Formation of Rings around a Field-Emission Image and Possible Applications of This Effect

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Received March 25, 2003; in final form, July 30, 2003

Abstract—By using the method of pulsed field electron emission, it is shown that, as the current density approaches the ultimate value, there appears a bright ring around a normal field-emission image. This effect is frequently observed in the case of planar field-emission cathodes. It is suggested that secondary electrons emitted from the anode return to the anode under the action of the electric field, producing the rings. Field-emission applications based on this effect are discussed. © 2004 MAIK “Nauka/Interperiodica”.

INTRODUCTION

When studying the field emissivity of planar cathodes, particularly those made of graphite powders and by chemical vapor deposition, we repeatedly observed bright luminous rings on the screen. The rings are diffusely illuminated phosphor areas surrounding the image. Their diameter frequently exceeds the size of the image, and their brightness increases with the emission current.

Studies of the pulsed field emission process in an electron projector [1–5] revealed unambiguously that a bright ring around the image appears as the current density approaches the ultimate value. This effect was first described by Dyke et al. [1]. The rings were observed when the density of the emission current from a tungsten tip approached the ultimate value. The appearance of the rings is accompanied by a jump in the emission current. Dyke et al. explained this effect by thermal–field emission. The cathode is heated by the field emission current, and the heating makes an additional contribution to the current. The appearance of the rings is explained by a jump in the emission current and the ring effect, were investigated with tips made of various materials. Several concentric rings were observed under certain conditions. Since the predischarge phenomena were sluggish and their duration depended on the time of passage of the field emission current, they were assumed to be of thermal nature. However, the nature of the rings was not conclusively established in the works cited because of the lack of experimental data. It was hypothesized that the rings are due to thermal–field emission from the circumference of the tip or asperities on the emitter surface and also that they are caused by electron diffraction. The first of the three hypotheses has received the most support in experiments and is considered the basic hypothesis today. Its primary disadvantage is that it fails to explain why the current in the ring increases by two or three orders of magnitude during the pulse while a temperature addition to the field-emission current (within the applicability of the Fowler–Nordheim equation) is only several tens of percent. Simulation performed in [6] showed that the rings may appear as a result of thermal–field emission from the circumference of the tip. However, this model cannot explain the appearance of several rings on the emission image.

MODEL OF RING FORMATION IN THE CASE OF PLANAR ANODE–CATHODE GEOMETRY

In [1–5], the rings were detected at the prebreakdown stage. Their occurrence was accompanied by a spontaneous growth of the current, causing the cathode breakdown and degradation. In our experiments, unlike [1–5], the rings persisted for a long time and their appearance did not cause the degradation of emitting centers. Figure 1a shows the time instant of ring origin. A further fourfold increase in the current adds substantially to the intensity of the rings, but the cathode remains operable (Fig. 1b).

Thus, the rings observed by us cannot be assigned to the prebreakdown stage, contrary to [1–5]. In the case of a planar field-emission cathode, the most plausible mechanism of ring formation appears to be the following. Primary electrons striking the anode knock out secondary electrons, which move to the cathode under the action of the electric field, forming a ring.

Consider a model of a planar diode with an electrode spacing \( L \) (Fig. 2). If the voltage applied to the anode is \( U \), the field in the electrode gap is \( E = U/L \). When considering the motion of secondary electrons near the anode, we ignore the existence of emitting centers on the cathode. They enhance the field near the cathode without affecting significantly the behavior of the electrons near the anode. Let a secondary electron with an initial energy \( \varepsilon_S \) leave the anode surface at an angle \( \alpha \).
Straightforward analysis of the electron trajectory in a constant electric field allows us to find the distance of the electron to the secondary emission site in the anode plane:

\[ r = \frac{2eS}{eU}L\sin2\alpha. \]  

(1)

The maximum distance to the anode is

\[ H = \frac{eS}{eU}L(\sin\alpha)^2. \]  

(2)

Thus, the outer radius of the ring formed by secondary electrons with an initial energy \( eS \) is given by

\[ r_{\text{max}} = 2L\frac{eS}{eU}. \]  

(3)

Assuming that elastically reflected electrons play a major role (specifically, they produce a ring of maximal radius), one may set \( eS/eU \approx 1 \). Hence, the maximal diameter of the ring is \( D_{\text{max}} = 4L \).

Thus, the ring diameter depends only on the anode–cathode spacing and does not depend on the cathode current and anode–cathode voltage. Since elastically reflected electrons constitute only a fraction of the secondary electrons knocked out from the anode and since the secondary electrons escape the surface at different angles, the entire area between the outer boundary of the ring and the image will be “illuminated.”

**EXPERIMENTAL DATA**

To verify our model, we tried to observe the rings in planar diode structures with variable electrode spacings. The spacing was adjusted with glass spacers of thickness 200, 400, and 600 \( \mu \)m. A glass plate with a transparent conducting coating and a phosphor layer served as an anode.

Figure 3 shows the image on the phosphor screen for an electrode spacing of 200 \( \mu \)m. Several bright rings, each formed around a single emitting center, are distinctly seen. All the rings are of the same diameter, although their contributions to the total emission current (i.e., their intensities) differ. Thus, the emission current does not influence the ring diameter.

The ring diameter versus electrode spacing is shown in Fig. 4. This dependence is given by formula (3). If the electrode spacing is kept constant, the ring diameter

![Fig. 1. Field-emission images of the rings. The anode–cathode voltage and current are (a) 2.84 kV and 10 \( \mu \)A and (b) 4.07 kV and 40 \( \mu \)A.](image1.png)

![Fig. 2. Model of ring formation in a planar diode.](image2.png)

![Fig. 3. Field-emission image of several rings with different brightness (voltage 1.8 kV, total cathode current 80 \( \mu \)A).](image3.png)