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SENSITIVITY AND SPEED OF RESPONSE OF A SUPERCONDUCTING OPTOELECTRONIC THERMAL RADIATION DETECTOR

O. S. Esikov, A. I. Krot, E. A. Protasov, V. P. Sobolev, and V. S. Kharitonov

UDC 535.231.62:621.315.5:538.945

Numerical estimates of the temperature sensitivity and speed of response are obtained for one type of sensing element of a superconducting optoelectronic thermal radiation detector. Possible ways to improve the performance characteristics of such an element are analyzed.

Esikov and Protasov [1] have proposed a new principle for the detection of thermal radiation, described a circuit for its implementation, and estimated the possible sensitivity of an integrated superconducting optoelectronic detector (ISOD) operating on this principle. The subsequent improvement of such systems, particularly in the design of widescreen detectors for moving images, calls for the solution of several problems pertaining to the optimization of their geometrical and thermophysical characteristics with a view toward maximizing the sensitivity, speed of response, and uniformity of the distribution of these parameters over the sensing area. The overall sensitivity of the ISOD is characterized by the product of the permeability variation of the superconducting sensing element per unit heat flux incident on it and the sensitivity of a magnetooptical transducer to a corresponding variation of the heat flux through the sensing element. The possible sensitivity of a magnetooptical transducer has been estimated previously [1]. The ultimate sensitivity of the sensing element depends on the width of the superconducting transition of the superconducting film, the strength of the magnetic field applied to the sensing element, and the thermal resistance of the elements used to create thermal coupling of the superconducting film with the thermostat [2]. The speed of the ISOD is limited mainly by the rise time of the temperature field in the sensing element and by the speed of the counting device.

In the present article we analyze the speed and sensitivity characteristics of the sensing element of a particular ISOD configuration (Fig. 1) with a uniformly illuminated sensing surface. The sensing element is a smooth thin wafer of strontium titanate with a superconducting film of the type Y—Ba—Cu—O deposited on its top surface. The thermostat is a copper ring with its outer circumference cooled by liquid nitrogen. The sensing element is thermally coupled with the thermostat through a thin-film thermal resistance, which serves as a regulator of the sensitivity and speed of the sensing element.

Engineering-Physics Institute, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 61, No. 1, pp. 136-140, July, 1991. Original article submitted July 19, 1990.

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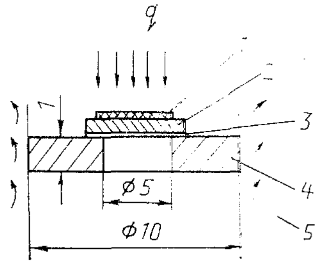

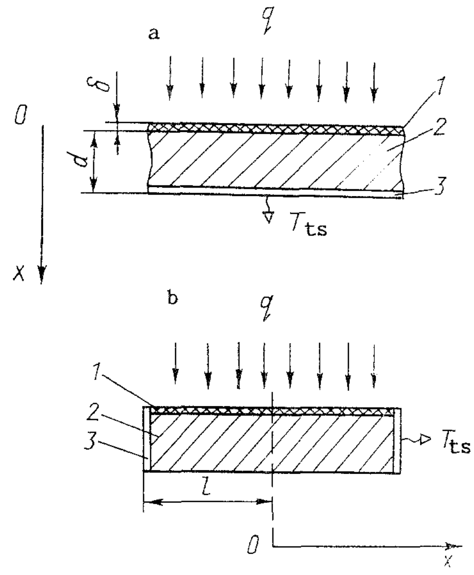

Fig. 1 Fig. 2

Fig. 1. Investigated version of sensing element for an integrated superconducting optoelectronic detector. 1) Superconducting film; 2) substrate; 3) thermal resistance; 4) thermostatting ring; 5) liquid nitrogen.

Fig. 2. Model sensing element configurations. 1) Superconducting film; 2) substrate; 3) thermal resistance.

