HEAT-FLUX TRANSDUCERS BASED ON ARTIFICIALLY ANISOTROPIC THERMOELECTRIC MATERIALS

O. A. Gerashchenko, E. K. Iordanishvili,
T. S. Gudkin, E. É. Fiskind,
and Zh. L. Pogurskaya

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The use of artificially anisotropic thermoelectric material as a heat-flux transducer, the method of selecting its components, and optimization of the parameters are discussed.

Anisotropic thermoelectric transducers using the transverse Seebeck effect are finding wide application in heat measurement. Their operation is based on the induction of an electric field component E_x in material with an anisotropic thermoelectric coefficient when heat flows through it in a direction that does not coincide with the main axes. The thermal emf generated by an anisotropic thermoelement is given by

$$\varepsilon = q \frac{\alpha_{xy}}{\varkappa_{yy}} l. \quad (1)$$

Relation (1) shows the highly important advantage of a transverse thermoelectric transducer in comparison with a longitudinal one. Since the magnitude of the signal depends on the heat flux density, the parameters of the material, and the length of the thermoelement, its response can be made faster without any loss of volt—watt responsivity by a reduction of height.

Another obvious advantage of the transverse transducer is the simplicity of its construction, requiring only one branch.

The number of thermoelectrically anisotropic materials is limited, however, and their thermoelectric quality $Z_{xy} = \alpha_{xy}^2/\rho_{xx}\varkappa_{yy}$ is low.

Z_{xy} is lower by a factor of 1.5-2 than the corresponding parameter of a thermoelement of the longitudinal type. This is responsible for the low detectivity [2], which is a very important characteristic, along with the volt—watt responsivity, of a heat-flux transducer.

The possible fabrication of heterophase thermoelectric anisotropic materials has recently been widely discussed. Geiling was the first to suggest that a heterophase system with macroscopic anisotropy of the thermal emf could be used as a heat transducer. In his paper [3] he reported that a flow of heat in a system of alternate layers of two thermoelectric materials with different thermoelectric coefficients, thermal conductivity, and electrical conductivity, set at an angle to the temperature gradient (Fig. 1), gives rise to a thermal emf across this gradient.

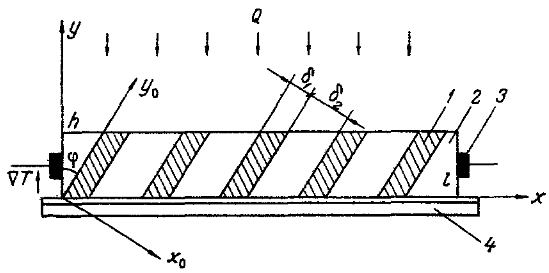

Fig. 1. Heat flux transducer based on AATEM: 1) layer of semiconducting material; 2) metal layer; 3) electrical contacts of transducer; 4) insulated heat-removing substrate.

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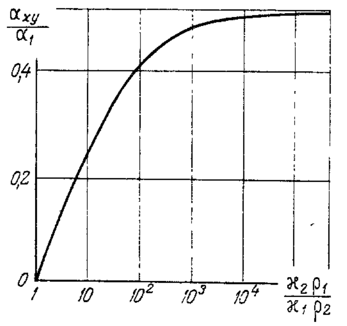

Fig. 2

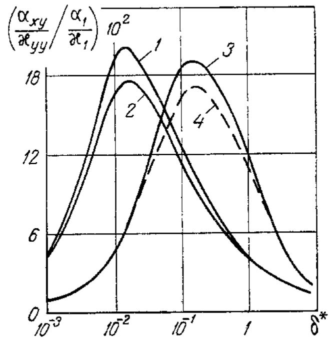

Fig. 3

Fig. 2. Dependence of α_{xy} of AATEM on contrast parameter $\varkappa_2\rho_1/\varkappa_1\rho_2$ of layer materials for $\varphi = 45°$; $\alpha_2 = 0$; $\varkappa_2\rho_1/\varkappa_1\rho_2 = 1$ (μV/K).

Fig. 3. Dependence of volt — watt responsivity of heat-flux transducer based on AATEM on ratio of layer thicknesses for $\alpha_2 = 0$; $\varkappa_2\rho_1/\varkappa_1\rho_1 = 1$; 1) ZT = 0; $\varkappa_2\rho_1/\varkappa_1\rho_2 = 10^4$; 2) ZT = 1; $\varkappa_2\rho_1/\varkappa_1\rho_2 = 10^4$; 3) ZT = 0; $\varkappa_2\rho_1/\varkappa_1\rho_2 = 10^2$; 4) ZT = 1; $\varkappa_2\rho_1/\varkappa_1\rho_2 = 10^2$.

The primary theory of the oblique-layered heat transducer was given in [1], where it was shown that the physical cause of the transverse thermal emf is the difference in thermoelectric coefficients of the system as a whole along and across the layers (it is obvious that the thermoelectric coefficient along the layers is determined by the material with the low resistivity, while that across the layers is determined by the material with low thermal conductivity).

