# Heat Flux Sensor Based on Ferroelectric

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***Abstract*****—We present a method for heat flux measuring with the use of polarization properties of ferroelectric ceramics. Heat flux innovative sensor is developed on the basis of the proposed method. Its experimental verification is carried out. The measurements are based on maintaining a balance between the processes caused by thermal energy and the energy of the electric field in the ferroelectric ceramics. The testing of the proposed heat flux sensor has been organized in two stages. At the first stage the primary calibration has been performed by calibrated sensors ITP MG4.03/x(y) "Potok". At the second stage the testing of heat flux sensor has been carried out for calculating the quantity of heat. The comparison of the results to the readings of serial heat meters VKT-7 and STK-15 has been performed. Experiments have shown that the polarization properties of the ferroelectric ceramics can be used to measure the heat flow. Practical Relevance. The proposed sensor can be recommended as an apartment-level heat meter. The calibration of the proposed heat flux sensor with more accurate measurement tools gives the possibility to include it on the State Register of Measuring Instruments.**

## I. INTRODUCTION

To estimate the thermal state of an object it is necessary to measure two quantities: heat flow and temperature. This simple temperature measurement can't give a picture of the thermal state, that could be considered an adequate, because the same temperature, may correspond different values of the heat flow. As an example, a comparison of the heat flow from the surface of the battery with temperature of +40ºC inside the room with the temperature of +20ºC and heat flow from the surface of a heating tube with temperature +40ºC to environment with temperature –10ºC. It is clear that in the first case the heat flow, i.e. heat consumption will be substantially lower than in the second, with equal temperatures of the heat sources. Counters that operating on this principle has significant disadvantage: they do not measure the consumed heat, but radiator heat. Therefore it is necessary to measure the heat flux.

Thus, heat flows have a key role in estimating the thermal state of different objects.

In known thermal resistance to heat flow may be indirectly determined from the temperature values measured at different points of the test object. Typically, the heat flux is determined, i.e. the flow through unit area, [W/m2]

$$q = -\lambda \frac{dt}{dx}$$

where $\lambda$ – thermal conductivity [W/m•K], $t_1$ and $t_2$ – temperatures at some points of the object, between which heat flow is determined, $x$ – coordinate along which the heat flux is distributed. Let us assume that the heat flow is determined through the wall. If the temperature distribution across its thickness has a linear character, it can be written:

$$q = -\lambda \frac{t_1 - t_2}{L},$$

where L – wall thickness.

Full heat flux through the wall can be written as:

$$P = \frac{\Delta t}{R} = \frac{\Delta t}{\left(\frac{L}{\lambda S}\right)}$$

where $P$, [W] – heat flux, $\Delta t = t_1 - t_2$, [K] - differential temperature; $S$, [m$^2$] – wall area; $R$, [K/W] – thermal resistance.

However, often heat resistance is not known, and then the measurement should be carried out by direct heat flux measurements from the heat flux sensor. Most often used sensors that measure the heat flux based on the determination of the temperature difference measured by the differential temperature sensor or two temperature sensors at a certain wall thickness. Heat flow measurement techniques are developed for a long time and are well described, for example, [1].

The heat flow is measured in the different areas of science and technology and for different purposes, such as:

- to determine the thermal conductivity of materials (including insulation);
- to determine the heat loss in buildings;
- to create comfortable conditions in living quarters;
- for heat transfer studies surfaces;
- to control heating (and cooling in the summer).

To achieve sufficient sensitivity existing heat flux sensors are necessary to produce these sensors are made of thick, of the order of units of mm of dielectric material, or increase its area up to tens of cm$^2$. Low sensitivity of the sensors due to the small temperature difference on the sensor heat flow and low sensitivity temperature sensors, which leads to a rather low value of heat flux sensor sensitivity, in the event that its output voltage is of the order of <0,01V/W. The large sensor size leads to large values of thermal resistance and to significant measurement error due to the distortion of the heat flux sensor.

Fig. 1 is an example: heat flow quantity q = 100W/m$^2$ passes through the wall thickness and thermal conductivity.