The general behavior of the sensitivity and speed of the investigated sensing element as a function of the characteristics of its elements and the heat-removal technique can be determined by means of simple one-dimensional models (Fig. 2), which well characterize the limiting cases of heat removal from the ends and from the bottom surface of the sensing element substrate. Allowing for the fact that the thickness of the superconducting film is generally much smaller than the thickness of the substrate in real sensing element structures and that the thermophysical parameters of the film and substrate materials differ to a lesser extent, we can assume for the purpose of estimation that the thermal behavior of the sensing element is governed entirely by the characteristics of the substrate and the value of the thin-film thermal resistance.

Under the stated assumptions, the temperature field along the thickness of the sensing element in downward heat removal (Fig. 2a) and the temperature field along the sensing element in heat removal from the ends (Fig. 2b) can be described by the equation [3]

$$T(x,\ t) = T_\infty(x) - (T_M - T_{ts}) \sum_{n=1}^{\infty} A_n \cos(\mu_n x/L) \exp\left(-\frac{\mu_n^2 a}{L^2} t\right). \tag{1}$$

The steady-state temperature distributions across the substrate (Fig. 2a) and along the substrate (Fig. 2b) are given by the expressions

$$T_\infty^a(x) = q\left(\frac{d-x}{\lambda} + R_f F\right) + T_{ts}, \tag{2}$$

$$T_\infty^b(x) = q\left[\frac{l^2}{2d\lambda}\left(1 - \frac{x^2}{l^2}\right) + R_f F\right] + T_{ts}. \tag{3}$$

The temperature sensitivity of the sensing element to the incident thermal radiation can be defined as the ratio of the temperature variation of the superconducting film to the heat flux density responsible for that variation:

$$S_T = \Delta T_{sc}/q = (R_s + R_f)F. \tag{4}$$

Figure 2a shows that the sensitivity does not depend on the coordinate and is determined by the ratio of the thickness to the thermal conductivity of the substrate and by the product of the thermal resistance of the regulatory film and the surface area:

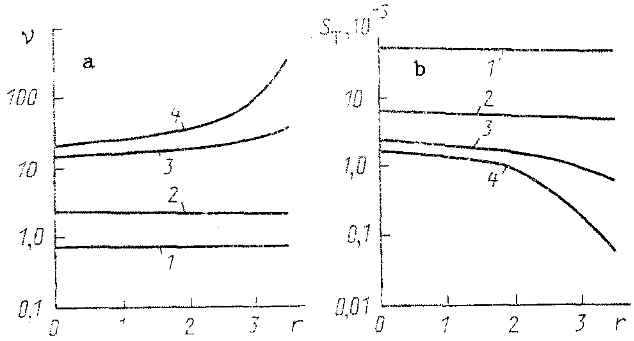

Fig. 3. Speed of response ν, sec^{-1} (a), and sensitivity S_T, $m^2 \cdot K/W$ (b), vs radius r of the investigated sensing element for various thermal resistances R_f of the thermal coupling between the substrate and the thermostatting ring. 1) $R_f = 10^{-1}\ m^2 \cdot K/W$; 2) 10^{-2}; 3) 10^{-3}; 4) $10^{-4}\ m^2 \cdot K/W$.

$$S_T^a = \frac{d}{\lambda} + R_f F. \tag{5}$$

In the case of Fig. 2b the temperature sensitivity depends also on the length of the substrate and on the coordinate:

$$S_T^b = \frac{l^2}{2d\lambda}\left(1 - \frac{x^2}{l^2}\right) + R_f F. \tag{6}$$

The thermal response of the sensing element can be characterized by the time $t_{1/2}$ for the temperature of the superconducting film to rise to half its peak value. All except the first term of the series in Eq. (1) can be disregarded in determining the dependence of this parameter on the geometrical and thermal characteristics of the sensing element. The following relation is then readily obtained:

$$t_{1/2} = \frac{L^2}{\mu_1^2 a} \ln\left[2A_1 \frac{(T_M - T_{ts})}{(T_\infty(x) - T_{ts})} \cos(\mu_1 x/L)\right]. \tag{7}$$