The thermoelectric coefficients of layered materials were subjected to a thorough analysis in [4], where for the description of the averaged characteristics and the signal developing along the specimen, whose length greatly exceeded the thickness of the layer, the heterophase system was regarded as a homogeneous anisotropic medium, whose kinetic coefficients were expressed as second-rank tensors. The analysis in [4] showed that by a suitable choice of materials for the layers and appropriate geometry, efficient transverse thermoelectric transducers based on artificially anisotropic thermoelectric material (AATEM) could be constructed.

Below, using the method developed in [4], we consider the method of selecting the components and optimization of the AATEM parameters for heat-flux transducers.

In the case of a transverse thermoelectric transducer the volt — watt responsivity is expressed in terms of the components of the thermal emf and thermal conductivity tensors:

$$K = \alpha_{xy}/\varkappa_{yy}, \tag{2}$$

where

$$\alpha_{xy} = (\alpha_{x_0} - \alpha_{y_0}) \sin\varphi \cos\varphi; \tag{3}$$

$$\varkappa_{yy} = \varkappa_{x_0} \sin^2\varphi + \varkappa_{y_0} \cos^2\varphi. \tag{4}$$

As was shown in [4], for the kinetic coefficients on the main axes of the AATEM we have the expressions

TABLE 1. Calculated Parameters of AATEM

Components of AATEM	$Bi_{0,5}Sb_{1,5}Te_3$	$Bi_{0,5}Sb_{1,5}Te_3$	$Bi_{0,5}Sb_{1,5}Te_3$
	Bi (type C)	Bi (type A)	Cu
φ_{opt}, deg	56	55	59
δ^*_{opt}	0,26	0,51	0,005
$Z\cdot10^3$ (for φ_{opt}), K^{-1}	0,41	0,83	0,43
$\frac{\alpha_{xy}}{\varkappa_{yy}}$, V/W·cm	0,0028	0,0036	0,0029

$$\alpha_{x_0} = \frac{\alpha_1/\varkappa_1 + \delta^*\alpha_2\varkappa_2}{1/\varkappa_1 + \delta^*/\varkappa_2}; \quad (5)$$

$$\alpha_{y_0} = \frac{\alpha_1\rho_2 + \delta^*\alpha_2\rho_1}{\delta^*\rho_1 + \rho_2}; \quad (6)$$

$$\varkappa_{x_0} = \frac{\delta^* + 1}{1/\varkappa_1 + \delta^*/\varkappa_2}; \quad (7)$$

$$\varkappa_{y_0} = \frac{\varkappa_1 + \delta^*\varkappa_2}{1 + \delta^*}(1 + Z_{1-2}T), \quad (8)$$

where subscripts 1 and 2 correspond to the order of the materials in the alternating layers.

The nondiagonal component α_{xy} of the thermal emf tensor for a heterophase layered medium depends greatly on the degree of contrast of the materials of the constituent layers with regard to electrical and thermal conductivity, given by the ratio $\varkappa_2\rho_1/\varkappa_1\rho_2$. As was shown in [4], the anisotropy of the thermoelectric coefficient increases with increase in this ratio, reaching the value $(\alpha_1 - \alpha_2)$ at the limit. The theoretical dependence of α_{xy} on $\varkappa_2\rho_1/\varkappa_1\rho_2$ is illustrated in Fig. 2, which shows that α_{xy} almost reaches its limiting value at the fairly easily attainable ratio $\varkappa_2\rho_1/\varkappa_1\rho_2 \approx 10^4$.

The volt–watt responsivity for the selected pair of materials of the layered structure attains a maximum at the optimal geometric parameters φ_{opt} and δ^*_{opt}.

The optimal angle of inclination of the layers is determined from relations (3) and (4):

$$\varphi_{opt} = \operatorname{arctg}\sqrt{\varkappa_{y_0}/\varkappa_{x_0}}. \quad (9)$$

In this case the maximum value of the volt–watt responsivity is given by the expression

$$\left(\frac{\alpha_{xy}}{\varkappa_{yy}}\right)_{max} = \frac{\alpha_{x_0} - \alpha_{y_0}}{2\sqrt{\varkappa_{x_0}\varkappa_{y_0}}}. \quad (10)$$

Another criterion for optimization of the volt–watt responsivity is the layer thickness ratio δ^*. The quantitative nature of this relation is illustrated in Fig. 3. The value of δ^* that optimizes $\alpha_{xy}/\varkappa_{yy}$ can be found from the relations (3)-(8) between the AATEM tensor components and the parameters of the initial material. For simplicity we put $\alpha_2 = 0$, which is a sufficiently accurate approximation for a semiconductor–metal structure. Then

$$\delta^*_{opt} \approx \sqrt{\rho_2\varkappa_1/\rho_1\varkappa_2}. \quad (11)$$

This expression is the same as the optimization condition for a longitudinal thermoelement whose branches are layers 1 and 2. In this case the thermoelectric quality Z_{1-2} reaches a maximum and, according to the expression for $\varkappa_{y_0}$ (8), the contribution of circulating currents in the layers to the heat transfer becomes appreciable. The effect of circulating currents in AATEM is illustrated by curves 2 and 4 in Fig. 3.

