

POTENTIAL APPLICATIONS OF PULSED ELECTRON EMISSION FROM FERROELECTRICS, FOR SOURCES OF ELECTRONS, IONS, AND ELECTROMAGNETIC RADIATION

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Abstract

The recently developed method of intense electron emission from ferroelectric PLZT ceramics offers several practical advantages compared with the conventional ways of electron-beam generation: these advantages are zero extraction voltage, modest vacuum, and rugged emitter material that can be formed into any arbitrary shape. Large-area electron beams in a wide range of cross-section, current, and current density could be generated for injection into linacs, or for triggering high-power gas or vacuum switches. The electron beams may also be used to produce intense ion beams by electron sputtering of a solid target in vacuum. By modulating the intensity of an electron beam emitted at low kinetic energy, new RF power sources in the gigahertz region can be envisaged. Some results of basic experiments on the different schemes of application are reported.

Introduction

The conventional methods of electron-beam generation used nowadays in most of the scientific and technical applications belong to one of the following categories:

- thermionic emission,
 - photoemission,
 - field emission,
 - secondary emission by bombardment with other particles (electrons, ions or neutrals),
 - extraction from a plasma,
- or any combination of the above methods.

None of these methods is based on a real electron-emission effect. Rather, each procedure requires a strong electric field in order to extract intense electron beams from a neutral medium. All conventional emission methods, except extraction from plasma, usually need also a very good vacuum. When high electron-beam intensities are envisaged, most methods are limited either by the electron production rate, or by damage to the surface material, or because of space-charge forces blowing up the beam, especially in vacuum.

Conventional ion sources are mostly based on one of the following effects:

- ion extraction from a plasma;
- ion production with energetic electrons from a neutral gas or plasma;
- ion generation by target sputtering with primary ions, electrons, or photons.

Because of their low velocity, ion beams are severely limited by space-charge forces, when transported through vacuum. Furthermore, with classical methods it is difficult to produce the energetic, multiply charged, heavy ions that are needed in order to reduce the length of the subsequent accelerator structures.

Recently, several new ways of producing electron and ion beams have been conceived and demonstrated experimentally at CERN [1-8]. These schemes offer not only intrinsic advantages, but also many practical ones, compared with the classical schemes. The new ways of obtaining electron emission appear

interesting for applications in all technical fields where the production of intense and modulated particle beams is needed.

The Principle of Ferroelectric Emission

The spontaneous polarization of a disk-shaped ferroelectric sample is rapidly changed by a fast HV pulse applied between a perforated (grid) electrode on one side of the sample and a full electrode on the other side [1-6]. The screening charges, which originally compensated the surface charges corresponding to the spontaneous polarization, become free on the surface after change of polarization. Unlike in a capacitor with metallic electrodes, the charges on the bare sample surface cannot move away. Hence a space-charge field is created by the surface charges, which is strong enough to expel them from the surface should the charge carriers be electrons. It has been shown that this way of emitting electrons works not only with a zero extraction potential, but even with an oppositely directed surface field with an amplitude up to the potential value of the order of the HV pulse that is applied in order to change the polarization [3]. To make a comparison with classical electron production schemes, the following main advantages can be cited:

- No extraction field is needed. External fields may be fully used for modulating and shaping the beam in space and time.
- The vacuum can be very modest (> 100 Pa). The emission of an electron beam also works in plasma or in low-pressure gas [5, 7].
- The ferroelectric material and the electrodes are rugged.
- The electrical conductivity of the ceramic ferroelectric materials is nevertheless high enough to cater for a rapid (submicrosecond) re-establishment of the original screening states between pulses, so that no special resetting of the ferroelectric sample is necessary after an emission has taken place.
- Ferroelectric electron-pulse emission is possible with high repetition rate [9], not only because of the fast recovery of the emitter material but also because the emitted beam can be easily modulated with low external fields. Maximum repetition rates of 2 MHz have been reached, up to now, with PLZT-2/95/5 material.
- Arbitrary beam cross-sections (e.g. single axial, multiple or hollow) can be shaped with the corresponding geometries of the emitting area or of the apertures.

The ferroelectric emission can extend over pulse durations of up to several microseconds [3-5]. High beam-power operation can be achieved by CW high-repetition-rate pulsing. Up to now, average emitted charge densities of $10 \mu\text{C}/\text{cm}^2$ and emitted current densities of $100 \text{ A}/\text{cm}^2$ have been observed in experiments. Faster, low-impedance electronic power circuits for spontaneous polarization reversal should speed up the emission process and lead to higher current densities. The samples of 0.5 to 1 mm thickness used in the experiments require threshold electric fields of the order of $10 \text{ kV}/\text{cm}$ for polarization reversal. Voltage amplitudes of less than 100 V may be sufficient for ferroelectric layers of less than 0.1 mm thickness. Normalized emittances of beams generated with ferroelectric emission have not yet been measured, but they are expected to be quite low

