EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

HR/afm

CERN/PS/88-66 (AR)
CLIC Note 82

PULSED ELECTRON EMISSION FROM FERROELECTRICS

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A new cold electron source is described, which is based upon fast change of the spontaneous polarization $\vec{P}_S$ of a ferroelectric sample induced by high-voltage pulses. After $\vec{P}_S$ reversal or change, part of the screening electrons are emitted and accelerated from the surface without any potential barrier. $\vec{P}_S$ can be rapidly (1 ns) reversed provided fast-rising fields (10^4 to 10^5 V/cm) with high current densities (>100 A/cm^2) are applied. Resulting electron beam current densities of more than 10^3 A/cm^2 have been achieved with PLZT ceramics. The emission mechanism works in vacuum, in low-pressure gas, and in plasma. Without external extraction field electrons of up to 30 keV kinetic energy were emitted from rugged ceramic ferroelectric samples of specific composition.

Paper to be published in Applied Physics Letters

Geneva, Switzerland
November 1988

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A new cold electron source is described, which is based upon fast change of the spontaneous polarization $\vec{P}_S$ of a ferroelectric sample induced by high-voltage pulses. After $\vec{P}_S$ reversal or change, part of the screening electrons are emitted and accelerated from the surface without any potential barrier. $\vec{P}_S$ can be rapidly (1 ns) reversed provided fast-rising fields (10^4 to 10^5 V/cm) with high current densities (>100 A/cm^2) are applied. Resulting electron beam current densities of more than 10^3 A/cm^2 have been achieved with PLZT ceramics. The emission mechanism works in vacuum, in low-pressure gas, and in plasma. Without external extraction field electrons of up to 30 keV kinetic energy were emitted from rugged ceramic ferroelectric samples of specific composition.

Electron beams with ever increasing density are required in accelerators, free-electron lasers, and electron tubes for radio frequency, microwave and x-ray generation, as well as in material processing. Most electron sources use either thermionic or photoelectric emission from surfaces or extraction from a plasma. All these methods require high electric extraction fields, since they separate electrons from a globally and locally quasi-neutral medium across a finite potential barrier W (Fig. 1a), which is of the order of a few eV for most solid matter. It can be rather small in the case of a plasma,[1] but the interior of a plasma is, on the other hand, screened against the extraction field.

Here we report on a new type of electron source which produces excess electrons being emitted from a surface, even without an external extraction field. However, an external field can be applied in addition to enhance the emission and to start the acceleration of the particles. Also surface heating or illumination with light is not required, though the emission effect is strongest at a defined temperature and may be enhanced by laser irradiation.

The principle of the new electron source is based upon fast reversal of the spontaneous polarization $\vec{P}_S$ of a prepoled ferroelectric sample (FE). It is known that in the ferroelectric phase such materials may be polarized with surface charge densities reaching 100 $\mu C/cm^2$, which are compensated by charge carriers coming from the exterior or the interior of the sample (Fig. 1b). When a strong change or reversal of $\vec{P}_S$ is achieved in a short time the compensating charges are set free at the surface and the electrons on the side with negative polarization charge (Fig. 1c) are expelled.

Methods and experimental results of fast $\vec{P}_S$ change (creation, annihilation and reversal) have been reviewed.[2-4] Significant $\vec{P}_S$ changes in nanosecond time can be achieved with fast-rising or falling pulses of strong electric field strength amplitude. Sufficient external pulse current density has to be fed into the sample prior to $\vec{P}_S$ change to remove the compensating charges in the desired time. Assuming the duration of the emitted electron pulse is of the order of the reversal time, emitted current densities of up to 10^5 A/cm^2 can be expected. Ideally an initial field strength of $\vec{E}_i = \vec{P}_S/\varepsilon$ will expel or attract electrons, where $\varepsilon = \varepsilon_r\varepsilon_0$ is the dielectric permittivity of the ferroelectric medium. The maximum electron energy is then determined by the thickness of the sample and may reach 100 keV for $\varepsilon_r = 10^3$ and d = 1 mm.

After the $\vec{P}_S$ reversal or change and before the next emission $\vec{P}_S$ has to be re-established in the old direction (Fig. 1b). This can be done with a dc field of the order of the coercive field E_C or by submitting the samples to specific prepoling procedures.[3]

Electron emission can only occur from free areas of the ferroelectric sample surface. The electrode on the emission side must be partially perforated similarly to a grid, a mesh, or a sieve. The ratio between electrode area and free surface area determines the efficiency of $\vec{P}_S$ change and of emitted beam current amplitude.