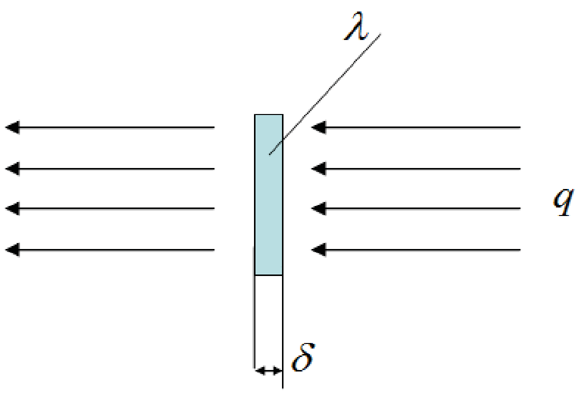


Fig. 1. – The passage of the heat flow q through the wall thickness $\delta$ and thermal conductivity $\lambda$

Let us assume $\delta = 3mm$ and $\lambda = 1\ W / m \cdot K$. Then the temperature drop on this wall:

$$\Delta t = \frac{q\delta}{\lambda} = \frac{100 \cdot 3 \cdot 10^{-3}}{1} = 0,3K$$

This is a fairly small value, the measurement of which with high accuracy is difficult, separate, task. Then you can go the other way: to take another material, such as thermal conductivity $\lambda = 0,1\ W / m \cdot K$. But then, if the measurement is carried out, for example, on the brick wall, wherein the thermal conductivity of the order $1\ W / m \cdot K$, so sensor material $\lambda = 0,1 W / m \cdot K$ isolates place its location on the wall, resulting in distortion of the heat flux (heat flux begins to bend around) at this location and incorrect readings.

In recent years, widely used for various tasks, including the creation of new types of sensors, received materials having ferroelectric properties. On the basis of such a material is created a new method of heat flow measurement [2, 3] and an innovative heat flux sensor (the sensor). The novelty of the proposed method and a sensor based on it is to use a ferroelectric material as the sensing element. The advantage of the proposed method of revealing the low cost and low inertia sensor.

## II. MATERIALS AND METHOD

There are different ways to measure heat flow, which can be divided into two groups:

- measuring the heat flow passing through the flat plate on the basis of the temperature difference measurement on this plate (Fig. 1) (see for example the sensors of the "auxiliary wall" [4]);
- measuring the amount of heat absorbed by sensors body (calorimetric methods, eg. [5]).

The first method is illustrated above. The author believes that today it has reached its limits. A significant disadvantage of the sensor type "Auxiliary wall" is the need for accurate temperature difference measurement sensor on the substrate, which is necessary to increase the thickness of the substrate and make sensitive sensor element, for example, based multijunction thermocouple.

Increasing the thickness of the substrate means an increase in weight and size of the sensor and improve its thermal insulating properties, which leads to increased systematic error of measurement of flow. Therefore, the authors of the article focused on measuring the amount of heat. For this innovative method of measuring the heat flux based on measurements of absorbed heat sensor has been developed. As the sensor is proposed to use a substrate of ferroelectric material - ferroelectric nanoceramics.

The method is based on the property of the ferroelectric material to change the polarization depending on the amount of heat absorbed by them [6],[7],[8]. This results in a strong dependence of dielectric constant on temperature. This dependence is nowadays well studied. For example, for a crystal of barium titanate ($BaTiO_3$), the first publication appeared in the forties of the twentieth century [7]. The value of the dielectric constant ε of barium titanate ranges from a few dozen to several thousand (Fig. 2, [7]).

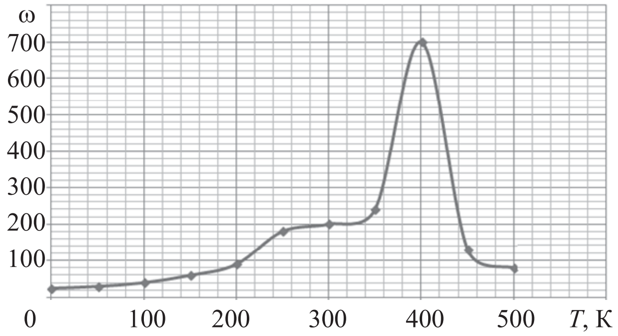


Fig. 2. The dependence of the dielectric constant ε of barium titanate on temperature [7]

The disadvantage of limiting the use of this effect in the sensory, is a strong hysteresis appears when polarization [9],[ 10]. On this basis, the basis of operation of the proposed device on the principle of maintaining a dynamic balance between the spontaneous polarization of the sensor caused by heat absorbed by the sensor, and the polarization of the electric field generated by an electronic circuit. At the same time the charge sensor is carried out by the absorbed heat (spontaneous polarization) and the discharge occurs by applying an electrical circuit, which takes into account also the sign of the charge [11], [12]. To confirm the theoretical possibilities of the method, a mathematical model of the sensor offered. It sensor represented as a flat plate of ferroelectric sprayed with metal electrodes on the edge (Fig.3) forming a capacitor whose capacitance depends on the amount of heat absorbed and the temperature.

