Determinations of plasma density and decay time in the hollow cathode discharge by microwave transmission*

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(Received 26 February 2013; revised manuscript received 25 April 2013)

The microwave (MW) transmission method is employed to measure both the plasma density and the plasma decay time in the hollow cathode discharge (HCD) in argon at low pressure. The plasma density in DC-driven or pulsed HCD is on the order of 10^{12} cm^{-3}, which can block the X-band MW effectively. In the case of pulsed HCD, the MW transmittance shows the same waveform as the pulsed current during the rising edge if the driving frequency is low, but with a longer delay during the falling edge. The MW transmittance reaches a constant low level when the driving frequency is high enough. The plasma decay time in the HCD system is measured to be about 100 μs around a pressure of 120 Pa. The ambipolar diffusion is considered to be the major mechanism in the decay process.

Keywords: hollow cathode discharge, plasma density, plasma decay, microwave transmission

PACS: 52.80.Hc, 52.70.–m **DOI:** 10.1088/1674-1056/22/12/125202

1. Introduction

Hollow cathode discharge (HCD) is gas discharge between a cathode that contains a hollow structure and an arbitrarily shaped anode. Compared with the normal glow discharge, HCD possesses high energy electron beams and a high plasma density at the same current density. A large number of theoretical and experimental researches have therefore been carried out on HCD and many useful results have been put into use, e.g., for many applications in the field of plasma chemistry material processing, etc.[1–5]

All the applications of HCD plasma depend on a better understanding of several fundamental plasma properties, such as electron density, electron temperature, and electron energy distribution function (EEDF). Among them, electron density n_e is one of the key parameters. Therefore, the accurate and reliable measurement of n_e becomes a significant step in most plasma-related researches and applications. The most widely used technique to measure n_e is the Langmuir probe,[6,7] which is easy to operate and also has a good spatial resolution. However, its accuracy is strongly influenced by the probe's condition as well as the discharge conditions. The deposition of nonconductive films on the probe tip in chemical vapor deposition plasma[8] for example, causes a great difficulty in using the Langmuir probe. The plasma oscillation method[9] can give directly the absolute value of the plasma density n_e; but disadvantages exist of using a hot filament as an electron-beam source:[10,11] the short lifetime of the filament, a narrow window in pressure, and it introduces contamination of metals into the plasma reactor. The hairpin or microwave resonator probe method is applicable for low pressure plasma but to minimize measurement error in high pressure conditions, the collision and sheath correction must be considered carefully.[12] A microwave (MW) transmission method using horn antennas is an alternative choice because it is nonintrusive in plasma density measurement.

On the other hand, a DC-driven HCD is relatively high in energy consumption despite its multiple advantages. One of the possible solutions lies in the pulsed HCD. In this condition, the pulse frequency of the power source should be determined carefully to keep the balance between maintaining a high enough plasma density and reducing power consumption. The plasma decay time should therefore be determined to operate the HCD under a proper pulse frequency.

In this paper, we employ a rectangular hollow cathode discharge to produce high-density plasma. The MW transmittance method is used to measure both the HCD plasma density and the plasma decay time in the cavity. The driving frequency can be changed continuously to find a proper level that can maintain high plasma density to block X-band MW. A brief analysis is also given to evaluate the major mechanism of the decay process.

2. Experiment setup and measurement

The experimental setup is schematically shown in Fig. 1, together with the cathode structure.

The rectangular hollow cathode was made of aluminum, with an inner dimension of 70 mm × 15 mm × 20 mm and was connected with the power source through a ballast resistor R_b. The anode, an aluminum plate with a size of 100 mm × 80 mm, was placed 10 cm above the cathode and grounded through a sampling resistance R. The outer surface of the cath-

*Project supported by the National Natural Science Foundation of China (Grant No. 11005009).

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ode was covered by mica so that the discharge could only be excited in or from the inner surface of the cathode. A pair of horn antennas working at X-band (8.2 GHz–12.4 GHz) were located symmetrically beside the hollow cathode and connected to a vector network analyzer (VNA, Agilent E8362C, 10 MHz–20 GHz) through 50-Ω coaxial cables. The cathode cavity was of 70 mm × 15 mm, which was slightly larger than the size of a MW horn antenna's opening (60 mm × 10 mm). The discharge system was located in a glass vacuum chamber filled with pure argon. The HCD was driven by a negative DC or square-wave voltage. The discharge current and the voltage applied to the cathode were measured by a digital oscilloscope (Tektronix DPO4104B). The MW excited by the VNA was fed into the cavity by the emitting antenna, interacted with the plasma, and then returned to VNA by the receiving antenna after passing through the HCD plasma. The MW could be changed in frequency and power in experiments. Also the VNA could operate in "time sweep" mode so that one could obtain comprehensive information about the MW passing through the HCD plasma.

