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Transverse energy distribution analysis in a field emission element with an insulator funnel

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Abstract

In a field emission display panel, an insulator funnel, which is called Hop funnel, has been used to separate the cathode and the anode. Secondary electrons generated on top of the insulating surface due to the primary electron bombardment are drawn to the exit hole of the funnel by the electric field. Therefore, the energy distribution of these secondary electrons influences the quality of the FED. In this paper, an experimental instrument has been built to study the energy distribution of the secondary electrons on the anode screen in a field emission display element. Simultaneously, the relevant simulation with different primary conditions has been made. The both numerical simulation and experimental results are compared, and it is found that: (1) The experimental results can be well described by the numerical simulations; (2) the distance between the emitting center and the funnel hole has a dramatic influence to the number of electrons that can leave the hop funnel; (3) the distance between the anode and the funnel does not have a strong influence on the energy distribution; (4) the transverse energy distribution of hop electrons is very low.

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Keywords: Secondary electron; Energy distribution; Field emission; Hop funnel

1. Introduction

Recently, a structure, which is called HOPFED, has been proposed for the field emission display [1–3]. Fig. 1 gives the basic structure of the Hop funnel. In this structure, an insulator funnel is used to separate the cathode and the anode.

As shown in Fig. 1, the primary electrons are emitted from the cold cathode, such as Spindt tip array, carbon nanotube array, etc. Extracted electrons from the cold cathode are accelerated towards the HOP plate where they induce secondary electrons. The secondary electron leaves the

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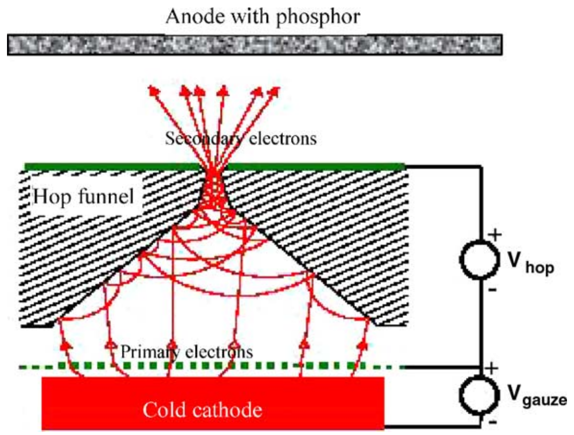

Fig. 1. The basic structure of the Hop funnel.

insulator surface with an initial energy. Due to the influence of the electric field, this secondary electron will bombard on the insulator surface again. Therefore, more secondary electrons can be generated. The electric field inside the insulator funnel has a component which is parallel to the insulator surface. With the influence of this electric field component which is parallel to the surface, the secondary electrons can hop along the surface of the funnel. A self-regulated transport mechanism based on SEE leads the current to the funnel. With the influence of the electric field, these secondary electrons are pulled out of the hop funnel and hit on the screen [4–6]. A few studies show that the hop funnel can improve the uniformity of the electron beam bombarded on the screen [2,3].

The spot size, brightness and other performances of the HOPFED are partially determined by the characteristics of the secondary electrons. In this paper, the energy distribution, especially the transverse energy distribution of secondary electrons in a HOPFED has been analyzed through both experiments and simulations. From the transverse energy distribution, the focus performance and the spot profile can be estimated.

2. Measurement of the transverse energy distribution

As shown in Fig. 1, the secondary electrons hop along the inner surface of the insulator funnel. At the exit of the hop funnel, these electrons are accelerated by the electric field between the hop plate and the anode. Consequently, the electrons are bombarded on the anode with a phosphor layer. This paper studies the transverse energy distribution of the secondary electrons with a hop funnel. In the field emission display panel, the normal energy of the electron beam is decided by the anode voltage approximately. Although the transverse energy of the electron beam is usually much smaller than the normal energy of the electron beam, it influences the divergence of the electron beam seriously. Thus, the size of the spot is directly correlated with the initial velocity of the electrons in the direction parallel to the screen. The transverse energy distribution can be determined by means of measuring of beam diameter after accelerating the electrons in a uniform electric field as shown in Fig. 2.

