PYROELECTRIC COEFFICIENT DIRECT MEASUREMENT TECHNIQUE AND APPLICATION TO A NSEC RESPONSE TIME DETECTOR†

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A direct method for measuring pyroelectric coefficients is described. The method is more straightforward than either the dynamic method or the charge integration technique. Pyroelectric coefficients measured by the direct measurement technique are applied to the design of pyroelectric detectors. A Sr,Ba1-x,Nb2O6 detector is described with variable response times from 1 msec to 4 nsec.

I. INTRODUCTION

Pyroelectric detectors have been discussed by a number of authors and their advantages of fast response at room temperature operation is well known.1,2,3 We have developed a direct technique to measure the pyroelectric coefficient which is more straightforward than the dynamic method4 in which the current produced by an absorbed radiation pulse is measured, or the charge integration method (static method)1,5,6,7,8 in which the current produced during heating is integrated in an operational amplifier and the resultant curve is differentiated to obtain the pyroelectric coefficient. In this paper we describe the direct measurement technique and apply the results to the design and demonstration of a variable response time detector.

II. DIRECT MEASUREMENT METHOD

In pyroelectric crystals a change in temperature alters the lattice spacing of a nonsymmetrically located ion which varies the spontaneous polarization of the crystal. This variation of spontaneous polarization produces a displacement current I parallel to the polar axis described by

\[ I = A p(T) \frac{dT}{dt}, \]  

where \( p(T) = \frac{dP}{dT} \) is the pyroelectric coefficient evaluated at temperature \( T \) and \( A \) is the surface area normal to the polar axis.

The pyroelectric coefficient is given by

\[ p(T) = \frac{I}{A \frac{dT}{dt}}. \]  

Therefore, when \( \frac{dT}{dt} \) is held constant over a wide temperature range, a measurement of the current \( I \) gives a direct plot of \( p(T) \) over that temperature range.

The equivalent circuit for the measurement apparatus is shown in Figure 1 where \( R_C \) is the crystal leakage resistance and \( R_M \) is the meter input resistance. For this circuit the pyroelectric current is given by Eq. (1) and the measured current is

\[ I_M = I \frac{R_C}{R_C + R_M}. \]  

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FIGURE 1 Measurement apparatus equivalent circuit.
As long as \( R_C > 100 R_M \) the measured current \( I_M \) equals \( I \) to within 1%.

The measurement apparatus is shown schematically in Figure 2a. For our measurements we use either an oven with a mechanically scanned 1°C/min rate or a standard differential thermal analyzer (DTA). With the 1°C/min rate and an electrode area of 0.25 cm\(^2\) a pyroelectric coefficient as low as \( 10^{-3} \mu \text{C/cm}^2\text{°C} \) produces current of 4.17 pamps, or a voltage of 0.417 \( \mu \text{Volts} \) across a \( 10^5 \Omega \) impedance, which is above the noise of a Hewlett Packard 419A dc Volt meter. The scan rate or the electrode area can be increased to improve the detection sensitivity if necessary.

**III. PYROELECTRIC FIGURE OF MERIT**

For response times greater than the thermal time constant the responsivity of the pyroelectric detector is

\[
 r = \frac{V}{W(\omega)} = \frac{p(T)R_L}{\rho c_p a [1 + \omega^2 (C_a + C_c)^2]^{1/2}}
\]

where \( R_L \) is the equivalent parallel resistance of the crystal and load resistor, \( \rho \) is the density, \( c_p \) is the heat capacity, \( a \) is the electrode separation, \( C_a \) is the amplifier capacitance, and \( C_c \) is the crystal capacitance equal to \( \varepsilon_0 \varepsilon_a A/a \). Here we assume total absorption of the energy \( W(\omega) \).

In the high frequency limit where \( \omega R_L(C_a + C_c) \gg 1 \) the responsivity reduces to a ratio which includes the crystal properties

\[
 V = \frac{p(T)}{W(\omega)} = \frac{\rho c_p a (C_a + C_c) \omega}{\varepsilon_0 \varepsilon_a A}
\]

From this expression we can write a crystal figure of merit

\[
 M_r = \frac{p(T)}{\rho c_p \varepsilon_0 \varepsilon_r}
\]

Table I gives the figure of merit for various crystals of interest. Note the high values for \( \text{Li}_2\text{SO}_4 \cdot \text{H}_2\text{O} \) and TGS even though the pyroelectric coefficient is lower than for other materials.

For a detector constructed using the edge electrode configuration, which maximizes the responsivity in Eq. (4) for zero amplifier capacitance, such that \( A = 1 \text{ mm} \times 0.1 \text{ mm} \) and \( a = 1 \text{ mm} \), the figure of merit is plotted as a function of amplifier capacitance in Figure 3(a). Note that the very high figure of merit of \( \text{Li}_2\text{SO}_4 \cdot \text{H}_2\text{O} \) and TGS is useful.
PYROELECTRIC COEFFICIENT MEASUREMENT

FIGURE 3(a) Figure of merit $M$, versus amplifier capacitance for edge electrodes.

