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Temperature dependence of the pyroelectric voltage response to step infrared signals in triglycine sulphate*

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An expression is derived for the pyroelectric (PE) voltage response to step radiation signals which can be applied up to temperatures close to the Curie point T_c under a "small-signal" condition. Based on the Curie-Weiss law and the thermodynamic theory of a second-order ferroelectric transition, a discussion is given of the temperature dependence of the parameters of the PE voltage response: initial slope, peak value, rise time, and fall time as functions of sample parameters and load resistance. It is found that the PE voltage may reach a maximum close to T_c , and expressions are derived for this value as well as for the temperature at which it occurs. These results were checked in detail on 12 samples of single-crystalline triglycine sulphate for temperatures from 20 °C to the Curie point, and good agreement between theory and experiment was observed. The application of the results to PE detection of ir is considered.

I. INTRODUCTION

The temperature dependence of the pyroelectric (PE) current response to ir pulses was first studied by Chynoweth¹ in BaTiO₃ and triglycine sulphate (TGS).² Similar measurements were since performed in various other materials.³⁻⁶ Less attention has been paid to the PE voltage response. White⁷ has studied the temperature dependence of the peak value of the PE voltage response to step microwave signals in TGS, and Hadni⁸ has considered the shapes of the PE voltage response in TGS to step ir signals at various temperatures.

In a previous paper⁹ we have shown that important physical information is contained not only in the usually measured peak values, but also in other parameters of the PE voltage response to step signals, such as the initial slope, rise time, and fall time. Here we extend our analysis to fit temperatures close to the Curie point, and then consider the temperature dependence of all four parameters of the PE voltage response. The results are compared with experiment in TGS.

II. EXPERIMENTAL TECHNIQUE

The samples are 15–70- μm thick slices of single-crystalline triglycine sulphate⁹ (TGS) with major faces perpendicular to the PE axis and provided with ir transparent electrodes (evaporated InSb). Attached to the electrodes were 8- μm thin leads of a soft metal alloy which also served as suspenders. The samples were placed in a small oven with a CdS window. The oven was thermistor controlled with temperature stability better than 0.05 °C. The temperature of the sample in the oven was measured to ~ 0.1 °C with a calibrated thermocouple attached very close to the rear electrode. The whole mount was held in a vacuum-tight (up to 10^{-6} Torr) cryostat with a KBr window, in which the sample could be poled in a field up to 10^4 V/cm.

The radiation source was a 500 °K blackbody with a shutter fast enough to provide step signals, and with a variable chopper. 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, as shown in Fig. 1. The PE response transients were displayed on a Tektronix RM 564 storage CRO with a 3A9 amplifier of usable sensitivity 50 $\mu\text{V}/\text{cm}$.

III. ANALYTICAL EXPRESSION FOR PE VOLTAGE RESPONSE

We assume that the absorbed radiation flux F causes a small temperature rise ΔT which is uniform throughout the PE crystal, and that the thermal capacitance C_T of the sample and its thermal conductance to ambient G_T are constant during the signal. From the equation of thermal flow

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

it then follows that during the step signal ΔT rises exponentially to a saturation value ΔT_s ,

$$\Delta T = \Delta T_s [1 - \exp(-t/\tau_T)], \quad (2)$$

where $\tau_T \equiv C_T/G_T$ is the thermal time constant of the sample, and $\Delta T_s = AF/G_T$, A being the sample area. The resulting PE charge flow in the circuit of the sample (Fig. 1) is then described by

$$\frac{d(CV)}{dt} + \frac{V}{R} = \alpha A \lambda \frac{d(\Delta T)}{dt}. \quad (3)$$

Here $V = V(t)$ is the PE voltage response, C is composed of the capacitance C_s of the sample and C_i of the pre-amplifier input, R is the resistance R_s of the sample with the parallel load R_L , α is a factor depending on the domain structure of the sample, $0 \leq \alpha \leq 1$, assumed constant during the signal, and $\lambda \equiv dP_s/dT$ is the PE coefficient, with P_s the spontaneous polarization. Equation (3) can be rewritten as

$$\frac{dV}{dt} + \frac{V}{\tau_e} \left(1 + R \frac{dC}{dt}\right) = k \exp\left(\frac{-t}{\tau_T}\right), \quad (4)$$

where $\tau_e \equiv RC$ is the electronic time constant of the sam-

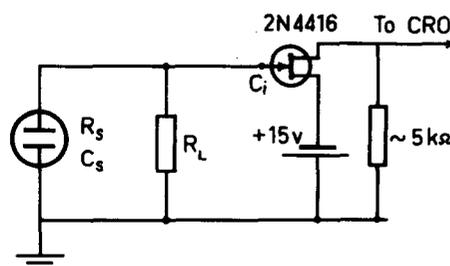


FIG. 1. Measuring circuit.