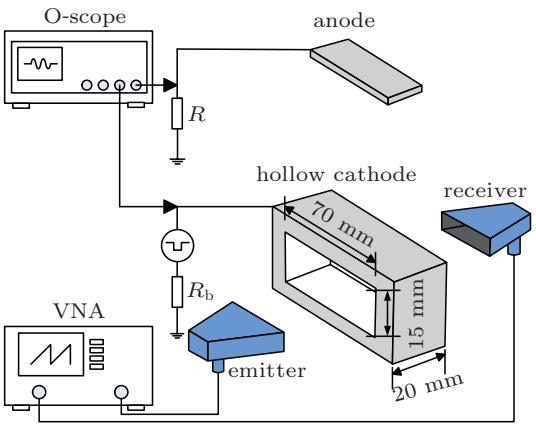


Fig. 1. (color online) Experimental set-up.

Physically, the plasma frequency f_p is determined by the plasma (mainly the electron) density n_e, given as

$$f_p = f_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}, \tag{1}$$

where e is the electric charge, m_e is the mass of the electron, and ε_0 is the permittivity of free space. The plasma density can therefore be estimated after the plasma frequency has been measured. The plasma frequency in this MW transmission method is determined by the critical frequency of the MW that is just able to be stopped by the plasma. When the MW frequency is higher than the plasma frequency, the MW can pass through the plasma. Otherwise, it will be reflected from the plasma surface. Therefore, the MW transmittance will change sharply when the frequency approaches the plasma frequency. The critical plasma frequency is generally recognized as the plasma cut-off frequency. Under the case of pulsed plasma, the MW transmittance shows a time-dependent characteristic, reflecting the change of plasma density in volume. From this time-dependent MW transmittance, one can estimate the decay time of the HCD plasma.

3. Results and discussion

3.1. DC-driven HCD

In experiments, a stable discharge can be obtained inside the hollow cathode when the pressure ranges from 30 Pa to 300 Pa. Below 30 Pa, the discharge becomes a little unstable in our HCD system, while above 300 Pa, the HCD is difficult to produce. For the following measurement, we set the gas pressure to be 120 Pa. Under this condition, the discharge is almost localized and the negative glow region is limited inside the cavity, with a long Faraday dark space between the cathode and the anode, or namely a "localized HCD".[13] The plasma is weak at the beginning when the current is small, but expands to the whole cavity as the current increases. The HCD can operate in abnormal glow mode or show the hollow cathode effect (HCE) according to the discharge current. The detailed characteristics of the localized HCD has been discussed in Ref. [13].

Since the characteristics of plasma-MW interaction might vary with the energy level, we check first this interaction by feeding different MW powers into the plasma. The "power sweep function" of VNA is used to obtain the relationship between MW input power P_I and transmission power P_T after transferring the plasma as shown in Fig. 2 for a discharge current of 80 mA (the corresponding current density is 6.7 mA·cm^{-2}).

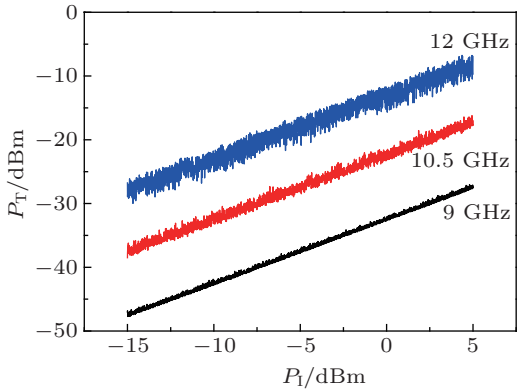


Fig. 2. (color online) Plots of transmission power versus input power for different MW frequencies with the current of the HCD plasma being 80 mA (6.7 mA·cm^{-2}).

It is seen in Fig. 2 that the received MW transmission power increases proportionally with the input power. This suggests that the HCD plasma has a linear response to the incident MW power. Or, the input power does not affect the transmission characteristics of the MW in the CD plasma system (at

least in the tested power range from −15 dBm to 5 dBm in X-band). Then, any input power of the MW will give the same relative transmission in the MW transmission method for measuring plasma density. Since the sensitivity increases with the input power, we set the input power to be 5 dBm in the next measurements.

