FERROELECTRIC CATHODES AS ELECTRON BEAM SOURCES *

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Abstract

In the past decade a number of research groups have studied electron emission from ferroelectric ceramics. These materials have saturation polarization P_s, of up to $100\mu C/cm^2$. The emission occurs when the polarization state of the ferroelectric is changed rapidly by an applied electric field, and a fraction of the surface screening charge is released. We report experimental results obtained using Lead-Zirconate-Titanate (PZT) ceramic as the electron source in a planar diode geometry. Experimental measurements of time-dependent variations in the emission are presented and results from a theoretical model are compared to these measurements. We also present new data on the scaling of the emission current density for anode voltages of up to $50kV$. The new data will be used in the design of an electron gun using a ferroelectric cathode.

I. INTRODUCTION

In the recent years a substantial effort [1]-[6] has been dedicated to the generation of dense electron beams from ferroelectric ceramic cathodes. Current densities of at least $70A/cm^2$ can be achieved for average diode electric fields as low as $60kV/m$. In addition, measurements show good beam quality and stable operation at high repetition rate. Electron emission from ferroelectric ceramics is based on the release of screening charge from the surface of the ceramic when its internal polarization field is switched. In previously published work the ferroelectric was switched at the same time as the voltage was applied to the anode. However, one can anticipate that the potential well in the diode gap is not dependent only on the switching voltage but also on the dynamic characteristics of the ceramic. In the following sections we examine the effects of delaying the anode voltage pulse relative to that applied to the ferroelectric. We also report scaling of the gap current with the anode voltage at voltages ($\leq 50kV$), up to 100 times that used in our previous experiments ($\sim 400V$).

II. EXPERIMENTAL DATA

The experimental setup [5] is shown schematically in fig. 1. A $1mm$ thick, $2.5cm$ diameter ferroelectric disk is coated with a thin uniform silver layer on the back and a gridded silver layer on its front surface; in both cases the thickness is $\sim 1\mu m$. The silver strips are $200\mu m$ wide and are separated by a similar distance.

The gridded electrode is grounded and its effective emission area is approximately $A \approx 0.8cm^2$. For these experiments we used Lead-Zirconate-Titanate as the ferroelectric sample. This sample is mounted as a load on a 10Ω transmission line which generates a $150ns$, $1-3kV$ pulse. A positive or negative pulse is applied to the back electrode of the ferroelectric and the grid

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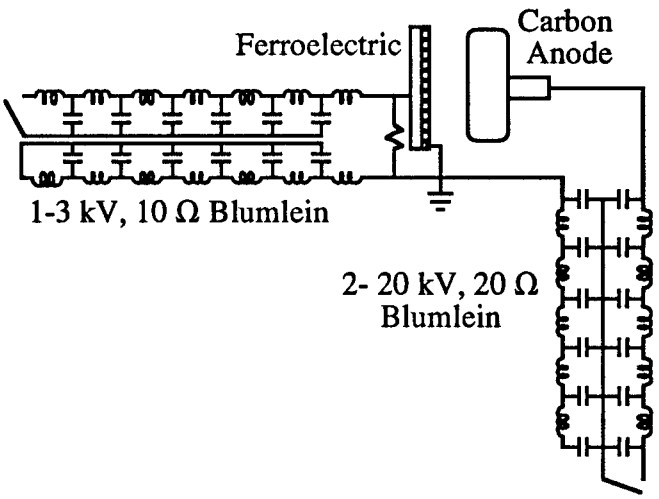

Figure 1. Ferroelectric experimental setup.

is grounded. A planar carbon anode is located at a distance of $g \approx 3-5cm$ from the grid. In the time variation experiments the anode is pulsed to $\sim 14kV$, by a charged transmission line with a characteristic impedance of $Z_{TL} = 20\Omega$. The applied pulse length is about $300ns$. The delay between the switching of the ferroelectric and the application of the anode pulse is varied between $0 \leq \tau \leq 2.5\mu s$.