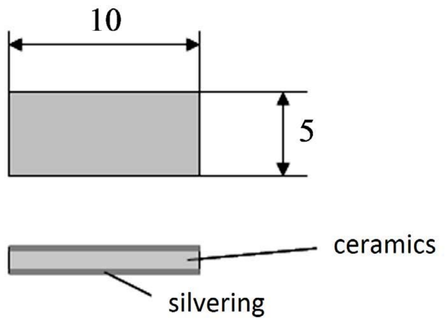


Fig. 3. The sensor element

The model is based on the principle of maintaining a dynamic balance between the spontaneous polarization of the sensor caused by heat absorbed by the sensor, and the polarization of the electric field generated by an electronic circuit. Thus for the direction of the electric field is selected direction opposite to the spontaneous polarization.

The special properties of ferroelectrics due to the fact that in a limited range of tempera-tour they consist of many microscopic regions - domains that are spontaneously polarized to saturation.

Consider a very simplistic as there are domains for example barium titanate. At high temperatures (T> 398K) barium titanate has a cubic lattice, shown in Fig. 4a.

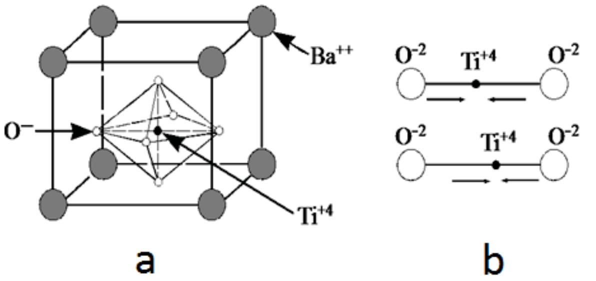


Fig. 4 - The crystal lattice of barium titanate ions are in the vertices of a cube, the oxygen ions - in the center of the cube, and the titanium ion - in the center of the cube

The unit cell of the distance between the centers of the oxygen and titanium ions is greater than the sum of their radii. Therefore, the titanium ions under the influence of the thermal motion can be moved between six oxygen ions that surround it symmetrically. Thanks to this symmetrical center position titanium ion coincides with the center of symmetry and the electric moment of each unit cell is equal to zero.

Upon cooling to the thermal motion of the crystal is less intense, and this leads to the fact that the titanium ion is shifted to any one of six oxygen ions. oxygen ion system - titanium ion - oxygen ion (Fig. 4b) becomes nonsymmetric and acquires electric moment.

The unit cells, which are in some small volume, the shift occurs in one direction, the moments of all the cells are formed, and as a result there spontaneously electrified area - domain. The crystal is divided into domains so that each domain orientation adjacent electric moments differ, and the crystal as a whole does not have a dipole moment.

When making a ferroelectric in an external field the orientation of the dipole moment in the direction of the field $\vec{E}$, as well as the displacement of the domain boundaries. Domains with a better orientation regarding $\vec{E}$ (the angle between the $\vec{p}$ and $\vec{E}$ greater 90°).

With further increase $\vec{E}$ domain rotation occurs in the direction of the field as long as the polarization reaches saturation. When reducing the strength of the external field is based on the pro-domains gradual disorientation. However, even in the absence of an external field of the dipole moments remain focused. This explains the existence of the residual polarization of $P_r$.

All ferroelectrics, which are in an alternating electric field, have dielectric losses. The dielectric loss is called the power of the alternating electric field, which is converted into heat. Dielectric losses are caused by the process of repolarization (reorientation of its domains). To quantify the characteristics of these losses dielectric loss tangens is used:

$$tg\delta = \frac{\omega_1}{\omega_0}\ , \qquad (1)$$

where - the loss of energy of the alternating electric field hysteresis per unit volume of ferro-electrics for one period; - Maximum energy density of the electric field in the ferroelectric crystal.