It is apparent from (11) that optimization of $\alpha_{xy}/\varkappa_{yy}$ by the angle of inclination of the layers leads to a much greater share of the semiconducting component in the AATEM in comparison with the metal component.

The limiting value of the volt–watt responsivity of a heat-flux transducer based on AATEM with semiconducting and metal components with optimal layer thickness ratio can be obtained from expression (10) in conjunction with (3)-(8), (11) and with $\varkappa_2\rho_1/\varkappa_1\rho_2 \gg 1$:

$$\left(\frac{\alpha_{xy}}{\varkappa_{yy}}\right)_{lim} \approx \frac{1}{6}\frac{\alpha_1}{\varkappa_1}. \quad (12)$$

Thus, the limiting value of the volt–watt responsivity of a heat-flux transducer based on AATEM can attain 1/6 of the volt–watt responsivity of the initial semiconducting material. The obtained expressions show that an effective selection of materials as AATEM components is possible.

The high value of $\alpha/\varkappa$ of the material is usually also responsible for the high thermoelectric quality Z. Thus, by selecting an effective thermoelectric material as the semiconducting component of the AATEM, it is possible to obtain high values not only of responsivity of the heat-flux transducer, but also of its detectivity D*.

Table 1 gives the results of calculation of the AATEM parameters for some particular structures which are promising, in our opinion, from the viewpoint of construction of heat-flux transducers.

NOTATION

ε, thermal emf; q, specific heat flux; l, length of thermoelement; φ, angle of inclination of layers; $\delta^* = \delta_2/\delta_1$, layer thickness ratio; α_{xy}, $\varkappa_{yy}$, ρ_{xx}, nondiagonal components of thermoelectric coefficient, thermal conductivity, and electrical resistivity tensors; α_{x_0}, α_{y_0}, $\varkappa_{x_0}$, $\varkappa_{y_0}$, components of thermoelectric coefficient and thermal conductivity tensors; α_1, α_2, $\varkappa_1$, $\varkappa_2$, ρ_1, ρ_2, thermoelectric coefficient, thermal conductivity, and electrical resistivity of initial materials; Z_{xy}, Z_{1-2}, thermoelectric quality of anisotropic and longitudinal classical thermoelement; D*, detectivity; K, volt—watt responsivity; $\bar{T} = (T_h + T_c)/2$, mean temperature.

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EFFECT OF NONUNIFORMITY OF HEATING OF FILM RESISTANCE THERMOMETERS ON MEASUREMENTS OF PULSED HEAT-FLUX DENSITIES

B. A. Grigor'ev and A. A. Kon'kov

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A method of correction for the nonuniformity of heating of metal and semiconducting film resistance thermometers of the calorimetric type in the measurement of pulsed heat flux densities is proposed.

Measurements of heat flux densities by means of film resistance thermometers (FRT) of the calorimetric type are based on determination of the mean excess temperature of the heated electrically conducting film and its first derivative with respect to time. If the film has an initial temperature t_0, °C (T_0, °K) in the unheated state the mean excess temperature of the film, heated in the absence of heat loss, is

$$\bar{\vartheta}^*(\tau) = \bar{t}^*(\tau) - t_0 = W(\tau)/c\gamma v, \tag{1}$$

where W is the amount of heat, in J, received by the film; τ is the time, in sec, measured from the start of the heat pulse.

When the heat flux density q is the same over the entire heated surface of a film of area s,

$$W(\tau) = s\int_0^\tau q(\omega)\,d\omega, \tag{2}$$

where ω is the time. Substituting the value of W from (2) in (1) and taking the film thickness as l, we obtain

$$\bar{\vartheta}^*(\tau) = \frac{1}{c\gamma l}\int_0^\tau q(\omega)\,d\omega. \tag{3}$$

If we differentiate (3) with respect to τ, we easily obtain

$$q(\tau) = \frac{d\bar{\vartheta}^*(\tau)}{d\tau}\,c\gamma l. \tag{4}$$

The heat loss by the film by the time of measurement is due to conduction of heat into the electrically insulating substrate and wire, and also to heat transfer to the surroundings. Reduction of heat loss is achieved primarily by the use of films which are not appreciably heated through by the time of measurement. This inevitably leads to a temperature gradient over the film thickness. Heat loss to the wire and surroundings can lead to temperature gradients along and across the film. The primary measured quantity is the varying difference in voltage

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