cavity or channel, the given method is preferable to the Monte Carlo method.

NOTATION

L, initial contour; L^*, contour approximating contour L; z(M), f(M), γ(M), arbitrary functions of the point M; z*(m), f*(m), γ* (m), step functions approximating the functions z(M), f(M), γ(M); μ, number of zones; φ(m, n), mean angular coefficient; l, contour length; α, molecular-capture coefficient; δ, relative error.

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HEAT TRANSFER OF THERMISTORS IN A NONUNIFORM ELECTRIC FIELD

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The results of an investigation of the action of dc and ac electric fields on the heat transfer of thermistors are described.

In recent years both in the Soviet Union and abroad increased attention has been given to finding new methods of improving heat transfer based on the use of electric fields. The basic principle of this method is the fact that under the action of intense electric forces in liquids and gases additional disturbances arise which under certain conditions can be localized in a narrow region of the boundary layer which has the highest thermal resistance and is therefore essentially a controllable heat transfer. The electroconvection disturbances that arise lead to a considerable increase in heat transfer.

However, despite the promising possibilities of the new method it has not been investigated to any great extent either theoretically or in practice. The theoretical assumptions and experimental results of different investigators are often questionable and even contradictory. This relates, first of all, to the nature of the action on the heat transfer of dc, ac, and mixed electric fields, and also to the quantitative estimates of the increase in heat transfer as a function of the field strength, the temperature difference, the configuration, the diameter of the heat-transfer and high-voltage electrodes, their mutual position, the temperature of the surrounding medium, etc. [6]. The methods for the experimental investigation of the effect are also far from ideal. Thus, in all the publications known to us [1-7] the heat transfer of the heated conductor has been investigated. The high-voltage was applied either to a coaxially situated conducting cylinder or to a plate placed parallel to the conductor. Hence, in all these cases the heat transfer of a conductor in a nonuniform electric field was

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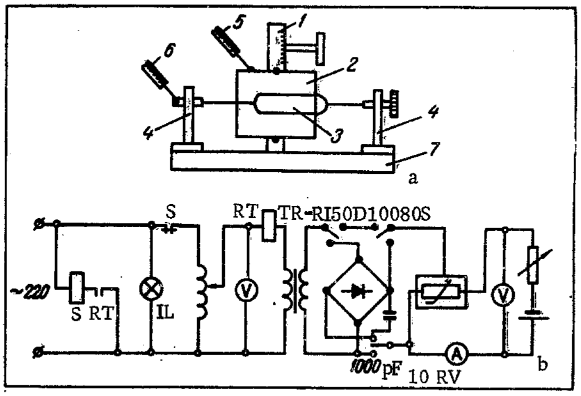

Fig. 1. Test model (a) and the electrical circuit used for the measurements (b).

investigated. The effect of an increase in the heat transfer was found from the amount of additional energy consumed in heating the wire in the field as compared with the energy consumed in heating to the same temperature when there is no field. For this purpose the conductor, as a rule, was connected in a bridge circuit which enabled one to maintain its temperature constant and to make all the measurements necessary to determine the average heat-transfer coefficient along the length. The main drawback of such a method of determining the energy consumed and the temperature of the heated wire is its comparatively low temperature coefficient of resistance which determines the low temperature sensitivity of such a thermal probe and, consequently, makes these measurements of low accuracy.

In the present article we attempt to extend the heat-transfer intensification effect in electric fields to semiconductors, and primarily to semiconductor thermistors which have a high sensitivity to changes in the heat-transfer conditions. We have two aims in mind: first, to study how the main parameters and characteristics of the heated semiconductor devices change when acted upon by electric fields, and, second, from the results obtained to determine the possibility of using thermistors as sensitive probes for studying heat-transfer intensification processes.