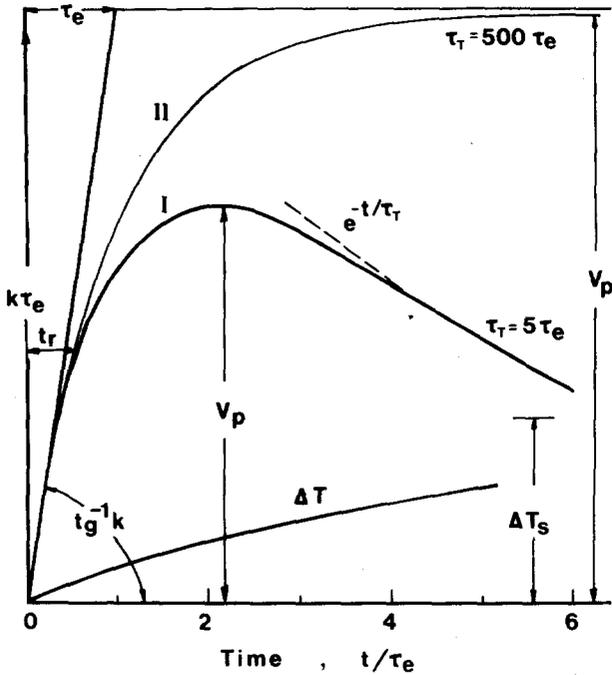


FIG. 2. Calculated PE voltage transients for $\theta=0.2$ (curve I) and $\theta=0.002$ (curve II). Also shown is the temperature rise ΔT causing the response I.

ple, and $k \equiv \alpha \lambda A \Delta T_s / C \tau_T = \alpha \lambda A^2 F / C C_T$. It is also useful to make the substitution

$$R \frac{dC}{dt} = R \frac{A d\epsilon}{L dT} \frac{d(\Delta T)}{dt} = \theta \mu \Delta T_s \exp\left(\frac{-t}{\tau_T}\right), \quad (5)$$

where L is the thickness of the sample, ϵ is the permittivity of the material, $\theta \equiv \tau_\theta / \tau_T$, and $\mu \equiv \epsilon^{-1} d\epsilon/dT$.

We restrict the analysis to conditions under which ϵ , λ , and μ remain constant during the signal. These can always be achieved by making ΔT_s sufficiently small. However, close to the Curie temperature T_c the "small-signal" condition has to be made more specific. Here the Curie-Weiss law yields $\Delta\epsilon/\epsilon \approx \Delta T_s / |T_c - T|$, and $\mu = 1/|T_c - T|$, where the thermodynamic theory of a second-order ferroelectric transition gives $\Delta\lambda/\lambda \approx \frac{1}{2} \Delta T_s / (T_c - T)$.¹⁰ Thus the increments can be disregarded and ϵ , λ , and μ considered constant during the pulse if

$$\Delta T_s \ll T_c - T. \quad (6)$$

Under condition (6), $\mu \Delta T_s \ll 1$, so that the term $R dC/dt$ can be disregarded in Eq. (4),¹¹ to yield the solution

$$V(t) = k(\tau_e^{-1} - \tau_T^{-1})^{-1} [\exp(-t/\tau_T) - \exp(-t/\tau_e)] \quad (7)$$

for $\tau_e \neq \tau_T$, and $V(t) = kt \exp(-t/\tau_T)$ for $\tau_e = \tau_T$. The same solution was obtained⁹ for temperatures far from T_c . Thus under condition (6) the previous results become applicable at temperatures close to T_c , the closer, the smaller ΔT_s .