In Fig. 2, the radius of the electron beam on the anode screen can be expressed as

$$r = 2L(E_t/eV_a)^{1/2}, \tag{1}$$

where V_a is the voltage of the anode, E_t is the transverse energy of the electron

$$E_t = 1/2m_e(v_x^2 + v_y^2), \tag{2}$$

where m_e is the mass of the electron, v_x and v_y are the velocity of the electron in x direction and y direction respectively.

According to Eq. (1), the transverse energy of the electron can be deduced from the spot profile

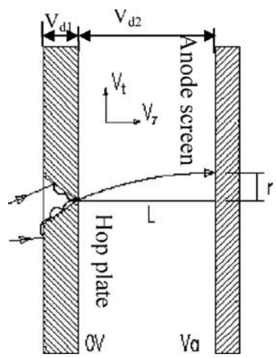

Fig. 2. The trajectories of electrons in a homogeneous electrical field.

on the screen. If the radius of the electron beam on the screen can be measured, the transverse energy of the electrons is estimated

$$E_t = \frac{eV_a r^2}{4L^2}. \tag{3}$$

In our experiment, the phosphor layer is deposited on the screen. When the electron beam hits the screen, a spot is generated. The dimension of the electron beam on the screen is estimated from the spot size.

In Eqs. (1) and (3), it is assumed that the electric field between the hop plate and the anode screen is a homogeneous field. However, there is an electrostatic lens effect in the vicinity of the hop plate output. In order to reduce this detrimental effect on our measurement, the dimensions of the hop plate and the anode screen have been chosen carefully. Apart from this, the potential differences V_{d1} and V_{d2} are set carefully. If the electric field inside the hop funnel is close to the electric field between the hop plate and the anode, the lens effect of the exit hole can be weak.

3. Simulation study of the transverse energy distribution of the secondary electrons

This paper also studies the characteristics of the secondary electron by the numerical simulation. In the simulations, the primary electrons are generated with some different initial conditions.

3.1. Simulation model and initial conditions

In order to keep the simulation simple and less time consuming, we made some simplifications and assumptions to the experimental structure, as shown in Fig. 3. All the simulations were done according to this simplified structure. The potential applied on the anode and the metal electrode are 6960 V and 3270 V respectively. The bottom radius of the hop hole is 0.175 mm, and the upper radius of the hop hole is 0.065 mm. The height of the hop hole is 0.42 mm.

In order to avoid a direct hit of primary electrons on the screen, the hop funnel has shifted a small distance from the cathode. In the simulation,

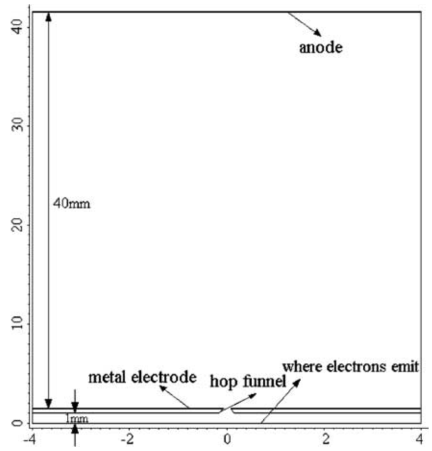

Fig. 3. Structure of the simulation model (including a simplification to the experimental set-up).

it is supposed that the electrons are emitted from a plane which is at a distance of 1 mm from the bottom of the hop funnel. In this paper, the primary energies of the primary electrons are assumed to be 50 eV. The dimension of the emission area of the incident electrons is 0.5 mm × 0.5 mm.

3.2. Simulation method

In this paper, the electron transportation process is simulated with the Monte Carlo method based on a secondary electron emission model. In the simulation process, the electrical potential is generated due to voltage difference between the anode and the bottom plane. Since the surface is insulating, the electron hitting may cause important secondary-electron generation [7]. The average number of emitted secondary electrons, which can be denoted by secondary yield function δ, depends on primary electron energy and angle of incidence [8,9]. Fig. 4 shows a typical curve of secondary yield according to primary energies.

