Study of Thermal Conductivity of Nanoporous Anodic Alumina Layer Formed in Sulphuric Acid Using Steady-State Heat Flow Technique

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Abstract – **The paper presents the results of studies of thermal characteristics of nanoporous anodic alumina layer formed in sulphuric acid. One-sided heating of aluminum boards by heating element from carbon filament was used. The temperature of the back side of the board was kept constant by using an aluminum heatsink. Thermograms of aluminum board surface were taken by thermal imaging camera MobIR M4.**

Keywords – **Nanoporous Anodic Alumina, Sulphuric acid, Heat transfer, Thermal conductivity**

I. Introduction

For modern micro and nanoelectronics, one of the important tasks is the creation of functional nanomaterials with given characteristics [1-3]. For this, an approach based on the fabrication of composite materials by placing nanoparticles in a porous matrix is applied [4]. One of the promising materials for use as such matrices is nanoporous anodic alumina. Geometric parameters of porous anodic alumina (pore diameter, interpore distance, film thickness) can be varied by changing the anodizing modes. An important advantage of such a material is the invariability of the characteristics of the porous structure of the anodic oxide up to a temperature of 1000 °C [5]. Due to the dielectric properties and good thermal conductivity, porous anodic alumina has a high potential for use in board printing technology. In [6, 7] it was shown that the use of printed circuit boards (PCB) with a metal core for high-power LEDs, in which the anodic alumina layer was used as an insulating layer, has allowed to improve the thermal dissipation and lower the temperature of the LED junctions. For the wide application of nanoporous anodic alumina in PCB technology, information is needed on both its thermal characteristics and possible ways to improve them. However, due to the fact that the anodic alumina is obtained in the form of thin coating, it is not easy to carry out the direct measurements of the thermal conductivity using the appropriate technique.

The aim of present paper was to investigate the thermal conductivity of nanoporous anodic alumina films obtained in sulfuric acid for samples of a two-layer structure consisting of a thick aluminum layer and a thin layer of porous anodic alumina. Thermal measurements based on the steady-state method were used for the studies, when the temperature distribution in the sample was independent of time and the samples had a uniform temperature field in bulk. An electric heater in the form of a carbon filament was placed on the surface of a porous anodic alumina.

A. Experimental

The samples of aluminum plates of 0.8 mm thickness were 60 × 24 mm in size. In order to form insulator layer the aluminum substrate was anodized in 2.0 M aqueous solution of sulfuric acid at constant current density of 32 A m^{-2} and temperature of (10.0 ± 0.1) °C. This results in alumina layer of thickness 20 μm. In order to establish the heat properties of porous anodic alumina layer the surface of the board was heated by the carbon fiber. It allows achieving the homogeneous heating over the board surface. The reverse board side was kept constant by the aluminum radiator of large area. In order to produce heating elements carbon fiber with liner dimensions 80 μm (thickness) × 2 mm (width) × 72 mm (length) was used. The ends of the carbon fiber were covered by 30 μm-thickness copper layer for further bending during heater assembly. Carbon fiber was fixed by 80 μm-thickness prepreg on the surface of nanoporous alumina. The heating element with carbon fiber possessed electric resistance 60 Ω [8]. The non-cooling thermal imaging camera (MobIR M4) was used to study the heat field of the samples.

B. Results and Discussion

In order to estimate the thermal characteristics of the specimens the electrical carbon fiber heater was used. As can be seen from Fig. 1, the temperature distribution on the surface of aluminum board in case of 3.3 W of electrical power is homogeneous, i.e. without local overheating. The temperature gradient of the heater relative to the surface of the board is caused by the thermal conductivity of the nanoporous alumina.

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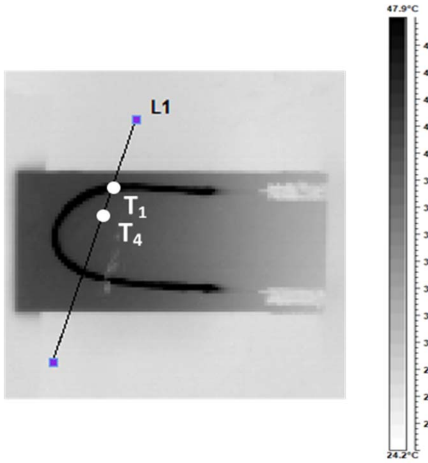

Fig. 1. The circuit board on aluminum with nanoporous alumina layer with carbon fiber heater under electrical power of 3.3 W in the thermal imaging camera measured in 50 s. L_1 is the given line with the control points of T_1 and T_4

For the heating element power of 3.3 W the temperature on the surface of the aluminum board reached 45.1 ºC and 66.1 ºC for carbon fiber in 50 s of heating respectively (Fig. 2).

