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A proposal for a new type of thin-film field-emission display by edge breakdown of MIS structure

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Abstract. A new type of field emission display (FED) based on an edge-enhanced electron emission from metal–insulator–semiconductor (MIS) thin-film structure is proposed. The electrons produced by an avalanche breakdown in the semiconductor near the edge of a top metal electrode are initially injected to the thin film of an insulator with a negative electron affinity (NEA), and then are injected into vacuum in proximity to the top electrode edge. The condition for the deep-depletion breakdown near the edge of the top metal electrode is analytically found in terms of the ratio of the insulator thickness to the maximum (breakdown) width of the semiconductor depletion region: this ratio should be less than $2/(3\pi - 2) \simeq 0.27$. The influence of a neighbouring metal electrode and an electrode thickness on this condition are analysed. Different practical schemes of the proposed display with special reference to the $M/CaF_2/Si$ structure are considered.

1. Introduction

Flat-panel field emission displays have the potential to be a low-cost, high-performance alternative to the currently dominant cathode ray tube and liquid crystal displays. The first major problem in FEDs is the development of a reliable and efficient cold-cathode electron emitter. Current FED prototypes use sharp metal or semiconductor tips as field emitters [1], that requires expensive lithography and other difficult fabrication processes. Besides, the control voltage for such tip emitters is rather high (about 100 V). Some researchers use diamond-like films that contain nanoscale crystalline structure as the electron source [2], or use diamond and other coatings of the sharp tips to improve the emission properties of the tips [3, 4].

In the present paper we propose another type of field emitter, where electrons are produced by an avalanche breakdown in the semiconductor near the edge of the top metal electrode in the MIS structure.

The plan of this paper is as follows: in section 2 we describe the proposed display, based on the edge breakdown of the MIS structure. In section 3 we discuss the condition under which edge breakdown in the MIS structure takes place. In section 4 we estimate the influence of a neighbouring electrode on the edge breakdown condition and in section 5 we discuss and summarize our results. In the appendix we briefly estimate the influence of electrode thickness on the edge breakdown condition.

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2. Field emission display based on edge breakdown of MIS structure

The display proposed is schematically shown in figure 1(a). Glass substrate 1 with conductive metal column lines 2 is coated with a thin semiconductor layer 3, which contains low-p-doped column lines 4 that coincide with the metal ones. The film of the insulator with NEA 5 is grown on the semiconductor, and conductive metal row lines 6 are deposited on the insulator film. Above the MIS structure the fluorescent screen 7 is located. The anode (fluorescent screen) and cathode (MIS structure) regions are separated by a vacuum space 8.

When a positive voltage pulse of duration which is short compared to the time constant of thermal generation of minority carriers (electrons in our case) is applied to the top electrode of the MIS structure, no inversion layer can form. Thus, a large potential drop across the semiconductor will take place. If the amplitude of the pulse voltage is increased, band bending reaches large values where minority carriers are generated by nonthermal effects (by avalanche in our case). The amplitude of the pulse voltage at which avalanche occurs we designate by V_{break}.

When we apply a pulse voltage $V_{control}$, of amplitude less than V_{break}, but more than $V_{break}/2$ to one row line, and simultaneously apply such a pulse voltage with another polarity to one column line, the avalanche breakdown in the semiconductor will take place at the intersection of these lines. Under conditions which will be pointed out below, the breakdown will take place near the edges of the metal

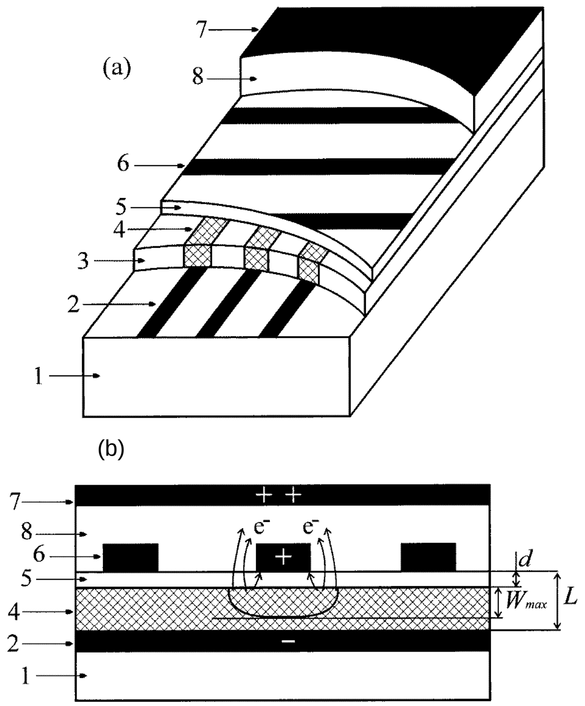

Figure 1. Sectional view (a) and side view (b) of the FED based on edge breakdown of MIS structure. 1—glass substrate, 2—metal column lines, 3—semiconductor layer, 4—p-doped column lines, 5—insulator with NEA, 6—metal row lines, 7—fluorescent screen, 8—vacuum spacing.