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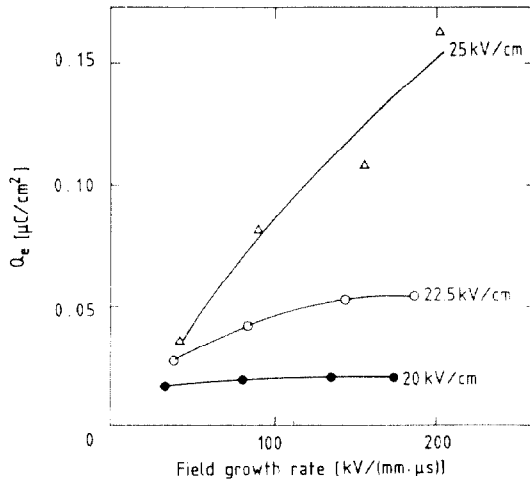


Fig. 1 The charge density emitted from PLZT-8/65/35 as a function of field growth-rate at three amplitudes of the electric-field strength.

owing to the high current density and the low temperature of the emitting surface [7].

Applications of Ferroelectric Emission

The ferroelectric electron emission without an external extraction field offers significant advantages in many applications that are much more difficult to realize with conventional sources. External fields can be fully implemented for modulating and shaping the emitted electron beam in space and time. Investigations have been undertaken with the aim of using the ferroelectric emission method in different fields of accelerator technology, such as for preionization, for triggering high-power gas and vacuum switches, for generating primary electron beams, and for generating secondary electron and ion beams by sputtering from solid electrodes.

Application in Electron Guns

Electron-beam pulses have been produced mostly with a pulse length between 10 and 100 ns [3, 4], containing total charges between 1 nC and several μC . The pulse length depends on the growth rate of the primary excitation field (Fig. 1). This beam pulse can be used directly, without modulation, for injection into an accelerator cavity or into a gas-filled volume that has to be ionized. The use of such electron beams for the triggering of HV, low-pressure gas switches has been described in Refs. [2] and [7]. The characteristics of this trigger type are superior to those of conventional glow-discharge triggers, which are used in thyratrons and pseudospark switches. High switching precision is combined with a higher voltage hold off capability and a low pre-firing rate of the switch.

A single-gap HV switch, as described in Ref. [7], has been triggered in a dynamic range between a few hundred volts and 27 kV, without changing the geometrical parameters or the gas pressure (Fig. 2). The discharge current was several kiloamperes. A switching precision of ± 1 ns was achieved without special optimization of the geometry or of the electrical circuit of the ferroelectric trigger system.

Generation of High-Intensity Electron and Ion Beams

The very high electron-beam current density of up to $100 \text{ A}/\text{cm}^2$, which is obtained by ferroelectric emission, can be

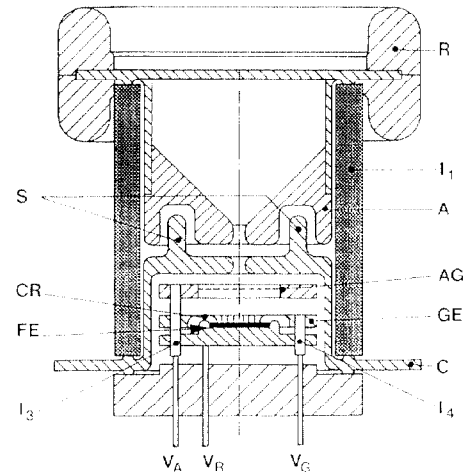


Fig. 2 Scheme of a hollow cathode, low-pressure, one-gap, high-voltage switch triggered by an electron beam emitted from the surface of a ferroelectric PLZT-2/94/6 sample (FE). A = anode; C = cathode; $I_{1,3,4}$ = insulators; S = electrode screens; R = grading ring; AG = auxiliary grid; FE = ferroelectric disc; GE = grid electrode; CR = contact ring; V_R = pulse voltage on back of the FE sample; V_G = potential on GE; V_A = potential of AG.