As is well known, the main characteristics of any thermistor when it is heated by the current passing through it is the static volt–ampere characteristic, i.e., the relation

$$U_T = F(I_T) \quad \text{or} \quad I_T = F(U_T)$$

when the parameters of the surrounding medium remain unchanged. The nature of this relationship is governed by many factors and mainly by the conditions under which heat transfer occurs to the surrounding medium. Consequently, the application of an electric field and the resulting intensification of heat transfer should lead to a change in the volt–ampere characteristics of the thermistor, other conditions being equal.

To check this suggestion and to make quantitative estimates we carried out a series of experiments with KMT-10, MMT-1, and KMT-4 thermistors, RIIZhT test high-power resistors, and ST5-1 posistors. Preliminary investigations enabled us to draw the following interesting conclusion: intensification of the heat transfer in an electric field is not possible in any heated body but only occurs from a metal or when there is direct thermal contact with a metal. Hence, for the further investigations, we used KMT-4 thermistors which have a metal body in combination with hollow cylinders of different diameter made from copper, brass, and aluminum. One of the cylinders had a continuous highly polished surface. In the others a large number of holes were drilled in the side surface to improve the heat transfer.

Figure 1a shows a sketch of the test model. A hollow cylinder 2 is fastened to the coordinate 1; inside the cylinder along its axis there is a thermistor 3 which is stretched by means of a spring between two electrically insulated supports 4. A high-voltage lead 5 is connected to the cylinder through a special terminal. The second terminal of the high-voltage source is connected to the current-carrying thermistor 6 which is connected to its metal body.

The coordinate with the cylinder and thermistor is connected to the base 7 which is made of an electrically insulating heat-resistant material.

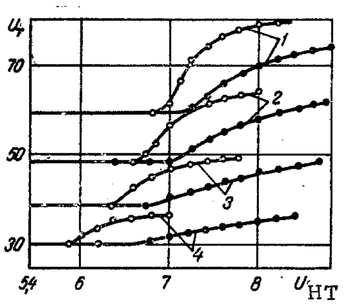

Fig. 2

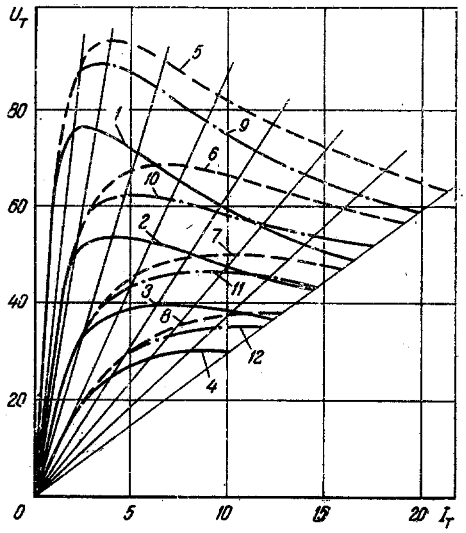

Fig. 3

Fig. 2. Voltage drop across the thermistor as a function of the high voltage for I_T = const = 10 mA and different temperatures of the surrounding medium: 1) 20°C; 2) 40; 3) 60; 4) 80°C (the circles correspond to the ac field and the black dots correspond to the dc field). U_T, V; U_{HV}, KV.

Fig. 3. Static volt–ampere characteristics of the KMT-1 thermistor with R_{20} = 100 k Ω for different temperatures of the surrounding media: 1-4) without the field; 5-8) in a dc field, U_{HV} = 8kV; 9-12) in an ac field, U_{HV} = 8 kV; 1, 5, 9) for Θ_0 = 20°C; 2, 6, 10) 40; 3, 7, 11) 60; 4, 8, 12) for Θ_0 = 80°C. U_T; V; I_T, mA.

The investigations were made in a thermostat which enabled the assigned temperature to be maintained with an accuracy of ± 0.1°C.

The electrical circuit used for the measurements is shown in Fig. 1b. The high-voltage current is applied to the circuit by means of a high-voltage cable which is additionally insulated inside the thermostat with a ceramic tube.

