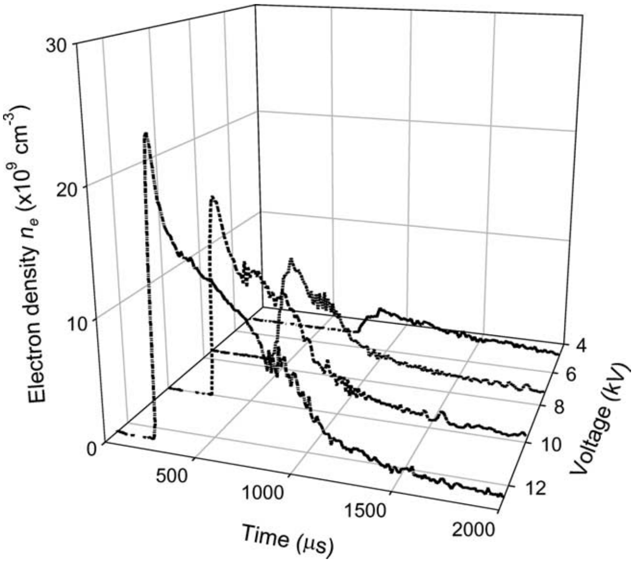

Fig. 3. Influence of the applied voltage on the electron density at pulse duration of 100 μs, argon flow rate of 18 sccm and distance from probe to cathode surface of $X = 4.5$ cm.

voltage and inversely proportional to the plasma density. However, the discharge current depends on the applied voltage and the plasma sheath. In our case, the cathode bias is −10 kV and the plasma sheath is approximately constant at 10 cm. Therefore, there is only a small increase in the time-dependent current when the pulse duration is increased (not shown here) since the plasma density shows an enhancement of one to two orders when the pulse duration is extended. Fig. 2 shows that no in-phase plasma signal (not in the time interval of the appearance of the discharge current) can be detected in the region of $X < 10$ cm and the results are similar to the observation of Khvesyuk and Tsygankov [8]. However, the delayed electron signal gives the clue that the plasma can gradually diffuse from the discharge region back to the target after the pulse is turned off. The detected plasma signal near the cathode surface is not in phase with that obtained in the other regions ($X \geqslant 10$ cm is in phase with the discharge current) whereas the plasma density can be as high as 10^9–10^{10} cm $^{-3}$.

The effects of the applied voltage on the plasma discharge characteristics are illustrated in Fig. 3 for a pulse duration of 100 μs, voltage pulse repetition rate of 30 Hz, and argon flow rate of 18 sccm. When the applied voltage is increased, a higher implantation current results. The electron density at $X = 4.5$ cm increases substantially and the delay time of the electron signal on the probe is reduced. Similar features can be observed when the argon flow rate is increased for an applied voltage of −10 kV. A higher working pressure or applied voltage increases the probability of ionization collisions enhancing the formation of the plasma. A theoretical study conducted by Hillmann et al. [18] shows that electron–neutral collision, ion–neutral collision and secondary electron emission by electron impact could be varied when changing the working pressure or applied voltage influencing the plasma generation. In Fig. 3, one can observe that the plasma signal can still be detected for 1 ms after the high-voltage pulse has been turned off. These plasma species rest in the chamber for such a long time and may be helpful to the generation of the plasma by the next pulse. Matossian reported that high frequency operation affected the current waveform [7]. It is believed that the residual plasma or excited neutrals produced by the previous pulse act as seed plasma altering the discharge properties of the next pulse. This also agrees with our previous work that seed plasma emitted from ion gauge could enhance the earlier ignition of plasma [10,11]. Thus, the proper process windows such as applied voltage, working pressure, pulse duration and frequency are essential so as to avoid over-current or electrical arcing and the subsequent damage to the hardware and sample surface.

4. Conclusion

The characteristics of pulsed high-voltage glow discharge have been investigated. The delayed discharge time and low discharge current reveal that the gas breakdown obeys the left side of the Paschen curve. Our results show that the discharge current changes significantly with the cathode bias voltage and the plasma can be distributed in a wide range of region in the chamber once it has been generated. Moreover, the plasma can be sustained for a long period of time even the pulse has been turned off. Therefore, plasma implantation and deposition can be achieved during the post-voltage-pulse period as the residual plasmas can diffuse back to the sample surface to facilitate chemical reactions and deposition on the sample surface.

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