A typical PE voltage response (calculated with $\tau_T = 5\tau_e$) is shown by curve I in Fig. 2. At the onset of the step signal it has an initial slope

$$\left. \frac{dV}{dt} \right|_{t=0} = k = \frac{\alpha \lambda A^2 F}{C C_T}, \quad (8)$$

rises to a peak value V_p ,

$$V_p = k \tau_T \theta^{1/(1-\theta)} = k \tau_e \theta^{\theta/(1-\theta)} \quad (9)$$

with a rise time t_r defined as the time needed for $V(t)$ to reach $1 - e^{-1} \approx 63\%$ of V_p , and then falls to zero with a fall time t_f , which is the time of decay to $e^{-1} \approx 37\%$ of V_p . Analytic expressions for t_r and t_f can hardly be given. However, in three limiting cases of the $\theta = \tau_e / \tau_T$ ratio of the sample parameters, the parameters of the response can be expressed⁹ very simply as

for $\theta \ll 1$

$$t_r = \tau_e, \quad t_f = \tau_T, \quad V_p = k \tau_T;$$

for $\theta \gg 1$

$$t_r = \tau_T, \quad t_f = \tau_e, \quad V_p = k \tau_e; \quad (10)$$

for $\theta = 1$

$$t_r = 0.32 \tau_T, \quad t_f = 2.2 \tau_T, \quad V_p = 0.37 k \tau_T.$$

IV. EXPECTED TEMPERATURE DEPENDENCE OF PARAMETERS

$\tau_e(T)$

Due to the high resistance of the PE samples, usually $R = R_L$. Because $C \approx C_s$ (which must anyhow occur with rising T), one has $\tau_e = (A/L) R_L \epsilon$, so that τ_e depends strongly on T , as does ϵ .¹⁰

$\tau_T(T)$

In comparison with ϵ , both C_T and G_T are rising very slowly with T , so that their ratio τ_T is not sensitive to temperature changes and may be considered constant. Therefore $\theta(T) \propto \tau_e(T)$.

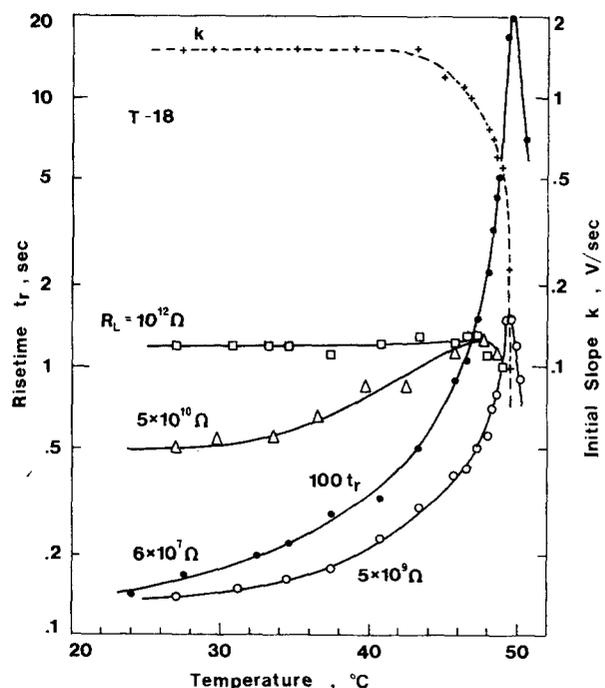


FIG. 3. Temperature dependence of initial slope and rise time of PE voltage response transients obtained on different load resistors in a TGS sample.