The energy transfer from the external HV pulse to the energy which changes polarization and to electron-beam energy is straightforward and quite efficient (1 to 10%). The energy losses are determined by the dielectric loss angle of the material and they are distributed over the bulk of the sample. Hence the surface remains relatively cold and high

repetition rates can be achieved.

The choice of material depends not only on the values of $\vec{P}_S$ but also on the desired reversal time. The speed of $\vec{P}_S$ reversal is limited by processes such as domain nucleation, domain-wall motion, and by factors such as grain size, domain size, and the concentration of defects.[5,6] In some ferroelectrics, such as Zr-rich PZLT [$(Pb_{1-x}La_x)(Zr_{1-y}Ti_y)O_3$] ceramics, with a phase sequence antiferroelectric-ferroelectric-paraelectric, very fast sideward domain-wall motion, and therefore $\vec{P}_S$ reversal, is possible in a temperature interval where ferroelectric and antiferroelectric domains coexist.[7]

The environment of the ferroelectric sample before, during and after $\vec{P}_S$ reversal and electron emission plays an important role not only for the screening and charge compensation process, but also for the emission itself. Although the effect functions in high vacuum, a low-pressure plasma more easily delivers screening charges and reduces space-charge forces which quickly blow up the emittance of the electron beam. In addition, plasma in contact with the free surface area reduces the adsorption of gas molecules, which reduce the emission efficiency.

Finally care has to be taken with the electrical impedances of the circuit which determine the desired potential variations on the sample in time as well as the electron beam transport away from the surface.

Single and multiple axial beams of arbitrary cross section can be generated by a suitable layout of electrodes and collimators. The method is favourable for producing dense hollow electron-beam pulses. Large-area electron emission with low kinetic energy (<1 keV) from thin layers of a ferroelectric medium represents an efficient means for ionizing large volumes of low- to medium-pressure gas. This can be applied

for generating homogeneous x-ray radiation, for preionizing gas lasers, e.g. excimer lasers, or for precisely triggering and interrupting high-power plasma switches.

First experimental results have been obtained with an electron beam source, the principle of which is given in Fig. 2. A ceramic $(Pb_{0.98}La_{0.02})(Zr_{0.92}Ti_{0.08})O_3$ sample of 1.5 mm thickness and 20 mm diameter forms the rear wall of a hollow cathode. Before emission the dc potential distribution leads to a $\vec{P}_S$ direction away from the emitter surface with the grid electrode G_p. By a fast triggered low-pressure gas breakdown (pseudospark)[1] between the electrode A and the grid electrode G_p the field direction across the PLZT sample is rapidly changed and $\vec{P}_S$ is reversed while the rear sample electrode stays at a constant negative potential. Emission of a partly space-charge- and current-neutralized electron beam starts from the surface continuing through the discharge plasma. Beam current, charge and energy can be measured by beam-current transformers, by a Faraday cup, and by electrostatic deflection, or via the bremsstrahlung spectrum. In order to minimize the plasma neutralization effects on the diagnostics the beam has to be reduced in size by collimation and to be ejected into a vacuum. Total current amplitudes of several hundred amperes, current densities above 10^3 A/cm^2 from a PZLT surface area of 1 cm^2, and kinetic energies around 30 keV were measured with a 10 kV charging voltage on the pseudospark gap filled with N_2 at a pressure of 40 Pa. The order of the kinetic electron energy follows also approximately from the material constants P_S = 0.15 Cb/m^2 and $\varepsilon_r \approx 300$ (value measured at 1 kHz). Figure 3 shows the electron-beam current waveforms, measured by a Faraday cup, of a part of the beam, the intensity of which was

reduced by collimation to 10^{-6} of the current amplitude at the sample surface. The beam is deflected by different levels of a transverse dc field in the vacuum region and injected through a graphite collimator into the Faraday cup.

Contrary to the electron beam from a normal pseudospark discharge, which is pinching in a low-pressure gas, the beam ejected from the PLZT does not contract. This is due to the almost full current neutralization in the plasma which is produced by the low-energy pseudospark beam preceding the main beam. Hence the transport through the plasma and the transfer to vacuum are much easier and more efficient to achieve. There is enough space and time available to focus and to synchronize the beam pulse accurately to the radio frequency phase of a vacuum cavity for further acceleration.

We believe that the new method of electron beam generation will not only be fruitful for future high-energy accelerators, but will have a strong impact on all fields of technology which need pulsed high-power electron beams.

ACKNOWLEDGEMENTS

The authors thank Daniel Boimond for the design and construction of the electron source and of the electron beam diagnostics equipment.

