

INITIAL RESULTS ON ELECTRON BEAM GENERATION USING PYROELECTRIC CRYSTALS*

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Abstract

Pyroelectric crystals, which produce large surface electric fields during heating and cooling, have been proposed as a mechanism for constructing a stand-alone electron beam source. We report on experimental tests of this concept, using a variety of field emission tips combined with a pyroelectric crystal to produce a low-energy electron beam during thermal cycling. The mechanism is suitable for generating very small electron bunches, with energies up to tens of kilovolts, for use in microaccelerator structures.

BACKGROUND AND MOTIVATION

A millimeter-scale, laser-driven resonant accelerating structure (the micro-accelerator platform, or MAP) is under development at UCLA [1, 2]. This device, constructed from dielectric materials [3], is expected to accelerate small electron bunches from 25–30 kV to several MV, thus creating an ultra-compact and inexpensive structure with a variety of potential uses in medicine and industry. However, a micron-scale kilovolt electron source is necessary for injection into such a device; conventional sources are far too bulky, cannot produce small enough beams, or require standing off large DC voltages within the structure. We are investigating pyroelectric crystals (PECs) as a potential source of sub-relativistic electrons for injection into the MAP structure. Such an emitter could also be packaged with a MAP structure as a single stand-alone tunable radiation source, producing electron beams of a few MV using only external laser power.

Pyroelectric crystals (PECs) are a class of materials known [4, 5, 6] to undergo spontaneous charge separation when out of temperature equilibrium, forming a layer of uncompensated surface charge that produces large electric fields near the crystal surface. These crystals, which include lithium niobate (LiNbO_3), lithium tantalate (LiTaO_3), barium titanate (BaTiO_3), and triglycine sulfate (TGS), among others, are ordinarily neutral, with a layer of surface charge cancelling the field of an intrinsic bound (polarization) charge. During temperature change, the bulk polarization alters, leaving uncompensated surface charges that generate a high electric field (10^4 – 10^8 V/m) at the Z-faces of the crystal surface. The sign of the field depends on whether the crystal is being heated or cooled. As the crystal resistance is extremely large, the relaxation time for the return to equilibrium via bulk conduction is typi-

cally on the order of hours. In this quasi-constant strong surface field, pyroelectric electron emission (PEE) can occur via field emission or field ionization effects, both of which have been demonstrated in a number of contexts [6, 7], though some details of the surface interactions remain poorly understood. Unlike other conventional sources for multi-kilovolt electron beams, a PEC-based miniature electron source would not require a high-voltage input, and the emitting region can be arbitrarily small or patterned.

While previous work has demonstrated that the external field generated by PECs can be strong enough to cause Fowler-Nordheim-like emission of surface electrons from the crystal, the emission can be greatly enhanced by adding needle cathodes or other sharp surface features, as has been well documented in conventional electron guns [8]. The combination of field generation by uncompensated charge in a PEC and field emission from a sharp tip represents a novel approach to electron beam generation.

EXPERIMENTAL CONFIGURATIONS

Previous experimental findings on PEE from lithium niobate crystals have demonstrated that both qualitative and quantitative features of the emission are strongly dependent on the detailed geometry of the experiment, including the vacuum vessel, anode configuration, and crystal size and shape. Depending on the ambient gas pressure, rate of temperature change, and anode distance, currents can be produced through field emission, surface plasma formation, or gas ionization; currents of picoamperes to nanoamperes have been reported, over time scales of a few minutes to a few hours. The large number of variables makes it a challenge to achieve reproducible results.

The accelerating field present between the crystal surface and an adjacent grounded anode located a distance d_g from the crystal is typically estimated by [5]

$$E = \frac{\gamma \delta T}{\epsilon_0} \frac{d_c}{d_c + d_g \epsilon} \quad (1)$$

where γ is the pyroelectric coefficient, δT the temperature departure from equilibrium, d_c the crystal thickness orthogonal to the emitting face, and ϵ the crystal's relative permittivity. As the crystal thickness increases relative to the anode spacing d_g , one would expect to enhance the field.

Thin Crystal

A first series of experimental tests was performed using a 1 cm \times 1 cm wafer of LiNbO_3 , 500 μm thick. The wafer was X-cut, with the Z-faces along the narrow edges. One of

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the narrow edges was plated with a gold layer, which was then milled away (using a focused ion beam machine) over a narrow strip ($10\ \mu\text{m} \times 100\ \mu\text{m}$) in the center, exposing the crystal and, optionally, creating one or more sharp tips (Figure 1). The sharpness of the surface features could not be measured directly but was believed to be well below a radius of curvature of $1\ \mu\text{m}$. The wafer was then placed in a test stand in which the emitted electrons were imaged on a scintillating screen while the temperature of the wafer was controlled from the side using a Peltier element adjacent to the crystal, while temperature was measured on the opposite side (see Figure 2). Vacuum pressure of roughly 10^{-5} Torr was maintained during the test runs.