We used an I-50 laboratory transformer as the high-voltage source to the input of which was connected a rectifier bridge assembled from D10080S diodes for making dc measurements. The primary winding of the transformer was connected into the network through an LATR-2M autotransformer which enabled us to vary the output voltage smoothly from 0 to 10 kV at ac, and from 0 to 14.1 kV at dc. The voltage was monitored on the low side using a VZ-2A voltmeter and on the high side with an AVO-5 voltmeter. To prevent the output from damaging the instruments in the case of breakdown of the air gap the circuit was provided with current protection.

In addition, to determine the difference between the effect on the heat exchange of the rectified constant field and a "pure" constant field a number of measurements were made using a high-voltage battery assembled from 50 dry anode batteries (type BAS-T-80-U-2.0). The volt–ampere characteristics of the thermistor were plotted when the field was applied in the following sequence. Initially, a steady-state operation was established in the absence of the field for a certain value of the current flowing through the thermistor. Then the high-voltage source was connected, the voltage was increased to the assigned value, and, keeping the thermistor current unchanged, a new stable mode of operation of the circuit was obtained. The potential difference between the body of the thermistor and the cylindrical electrode produces a fairly high electric field on the surface of the thermistor and the new steady-state mode of operation is characterized by a considerably increased voltage drop across the thermistor.

The value of the voltage of the high-voltage source was chosen so as to prevent breakdown of the air gap and also so that the heat-transfer intensification effect in the electric field has a threshold form.

Figure 2 shows curves of the voltage drop across the thermistor as a function of the voltage of the high-voltage source for fixed current flowing through the thermistor and for different temperatures of the surrounding medium. It is seen from these curves that for each temperature of the surrounding medium there are certain threshold voltages corresponding to the beginning of a change in the heat transfer and also limiting permis-

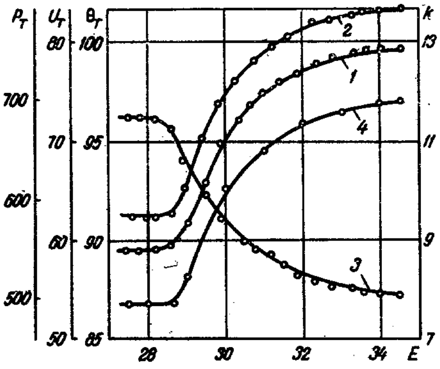

Fig. 4

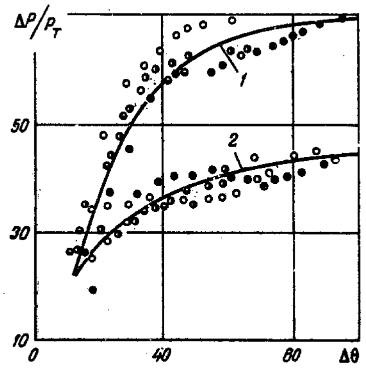

Fig. 5

Fig. 4. The voltage (1), dissipated power (2), temperature (3), and dissipation factor of the thermistor (4) as a function of the electric field for Θ_0 = 20°C and I_T = 10 mA.

Fig. 5. Relative variation of the dissipated power (%) of the thermistor as a function of the temperature drop (°C): 1) in a dc field; 2) in an ac field.

sible voltages which precede breakdown. The value of both these and the others is determined, besides the temperature of the surrounding medium, by such factors as the value of the air gap, i.e., the diameter of the thermistor and the cylindrical electrode, the temperature of the thermistor, and the nature of the electric field.

Thus, the threshold dc voltages which we measured were less than the ac voltages, in agreement with the results obtained in [3], while the heat transfer in the dc field occurs much more intensely than in the ac field. In the ac field the relation $U_T = F(U_{HV})$ is a mildly sloping curve and the voltage across the thermistor continues to increase as U_{HV} increases until the breakdown voltage is reached. On the other hand, in the dc field immediately after the threshold voltage the voltage across the thermistor increases sharply and there is a tendency to reach saturation when U_{HV} is increased further.

