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THERMOELECTRIC HEAT FLUX SENSORS

Results of theoretical and experimental investigations of heat flux sensors based on the technology of thermoelectric micromodules are reported. Dependences of the main parameters of such sensors on the properties of thermoelectric materials and parameters of module design were investigated. On the basis of theoretical investigations a new method of self-calibrations of thermoelectric heat flux sensors using measurement of the module Figure-of-Merit Z and resistance ACR was developed. The technology of thermoelectric micromodules of the company RMT Ltd. allows designing miniature heat flux sensors with a wide range of performance parameters on demands of variety of applications. Advantages of thermoelectric heat flux sensors – high sensitivity, fast response, miniature design, variable performance parameters, scalability, and some others were confirmed.

Keywords: thermoelectric, module, heat, flux, sensor.

Introduction

Heat fluxes accompany most of physical-chemical transformations that occur in nature, industrial processes, as a result of human activity. Measurement of heat fluxes and temperature allows us to control these processes. Heat fluxes are measured by heat flux sensors [1]. Measurement of heat fluxes is required in various areas: scientific investigations, agriculture, climatology, building construction, solar energy, industrial applications, housing and communal services, safety and security, etc. Heat flux and temperature sensors occupy a significant niche in the market of modern sensors.

Units of heat flux and characteristics of sensors

The heat flux *Pe* is measured in Watts per unit of area *S* perpendicular to its direction – W/m^2. Or it is measured in units of total heat flux *P* – Watts. Heat flux sensors are also characterized by sensitivity to the heat flux, which is also measured in two types of corresponding units.

The sensitivity *Se* to heat flux density is the ratio of the electric signal *E* to the heat flux density *Pe*. The units are μV/(W/m^2).

$$S_e = \frac{E}{P_e}. \tag{1}$$

The integral sensitivity *Sa* is the ratio of the electric signal to the total heat flux *P* incident on the sensor. The units are V/W.

$$S_a = \frac{E}{S \times P_e} = \frac{S_e}{S}. \tag{2}$$

The concept of the integral sensitivity makes heat flux sensors similar to photodetectors. It is true, because the radiation is also an energy flux. Heat flux sensors are used to measure thermal radiation.

State-of-the-Art heat flux sensors

The majority of the heat flux sensors are based on the method of "additional wall" [1]. The "additional wall" with a known thermal conductivity K is placed in the way of a heat flux P that is to be measured. The temperature gradient ΔT between the wall sides is proportional to the amount of the heat flux. The thermal resistance R_T of the wall is the reciprocal value of the thermal conductance K:

$$\Delta T = R_T \times P . \quad (3)$$

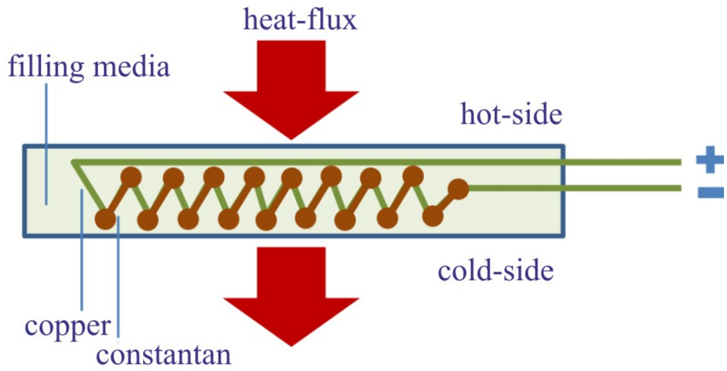


Fig.1 Schematic view of heat flux sensor of differential thermocouples.

Most of state-of-the-art heat flux sensors are made on the basis of differential thermocouples (Fig. 1) [2]. They involve the Seebeck effect in metals. Absolute values of electromotive force (the Seebeck coefficient) of metals are low - tens of μV/°C maximum. Therefore, series connection of many thermocouples is used to increase the sensitivity (Fig. 1) [3, 4]. The density of the thermocouples can reach up to 1000 – 2000 thermocouples per square centimeter. This assures multiple (of the number N of thermocouples) thermopower increase.

$$E = N \times \alpha \times \Delta T , \quad (4)$$

where α – the Seebeck coefficient of each thermocouple.