In this paper, the yield function δ is expressed as the following equation:

$$\frac{\delta}{\delta_m} = 1.85F\left(\frac{0.92eV_p}{eV_{pm}}\right), \tag{4}$$

$$F(r) = \exp(r^2)\int_o^r \exp(Y^2)\,dY, \tag{5}$$

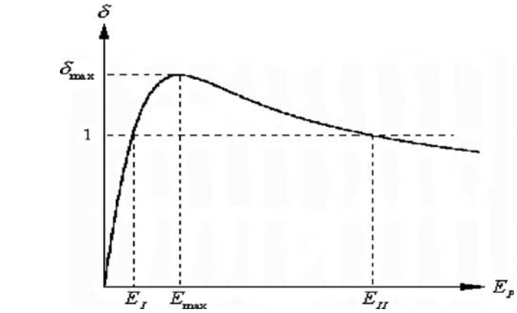

Fig. 4. The yield curve of secondary electrons versus the landing energy of primary electrons for a typical insulator.

where $\delta_{\rm m}$ is the maximum value of δ. The parameter $eV_{\rm pm}$ is the energy of the primary electron when the yield function is the maximum value $\delta_{\rm m}$.

In the simulation, we use a finite difference method to solve the Poisson equation, then the electrical potential distribution in a charged funnel can be obtained. The charge accumulation process will continue, until the average number of leaving electrons is equal to that of incident electrons. At that time, the electrical potential is going to a steady state.

4. Results and discussion

4.1. Analysis of the experimental results

Fig. 5 gives the basic structure of our experiment to measure the transverse energy distribution.

In our experiments, the primary electrons are generated by the carbon nanotube cathode. A metal mesh is mounted in front of the carbon nanotube cathode to provide the strong electric field. In the experiment, the anode is the ITO glass coated with a phosphor layer. Hence, a bright spot can be captured when the electron beam impinges on the anode. As mention above, the transverse energy distribution of the electron can be deduced from the spot profile. A CCD camera is used to capture the spot profile on the screen. A set of programs was developed to analyse the luminance distribution. From this analysis, the transverse energy distribution can be estimated from Eqs. (1) and (3).

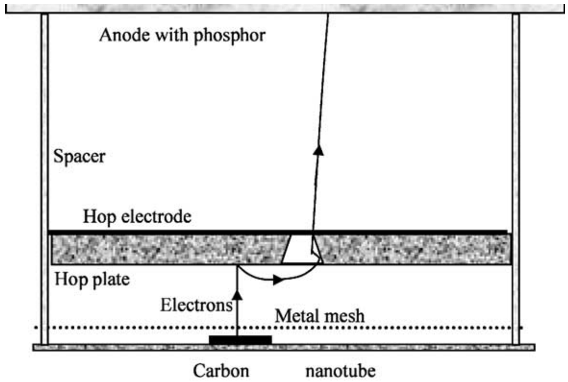

Fig. 5. The experiment for the transverse energy distribution measurement.

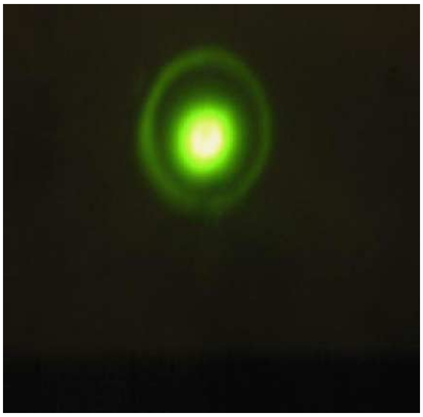

Fig. 6. The spot profile on the screen.

In our experiments, the CNT cathode is shifted from the center of the hop funnel, as shown in Fig. 5. By changing this shift distance, we can control the proportion of the secondary electrons approximately on the exit hole of the hop plate [10]. If the shift distance is small, some primary electrons may bombard on the screen directly. Fig. 6 gives the spot profile on the screen when the shift distance is 1 mm. As the figure shown, there is a ring around the core of the spot due to the influence of the primary electrons. Fig. 7 gives the transverse energy distribution which is estimated from the spot profile.

In Fig. 8, the shift distance is 5.0 mm. Therefore, all of the primary electrons are shielded by

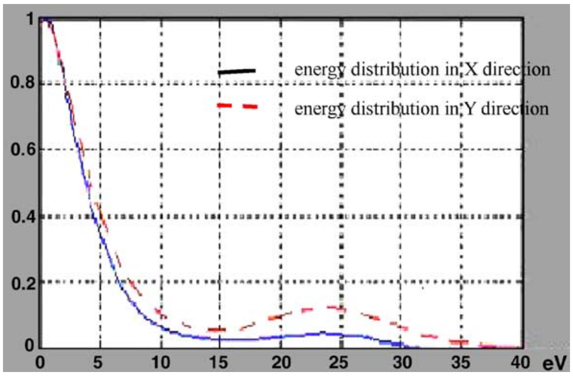

Fig. 7. Transverse energy distribution.