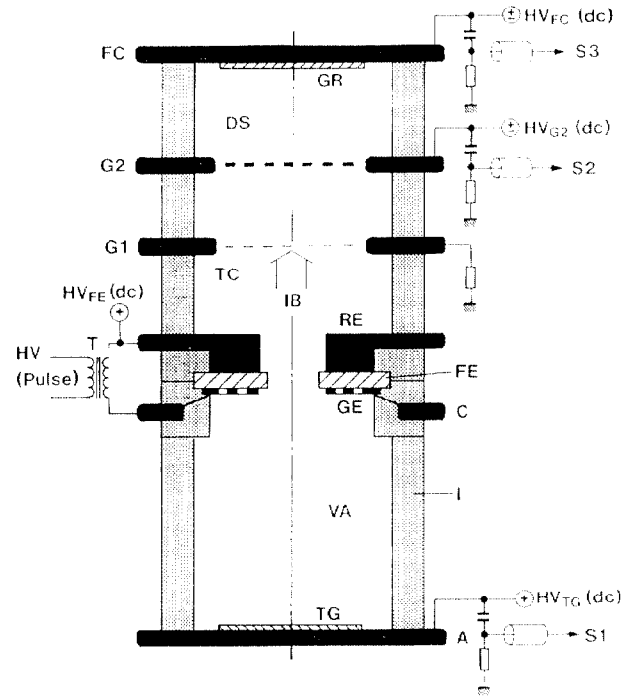


Fig. 3 Schema of experimental set-up for the ion beam source: FE = PLZT-2/95/5; GE = grid electrode; RE = rear electrode; G1 = grid 1; G2 = grid 2; FC = Faraday cup; GR = graphite; TG = target; A = anode; C = cathode; DS = drift space; $HV_{TG,FE,G1,G2}$ = d.c. potentials; T = transformer; I = insulator; VA = vacuum; TC = transport channel; IB = ion beam; S1, S2, S3 = signals.

used to sputter-off electrons and ions from suitable targets in a vacuum gap [8] (Fig. 3). By applying an accelerating voltage of 2 to 20 kV across the gap acting on the sputtered surface plasmas, dense electron and ion beams moving in opposite directions can

be accelerated through the vacuum gap. The gap can virtually be transformed into a short circuit. The resulting vacuum discharge, which has been observed at discharge currents up to 5 kA, is homogeneous (Diffuse Vacuum Discharge). The beam currents through the vacuum gap are determined by the external electrical circuit parameters. Electron or ion beams can be extracted through holes in the corresponding electrodes of the gap. Outside the gap, both beams are submitted to space-charge limitations, which, for the electrons, can be partly overcome by means of a plasma generated in the transport channel behind the anode hole. The strong space-charge limitations for the ion beam may be reduced by electrons sputtered-off from several transparent metal grids in the transport channel adjacent to the cathode. This scheme of plasma-assisted beam generation is not submitted to the usual disturbance caused by 'dead' material in the source, such as plasma or low-pressure gas, which does not contribute to the beams. There are only thin layers of surface plasma from which the main, fast-moving charge carriers are extracted. The main volume of the gap is filled with particles belonging to either the electron or the ion beam. Recombination and charge-exchange rates are small; hence, high intensities of multiply charged ions can be expected.

Applications in Vacuum Microelectronics

Ferroelectric emission, as a solid-state phenomenon induced in an electrical circuit, seems to be predestined for applications at the microelectronic level. For accelerator technology, the generation of RF power in the gigahertz range—as for Lasertrons or Gigatrions—seems to be attractive. The feasibility of such a microwave source depends on the decrease of electron-emission energy and of excitation voltage with respect to the thickness of the ferroelectric sample. Systematic studies of emission as a function of sample thickness have not yet been performed. However, in a test with PLZT-2/95/5 samples of 1 mm and 0.3 mm thickness, threshold excitation fields of 3.3 and 3.0 kV/mm were measured, respectively, indicating a nearly linear dependence of threshold voltage on thickness. There is no proof that the ferroelectric emission works for layers below 100 μm . Only then could emission be induced with voltage amplitudes of less than 100 V and the modulation of the emitted beam be performed at the same level.

Large-area ribbon-like ferroelectric emitters (Fig. 4a) could be used in the the same way as photocathodes in Lasertrons

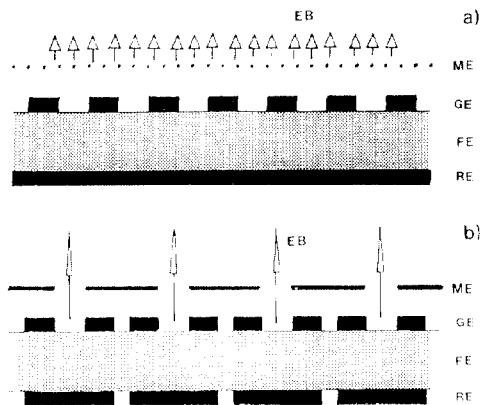


Fig. 4 Schema of thin-layer ferroelectric emission for the generation of a) large-area ribbon beams for microwave generation and b) individual pixel-controlled electron beams for flat TV screens. EB = electron beam; ME = modulating electrode; GE = grid electrode; RE = rear electrode; FE = ferroelectric layer.

and as micro-needle field-emission arrays in Gigatrions [10, 11] to produce ribbon beams of electrons that are modulated and accelerated after emission.

In a similar way, a large emitting area can be subdivided into an arrangement of single, individually controlled pixels (Fig. 4b). This would allow the construction of compact information and image-processing devices.

Conclusions

The first successful applications of ferroelectric emission have been started in the field of electron guns. The emitted beams may be used for triggering the high-power low-pressure gas switches, for injection into accelerators, or for the generation of RF radiation. Some experimental results, which are the basis for these applications, underline the advantages of ferroelectric emission over conventional methods. In order to profit from this new emission method, appropriate technologies of ferroelectric material production and processing, of electrode deposition, and of microcircuit layout and production have to be developed. Existing microelectronics technologies may help to accelerate the development of such a special technology. It can also be expected that more research and development will push the present limits of current density emitted in vacuum to above 100 A/cm².

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