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# Improved figure of merit in obliquely cut pyroelectric crystals

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In pyroelectric crystals with high dielectric anisotropy, a significantly higher figure of merit can be obtained using cuts at oblique angles to the pyroelectric axis, rather than the conventional cuts lying perpendicular to it. For a particular material an appropriate cut can be selected to provide the maximum figure of merit attainable at the chosen temperature of operation. Experimental data obtained in deuterated triglycine fluoroberylate crystals show that optimum oblique cuts can yield an increase as great as a factor of 3 in the figure of merit of this material.

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Improved pyroelectric materials for use in infrared detectors and vidicons have been the subject of several studies in recent years.[1–3] Materials are commonly evaluated using a figure of merit given by the ratio $p/\epsilon c$ of the pyroelectric coefficient $p$ to the product of the dielectric permittivity $\epsilon$ and the volume specific heat $c$. This ratio influences the responsivity bandwidth product in small area detectors,[4] and also the signal-to-noise ratio in the pyroelectric vidicon designs currently in use.[1,5] Normally, crystal plates are cut perpendicular to the pyroelectric axis to maximize the component of the pyroelectric coefficient normal to the faces of the plate. In general, such cuts also maximize the dielectric permittivity and consequently limit the figure of merit. The aim of the present work is to show that in pyroelectric crystals with strong dielectric anistropy, a significantly higher figure of merit can be obtained using cuts at oblique angles to the pyroelectric axis. The oblique cut can be optimized to provide the maximum figure of merit attainable for the particular material used at the chosen temperature of operation.

Let us refer to the principal axes $x$, $y$, and $z$ of the permittivity tensor in a given pyroelectric crystal. To simplify the mathematics we assume that the pyroelectric axis coincides with a principal axis ($y$ axis). This assumption holds true for crystals belonging to all the pyroelectric point groups except for the triclinic and monoclinic $m$ groups. Consider a flat parallel-faced plate cut normal to a direction that forms an angle $\theta$ with the $y$ axis and its projection in the $x$, $z$ plane forms an angle $\phi$ with the $x$ axis. The pyroelectric coefficient and permittivity measured in this plate are

$$p(\theta) = p\cos\theta,$$
$$\epsilon(\theta,\phi) = \epsilon_x \sin^2\theta\cos^2\phi + \epsilon_z \sin^2\theta\sin^2\phi + \epsilon_y\cos^2\theta, \quad (1)$$

where $p$ and $\epsilon_y$ are the pyroelectric coefficient and permittivity along the pyroelectric axis; $\epsilon_x$ and $\epsilon_z$ are the permittivities along the $x$ and $z$ axes, respectively. Accordingly, the figure of merit, $M(\theta,\phi)$, for this cut is related to the figure of merit, $M(\theta=0)$, in the normal cut by $M(\theta,\phi) = GM(\theta = 0)$, where the gain factor $G$ is

$$G = \epsilon_y\cos\theta / [(\epsilon_x\cos^2\phi + \epsilon_z\sin^2\phi)\sin^2\theta + \epsilon_y\cos^2\theta]. \quad (2)$$

Maximum gain

$$G_{\max} = \epsilon_y / [4\epsilon_m(\epsilon_y - \epsilon_m)]^{1/2}, \quad (3)$$

is obtained for a cut perpendicular to a direction $(\theta_{\rm opt}, \phi_{\rm opt})$:

$$\theta_{\rm opt} = \tan^{-1}[(\epsilon_y/\epsilon_m) - 2]^{1/2},$$
$$\phi_{\rm opt} = 0 \text{ if } \epsilon_x < \epsilon_z$$
$$= 90^\circ \text{ if } \epsilon_x > \epsilon_z, \quad (4)$$

where $\epsilon_m$ is the smaller one among $\epsilon_x$ and $\epsilon_z$.
When $\epsilon_y$ is much larger than $\epsilon_m$, $G_{\max} \approx 0.5(\epsilon_y/\epsilon_m)^{1/2}$, and the optimum figure of merit is

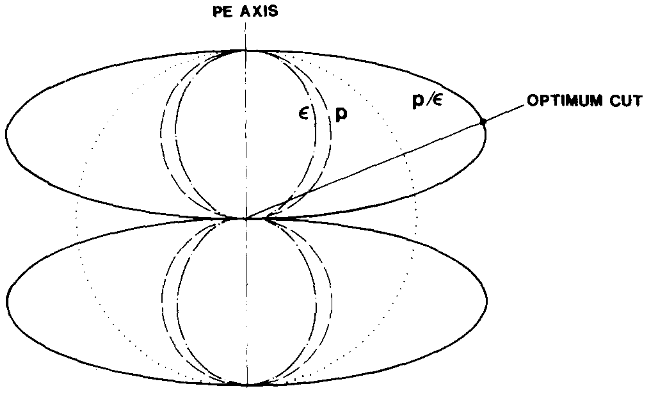


FIG. 1. Polar graphs displaying the dependence of the pyroelectric coefficient, dielectric permittivity, and figure of merit, upon the direction in a crystal.