lines. Inasmuch as velocities of the avalanche electrons at the semiconductor–insulator interface are directed in an arbitrary way, it is clear that at least a portion of the avalanche electrons, ballistically passing through the thin film of the insulator, will be extracted with a good efficiency (due to the NEA of the insulator) into the vacuum and will not impinge on the top metal layer. Then this portion of electrons will be accelerated by screen voltage V_{screen} ($\sim +100$–$+1000$ V) and will hit the fluorescent screen as shown in figure 1(b).

3. Edge breakdown condition

The deep-depletion breakdown of MOS capacitors was first reported by Goetsberger and Nicollian [5, 6], who experimentally investigated doping conditions under which uniform avalanche takes place. Later a 'universal and normalized' criterion for 'field uniformity' in MOS capacitors was offered in the form $d/W_{\max} > 0.3$ (where d is the insulator thickness and $W_{\max}$ is the maximum (breakdown) width of the semiconductor depletion region) [7, 8]. This criterion was suggested in [7] based on computer-calculated values of the field distribution in MOS capacitors.

In this section we obtain this criterion in an analytical form, with an emphasis on physical explanation of the result, that helps us to analyse operating conditions and an ultimate resolution of the display proposed.

For this purpose let us at first consider a simple two-dimensional model of the electric field near the edge of the metal plate (see figure 2(a)). Here A_1–A_2 and A_2–A_3–A_4 are conductive plates. Let one plate have the potential V, and the other plate have zero potential.

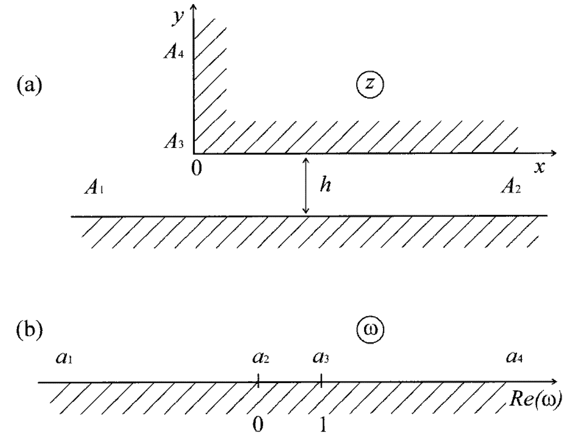

Figure 2. Plane z (a) and plane ω (b) related by equation (1).

We will use a method of conformal transformations (see [9] or any textbook in this field) to find an electrical field distribution in such a system. The Schwarz–Chrisoffel transform

$$z = \frac{\mathrm{i}h}{\pi}\left[2\sqrt{\omega - 1} - \mathrm{i}\ln\left(\frac{1 - \mathrm{i}\sqrt{\omega - 1}}{1 + \mathrm{i}\sqrt{\omega - 1}}\right)\right] \qquad (1)$$

relates the upper half ω plane (figure 2(b)) to the interior of the region A_1–A_2–A_3–A_4 of the z plane (figure 2(a)) [10]. Thus, half of the real axis $\Re(\omega) > 0$ is at potential V while $\Re(\omega) < 0$ is at zero potential. The potential of the electric field in the ω plane is the real part of the complex potential given by the analytical function

$$F = \varphi + \mathrm{i}\psi = \frac{V}{\mathrm{i}\pi}\ln\omega. \qquad (2)$$

The electric field in the z plane is

$$\frac{\mathrm{d}F}{\mathrm{d}z} = \frac{\partial\varphi}{\partial x} - \mathrm{i}\frac{\partial\varphi}{\partial y} = E_x - \mathrm{i}E_y = \frac{\mathrm{d}F}{\mathrm{d}\omega}\frac{1}{\mathrm{d}z/\mathrm{d}\omega}. \qquad (3)$$

