Electron-beam diodes using ferroelectric cathodes

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A new high-current density electron source is described. The source consists of a polarized ferroelectric ceramic disk with silver electrodes coated on both faces. The front electrode consists of a periodic silver grid alternating with exposed ceramic. A rapid change in the polarization state of the ceramic results in the emission of a high-density electron cloud into a 1–10-mm accelerating diode gap. The anode potential is maintained by a charged transmission line. Some of the emitted electrons traverse the gap and an electron current flows. The emitted electron current has been measured as a function of the gap spacing and the anode potential. Current densities in excess of 70 A/cm^2 have been measured. The current is found to vary linearly with the anode voltage for gaps <10 mm, and typically exceeds the Child–Langmuir current density by at least two orders of magnitude. The experimental data is compared with predictions from a model in which the electrons emitted from the ferroelectric reflex in the diode gap.

I. INTRODUCTION

Recent experiments at CERN[1-3] and at the Lebedev Institute[4] have demonstrated that it is possible to extract high-current density electron beams from ferroelectrics. The emitted beams may be useful in injectors for both low- and high-current accelerators and for microwave generation devices. Ferroelectric materials typically have a bound surface polarization charge density of order of or greater than 0.1 C/m^2. The electric field in the diode gap, arising from the remnant polarization charge of the polled ceramic, is of order of $\mathbf{P}/\epsilon_0 \sim 10^{10}$ V/m, i.e., the polarization field, but is screened from the diode by free charge attracted to the surface of the ferroelectric. Electron emission occurs when the polarization state of the ferroelectric is changed and the surface density of free charge required (electrons, in our experiment) to screen the polarization field from the region exterior to the ceramic is changed. The emitted electrons are accelerated into the diode gap, over a distance comparable to the grid periodicity, by the large partially unscreened electric field. The potential reaches a minimum at this location and the electrons decelerate as they cross the diode toward the grounded anode. In the absence of an applied voltage across the diode the electrons reflex in the gap and, unless the gap is small (comparable to the gridded structure periodicity), no net current flows. Current flows through the gap when a diode voltage is applied as a result of electron emission from the ceramic disk with the emission controlled by changing the polarization state of the cathode. The current flow and the cathode processes are closely connected and the description of the emission characteristics requires a coupling of the two regions. In this paper we present experimental observations of the current-voltage characteristics of a vacuum diode using a ferroelectric cathode. The results are compared with predictions from a theoretical model which will be described in detail elsewhere.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown schematically in Fig. 1. A 1-mm-thick, 2.5-cm-diam ferroelectric LTZ-2 (lead-zirconium-titanate) disk is mounted as the load on a 10-Ω characteristic impedance transmission line. The line is switched by a krytron applying a 200-ns, 1-kV pulse to the sample. The sample is oriented with the polarization vector pointing into the diode. A positive pulse is applied to the rear face of the ferroelectric and the gridded portion of the emission surface is held at ground potential. The effective emission area is ~ 1 cm^2. The cathode is coated with a thin (~ 1 μm) silver coating on its rear surface and a gridded emission surface with alternate silver and uncoated strips of 200 μm width on its front surface. A planar graphite anode is located 2–10 mm from the emission surface. The anode is maintained at a positive potential with respect to the cathode by a charged transmission line. Current flow through the diode partially discharges the line. We record the line current at the diode and calculate the instantaneous gap voltage from the known line current, the transmission line impedance, and the initial voltage on the transmission line. Lines with characteristic impedances ranging from 12.5 to 50 Ω have been used as the load. The diode is maintained at a base pressure of 10^{-5} Torr.

Figure 2 shows three oscilloscope traces obtained for the diode current with a 4-mm gap and a 25-Ω load with an LTZ-2 ferroelectric cathode. The transmission line load was initially charged to 100, 300, and 500 V for the three data events. The beam current length was determined by the length of the cable. The steady nature of the current is typical of this data although for order of magnitude greater current density emission the current increases in time during the first half of the pulse and becomes more triangular in shape. We have not observed any pulse shortening due to limits on the free charge available from the surface of the ferroelectric. Peak emission current densities of up to 70 A/cm^2 have been obtained experimentally. The current densities recorded are typically a factor of 2 orders of mag-

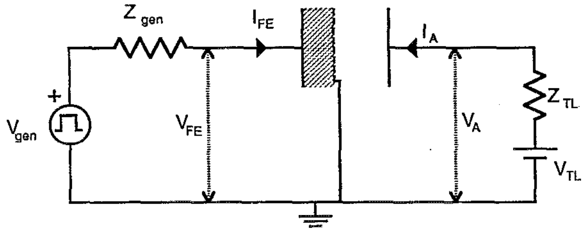

FIG. 1. Schematic showing the experimental arrangement of the ferroelectric cathode in a vacuum diode.