Thermoelectric heat flux sensors

In recent years, the interest in the use of thermoelectric modules as heat flux sensors has grown [5, 6]. Thermoelectric modules are widely used for cooling (the Peltier effect) or generation of energy (the Peltier and Seebeck effects). In heat flux sensors the thermoelectric effect – the Seebeck effect is also used, which is the physical basis for the differential thermocouple sensors, too. The construction of thermoelectric modules is similar to that of an array of thermocouples. Only here a "couple" is a pair of semiconductor thermoelements with different conductivity (*n*- and *p*-types), and in a thermocouple it is a junction of dissimilar metals. The Seebeck effect in semiconductors is many times higher than in metals. For example, in a copper-constantan thermocouple the Seebeck coefficient of a couple is about 38 μV/°C. In a thermoelectric module for one *p*-*n* pair it is more than 400 μV/°C.

While thermoelectric modules have long been used as generators and coolers, this advantage for the sensors applications has not been realized for a long time. The key reason is a low degree of integration of thermoelements. For a long time it was at the level of 100 – 150 pellets per 1 cm^2. With such a low elements density, thermoelectric modules used as heat flux sensors are inferior to arrays of differential thermocouples [4]. However, the modern trend to miniaturization of thermoelectric modules (Fig. 2), mainly because of the needs of optoelectronics, where thermoelectric cooling is widely used, has led to significant progress in the construction of thermoelectric micromodules – extremely miniature design and dense packing.

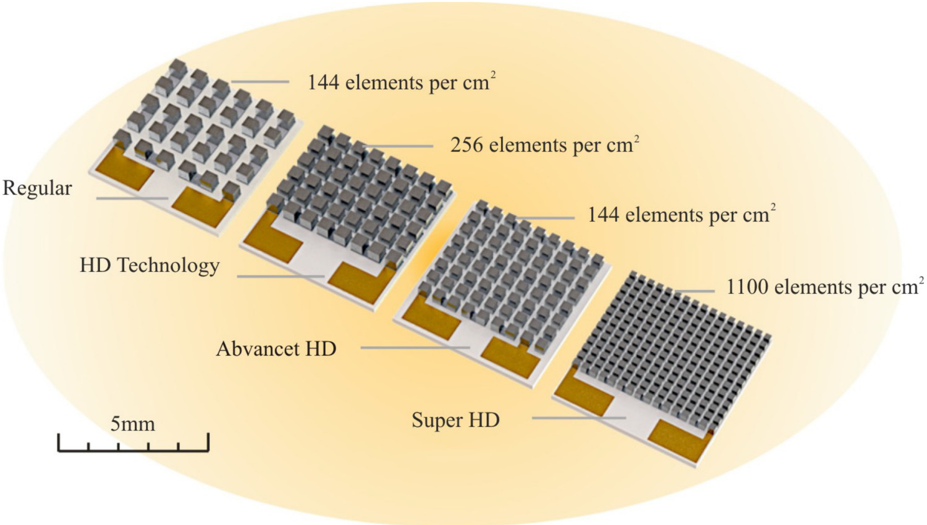


Fig. 2. Advances in miniaturization of thermoelectric modules - example of RMT micromodules technology development.

Advanced thermoelectric micromodules are comparable with sensors based on differential thermocouples in dimensions and dense integration, which enables us to use them as heat flux sensors. Miniature and high-density packaged modules are manufactured by two technologies: thin film (new) and bulk (conventional) technology (Fig. 3).

Each technology has its advantages and limits of use, but both provide the ability to produce miniature modules undreamed of quite recently (down to the level of 1 mm^2 and less) and high density of their packing.