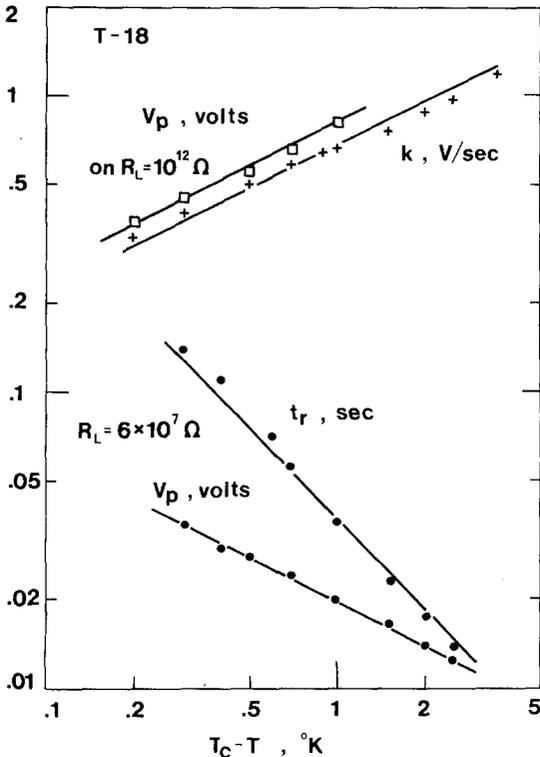


FIG. 4. Behavior of parameters of PE voltage response at temperatures close to Curie point in a TGS sample.

k(*T*)

When $C \approx C_s$, $k = \alpha F \lambda / \epsilon c$,⁹ where c is the volume specific heat. The rise of c with T is very slow,¹² so that if $\lambda(T)$ and $\epsilon(T)$ behave similarly, then k depends weakly on T . Close to T_c , the Curie-Weiss law and the thermodynamic theory yield $k \propto (T_c - T)^{1/2}$, as long as α and c can be considered constant.

t_r(*T*)

For $\theta \ll 1$, $t_r = \tau_\theta$, the temperature dependence of t_r depicts that of ϵ , and close to T_c , $t_r \propto |T_c - T|^{-1}$. For $\theta = 1$, $t_r = 0.32 \tau_T$, and for $\theta \gg 1$, $t_r = \tau_T$ so that in the whole range $1 < \theta < \infty$, t_r is essentially independent of T .

t_f(*T*)

For $\theta \ll 1$, $t_f = \tau_T$, and for $\theta = 1$, $t_f = 2.2 \tau_T$, so that in the region $0 < \theta < 1$, t_f is essentially independent of T . For $\theta \gg 1$, $t_f = \tau_\theta$ and depicts the temperature dependence of ϵ .

V_p(*T*)

For $\theta \ll 1$, $V_p = k \tau_\theta = (\alpha F R_L A / c L) \lambda$, the temperature dependence of V_p depicts that of λ , and V_p rises with T . Close to T_c , $V_p \propto (T_c - T)^{1/2}$, if only α/c remains constant. When $\theta \gg 1$, $V_p = k \tau_T = (\alpha F \tau_T / c) \lambda \epsilon^{-1}$, $V_p(T)$ behaves like $k(T)$; i. e., if $\lambda(T)$ and $\epsilon(T)$ are rising similarly, V_p depends weakly on T ; close to T_c , $V_p \propto (T_c - T)^{1/2}$, decreasing with T .

Let us now consider a PE sample, initially with $\theta \ll 1$, in which, due to the fast rise of $\tau_\theta(T)$, θ approaches unity at a certain temperature T_M , continuing to rise afterwards. If T_M is close to T_c , then, because $V_p(T)$ rises

for $\theta \ll 1$ and decreases for $\theta \gg 1$, V_p must have a maximum in between. It can be shown,¹³ taking dV_p/dT from Eq. (9) for constant α/c and using $\epsilon \propto (T_c - T)^{-1}$, $\lambda \propto (T_c - T)^{1/2}$, that $(V_p)_{max}$ occurs where $\theta = 1$, i. e., at $T = T_M$. Then, the condition $\tau_\theta = \tau_T$ and the Curie-Weiss law yield $R \gamma \epsilon_0 A / L (T_c - T_M) = \tau_T$, where $\epsilon_0 = 8.85 \times 10^{-12}$ F/m, and γ is the Curie constant of the material, so that

$$T_c - T_M = (\epsilon_0 \gamma A / L \tau_T) R. \tag{11}$$

In the narrow T region, in which Eq. (11) holds, and for $R \approx R_L$, the shift of $(V_p)_{max}$ from T_c is proportional to R_L , depending on the sample's geometry, material, and construction. When R_L is so small that τ_θ never approaches τ_T , $(V_p)_{max}$ occurs at T_c . For $(V_p)_{max} = 0.37 k(T_M) \tau_T$ one obtains¹³ from the thermodynamic theory

$$(V_p)_{max} = 0.18 \frac{\alpha F}{\epsilon_0 \beta \gamma} \left(\frac{A \tau_T}{L} R_L \right)^{1/2}, \tag{12}$$

where β is the square root of the coefficient¹⁰(ξ) at the term with P^4 in the expansion of free energy.

