TEMPERATURE FIELDS IN THERMAL RADIATION DETECTORS

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Results of analysis of thermal processes in a superconducting thermal radiation detector, formulated as a boundary-value problem of complicated heat transfer in a three-dimensional region of complex geometry, are reported. Variants of the problem for simplification are given; the limitations of these assumptions are pointed out.

Use of infrared radiation detectors based on superconducting materials allows substantial improvement of such characteristics as response, resolving capacity, speed of response, i.e., time constant, as compared to semiconductor IR detectors [1, 2] and, as a consequence, makes realistic the creation of detectors for recording low-contact rapid processes or moving objects [3, 4]. Despite the availability of diverse principles of recording thermal images [2, 3, 5], for the limiting characteristics of superconducting material-based IR detectors to be achieved a number of problems concerned with optimization of their geometric and thermal parameters are to be solved [6], with the most important one relating to determination of the temperature distribution in the two-layer system "superconducting film–dielectric substrate" because just these detectors find wide application. In the majority of works, e.g., [2, 3, 5], the statement of the problem on heat transfer in an IR detector is a matter of insufficient concern. The problems are analyzed and solved under simplifying assumptions, inadequate to the physical situation, which yields results having limited application.

The present work is devoted to the analysis of heat transfer processes and the construction of an adequate mathematical model on the example of the IR detector depicted in Fig. 1. Detailing the detector consideration does not restrict the generality of the problem since the heat transfer processes occurring during its functioning are general for the photodetector designs most often used.

Up to some moment of time t_0 the IR radiation detector is in a superconducting condition at a certain temperature T_{in}. At the moment t_0 the detector receives a heat flux q_r from the investigated object (see Fig. 1b), while a light flux q_ℓ serving as a commutative one is brought to some part $\partial\Omega_i$ of the superconducting strip. As is seen, these fluxes are on opposite sides of the substrate. The light beam is partly absorbed by the dielectric substrate with the assumption of a small absorption coefficient, with its main portion being consumed for heating the section $\partial\Omega_i$. Due to the engineering specific features involved in the detector manufacture the Kapitsa thermal resistance developing at the superconducting strip–substrate interface due to a difference in the acoustic properties of the contacting bodies is negligible at cryogenic temperatures, which provides an ideal thermal contact at the strip–substrate interface. The area of the light spot is assumed to be comparable with the width of the superconducting strip. On heat propagation in the strip–substrate system radiative and connective heat transfer with the surrounding medium occurs. The substrate is temperature-controlled over its perimeter. Heating by commutative radiation proceeds up to a change of temperature by the fixed value ΔT, determining the moment of time $t_1 > t_0$. Simultaneously with the commutative radiation being applied, the transport current is passed through the superconducting strip, which causes a release of Joule heat q_γ on the investigated section owing to the resistive properties of the strip. As a result, the investigated section is heated to temperature T_γ. The temperature of the normal regime of the strip T_0 is known. The device is switched off at the moment t_k, i.e., the fluxes q_γ, q_l ceases when the relation $T_c = \Delta T + T_\gamma + T_r$ is fulfilled. The last term is specified by the heat flux from the object investigated. It is noteworthy that during $t_0 < t \le t_k$ the heat transfer processes described above proceed; here the time constant is $\tau = t_k - t_0$. The process is repeated as many times as there are inquiry points.

Taking into consideration the region geometry, the temperature dependence of the thermophysical parameters [7], and the short duration of the processes in the IR detector, the design under consideration may be mathematically described by the following system of nonlinear nonsteady-state equations [8, 9]:

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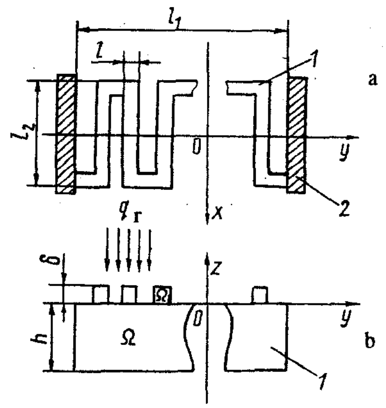

Fig. 1. Projections of the IR radiation detector circuit: a) onto plane xOy [1) superconducting strip; 2) contact spots]; b) onto plane zOy [1) substrate].