We consider the MW transmittances for different discharge conditions. In the experiment, when the HCD is powered off (or OFF state), there is still MW energy loss (about −10 dB) of transmission for the whole X-band due to the mismatch between the antenna and the cavity. Therefore, we use a relative instead of an absolute transmittance to evaluate the MW transfer in the HCD plasma. The function "through-response calibration" of the VNA is adopted and the hollow cathode system without discharge plasma (or OFF state) is modeled as the calibration standard (or the reference level). In this way, the transmittance is evaluated by comparing each of the transmitted powers in different conditions of the discharge plasma with the transmitted power of the OFF state, i.e., the ratio of the detected MW power P_t to the reference value P_{t0}.

Figure 3 shows the variations of transmittance with current increasing for MW frequencies of 9 GHz, 10.5 GHz, and 12 GHz.

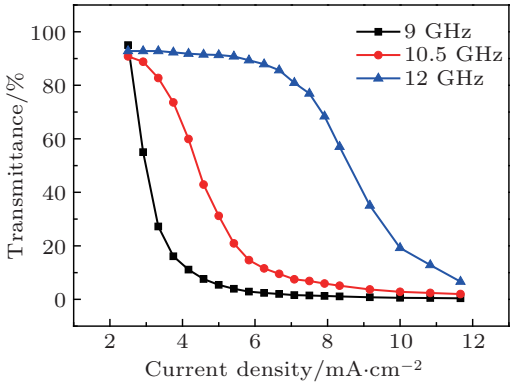


Fig. 3. (color online) Variations of transmittance with current increasing for different MW frequencies.

As expected, the MW transmittance depends on the discharge current density, which is a function of plasma density n_e. When the current density is small (e.g., 3 mA·cm^{-2} at beginning), the transmittances of MWs at three different frequencies are all around 90%, showing a transmission state of MW. As the current density increases, the transmittance decreases quickly. For MW frequencies of 9 GHz and 10.5 GHz, the transmittance decreases rapidly and reaches 5% or below, when the current density exceeds 5 mA·cm^{-2} and 8 mA·cm^{-2}, respectively, showing a blockage state. This means that the plasma frequency is approaching the MW frequency that leads to a significant drop in transmittance. For higher-frequency MWs (i.e., 12 GHz), the transmittance stays at a high level and remains almost unchanged before a current density of 6.5 mA·cm^{-2}. Then the transmittance decreases significantly and reduces finally below 5% when the current density reaches 12 mA·cm^{-2}.

The variations of transmittance with the MW frequency increasing are shown in Fig. 4 for different current densities.

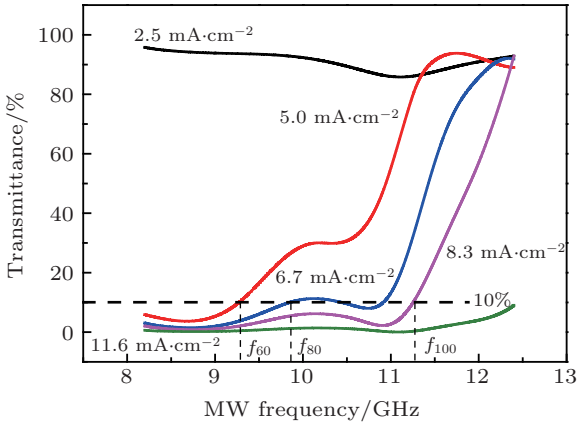


Fig. 4. (color online) Dependences of transmittance on MW frequency for different discharge current densities.

It is seen that when the discharge current density is as small as 2.5 mA·cm^{-2}, the whole X-band MW can pass through the HCD plasma with a very low energy loss (less than 10%). For higher current densities, the transmittance rises to 10% when the MW frequency reaches a certain value and rises rapidly to above 90% as the MW frequency continues increasing. For a very large current density (e.g., 11.6 mA·cm^{-2}), the whole X-band MW keeps a low level of transmittance below 10% or in blockage state.

