Analysis of a diode with a ferroelectric cathode

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It has been shown experimentally that electron current densities of more than 30 A/cm² can be achieved from a cathode made of ferroelectric ceramic, when applying a field of order 0.1 MV/m. This current exceeds the Child–Langmuir current by two orders of magnitude. The current in the diode varies linearly with the applied voltage, provided that the latter is positive. In this theoretical study we show that the ferroelectric material plays a crucial role in the emission process. When a voltage is applied to the ferroelectric, the internal polarization field varies and the amount of screening charge required decreases. As a result, the electrons distribution near the cathode changes, forming a cloud which fills part of the diode gap. If now a positive voltage is applied to the anode, electrons are readily transferred through the diode gap. The qualitative and quantitative results of the theory are in good accordance with the experiment.

I. INTRODUCTION

In the recent years a renewed interest in ferroelectric ceramics for generation of electron beams has been initiated by Riege and his collaborators at CERN. High intensity electron beams, 100 A/cm², were produced for a pulse duration of 10–100 µs containing between 1 nC to several µC of charge. At the Lebedev Institute, Aitapetov et al. measured current densities of 400 A/cm² in a diode of 0.3–1.0 mm gap, with an extraction (gap) voltage of 1.6 kV at high repetition rate and with a total (train) pulse duration of 160 ns. We have examined the operation of a similar device but with a diode gap of 2–10 mm width, extraction voltage lower than 250 V (200–600 ns), and a 100-ns-long switching voltage. The maximum current density measured was 70 A/cm², which is almost two orders of magnitude above the Child–Langmuir limit.

The basic mechanism is what we call externally controlled field emission, namely, the electrons extraction is due to an electric field which is generated behind the cathode and, at least in the regime our system was operated, it is almost unaffected by the anode voltage. General speaking, the device consists of a ferroelectric slab which has a uniform electrode on its back side and a gridded and grounded electrode on the front which faces the diode. This is the cathode. A uniform piece of carbon consists the anode. A voltage can be applied to the back electrode of the ferroelectric. If no such voltage is applied, the system behaves like a regular diode and practically for the anode voltage we are interested on, the current is zero. When the ferroelectric is pulsed, a substantial amount of charge is expelled into the gap. For this purpose the ferroelectric has to extract them from the metallic grid. At this point the geometry of the grid comes into play. The local electric field near each one of the grounded strips is sufficient to extract the electrons from the metal. The amount of charge repelled is determined by the electrical characteristics of the ferroelectric, the voltage applied on the back electrode, and the electrostatic coupling of the ferroelectric to the gap via the grid. In our experiment the anode voltage plays practically no role in this process. The electron cloud in the gap forms a “distributed cathode” which allows electrons to flow to the anode, if a voltage is applied on the latter.

The fact that the emission process is controlled by an external electric field which is not the one which accelerates the electrons in the diode, has the potential of producing high quality beams. For two other processes in which the emission is controlled externally the beam quality is limited by an increase in the temperature associated with the emission process. In the case of thermionic emission the cathode is heated such that the electrons in the metal acquire enough kinetic energy to locally overcome the work function and they form a cloud above the surface. Thus to heat the cathode is essential for emission. For photoemission the cathode is illuminated by a laser beam whose photons supply the energy required by the electrons to overcome the work function. However, today’s materials have low quantum efficiency.

In the present study we shall first review the experimental results (Sec. II) and then we shall give a detailed theoretical interpretation of the various processes which occur when pulsing a ferroelectric ceramic, Sec. III.

II. REVIEW OF EXPERIMENTAL RESULTS

A. Experimental setup

The experimental setup is shown schematically in Fig. 1. A 1-mm-thick, 2.5-cm-diam ferroelectric disk is coated with a thin uniform silver layer on the back and a gridded