$$\frac{\partial T}{\partial t}(c\rho T) = \operatorname{div}(\lambda \operatorname{grad} T) + q_j,$$
$$\frac{\partial T_1}{\partial t}(c_1\rho_1 T_1) = \operatorname{div}(\lambda_1 \operatorname{grad} T_1) + \varepsilon_1 q_l \tag{1}$$

with the initial conditions $T(x, 0) = T_1(x, 0) = T_{in}$. The complicated heat transfer in the system "strip-substrate–thermostat–surrounding medium" is described by the following boundary conditions:

$$\lambda \frac{\partial T}{\partial n} = \lambda_1 \frac{\partial T_1}{\partial n}, \quad T(\mathbf{x}, 0) = T_1(\mathbf{x}, 0), \quad \mathbf{x} \in \partial\Omega \cap \partial\Omega_0,$$

where $\partial\Omega \cap \partial\Omega_0$ is the set of points of the contact "strip–substrate":

$$-\lambda \frac{\partial T}{\partial n} = \alpha (T - T_0) + q_r, \quad \mathbf{x} \in \partial\Omega_0 / (\partial\Omega \cap \partial\Omega_0),$$

here $\alpha = \alpha_l + \alpha_c$ is the total heat transfer coefficient given on the strip surface with the exception of the points of contact with the substrate

$$\alpha_l = \varepsilon_{red}\sigma_0 (T^2 + T_0^2)(T + T_0);$$
$$-\lambda \frac{\partial T_1}{\partial n} = \alpha_1 (T - T_0) + q_r, \quad \mathbf{x} \in \partial\Omega / (\partial\Omega \cap \partial\Omega_0 \cap \partial\Omega_h),$$

where $\alpha_1 = \alpha_{1l} + \alpha_{1c}$ is the total heat transfer coefficient given on the substrate surface without its side surface and the points of contact with the strip; α_{1l} has a form analogous to α_l;

$$\lambda \frac{\partial T}{\partial n} = (q_l - \varepsilon_1 q_l) - \lambda_1 \frac{\partial T_1}{\partial n}, \quad T(\mathbf{x}, t) = T_1(\mathbf{x}, t),$$
$$\mathbf{x} \in \partial\Omega_l'$$

($\partial\Omega'_i$ is the section of local irradiation by commutative radiation);

$$\lambda \frac{\partial T_1}{\partial n} = \frac{1}{R}(T_1 - T_{in}), \quad \mathbf{x} \in \partial\Omega_h$$

($\partial\Omega_h$ is the side surface of the substrate).

The fact that the formulated problem has a complicated character lies in the absence of results for the existence and uniqueness of its solution in the general theory of boundary-value problems. This is explained by the complicated geometry of the region, and different boundary conditions, which leads, generally speaking, to the appearance of discontinuity of solutions and nonlinearity of the problem. At the same time consideration of the geometric and functional specific features of the IR detector as well as of the physical processes proceeding in it allows simplification of the mathematical model.

The literature data [2-5, 7] testify to the fact that the processes in an IR detector are rapid: for instance, the time of attaining a stationary regime by the detector is about 10^{-2} sec, and temperature fields undergo a small change ($\Delta T \leq 5$ K). In this temperature range the thermophysical characteristics of the superconducting strip and the substrate may be assumed constant, which results in linearization of the equations. The assumption on radiotransparency of the substance ($\epsilon_1 = 0$) at comparatively insignificant thermal powers of commutative radiation (10^{-4} W) in combination with short radiation times makes the assumption on slight radiative transfer between the IR detector and the ambient medium ($\alpha_l = 0$) realistic, while the presence of moderate vacuum, being this medium, permits one to model the situation by the absence of convective heat transfer ($\alpha_c = 0$) on the corresponding surfaces. Ideally, the constant temperature T_{in} is maintained on the side surface of the substrate.

With the assumptions made, propagation of the temperature front in the superconducting thermal detector is described by the following linear equations:

$$
\begin{gathered}
c\rho \frac{\partial T}{\partial t} = \lambda \Delta T + q_j, \\
c_1\rho_1 \frac{\partial T_1}{\partial t} = \lambda \Delta T, \; T(\mathbf{x}, 0) = T_1(\mathbf{x}, 0) = T_{\text{in}}; \\
\lambda \frac{\partial T}{\partial n} = \lambda_1 \frac{\partial T_1}{\partial n}, \; T(\mathbf{x}, t) = T_1(\mathbf{x}, t), \; \mathbf{x} \in \partial\Omega \cap \partial\Omega_0; \\
-\lambda \frac{\partial T}{\partial n} = q_r, \; \mathbf{x} \in \partial\Omega_0 / (\partial\Omega \cap \partial\Omega_0); \\
-\lambda_1 \frac{\partial T}{\partial n} = q_r, \; \mathbf{x} \in \partial\Omega / (\partial\Omega \cap \partial\Omega_0 \cap \partial\Omega_h); \\
-\lambda \frac{\partial T}{\partial n} = q_l - \lambda_1 \frac{\partial T_1}{\partial n}; \; T(\mathbf{x}, t) = T_1(\mathbf{x}, t), \; \mathbf{x} \in \partial\Omega_l'; \\
T_1(\mathbf{x}, t) = T_{\text{in}}, \; \mathbf{x} \in \partial\Omega_h.
\end{gathered}
\tag{2}
$$

Linear problem (2) is most often discussed in the literature; nevertheless almost the same difficulties [10] as in problem (1) must be overcome to obtain its solution.

