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OPTIMIZATION OF A PYROELECTRIC DETECTOR

1975-2015: 40 years ago the company "Eltec Instruments", the U.S.A., manufactured the world's first pyroelectric detector based on a single crystal such as lithium tantalate.

A new thermal capacity equation for obtaining the thickness of a crystal in the voltage mode is given. A new boundary condition for the equation is given as well. Geometry of the crystal in both voltage and current mode is compared.

Keywords: *pyroelectric detector, optimization, time constants, heat flux.*

Introduction

Pyroelectrics are the subclass of thermal detectors. These can detect pulses of electromagnetic radiation in the range between ultraviolet and terahertz. The principle of operation is to generate electrical charges in response to the heat flux pulsed or permanent being chopped.

Pyroelectric detectors are used in many fields. The widest applications are flame and motion detectors. These detectors are not designed to be applied to instrumentation. However, gas analyzers, optical pyrometers, optical radiometers, electrically calibrated radiometers, or the like, are related to the instruments. Each application requires that a detector to be used, be optimized.

At least, three major criteria for thermal detectors of optimization, have been postulated [1]:

- maximum thermal isolation;
- minimum thickness of the sensor element;
- maximum area of the sensor element.

The three criteria should be considered in details. The first criterion meets the requirement that the sensitive element should be used in vacuum, with thermal losses occuring due to radiation. In this case, a thermal contact between the sensitive element and a mounting should be minimal. In practice, pyroelectric detectors as vacuum sensors are not widely produced. A problem is that the detector may collect air, moisture, dust, or other contaminants that may result in bad. For example, if the sensitive element of an open detector is observed with a microscope, one can see some parts of dust attracted by the former. These parts of dust are, at least, one more source of noise. Moisture decreases the electrical resistance of the high-ohm circuit. Air and other contaminants absorb the infrared radiation that results in false measurement [2]. In order to avoid said problems, pyroelectric detectors are filled with gas preferably optically transparent in infrared. Such a gas is found to be nitrogen [1]. This gas relates to a group of inertia gases. Other gases from the group can be used as well [3]. As a result, it is hardly possible to meet the first criterion.

The second criterion is limited with mechanical performance. Also, it is not possible to provide the thickness of a crystal close to some layers of molecules, probably, theoretically, due to the pyroelectric effect itself may have a strange behavior. Besides, the thinner the crystal, the higher the electrical capacitance which is not always desirable. As a result, to meet the second criterion is pretty hard.

The third criterion is limited with manufacturing feasibility. It is hard enough to manufacture a single crystal of a large area. Another problem is to make the domains be uniform. This problem seems to be major and is near-impossible to control. As a result, the third criterion is not assumed to be met.

The three criteria are postulated to provide the highest output. The latter is observed at a special moment of time, hereinafter called t_{max}, that depends on time constants. The time constants determine the transient process of a detector. However, it has been noted that the detector absorbs the energy of electromagnetic radiation pulsed, or being chopped. It is clear that when the pulse width, so-called t_{pulse}, equals t_{max}, the output is the highest. Otherwise, it is not.

It is an object of the paper to provide a pyroelectric detector with a predetermined t_{max}, with the output being maximum.

Thermal model of a detector

A pyroelectric detector shown on Fig.1, includes a sensitive element 1 preferably a thin wafer made of a single crystal such as lithium tantalate. The sensitive element 1 through thermal contact 2 is installed on, at least, one (or more) mounting 3. The mounting 3 is in contact with a flat supporting surface 4. Above and below the sensitive element 1 is gas.

The principal symbols used in this paper, are given in Table 1.