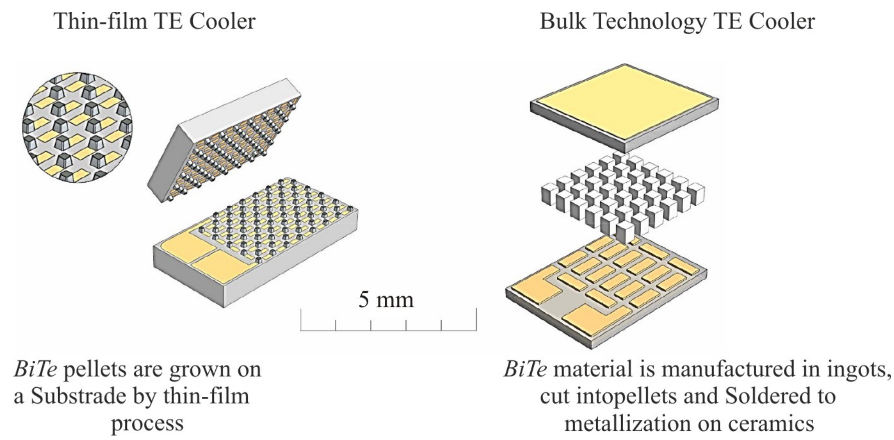


Fig. 3 Comparison of designs of thermoelectric modules: thin-film and bulk.

Parameters of thermoelectric heat flux sensors

Integral sensitivity *Sa*

The electrical signal E of the thermoelectric heat flux sensor is the following.

$$E = 2N \times a \times \Delta T , \tag{5}$$

where α – the average Seebeck coefficient for a *p-n* pair; $2N$ – the number of thermoelements.

Where at given ΔT (3) the absolute sensitivity sensor *Sa*

$$E = 2N \times a \times \Delta T. \tag{5}$$

In the ideal case (heat flows only through the thermoelements):

$$R_T = \frac{1}{K_T} = \frac{1}{2N \times k \times \frac{s}{h}}, \tag{7}$$

where K_T – thermal conductance of the sensor; k – the average thermal conductivity for thermoelement; $\frac{s}{h}$ – ratio of cross-section (s) of the element to its height (h), which is the form factor (f) of a thermoelement.

Thus, the sensor sensitivity

$$S_a = \frac{1}{f} \times \frac{\alpha}{k}. \tag{8}$$

The thermoelectric heat flux sensor sensitivity is determined by the ratio of the Seebeck coefficient α to thermal conductivity k and is inversely proportional to the form factor f of the thermoelement (pellet). The important consequence of expression (8): the sensitivity does not depend on the number of the thermoelements in the sensor. The inverse proportionality to the thermoelement's form factor works instead. The sensitivity can be increased by smaller cross-sections of thermoelements at a relatively large height.

Sensitivity *Se*

The sensitivity *Se* to the density of heat flux is derived from the integral sensitivity *Sa*, if you multiply it by the area of the sensitive surface of the sensor *S* (2).

Thermal Resistance R_T

The value of the thermal resistance of the thermoelectric heat flux sensor is crucial. On the one hand it is the thermal resistance that gives a temperature difference (3) which causes the signal. High thermal resistance means high sensitivity of the sensor. On the other hand the effect of the presence of the measuring sensor (the "additional wall"), i.e. its thermal resistance, should be preferably minimized.

Time constant τ

The expression of the time constant of thermoelectric microcoolers is applicable for such heat flux sensors, too:

$$\tau = \frac{C_c}{f \times k \times 2N}, \tag{9}$$

where *Cc* – heat capacity of side of thermoelectric module or the sensor cover.

Calibration method of thermoelectric heat flux sensors

The sensor calibration is required to ensure the high accuracy for applications. The calibration allows getting the coefficient of the output signal proportionality to the heat flux. For the calibration two methods are known.

One method is to use an external heat flux reference source [7, 8]. This calibration is carried out with the use of special equipment and in the laboratory. It is available only in periodical maintenance of the sensor. So it is time-consuming, expensive and limited in application.

Another method is to embed a reference heat source into the sensor [9, 10]. For example, it is a vacuum deposition of a resistive heater to one of the sensor side [10]. When electric power is applied to the embedded heater, it produces the heat of a known value. It results in a signal of the sensor. With this calibration method the sensor is called self-calibrating. It is possible to calibrate it at any time without external hardware. The downside is that the reference heat source should be integrated in the sensor. This complicates the design and production costs.

Thermoelectric modules have long been widely used for cooling and power generation. In these applications a number of measurement parameters of the modules are used to determine their quality and performance properties. These parameters are: thermoelectric Figure-of-Merit Z, internal electrical resistance ACR and, less commonly, time constant τ. The use of these parameters to specify the basic properties of thermoelectric heat flux sensors is also attractive.