Since the bulk density of the electric field energy is

$$\omega = \frac{1}{2}\varepsilon\varepsilon_0 E^2 = \frac{1}{2}ED\ ,$$

then with increasing field strength in the volume energy density is changed to

$$d\omega = d\left(\frac{1}{2}\varepsilon\varepsilon_0 E^2\right) = Ed\left(\varepsilon\varepsilon_0 E\right) = EdD\ .$$

During one period of variation of the electric field energy losses are equal

$$\omega_1 = \oint EdD\ . \qquad (2)$$

Maximum energy density of the electric field in the crystal is

$$\omega_0 = \frac{1}{2}E_0 D_0\ , \qquad (3)$$

where $E_0$ - $D_0$ and the amplitude of the induction electric field.

Taking into account (2) and (3) the expression (1) takes the form:

$$tg\delta = \frac{1}{2}\frac{\oint EdD}{E_0 D_0}\ .$$

The area of the hysteresis loop is proportional to the amount of heat generated per unit volume per cycle.

At a temperature above the Curie point of the ferroelectric domains are destroyed and loses its special electrical properties [3].

The heat equation for the one-dimensional case has the form

$$\lambda\frac{\partial^2 t}{\partial x^2}+P_V=\rho c_T\frac{\partial t}{\partial\tau},$$

where $P_V$ – capacity of domestic sources of energy; $c_T$ – heat capacity; ρ – density, τ – time. If the temperature field is unifrom, so

$$P_V=\rho c_T\frac{\partial t}{\partial\tau}.$$

Then the total heat generation capacity is

$$P=\rho c_T V\frac{\partial t}{\partial\tau},$$

where $V$ – volume of plate. The last expression can be rewritten:

$$P=C_T\frac{\partial t}{\partial\tau},$$

where $C_T=\rho c_T V$ – full heat capacity.

Fig. 5 and 6 shows the result of simulation of the capacitor charge-discharge process of the dielectric material for two different cases:

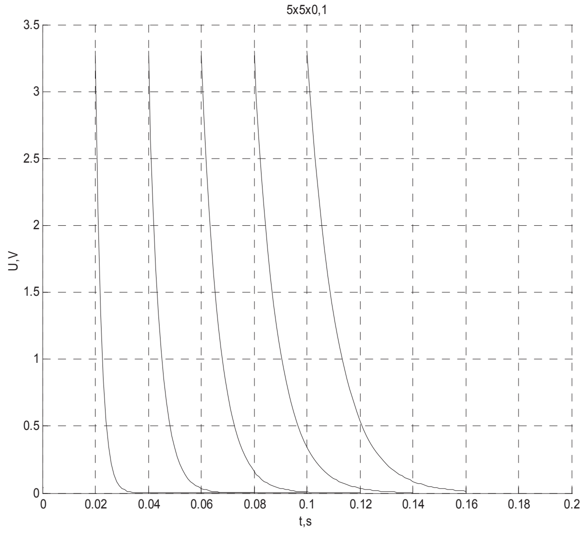


Fig. 5 – The result of the simulation of the capacitor charge-discharge process of the dielectric material in the area of 25mm2 capacitor, with the thickness of 0.1mm, voltage, where temperature changes from 40 ° C to 80 ° C

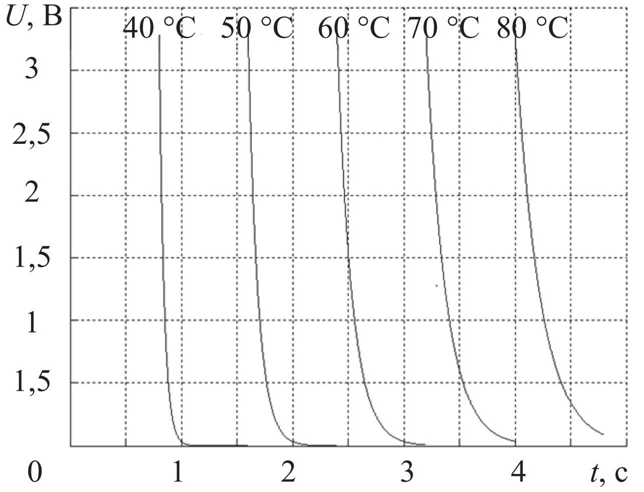


Fig. 6. The result of the simulation of the capacitor charge-discharge process of the dielectric material in the area of 100 mm2 and a thickness of 0.1 mm, a voltage of U = 3,3 V, the temperature varies from 40 ° C to 80 ° C

The energy of the charged capacitor is $E=\frac{C_e U^2}{2}$, where $C_e$ – capacity of capacitor; $U$ – the voltage on the capacitor plates. Then we can write:

$$C_T\frac{\partial t}{\partial\tau}=C_e\frac{U^2}{2}\frac{1}{\tau}.$$

Fig. 3 shows the result of simulation of the capacitor charge-discharge process of the dielectric material BaTiO3.

