SEMICONDUCTOR FILM THERMOELECTRIC ELEMENTS AS RADIATION TEMPERATURE SENSORS

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The sensitivity is calculated for a thermoelectric unit used as a radiation temperature sensor in a null method.

Temperature measurement by radiation methods has a number of advantages over the contact method. These include the capability of obtaining undistorted results, efficiency and simplicity of measurement, and the averaging of temperature over large areas.

The basic element of the radiation temperature sensor is the sensitive element (SE) – a semiconductor film thermounit made up of several thermoelements. The SE is connected in a null indication scheme. The optical symmetry of the sensor body structure allows the measurements to be made by comparing the thermal radiation of the test surface with that of a reference surface whose temperature can be measured by a contact method. Clearly, when the radiant fluxes being compared and the emittances of the test and reference surfaces are equal (zero signal in the null indicator), the temperatures are equal.

The thermoelements considered as radiation temperature sensors make possible an instrument with high sensitivity (of the order of 0.05°C). The null indicator arrangement makes possible absolute measurements without calibration of the sensitive element, and the instrument readings during operation are not distorted by possible change in the thermoelement characteristics with time.

The insignificant mass of the film thermounit gives the SE a comparatively small time constant (150 to 200 msec), so that measurements of the temperature of a surface which changes with time can be made, and the temperature can be recorded on a recorder if need be.

The operating principle of the radiation thermometer is illustrated in Fig. 1, where 1 is the film thermounit (see Fig. 2); 2 are windows in the sensor body which expose the working junctions at temperature T_1 and the compensation junctions at temperature T_2 to the test surface at temperature T_a and the reference surface at T_K, respectively. A null indicator is connected to the opposite electrodes of the thermounit-responding to the signal $E = f(\Delta T)$, where $\Delta T = T_1 - T_2$. Clearly, when $\Delta T = 0$, $T_a = T_K$ (condition of symmetry). At the moment of equality of temperatures T_a and T_K, the latter is measured by a contact method (thermocouple, thermistor, etc.). It is also clear that the condition $\Delta T = 0$ when $T_a = T_K$ also holds when the infrared emittances of the test and reference surfaces are equal (the reference surface is the junction of a semiconductor thermopile of finite size). The reference surface temperature T_K is controlled by the amount and direction of current passing through the thermopile, and can have values both larger and smaller than the temperature of the surrounding medium.

Figure 2 shows the SE, made up of five semiconductor legs 1, deposited in vacuum on a thin mica substrate 2. The substrate thickness is 10 μ, and the film thickness is 3 to 4 μ. The legs are interconnected to form a unit with antimony electrodes 5, also deposited by heating in vacuum. Item 3 is a black layer deposited on the free side of the substrate to form the windows, and 4 are thin copper wire leads (0.02 mm). The thermounit dimensions are given in mm.

The following materials can be used as thermoelements:

1) leg from hole-conduction Bi–Te–Sb, whose parameters in a thin layer are: thermal electromotive force $\alpha_+ = 160$ μV/deg; electrical conductivity $\sigma_+ = 500\text{-}600$ $\Omega^{-1} \cdot cm^{-1}$; thermal conductivity $\varkappa_+ = 1.5 \cdot 10^{-2}$ W/cm · deg;

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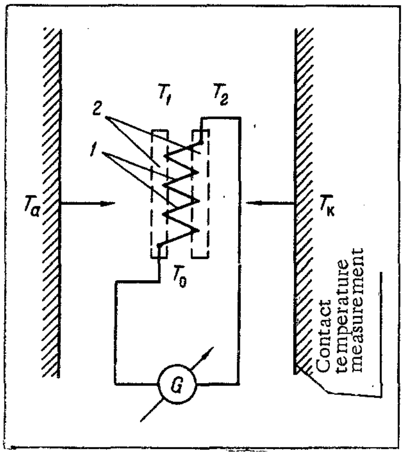

Fig. 1

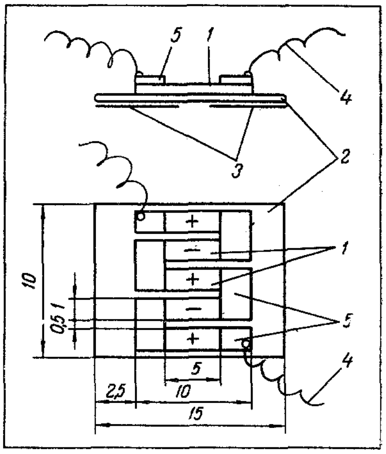

Fig. 2

Fig. 1. Principle of the radiation measurements by a comparison method.

