Pyroelectric Voltage Response to Step Signals of Infrared Radiation in Triglycine Sulphate and StrontiumBarium Niobate

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Pyroelectric Voltage Response to Step Signals of Infrared Radiation in Triglycine Sulphate and Strontium-Barium Niobate

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Theoretical and experimental analysis of voltage transients obtained in triglycine sulphate and strontium-barium niobate in response to step radiation signals yields information important for pyroelectric ir detection. The response transients are shown to be symmetrical with respect to the electronic and thermal time constants τ_e and τ_T of the samples. When τ_e and τ_T differ appreciably, the rise of the response and its decay are exponentials whose time constants are, respectively, the smaller and the larger one from among τ_T and τ_e. The peak voltage values are proportional to the load resistance R_L when $\tau_e \ll \tau_T$; they become independent of R_L and proportional to τ_T when $\tau_e \gg \tau_T$. The initial slope of the response in a given sample is found to be independent of R_L for a given radiation flux. The pyroelectric coefficient of a material, divided by the product of its permittivity, density, and specific heat is shown to be a figure of merit for use in pyroelectric ir detection

I. INTRODUCTION

The pyroelectric effect has been widely investigated[1,2] especially since its use has been established[3] for the detection of electromagnetic radiation.[4-6] In ir detection, efforts were concentrated on triglycine sulphate (TGS),[7,8] and more recently on strontium-barium niobate (SBN).[9]

In our work on TGS and SBN pyroelectric ir detectors we found that important information can be obtained from the transients of their voltage response to a step radiation signal.[4,6,10] The present work is based on a detailed analysis, both theoretical and experimental, of such transients; the results are useful for the prediction of the performance of the detectors under various conditions as well as for the understanding of the physical processes involved.

II. EXPERIMENTAL TECHNIQUE

Thin slices of TGS and SBN were cleaved and/or cut from single crystals[11] normal to the pyroelectric axis and polished to a thickness of 10 to 40 μm. ir-transparent electrodes (area 0.2–3 mm²) of semiconductor materials were evaporated on the major faces, and thin metal leads were attached to them with conducting Epoxy. The crystals were mounted in vacuum in transistor cases having ir-transparent windows. After preparation, samples were poled with a steady field of 10^4 V/cm, applied for several minutes, mostly at room temperature.

To provide a step radiation signal on the samples, a high-speed shutter was used with a 500 °K blackbody source, or with a Model 42 Coherent Radiation CO$_2$ Laser (wavelength 10.6 μm). The measuring circuit consisted of a set of interchangeable load resistors (10^6–10^{12} Ω), connected parallel to the sample and to a FET source-follower circuit,[5] as shown in Fig. 1. The pyroelectric response voltages were measured on a Tektronix RM 564 CRO with a 3A9 amplifier.

III. THEORETICAL ANALYSIS

We assume that the absorbed radiation causes a spatially uniform small temperature rise ΔT of the pyroelectric crystal. Hence[12] its heating is governed by the differential equation

$$C_T \frac{d(\Delta T)}{dt} + G_T \Delta T = AF(t), \tag{1}$$

where C_T is the thermal capacity of the crystal, G_T is the thermal conductance of the coupling between the crystal and its ambient (radiative, convective, and conductive), A is the area of the crystal, and $F(t)$ is the radiation power absorbed per unit area of the crystal.

The rise in temperature changes the spontaneous polarization P_s of the crystal, causing a charge flow through it and the load (see Fig. 1). The effect of permittivity variation with temperature can be neglected,[3] so that the charge flow is described by the differential equation

$$C \frac{dV}{dt} + \frac{V}{R} = A\lambda \frac{dT}{dt}. \tag{2}$$

Here the capacitance C and the resistance R are composed of the crystal, load, and source-follower input capacitances and resistances, respectively. V is the pyroelectric voltage developed across crystal and load, and λ is the pyroelectric coefficient, $\lambda = dP_s/dT$. It is assumed that the temperature is far enough from the Curie point so that λ, as well as the dielectric constant ϵ and the specific heat c_p of the material, can be considered constant for small ΔT.