Figure 2 illustrates the anode voltage and current for two different delays: $165ns$ and $1.2\mu s$. The average currents range from somewhat less than $12A$ in the first case to $50A$ for the larger delay. The latter represents an increase by a factor of more than 4 over that obtained with $165ns$ delay. For longer delays the current decreases.

Figure 3 shows the anode current for various delays at an anode voltage of $\sim 14kV$. The behavior is similar if either positive or negative voltage is applied to the back of the ferroelectric. Results displaying a similar time dependence have been obtained at an anode voltage of $\sim 35kV$.

We have also extended our previous scaling results for the gap current as a function of the anode voltage. The Blumlein pulser mentioned above is used to feed the primary of a 4:1 step up transformer and the secondary output is applied to the diode. The source impedance is now $\sim 320\Omega$. Figure 4 shows the results of this investigation. The V-I characteristics are still approximately linear although there is now evidence of current saturation in at least the $3cm$ gap data. The resistances of the gap for the $3cm$ and $5cm$ spacings are about 300Ω and 1000Ω respectively. The data reported were obtained with $\sim 150ns$ delay between the ferroelectric pulse and the anode voltage. The current waveforms are quite flat and repeatable especially, as expected, when the gap resistance is comparable to the source impedance.

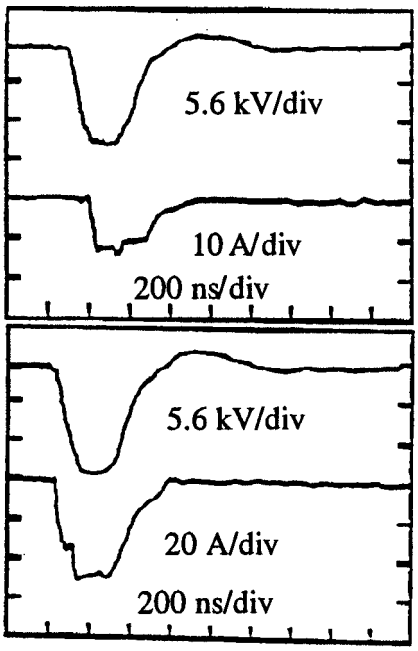

Figure 2. Anode voltage and gap currents for two delays [Upper: $165ns$, Lower: $1.2\mu s$].

III. DISCUSSION OF RESULTS

The current measured in various experiments exceeds [5] the space-charge (Child-Langmuir) limit for electrons with zero (or low) energy electrons emitted from the cathode. Measurements show that the emission energy of the electrons is less than $60eV$ in our experiments. Since the space charge limit is based on energy conservation in the system, the excess of current requires an external energy source other than that applied to the anode. This is provided by a fraction of the energy initially stored in the ferroelectric [6]. On pulsing the ferroelectric some electrons are forced into the diode gap. For zero voltage applied to the gap and assuming zero diode current we obtain a deep potential well in the diode and the electrons oscillate in the well. The well depth may be estimated and is found to be much larger than the the maximum energy measured for the electrons emitted from the cathode. In other words, the electron kinetic energy on emission ($\leq 60eV$) cannot account for the excess current. Assuming that the applied anode voltage V_{AN} is small enough such that it has a negligible effect on the initial charge distribution, the gap becomes resistive and has a resistance of

$$R_{gap} \equiv \frac{V_{AN}}{I_{AN}} = \eta_0 \frac{1}{36}\frac{g^2}{A}\gamma_0^2\sqrt{\frac{\gamma_0+1}{\gamma_0-1}} \quad ; \qquad (1)$$

where $\gamma_0 = 1 + (eQ_{gap}g)/(36\epsilon_o mc^2)$ is the average energy of the electrons in the potential well and $\eta_0 \simeq 377\Omega$ is the vacuum characteristic impedance. The linear $I-V$ characteristic predicted for the diode is consistent with the experimental results reported previously [5]. For example, given a $4mm$ gap and $2.5cm$ cathode diameter with $1\mu C$ of charge released into the gap,the diode resistance is 10Ω. For the present data, where the applied voltages are about 100 times greater than those used in the earlier work, the above relationship continues to give agreement with the measured gap resistance to within thirty-five percent. It should be noted that the applied voltages are now sufficiently large that one would expect them to modify the charge distribution significantly. However it appears that the model's assumption of a charge distribution with zero applied voltage is still relevant.