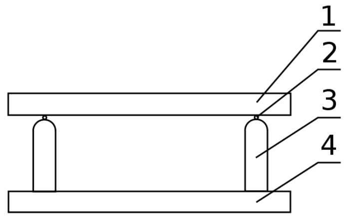

Fig. 1. A pyroelectric detector

Table 1

The principal symbols

Number	Parameter	Unit of measurement	Description
1	t_{max}	s	Time at which the peak output is provided
2	t_{pulse}	s	Time of pulse
3	α	unitless	Absorbance of a detector
4	τ_W	unitless	Transmission of a window
5	Φ	W	Heat flux
6	R_{bias}	Ohm	Bias resistor (voltage mode)
7	R_{fb}	Ohm	Feedback resistor (current mode)
8	C_{fb}	F	Capacitance of feedback resistor (current mode)
9	C_{E_pyro}	F	Capacitance of pyroelectric element
10	C_{T_pyro}	J/m^{3}K	Volume heat capacity of a detector
11	p_{pyro}	C/m^{2}K	Pyroelectric coefficient
12	d_{pyro}	m	Thickness of a sensitive element
13	τ_T	s	Thermal time constant
14	τ_E	s	Electrical time constant
15	τ_{E_VM}	s	Electrical time constant (voltage mode)
16	τ_{E_CM}	s	Electrical time constant (current mode)
17	A_{mount}^{unit}	m^2	Contact area between the sensitive element and a mounting
18	A_{mount}	m^2	Full area between the sensitive element and a mounting
19	C_{T_mount}	J/m^{3}K	Volume heat capacity of a mounting
20	d_{mount}	m	Height of a mounting
21	λ_{mount}	W/m K	Thermal conductivity of a mounting
22	ε_0	F/м	Dielectric constant
23	ε_{pyro}	unitless	Dielectric constant of a detector
24	C_{T_gas}	J/m^{3}K	Volume heat capacity of gas
25	d_{gas_top}	m	Gas layer above a detector
26	d_{gas_btm}	m	Gas layer below a detector
27	σ	W/m^{2}K^4	Stefan-Boltzman constant
28	T_0	K	Ambient temperature
29	λ_{gas}	W/m K	Thermal conductivity of gas
30	C_{JFET}	F	JFET input electrical capacitance
31	t	s	Time
32	$u_{pyro}(t)$	V	Output voltage of a detector

The thermal time constant τ_T is known to be an important parameter that defines the thermal transient process of a detector. It can be described as $\tau_T = C_T / G_T$ where C_T being thermal capacitance of the detector; G_T being thermal loss of that. Thermal capacitance C_T is the sum of thermal capacitances of the detector element $C_{T\_pyro\_det}$, gas layers above $C_{T\_gas\_top}$ and below $C_{T\_gas\_btm}$ the detector, and thermal capacitance of the mounting C_{T_mount}. Thermal loss G_T is the sum of thermal losses of radiation G_{Rad}, gas layers above $G_{T\_gas\_top}$ and below $G_{T\_gas\_btm}$ the detector, and thermal conductivity of the mounting G_{T_mount}. Thermal capacitance C_T

$$\begin{aligned} C_T = {} & C_{T\_gas}A_{pyro}d_{gas\_top} + \\ & + C_{T\_gas}A_{pyro}d_{gas\_btm} + C_{T\_pyro}A_{pyro}d_{pyro} + \\ & + C_{T\_mount}A_{mount}d_{mount}, \end{aligned} \tag{1}$$

and thermal losses G_T

$$\begin{aligned} G_T = {} & \lambda_{gas}\frac{A_{pyro}}{d_{gas\_top}} + \lambda_{gas}\frac{A_{pyro}}{d_{gas\_btm}} + \\ & + \lambda_{mount}\frac{A_{mount}}{d_{mount}} + 4\sigma A_{pyro}T_0^3 \end{aligned} \tag{2}$$

are equal to correspondingly [1,4].

Electrical model of a detector

Voltage mode. A pyroelectric detector connected to a JFET, is called a detector working in voltage mode. In the voltage mode, the electrical time constant τ_{E_VM} is determined as a product of electrical resistance R_{E_VM} and electrical capacitance C_{E_VM}. The former is the inversed sum of electrical resistance of the crystal R_{pyro}, bias resistor R_{bias}, and the input resistance of a JFET R_{JFET}. The latter is that of electrical capacitance of the crystal C_{E_pyro}, bias resistor C_{R_bias}, and the input capacitance of the JFET C_{E_JFET}. In principle, the values R_{pyro} and R_{JFET} are too high and can be neglected. The value C_{R_bias} is low enough and can be done as well. Therefore, the electrical time constant in the voltage mode equals

$$\tau_{E\_VM} = R_{bias}\left(C_{E\_pyro} + C_{JFET}\right), \tag{3}$$

where

$$C_{E\_pyro} = \varepsilon_0\varepsilon_{pyro}\frac{A_{pyro}}{d_{pyro}}. \tag{4}$$