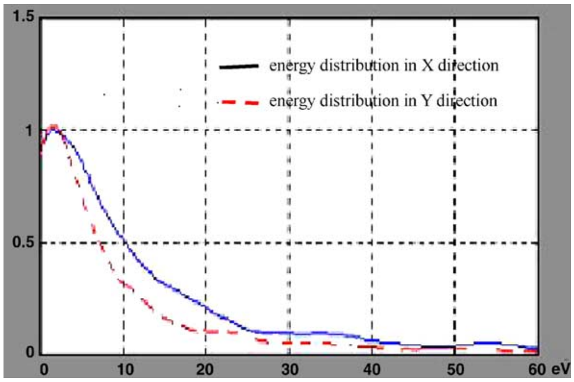

Fig. 9. Transverse energy distribution.

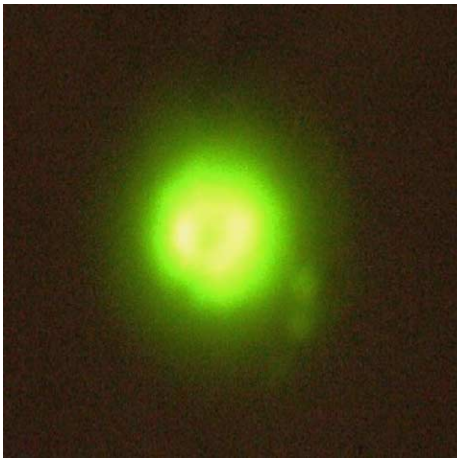

Fig. 8. The spot profile on the screen.

the hop plate. To increase the yield of the secondary electrons, the inner surface of the hop funnel is coated with MgO layer [11]. Fig. 9 gives the transverse energy distribution according to the spot profile shown in Fig. 8.

As shown in Fig. 8, there is no outer ring in Fig. 8 because none primary electron can hit the screen directly. Therefore, the shift distance between the CNT cathode and the center of the hop funnel influences the spot profile and the transverse energy distribution on the screen.

4.2. Analysis of the simulation results

In order to find out the effect of different initial conditions of the primary electrons, we make a few simulations of the structure with several different initial conditions. Table 1 shows initial conditions in six different examples.

In the simulation, every example has been simulated for enough steps to get a steady state of electric field. Fig. 10 shows the plot of equi-potential lines and electron trajectories near the hop funnel of example 1 in a steady electric field. It can be seen that electrons hit the bottom plane of the hop funnel, and hop on the plane under the influence of the electric field. Some of the electrons go through the hop funnel and hit the anode at last. Others stay on the bottom plane of the hop funnel and make surface charging, which induces changes of the electric field.

Table 1
Initial conditions in six different examples

	Example 1	Example 2	Example 3	Example 4	Example 5	Example 6
Number of incident electrons	10,000	10,000	10,000	10,000	10,000	10,000
Emit angle	Vertical	Emanative	Vertical	Emanative	Vertical	Emanative
Distance between emitting center to hop hole center	1.5 mm	1.5 mm	1.5 mm	1.5 mm	2.5 mm	2.5 mm
Distance between anode and the metal electrode	40 mm	40 mm	60 mm	60 mm	40 mm	40 mm
Number of electrons on anode	2943	1426	1975	1784	159	149

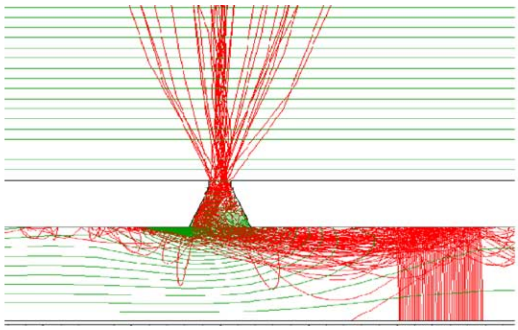

Fig. 10. The equi-potential lines and electron trajectories near the hop funnel of example 1.