The formula for the sensitivity (6) shows its dependence on the ratio $a \times R_T$. It is possible to express it by the parameters Z and ACR of a thermoelectric module.

$$Z = \frac{(2N \times a)^2 \times R_T}{ACR}. \tag{10}$$

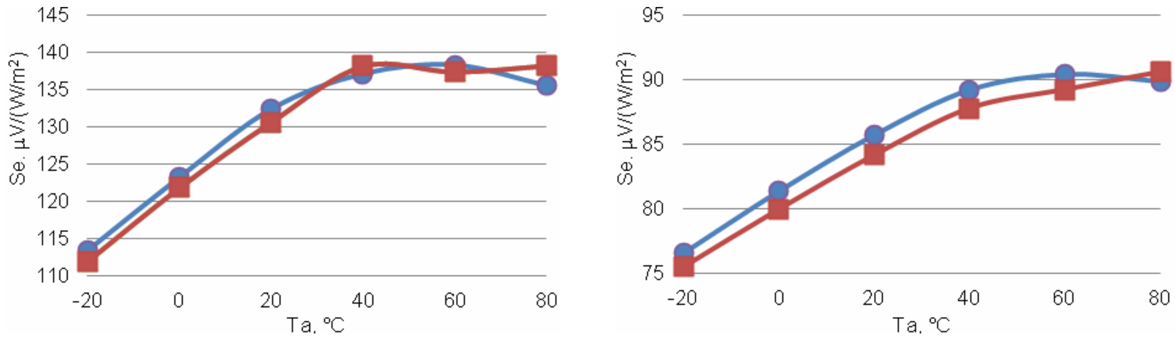
Thus

$$\alpha \times R_T = \frac{1}{(2N)^2 \times a} Z \times ACR. \tag{11}$$

Then equation (6) is finally converted to the following

$$S_a = \frac{1}{a \times 2N} Z \times ACR. \tag{12}$$

Formula (12) is a basis of the new method of calibrating of the thermoelectric heat flux sensors. The design of a thermoelectric module (the number of pellets is *2N*) is known in advance. The Seebeck coefficient of thermoelectric material α used for manufacturing of sensors can be controlled. At a given area of the sensitive surface S, the number of the thermoelements in the sensors *2N* and known Seebeck coefficient of the thermoelectric material α, it is easy to determine the sensitivity (*Sa* and *Se*) by equations (12) and (2) respectively, by measuring the thermoelectric Figure-of-Merit Z and the resistance ACR of the sensor.



Sample 1 *Sample 2*

Fig. 4. Comparison of calibrations by the method with external heat flux reference source (red) and the proposed method (blue) in a range of ambient temperatures Ta.

The calibration by the new method is no more than 2% different from the results of the calibration with a reference source (Fig. 4). This is a good result for the practical use of the new method. It does not require applying reference thermal sources, does not need maintenance of sensors for the calibration procedure, and can be performed with any periodicity in a field.

Optimal design of RMT heat flux sensors

As seen from expressions (8), (2), the key parameters of thermoelectric heat flux sensors depend on the design features:

- properties of thermoelectric material – α, k.
- design parameters of thermoelectric module and its thermoelements – f.
- sensitive surface area S.

RMT technology allows producing miniature thermoelectric modules in wide ranges of dimensions, degree of miniaturization, thermoelements form-factors, etc. (Fig. 2). This makes it possible to develop both individual sensors and their series optimized for different applications. This practice is applied by the company in the design and manufacture of micromodules for cooling and generation. The approach is applicable to the heat flux sensors.

Properties of thermoelectric material

The properties of thermoelectric material are specified by its manufacturing technology. These parameters can hardly be varied significantly for the optimization of sensors. The only important thing is to select material with a maximum Seebeck coefficient α, typically at the level of the average values of 200 – 240 μV/K.

Thermoelectric module design

The design parameters of thermoelectric module can be controlled. RMT technologies allow producing modules of pellets in wide ranges of cross-sections and heights, packing densities and elements numbers (Fig. 2).

Form factor of thermoelements

The dependence of the sensitivity *Sa* of thermoelectric heat flux sensors on form factor (8) is shown in Fig. 5. The Table 1 shows the values of the form-factor of pellets of RMT thermoelectric modules. Respectively, in Fig. 5 the available range of sensitivities of heat flux sensors based on RMT modules is marked by color.