Performing the differentiation with respect to ω in (1) and (2)

$$\frac{\mathrm{d}z}{\mathrm{d}\omega} = \frac{\mathrm{i}h}{\pi}\frac{\sqrt{\omega - 1}}{\omega} \qquad (4)$$

$$\frac{\mathrm{d}F}{\mathrm{d}\omega} = \frac{V}{\mathrm{i}\pi\omega} \qquad (5)$$

we obtain

$$E_x - \mathrm{i}E_y = -\frac{V}{h\sqrt{\omega - 1}}. \qquad (6)$$

Our main interest is the field near $z = 0$ ($\omega = 1$). Expanding logarithm in (1) in a Taylor series at $\omega = 1$ and retaining the first two terms, we obtain

$$\sqrt{\omega - 1} = \left(\frac{3\pi}{2h\mathrm{i}}z\right)^{1/3} \qquad (7)$$

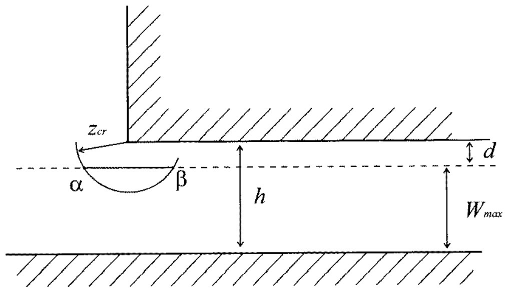

Figure 3. Distance z_{cr} and electron emission area α–β near the edge.

and from (6) we have

$$E_x - iE_y = -\frac{V}{h(3\pi z/2hi)^{1/3}} \tag{8}$$

or

$$|E| = \frac{V}{h}\frac{(2h/3\pi)^{1/3}}{(x^2+y^2)^{1/6}}. \tag{9}$$

We may define

$$z_{cr} = \frac{2h}{3\pi} \simeq \frac{h}{4.71} \tag{10}$$

as a 'critical' distance from the edge at which field strength is still higher than V/h—the field strength between the plates far from the edge.

Now the condition for edge breakdown is rather obvious: if insulator thickness is less than z_{cr} (as shown in figure 3) the breakdown takes place near the edge. But if $d > z_{cr}$ uniform breakdown occurs. The value $d + W_{max}$ in the real MIS structure plays the role of the distance h between the conductive plates in our model consideration. (The exception is the case when the distance L (see figure 1(b)) between the real metal plates is less than $d + W_{max}$. In this case $h = L$.) From the equations

$$h = d + W_{max} \tag{11}$$

$$d < z_{cr} = \frac{2h}{3\pi} \tag{12}$$

we may obtain the criteria for the deep-depletion edge breakdown in terms of ratio of the insulator thickness to the maximum (breakdown) width of the semiconductor depletion region:

$$\frac{d}{W_{max}} < \frac{2}{3\pi - 2} \simeq 0.27. \tag{13}$$

One can see that the value obtained (0.27) is consistent with the value 0.3 obtained in the work [7] by numerical computer-aided calculations for the particular system $M/SiO_2/Si$.

The model considered is applicable to real systems subject to the condition that the radius of the edge curvature of the top electrode is less than the insulator thickness.

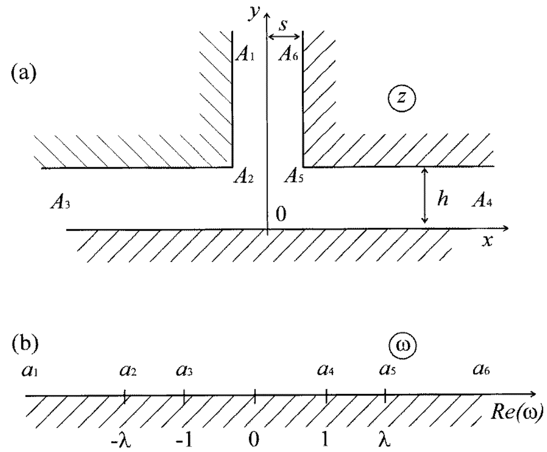

Figure 4. Plane z (a) and plane ω (b) related by equation (14).

4. Breakdown condition for double-edge structure

In this section we apply an analogous approach to find the breakdown condition for the system illustrated in figure 4(a). It is necessary for several reasons: first, one may like to initiate electron emission into a slit in the top electrode. Second, it may be convenient to apply a voltage simultaneously to a set of neighbouring row and column lines for more stable emission. Third, minimal distance between top electrodes defines the ultimate resolution of the proposed display.