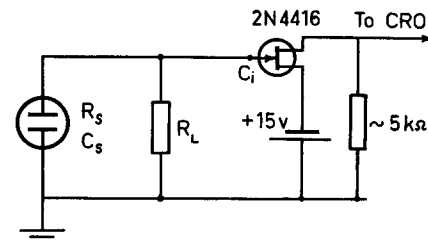For step irradiation, $F(t) = 0$ if $t < 0$ and $F(t) = F_0$ if
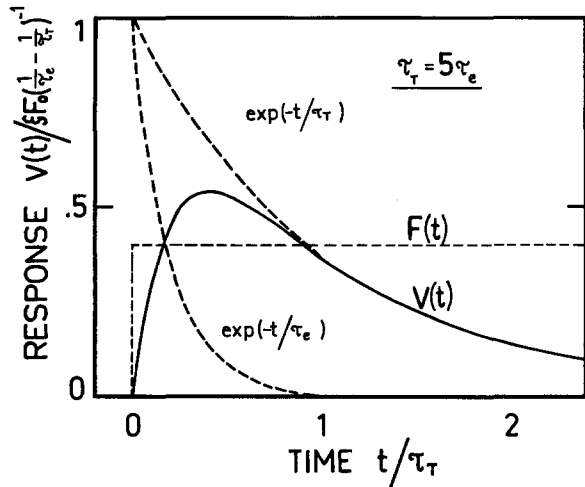

FIG. 1. Measuring circuit.

FIG. 2. Theoretical plot of the voltage response vs time (normalized).

$t > 0$, with the boundary condition $V(0) = 0$, one obtains

$$V(t) = \xi F_0 (1/\tau_e - 1/\tau_T)^{-1}(e^{-t/\tau_T} - e^{-t/\tau_e}), \quad \tau_e \neq \tau_T. \quad (3)$$

Here $\tau_e = RC$, $\tau_T = C_T/G_T$ are the electrical and thermal time constants of the system, respectively, and ξ is a constant, $\xi = \lambda A^2/CC_T$. Equation (3) represents the difference between two exponentials having the same initial value, one decaying with the thermal time constant τ_T, and the other decaying with the electrical time constant τ_e. The two exponentials are shown in Fig. 2 by dashed curves together with the response (solid curve) for the case $\tau_T = 5\tau_e$. In the special case $\tau_T = \tau_e = \tau$, one obtains a similarly behaving response $V(t) = \xi F_0 t e^{-t/\tau}$.

The response $V(t)$ is symmetrical with respect to τ_T and τ_e. When τ_T and τ_e differ appreciably, the rise of the response and its decay are exponentials whose time constants are, respectively, the smaller and the larger one from among τ_T and τ_e.

The initial slope k of the response,

$$k = \frac{dV(t)}{dt}\bigg|_{t=0} = \xi F_0, \quad (4)$$

is constant for a given radiation flux. The peak value[4] V_p of the response is reached at a time[4,10] t_p,

$$t_p = \tau_e \ln\theta/(\theta - 1), \quad (5)$$

where $\theta = \tau_e/\tau_T$, and is, for $\theta \neq 1$,

$$V_p = k\tau_T \theta^{1/(1-\theta)}. \quad (6)$$

If $\theta = 1$, $t_p = \tau$ and $V_p = 0.37k\tau$.

For $\theta \ll 1$, $V_p = k\tau_e$. Therefore, if R is small enough for the condition $\tau_T \gg \tau_e$ to hold, the peak value of the voltage is proportional to R, and independent of τ_T. For $\theta \gg 1$, on the other hand, $V_p = k\tau_T$, so that for samples with small τ_T and/or high R, the peak value of the voltage is proportional to τ_T and independent of

the load resistance. In any given sample, $k\tau_T$ is the upper limit value of V_p.

When the capacitance C_s of the sample dominates, $C_s \cong C$, the factor ξ is a material constant ξ_0:

$$\xi_0 = \lambda A^2/C_s C_T = \lambda/\epsilon d c_p, \quad (7)$$

d is the density of the material. If the input capacitance C_i of the source follower cannot be neglected, $C = C_s + C_i$ and

$$\xi = \xi_0 (1 + C_i/C_s)^{-1}. \quad (8)$$

IV. EXPERIMENTAL RESULTS

Detailed studies of the pyroelectric response have been carried out at room temperature on 15 TGS samples and on 6 samples of SBN. A typical voltage response to a step ir signal obtained in a SBN sample is shown by the two CRO traces of Fig. 3. They were obtained with the same load resistor ($R_L = 10^9$ Ω) and vertical amplification (2.7 mV/cm), but with different time scales. Trace 1, taken with the slower sweep (0.2 sec/cm) depicts most of the response, whereas trace 2 (sweep 50 msec/cm) expands only the initial part of it. The traces are in good general agreement with the theoretical curve of Fig. 2 and allow one to measure the characteristic parameters of the response: the initial slope k, the time constants t_r and t_f of the exponential rise and fall, the peak voltage V_p, and time t_p. These parameters are shown in Fig. 4, plotted against load resistance R_L, for sample B-1.

