Influence of destruction of the bismuth crystal structure on the features of measuring pulsed heat fluxes using a sensor based on anisotropic thermoelements

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Abstract. The results of heat flux measurements using a sensor based on anisotropic thermoelements with defects in the crystal structure during reflection of a shock wave are presented. Using numerical simulation, the influence of the defective layer thickness on the sensor electrical signal and the calculated heat flux is analysed. It is shown that the presence of even a thin defect layer makes it unsuitable for measuring pulsed heat fluxes with a characteristic time of ~1 μs.

1. Introduction
Experimental studies of high-enthalpy gas flow around bodies are carried out mainly on pulsed facilities with working time ~1 – 10 ms [1]. This imposes stringent requirements on diagnostic tools, in particular on heat flux sensors. They must have high mechanical strength, short response time ~1 μs, large dynamic range, high noise immunity. These requirements are fully met by the sensor based on anisotropic bismuth thermoelements, developed at St. Petersburg Polytechnic University [2].

The sensitive element of the sensor (Figure 1a) is a battery of series-connected anisotropic thermoelements 1 cut from a bismuth single crystal, fixed on a mica substrate 2 and separated from each other by strips of lavsan 3. The ends of adjacent thermoelements are soldered to each other 4. Wires 5 are soldered to the side thermoelements for connection to the oscilloscope. The dimensions of the sensor in plan can be from 2 × 2 mm to 10 × 10 mm, depending on the required sensitivity and dimensions of the investigated model. The working principle is based on the Seebeck effect. In a sensitive element made of a material with anisotropy of the thermoelectric coefficient, thermoelectric power generates in the direction perpendicular to the temperature gradient [3]. The response time to a pulsed heating is ~10 ns [4]. Figure 1b shows the 4 × 7 mm sensor used in this work, fixed on the end cap of the shock tube.

Due to the peculiarities of manufacturing process of anisotropic thermoelements, the crystal structure in a thin layer adjacent to the working surface of the sensor can be disturbed [5]. In this case, the defect layer no longer participates in the generation of thermoelectric power and it appears only when a temperature gradient appears at a certain depth inside the thermoelement. This leads to increasing of the response time during pulsed heating, since this layer is a thermal resistance. Also, the shape and amplitude of the electrical signal of the sensor changes. Thus, a sensor with a destructed crystal structure at the working surface becomes unsuitable for registering heat fluxes in experiment on short-time facilities. Since these features manifest themselves only in a non-stationary thermal regime with short characteristic times, the presence of such a layer cannot be determined using...
stationary calibration of the sensor [6] and it is necessary to carry out an additional dynamic check. Possible options are the analysis of the sensor response to the irradiation of the working surface by a pulsed laser [4] or its heating by hot gas behind the reflected shock wave [7].

![Figure 1](image1.png)

**Figure 1.** Construction of thermal sensor based of anisotropic thermoelement (a), appearance of the sensor installed on the shock tube end cap (b).

2. **Experimental facility**

The experiments were carried out on the shock tube at the Ioffe Institute (Figure 2). In the experiments, we used only low-pressure channel 2 with 4.32 m length and 50 mm inner diameter. Atmospheric air was used as a driver gas. One side of the channel was separated from the atmosphere using a block of diaphragms 1, the other one was closed with an end cap 3 with a thermal sensor 6 (Figure 1b). Since the pressure of the driver gas is fixed in this configuration, the velocity of the incident shock wave varied within small limits with variation of the initial pressure in the channel. The shock wave velocity was measured using piezoelectric pressure sensors 4 and 5 installed flush with the inner surface of the channel at a distance of 60 mm from each other. The Mach numbers of the incident shock wave in these experiments were $M = 1.5 - 1.6$.

![Figure 2](image2.png)

**Figure 2.** Scheme of the experimental facility: (1) – diaphragm block, (2) – low pressure channel, (3) – shock tube end cap, (4) and (5) – pressure sensors, (6) – thermal sensor.

The dimensions of the thermal sensor in the plan were $4 \times 7 \, \text{mm}$, the thickness of thermoelements was $0.25 \, \text{mm}$, the width was $0.4 \, \text{mm}$, the volt-watt coefficient was $k = 10 \, \text{mV/W}$. The electrical signal of the sensor was recorded with a Tektronix TDS 1002 digital oscilloscope with $\Delta t = 10 \, \text{ns}$ time resolution.
3. **Mathematical model of the thermal sensor based on anisotropic thermoelements**

As mentioned above, during the manufacture of anisotropic thermoelements, a destruction of the bismuth crystal structure in a thin layer at its working surface is possible. With the help of dynamic verification, it is possible to establish only the presence of such a defective layer, but it is difficult to determine its thickness and effective properties. For this reason, a series of calculations was carried out in which the influence of the thickness of the isotropic layer on the shape and amplitude of the electrical signal of the sensor was analyzed.