In all these examples, since the structure of the models and the number of primary electrons are equal, the change of emission mode and change of emission position for primary electrons do not affect the distribution of the whole electric field considerably, also the electron trajectories are similar in the different examples.

Fig. 11(a)–(f) show the position distribution of electrons hitting on the anode in the six examples. In Fig. 11, the influence of the different energy is ignored.

It is well known that the electrons transfer their energy to the phosphor layer when they bombard on the screen. Therefore, the brightness of the phosphor is proportional to the energy of the electrons. According to this relationship, Fig. 12 gives the brightness distribution of the spot on the screen with the different electrons bombardments. As shown in Fig. 12(a), a smeared-out ring appears. This ring looks similar to the experimental results of sample 1. Thus, the simulation reproduces some aspects of the experimental results.

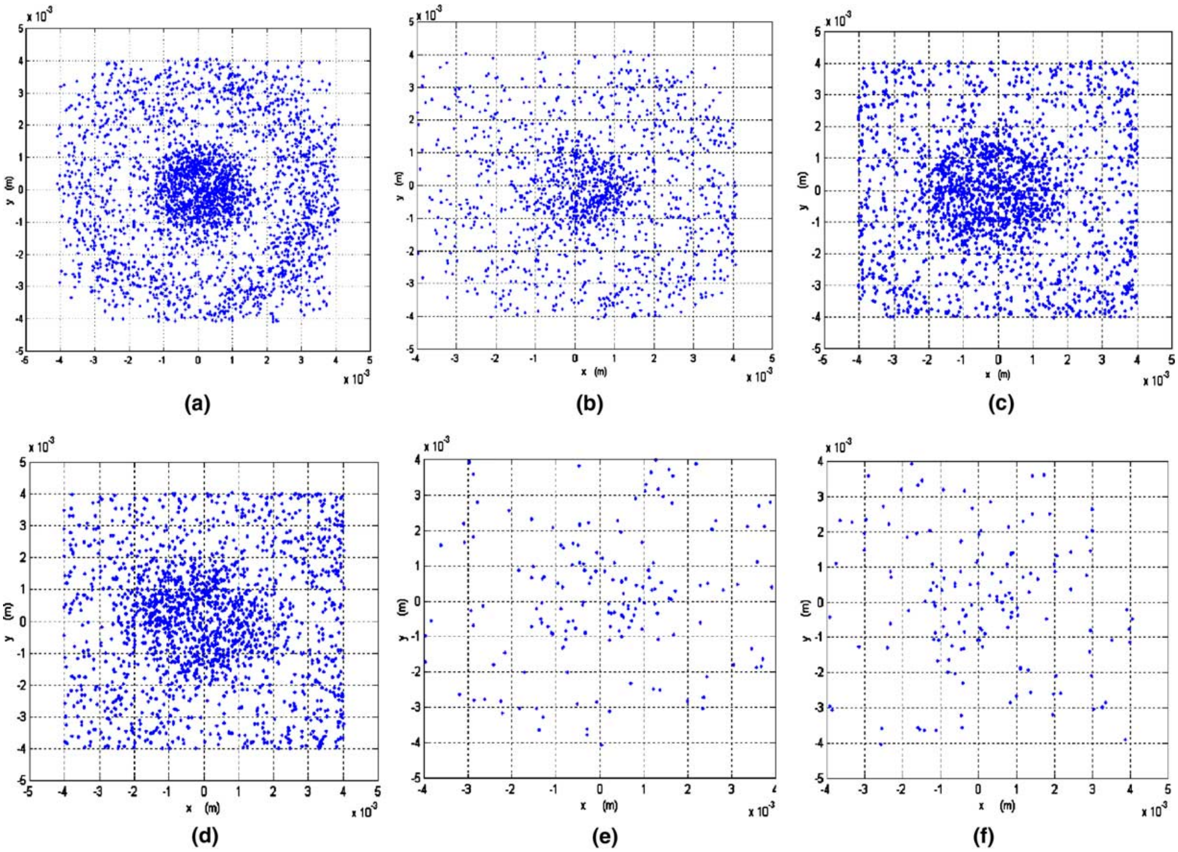

Fig. 11. Position distribution of electrons hitting the anode in the six examples.