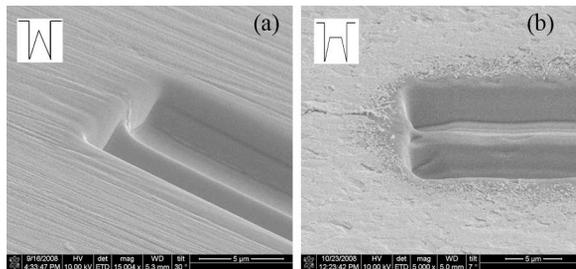


Figure 1: SEM images of (a) “pointed” tip; (b) “flat” tip (insets: cross-section of tip geometry).

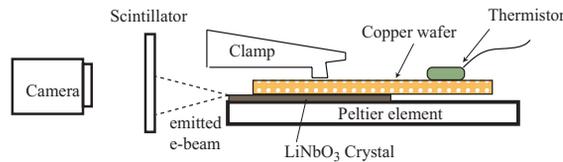


Figure 2: Side view of experimental arrangement for demonstration of emission from thin LiNbO_3 crystal.

Several different methods for gold deposition were tried, including sputtering and evaporation, with thicknesses varying from 20–30 nm to 175 nm. While surface quality had little effect on the results, the metal thickness (equivalently, the depth of the milled trench) was optimal in a range of 50–100 nm; deeper trenches inhibit emission, and thinner coatings may allow less conduction.

A variety of tip configurations were tested (such as the “flat” and “pointed” cross-sectional geometries in Fig. 1), with roughly consistent rates of temperature change, followed by frame-by-frame postprocessing of the resulting video images. It was conjectured that current emission would be limited to the milled region but enhanced by the presence of the gold layer, which could allow surface electrons to migrate.

Thick Crystal

Given the implications of Eq. 1, a second configuration investigated a cylinder of LiNbO_3 with height 1 cm and diameter 7.6 cm, cut so that the flat surfaces were the Z

faces of the crystal. As with the thin crystal, several emitting tips (in this case with a 1:1 aspect ratio) were milled into the surface [Figure 3(a)], but in this case the tips were re-metallized after milling. The radius of curvature of the tip was measured to be approximately $1\ \mu\text{m}$. The crystal was placed atop a thin copper plate and heated from below, with temperature monitoring via thermistors. A scintillator screen was imaged with a CCD camera as before.

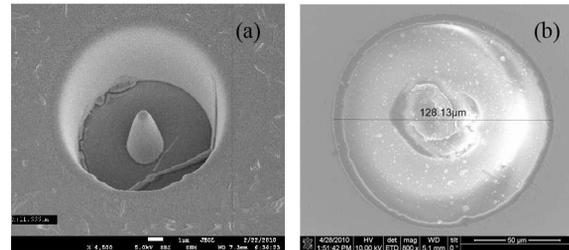


Figure 3: SEM images of (a) emitting tip in thick crystal after initial machining; (b) re-imaging of same tip after 5 experimental runs.

RESULTS AND INTERPRETATION

Electron emission was successfully observed from 3 thin crystals during heating or cooling, with results that were clearly dependent on the geometry of the emitting tips. In these tests, the temperature was varied between 5°C and 35°C above ambient, and was changed at a rate of $4\text{--}6^\circ\text{C}/\text{min}$. Figure 4 shows emission from the tips pictured in Fig. 1, both of which produced a slowly decaying steady current combined with several “flashes” (runaway discharge events) during cooling. Both “flat” and “pointed” cross-sections produced emission—the sharp edges of the central flat region may have contributed to the field enhancement in the former case. As a comparison, an emitter was fabricated having a central milled region with a flat bottom (no tip); this geometry did not produce any detectable current. The field enhancement due to the tips thus makes a necessary contribution to the PEE.

The intensity of emission showed considerable variation among runs, even for the same crystal. In addition, it was impossible to characterize the emission location on the crystal using the beam image on the scintillator; in some cases, the beam image split into two halves, likely indicating the presence of a bi-domain crystal. From these observations, it appears that the primary emission mechanism observed was gas ionization in the relatively poor vacuum, with the resulting low-density plasma supporting a steady current between crystal and anode for periods of at least 2 to 5 minutes. Though the tips clearly contributed to the formation of an ionizing electric field, emission from the surface may not have made a significant contribution to the steady current (though isolated surface breakdown events led to single bursts of current at the detector).