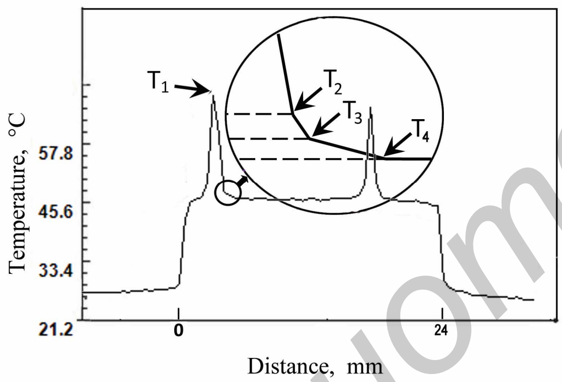

Fig. 2. The temperature distribution profile along the given line (see Fig. 1) for the aluminum board under electrical power of 3.3 W measured in 50 s. The insert shows the points which were chosen to determine the thermal conductivity of the nanoporous alumina: T_1 is the temperature of carbon fiber, T_2 and T_3 are the temperatures of nanoporous alumina layer at the interface with heater and aluminum, respectively, T_4 is an equilibrium temperature of the aluminum layer

For comparison, an experiment was performed with a heating power 2 times greater (6.6 W) than in Fig. 1. As can be seen from Fig. 3, in this case, as well as for an electric power of 3.3 W the thermal field is homogeneously disturbed over the surface of circuit board on aluminum with nanoporous alumina. For the heating element power of 6.6 W the temperature on the surface of the aluminum board reached 101.5 ºC and 57.7 ºC for carbon fiber in 50 s of heating respectively (Fig. 4). Table 1 shows the results of temperature measurements at control points T_1, T_2, T_3 and T_4 on the surface of an aluminum plate with nanoporous anodic alumina if an electric power is 3.3 and 6.6 W, respectively. As can be seen, an increase in the heating power by a factor of 2 leads to a 2-fold increase in the temperature gradient between the carbon filament and the surface of nanoporous anodic aluminum oxide, from 19.4 ºC to 40.6 ºC.

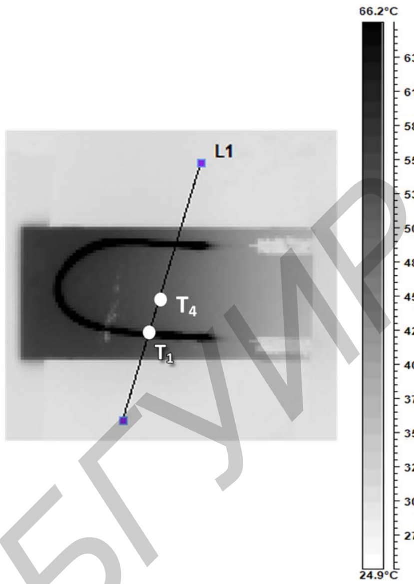

Fig. 3. The circuit board on aluminum with nanoporous alumina layer with carbon fiber heater under electrical power of 6.6 W in the thermal imaging camera measured in 50 s. L_1 is the given line with the control points of T_1 and T_4

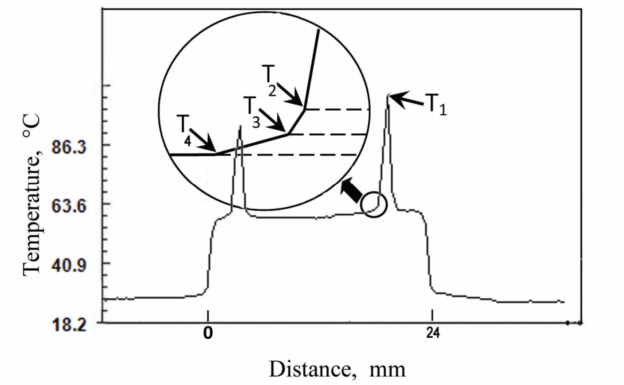

Fig. 4. The temperature distribution profile along the given line (see Fig. 1) for the aluminum board on under electrical power of 6.6 W measured in 50 s. The insert shows the points which were chosen to determine the thermal conductivity of the nanoporous alumina: T_1 is the temperature of carbon fiber, T_2 and T_3 are the temperatures of nanoporous alumina layer at the interface with heater and aluminum, respectively, T_4 is an equilibrium temperature of the aluminum layer