Fig. 2. The film thermoelement unit.

2) leg from electron-conduction PbTe with parameters: $\alpha_- = 180\ \mu V$ deg; $\sigma_- = 400\text{-}500\ \Omega^{-1} \cdot cm^{-1}$; $\varkappa_- \simeq 1.5 \cdot 10^{-2}$ W/cm · deg.

We now calculate the sensitivity of the thermounit equipped with a type M195/1 galvanometer as null indicator, with current factor $C_I = 1.0 \cdot 10^{-8}$ A/division, and internal resistance $r_G = 50\ \Omega$.

We take the thermounit sensitivity $\Delta T = T_1 - T_2$ to be the temperature difference between the junctions required to deflect the galvanometer one division. This deflection is determined by the signal e, which in our case is:

$$e = C_I (r_G + r_{tu}) = 1.0 \cdot 10^{-8} \cdot 90 = 0.9 \cdot 10^{-6}\ \text{V/division},$$

where $r_{tu} = 40\ \Omega$ is the total resistance of the thermounit with current and connecting leads. Hence the thermounit sensitivity is:

$$\Delta T = T_1 - T_2 = \frac{e}{\alpha_u} = \frac{0{,}9 \cdot 10^{-6}}{860 \cdot 10^{-6}} \simeq 1{,}0 \cdot 10^{-3}\ \text{deg/division}.$$

Here α_u is the coefficient of the thermal electromotive force unit, consisting of five legs (2.5 thermocouples).

We also need to know the temperature difference between the test and reference surfaces for which the temperature drop at the junctions is ΔT. We call the minimum drop $T_a - T_K = C_T$, corresponding to the radiation thermometer sensitivity, the instrument constant. Since there is interaction between the thermounit junctions and the test and reference surfaces only via radiant heat transfer, we calculate the radiant heat-transfer coefficient h_r in the temperature range of interest.

We consider the case where one is required to measure the temperature of the ground or vegetation cover. The range of possible temperatures is $T_a = +60$ to $-40°C \simeq 330$ to 230°K. The maximum temperature difference between the surface and the surrounding medium under natural conditions does not exceed ±20°C, and the minimum is 0°C.

To determine the radiant heat-transfer coefficient we use the equation for radiant heat transfer between two infinite parallel black surfaces [1, 2]

$$Q = 5{,}7 \left[\left(\frac{T_a}{100} \right)^4 - \left(\frac{T_1}{100} \right)^4 \right] = h_r (T_a - T_1),$$

where

$$h_r = \frac{5{,}7 \cdot 10^{-2} \left[\left(\frac{T_a}{100} \right)^4 - \left(\frac{T_1}{100} \right)^4 \right]}{\frac{T_a}{100} - \frac{T_1}{100}};$$

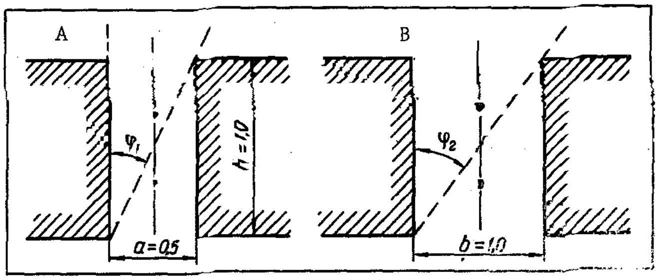

Fig. 3. Sensor window [A) section along the thermounit legs; B) section across the thermounit legs]. The dimensions are in cm.

$$h_r = 5{,}7\cdot 10^{-2}\frac{x^4-y^4}{x-y} = 5{,}7\cdot 10^{-2}(x+y)(x^2+y^2)\ \mathrm{W\cdot m^{-2}\cdot deg^{-1}}$$

Under actual conditions the dimensions of the surface whose temperature is being measured are limited by the window (see Fig. 3). Therefore the radiant heat-transfer coefficient is:

$$h'_r = R\cdot 5{,}7\cdot 10^{-2}(x+y)(x^2+y^2),$$

where

$$R = \frac{1}{4}\sin\varphi_1\sin\varphi_2 = \frac{1}{4}\frac{ab}{\sqrt{a^2+h^2}\sqrt{b^2+h^2}} = 0{,}08.$$

