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Degradation of the Emission Current from the Field Emitter Caused by Ion Bombardment ※

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Abstract: In field emission devices, the emission current sometimes degrades with the time. The mechanism of the current degradation is complicated. In this paper, a program is used to simulate the movement of the electron beam from a field emitter. According to the current distribution and the trajectories of the primary electron beam, it is shown that the residual gas is ionized and the ion pairs are generated. The trajectories of the positive ions are simulated. With the different locations and kinetic energy of ions, the damage of the emitter surface is analysed and the variation of the profile of the field emitter is obtained. Finally, the degradation of the emission current is predicted with different gas pressures and primary electron beam current.

Key words: field emitter, degradation of the emission current, ion bombardment

In the field emission device, the electrons are emitted from the field emitter. However, the emission current is not very stable. Sometimes it decreases with the working time. The variation of the emission current will cause the shifting of working performance for the field emission devices[1,2].

The degradation of the emission current is caused by ion bombardment. In the field emission device, the primary electron beam is emitted from the tip of the emitter. Due to the residual gas, a few ion pairs are generated by the electron-gas collisions. The positive ions are pulled back to the field emitter by the strong electric field. Due to the bombardment of the high-energy ions, the surface of the emitter tip is damaged. The profile of the tip has a variation. As results, the electric field around the tip also has a perturbation. Because the emission current density is very sensitive to the electric field, the emission current can have degradation because of the ion bombardment.

Some methods have been proposed to protect the field emitter[2]. However, the mechanism of degradation of the emission current is not well known. This article uses simulation programs to analyse the degradation of emission current. Firstly, the current distribution and the movement of the primary electron beam are simulated. According to the simulation results, the ionization efficiency of the residual gas is calculated. The initial conditions of the positive ions are also determined. The trajectories of these positive ions are simulated. With the different locations and kinetic energy of the ions, the damage of the emitter surface is analysed. The degradation of the emission current because of the profile variation of the tip is predicted.

1 Simulation Model of the Degradation of the Emission Current Caused by Ion Bombardment

In the electrostatic field, it is usually said that the charge mass ratio can be made to disappear from the trajectory equation. Hence, the trajectories of ions should be the same as that of electron in the electrostatic field[3]. In the field emitter device, all of the positive ions should bombard on the tip of the emitter. However, in the practical application, the initial velocity of the positive ion is not zero. It is also different from that of the primary electron. Therefore, the charge mass ratio influences the trajectory of the charged particle. The movements of positive ions are not the same as the primary electrons.

1.1 Simulation of the primary electron beam

To analyse the effect of the ion bombardment, the behaviors of the primary electron beam must be obtained first. In our calculation, the space charge effect is ignored. Therefore, the distribution of the potential can be obtained by solving Laplace equation.

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$$\left.\begin{aligned}&\frac{\partial^2 \phi}{\partial x^2}+\frac{\partial^2 \phi}{\partial y^2}+\frac{\partial^2 \phi}{\partial z^2}=0\\&\phi|_{\text{emitter}}=\phi_{\text{cathode}}\\&\phi|_{g1}=\phi_{g1},\phi|_{g2}=\phi_{g2},\cdots,\phi|_{gn}=\phi_{gn}\end{aligned}\right\}\quad(1)$$

where ϕ is the potential of the grid; g_1, $g_2,\cdots$, g_n represent the different electrodes.

After the calculation of the potential, the electric field at arbitrary point can be estimated with the interpolation method. The emission current density of the field emitter is obtained from Fowler-Nordheim formula[4]

$$J=1.54\times10^{-6}\frac{E^2}{\phi t^2(y)}\exp\left(-6.87\times10^{7}\frac{\phi^{\frac{3}{2}}v(y)}{E}\right)\quad(\text{A/cm}^2)\quad(2)$$

where E is the electric field at the tip in V; $v(y)$ and $t^2(y)$ are electric field dependent elliptical functions; ϕ is the work function of the emitter material in eV; y, the image charge lowering contribution to the work function, is given by $y=3.79\times10^{-4}E^{\frac{1}{2}}/\phi$. With an approximation over the operation range of most cathodes, it is generally assumed that $t^2(y)=1.1$ and $v(y)=0.95-y^2$.

