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TEMPERATURE STRESSES IN HETROGENEOUS BARIUM-TITANATE-BASED THERMISTORS

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Temperature stresses in semiconductor barium-titanate-based ceramics with a layer structure under the action of current loads have been investigated by numerical methods. It has been shown that by optimizing the thickness ratios between the layers and their properties one can markedly decrease the maximum stresses compared to homogeneous thermistors.

Keywords: *barium titanate, PTCR, temperature stresses, heterogeneous thermistors.*

Introduction. Semiconductor barium-titanate-based ceramics with a positive temperature coefficient of resistance (PTCR) are used for making PTCR-thermistors (posistors) which have found wide application in production and household appliances [1, 2]. However, under the action of large current loads thermistors may fail by separation [3]. Heavy currents cause nonuniform heating of the posistor, resulting in the appearance of temperature stresses leading to failure of the ceramics (breakdown into two practically equal parts in the plane parallel to the electrodes). Therefore, the thermal fields and temperature stresses have been given fairly great consideration [3–9]. In particular, on the basis of the numerical experiments performed it has been shown that the cause of separation of the thermistor into layers is the temperature tensile stresses determined by the nonuniform temperature distribution along the *OZ* axis perpendicular to the plane of electrodes [9] (the *OZ* axis is the symmetry axis of a cylindrical posistor on whose base electrodes are deposited). The values of tensile stresses may exceed 50 MPa, which is comparable to the critical values for semiconductor barium-titanate-based ceramics. The theoretical calculations were verified by experiment [10]. To increase the insensitivity of the PTCR of thermistors to current loads, it is necessary to develop methods for decreasing the temperature stresses. One such method based on the formation of posistor elements with a heterogeneous structure has been considered in the present paper.

Results and Discussion. The temperature distribution in posistor elements was determined on the basis of the simultaneous solution of the heat conduction and electrical conduction equations [7, 8]. To calculate the temperature stresses, we solved the quasi-static thermoelasticity equation [9].

As our previous calculations for homogeneous thermistors have shown, the maximum tensile stresses are concentrated near the lateral surface of the posistor. The temperature distribution and, accordingly, the value of maximum stresses (τ_z) strongly depend on the value of the specific resistance (ρ_{25}), the PTCR value, the Curie temperature (T_C), as well as on the thermal properties of the ceramics. However, variation of the thermal properties over the possible range influences the temperature field insignificantly. But the electrical properties of semiconductor ceramics can be controlled over a wide range [2].

Consider the simplest case where the posistor (of diameter 5 mm and thickness 2 mm, with electrodes of thickness 200 μm) consists of three layers parallel to the electrodes with a different specific resistance at room temperature. The middle layer has the PTCR effect (T_C = 87°C, ρ_{25} = 0.285 Ω·m, the thickness of each layer is 1.90 mm). The other two layers are identical and have a higher constant resistance (p = 0.714 Ω·m, the thickness of each layer is 0.05 mm). The total specific resistance ρ_{25} of the specimen is 0.31 Ω·m and equals the corresponding value of the homogeneous thermistor calculations for which were performed in [9]. The heat transfer coefficient of the surface was taken for the case of still air (σ = 50 W/(m^2·K)). The distributions of temperatures and stresses in the thickness of the thermistor with a layer structure (on the lateral surface) are given in Fig. 1a and b, respectively.

It is seen that due to the more intensive heat generation in the near-electrode layers the character of the temperature fields changes. In the initial time interval, a temperature burst in these regions is observed, which, decreasing

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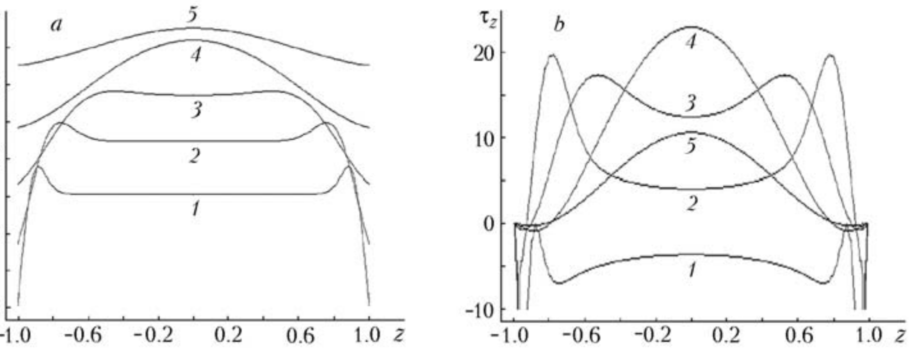
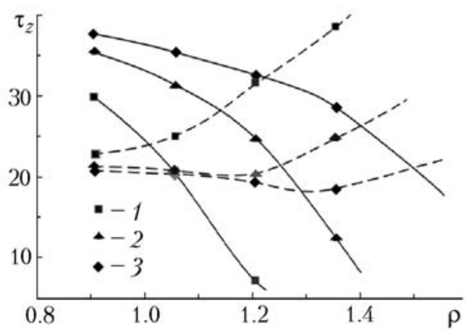


Fig. 1. Distribution of the temperature T (a) and temperature stresses τ_z (b) in the thickness of a specimen with a layer structure for various instants of time: 1) 0.006; 2) 0.016; 3) 0.050; 4) 0.166; 5) 0.500 sec. The data for calculations are given in the text. T, ^{o}C; τ_z, MPa; z, mm.