Under the same conditions for the same heating current the start of the change in the heat transfer is shifted towards lower fields as the temperature of the surrounding medium is increased, and when the latter is maintained constant the threshold and limiting fields are less for higher heating currents; i.e., for higher thermistor temperatures. Hence, before plotting the volt–ampere characteristics in the field we determined the high voltage prior to breakdown for maximum thermistor current and temperature of the surrounding medium corresponding to the upper limit of the chosen temperature range. For other temperatures this voltage was maintained constant.

Families of static volt–ampere characteristics plotted without a field and also in dc and ac fields are shown in Fig. 3.

The figure shows that both dc and ac electric fields have a considerable effect on the heat transfer of the thermistor. The volt–ampere characteristics are deformed by the field and are shifted to the right and upwards towards higher voltages, corresponding to a reduction in the thermistor temperature, and an increase in its resistance with considerably increasing dissipated power (Fig. 4).

The curves plotted in a field are similar in shape to the initial curves at the corresponding temperatures of the surrounding medium. The latter only has an effect on the absolute value of the action: as the temperature of the surrounding medium is increased, the increase in voltage across the thermistor for constant current flowing through it is reduced.

The nature of the action of the field up to the maximum of the volt–ampere characteristics and after it is not the same.

Up to the maximum of the curve the heating of the thermistor by the current flowing through it is small, and the effect of the field on the heat transfer is practically negligible. As the current is increased heating of the thermistor increases and the volt–ampere characteristics obtained when the field is applied are not the same as the initial curves.

We can use as a criterion of the intensification of the heat transfer of a thermistor by the field, as in the experimentally heated conductor, the relative change in power dissipated by the thermistor for the same heating

TABLE 1. Effect of the Material, Internal Diameter, and State of the Surface of the Cylindrical Electrode on the Heat Transfer of a Thermistor in an Electric Field

Material and surface of the cylindrical electrode	Internal diameter of the cylindrical electrode, mm	Voltage of the high-voltage source U_{HV}, kV	Thermistor current I_T, mA	Voltage across the thermistor U_T, V
Dural cylinder with openings	26	0	7	52.2
		7.6	7	66.0
Dural cylinder without openings	26	0	7	52
		7.6	7	65.0
Aluminum cylinder with openings	16	0	7	51
		5.6	7	61.2
Copper cylinder with openings	16	0	7	51.5
		5.6	7	60.5

temperatures. Then by using the thermistor as a heated body it is not necessary to take any special steps to maintain the temperature constant when the field is applied. To calculate the value of $\Delta P/P_T$ for different thermistor temperatures over a given temperature range of the surrounding medium it is sufficient on the graph of the families of volt–ampere characteristics, plotted in the field and without it, to draw from the origin of coordinates a number of lines which in the theory of thermistors are called lines of equal resistance or equal temperature (Fig. 3). The points of intersection of the volt–ampere characteristics with each of these straight lines define the mode of operation of the thermistor for the same heating temperature. In Fig. 5 using theoretical data, we have constructed graphs of $\Delta P/P_T = F(\Delta\Theta)$ in dc and ac fields for different temperatures of the surrounding medium. It is seen from this figure that in a dc field the heat transfer of the thermistor is much higher than in an ac field, while the relative change in the dissipated power increases with the temperature drop, reaching approximately 70% in a dc field and approximately 45% in an ac field. The temperature of the surrounding medium in the range considered (20-80°C) has practically no effect on the intensification of the heat transfer.

The above experimental results were obtained using a KMT-1 thermistor and a Duralumin cylinder with an internal diameter of 22 mm. The data obtained with other cylinders are presented in Table 1. It is seen from this table that the material of the cylinder has practically no effect on the heat transfer in the field. We also did not observe any practical difference in the heat exchange of the thermistor when a field is applied when the cylindrical electrode has a continuous smooth surface and when its surface is a grid with openings 1 mm in diameter. At the same time, the diameter of the high-voltage electrode, as mentioned above, has a considerable effect on the intensification of the heat transfer. It would seem to be a natural assumption that for small diameters of the high-voltage electrode one can attain the same intensification of the heat transfer at lower voltages, but in practice this turns out to be untrue.