Making use of the fact that μ_1 is the root of the characteristic equation $\tan\mu_1 = R_s/R_f\mu_1$ [3] and substituting $a = \lambda/\rho/c_p$ for the thermal diffusivity, we transform relation (7) as follows:

$$t_{1/2} \approx B(R_s/R_f;\ x)\rho c_p V(4R_s + \pi^2 R_f)/\pi^2. \tag{8}$$

In both cases the coefficient B depends on the ratio of the thermal resistance of the regulatory film, varying from 0.2-0.3 in the limit $R_s/R_f \to \infty$ to 0.7-1.4 in the limit $R_p/R_f \to 0$, and it depends only slightly on x (see Fig. 2b). At a fixed ratio R_s/R_f the thermal response parameter $t_{1/2}$ is directly proportional to the specific heat of the substrate and the total thermal resistance between the superconducting film and the thermostat.

It is evident from a comparison of Eqs. (4) and (8) that an increase in the temperature sensitivity of the sensing element is accompanied by a proportionate loss in the speed of response. However, the response can be quickened without detracting from the sensitivity of the sensing element by decreasing the specific heat of the substrate and reducing the film part of the thermal resistance at a fixed total thermal resistance. Equations (4) and (8) permit the temperature sensitivity and the thermal response parameter to be interrelated through the simple expression

$$S_T/t_{1/2} \approx 1/(BC_s). \tag{9}$$

Relation (9) shows that in order to maximize the sensitivity and speed of response of the sensing element, every effort must be made to use substrate materials with minimal volumetric specific heats (large Debye temperatures), to diminish the thermal coupling between the superconducting film and thermostat, and to remove heat quickly at the thermal-stabilizing surfaces. It must be taken into consideration, however, that large nonuniformities in the distribution of the speed and sensitivity characteristics of the sensing element with respect to the coordinate can be observed in the event of rapid heat removal (Fig. 2b). Regulatory films with relatively high resistances must be used in order to eliminate these effects detrimental to the ISOD.

The above-derived relations can be used to develop general recommendations for the optimal selection of materials, construction, and thermal stabilization systems and to estimate the ultimate sensitivity of the sensing element at a given speed or to estimate the response time at a selected sensitivity for simple sensing element models. However, they are not suitable for calculating the speed and sensitivity characteristics of real instruments having intricate geometries, heterogeneous structures, or heat removal that is nonuniformly distributed over the surfaces. Numerical modeling methods must be invoked in this case.

A two-dimensional computer model based on an SSTE program, which was written using the channel modeling method proposed by Merinov [4], has been developed for quantitative analysis of the speed and sensitivity characteristics of the sensing element shown in Fig. 1. In the version investigated here, it was assumed that heat is removed from the substrate only through the contact surface with the thermostatting ring via the regulatory thermal resistance. The total modeling domain was partitioned into 156 cells. The following geometrical and thermophysical parameters of the cells of the sensing element were adopted in the computations: thickness of the superconducting film $\delta = 1$ μm; thickness of the substrate $d = 0.3$ mm; diameter of the superconducting film 6.8 mm; diameter of the substrate 9.0 mm; diameter of the hole in the thermostatting ring 5.0 mm; density of the substrate 6.45 g/cm^3; specific heat of the substrate 165 J/kg·K; thermal conductivity of the substrate 4.5 W/m·K; density of the superconducting film 6.35 g/cm^3; specific heat of the superconducting film 105-205 J/kg·K; thermal conductivity of the film 2.8 W/m·K. The values of the thermophysical parameters were taken from [5-8]. The regulatory thermal resistance was varied in the interval 2-2500 K/W.