In the simulation, the surface of the field emitter is divided into a few elements. The electrons are emitted from the surface elements. However, the distributions of these electrons to the ionization are different. The emission currents are regarded as the weighted factors.

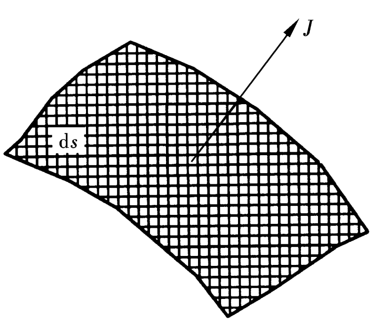

Fig.1 Surface element for the electron trajectory

In Fig.1, J is the current density and ds is the area of the emission element, $J\cdot \mathrm{d}s$ is the weighted factor of the trajectory. From the motion equations, the trajectories of the electrons and ions can be obtained. In Cartesian system, trajectories are described as[3]

$$\left.\begin{aligned}m\frac{\partial^2 x}{\partial t^2}&=-q\frac{\partial \phi}{\partial x}\\m\frac{\partial^2 y}{\partial t^2}&=-q\frac{\partial \phi}{\partial y}\\m\frac{\partial^2 z}{\partial t^2}&=-q\frac{\partial \phi}{\partial z}\end{aligned}\right\}\quad(3)$$

where m is the mass of the particle; q is the charge of the particle.

In our calculation, it is suggested that the primary electron transfers its energy to the ion after the ionization. Apart from this, the ion also has thermal velocity, which can be determined by Maxwell-Boltzmann distribution.

$$v_{\text{thermal}}=\sqrt{\frac{2.0kT}{nm}}\quad(4)$$

where k is Boltzmann constant; m is atomic mass unit; n is the atomic number. The direction of the thermal velocity is generated randomly.

1.2 Degradation of the emission current

The electrons emitting from the emitter tip are accelerated by the electric field and move to the anode. These electrons cause ionization of residual gas atoms in the vacuum. The number of ion pairs generated per primary electron per unit length and per unit residual gas pressure can be expressed as

$$\left.\begin{aligned}&P_e(V_p)=0 && V_p\leqslant V_{\text{ion}}\\&P_e(V_p)=\frac{1}{\left(\frac{1}{\alpha(V_p-V_{\text{ion}})}+\frac{1}{\beta V_p^{-\gamma}}\right)} && V_p>V_{\text{ion}}\end{aligned}\right\}\quad(5)$$

where V_p is the ratio between energy of the primary electron and the charge of electron; V_{ion} is the ionization potential; α,β,γ are some constants, which can be obtained from the experimental curves.

After determination of the initial conditions of the ions, the movements of the ions are calculated with Eq.(3). These ions bombard on the surface of the field emitter and cause the degradation of the emission current. In this article, we use a semi-empirical model to estimate the ion damage.

According to the Sigmund model, the number of atoms leaving the surface of target is[5,6]

$$Y(E_i)=\frac{3.56}{U_0}\frac{Z_t Z_p}{(Z_t^{\frac{2}{3}}+Z_p^{\frac{2}{3}})^{\frac{1}{2}}}\cdot\frac{M_p}{M_t+M_p}\alpha\left(\frac{M_t}{M_p}\right)S_n(\varepsilon)\frac{n_{\text{atoms}}}{n_{\text{ion}}}\quad(6)$$

where $(Z,M)_{t,p}$ stand for target and projectile atomic number and mass, respectively; U_0 is an average binding energy of escape barrier; ε is the reduced energy.

$$\varepsilon=\frac{E_p}{E_0}\quad(7)$$

where E_p is the kinetic energy of the incident ion; E_0 is a normalising constant determined by the atomic mass and respective atomic number of the incident ion and target material. $S_n(\varepsilon)$ in Eq.(6) is the reduced nuclear or elastic stopping. It can be well represented by

$$S_n(\varepsilon) = \frac{0.5\ln(1+\varepsilon)}{\varepsilon + 0.14\varepsilon^{0.42}} \tag{8}$$

2 Degradation of the Emission Current of the Field Emitter

With the method described in section 1, the trajectories of the primary electron beam are calculated. The weighted factor of every trajectory is determined by its current, which is obtained from Fowler-Nordheim equation. The primary electron beam is shown in Fig.2.