A specific design feature of the IR detectors based on superconducting films is concerned with the fact that the film thickness is a minor parameter as compared to its other linear dimensions and the substrate dimensions. Consequently, heat propagation in the strips may be considered in the approximation of an infinitely thin plate. The width of the film is considerably less than its length (see Fig. 1a) which leads to one-dimensional equations of heat conduction on the superconducting strips. Also, it should be noted that the length of the strip conjugate to its perimeter is considerably larger than its width and the distance from that part of the strip to its edge, which, as a consequence, gives boundary conditions for the region $\partial\Omega_h$ on those sections of the strip. Stemming from the discussion above, heat transfer in the IR detector may be modeled by the following system of equations:

$$
\begin{gathered}
c\rho \frac{\partial T}{\partial t} = \lambda \frac{\partial T}{\partial x^2} + q_j + \frac{1}{\delta}\left(q_r + q_l - \lambda_1 \frac{\partial T_1}{\partial z}\right), \\
c_1\rho_1 \frac{\partial T_1}{\partial t} = \lambda_1 \Delta T_1.
\end{gathered}
\tag{3}
$$

The initial conditions are:

$$T(\mathbf{x},\ 0) = T_1(\mathbf{x},\ 0) = T_r,$$

the boundary conditions are:

$$T|_{\mathbf{x}=\pm\frac{l_1}{2}} = T_r,$$

$$T_1(\mathbf{x},\ t)|_{z=0} = T(x,\ t),\ \mathbf{x}\in\partial\Omega_i;$$

$$-\lambda\frac{\partial T}{\partial z}\Big|_{z=0} = q_r,\ \mathbf{x}\ \text{refers to the substrate},$$

$$\frac{\partial T_1}{\partial z}\Big|_{z=-h} = 0,\ T_1(\mathbf{x},\ t) = T_{in},\ \mathbf{x}\in\partial\Omega_h.$$

System of equations (3), in which the first equation gives the temperature distribution in the superconducting strip receiving the heat flux of light radiation, while the thermal field in the other strips is described by the same equation without q_l, q_j, models heat transfer in the IR radiation detector considered as a two-layered structure consisting of the two-dimensional part $\partial\Omega$ and a three-dimensional substrate. It is seen that it is considerably easier to find a solution of the problem (3) than of (2), and the more so of (1) although the latter presents difficulties connected with the presence of the three-dimensional region Ω. Further simplification of problem (2) consisting in passing from the two-layer to the one-layer structure, as is sometimes done, is unreasonable since in this case the main specific feature of the IR radiation detector design, namely, the presence of the superconducting film is not taken into consideration. Note that with the assumptions made, transition from problem (1) to nonlinear problem (3) is possible.

The conducted analysis of modeling the thermal fields in superconducting IR radiation detectors allows the following conclusions to be made. In the detectors, complicated heat transfer takes place which in the general case is described by a nonlinear nonstationary problem in two three-dimensional regions. Consideration of the construction specificity and the physical processes proceeding in it makes it possible to model a detector as a two-layer structure and to obtain a linear system of heat conduction problems, whose solution is considerably simpler. Further simplification, for instance, reduction to a one-layer region, seems to be unreasonable.

NOTATION

T, temperature; t, interval of time from the onset of heat transfer; x = (x, y, z), vector of spatial coordinates; q, specific heat flux; c, specific heat capacity; p, density; λ, thermal conductivity; α_c, coefficient of convective heat transfer; ϵ_1, absorption coefficient; ϵ_{red}, reduced black emissivity; σ_0, Stefan–Boltzmann constant; R, thermal resistance; l_1, l_2, width and length of the substrate; l, width of the superconducting film; h, δ, thickness of the substrate and the film, respectively; Ω, region occupied by the substrate; $\partial\Omega$, boundary of the region Ω; Ω_0, region occupied by the strip; $\partial\Omega_0$, boundaries of the region Ω_0; Ω_i, region of a single strip; $\partial\Omega_i$, boundaries of the region Ω_i; $\partial\Omega_h$, side surface of the substrate; $\bigcap$, /, signs of theoretical-multiple intersection, difference; $\bar{n}$, unit normal to a surface.

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