V. EXPERIMENTAL RESULTS

Experiments were carried out on 12 TGS samples. Because their room temperature (RT) resistance is $\lesssim 10^{12}$ Ω , by using load resistors of $10^7 - 10^{12}$ Ω we can change τ_θ up to five orders of magnitude, being able to consider $R = R_L$ and disregard in most measurements the resistance of the sample and its temperature dependence. The RT capacitance of the samples is of the order of 20 pF and that of circuitry is ~ 5 pF, so that one can consider $C = C_s$, at least starting from a few degrees above RT. Whenever τ_θ was so small that the shutter speed was not sufficient to provide a step signal, a chopper was used to obtain rectangular and triangular responses, from which the parameters of the response to a step signal could be calculated.¹⁴ The flux F , absorbed in the sample from the blackbody radiation, was calculated as 0.5 mW/cm².

The values of the initial slope k and the rise time t_r of PE voltage response transients obtained in a typical TGS sample (T-18) with different load resistors are plotted against temperature in Fig. 3. The k values (crosses, uppermost line) are ~ 1.5 V/sec, identical for different R_L , and essentially independent of T up to $\sim 44^\circ\text{C}$. Thereafter they decrease, first mildly, to half that value at $\sim 48^\circ\text{C}$, then sharply towards the Curie temperature, which is 49.5°C .

The parameters of $V(t)$ in the vicinity of T_c are plotted against $T_c - T$ in Fig. 4. It is seen that the k plot (crosses) is a straight line with a slope of $\frac{1}{2}$, as expected from the thermodynamic theory.

The plot of t_r vs T obtained with $R_L = 6 \times 10^7$ Ω (Fig. 3, closed circles) corresponds to the case $\theta \ll 1$, the τ_T of the sample being 2.4 sec. In the whole temperature range (24°C to T_c) t_r increases 150-fold (from 1.4 to 200 msec) resembling the behavior of $\epsilon(T)$.¹⁰ This is also seen in Fig. 4, where the line of t_r vs $T_c - T$ has a slope of -1 , in obedience of the Curie-Weiss law. With $R_L = 10^{12}$ Ω (Fig. 3, squares), in the case of $\theta > 1$, t_r is 1.2 sec $\approx 0.5 \tau_T$, nearly constant up to T_c . With $R_L = 5 \times 10^{10}$ Ω , θ is below unity in most of the T region, and $t_r(T)$ rises quite sharply from the RT value of 0.14

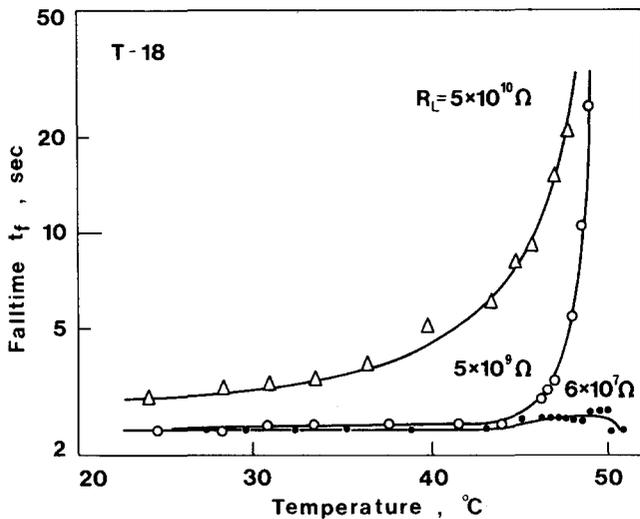


FIG. 5. Temperature dependence of fall time of PE voltage response on different load resistors in a TGS sample.

sec. Close to T_c , θ becomes larger than 1, and t_f equals $1.5 \text{ sec} \approx 0.6\tau_T$. (The t_f values for $T > T_c$ are those of residual PE responses.^{2,13})