## III. RESULTS

Manufactured and tested sensitive sensor elements from ceramic barium titanate with characteristic dimensions of 10 × 5 × 1 mm (Fig. 7).

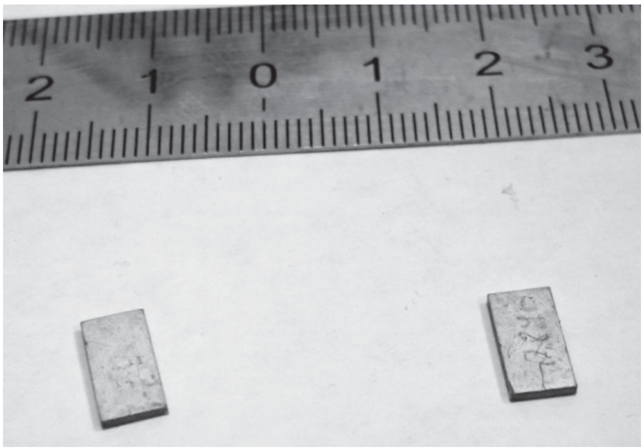
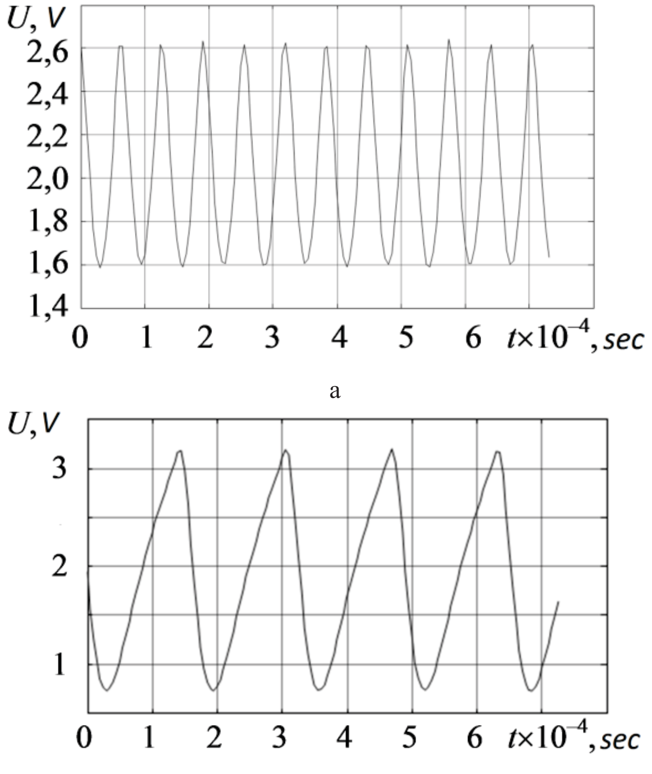


Fig. 7. Sensitive element of heat flux sensor



a

b

Fig. 8. The voltage on the sensor during the testimony of "flow" control panel: 100 W / m2 (a); 280 W / m2 (b)

When exposed to the heat flux, depending on its direction, is generated a positive or negative charge. We applied an electric circuit with single supply. When using it to measure positive and negative charges directly impossible.. As a result of the proposed scheme, which allows you to avoid the negative charge on the sensor, due to its constant trickle charging. Thus, the heat flux is converted into a change in the charging rate: by increasing the charging rate the heat flux increases with decreasing - falls.

When testing the sensor is mounted on the radiator section [13], [14]. On the same section, in close proximity to him, was placed the standard of the heat flux sensor with a known characteristic of the type of ITP MG4.03 / x (y) «stream», designed to measure and record the heat flux density passing through the monolayer and multilayer building envelope and structures.

