STRAIN-MEASUREMENT METHODS AS A FORECASTING FACTOR FOR THE BEHAVIOR OF SEMICONDUCTOR THERMOELEMENTS UNDER EXTREME TEMPERATURES

E. K. Iordanishvili, Kh. O. Olimov,
and Yu. I. Ravich

UDC 621.362.1

Strain effects, arising owing to shear stresses in a thermoelement with low branches, are studied.

Formulation of the Problem. Semiconductor cooling and electricity-generating thermoelements are now being increasingly employed in low-power power production, radioelectronics, medicine, and other areas of technology and the national economy. At the same time, a number of units (thermoelectric generators, solid-state thermoelectric coolers) operate under conditions of significant temperature differentials, which, combined with the small heights of the thermoelements, creates very significant temperature gradients in their branches. Thus, in thermoelectric generators with thermoelements 5 mm high, operating under conditions of temperature drops of 250-300°K, the gradients will reach values of 500-600 K/cm, while in Peltier cooling thermoelements, providing a temperature drop between the cold and hot junctions of 50-60°K with a branch height of only 0.5 mm (real cryothermal electric probes used in medicine), the gradient, as can be easily calculated, will exceed 1000 K/cm.

Under such extreme temperature conditions the different thermal expansion of the sections of the branches adjacent to the different junctions will begin to have a significant effect on the operation of the thermoelements, and this must be taken into account already in the design and then also in operation of these thermoelements and thermopiles.

The existence of this complex of technical complications and the difficulty of experimental modeling under conditions of thermoelements with very small heights make it necessary to seek different methods for forecasting and modeling the behavior of thermoelements and thermopiles under conditions with temperature gradients of the order of 1000 K/cm. In this connection we propose a fundamentally different method for forecasting the behavior of semiconductor thermoelements under extreme temperatures, based on the mathematical and experimental analysis of the results of studies of the piezoelectric properties of thermoelectric materials.

Mathematical Model. We shall estimate the magnitude of the strain effect in the presence of shear stresses in the working thermoelement shown in Fig. 1. Because the heat-absorbing contact is cooled the working substance in the cold part of the thermoelement is compressed and the cold ends of the branches strive to move away from one another. The commutating plate, however, prevents the branches from moving apart, as a result of which a shear stress, characterized by the component of the stress tensor P_{xy}, appears in the arms of the thermoelement. We shall evaluate this quantity and its possible effect on the resistance of the thermoelement.

The relative decrease in the thickness of the branch l near the cold contact equals $\Delta l/l = \delta\Delta T$. The component ε_{xy} of the strain tensor equals the angle characterizing the shear strain of the thermoelement under study:

$$\varepsilon_{xy} = \frac{\Delta l}{2h} = \frac{\delta\Delta T}{2}\frac{l}{h}. \tag{1}$$

Further calculations require information about the crystal symmetry of the semiconductor used to prepare the thermoelement. Although the branches of real thermoelements, as a rule, are fabricated from polycrystalline materials, to simplify the problem and taking into account the existing experimental data we shall assume that the branches of the thermoelement are pre-

All-Union Scientific-Research Institute of Current Sources, Leningrad Division. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 53, No. 1, pp. 52-55, July, 1987. Original article submitted April 29, 1986.

 0022-0841/87/5301-0780$12.50

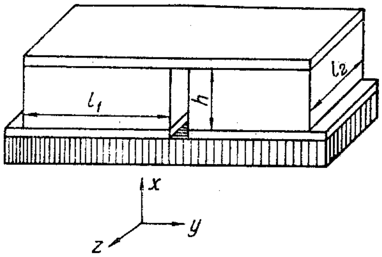

Fig. 1. Schematic diagram of the thermoelement and the arrangement of its coordinate axes.

pared from Bi_2Te_3 single-crystals (class $R\bar{3}m$). We shall denote the third-order axis by x_3, the second-order axis by x_1, and the direction perpendicular to the axes by x_2. For simplicity we shall also assume that the crystal is arranged so that these three axes coincide with the coordinate axes x, y, z, and in addition, the orientation of the current (x axis), as usual in a thermoelement, is perpendicular to the third-order axis x_3.

The form of the elastic moduli tensor $\hat{c}$ and the piezoresistance tensor $\hat{\Pi}$ required below for crystals of different symmetry classes is studied, for example, in [1]. Using the results of this analysis it can be shown that from the four possible variants of the arrangement of the crystal relative to the coordinate axes a nonzero piezoelectric resistance in the direction x, proportional to P_{xy}, arises only when the x_2 axis coincides with the x axis, while the x_3 axis coincides with the y axis.

Assuming that $P_{xy} = P_{23}$ is the only nonzero component of the stress tensor and using the form of the matrix of elastic moduli from [1], we find that aside from the components of the strain tensor $\varepsilon_{xy} = \varepsilon_{23}$, the quantity

$$\varepsilon_{11} - \varepsilon_{22} = -\frac{c_{14}}{c_{66}}\varepsilon_{23} \tag{2}$$

is also nonzero, while P_{23} and ε_{23} are related by the relation

$$P_{23} = \left(c_{44} - \frac{c_{14}^2}{c_{66}}\right)\varepsilon_{23}. \tag{3}$$