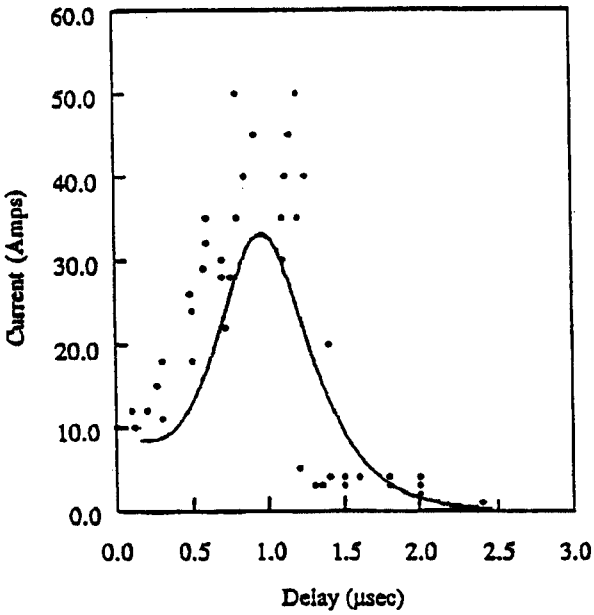

Figure 3. Gap current as a function of delay at $14kV$, $5cm$.

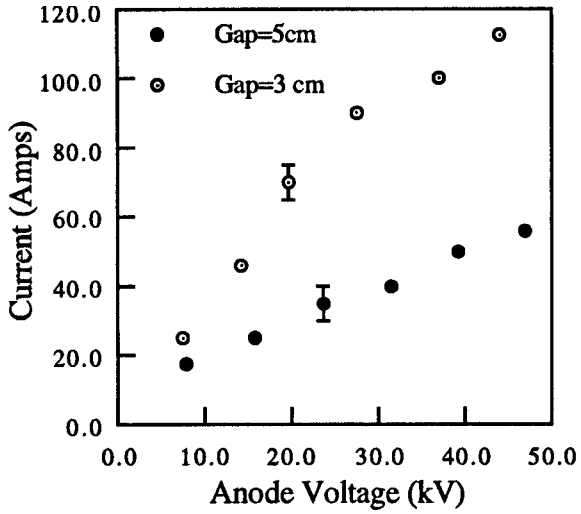

Figure 4. Current as function of anode voltage for 3 and $5cm$ gaps.

The dynamics of the polarization field are described by a Weiss model (as in ferromagnetics) and hence the surface charge $Q(t)$ may be represented by

$$\frac{dQ}{dt} + 2\Omega Q cosh\left(\frac{CV_{FE}+Q}{CV_1}\right) = 2\Omega Q_0 sinh\left(\frac{CV_{FE}+Q}{CV_1}\right); \qquad (2)$$

where V_{FE} is the voltage on the ferroelectric, $V_1 = k_B T d/p$, $C = \epsilon_o \epsilon_r A/d$ and $Q_0 = P_1 A$. The dipole moment of an individual dipole in the material is denoted by p, k_B is Boltzmann