The temperature dependence of the fall time is presented in Fig. 5. With $R_L = 6 \times 10^7 \Omega$ (closed circles), which results in $\theta \ll 1$, one measures $t_f = 2.4 \text{ sec} = \tau_T$ in the whole T range (slight changes are observed at and above T_c ¹³). With $5 \times 10^9 \Omega$ (open circles), the condition $\theta \ll 1$ holds up to 44°C , and $t_f = 2.4\text{--}2.5 \text{ sec} \approx \tau_T$, independent of T . Closer to T_c , the rise of θ to and above unity causes t_f to approach τ_T , i. e. to increase tenfold. With $R_L = 5 \times 10^{10} \Omega$ (triangles), a similar but more obtuse turnover happens at $\sim 40^\circ\text{C}$, and fall times above 20 sec are already observed 0.5°C before T_c . Closer to T_c , t_f cannot be measured because the tails of PE transients with still longer fall times are unstable. For this reason, with $R_L = 10^{12} \Omega$, t_f could be measured only at and slightly above RT.

The temperature dependence of the peak voltage is shown in Fig. 6. With $R_L = 6 \times 10^7 \Omega$ (closed circles), $\theta \ll 1$ for all T , and V_p rises from 1.5 mV at RT to 30 mV at T_c , resembling the behavior of λ .⁶ This is also seen in Fig. 4, where the plot of V_p vs $T_c - T$ (lowermost line) has a slope of $-\frac{1}{2}$. In the opposite case of $R_L = 10^{12} \Omega$ (Fig. 6, squares), $\theta > 1$, and $V_p(T)$ resembles the behavior of $k(T)$. It has a value of 2.5 V, essentially independent of T up to $\sim 44^\circ\text{C}$, and decreases thereafter. Close to T_c , V_p vs $T_c - T$ (Fig. 4, upper line) has a slope of $+\frac{1}{2}$.

In the two intermediate cases, with $5 \times 10^9 \Omega$ (Fig. 6, open circles), and $5 \times 10^{10} \Omega$ (triangles), $V_p(T)$ rise to maximum values of 0.7 and 2 V, respectively, which are reached at temperatures T_M of 2 and 6°K before T_c , and then decrease sharply toward T_c , as expected in Sec. IV. The changes in $(V_p)_{\text{max}}$ and T_M due to the increase of R_L cannot be closely described here by Eqs. (11) and (12) because with $R_L = 5 \times 10^{10} \Omega$ the maximum occurs out of the region where one would expect the equations to be accurate.

An experimental check of Eqs. (11) and (12) is presented in Fig. 7 in plots against $A/L\tau_T$ for seven TGS samples,

their pertinent data listed in Table I. The values of R_L in each sample are chosen so that $(V_p)_{\text{max}}$ occurs within the region of applicability of Eqs. (11) and (12). The plot of $(T_c - T_M)/\epsilon_0 R_L$ vs A/τ_T (circles) is linear, in agreement with Eq. (11), and has a slope of 1300°K , which is quite good a result for the Curie constant γ .¹⁰ The dashed line is the plot of $(V_p)_{\text{max}}/\tau_T R_L^{1/2}$ vs $A/L\tau_T$, calculated from Eq. (12) with $F = 0.5 \text{ mW/cm}^2$, $c = 2.7 \text{ J/cm}^3 \text{ deg}$,¹² $\gamma = 1300^\circ\text{K}$, $\beta = 8 \times 10^5 \text{ (m}^2/\text{C) (m/sec } \Omega)^{1/2}$.¹⁰ The values of α (see Table I) are the measured RT values of k , divided by a calculated value $k_1 = F\lambda/\epsilon c = 2.5 \text{ V/sec}$. The experimental points (crosses) are seen to be spread around the calculated line in not too bad an agreement, taking into account the number of parameters involved.

VI. DISCUSSION AND CONCLUSIONS

The samples in our experiment are suspended freely on very thin and soft metal alloy leads, so that strains during the signal are minimal and piezoelectric voltages can be disregarded. The spatial uniformity of the temperature rise is questionable,⁹ however, the eventually developed temperature gradients and heat flows have apparently no effect on the observed PE charge flow.