Finally, knowing P_{23} we can find the relative change in the resistance of the branch

$$\frac{\Delta\rho_{22}}{\rho_{22}} = -\Pi_{14}P_{23}. \tag{4}$$

Evaluation of the Strains, Stresses, and Strain Sensitivity. The formulas (1), (3), and (4) permit evaluating the magnitude of the shear strain $\varepsilon_{xy} = \varepsilon_{23}$, the elastic stress $P_{xy} = P_{23}$, and the relative change in the resistance of the branch $\Delta R/R = \Delta\rho_{22}/\rho_{22}$. For the crystal orientation under study δ must be chosen as the coefficient of thermal expansion along the third-order axis $\delta_3 = 22.2 \cdot 10^{-6}\ K^{-1}$ [2]. If the temperature differential over the distance h = 0.5 mm equals $\Delta T = 50°K$ and $l = 3$ mm, the strain, according to (1), equals $\varepsilon_{23} \simeq 3.3 \cdot 10^{-3}$. Employing the values of the elastic moduli c_{44}, c_{66}, and c_{14} presented in [2], from the formulas (2) and (3), we obtain the strain $\varepsilon_{11} - \varepsilon_{22} = 1.9 \cdot 10^{-3}$, the stress $P_{23} = 6.7 \cdot 10^7$ N/m^2, and the force exerted on the commutation plate $F = P_{23}l^2 = 600$ N.

It is more difficult to find the relative change in the resistance using the formula (4), since the component of the piezoresistance matrix with the shear strain Π_{14} was not measured. To evaluate $\Delta R/R$ it may be assumed that all nonzero components of the piezoresistance tensor are of the same order of magnitude, and the result of the measurement [3] of the piezoresistance in the crystal p-Bi_2Te_3 with the tensile strain in the cleavage plane $\Pi = 6.5 \cdot 10^{-10}$ m^2/N can be used. Then from (4) we obtain $\Delta R/R \simeq 0.043$. Thus, for a temperature drop of 50°K in the 0.5-mm-thick thermoelement under study the relative change in the resistance owing to the piezoelectric effect is of the order of $\pm$(4-5)%.

To evaluate the quantity of interest to us we can also employ the results of measurements of the strain sensitivity in polycrystalline solid solutions based on Bi_2Te_3, used for fabricating thermopiles. A relative change of the resistance of up to 2.4% with a strain sensitivity coefficient $K = \Delta R/\varepsilon R = 65$ was observed in [4] with a relative compression and tension strain ε up to $0.45 \cdot 10^{-3}$. According to the theory of [5], the compression and tension strain components ε_{11} and ε_{22} appear in the expression for the piezoresistance only in the form of the difference $\varepsilon_{11} - \varepsilon_{22}$. If the coefficient of proportionality between $\Delta R/R$ and $\varepsilon_{11} - \varepsilon_{22}$ is assumed to equal in order of magnitude the coefficient K measured in [4], then the strain $\varepsilon_{11} - \varepsilon_{22}$ arising in our model gives rise to the strain sensitivity $\Delta R/R \approx 10\%$.

Comparing our estimates for ε and $\Delta R/R$ with the values observed experimentally in the study of strain sensitivity in the material used to fabricate the thermoelements, we can see that the strain sensitivities in thermopiles with the dimensions studied are relatively high and can be measured. Their magnitude is of the same order as is the change in the resistance of a semiconductor material accompanying a decrease in the average temperature of the branches in the course of the operation of the thermoelement. This last effect, which distorts the measurement of the strain sensitivity, can be calculated, if the properties of the material are known, or measured directly in the absence of a temperature gradient and at a temperature equal to the average temperature in the working regime. A reversible symmetric thermoelement, for which both contacts can be heat absorbing, can also be fabricated. When the direction of the temperature gradient changes and for a fixed average temperature, the strain sensitivity changes sign, and the resistance of the undeformed branch remains constant, which makes it possible to determine the strain sensitivity in a pure form. Elastic stresses which can exist in a thermoelement without a temperature gradient and are linked with its history do not influence the effect, which is linear as a function of the strain, under study.

The elastic stresses arising in a thermopile can be judged from the measured strain sensitivities.

NOTATION

c_{ik}, components of the matrix of elastic moduli; F, force exerted on the commutation plate; h, height of the branches of the thermoelement; K, coefficient of strain sensitivity; l, thickness of a branch of the thermoelement; P_{ik}, components of the stress tensor; R, resistance of the branches of the thermoelement; ΔT, temperature drop in the thermoelement; x_1, x_2, and x_3, main crystallographic directions in crystals of the Bi_2Te_3 type; x, y, and z, coordinate axes associated with the thermoelement (see Fig. 1); δ, coefficient of linear thermal expansion; ε_{ik}, components of the strain tensor; Π_{ik}, components of the piezoresistance matrix; and ρ_{ik}, components of the resistivity tensor.

LITERATURE CITED

1. O. S. Gryaznov, Calculation of Kinetic Coefficients for Semiconductors [in Russian], Leningrad (1977).
2. B. M. Gol'tsman, V. A. Kudinov, and I. A. Smirnov, Semiconductor Thermoelectric Materials Based on Bi_2Te_3 [in Russian], Moscow (1972).
3. Yu. V. Ilisavskii, Fiz. Tverd. Tela, 3, No. 6, 1898-1899 (1961).
4. É. A. Abdullaev, B. A. Atakulov, Kh. Ō. Olimov, et al., Physical Phenomena Produced by Bombardment of a Solid with Atomic Particles [in Russian], Vol. 2, Tashkent (1974), pp. 101-105.
5. M. I. Klinger, Fiz. Tverd. Tela, 2, No. 6, 1353-1356 (1960).