It is seen that k is independent of R_L over the whole range of 10^7 to 10^{12} Ω. (With $R_L < 10^7$ Ω, k, as well as t_r and t_p, could not be adequately measured because of the limited shutter speed; see Sec. V.) The fall time t_f in the range $R_L < 10^{10}$ is independent of R_L. According to the analysis, it represents therefore the thermal time constant τ_T. For $R_L > 10^9$ Ω, t_f is proportional to R_L and coincides with
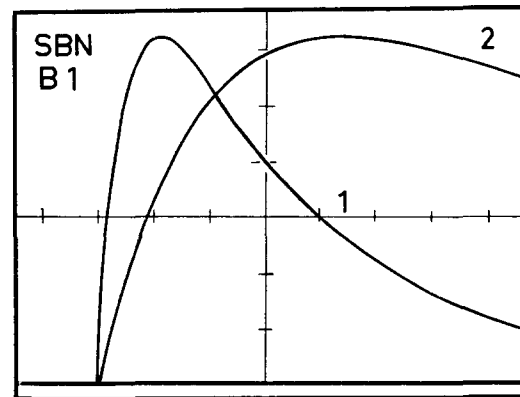

FIG. 3. CRO traces of pyroelectric voltage transients in a SBN sample in response to a step ir signal. $F_0 = 0.7$ mW/cm^2; $R_L = 10^9$ Ω. Vertical scale is 2.7 mV/cm. Horizontal sweep is 0.2 sec/cm for trace 1 and 50 msec/cm for trace 2.
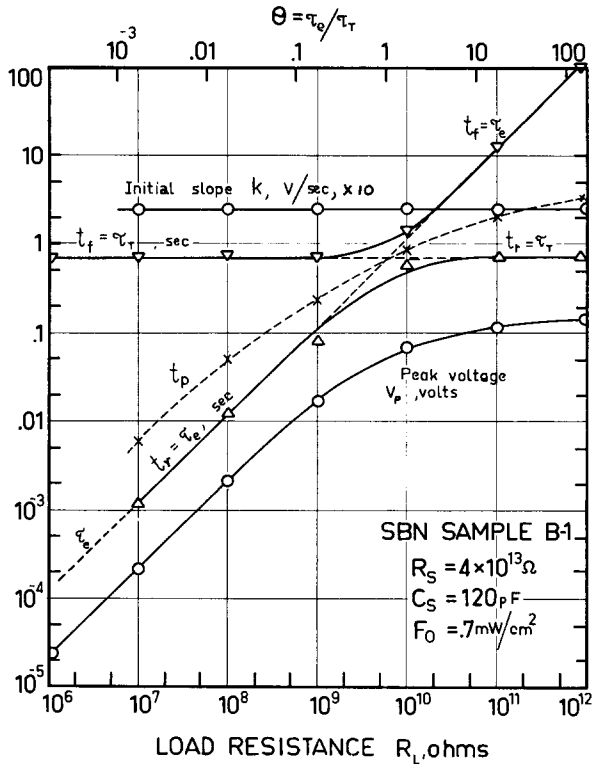
FIG. 4. Parameters of the pyroelectric voltage transient as functions of load resistance in sample B-1.

the electrical time constant τ_e (dashed line) calculated as $R_L C_s$. ($R_L \ll R_s$, the resistance of the sample; C_s is the geometrical capacitance of the sample, $C_s \gg C_i$.) Also for $R_L > 10^9$ Ω the rise time t_r is independent of R_L and equal to τ_T, whereas for $R_L < 10^{10}$ Ω, t_r coincides with τ_e.