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FIGURE CAPTIONS

Fig. 1 a) Electron emission with a finite work function W from the conduction band (CB) of a metal or a photoemitter surface.

b) Accumulation of screening electrons (SE) at the surface of a ferroelectric material (FE).

c) The electrons are expelled after polarization reversal without obstruction by a potential barrier.

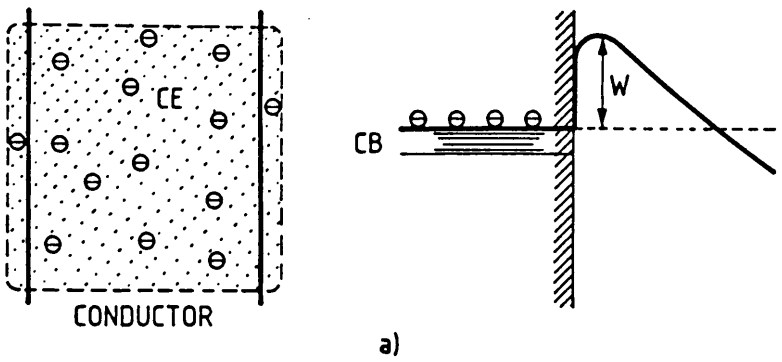
SE = screening electrons, SH = screening holes, IE = injected electrons.

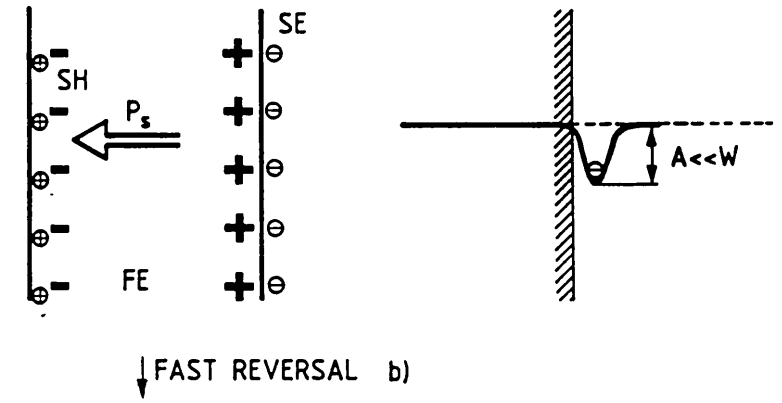
Fig. 2 A simple device which generates electron beams (EB) by fast polarization reversal of a ferroelectric sample (PLZT). Emission occurs from a surface with a grid electrode (G_p) into a vacuum, a low-pressure gas, or a plasma.

A = anode, HV = high voltage, Cs = series capacitor,

RB = blocking resistors, FS = fast switch.

Fig. 3 Electron beam-current waveforms measured in vacuum on a collimated beam ejected from the FE-source via a plasma channel through a 1 mm diameter hole into vacuum. Gradual removal of the low-energy pseudospark electrons by applying a dc deflection field transverse to the beam axis leads to the appearance of the high-energy beam current from the ferroelectric sample surface reduced by a factor of 10^{-6}.