We set the critical transmittance to be 10%, below which the MW is suggested to be blocked by the plasma. Then one can obtain the plasma frequency from the turning point at 10% in Fig. 4 for HCD plasma at each current, which is determined to be 9.3, 9.9 and 11.3 GHz for HCD current densities of 5.0, 6.7 and 8.3 mA·cm^{-2}, respectively. The corresponding plasma densities are estimated (according to Eq. (1)) to be 1.07, 1.22 and 1.58×10^{12} cm^{-3}. This result is in agreement with the previous experimental data that the localized HCD plasma in a similar structure can act as a metal to transfer the X-band MW in microstrip lines.[14] The plasma density under a smaller or larger current density (e.g., below 2.5 mA·cm^{-2} or above 11.6 mA·cm^{-2}) can also be determined if one expands the MW band of the measuring system.

3.2. Pulsed HCD

When a negative square-wave voltage is applied to the hollow cathode, both the discharge current and the MW transmittance change with time accordingly. Figure 5 shows the waveforms of the applied voltage, the discharge current, and the transmittance of 9.1-GHz MW with a voltage amplitude of 450 V and a driving frequency of 1 kHz.

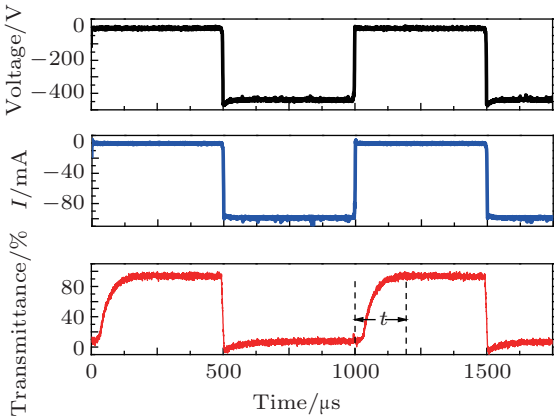


Fig. 5. (color online) Time evolutions of the applied voltage, the discharge current and the transmittance of 9.1-GHz MW with a voltage of 450 V and a driving frequency of 1 kHz.

It is seen that during the rising edge of the voltage pulse, the HCD current and the MW transmittance follow well the voltage waveform with a time lag of less than 10 μs. This indicates that the change of MW transmittance nearly synchronizes with the process of plasma discharge. Once the plasma is generated, the MW will be blocked immediately, with a transmittance of less than 10%. When the voltage is powered off (i.e., during falling edge or the decay of the plasma) however, it takes a relatively long time for the transmission signal to fully return to its initial level. Actually, the MW transmittance increases gradually from the minimum (about 10%) to the maximum (more than 90%) in a period of $t = 200$ μs, even if the plasma current has disappeared in the HCD. The time for the density reducing to the half maximum (or the plasma decay time) can be estimated to be of the order of 100 μs.

Generally, the plasma decay relates to two aspects, i.e., the plasma diffusion and the recombination of ions and electrons. The plasma diffusion will be ambipolar if its density is greater than 10^8 cm^{-3}. This is satisfied in our HCD system. In fact, the plasma density can reach as high as 10^{12} cm^{-3}, as mentioned above. Then the relationship between the diffusion displacement r and the decay time can be expressed as[15]

$$\bar{r}^2 = 4D_\alpha \tau = 4D_\mathrm{i}\left(1 + \frac{T_\mathrm{e}}{T_\mathrm{i}}\right)\tau, \qquad (2)$$

where D_i is the diffusion coefficient of the ion and T_e and T_i are the temperatures of the electron and the ion. In low pressure HCD, the typical electron temperature T_e is about 1 eV (10^4 K) and the ion temperature T_i is the room temperature of 300 K, D_i is about 47 cm^2·s^{-1} for Ar^+ in argon at 133 Pa,[16] and the diffusion displacement can be regarded as the size of the discharge cell (or 1 cm). Then the decay time due to ambipolar diffusion is estimated to be about 150 μs, which is of the same order as the measured value.

On the other hand, the main ions in low pressure argon plasma are Ar^+ and the density ratios of Ar^{2+}/Ar^+ and Ar_2^+/Ar^+ are very low (only of the order of 1%–10%).[17] Therefore, the major recombination processes should be the radiation recombination ($e + Ar^+ \rightarrow Ar + h\upsilon$) and/or the three-body recombination ($e + Ar^+ + M \rightarrow e + Ar + M$) due to Ar^+ and the electron. For the radiation recombination, the rate is $k_\mathrm{r} = 10^{-13}$ cm^3·s^{-1} under these conditions.[18] For the three-body recombination, the main third partner is the electron, which has a recombination rate of $k_\mathrm{t} = 10^{-27}$ cm^6·s^{-1}, while the heavy particles (ions and neutrals) are ineffective as the third-body partner.[19] Then the corresponding characteristic time determined by the two recombination reactions is estimated to be $\tau = 1/k_\mathrm{r} n_\mathrm{e} = 10$ s or $\tau = 1/k_\mathrm{t} n_\mathrm{e}^2 = 10^3$ s respectively, which are much longer than the measured value (of the order of 100 μs). This suggests that the plasma decay in the pulsed HCD is mainly controlled by the ambipolar diffusion process rather than the recombination. This is consistent with the previous results in Ref. [17].

