Investigation of the quasi-harmonic field emission behavior of epoxy-coated field emission tips

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ABSTRACT

A novel theory is presented to explain the field-emission effects of polymer-graphite-coated cathodes based on an experiment. The experimental data were obtained by measuring the total emission current from an apex of an electrochemically etched polymer graphite rod acting as an unordered field emission array of cathodes. A physical model describing the quasi-harmonic behavior of the latter, based on effects of periodical charging and discharging, is presented in the paper. The explanations of desirable effects like current stabilization or decreasing in a threshold voltage that are all caused by dielectric coating and were reported earlier on a single tip are addressed as well and put into context with existing results reported by several authors. Finally, based on the experimental findings, the paper suggests possible application of such a pulse structure towards vacuum devices utilizing field emission current.

INTRODUCTION

The effect of **improved and more stable field emission of electrons** that was firstly observed on tungsten cathodes with thin dielectric layer (40-200 nm thick layer of epoxy resin) was firstly introduced by Latham and Mousa [1-3]. Several advantages have been found for this type of cathode over the conventional single crystal tungsten cathode such as achieving the so-called **switch-on phenomenon** (intense current suddenly appears whose threshold field was 3 to 4 times lower, the total emission current **was saturated at a lower field** and therefore **the stability was better** [4-6], the emission consisted only of a **single bright spot**.

In our work we apply the same technique to polymer graphite cathodes. These cathodes consist of randomly distributed and oriented sub-emitters (flakes). This helps to easily achieve several thicknesses of the coating material, which helps to study the and improve the physics of such characteristics.

A unique phenomenon has been detected when using such composite-material, which can be described by a **quasi-harmonic field emission behavior**. This phenomenon has been discussed here and explained based on charging and discharging of nano capacitors.

EXPERIMENTAL EMITTER STRUCTURE

To optically observe the effects associated with charging or discharging in a classical FEM, it is necessary to obtain an active emitter area at least 3 orders of magnitude larger than that of classical tip cathodes. In this way, it is possible to charge a large enough area of the dielectric to obtain a sufficiently light intensity or electric current to analyse the behaviour of the interface.

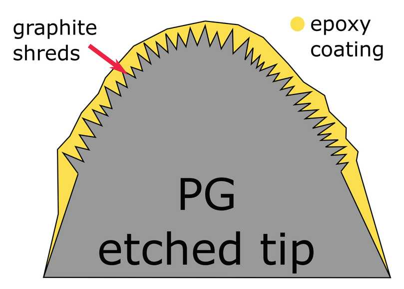

Fig. 1. Schematic sketch of a coated tip of a cold field-emission cathode, made electrochemically from a rod of polymer graphite. Graphite shreds on the tip surface form an array of emitters.

For this reason, we chose **polymer graphite** with electrochemically formed tips as the material for the experimental emitter [7]. A characteristic feature of this material is the **flakes of graphite** that protrude from the tip surface to form a **quasi-ordered field** of emitters. The cathode was connected in a classical **diode arrangement** where the emitted electrons were accelerated to the anode and the beam profile displayed on a **YAG:Ce scintillator**. The scintillator crystal was coated on one side with a thin layer of metal (Al) to measure the current through the picoammeter [8].

PHENOMENOLOGICAL DESCRIPTION

The experimental results can be characterized by the following series of graphs showing the **relative light intensity** versus **time**. The data was obtained by integrating the brightness of the screen area using a CCD camera. A **linear increase** in the oscillation frequency can be observed with increasing extraction voltage.

Assuming that the capacitance of the dielectric layer is constant, the equation **$C = \tau/R$** can be considered valid. It should be added that this is an **approximation** since the equation is valid for a planar plate capacitor. The approximate value of the **emitter's overall capacitance is 22.6 nF**.