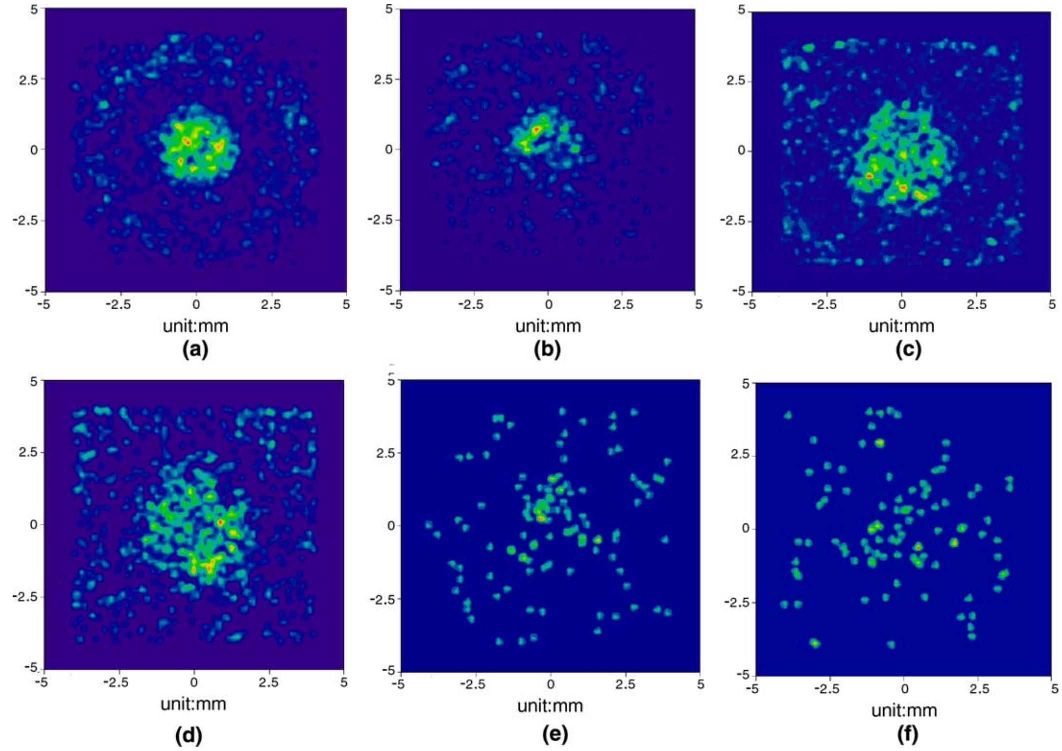

Fig. 12. Light distribution of electrons hitting the anode in the six examples.

The ring is not very clear partly because the number of electrons is not large enough (this is a limitation of the software). In addition, the spot in example 2 (Fig. 12(b)) does not have a visible ring, and this is similar to the phenomenon in the experiment sample 2.

In example 3 (Fig. 12(c)) and example 4 (Fig. 12(d)), there is also a light cluster in the center, but the distribution of around spot is disordered. In these two examples, the distance between the anode and the metal electrode of the hop plate is large. Since the voltages on the electrodes are the same as that in example 1, the relative average electric field decreases. But the field direction is unchanged, so the direction of electron trajectories changes little. The only change is that the spot cluster size on the anode is enlarged due to the increasing distance of the transport of electrons. In example 5 (Fig. 12(e)) and example 6 (Fig. 12(f)), the number of electrons on the anode is too small due to the large shift distance between the cathode and the center of the hop funnel.

From the simulation results, the velocity of the electron on the screen can be obtained. Therefore, the transverse energy of the electron can be obtained with Eq. (2) directly.

The transverse energy distribution of the electron beam can also be estimated from the spot profile. With Eq. (3), the transverse energy of the electron can be obtained if the location of the electron on the screen is known. This paper uses these two methods to calculate the transverse energy distribution. The results are shown in Fig. 13.