Fig. 7 shows the process of charging and discharging the sensing element of the sensor when the heat flux of 100 W / m2 (Fig.7a) and 280 W / m2 (Fig. 7b). It is clearly seen that the sensor element is charged faster with increasing heat flux. It creates a module that allows to carry out corresponding measurements.

The method considered without drawbacks sensor type "Auxiliary wall", can be made sufficiently thin (0.5 mm). Its sensitivity while reducing wafer thickness will increase and distortion of the initial thermal state of the object are negligible. As a result, it is possible to measure the rapidly changing heat flow. An important advantage of the sensor is that it can be produced in virtually any enterprise electronics industry, any size of party. Process sensor manufacturing process is relatively simple and offers good reproducibility of the properties [15], [16].

To assess the quality and accuracy of the readings of the heat flux sensor developed its readings were compared in the experiment the amount of heat metering devices VKT-7 and STK-15 "Mars".

Sensor unit STK-15 installed at the inlet and outlet radiator, VKT-7 instrument calculates the total loss of heat to the pipes and the radiator (see Fig. 9). According to the testimony of the heat flux sensor calculated the amount of heat given radiator. Comparative results are presented in Fig. 10. The graph shows that the heat flux sensor readings do not differ from the heat metering unit STK-15. Both sensors were calculated heat loss only on the radiator. Indications VKT-7 is much higher, as the instrument calculates the loss in the whole circuit. The peaks on the testimony of STK-15 due to its low sensitivity and accuracy.

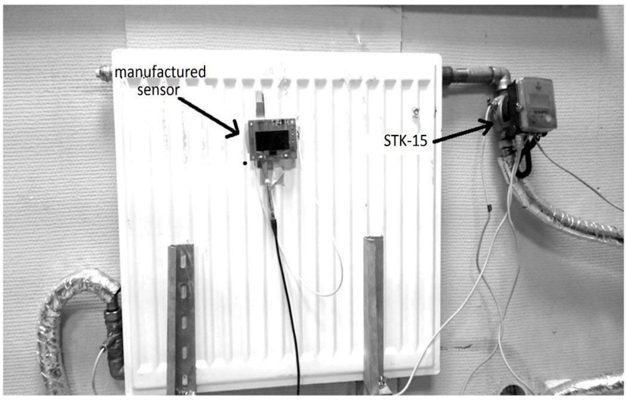


Fig. 9. Radiator with STK-15 sensor mounted on it and developed a sensor

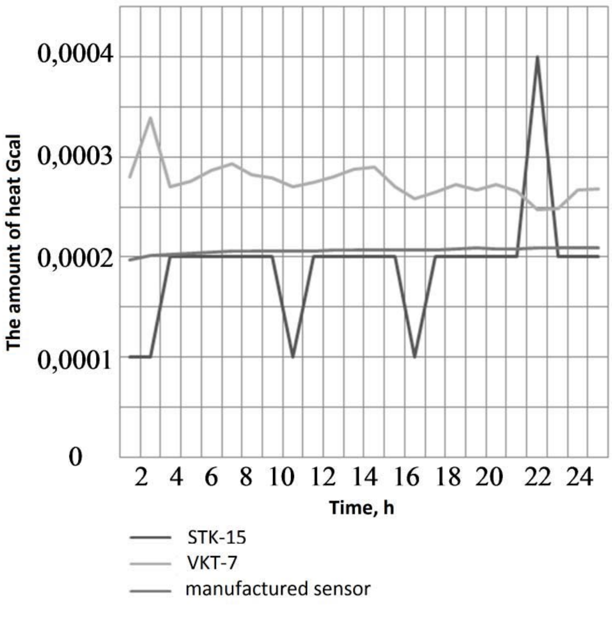


Fig. 10. the testimony attorneys counters Heat and the developed sensor

## IV. CONCLUSION

In this paper we propose a new principle of measuring heat flow, based on maintaining a dynamic equilibrium between the spontaneous polarization of the sensor caused by heat absorbed by the sensor, and the polarization of the electric field generated by an electronic circuit. This principle is developed and tested an innovative sensor.

Tests Sensor has shown that the polarization properties of the ferroelectric can be used to measure the heat flow. Testing prototypes showed satisfactory results when compared with the work of attorneys sensors. Characteristics of sensors have a high repeatability as ceramic plates from the same lot have almost identical characteristics.

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