Current mode. If a detector is connected to an operational amplifier (current mode), then the electrical time constant is a product of electrical resistance of a feedback resistor R_{fb} and its capacitance C_{fb}. In the current mode, the electrical time constant is [1]:

$$\tau_{E\_CM} = R_{fb}C_{fb}. \quad (5)$$

Solution

Voltage mode. The output is described as [5]:

$$u_{pyro}(t) = \alpha\tau_W\widehat{\Phi}R_{bias} \times \times\frac{p_{pyro}}{C_{T\_pyro}}\frac{1}{d_{pyro}}\left(e^{-1/\tau_E} - e^{-1/\tau_T}\right). \quad (6)$$

The output reaches its maximum at the point

$$t_{max} = \ln\frac{\tau_T}{\tau_E}\left(\frac{1}{\tau_E} - \frac{1}{\tau_T}\right)^{-1} \quad (7)$$

of time [6].

From here, new criteria of optimization can be postulated:

– the time t_{max} should be equal to the pulse width t_{pulse};

– the output should be maximum.

It is seen from the equation (7) that t_{max} depends on two variables and, therefore, has a set of solutions. Let t_{max} be a predetermined value. The time constants τ_T and τ_E are set in the range $\{a_T; b_T\}$ and $\{a_E; b_E\}$ correspondingly. Step may be chosen individually. Let $t_{max} = x$ [s]. Then, one should select the couples of τ_T and τ_E which give the smallest difference between x and the result. If necessary, the step can be decreased.

The thermal capacity equation found by the author, give the solution for the thickness of a crystal

$$Az^2 + Bz + C = 0, \quad (8)$$

where

$$A = P_2N_1;$$

$$B = P_1\left(M_1N_1 - M_2N_2\right);$$

$$C = A_{mount}\left(C_{T\_mount}d_{mount} - \tau_T\frac{\lambda_{mount}}{d_{mount}}\right);$$

$$P_1 = \frac{1}{\varepsilon_0\varepsilon_{pyro}};$$

$$P_2 = P_1C_{T\_pyro};$$

$$M_1 = C_{T\_gas}\left(d_{gas\_top} + d_{gas\_btm}\right);$$

$$M_2 = \tau_T\left(4\sigma T_0^3 + \lambda_{gas}\left(\frac{1}{d_{gas\_top}} + \frac{1}{d_{gas\_btm}}\right)\right);$$

$$N_1 = \frac{\tau_E}{R_{bias}} - C_{JFET};$$

$$N_2 = \frac{\tau_E}{R_{bias}} + C_{JFET}.$$

The equation (8) has two roots. One root is negative and should be given up. Another root is positive and can be taken into account. Therefore

$$z = d_{pyro} = \frac{-B + \sqrt{B^2 - 4AC}}{2A}, \quad (9)$$

under a boundary condition

$$d_{mount} < \sqrt{\tau_T\frac{\lambda_{mount}}{C_{T\_mount}}}. \quad (10)$$

If the boundary condition (10) is not satisfied, then the root (9) of the equation (8) has no real value.

Current mode. In the current mode, the detector is connected to an operational amplifier. The electrical time constant is the product of resistance of a feedback resistor and its capacitance. Here, the equation (7) has the only solution relatively to the thermal time constant. It means that in contrast to the voltage mode, the current mode provides the only couple of the time constants that satisfy the optimization. Therefore, geometry for a detector have to be chosen according to thermal properties of the detector only. It is necessary to determine the thickness of the crystal that is

$$d_{pyro} = \frac{1}{A_{pyro}} \times \times\left(\frac{\tau_T\lambda_{mount}A_{mount}}{C_{T\_pyro}d_{mount}} - \frac{C_{T\_mount}A_{mount}d_{mount}}{C_{T\_pyro}}\right) + +\frac{\tau_T}{C_{T\_pyro}}\left(\lambda_{gas}\left(\frac{1}{d_{gas\_top}} + \frac{1}{d_{gas\_btm}}\right) + 4\sigma T_0^3\right) - -\frac{C_{T\_gas}}{C_{T\_pyro}}\left(d_{gas\_top} - d_{gas\_btm}\right) \quad (11)$$

Discussion

Current mode. The equation (11) shows that the best solution can be obtained if the crystal has infinite area and zero thickness. This does correspond to the second criterion of optimization given in [1], but differs from the one used in the voltage mode. The crystal area can be chosen depending on the market requirements and is limited by technological options. The ratio between the thickness and the area should satisfy mechanical performance of the crystal. The parameters other than the thickness and the area, are discrete and, therefore, can't be changed widely. Therefore, it is not necessary to plot graphs or draw tables for them.