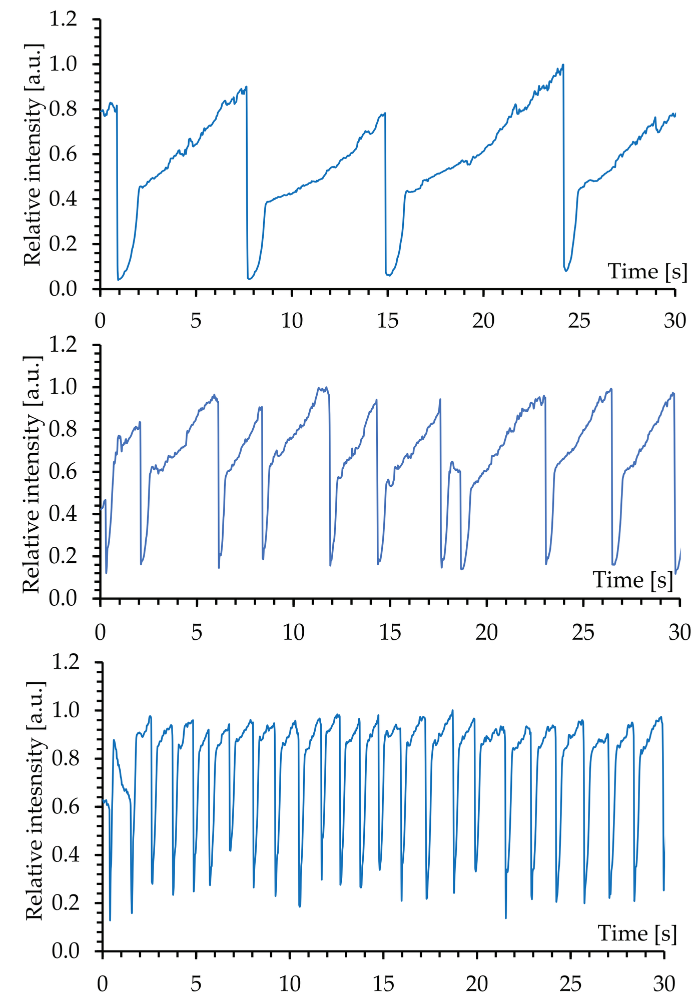

Fig. 2. Plot of relative light intensity obtained by the CCD camera from the YAG scintillator; (top) extraction voltage 2.5 kV, (middle) extraction voltage 2.7 kV and (bottom) extraction voltage 3.0 kV.

Figure 2 shows **the quasi-harmonic behaviour**, the waveform of which resembles that of a **two-way harmonic current waveform**. Since the sweeps are orders of magnitude higher than the noise fluctuations, and since the pulses are very steep, we believe that this can be considered as an **explanation for the increased degree of stability** of the FE current in coated cathodes as stated under point 2. The average period for the V_{ext} = 2.5 kV is 7.8 s; for the V_{ext} = 2.7 kV is 2.9 s and for the V_{ext} = 3.0 kV is 1.23 s.

THEORETICAL EXPLANATION

Under the influence of external electrostatic fields, the dielectric layer will start to polarize. The polarization level, resorting and creation of the dipole moments depend on the intensity of the electric field and the thickness of the nano-dielectric layer **d**:

1. The switch-on phenomena appears only when the nano-dielectric layer has a range of specific thicknesses, $\mathbf{d}_{min} \leq \mathbf{d} \leq \mathbf{d}_{max}$.

2. When $\mathbf{d} \ll \mathbf{d}_{min}$, electrons from the metal surface can tunnel through the dielectric layer and the switch-on phenomena will not be detected. If **d** lies in the switch-on range $\mathbf{d}_{min} \leq \mathbf{d} \leq \mathbf{d}_{max}$, charge carriers will start to distribute on the two faces of the dielectric layer, allowing a large electron density to start occupying the conduction band of the metal as shown in **Figure 3(a)** and **(b)**.

3. As the intensity of the electric field increases, the **arrangement of the electric dipole moments** will be more uniform at the apex of the tip since the electric field is more uniform at that region. The **dipole moments will reshape** because of the extension in the displacement between the negative and positive charges as shown in **Figure 3(c)**. Because of this, the dipole moments will start to **merge inner induced nano-capacitors**, and these induced nano-capacitors will start to merge in turn to form **larger capacitors** as shown in **Figure 4**.

