Effect of the cathode structure on micro-hollow cathode discharge

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Abstract: Micro-hollow cathode discharges (MHCD) have been investigated by two-dimensional particle-in-cell/Monte-Carlo collision (PIC/MCC) simulations. The discharges were produced in a metal/dielectric/metal sandwich structures with a cylindrical hollow cathode. The diameter of the hollow cathode is about 200 ~ 400 μm. The discharge gas is argon at 200 Torr. The discharge processes of micro-hollow cathode with planar electrode at the edge of cavity and without planar electrode were obtained. The distributions of the electric field and electron density in the two different micro-hollow cathodes have been compared. The effect of the diameter of the micro-hollow cathode was also investigated.

Keywords: MHCD, Micro-plasma, numerical simulation

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1. Introduction

The study of Hollow cathode discharges (HCD) has a long history in the field of gas discharges, and HCDs are widely used in many applications including spectral lamps, lasers et al[1]. The conventional hollow cathode can be in various structures, such as a pair of plane parallel plates or a hollow cylinder. A “hollow cathode effect” (HCE) will be obtained in the discharge of aforesaid structures. Generally, the HCE indicates that the electrons oscillate between the negative glows regions of the faced cathode surfaces[2]. During the oscillation, the high energy electrons can ionize and excite the gas atoms. Therefore high density plasma and large numbers of active particles can be obtained in HCD.

In last two decades, Micro-Plasma has attracted many attentions[3]. Schoenbach et al propose that reducing the dimension of hollow cathode to about tens to hundreds of micrometers, to obtain micro-plasma under higher pressure. And a sandwich type micro-HCD had developed by them[4]. After that, various structures of MHCD were investigated by experiments in many groups. But the hollow cathode effect in MHCD is still not confirmed in those experiments[3].

Because of the sub-millimeter dimensions in MHCD, study of the discharge processes by experiment is difficult. Computer simulation of MHCD can be a useful tool to reveal the physics characteristics of micro-discharge. Many researches use fluid model to investigate the characteristics of sandwich type MHCD[5-7]. Few results of MHCD are provided by PIC/MCC method[8].

In this paper, the discharge evolution in sandwich type MHCD is investigated by PIC/MCC simulation. The effect of the cathode structure is discussed. Two different discharge processes are obtained by simulation.

The article is organized as follows. Section 2 describes the discharge device used in 2D PIC/MCC simulation. The calculated results are given Section 3. And the effects of different discharge structure have been discussed. Finally, the conclusion is summarized in Sec. 4.

2. Structure and model of MHCD

2.2 Structure of MHCD

The MHCD device investigated in our simulation consists of a dielectric layer covered with two metal electrodes. A hole drills through the three material
layers. According to the characteristics of MHCD structure, an axisymmetric coordinates system is adopted in this work. The cross section of the MHCD is shown in Figure 1. The region with oblique line represents the dielectric layer with thickness $z_2$, and the permittivity of the dielectric layer is 7. The cathode with thickness $z_1$ is set at the left side of the dielectric layer. The anode is at the right side and the thickness is $z_3$. The radius of the MHCD hole $d$ is set to 100–200μm, and the radius of the whole region $r$ is 400μm. The left boundary of simulation region is $z_0$ apart from the cathode. A second anode is used as the right boundary. The distance between the left and the right boundary $z_a$ is 1500μm. The discharge gas is pure Ar, and the pressure is 200Torr.

2.2 Simulation models and conditions

The discharge process is simulated by a two-dimensional PIC/MCC method [9]. Two species are considered in simulation: electron, Ar+. The coefficients of secondary electron emission $\gamma_{Ar}$ of Ar$^+$ on the metal layers and the dielectric layer are 0.2 and 0.05, respectively.

In our simulation, the ionization and elastic collisions between electrons and Ar atoms are considered, also the elastic and charge exchange collisions between Ar$^+$ and Ar atoms. The cross sections are taken from Ref.[9].

The potentials applied on the cathode and the anode in the simulation is -500V and 0V respectively. A potential of 10V is applied to the second anode to provide a bias voltage. Neumann boundary condition is adopted at other boundaries.