Assuming dimensions for the window (Fig. 3), we calculate the radiant heat-transfer coefficient h_r for the case T_a = 330°K, T_1 = 330°K (here and below we assume that the film temperature is negligibly different from that of the surrounding medium T_0)

$$h'_{r\,max} = 0{,}08\cdot 5{,}7\cdot 10^{-2}(3{,}3+3{,}3)(10{,}89+10{,}89) = 6{,}55\cdot 10^{-5}\ \frac{\mathrm{W}}{\mathrm{cm^2\cdot deg}}.$$

If T_a = 330°K, T_1 = 310°K, then

$$h'_{r\,min} = 0{,}08\cdot 5{,}7\cdot 10^{-2}(3{,}3+3{,}1)(10{,}89+9{,}61) = 6\cdot 10^{-5}\ \frac{\mathrm{W}}{\mathrm{cm^2\cdot deg}}.$$

The mean radiant heat-transfer coefficient at the upper limit of measurement (T_a = 60°C) is

$$\bar{h}'_{r\,(60\,°C)} = \frac{h'_{r\,max}+h'_{r\,min}}{2} = 6{,}25\cdot 10^{-5}\ \frac{\mathrm{W}}{\mathrm{cm^2\cdot deg}}.$$

By a similar calculation for the lower limit of measurement (T_a = 230°K, T_1 = 230°K and T_a = 230°K, T_1 = 250°K), we find the mean radiant heat-transfer coefficient

$$\bar{h}'_{r\,(-40\,°C)} = 2{,}4\cdot 10^{-5}\ \frac{\mathrm{W}}{\mathrm{cm^2\cdot deg}}.$$

Sensitivity of Radiation Thermometer (See Fig. 4). The calculation does not account for convective and radiative heat transfer in the section l corresponding to the distance between the junctions.

We consider the thermal balance equation for the heat-sensitive surface S on the measuring junction side of the thermounit:

$$Q_{meas} = Q_{conv} + Q_{rad.\,sur.} + Q_{rad.\,test} + Q_{cond}. \tag{1}$$

Here $Q_{meas} = (T_a - T_1)S\bar{h}'_r$ is the heat flux transferred by radiation from the test surface with temperature T_a; $Q_{conv} = 2S(T_1 - T_0)h_K$ is the convective heat flux given out by the two sides of the heat-sensitive surface S to the surrounding medium with temperature T_0. Here h_K is the convective heat-transfer coefficient; $Q_{rad.\,sur.} = S(T_1 - T_0)h_0$ is the heat flux radiated by the surface S to the surrounding medium, the temperature of the surrounding medium is T_0, and h_0 is the reduced coefficient for radiation from the film to the surrounding medium; $Q_{rad.\,test} = S(T_1 - T_0)\bar{h}'_r$ is the heat flux radiated by the sensitive surface towards the test surface; $Q_{cond} = (\lambda_{equiv}f_0/l)(T_1 - T_2)$ is the heat flux transferred via conduction of the

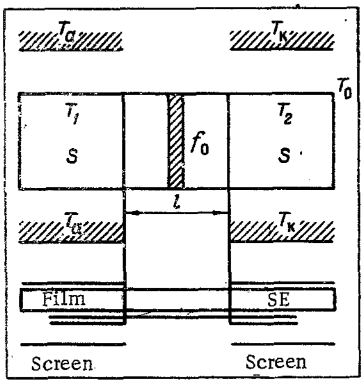

Fig. 4. Model for calculating sensitivity.

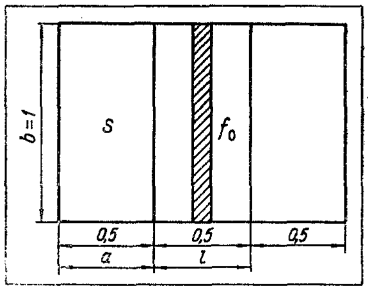

Fig. 5. Calculation scheme (dimensions are in cm).

film and substrate (λ_{equiv}) from the measuring junctions at temperature T_1 to the compensation junctions at temperature T_2. Denoting $B = \lambda_{equiv} f_0/lS$ and carrying out a number of transformations of the original Eq. (1), we obtain

$$T_a - T_1 = (T_1 - T_0)\left(\frac{2h_к}{h'_r} + \frac{h_0}{h'_r} + 1\right) + \frac{B}{h'_r}(T_1 - T_2). \tag{2}$$