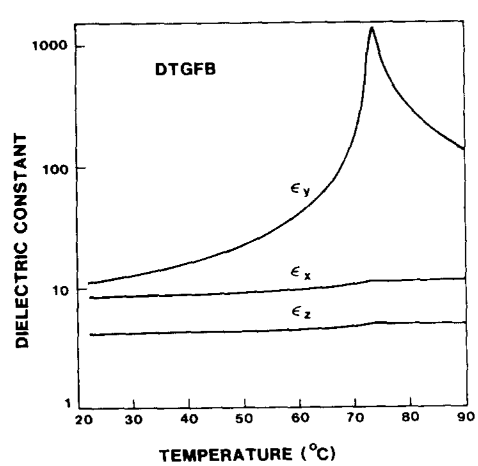


FIG. 2. Temperature dependence of dielectric permittivity along the principal axes in a DTGFB crystal.

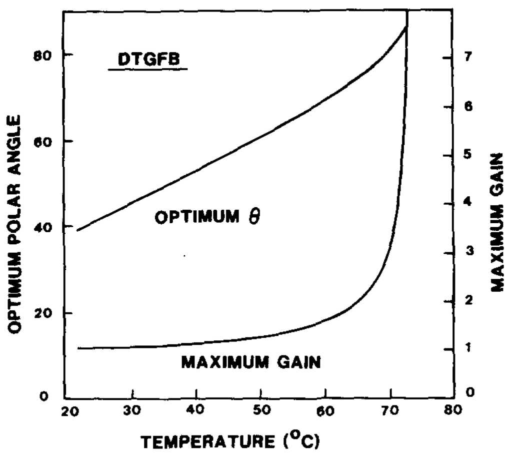


FIG. 3. Calculated optimum angle and maximum gain vs temperature for a DTGFB crystal.

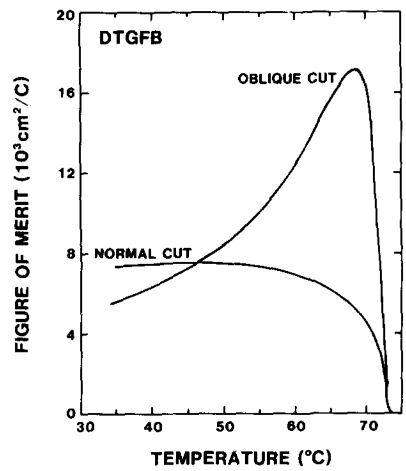


FIG. 4. Measured figure of merit vs temperature in DTGFB at normal cut and in a cut perpendicular to a direction that forms an angle of 74° with the pyroelectric axis.

$$M_{\rm opt} = p/[2c(\epsilon_m \epsilon_y)^{1/2}]. \quad (5)$$

A geometrical illustration of this concept is given in Fig. 1. The three polar graphs shown describe the dependence of $p$, $\epsilon$, and the ratio $p/\epsilon$, upon the direction in a crystal. In this example the ratio between the permittivity along the pyroelectric axis and that perpendicular to it is 8. This gives rise to a maximum gain of 1.5 in samples cut normal to a direction that forms an angle of 67.8° with the pyroelectric axis. As the dielectric anisotropy increases, the maximum gain increases, as well as the deviation of the optimum direction from the pyroelectric axis.

The results of this analysis were examined experimentally in deuterated triglycine fluoroberylate (DTGFB) crystals.[6] Below the transition point ($T_c \simeq 74$ °C), DTGFB belongs to the point group 2 of the monoclinic symmetry. The two-fold axis ($b$ axis) is the pyroelectric axis, and a principal axis of the permittivity tensor.

Dielectric and pyroelectric measurements were performed using a computer controlled system similar to that described in Ref. 7. Pyroelectric currents were measured with an HP 4140-pA meter, while the sample was heated at 2 °C/min. Dielectric permittivity was measured in a field of 5 V/cm at 10 kHz using an HP 4274A LCR meter. A programmable switch (HP 4083, 19657A) was incorporated to permit simultaneous measurement of capacitance and pyroelectric current. These measurements, together with published data for $c$,[6] were used to determine the figure of merit as a function of temperature.

Dielectric measurements were performed on five plates ($4\times4\times0.1$ mm) of DTGFB cut at different directions to determine the orientation of the principal axes and the permittivities $\epsilon_x$, $\epsilon_y$, $\epsilon_z$ along these axes. On the basis of these data the optimum directions and the maximum gain were calculated using Eqs. (3) and (4).

The temperature dependence of $\epsilon_x$, $\epsilon_y$, and $\epsilon_z$ in DTGFB is shown in Fig. 2. From this figure it is evident that $\epsilon_m = \epsilon_z$ and that the ratio $\epsilon_y/\epsilon_m$ increases dramatically as the transition point is approached. Thus $\theta_{\rm opt}$ and $G_{\rm max}$ increase with temperature as shown in Fig. 3. Figure 4 shows experimental results obtained for the temperature dependence of the figure of merit in DTGFB at a normal cut and in a cut perpendicular to a direction that forms an angle of 74° with the pyroelectric axis. The latter is the optimum cut for DTGFB operated at 64 °C. The figure of merit obtained at this temperature with this cut is about twice the maximum figure of merit obtained in the normal cut. Optimum cuts corresponding to temperatures of operation closer to the transition point yield an increase as great as a factor of 3 in the figure of merit of DTGFB.

The dielectric behavior of DTGFB is typical of many proper ferroelectrics. The high permittivity along the pyroelectric axis, which limits the performance of these materials in the normal cut, has a lesser effect in the oblique cut. According to Eq. (5) the pertinent permittivity in an optimum oblique cut is the geometric average of the permittivity along the pyroelectric axis and the minimum permittivity in a direction perpendicular to it. In materials with high dielectric anisotropy, this gives rise to an appreciable enhancement in the figure of merit when optimum cuts are used.

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