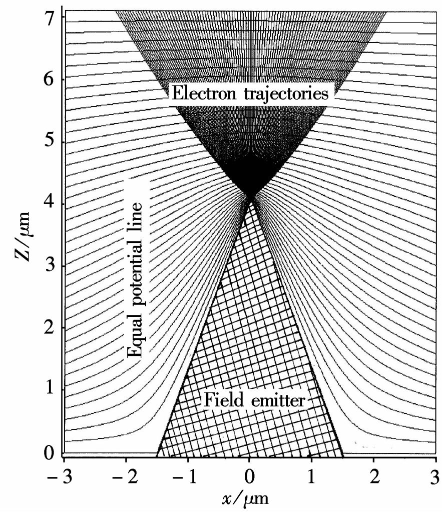

Fig.2 Primary electron beam which is emitted from field emitter

After the calculation of the primary electron beam, the efficiency of ionization and the movement of positive ions are simulated. Due to the effect of the getter, some types of the positive ions can be absorbed. In this article, we only study the bombardment of Ar positive ions on silicon emitter. Fig.3 gives the trajectories of Ar positive ions.

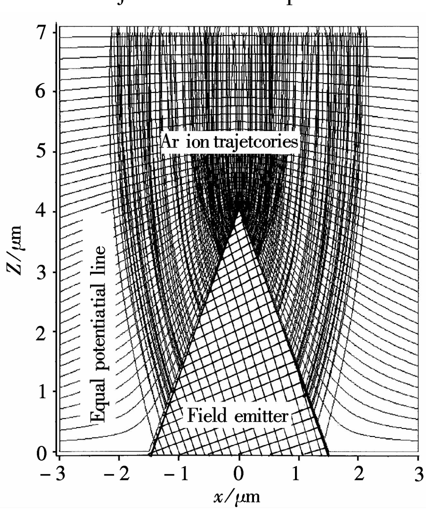

Fig.3 The ion trajectories for the field emitter

When the ionization happens near the tip of the field emitter, most of the positive ions are accelerated and hit on the tip of the emitter. When the ions are generated in the region in which the potential is high, such as near the anode, ions are also pulled back to the emitter. However, most of the ions hit on the lower part of the emitter. In other words, these ions can not influence the profile of the tip seriously.

Due to the bombardment of positive ions, a few materials will fly off from the emitter tip. Therefore, the profile of the emitter tip has a variation. Fig.4 shows the variation of the tip after ion bombardment.

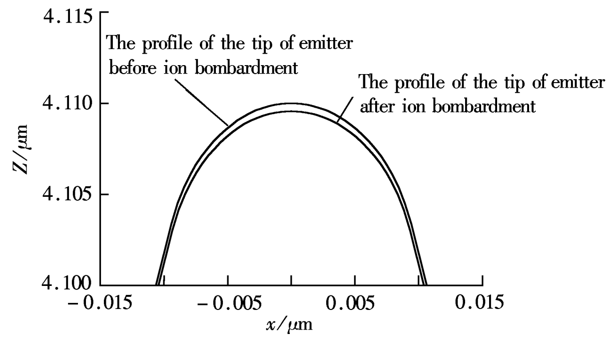

Fig.4 The variation of the emitter tip after ion bombardment

The variation of the profile of emitter tip will change the electric field. It is well known that the density of emission current is very sensitive to the electric field. Consequently, the variation of the emitter tip causes the degradation of the emission current. Fig.5 to Fig.7 give the degradation of the emission current with different primary electron beam currents and different pressures of the residual gas.