The experimental values of t_p match well the calculated [Eq. (5)] plot of t_p vs θ (dotted curve). The peak voltages V_p in the range $R_L < 10^{10}$ Ω are proportional to R_L and very close to the theoretically predicted value $V_p = k\tau_e$ for $\tau_e \ll \tau_T$. For rising load resistances, V_p seems to approach a limit, which is close to the theoretically predicted value $V_p = k\tau_T$ for $\tau_e \gg \tau_T$. This behavior is illustrated in Fig. 5, where the normalized measured peak voltages $V_p/k\tau_T$ in TGS and SBN samples are plotted against the corresponding experimental values of θ. The experimental points are seen to fit well the computed plot of Eq. (6), $V_p/k\tau_T = \theta^{1/(1-\theta)}$ (solid curve).

Similar results were obtained in other SBN samples, as well as in a large number of TGS samples. In TGS, k and V_p, obtained with a given F_0, are an order of magnitude higher than in SBN. In the shown case of sample B-1, $k/F_0 = \xi$ is 340 (V/sec)/ (W/cm²), or cm²/C; in other SBN samples it never exceeded 500. In TGS samples, on the other hand, initial slopes of 4.5 V/sec in response to $F_0 = 1$ mW/cm² are mostly obtained, and this yields ξ = 4500 cm²/C.

V. DISCUSSION

Our analysis was based on the assumption that the temperature rise caused by the abosrbed radiation is uniform throughout the crystal. This assumption fits the experiment because the electrodes are transparent to the radiation so that absorption occurs mostly in the bulk of the crystal, and the crystal thicknesses are within the absorption depths for the 500 °K blackbody radiation, which are ~100 μm in SBN,[9] and ~10 μm in TGS.[13] The agreement between experimental results and theory even in TGS samples above 20 μm thick proves that the assumption of a uniform heating is suitable and/or that the eventually developed temperature gradients and heat flow are unimportant.

We consider as the most important part of this work the derivation and experimental proof of the fact that the initial slope of the pyroelectric voltage response to a step radiation signal does not depend on the load resistance. Deviations from this rule were observed only when the rise of the radiation signal was too slow. To insure a step signal, its rise should be much faster than that of the response, and this is hard to achieve with low load resistors, e.g., already with $R_L = 10^6$ Ω, and $C = 10$ pF, the rise time of the response (equal to τ_e) is 10 μsec, and we could not shutter the radiation in a time shorter than that. However, we could extend our measurement range to even $R_L = 10^5$ Ω by using fast CO_2 laser pulses, and the same rule was obeyed. Hence k is an important factor in more general cases of pyroelectric detection, too; this will be discussed elsewhere.[14]

Another interesting result is the symmetry of the response with respect to the time constants τ_e and τ_T: the switching of the rise time from τ_e to τ_T, with increasing R_L, when τ_e exceeds τ_T, and the simultaneous turn of the fall time from τ_T to τ_e. This is also seen on the peak signal values: They are proportional to τ_e when $\tau_e \ll \tau_T$ and become independent of τ_e (and R_L) and proportional to τ_T when $\tau_e \gg \tau_T$. These properties of the response are important for the design of pyroelectric detectors intended for operation in proper frequency ranges.[14]
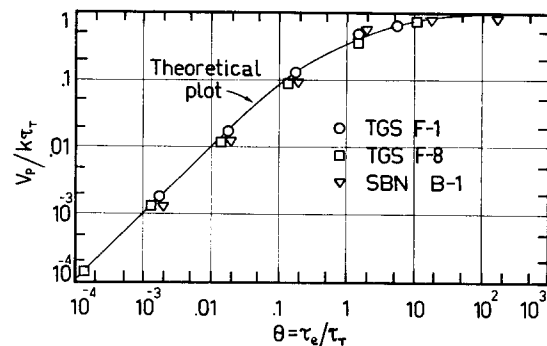

FIG. 5. Peak signal (normalized) as function of τ_e/τ_T in three samples. The solid curve is the plot of Eq. (6).

We have shown that the material constant $\xi_0 = \lambda/\epsilon d c_p$ is closely connected with the factor ξ in the expressions for k, $V(t)$, and V_p, and can therefore be considered as a figure of merit evaluating the material for the use in pyroelectric ir detection.[14] Using published data,[4,8,9,15] one obtains $\xi_0 = 4600$ and 630 cm^2/C in TGS and SBN, respectively. This fits very well the experimentally observed values of k/F_0, especially in TGS. Some discrepancy in a number of SBN samples is possibly due to small deviations in stoichiometry and/or orientation relative to the polar axis; each of these factors has in SBN a very strong effect on the values of λ and ϵ.[9]

ACKNOWLEDGMENTS

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