Fig. 13 shows comparisons of transverse energy distribution in the six examples got from different methods—(1) The energy distribution from the velocity of electrons, which is denoted by thick line; (2) the energy distribution from the brightness of electrons, which is denoted by light line. The comparison indicates that the transverse energy distributions derived from the two methods are similar. The transverse energy of electrons on the anode is small compared to the longitudinal component, and it can be seen that these results have

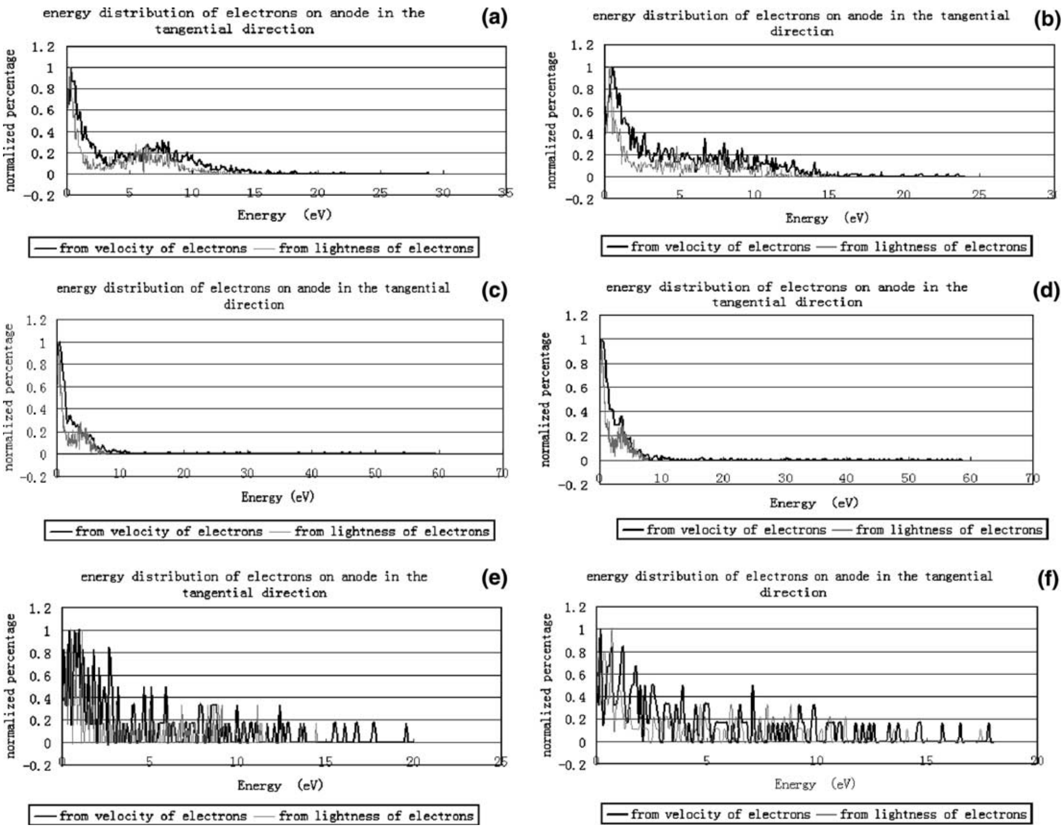

Fig. 13. Comparison of transverse energy distributions of electrons on the anode with different initial conditions.

the same trend to the experimental results, which are shown in Fig. 4(d) and Fig. 5(d). The narrow transverse energy distribution is directly linked to the low beam divergence. Therefore, the uniformity of the spot on the screen can be improved if the transverse energy distribution of the electrons is decreased.

5. Conclusion

In this paper, the transverse energy of electrons in a HOPFED element is studied. From the simulation, the following conclusions are obtained:

(1) The distance between the emitting center and the funnel hole strongly influences the number of electrons that can go out of the hop funnel.
(2) The distance between the anode and the funnel has no significant influence on the energy distribution.
(3) The transverse energy distribution of hop electrons is very low. Therefore, the uniformity of the spot can be improved if the insulator tunnel is used in a FED element.

Some experiments were performed to verify the simulation results. The simulation results are compared with the experimental data. From the comparison, it can be seen that the trends of the simulation results is close to that of the experimental results.

As the results obtained in this paper shown, the enough hop electrons can hit on the anode with the optimization of the electron hop structure. At this moment, the transverse energy distributions of hop electrons are small. Therefore, these hop electrons may be used as the electron source in the microwave tube and the field emission display panel [10]. With this hop electron source, it is easily to modulate the electron beam and keep the proper beam shape.

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