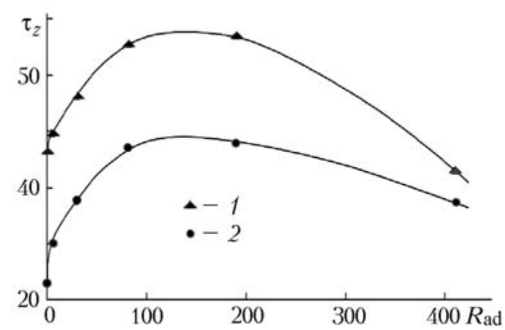


Fig. 2. Value of the "first maximum" (dashed curves) and of the "second maximum" (solid curves) of tensile stresses as a function of the specific resistance ρ of the near-electrode layers at their thickness of: 1) 100 μm; 2) 60; 3) 40. τ_z, MPa; ρ, Ω·m.

Fig. 3. Change in the maximum tensile stresses τ_z in the homogeneous (1) and heterogeneous (2) thermistors depending on the value of the ballast resistance R_{ad}. τ_z, MPa; R_{ad}, Ω.

with time, moves to the posistor center. At later heating stages the temperature difference in the specimen thickness decreases compared to homogeneous structures. This leads to the appearance of two time extremes of stresses in the near-electrode region ("first maximum") and at the center of the lateral surface ("second extremum") (Fig. 1b). In both cases, however, the values of the maximum stresses are much lower than the critical ones. It should be emphasized that in homogeneous thermistors the τ_z value may exceed 50 MPa.

To minimize stresses, a proper choice of the properties of the layers is required. Figure 2 shows the change in the maximum stresses depending on the thickness and specific resistance of the outer layers.

At the thermistor center, the values of tensile stresses decrease with increasing thickness and specific resistance of the outer layers (the "second maximum" is given by solid curves). At the same time there is an increase in the "first maximum" (dashed curves). The intersection points of dashed and curved lines are optimal. In optimizing the ratios of thicknesses and specific resistances of the layers, we can theoretically attain a two-fold decrease in the maximum stresses as compared to homogeneous thermistors. However, taking into account the possible deviation of the ceramics properties from the given ones, the decrease in the value of maximum temperature stresses will be smaller. For example, if the deviation of the near-electrode layer thickness is 50 ± 10% μm and the deviation of the specific resistance is 1.40 ± 10% Ω·m, then a decrease in the maximum temperature stresses by up to 35% (compared to homogeneous specimens) may be expected.

PTCR-type thermistors are usually elements of protection against current and power overloads. Therefore, they are placed in the electric circuit in sequence with a certain load resistor. The presence of limiting resistance promotes an increase in the temperature stresses (Fig. 3). However, also in this case the effect of decrease in the stresses in using heterogeneous posistors is observed.

It should be noted that a greater decrease in the maximum temperature stresses can be obtained with the use of near-electrode layers with the PTCR-effect by selecting their specific resistance, the PTCR value, and the Curie temperature T_C, as well as by forming a structure with a larger number of layers. However, because of the high sensitivity of the temperature field distribution to insignificant changes in the PTCR value and, even to a greater extent, to T_C, it will be practically difficult to obtain a considerable decrease in the maximum temperature stresses with account for the possible deviations of the ceramics characteristics from the given ones.

The properties of semiconductor barium titanate ceramics are easy to vary by adequate doping of materials [2]. For example, the Curie temperature is shifted when barium is substituted by strontium or lead (additives for substituting elements in other positions of the $BaTiO_3$ lattice are known), the ceramics resistance is sensitive to the introduction of 3-*d* elements, donor elements, etc. The technological aspects of obtaining ceramics layer structures have also been well developed by now (e.g., as in the case of manufacturing multilayer structures of capacitors). Therefore, the proposed method for minimizing temperature stresses by creating layer structures can fairly easily be realized in practice.

Conclusions. The temperature stresses in PTCR-type thermistors in the process of heating by electric current have been investigated. A method for decreasing the inhomogeneity of thermal fields and temperature stresses has been proposed. The method is based on the formation of specimens with a layer structure in which different layers of the posistor have different properties (phase transition temperature, specific resistance). It has been shown that with an optimal thickness ratio between the layers and their properties a twofold decrease in tensile stresses compared to homogeneous specimens is possible.

NOTATION

R, resistance, Ω; *T*, temperature, ^oC; T_C, Curie (switching) temperature, ^oC; *z*, coordinate in the cylindrical coordinate system (the *OZ* axis is the symmetry axis of the posistor element), mm; ρ, specific resistance, Ω·m; σ, heat transfer coefficient of the surface, $W/(m^2 \cdot K)$; τ_z, stress tensor component in the cylindrical coordinate system, MPa. Subscripts: 25, at a temperature of 25^oC; ad, additional (ballast).

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