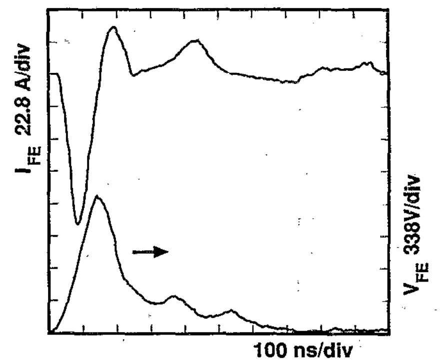

FIG. 3. Experimental data showing the currents (I_{FE}) through and the voltage across the ferroelectric (V_{FE}). Details of these traces are insensitive to the diode current and gap spacing. Note that the voltage pulse on the ferroelectric is only about 150 ns long.

nitude greater than the vacuum space-charge-limiting current. For example, the Child–Langmuir limiting current density for a 4-mm gap and for 300 V applied across the gap is 76 mA/cm^2 and is to be compared with the current density of about 12 A/cm^2 found in these experiments.

Figure 3 shows traces of the voltage across and the current through the ferroelectric cathode. Note that the current through the ferroelectric is of order 100 A and is always larger than the diode current in our present experiments. The details of the current through and the voltage across the ferroelectric are remarkably independent of the diode operating conditions. However, the diode characteristics are strongly dependent on the state of the ferroelectric ceramic. For example, the diode current drops to zero if the ceramic is not pulsed. Reversing the direction of the remnant polarization vector also resulted in zero current in all conditions including positive diode voltage and pulsing of the ceramic at levels which gave emission in the opposite polarization. These observations demonstrate that the current flow does not result from a plasma fill of the diode as a result of the pulsing of the ferroelectric. Note also that the duration of the beam current exceeds that of the pulsing voltage on the ferroelectric (V_{FE}) and that the current flow in the diode is controlled by changing the polarization of the ferroelectric. This situation should be compared with that found in a field emission diode in which the emission is determined by the electric field in the gap resulting from the voltage applied to the diode.

One can obtain information on the state of the ferroelectric from plotting the voltage across the ferroelectric against the integral of the current through the ceramic. The resulting charge-versus-voltage curve, which is illustrated in Fig. 4, is a dynamic hysteresis loop for the ferroelectric. The curve is much as expected and illustrates the potentially available charge for diode current flow. For pulse durations of, say, 100 ns, the charge available would limit the diode current to about 700 A/cm^2. The charge available may be increased by increasing the voltage pulse applied to the ceramic disk. The structure on the upper portion of the curve is a result of the piezoelectric properties of the ceramic and, in zero order, we believe is not important in the emission process. The resonant frequency of the ceramic samples used is about 2 MHz.

In Fig. 5 we present plots the diode current versus the gap voltage constructed as described earlier for four gaps ranging from 2 to 8 mm and an LTZ-2 cathode. The pulse voltage measured across the ceramic disk was about 1150 V. Similar data have been obtained using other ferroelectric cathodes and with different pulse voltages. In all cases the diode current starts to flow when the voltage across the ferroelectric is approximately at its maximum value and continues even after the ferroelectric voltage pulse has returned to zero. The results indicate an almost linear scaling of the beam current with the diode voltage. The beam current is only very weakly dependent on the diode gap spacing for fixed gap voltage and ranges from 12 Ω at the

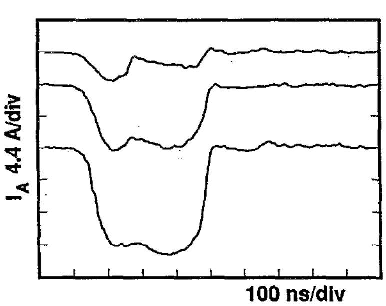

FIG. 2. Three records of the diode current corresponding to $V_{TL}=100$, 300, and 500 V for a 4-mm-wide gap and a load transmission line impedance of $Z_{TL}=25$ Ω.