The results of calculations of the local sensitivity and speed of response $\nu = 1/t_{1/2}$ for various values of the regulatory thermal resistance are shown in Fig. 3. In the case of strong thermal coupling of the substrate with the thermostatting ring in the investigated sensing element configuration, we observe large radial nonuniformity of the sensitivity and speed, as is characteristic of the simplified model (Fig. 2b). In particular, for $R_f = 2.5$ K/W the sensitivity decreases 15-fold in transition from the center toward the edge of the superconducting film, and the speed decreases tenfold; these variations are unacceptable for widescreen-display ISODs. Acceptable nonuniformity of these characteristics in the given sensing element configuration at the 5% level can be achieved by using a regulatory thermal resistance of approximately 2500 K/W. In this case the sensitivity is almost 0.05 K·m^2/W, and the response time is ~1.5 sec; the overall sensitivity of the total sensing area is approximately $1.4 \cdot 10^3$ K/W. The speed of the investigated sensing element configuration can be enhanced by decreasing the thickness of the substrate to 50-100 μm or by replacing the strontium titanate substrate with a diamond substrate.

These estimates demonstrate the technical feasibility of the proposed [1] concept of a widescreen-display infrared radiation detector that has high sensitivity and acceptable speed and utilizes films of state-of-the-art high-temperature superconducting films as the sensing layer.

NOTATION

x, coordinate; t, time interval from first arrival of heat flux at sensitive surface of sensing element; T_{ts}, temperature of thermostat; $T_\infty(x)$, steady-state temperature distribution in substrate; L, a characteristic length (substrate thickness in Fig. 2a or distance ℓ from center to edge of sensing element in Fig. 2b); , thermal diffusivity; A_n, μ_n, coefficients depending on ratio of thermal resistance R_s of substrate to thermal resistance R_f of regulatory film; T_M, maximum temperature of sensing element; λ, thermal conductivity; q, heat flux density; F, sensing surface; S_T, temperature sensitivity of sensing element; ρ, density; c_p, specific heat at constant pressure; C_s, total heat capacity of substrate.

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DETERMINATION OF THERMOPHYSICAL PROPERTIES OF MATERIALS WITH THE HELP OF CHARACTERISTICS OF IMAGINARY FREQUENCIES

A. V. Kozlov, A. G. Shashkov, and A. S. Trofimov

UDC 536.22.083

An effective method has been developed to determine thermophysical properties of materials from the available thermophysical measurements.

The identification of the parameters of heat transfer — the coefficients of thermal conductivity and thermal diffusivity — constitutes the essence of the internal inverse problem of thermal conduction and is reduced to determining the coefficients of the differential equation of thermal conduction from the available thermal measurements. The creation of simple engineering methods for solving such problems is a timely problem of modern thermophysics.

At present, unsteady methods of the regular regime and the initial stage of heat exchange are the best developed methods [1]. The simplicity of these methods of identification of thermophysical characteristics makes them certainly worthwhile; however, the need to perform a special experiment (to create a definite law of variation of the boundary conditions, to rapidly attain the regular regime, etc.) restricts their application. Another disadvantage is the use of temperature values obtained experimentally at fixed times in the calculated dependencies for the transfer coefficient. Possible substantial fluctuations in the measurement errors at these times can lead to substantial errors in the result. Even to a greater extent, the accuracy of determination of thermophysical characteristics depends on the quality of the experiment in algorithms [2], where the derivatives of unsteady temperatures contribute to the calculated dependencies.

In [3], an effective method of identification has been proposed, which assumes an arbitrariness in the change of the boundary conditions, and based on sufficiently simple calculated dependencies that incorporate the integrals of the temperatures taken during the experiment. Such an approach allows one to decrease the effect of measurement errors (especially, random errors) on the precision of the determination of thermophysical characteristics. However, the use by Vlasov et al. [3] of a "precise" model of heat conduction allows them to

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Institute of Applied Physics, Academy of Sciences of the Belorussian SSR, Minsk. Krasnodar Polytechnic Institute.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 61, No. 1, pp. 141-145, July, 1991. Original article submitted August 20, 1990.

0022-0841/91/6101-0922$12.50