Investigations showed that when the diameter of the electrode is reduced both the threshold voltages and the increase in voltage are reduced for the same currents. The range between the threshold and the breakdown voltages is considerably reduced so that for diameters of the high-voltage electrode which differ from the diameter of the thermistor by 3-4 mm, the threshold voltages are equal to the breakdown voltages and intensification of the heat transfer becomes impossible. On the other hand, an increase in the diameter of the high-voltage electrode leads to an unjustified increase in the threshold voltages, from which it follows that there are optimum ratios between the diameter of the heated body and that of the high-voltage electrode which must be determined. It is precisely for this reason that we were unable to determine the intensification of the heat transfer of the thermistor in a "pure" dc field produced by a dry battery due to its limited voltage. The effect of the action of a pure dc field was observed on a heated nickel conductor with a Dural plate placed horizontally above it as the second electrode. The intensification of the heat transfer was estimated, as in [1], only qualitatively from the blackening of the conductor, from which we were able to conclude that pure dc fields have the same effect on the heat transfer as rectified and ac fields.

The following conclusions can be drawn from the above investigations.

First, the static volt–ampere characteristics of a thermistor undergo considerable changes when dc and ac electric fields are applied. The relative increase in the dissipation factor of the thermistor (the heat-transfer coefficient) may reach approximately 75% in dc fields and approximately 45% in ac fields. This opens up new possibilities for using thermistors in measurement technique, for monitoring and controlling high voltages.

Second, in view of the high sensitivity of thermistors to a change in the heat-transfer conditions, they can possibly be used successfully as probes to investigate intensification of heat transfer in electric fields and enable much better methods of investigation to be developed, as well as simplifying the circuit and increasing the accuracy of measurements.

NOTATION

I_T, current through the thermistor, mA; U_T, thermistor voltage, V; U_{HV}, voltage of the high-voltage source, kV; Θ_T, thermistor temperature, °C; Θ_0 the ambient temperature, °C; $\Delta\Theta$, temperature drop, °C; P_T, power dissipated at the heating temperature Θ_T with no field, mW; ΔP, increase in power dissipated in a field at a temperature Θ_T, mW; k, dissipation factor of the thermistor, mV/°C; R_{20}, rated resistance of the thermistor at $\Theta_0 = 20°C$, kΩ; $E = U_{HV}\,[2.3\, r\log(R/r)]^{-1}$, electric field strength, kV/cm; R, inner radius of the cylinder, cm; r, radius of the thermistor, cm.

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DETERMINATION OF THERMOPHYSICAL CHARACTERISTICS OF HIGH HEAT-CONDUCTANCE MATERIALS ON THIN SAMPLES

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UDC 536.2.083

A method is proposed that makes it possible to eliminate the contact thermal resistances in the determination of the thermophysical characteristics of high heat conductance materials on samples with thickness $h \le 5 \cdot 10^{-3}$ m.

Thin samples of solid dielectrics with high heat conductance are widely used in radio equipment for space research. The thermophysical characteristics (t.p.c.) of the solid dielectrics has to be determined on thin samples. Such samples are easier to prepare without defects in the internal structure. Furthermore, samples of small thickness more closely correspond to real conditions of operation of solid dielectrics.

The thermophysical characteristics of very hard materials with thermal conductivity above 20 W/m·deg on samples of thickness less than $5 \cdot 10^{-3}$ m cannot be determined by the existing methods.

Stationary and many nonstationary methods require the introduction of the temperature measuring device into the investigated sample; this is difficult to accomplish in thin samples of great hardness. Moreover, in thin high heat conductance samples it is difficult to measure small time intervals of temperature increase due to rapid heat transfer.

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