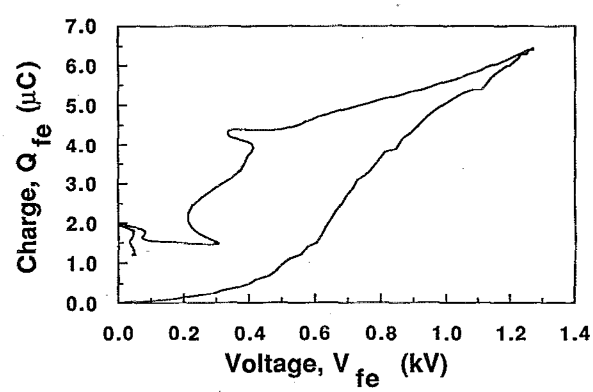

FIG. 4. Q-V characteristic of the ferroelectric obtained in the course of a single shot, using data similar to that shown in Fig. 3.

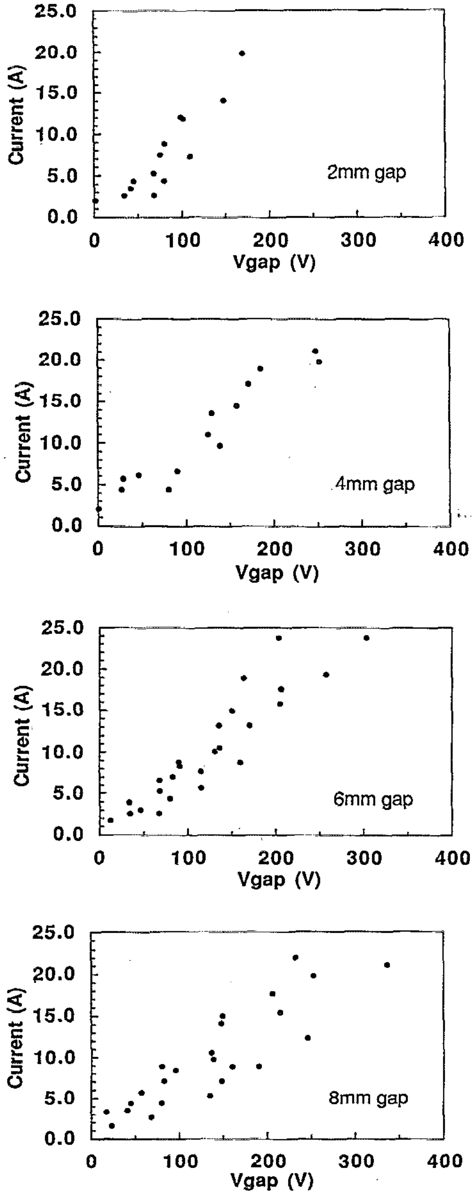

FIG. 5. *I-V* characteristic of the diode with a 2-, 4-, 6-, and 8-mm gaps, and using an LTZ-2 ferroelectric cathode. Similar results have been obtained for other gaps and different cathode materials.

largest spacing (10 mm) to 9 Ω for the 2-mm gap. The results are repeatable and breakdown does not occur. For small gaps (≤4 mm) there is a beam current when the diode voltage is reduced to zero. This effect is shown in Fig. 6 for a 4-mm gap and for three different values of the pulsing voltage. In all cases the current drops to zero when the gap voltage is decreased to −60 V, indicating that the maximum electron energy on emission is ∼60 eV. A 60-V electron injection energy is insufficient to account for the enhancement observed in the diode current over the space-charge limit. Finally we show the dependence in Fig. 7 for low diode voltages of changing the anode cathode spacing for gaps less than or equal to 4 mm. Once again the current flow is very insensitive to the gap dimensions. In this case the ceramic pulsing voltage was maintained at a peak value of 1150 V.

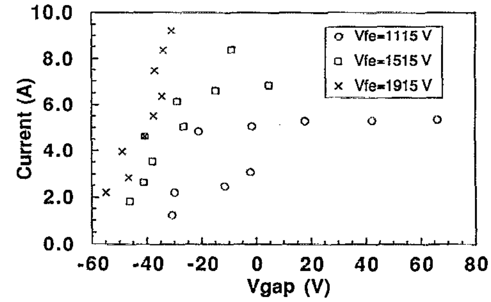

FIG. 6. *I-V* characteristic of the diode for a 4-mm gap with varying voltages applied to the ferroelectric. Increasing the voltage on the cathode disk increases the diode current for otherwise fixed conditions.