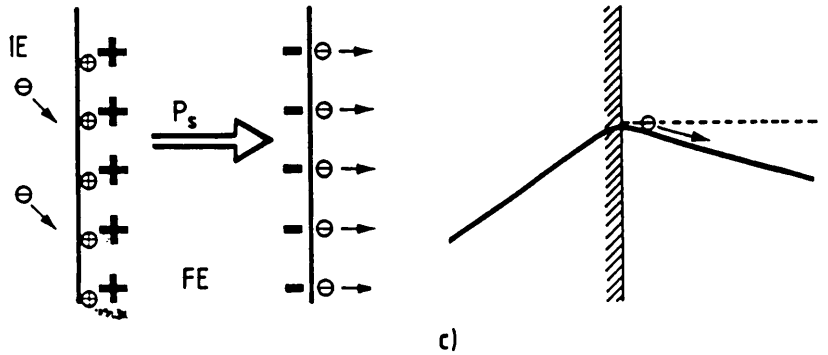


Figure 1

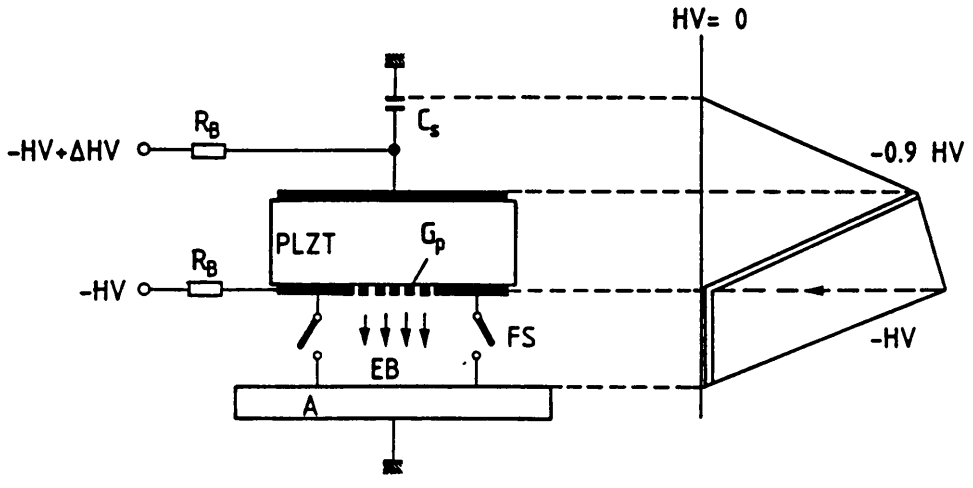


Figure 2

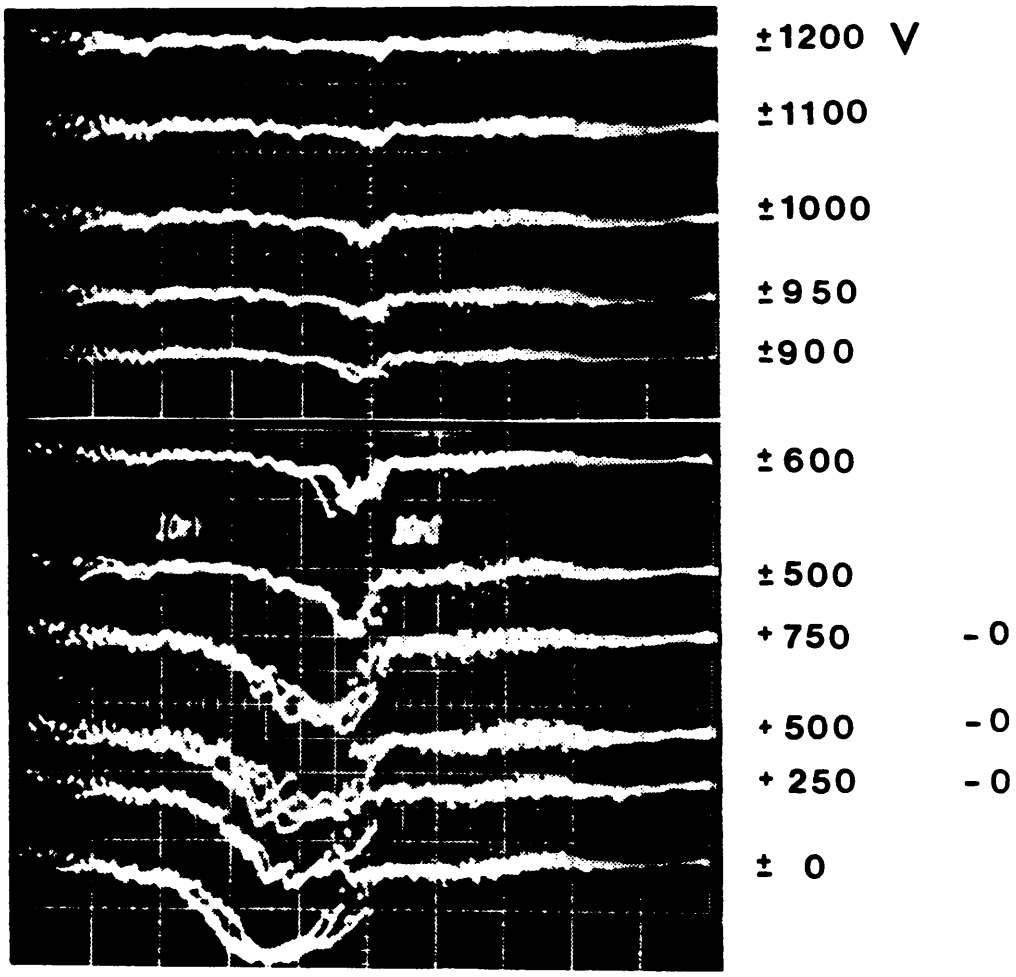

Deflection voltage
±1200 V
±1100
±1000
±950
±900
±600
±500
+750 -0
+500 -0
+250 -0
± 0
2 mA / div

Figure 3