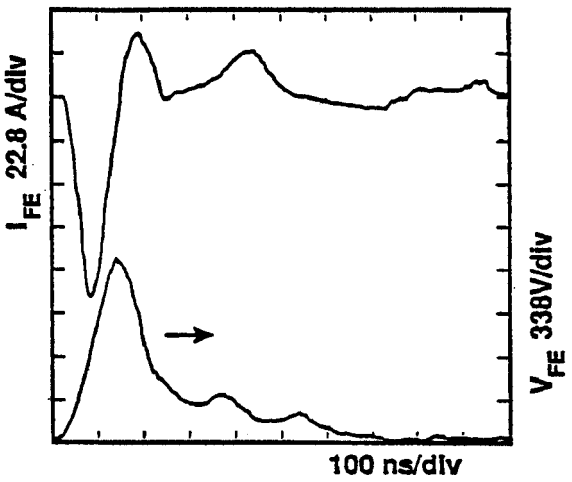

Figure 5. Current and voltage pulses applied to switch the ferroelectric

constant, ϵ_r and P_1 are characteristic of the material. The equilibrium surface charge, is denoted by $Q^{(eq)}$ and it is a solution of

$$Q^{(eq)} = Q_0 tanh\left(\frac{Q^{(eq)}}{CV_1}\right) \quad . \tag{3}$$

The free charge due to the applied voltage is denoted by Q_{app} and is given by $C_0 V_{FE}$ where $C_0 = \epsilon_o A/d$. The total change in the charge, δQ, of the capacitor is $\delta Q \equiv Q + Q_{app} - Q^{(eq)}$; a fraction of this charge is released into the gap. This fraction is assumed to be unity in the data displayed in fig. 3.

These equations were used to simulate the performance of the ferroelectric with the delayed anode pulse and the result is overlayed in fig. 3. The model is in good accordance with the experimental data. The timing of the peak and"cut-off" current were predicted theoretically and confirmed experimentally. The same simulations indicate that the delay difference between the peak current and cut-off depends primarily on the properties of the ceramic. No clear dependence on other time-parameters was observed.

The peak emission occurs exactly at the point where the voltage on the ferroelectric drops to zero. This can be understood in terms of total number of charges released into the gap since this process continues as long as the applied voltage is non-zero. Once the voltage drops to zero, electrons from the gap return to the ferroelectric. Consequently, less electrons are present in the diode gap and its resistance increases causing a decrease in the anode current. Figure 5 shows the ferroelectric switching voltage. Note that it drops to zero after $\sim 900ns$ which corresponds with the occurrence of the peaks in the theoretical and experimental data of fig. 3.

In conclusion, it was shown that the anode current increases when extending the delay time between the ferroelectric and the anode pulses. This increase continues for the entire duration of the ferroelectric voltage pulse. Once this voltage drops to zero, electrons from the gap return to the ferroelectric and the current decreases. In addition, it was shown that the emission is not dependent on the applied voltage and the same scaling laws which were developed for the low voltage ($V_{AN} < 600V$) hold for the higher voltage regime ($\leq 50kV$) as indicated throughout this set of experiments.

References

[1] H. Riege, *Nucl. Instrum. Methods in Phys. Res. A*, **340**, 80 (1994).

[2] S. E. Sampayan, G. J. Caporaso, C. L. Holmes, E. J. Lauer, D. Prosnitz, D. O. Trimble & G. A. Westenskow, *Nucl. Instrum. Methods in Phys. Res. A*, **340**, 90 (1994).

[3] G. A. Mesyatz, *Tech. Phys. Lett.*, **20**, 8 (1994).

[4] T. C. Cavazos, W. L. Wilbanks, C. B. Fleddermann and D. A. Shiffler, *Appl. Phys. Lett.*, **65**, 2612 (1994).

[5] J. D. Ivers, L. Schächter, J. A. Nation, G. S. Kerslick and R. Advani, *J. Appl. Phys.*, **73**, 2667 (1993).

[6] L. Schächter, J. D. Ivers, J. A. Nation and G. S. Kerslick. *J. Appl. Phys.*, **73**, 8097 (1993).