The initial densities of electron and Ar ions are both $10^{14}$m$^{-3}$. In order to reduce the time of calculation, particles are initialized on in the hole. The maximum total number of macro-particles is set to $10^6$. The time step of Poisson solver is $10^{-12}$s. The time step of electron and ion advancing is $10^{-13}$s and $5\times10^{-12}$s respectively.

3. RESULTS AND DISCUSSION

Firstly, we simulate the discharge process in a micro-hollow cathode. The radius of the cathode hole is 200μm, viz. the $pD$ product is 8 Torr·cm. The other parameters of the sandwich structure are given in Table 1.

<table>
<thead>
<tr>
<th>parameter</th>
<th>$z_0$</th>
<th>$z_1$</th>
<th>$z_2$</th>
<th>$z_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>μm</td>
<td>600</td>
<td>100</td>
<td>200</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 2 shows the spatial distributions of electrons at the initial stage of the discharge. From the two figures one can see that, most of electrons are accumulated in the hole and will be collected by the anode. For this structure, the discharge is ignited at the inner edge of the anode.

After the charge formed in space, the discharge develops fast, as shown in figure 3. At 585 ns, the maximum density of electron is increased from the initial value $10^{14}$m$^{-3}$ up to $7.3\times10^{16}$m$^{-3}$. The plasma still locates near the anode. Then electrons move toward to the cathode along the dielectric layer. The
maximum density increases by 2 orders in about 50 ns. Finally the high density plasma over 10^20 m^-3 is formed in the cathode region.

**Figure 3.** Spatial-temporal distributions of electron density in micro-hollow cathode discharge (d=200μm, z1=100μm).

Figure 4 is the spatial-temporal distribution of the potential during the development of micro-hollow cathode discharge. At the beginning of the discharge, the electric field is uniform approximately in the center of the hole, while the field is stronger near the inner edges of the cathode and the electrode. Electrons will move along the electric field at the initial stage as shown in figure 2. When the particle density is over 10^{18} m^-3, an equi-potential region also the plasma channel is formed and contract to the cathode. The plasma channel is over 120 μm apart from the axis of the hole. From the figures, one can see that the discharge is close to the electrodes and the dielectric layer. The discharge process is similar to the DC discharge along a dielectric layer. According to the distributions of electron density and potential, a bright ring will be formed in the micro-hole.

**Figure 4** The evolutions of potential distribution in micro-hollow cathode discharge (d=200μm, z1=100μm).

Another discharge process under different micro-hollow cathode parameter is also simulated. The cathode is considered as a planar electrode with a hole, viz. the thickness of cathode z_1 is increased to 700μm and z_1=0μm, the left side of the hole is also a metal electrode. The radius of the micro-hole is 150μm. Other parameter is the same as that described in Table 1.

Figure 5 and figure 6 is the distribution of the electron density and the potential during the discharge respectively. Like the evolution of previous MHCD, the discharge is also initiated at the edge of the anode. But as the discharge developing, high density electron and equi-potential region are formed near the axis of the anode hole. This region moves towards the cathode along the axis. We consider that a bright line will be formed in the center of the hole.

Comparing figure 4 and figure6, one can find that the potential distribution in the micro-hole of two discharge structures at 1ns is similar to each other. But a ring-type and a linear-type discharge are
formed eventually. This is mainly caused by reducing the radius of micro-hole.

Figure 5 The evolutions of potential distribution at $d=150\mu m$, $z_1=700\mu m$.

Figure 6 The evolutions of potential distribution at $d=150\mu m$, $z_1=700\mu m$.

4. Conclusion

In this paper, the metal/dielectric/metal sandwich structures with a cylindrical micro-hollow cathode have been investigated by two-dimensional PIC/MCC simulations. The distributions of the electric field, electron density in two different micro-hollow cathodes have been obtained. The results show that ring-type and linear-type discharge can be formed in MHCD with different radius of the micro-hole. The influence of the cathode structure on the discharge will be investigated further in future.

Acknowledgments

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References