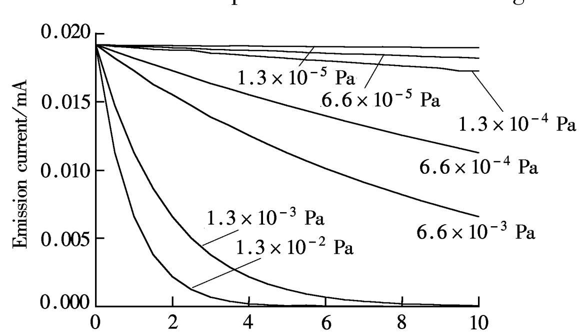

Fig.5 The degradation of the emission current, the primary electron beam current is 20?mA

From these curves, it can be seen that the degradation of the emission current is determined by the pressure of the residual gas. If the vacuum condition becomes poor, more ion pairs are generated. The emission current decreases quickly.

The degradation of the emission current is also determined by the working time. With the increment of

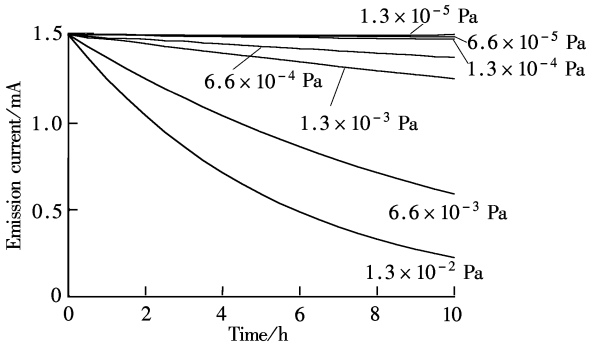

Fig. 6 The degradation of the emission current, the primary electron beam current is 1.5?mA

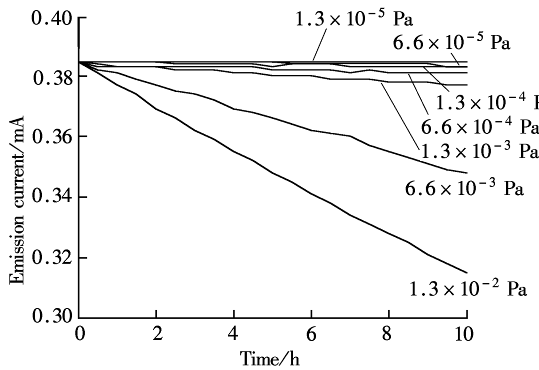

Fig. 7 The degradation of the emission current, the primary electron beam current is 0.38?mA

the time, more materials fly off from the surface of emitter. As results, the emission current degrades with the working time, especially for the bad pressure of residual gas.

The current of primary electron beam influences the efficiency of the ionization. When the primary electron beam current is high, more ions are generated. Therefore, the ion bombardment causes a large degradation of emission current. The current of primary electron beam in Fig.7 is the lowest. Hence, the emission current degrades much slower than that in Fig.5 and Fig.6.

3 Conclusions

The ion bombardment causes the degradation of the emission current of the field emitter. However, the damage from ion bombardment is not well known. This article simulates the processes of the electron emission, the ionization, the ion bombardment, and the degradation of the emission current.

The ions generated near the tip of the field emitter influence the emission current most seriously. Most of the ions, which are generated in the region near the anode, bombard on the low part of the field emitter. Thus, they do not contribute a lot to the degradation of the emission current.

The degradation of the emission current is determined by the pressure of the residual gas. If the pressure of the residual gas is very bad, a lot of ion pairs are generated. The emission current of the field emitter degrades quickly.

With the increment of the working time, more and more materials fly off from the surface of the emitter. The emission current decreases with the working time due to the ion bombardment, especially for the bad pressure of the residual gas.

The current of the primary electron beam influences the ionization efficiency. When the primary electron beam current is high, more ions are generated. Therefore, the emission current decreases faster than that with low primary electron beam current.

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离子轰击引起的场致发射体发射电流跌落的研究

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摘　要　在场致发射器件中,发射电流通常会随着工作时间的增加而跌落.发射电流跌落的机理较为复杂.本文模拟分析了一次电子从场致发射发射体表面的发射情况.根据一次电子的电流密度分布和运动轨迹,研究残余气体分子的电离.然后计算正离子在电场中的运动轨迹,利用半经验模型分析不同能量的正离子对发射体表面的损伤情况,最后估计出在不同残余气压和一次电流下发射电流的衰减.

关键词　场致发射体, 发射电流跌落, 离子轰击

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