III. DISCUSSION OF RESULTS

The data presented above characterize the static characteristics of a diode with a ferroelectric cathode. In order to understand the emission it is necessary to recognize that the system consisting of the ferroelectric disk and the vacuum diode must be treated as a single entity. The ferroelectric disk is permanently polarized and hence has a net surface density of bound charge. The electric field at the surface of the dielectric is of order 10^{10} V/m, as may be readily calculated using the boundary conditions at the surface of the ceramic. In our experiments we have a net positive bound charge on the front surface (i.e., the surface within the vacuum diode) of the ferroelectric. Electrons are attracted to the surface to reduce the external field and to a first approximation the ferroelectric has zero net charge, i.e., the free-charge density on either surface is equal and opposite to the density of the polarization charge. If the state of the ceramic is changed by application of, say, a positive pulse to the rear surface of the dielectric, then a net charge imbalance occurs on the surface of the dielectric with the resulting field distribution appearing as shown schematically in Fig. 8. For a positive polarity pulse on the rear surface the magnitude of the density of free charge on either surface is increased. On the rear surface this is readily accomplished by current flow, which leads to an increase of the density of positive free charge (holes) on the surface of the silver plating between the silver electrode and the ceramic. On the front surface there is a corresponding increase in the electron charge in the vicinity of

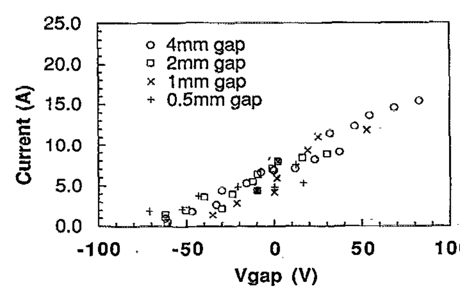

FIG. 7. *I-V* characteristic of the diode with small ≤4 mm gaps, and using an LTZ-2 ferroelectric cathode. The peak voltage applied to the ceramic was 1150 V.

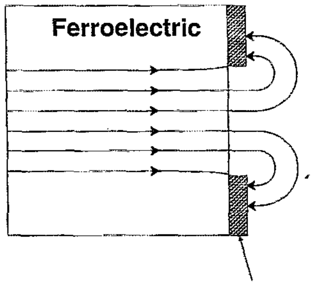

FIG. 8. Schematic illustration of the local cathode electric field when a positive polarity pulse is applied to the rear surface of the ceramic cathode. The average electric field is of order 4×10^9 V/m and may be considerably greater close to conductor boundaries.

the silver grid. Free charge can only redistribute on the surface of the ferroelectric in the time scale of the changing field by flow of electrons in the vacuum from the silvered regions to the ceramic or by surface flashover. We believe, based on the observations reported earlier, that the former explanation is the more probable. Based on the change in the charge on the ferroelectric as a result of the pulsing, we estimate that the surface field due to the charge imbalance between the bound and free charge on the front surface of the dielectric is of order 4×10^9 V/m. A field of this magnitude at the surface of the silver will yield a current density of order 20 A/cm^2 as a result of field emission. Close to the edges of the silver grid the electric field and the emitted current density will be substantially increased over these values. If the applied pulse is reversed in polarity, then the direction of the field in the diode reverses with the field lines finishing on the ceramic sections of the cathode. In either case it is clear that a substantial current can flow from one portion of the cathode to another. Note that the current flow is through the generator used to pulse the ferroelectric.