For the emittance of the compensation surface we can obtain an equation analogous to Eq. (2):

$$T_к - T_2 = (T_2 - T_0)\left(\frac{2h_к}{h'_r} + \frac{h_0}{h'_r} + 1\right) - \frac{B}{h'_r}(T_1 - T_2). \tag{3}$$

From simultaneous solution of Eqs. (2) and (3) we obtain

$$T_1 - T_2 = \Delta T = \frac{T_a - T_к}{2 + 2\frac{h_к}{h'_r} + \frac{h_0}{h'_r} + \frac{2B}{h'_r}}$$

or

$$\frac{\Delta T}{T_a - T_к} = \frac{1}{2 + 2\frac{h_к}{h'_r} + \frac{h_0}{h'_r} + \frac{2B}{h'_r}}. \tag{4}$$

If, by way of example, we consider the actual film shown in Fig. 5 with $h_{0(60°C)} = 8.25 \cdot 10^{-5}$ W/cm² · deg and $h_{K(60°C)} = 1.8 \cdot 10^{-4}$ W/cm² · deg (in air),* we obtain

$$\left.\frac{\Delta T}{T_a - T_к}\right|_{60\,°C} = 0.095.$$

Similarly, with $h_{0(-40°C)} = 2.8 \cdot 10^{-5}$ W/cm² · deg and $h_{C(-40°C)} = 1.6 \cdot 10^{-4}$ W/cm² · deg (in air), we have

$$\left.\frac{\Delta T}{T_a - T_к}\right|_{-40\,°C} = 0.050.$$

Thus, the sensitivity at the ends of the range +60 to −40°C differs by almost a factor of two. We recall that the calculation was made for structures with screens, and no account was taken of heat transfer in the section l and of losses to the leads.

From Eq. (4) we can draw qualitative conclusions as to possible ways of increasing the sensitivity of sensors:

1) the values of h_0 and h_K should be reduced, i.e., we should increase the quality of the screens and place them closer to the film, and also either evacuate the volume containing the sensitive element or fill it with gas with low-thermal conductivity;

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* In calculating h_0 the reduced emittance of the SE–screen system was taken as 0.1; h_K was calculated for the case of heat transfer to a finite space.

2) the value of B should also be reduced by increasing the heat-sensitive area (dimension a) and increasing the thermal resistance (reducing the film thermal conductivity λ_{equiv} and its cross section f_0);

3) the width b of the film is immaterial.

Calculation of Heat Transfer at Section l. Omitting the intermediate mathematical steps, we give the final equation

$$\frac{\Delta T}{T_a - T_к} = \frac{1}{2 + 2\frac{h_к}{h_r'} + \frac{h_0}{h_r'} + \frac{k}{h_r'}}, \tag{5}$$

where

$$k = \frac{\lambda_{equiv} f_0 m \operatorname{ch}(ml) + 1}{S \operatorname{sh}(ml)};$$

$m = \sqrt{h_{scr} p / \lambda_{scr} f_0}$; $h_{scr} = h_K + h_0$; and p is the perimeter of the film section (in our case p = 2b).

Calculating the sensitivity from Eq. (5) for the ends of the temperature range, we obtain

$$\left.\frac{\Delta T}{T_a - T_к}\right|_{60\,°C} = 0.088; \quad \left.\frac{\Delta T}{T_a - T_к}\right|_{-40\,°C} = 0.046,$$

i.e., the sensitivity is reduced (compared with the previous case) by 7 to 8%.

Calculation of Heat Transfer at the Surfaces of the Leads and of Losses in Heat Flow Due to Lead Conductance. In this case the final formula for calculating the sensitivity is as follows:

$$\left[\frac{\Delta T}{T_a - T_к}\right]_{constr} = \frac{1}{2 + 2\frac{h_к}{h_л'} + \frac{h_0}{h_r'} + \frac{k}{h_r'} + \frac{L}{h_r'}}, \tag{6}$$

where

$$L = \frac{\lambda_W f_W m_W}{S_W} \cdot \frac{\operatorname{ch}(m_W l_W)}{\operatorname{sh}(m_W l_W)}$$

is a coefficient allowing for one lead on each side. Here $m_W = 2\sqrt{h_{scr}/\lambda_W d_W}$ for a circular cross section.