Our analysis is applicable only under the "small-signal" condition (6), which means that the Curie temperature can be approached the closer the smaller ΔT_s , or (because $\Delta T_s = AF/G_T$) the closer the smaller the signal and faster the heat dissipation by the sample; e.g., if $\Delta T_s = 0.1^\circ\text{C}$, then $T_c - T$ may be $\sim 1^\circ\text{C}$. However, if one is interested only in the parameters k , t_f , and V_p one can approach T_c even closer by using small R_L to maintain $\theta \ll 1$. During the rise of V_p , for $\theta \ll 1$ one has $\Delta T/$

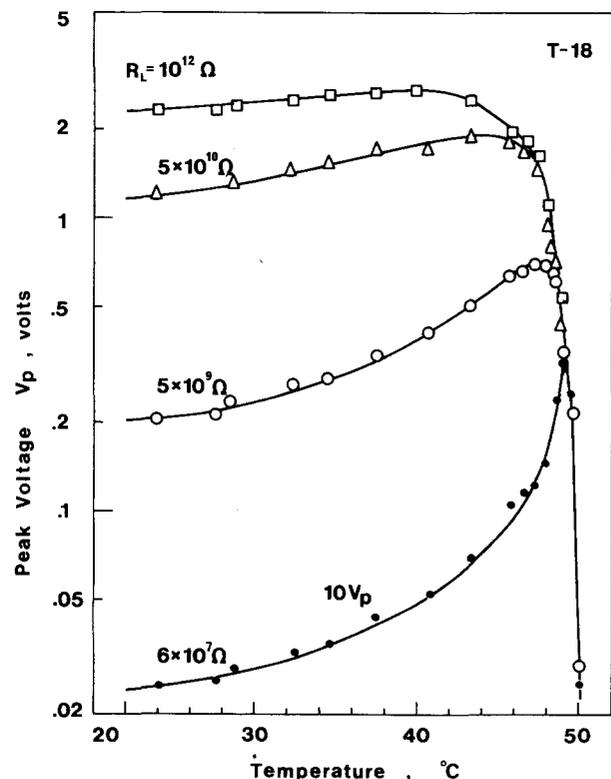


FIG. 6. Temperature dependence of the peak value of PE voltage response on different load resistors in a TGS sample.

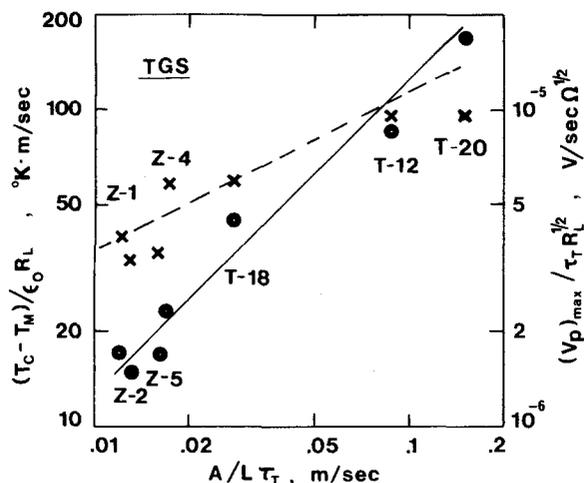


FIG. 7. Maximum PE voltage response (crosses) and temperature of its occurrence (circles) as functions (normalized) of sample parameters in seven TGS samples. The pertinent data for the samples and their loads are listed in Table I. The solid line is calculated from Eq. (11) with $\gamma = 1300^\circ\text{K}$. The dashed line is calculated from Eq. (12) with $F = 0.5 \text{ mW/cm}^2$, $c = 2.7 \text{ J/cm}^3 \text{ deg}$, $\gamma = 1300^\circ\text{K}$, $\beta = 8 \times 10^5 \text{ (m}^2/\text{C})(\text{m/sec } \Omega)^{1/2}$.

$\Delta T_s \approx \tau_e / \tau_T$, i. e., $\Delta T \approx \theta \Delta T_s$. Thus, e. g., with $\Delta T_s = 0.1^\circ\text{C}$ and $\theta = 0.01$ one can approach T_c to $\sim 0.01^\circ\text{C}$.