The transformation

$$z = \frac{2i}{\pi}\left[s\tanh^{-1}\left(\frac{\omega}{\sqrt{\omega^2-\lambda^2}}\right) + h\tan^{-1}\left(\frac{h}{s}\frac{\omega}{\sqrt{\omega^2-\lambda^2}}\right)\right] \tag{14}$$

where

$$\lambda = \sqrt{1+\frac{h^2}{s^2}} \tag{15}$$

relates the upper half ω plane (figure 4(b)) to the interior of the region A_1–A_2–A_3–A_4–A_5–A_6 of the z plane (figure 4(a)) [11]. Thus, parts of the real axis $\Re(\omega) < -1$ and $\Re(\omega) > 1$ are at potential V while part $-1 < \Re(\omega) < 1$ is at zero potential. The potential of the electric field in the ω plane is the real part of the complex potential given by the analytical function

$$F = \frac{V}{i\pi}\ln(w-1) - \frac{V}{i\pi}\ln(w+1). \tag{16}$$

Using the differentials with respect to ω of (14)

$$\frac{dz}{d\omega} = \frac{2is}{\pi}\frac{\sqrt{\omega^2-\lambda^2}}{(\omega^2-1)} \tag{17}$$

and (16)

$$\frac{dF}{d\omega} = \frac{2V}{i\pi(\omega^2-1)} \tag{18}$$

we may find the electric field in the z plane from (3).

$$E_x - iE_y = -\frac{V}{s\sqrt{\omega^2-\lambda^2}}. \tag{19}$$

Our concern is the field near $z = \mathrm{i}h \pm s$ ($\omega = \pm\lambda$) points. Expanding $\tanh^{-1}$ and $\tan^{-1}$ in (14) in a power series at $\omega = \lambda$ and retaining the first two terms, we have

$$\sqrt{\omega^2 - \lambda^2} = \frac{h}{s}\left[\frac{3\pi}{2h\mathrm{i}}(z + h - \mathrm{i}s)\left(1 + \frac{h^2}{s^2}\right)^2\right]^{1/3} \quad (20)$$

and from (19) we have

$$E_x - \mathrm{i}E_y = -\frac{V}{h[(3\pi/2h\mathrm{i})(z + h - \mathrm{i}s)(1 + h^2/s^2)^2]^{1/3}}. \quad (21)$$

Now the ‘critical’ distance from the edge at which field strength is still higher than V/h is

$$z_{\mathrm{cr2}} = \frac{2h}{3\pi(1 + h^2/s^2)^2}. \quad (22)$$

One can see that this value is coincident with (10) when $s \gg h$.

For example, if $s = h$ z_{cr2} is

$$z_{\mathrm{cr2}} = \frac{z_{\mathrm{cr}}}{4} = \frac{h}{6\pi}. \quad (23)$$

One can see that the distance $2s$ between the top electrodes should be more than twice $h = d + W_{\max}$ to avoid drastic decrease of z_{cr2}.

5. Discussion and summary

Firstly, let us mention the kind of insulator that may be used in this display. At least three kinds of insulator are appropriate for our purpose: hydrogen-terminated diamond (111), LiF and CaF_2. Diamond has long attracted considerable attention as a cold cathode for FED due to its NEA and robust mechanical and chemical properties.

LiF has the largest NEA of any solid. The NEA of an LiF crystal is −2.7 eV [12]. The possibility of epitaxial grown of LiF films on the Ge was also reported in [12].

But we assume that the CaF_2/Si system is the best choice. The reasons for this are as follows:

(i) CaF_2 has a small but negative electron affinity [13].

(ii) A very attractive property of CaF_2 is the similarity of its crystal structure to Si: CaF_2 has cubic $m3m$ structure with only 0.6% of lattice mismatch with Si(111) at room temperature. This fact makes it possible to grow perfect single-crystal films of CaF_2 on silicon by the molecular beam epitaxy technique [14, 15]. The crystalline quality, chemical stability and electrical characteristics of CaF_2 films grown on Si(111) may be further improved by rapid thermal annealing [16].

(iii) The barrier height between the conductive band minimum of Si and the conductive band minimum of CaF_2 is only ∼2.2 eV [15].

(iv) An additional attractive property of CaF_2 is the anomalously large low-energy electron escape depth of the order of 260 nm [17].