By comparison, the 1-cm thick crystals showed very poor emission. Figure 5 shows typical results, in which

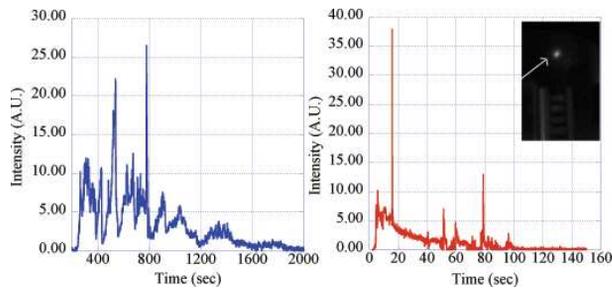


Figure 4: Variation of emitted current during cooling for the “pointed” emitter (left) and the “flat” emitter (right), as described in Fig. 1. Strong flashes or sparks are overlaid with a continuous focused beam, showing intensity fluctuations but persisting from 2 to 20 minutes. Inset: Beam image (marked with arrow), taken from video.

some isolated flashes and current bursts were observed, but without a continuous current. This was attributed in large part to unanticipated difficulty in heating such a large crystal successfully. As the resistive heater was located at the bottom face of the crystal, 1 cm from the emitting surface, the very poor thermal conductivity of LiNbO_3 and the large thermal mass of this system made it difficult to achieve large temperature change at the emitting surface. The large variations in temperature at the bottom face were largely washed out at the top face; relatively quick changes in emitter temperature were correlated with observed emission flashes. We conclude that the larger field generated by a thicker crystal, as Eq. 1 implies, is more than offset by the difficulty of generating sufficiently large δT . In addition, the large emitter likely had less field enhancement due to the tip, as the sharpness of the features was known to be somewhat larger. Metallization may also have limited the emission.

The large crystal tests were carried out at a vacuum pressure of $1\text{--}5 \times 10^{-5}$ Torr. Previous investigators have found that the uncompensated surface charges become depleted after several temperature cycles in good vacuum [7]; we did not observe this effect clearly, but we did note deterioration of the emitting tip after multiple cycles. Re-imaging after 5 experimental runs showed that the sharp peak had been nearly flattened (Figure 3(b)).

CONCLUSION

We have shown that sharply pointed surface features can enhance pyroelectric emission from lithium niobate crystals, leading to a persistent and steady current over several minutes. Field enhancement by sharp tips has been shown to contribute directly to the emission. Pyroelectric crystals enhanced in this way have potential to serve as sources of miniature electron beams suitable for micron-scale acceleration devices. Though the beams produced are unlikely to be of sufficient quality for particle physics applications, they do have potential for industrial or medical radiation sources, either of electrons or of X-rays, where divergence

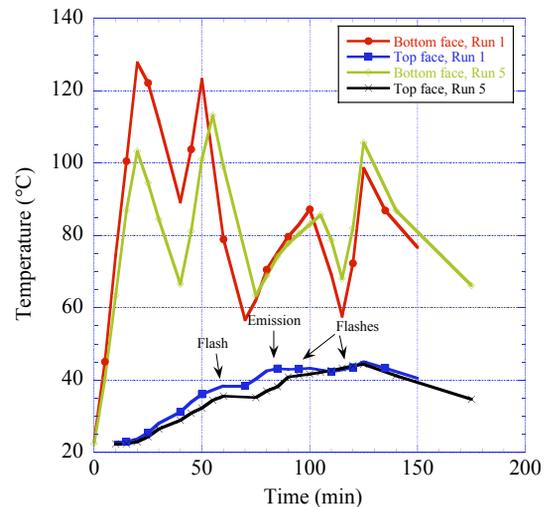


Figure 5: Temperature measurements at top (emitting) and bottom (heated) faces of thick LiNbO_3 crystal, for two experimental runs. Flash discharge and brief emission occurred only during Run 1, as marked, as the tip had likely deteriorated by Run 5.

is not a concern.

These initial results, while promising, indicate that reproducibility is a significant challenge. Systematic work is necessary to establish the effect of the many important parameters in the system, including the geometry of the emitting tip, the role of the metallic coating, the size and temperature history of the crystal, and the configuration of the anode and vacuum chamber. A better understanding of the key parameters could lead to a valuable and unique electron source with many possible uses.

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