The time-dependent change of MW transmittance reflects the change of plasma density with time. The above experimental result indicates that the plasma takes a period of time to decay before the density decreases below a critical value. If the driving frequency is high enough, there will be high-density plasma remaining in the volume so that the MW cannot pass freely through the plasma region. This can be demonstrated when we increase the frequency of the square-wave voltage, as shown in Fig. 6.

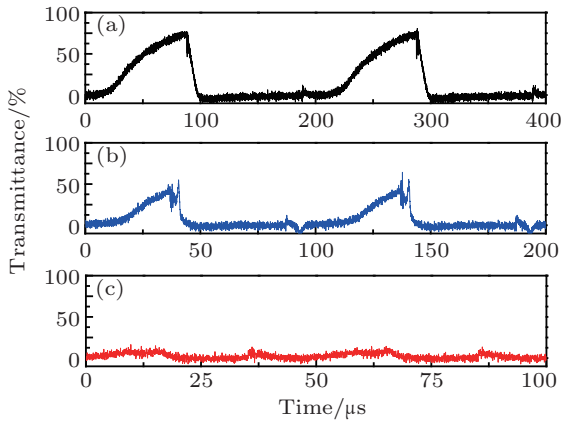


Fig. 6. (color online) Time evolutions of MW transmittance at different driving frequencies of (a) 5 kHz, (b) 10 kHz, and (c) 20 kHz. The pulsed voltage is 450 V in amplitude and the MW frequency is 9.1 GHz.

One sees in Fig. 6 that the MW signal becomes smaller and smaller both in the magnitude and in the time duration with the driving frequency increasing. When the frequency is 20 kHz or above, the MW is actually blocked by the plasma, even during the OFF period of the applied voltage. In fact, the amplitude of MW transmittance decreases almost linearly with the driving frequency, as shown in Fig. 7. This demonstrates that the remaining plasma density is controlled mainly by the decay time. When the pulse duration of the applied voltage is shorter than the plasma decay time, the plasma density will keep a high level as in the ON state of the voltage. The critical

driving frequency is about 20 kHz in these conditions for the MW blocked completely by the pulsed HCD plasma. That is to say, if the frequency is higher than 20 kHz, the pulsed HCD plasma can act as a stable plasma to block 9.1-GHz MW.

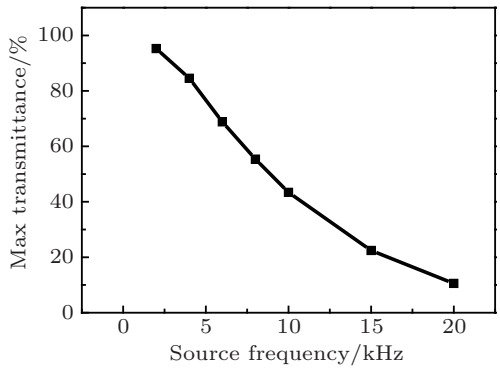


Fig. 7. Variations of maximum of 9.1-GHz MW transmittance with driving frequency increasing. The pulsed voltage is 450 V in amplitude.

4. Conclusion

We employ the microwave transmission method to measure both the plasma density and the plasma decay time in localized HCD at low pressure. The MW transmission through the HCD plasma decreases significantly when the discharge current grows up sufficiently in DC-driven HCD. The plasma density in this HCD system is of the order of 10^{12} cm^{-3}, which is high enough to block X-band MW effectively. In the case of pulsed HCD, the MW transmittance shows the same waveform as the pulsed current waveform during the rising edge if the driving frequency is low, but with a longer delay during the falling edge. The MW transmittance decreases linearly in amplitude with the driving frequency at a given current density and finally reaches a constant of a low level. For 9.1-GHz MW, the pulsed HCD plasma at 450 V in amplitude of the pulsed voltage shows a blockage state when the driving frequency rises above 20 kHz. The plasma decay time is of the order of 100 μs in this HCD system, around 120 Pa. The decay process is mainly controlled by ambipolar diffusion.

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