FIGURE 3(b) Figure of merit $M$, versus amplifier capacitance for optimum electrode configuration at $C_a \approx 1 \text{ pF}$. 

$V_{\omega} = \frac{p(t)}{W(t)}$, $p(t) = \rho C_p (C_d + \varepsilon_0 \varepsilon A)$, $\times 10^6$

- LiTaO$_3$
- Sr$_{46}$Ba$_{54}$Nb$_2$O$_{6}$
- Sr$_{48}$Ba$_{52}$Nb$_2$O$_{6}$
- Sr$_{73}$Ba$_{27}$Nb$_2$O$_{6}$
- Li$_2$SO$_4$H$_2$O

AMPLIFIER CAPACITANCE $C_a$ IN pF

- FACE ELECTRODES
- EDGE ELECTRODES
TABLE I
Pyroelectric crystal properties

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>$p(T)$</th>
<th>$\epsilon_r$</th>
<th>$c_p$</th>
<th>$\rho$</th>
<th>$M_p = \frac{p(T) \times 10^{-10}}{c_p \rho \epsilon_r}$</th>
<th>$M_N = \frac{p(T) \times 10^{-9}}{\rho c_p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Sr}<em>{0.73}\text{Ba}</em>{0.27}\text{Nb}_2\text{O}_6$</td>
<td>0.28</td>
<td>8200</td>
<td>0.4</td>
<td>5.2</td>
<td>0.164</td>
<td>135.0</td>
</tr>
<tr>
<td>$\text{Sr}<em>{0.48}\text{Ba}</em>{0.52}\text{Nb}_2\text{O}_6$</td>
<td>0.065</td>
<td>380</td>
<td>0.4</td>
<td>5.2</td>
<td>0.823</td>
<td>31.0</td>
</tr>
<tr>
<td>$\text{Sr}<em>{0.44}\text{Ba}</em>{0.56}\text{Nb}_2\text{O}_6$</td>
<td>0.043</td>
<td>380</td>
<td>0.4$^{10}$</td>
<td>5.2$^{10}$</td>
<td>0.545</td>
<td>20.7</td>
</tr>
<tr>
<td>$\text{LiTaO}_3$</td>
<td>0.0176</td>
<td>43</td>
<td>0.4$^{11}$</td>
<td>7.4$^{12}$</td>
<td>1.27</td>
<td>5.5</td>
</tr>
<tr>
<td>TGS$^{b}$</td>
<td>0.0158-0.035$^{13}$</td>
<td>26-50$^{14}$</td>
<td>0.97$^{15}$</td>
<td>1.69$^{16}$</td>
<td>3.72</td>
<td>9.65</td>
</tr>
<tr>
<td>$\text{Li}_2\text{SO}_4\text{H}_2\text{O}$</td>
<td>0.01</td>
<td>8</td>
<td>0.4$^{12}$</td>
<td>2.0$^{13}$</td>
<td>15.2</td>
<td>12.2</td>
</tr>
<tr>
<td>$\text{LiNbO}_3$</td>
<td>0.0083</td>
<td>28</td>
<td>0.63$^{14}$</td>
<td>4.6$^{15}$</td>
<td>0.99</td>
<td>2.78</td>
</tr>
</tbody>
</table>

* These crystal properties are from Ref. 1.

The properties of TGS vary widely in the literature. See Refs. 13 and 16 for $p(T)$ and $\epsilon_r$ data, Ref. 17 for a lower value of $c_p$, and Ref. 18 for a higher value of $c_p$. We have used our measured data in Table I, Figure 3, and Figure 4 since the higher $p(T)$ seems to correspond to the higher $\epsilon_r$, so that, except for $M_N$, the difference in figure of merit is slight.

**FIGURE 4** Figure of merit $M_N(\omega)$ versus amplifier capacitance for edge electrodes and face electrodes.
only if an amplifier capacitance of less than about 0.2 pF is used. With a more realizable amplifier capacitance of about 1 pF Sr$_{0.46}$Ba$_{0.54}$Nb$_2$O$_6$ with a composition near $X = 0.5$ gives the best results.

Because of the low dielectric constant of Li$_2$SO$_4$.H$_2$O and TGS, the face electrode configuration gives better results when the amplifier capacitance is near 1 pF and higher. Maintaining the same size crystals as above but using face electrodes on the lower dielectric constant materials so that $A = 1$ mm $\times$ 1 mm and $a = 0.1$ mm, the figure of merit is again plotted versus amplifier capacitance in Figure 3(b). Note that under these conditions face electrode Li$_2$SO$_4$.H$_2$O and TGS are superior to edge electrode Sr$_{0.46}$Ba$_{0.54}$Nb$_2$O$_6$ throughout the most typical amplifier capacitance range. However, with a carefully designed amplifier such that $C_a$ is less than 1 pF, Sr$_{0.46}$Ba$_{0.54}$Nb$_2$O$_6$ is better than TGS and approaches Li$_2$SO$_4$.H$_2$O within a factor of 2 to 4. Thus the more stable properties of Sr$_{0.46}$Ba$_{0.54}$Nb$_2$O$_6$ can be used and a window is not required to separate the detector from the atmosphere.