Since all thermoelements in the sensor are in the same thermal conditions, we will further consider a single thermoelement (Figure 3). Due to the symmetry of the crystal structure, the distribution of temperature and electric potential in all vertical planes is identical [2]. Therefore, the computational domain is a rectangle corresponding to a bismuth thermoelement (1), a mica substrate (2), and the part of the end cap (3). The thermoelement length is 7 mm, the thickness is 0.25 mm, the substrate thickness is 0.1 mm. The model takes into account the anisotropy of the coefficients of thermal conductivity, electrical conductivity and thermoelectric power. Effective isotropic properties of bismuth are set in a defect layer 5–20 μm thick adjacent to the working surface of the thermoelement (red rectangular in Figure 3).

A constant heat flux $q_h = 50 \text{kW/m}^2$ was applied to the working surface of the thermoelement, simulating heating by hot gas behind the reflected shock wave at low Mach numbers. The side faces of the thermoelement are thermally insulated. All surfaces of the thermoelement are electrically insulated. The generated potential difference $\Delta \varphi$ is recorded between the extreme points on its back side.

\[ \text{Figure 3. Model of the heat sensor based on anisotropic thermoelements.} \]

The distribution of temperature $T(x, y)$ and electric potential $\varphi(x, y)$ is found by solving the system of equations [3]:

\[
\begin{align*}
Cp \frac{\partial T}{\partial t} &= \text{div} \mathbf{q} \\
\text{div} \mathbf{j} &= 0
\end{align*}
\]

where $\mathbf{q} = -\lambda \nabla T$, $\mathbf{j} = -\sigma \nabla \varphi - \sigma \alpha \nabla T$ – heat flux and electric current, $T$ – temperature, $\lambda$, $\sigma$, $\alpha$ – tensors of thermal conductivity, electrical conductivity and thermoelectric power. The numerical solution of the equation system is carried out in the COMSOL Multiphysics. This model has shown its applicability both in the case of stationary and non-stationary thermal regimes and the calculation results are in good agreement with the experimental data [8-10].
The electrical signals of the sensor with different thickness of the defect layer obtained using this model were used to solve the inverse problem – to calculate the heat flux $q_h$. For this, we used the method proposed in [10] and consisting in the iterative calculation of the temperature distribution in the thermoelement – substrate structure:

$$C\rho \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right)$$

with the boundary condition connecting the change in the temperature of the working surface of the sensor $T_h(t)$ with the electrical signal $\Delta \varphi(t)$ obtained earlier:

$$T_h^{i+1}(t) = \frac{h\Delta \varphi(t)}{\alpha_{xy}l} + T_0^i(t)$$

where $h$ and $l$ are the height and length of the thermoelement battery, $\alpha_{xy}$ is the thermoelement tensor element, $T_0$ is the temperature of the rear surface of the thermoelement. Further, from the known temperature distribution, the heat flux $q_h(t)$ passing through the working surface of the sensor was calculated. Thus, it was possible to analyze the effect of the thickness of the defect layer on their applicability for recording pulsed heat fluxes.

4. Results

With pulsed heating, the electrical signal of long thermoelements is proportional to the change in the temperature of the working surface $\Delta \varphi \sim \Delta T_h$ [11]. If during the manufacturing process a defect layer is formed on the surface of the thermoelement, which is a thermal resistance, then the change of $T_h$ will be quite smooth. Figure 4a shows the $\Delta \varphi$ sensor signals calculated using the above model with different defect layer thicknesses and without it. It can be seen that damage to the crystal structure at a thickness of even several microns dramatically changes the shape of the signal and decreases its amplitude at a constant heat flux $q_h$. Figure 5b shows the result of solving the inverse problem - determining the heat flux from the sensor signal.

![Figure 4](image-url)

**Figure 4.** The calculated electrical signals (a) and corresponding reconstructed heat fluxes for the sensor with different thickness of the defect layer and without it (b).

It is known that in the initial phase of shock wave reflection $t \approx 1\mu s$, the heat flux to the wall rapidly increases to a maximum value and remains constant [7] (similar to the black curve in Figure 4b). Figure 5a shows the experimentally obtained electrical signals of the sensor upon reflection of a shock wave with Mach number $M \approx 1.5$. It can be seen that the nature of the signal change corresponds to the presence of a defective layer on the surface of the thermoelement with a thickness $\approx 5 - 10\mu m$. Figure 4b shows the signals of the same sensor after mechanical removal of the defective layer upon reflection of shock waves with Mach numbers $M \approx 2.2$. They are similar to signals recorded by other sensors of a similar design without a defective layer [7].
Thus, a smooth increase in the electrical signal of the sensor based on anisotropic thermoelements during pulsed heating can serve as a criterion for the presence of crystal structure defects on its surface. The use of such sensors in a gas dynamic experiment will lead to qualitatively and quantitatively incorrect measurement results.

![Figure 5](image)

**Figure 5.** Measured electrical signal of the thermal sensor with a defective layer (a) and with removed defective layer (b) upon reflection of a shock wave with low Mach numbers.

5. **Conclusion**

The results of heat flux measurements using the sensor based on anisotropic thermoelements with reflection of a shock wave with and without the isotropic defect layer on its working surface are presented. Numerical simulation of thermal and thermoelectric processes in the thermoelement for conditions close to experimental is carried out. Calculations have shown that the presence of a defect layer even several microns thick makes it unsuitable for measuring pulsed heat fluxes with a characteristic time \( \sim 1 \mu s \).

5. **References**

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