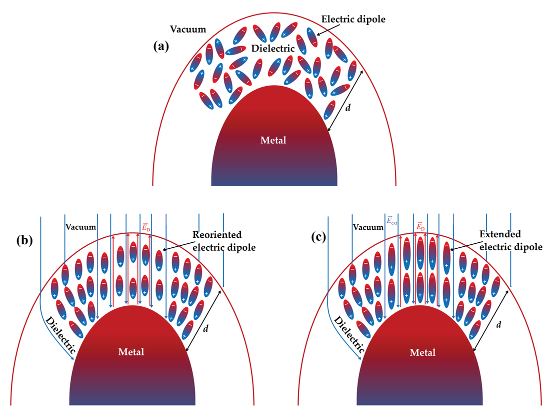

Fig. 3. Coated single tip field emitter, the dielectric layer have (a) randomly distributed dipole moments before applying E_{ext}; (b) rearranged and distributed dipole moments after applying E_{D}; (c) The extension of the electric dipole moments due to the increase in the intensity of E_{ext}.

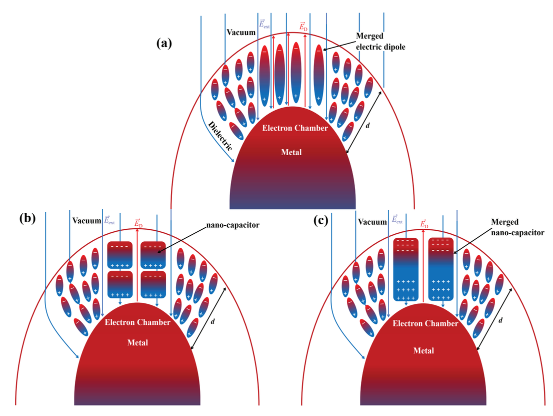

Fig. 4. Description of the merging process; (a) merged dipole moments; (b) creation of the induced nano-capacitors; (c) the merged induced nano-capacitors.

This will form a conductive channel between the negative and positive surfaces of the dielectric layer. In this model, this channel is called the electric vent, and the conduction band of the metal is called the electrons chamber.

The surrounding region of the channel will consist of non-uniformly distributed dipole moments forming electric conduit (like a volcano conduit) as shown in **Figure 5**.

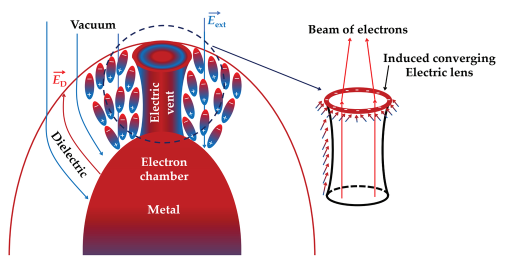

Fig. 5. Schematic diagram to present the volcano like behavior of the emission process.

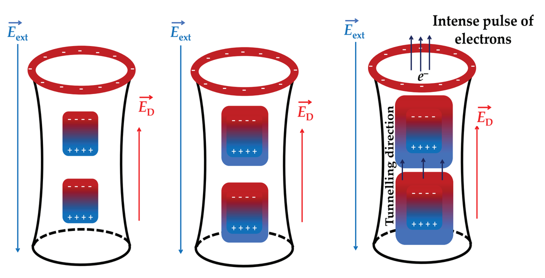

Fig. 6. Schematic diagram for the quasi-harmonic field emission behavior, as described by qua-si-harmonic charging-discharging of nano-capacitors.

The thickness of the dielectric layer will vary along the generator of the cones. Thus, it is expected for the electric vent to not fully established at certain thickness $\mathbf{d}_H$, which must be less than but very close to $\mathbf{d}_{min}$. This unsuccessful electric vent will contain charged nan-capacitors that can be periodically charged-discharged because the separation distance between them is too small, allowing the electrons to tunnel through between these nano-capacitors until released from the electric crater in the form of a uniform quasi-harmonic pulse as shown in **Figure 6**.

CONCLUSIONS

1. The focused electron beam has been explained by creation of a negative electric crater and along through of the electric vent.

2. The cold-thermionic regime has been explained by introducing the electron chamber, since the electrons are emitted by tunneling through a reduced image potential barrier and by elevating from above this barrier because of the high density of the occupied energy states.

3. The quasi-harmonic behavior has been explained by introducing the barriers of achieving the switch-on phenomena.

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