(v) Lastly, the good emission properties of the CaF_2/Si structure have recently been demonstrated in experiment [4].

A thickness of the insulator film of $d \sim 10$ nm seems to be nearly optimum because it is large enough to avoid direct tunnelling of electrons from semiconductor to metal, but it is small enough for ballistic passing of electrons through insulator film.

So, if one has a 10 nm thick CaF_2 film on a 1 μm thick Si layer with p-dopant concentration $n \sim 10^{16}$ cm^{-3} ($W_{\max} \sim 1$ μm [8]), one may be sure that when pulse voltages with the amplitude $V_{\mathrm{control}} \sim \pm 10$ V are applied to one row and one column lines an avalanche breakdown will occur at the edges of metal lines ($d/W_{\max} \sim 0.01$). The control voltage may be still decreased if the distance between metal electrodes L is less than $d + W_{\max}$ (but L must always be more than $3\pi d/2$). The avalanche electrons will be injected into insulator at the α–β line, which is shown in figure 3. From geometrical considerations, up to several tens per cent of electrons may be injected into vacuum.

To summarize, we have proposed a simple design of the field-emission display based on the deep-depletion edge avalanche breakdown of the MIS structure. The control voltage of this display may be as small as tens of volts and its ultimate resolution may reach several micrometres.

Appendix

Here we mention the influence of the top electrode thickness on the edge breakdown condition. To avoid complicated expressions, we give only a simple estimation of the effect by solving the problem presented in figure A1(a), where top electrode has zero thickness. The equation

$$z = \frac{h}{\pi}(\omega - \ln(w) - 1) \quad (A1)$$

relates the upper half ω plane (figure A1(b)) to the interior of the region A_1–A_2–A_3–A_4 of the z plane (figure A1(a)). The potential of the electric field in the ω plane is the real part of the complex potential given by the analytical function

$$F = \frac{V}{\mathrm{i}\pi}\ln\omega. \quad (A2)$$

The electric field in the z plane is

$$\frac{\mathrm{d}F}{\mathrm{d}z} = \frac{\mathrm{d}F}{\mathrm{d}\omega}\frac{1}{\mathrm{d}z/\mathrm{d}\omega}. \quad (A3)$$

Performing the differentiation with respect to ω in (A1) and (A2)

$$\frac{\mathrm{d}z}{\mathrm{d}\omega} = \frac{h}{\pi}\frac{\omega - 1}{\omega} \quad (A4)$$

$$\frac{\mathrm{d}F}{\mathrm{d}\omega} = \frac{V}{\mathrm{i}\pi\omega} \quad (A5)$$

we obtain

$$E_x - \mathrm{i}E_y = \frac{V}{\mathrm{i}h(\omega - 1)}. \quad (A6)$$

Our main interest is the field near $z = 0$ ($\omega = 1$). Expanding the logarithm in (A1) in a Taylor series at $\omega = 1$ and retaining the first two terms, we obtain

$$\omega - 1 = \left(-\frac{2\pi}{h}z\right)^{1/2} \quad (A7)$$

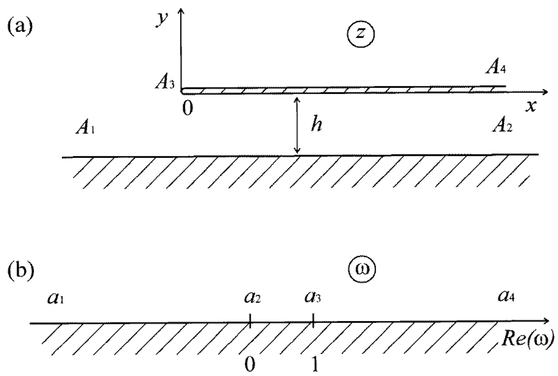

Figure A1. Plane z (a) and plane ω (b) related by equation (A1).

and from (A6) we have

$$E_x - \mathrm{i}E_y = -\frac{V}{h(2\pi z/h)^{1/2}}. \tag{A8}$$

One can see that the 'critical' distance in this case is

$$z_{\mathrm{cr0}} = \frac{h}{2\pi} \tag{A9}$$

and the edge breakdown condition is

$$\frac{d}{W_{\max}} < \frac{1}{2\pi - 1} \simeq 0.19. \tag{A10}$$

This edge breakdown condition should be used when top electrode thickness is less than any other dimensions in the system. Essentially it means that top electrode thickness should be less than thickness of the insulator film.

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