Voltage mode. It is obvious that in order to satisfy the equation (7), the root (9) is influenced by other parameters. These influences are given in the Table 2. The top line shows the parameters to be, here, for instance, increased. The bottom line shows if the crystal should be thicker or thinner.

Table 2

Influences by other parameters

$\uparrow$	R_{bias}	d_{gas_btm}	d_{gas_top}	C_{mount}	λ_{mount}	C_{gas}	λ_{gas}	C_{JFET}	A_{mount}
$z = d_{pyro}$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$

The parameters given in the Table 2, are discrete. It means that it is impossible to set a range of each of them separately. It is not necessary to plot graphs as well.

The bias resistor is chosen from the list. The gas layers above d_{gas_top} and below d_{gas_btm} the crystal are characterized by the field of view that is dictated by the market. The height of a mounting d_{mount} in this paper equals the gas layer d_{gas_btm} below the crystal. The parameters, thermal capacitance of a mounting C_{T_mount}, thermal capacitance of gas C_{T_gas}, thermal conductivity of the mounting λ_{mount}, thermal conductivity of gas λ_{gas}, are set depending on material used for the mounting, and gas correspondingly. The input electrical capacitance C_{JFET} is considered to be constant and is taken from the specification.

The last parameter is the area of thermal contact A_{mount} between the crystal and the mounting. This parameter is not discrete. It determines how much energy is lost due to thermal conductance through the mounting.

However, probably, it is not possible to provide A_{mount} too low due to technological restrictions.

Let the unit area for the thermal contact A_{mount}^{unit} be y [mm^2]. Let the number of mountings be n. Then, the value A_{mount} equals the sum of n mountings A_{mount}^{unit}, i.e. $A_{mount} = ny$ [mm^2].

The couples τ_T and τ_E, which have already been found, in combination with the other parameters are put in the equation (6). The maximum output will be obtained at the only couple of τ_T and τ_E that satisfies the new criteria of optimization.

Conclusion

It has been shown that for a pyroelectric detector with the predetermined t_{max} in the voltage mode, the highest output may be achieved when the crystal is as small as possible. In contrast, in the current mode, the large area is preferable. The thickness of the crystal is known to be as small as possible.

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ОПТИМІЗАЦІЯ ПІРОЕЛЕКТРИЧНОГО ДЕТЕКТОРА

О.Ю. Бондаренко

Наводиться нове рівняння теплоємностей для визначення величини товщини кристала в режимі роботи по напрузі. Також для даного рівняння наводиться гранична умова. Порівнюються геометричні фактори кристалів в режимі роботи по напрузі і струму. Показано, що для піроелектричного детектора із заданим часом досягнення максимального сигналу, геометричні розміри повинні бути мінімально можливими, а в режимі роботи по струму переважно використання кристалів великої площі.

Ключові слова: *піроелектричний детектор, оптимізація, сталі часу, тепловий потік.*

ОПТИМИЗАЦИЯ ПИРОЭЛЕКТРИЧЕСКОГО ДЕТЕКТОРА

А.Ю. Бондаренко

Приводится новое уравнение теплоемкостей для определения величины толщины кристалла в режиме работы по напряжению. Также для данного уравнения приводится граничное условие. Сравниваются геометрические факторы кристаллов в режиме работы по напряжению и току. Показано, что для пироэлектрического детектора с заданным временем достижения максимального сигнала, геометрические размеры должны быть минимально возможными, а в режиме работы по току предпочтительно использование кристаллов большой площади.

Ключевые слова: *пироэлектрический детектор, оптимизация, постоянные времени, тепловой поток.*