Carrying out the calculation with Eq. (6), for our example we obtain

$$\left.\frac{\Delta T}{T_a - T_к}\right|_{60\,°C} = 0.084; \quad \left.\frac{\Delta T}{T_a - T_к}\right|_{-40\,°C} = 0.043.$$

It is easy to see that the sensitivity has been reduced by 5%.

If we take into account the effect on the emittance of the optical filters required to avoid interference from reflected solar radiation, then the appropriate correction for the filters should be used in all the expressions for the coefficient of radiant heat transfer h_r'.

Thus, the final Eq. (3) can be rewritten as follows:

$$\left[\frac{\Delta T}{T_a - T_к}\right]_{s.f.} = \frac{1}{2 + \frac{1}{R_f}\left(2\frac{h_к}{h_r'} + \frac{h_0}{h_r'} + \frac{k}{h_r'} + \frac{L}{h_r'}\right)} \tag{6a}$$

(where s.f. indicates a structure with a filter).

If we choose a germanium filter with $R_f = 0.5$ [5, 6], then

$$\left[\frac{\Delta T}{T_a - T_к}\right]_{s.f.} = 0.046 \text{ for measurements at } 60°C$$

and

$$\left[\frac{\Delta T}{T_a - T_K}\right]_{\text{s. f.}} = 0.023 \text{ for measurements at } -40°\text{C}.$$

Hence we obtain the minimum temperature difference between the test surface at T_a and the compensation surface at T_K for which the measurement can still be performed, i.e., the sensitivity of the instrument C_T, deg/division is:

$$C_{T(60\,°C)} = (T_a - T_K)_{\min} = \frac{\Delta T}{0.033} = \frac{1 \cdot 10^{-3}}{0.046} = 2.2 \cdot 10^{-2} \text{ deg/division},$$

$$C_{T(-40\,°C)} = \frac{1 \cdot 10^{-3}}{0.023} \simeq 4.4 \cdot 10^{-2} \text{ deg/division}.$$

It should be noted that the whole calculation assumed that the emittances in the infrared of the test and reference surfaces are equal and close to 1. This assumption is valid for soil and vegetation cover surfaces, although there are undoubtedly differences in the value of emittance for different kinds of soils and vegetation covers. The emittance values for various surfaces of this type range from 0.92 to 0.98 [4, 7]. When the emittances of the test and reference surfaces differ, a correction should be applied to the measured results or the error tolerance should be increased.

It follows from what has been said that the method of surface temperature measurement by the radiation thermometer with semiconductor film thermoelectric sensor, based on comparison of the test surface temperature with that of a reference surface, offers high instrumental resolution.

The radiation thermometer can be connected to a recorder. For this one can replace the galvanometer by a DC amplifier with a transistor switch at its output. The latter controls and varies the direction of current in the compensating thermopile circuit. The reference surface temperature recorded is connected over a diagonal of the nonequilibrium measuring bridge, replacing the microammeter. This type of arrangement for automatic measurement and monitoring of surface temperature has been currently constructed and tested.

NOTATION

T_a	is the surface temperature of test object;
T_K	is the temperature of compensating surface;
T_1, T_2	are the junction temperatures;
E	is the thermounit electromotive force;
α	is the thermal electromotive force coefficient;
σ	is the electrical conductivity;
$\varkappa$	is the thermal conductivity;
C_I	is the galvanometer current constant;
r_G	is the internal resistance of galvanometer;
r_{tu}	is the resistance of thermounit;
T	is the temperature drop at the thermounit junctions;
h_r, h_0	are the coefficients of radiant heat transfer;
R	is the diaphragm factor;
l	is the distance between junctions;
S	is the area of heat-sensitive surface of thermounit, limited by one window;
Q	is the heat flux;
h_K	is the convective heat-transfer coefficient;
λ	is the equivalent thermal conductivity of film and substrate;
f_0	is the film cross-sectional area (thermounit and substrate legs);
b	is the film width;
p	is the perimeter of film section;
λ_w	is the thermal conductivity of leads;
f_w	is the cross-sectional area of leads;
l_w	is the length of leads;
d_w	is the lead diameter;
R_f	is the transmittance of filter;
C_T	is the instrument sensitivity.

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