We consider the emission from the surface of the ferroelectric/silver grid as forming a cloud of electrons close to the cathode. Until the electron current flows the potential close to the cathode can reach potentials of order several hundred kilovolts, i.e., the product of the surface field strength and the grid spacing. Of course the field is reduced by the electron emission; there will, however, still be a significant potential depression in the cathode vicinity which could readily amount to the 20–20 kV required to account for the observed current density. The emitted electron energies recorded for small gap spacings are not sufficient to account for the high-current density measured. Note that not all of the electric field lines will begin and end on the cathode surface and that some will traverse the diode finishing on the anode. This is most likely for small gap spacings. In the absence of any applied diode voltage the emitted electrons that traverse the diode will reflex. Current will flow only if the electrons are emitted with an initial energy or if the equilibrium is perturbed by the application of a given diode voltage. Note once again that the flow of current must be completed through the 10-Ω generator used to pulse the ceramic. Any change in the charge density on the front surface of the dielectric is felt by an equal magnitude change on the rear surface of the ferroelectric. This implies that the emission is limited to the current delivered by the pulser. An increase in the applied voltage on the ferroelectric will increase the local field at the cathode and hence the density of the electron plasma at the cathode. This process is consistent with the observations described earlier as shown in Fig. 6.

We now consider a more realistic picture of the electrons in the gap. It is assumed that the cloud can be described by a one-dimensional (1D) density function $n(z)=n_0e^{-kz}$, where k is determined from the radial dimensions of the system. The density near the cathode, $n_0(t)$, is obtained by noting that the total charge in the gap is $Q_{\text{gap}}=en_0A(1-e^{-kg})/k$ and is determined by the difference between the charge on the back electrode of the ferroelectric capacitor and the charge stored on the gridded surface. The potential in the gap is readily found from Poisson's equation subject to the boundary conditions that at the anode ($z=g$) the potential is V_A and that the electric field is the same as if no electrons were in the gap. In this representation we tacitly assume that the distance of potential peak from the grid is much smaller than the diode gap g. We do not identify the details of the emission; we only specify that the electrons are accelerated into the gap. We estimate the time varying current in the gap for a positive anode voltage ($V_A>0$) from the slight increase, $\delta U\sim eV_A/(2\beta_0\gamma_0^3mc)$ in the electron velocity due to the quasistatic externally applied gap potential, where γ_0 is the value of the electron relativistic factor averaged over the diode gap. In our 1D model the current is uniform in space and is given by $I_A=en_0\delta UA$. Since δU is linearly dependent on V_A, we may determine the resistivity of the gap R_{gap}:

$$R_{\text{gap}}\equiv\frac{V_A}{I_A}=2\beta_0\gamma_0^3\sqrt{\frac{\mu_0}{\epsilon_0}}\frac{g^2}{A}\left(\frac{c}{\omega_p g}\right)^2=\frac{F_f}{\omega_p\epsilon_0}\frac{g}{A}. \tag{1}$$

The cloud form factor, F_f, depends mainly on the distribution profile and partially on the plasma frequency $\omega_p = \sqrt{e^2n_0/m\epsilon_0}$. The linear V-I characteristic of the gap is in numerical agreement with the experimental results. The equations are nonlinear and have been solved numerically. A more detailed analysis will be published elsewhere.[5] Our calculations indicate that the total charge in the cloud is reasonably constant, in spite of the time variation of the voltage applied to the ferroelectric. We compare the experimental result with the current calculated using this model and with that predicted using the Child–Langmuir relationship. For example, in a 4-mm gap with $V_{\text{TL}}=300$ V, $Z_{\text{TL}}=25$ Ω, and $V_{\text{gen}}=1900$ V, a current of 8.8 A was measured. The Child–Langmuir current for the gap is about 39 mA. The proposed model predicts a current which varies throughout the pulse of 8.7–9.7 A, in agreement with the experimental data. More details regarding the theoretical treatment of the ferroelectric diode will be published in the near future.

IV. CONCLUSIONS

We have shown experimentally that when a ferroelectric ceramic is used as the cathode of a vacuum diode we may extract a current which exceeds, by about two orders of magnitude, the Child–Langmuir limiting current. This result may be explained using a model in which the screening charge on the surface of the ceramic is injected into the diode as the polarization state of the ferroelectric is changed. The charge forms an electron cloud very close to the cathode and depresses the potential locally. The current flow through the diode then consists of two parts, one the flow into the cloud from the ferroelectric, and two the flow through the remaining part of the diode as described above. The dependence of the current on the voltage is approximately linear rather than $V^{3/2}$, as found in the Child–Langmuir case and is limited by the impedance of the generator driving the ferroelectric disk. Calculations using the model are in good accord with the experiment. In the present experiments we achieved a beam current density of up to 70 A/cm^2. It would appear possible with suitable modifications to the system to generate beam current densities in excess of 1 kA/cm^2 for short ~100-ns pulses, using ferroelectric cathodes.

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