The above figure of merit is for optimum crystal responsivity and not signal to noise ratio. If the detector is Johnson noise limited such that

$$V_N = \frac{(4KT BR_l)^{\frac{1}{2}}}{1 + \omega R_l[C_a + C_j]^{\frac{1}{2}}}$$

then the signal to noise ratio of the detector is

$$\frac{V/W(\omega)}{V_N} = \frac{\rho(T) R_l^{\frac{1}{2}}}{\rho_e a(4KT B)^{\frac{1}{2}}}$$

Assuming that the amplifier load resistance is much smaller than the crystal resistance, which will be true for many applications and especially high frequency applications, Eq. (7) suggests a crystal figure of merit given by

$$M_N = \frac{\rho(T)}{\rho_e} \propto \frac{V/W(\omega)}{V_N}.$$  (8)

Equation (8) is tabulated as part of Table I which shows the advantage of Sr$_{0.73}$Ba$_{0.27}$Nb$_2$O$_6$ with near room temperature Curie point for maximum signal to noise. For the design of a minimum NEP detector, however, Eq. (7) should be used and the maximum $R_l$ will depend on the resistivity which may vary from crystal to crystal and also depend on the frequency on interest. The figure of merit $M_N$ neglects any frequency response considerations. The improved signal to noise, obtained by making $R_l$ large results in poor pulse resolution. When pulse resolution is of interest, such as when time resolving Q-switched pulses, $R_l$ is chosen such that $\omega R_l[C_a + C_j] \cong 1$ for the highest frequency $\omega$ of interest. When this is done Eq. (7) takes the form

$$\frac{V/W(\omega)}{V_N} = \frac{\rho(T)}{\rho_e a[C_a + C_j]^{\frac{1}{2}}(4KT B)^{\frac{1}{2}}}$$

and a figure of merit including frequency response becomes

$$M_N(\omega) = \frac{\rho(T)}{\rho_e a[C_a + C_j]^{\frac{1}{2}} \propto \frac{V/W(\omega)}{V_N}}.$$  (9)

Figure 4 shows a plot of Eq. (10) versus amplifier capacitance for a 1 mm $\times$ 1 mm $\times$ 0.1 mm crystal with separate abscissa for edge and face electrodes. Face electrode Li$_2$SO$_4$.H$_2$O is again superior up to about 10 pF amplifier capacitance. However, either edge electrode or face electrode Sr$_{0.46}$Ba$_{0.54}$Nb$_2$O$_6$ now compares very favourably with TGS, is within a factor of 2 of Li$_2$SO$_4$.H$_2$O, and is also useful for very large capacitance applications.

IV. FAST RESPONSE DETECTOR

A fast response FET detector has been designed with less than 1 pF input capacitance so that the characteristics of Sr$_{0.46}$Ba$_{0.54}$Nb$_2$O$_6$ with edge electrodes can be used effectively. This composition has a Curie Temperature near 125°C and is stable against spontaneous depoling. The measured responsivity agrees to within experimental error to that calculated using Eq. (4) and the values in Table I. An in-circuit switchable load resistance allows a tradeoff between detector response time and responsivity. The available response times vary from 1 msec to 4 nsec.

Figure 5(a) shows a chopped CO$_2$ laser beam detected with a 22 M$\Omega$ amplifier resistance. At this high voltage response the detector does not resolve the pulse shape. Also shown is the chopped beam detected with $R_l = 1$ M$\Omega$. The pulse shape is resolved but the responsivity is a factor of 22 smaller in amplitude, as expected from Eq. (4).

Figure 5(b) shows an unresolved Q-switched CO$_2$ pulse detected on the medium speed 1 M$\Omega$ load resistance. The Q-switched pulse is fully resolved
capacitance. For realizable amplifier input capacitance values of 1 pF, \( \text{Sr}_2\text{Ba}_{1-x}\text{Nb}_2\text{O}_6 \) crystals with a composition near \( x = 0.50 \) provided the optimum crystal tradeoff between responsivity, signal to noise ratio, and minimum handling problems, especially when operation without a window is desired.

Using \( \text{Sr}_{0.46}\text{Ba}_{0.54}\text{Nb}_2\text{O}_6 \) crystals 1 mm \( \times \) 0.1 mm oriented in the edge configuration we have demonstrated a pyroelectric detector with measured responsivity to within experimental error of the calculated value. In addition, the detector employs a very useful in-circuit switchable load to allow a choice of responsivity and response time. The measured rise times of the detector vary from 1 msec to 4 nsec.

V. CONCLUSION

We have described a technique which allows the direct measurement of pyroelectric coefficients. Using the direct measurement method we have measured pyroelectric coefficients for various crystals. The resultant values along with the measured dielectric constants were used to calculate crystal figures of merit versus amplifier capacitance.

REFERENCES

9. A 1°C/min scan rate from 50°C to 450°C is available as a model 300 oven from Chromatix, Inc., Mountain View, California.