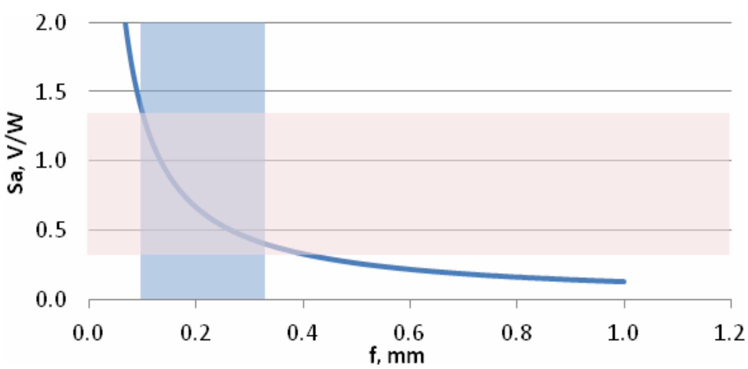


Fig. 5. Dependence of thermoelectric heat flux sensor sensitivity on the pellet form factor.

Table

Value of form-factors of the thermoelectric pellets of RMT

Height *h*, mm	*f*, mm (at given cross-section *axb*)		
	0.2 × 0.2 mm^2	0.3 × 0.3 mm^2	0.4 × 0.4 mm^2
0.3	0.133	-	-
0.4	0.100	0.225	-
0.5	0.080	0.180	0.320
0.8	-	0.113	0.200
1.0	-	-	0.160
1.2	-	-	0.133
1.5	-	-	0.107

Height of thermoelements

From expression (5) and determination of form-factor it follows that at a given value of thermoelement cross-section *axb* the sensor sensitivity will increase with the growth of the thermoelement height. However, with increasing the thermoelement height, the sensor time constant will also grow in conformity with (9). Therefore, obtaining the highly sensitive sensor together with high-speed performance is the optimization task for particular applications (Fig. 6).

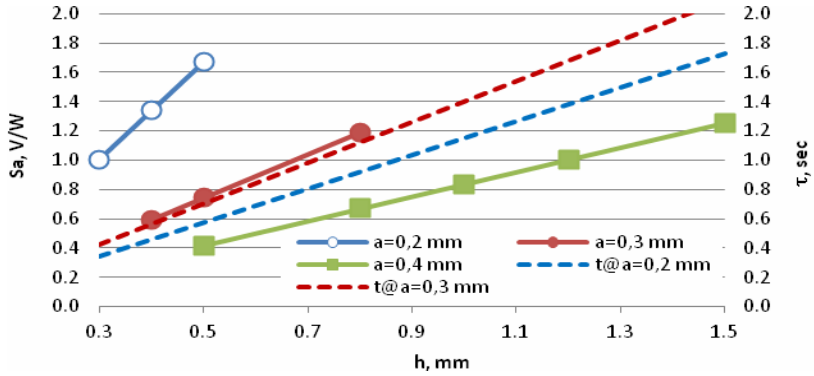


Fig. 6. Estimated dependences of the sensitivity Sa and the time constant τ of the sensor on thermoelements height h for their different widths: 0.2; 0.3 and 0.4 mm.

The most fast and sensitive sensors have thermocouples with a minimum cross-section 0.2 mm. A high sensitivity is attainable for large elements cross-sections, but this reduces performance due to larger thermoelement height of such sensors.

Sensor dimensions

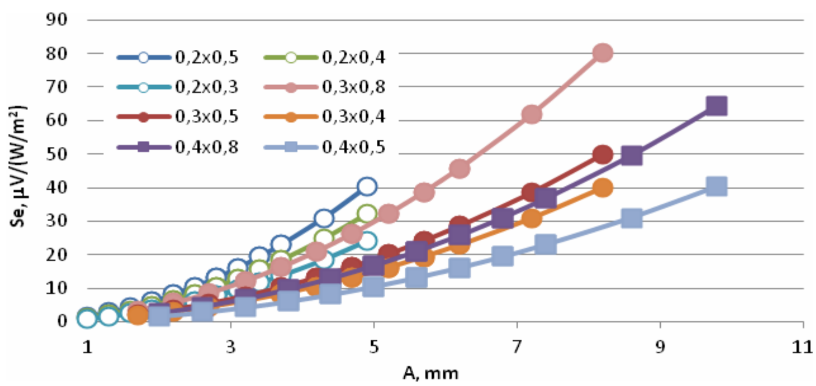


Fig. 7. Dependence of sensitivity of thermoelectric sensors Se on their linear size A.