$\theta \ll 1$ is close to the "short-circuit" condition, and $\theta \gg 1$ resembles the "open-circuit" condition often discussed in analyzing PE responses.³ Clearly, with rising temperature the rapid increase of C may cause the switching from "short-circuit" to "open-circuit" conditions with R_L remaining constant.

The apparent harmony between analytical and experimental results is disturbed in two cases. *First*, with the largest resistor we obtain $t_r = 0.5\tau_T$, instead of $t_r = \tau_T$. Obviously, we never achieved conditions $\theta \gg 1$ in TGS, except very close to T_c , where the observed value of t_r can be explained by a more elaborate analysis.¹³ To keep the experiment within the frame of the present analysis, one has to use samples of higher resistance and/or capacitance, which can be achieved in other materials, e. g., in strontium-barium niobate.⁹

Second—the spread of the maximum PE voltage values around the line calculated from Eq. (12). It can be caused by the uniform values of β , γ , ϵ , and λ used in the calculation, while each of them may vary from sample to sample. A source of error may also be in using the RT value of the domain structure coefficient α . There are indications that the assumption of a constant α may not always be true at the different T_M temperatures in different samples; e. g., some of the samples hold their polarization at elevated temperatures, their voltages and initial slopes remain constant during long periods of time or change by 10–20% requiring little or no repoling, while in other samples, voltages and initial slopes decrease in time twofold to threefold, and repoling may be required after each measurement.

A detailed check of the dependence of $(V_p)_{\text{max}}$ and T_M on R_L , as expressed by Eqs. (11) and (12), was not performed. The region of their applicability is very nar-

TABLE I. Data for TGS samples of Fig. 7.

Sam- ple No.	A (mm ²)	L (μm)	τ_T (sec)	R_L (10 ⁹ Ω)	$T_c - T_M$ (°K)	$(V_p)_{\text{max}}$ (V)	α
Z-1	0.8	50	1.3	10	1.5	0.52	0.7
Z-2	1.3	63	1.6	10	1.3	0.53	0.65
Z-5	0.4	16	1.6	10	1.5	0.56	0.96
Z-4	2.0	70	1.7	10	2.0	1.0	1
T-18	4.0	60	2.4	5	2.0	0.70	0.65
T-12	3.0	20	1.7	5	3.5	0.85	0.87
T-20	3.3	15	1.5	1	1.5	0.26	0.61

row—not farther than $\sim 3^\circ\text{C}$ from T_c and not closer than allowed by the small-signal condition, and the check could be made only in a narrow range of R_L . Load resistors exceeding by an order of magnitude those chosen in Table I cause the maximum to occur too far from T_c .

The increase of the peak voltage with temperature can be employed to enhance the sensitivity of PE ir detection. However it is of little use when the speed of detection is also a matter of concern.¹⁴ For the increase is large only when $\theta \ll 1$, but then $V_p \propto \lambda$, while $t_r \propto \epsilon$, i. e., $t_r(T)$ may rise faster than V_p ; e. g., with $R_L = 6 \times 10^7 \Omega$ in sample T-18 (Figs. 3 and 6, closed circles) heating results in a 20-fold increase of V_p , but also in a 150-fold increase in t_r , causing the "speed-sensitivity" product to decrease. On the other hand, if a larger load resistor is used to increase V_p , then t_r increases equally, as long as $\theta \ll 1$, and "speed-sensitivity" remains constant.

For $\theta \ll 1$, $k = \alpha F \lambda / \epsilon c \propto V_p / t_r$, so that k is actually a measure of the "speed-sensitivity" (or "gain-bandwidth") product. In the temperature region where k remains constant, V_p and t_r increase equally. Closer to T_c , where $k(T)$ decreases, the increase of V_p is accompanied by a much larger increase in t_r . A "valuable" increase of V_p is one caused by an increase of k . This points out again the importance of k as a figure of merit⁹ in PE detection.

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substituting $V = u(t) \exp[-t(\tau_e^{-1} - \tau_T^{-1})]$ in Eq. (3) to obtain $du/dt + (u/\tau_T)[1 + \mu\Delta T_s \exp(-t/\tau_T)] = k \exp[t(\tau_e^{-1} - 2/\tau_T)]$, then leaving out the term $\mu\Delta T_s \exp(-t/\tau_T) \ll 1$ and returning to variable V .

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