The sensitivity to heat flux density *Se* depends on the heat absorption side area of the sensor (2). The thermoelectric module size is determined by the number of elements, their cross-section and density of packing.

Experimental family of heat flux sensors

Based on the above analysis the experimental family of heat flux sensors consisting of three subseries was developed in RMT.

HTX heat flux and temperature sensors (HT – Heat flux & Temperature). The sensors contain thermoelectric heat flux sensor and embedded Pt1000 thermistor. They have a round shape, external aluminum sides with black finish. The sensors are potted by a silicone compound.

HFX heat flux sensors without temperature (HF – Heat Flux). Their features are a square shape, external sides AlN ceramics with black paint finish. The sensors are potted by a silicone compound.

HRX sensors IR radiative heat flux (HR – Heat flux Radiation). These are miniature thermoelectric heat flux sensors. They are made as SMD style components suitable for flip-chip mounting. They have a square shape, and external sides of AlN ceramics. The radiation absorption surface has a black finish with high emissivity.

Comparison of heat flux sensors

In Fig. 8 the sensitivity of the heat flux sensors of RMT experimental family is compared with the sensitivity of heat flux sensors of well-known manufacturers at the market.

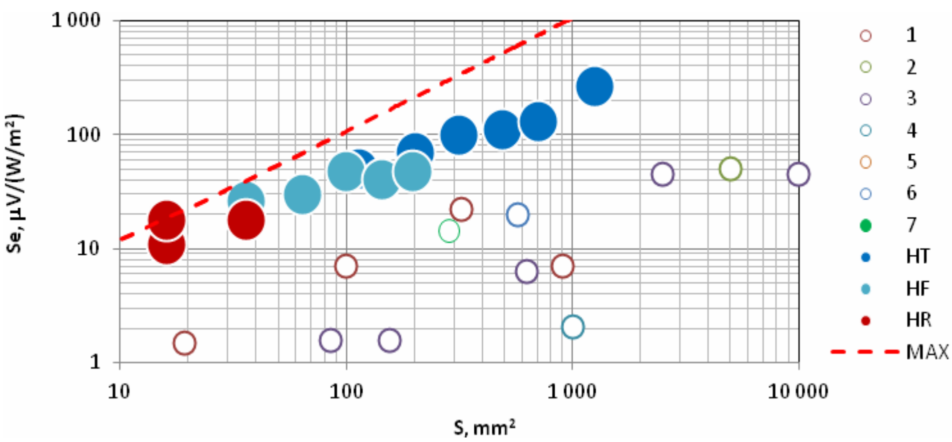


Fig. 8 Sensitivity Se of heat flux sensors of different producers (1 - 7) and experimental series of RMT (HT, HF, HR), depending on the sensor area. Dotted line – maximum available sensitivity of RMT technology.

The sensors of the developed experimental series have significant advantages over heat flux sensors that are present at the market now:

1) Sensitivity is significantly higher than that for the sensors based on differential thermocouples.
2) Miniature design due to a high packing density of elements in thermoelectric micromodules.
3) Variable thermal resistance due to the flexibility in the design of the micromodules.
4) High-speed performance.

The conclusions

1. Thermoelectric micromodules have three major areas of the market and applications perspectives: cooling, generation and heat flux sensors.
2. The Seebeck effect in semiconductors is considerably higher than that in metals. This makes the use of thermoelectric micromodules heat flux sensors promising, able to compete with the differential thermocouple sensors.
3. The sensitivity does not depend on the number of thermoelements. It is determined by the ratio of the Seebeck coefficient and thermal conductivity and is inversely proportional to the form factor of the thermoelement.
4. The highly accurate self-calibration method of thermoelectric heat flux sensors by Z and ACR does not require the use of reference thermal sources or maintenance of sensors for the calibration procedure and can be performed with any periodicity.

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