The graphs of temperature change with time for the control points T_1 (temperature of the carbon fiber) and T_4 (the equilibrium temperature of the aluminum layers) for the electric power 3.3 W and 6.6 are shown in Fig. 5. It can be seen that all the temperature curves pass to the saturation area after 30 s of heating. The results of the measurements of the changes in the temperature profile of the aluminum board at the interface with heating element allow calculating the thermal conductivity of the nanoporous alumina layer.

TABLE 1. THE VALUES OF TEMPERATURE AT THE CONTROL POINTS OF T_1, T_2, T_3 AND T_4 FOR THE CIRCUIT BOARD ON ALUMINUM UNDER ELECTRICAL POWER OF 3.3 (FIG.2) AND 6.6 W (FIG.4)

Electrical power, W	3.3	6.6
Temperature of carbon fiber (T_1), °C	66.1	101.5
Temperature of nanoporous alumina layer at the interface with heater (T_2), °C	46.7	60.9
Temperature of nanoporous alumina layer at the interface with aluminum (T_3), °C	45.4	58.3
Equilibrium temperature of the aluminum layer (T_4), °C	45.1	57.7

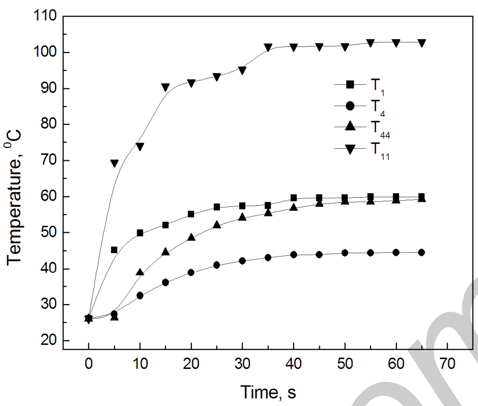

Fig. 5. The change in temperature at the control points T_1 and T_4 (Figs. 2 and 4) on the heating time for the aluminum board with nanoporous alumina layer under electrical power of 3.3 W (T_1, T_4) and 6.6 W (T_{11}, T_{44})

This means that temperature profile has inflection points that correspond to the temperature on the surface of alumina layer at the interface with heater (T_2), the temperature of the alumina layer at the interface with aluminum (T_3) and equilibrium temperature of the aluminum (T_4) (Figs. 2 and 4).

In case when thermal flow passing through the nanoporous alumina layer and aluminum one is the same and cross section is S, the following equation can be written:

$$\lambda_{Al}\frac{(T_3 - T_4)}{d_{Al}}S = \lambda_{Al_2O_3}\frac{(T_2 - T_3)}{d_{Al_2O_3}}S \qquad (1)$$

from where we can obtain the thermal conductivity of nanoporous alumina:

$$\lambda_{Al_2O_3} = \lambda_{Al}\frac{d_{Al_2O_3}(T_3 - T_4)}{d_{Al}(T_2 - T_3)} \qquad (2)$$

where $\lambda_{Al_2O_3}$ is the thermal conductivity of nanoporous alumina; λ_{Al} is the thermal conductivity of aluminum layer; $d_{Al_2O_3}$ is the thickness of nanoporous alumina layer; d_{Al} is the thickness of aluminum layer; T_2 and T_3 are the temperatures of nanoporous alumina layer at the interface with heater and aluminum, respectively; T_4 is an equilibrium temperature of the aluminum layer.

In accordance with equation (2) the value of the thermal conductivity of the nanoporous alumina measured in 50 s for 3.3 and 6.6 W (Table 1) was the same and equaled to 1.0 W K^{-1} m^{-1}. The following raw data were used: the thickness of alumina 20 µm; the thickness of aluminum 0.8 mm; thermal conductivity of AA3003 alloy 180 W K^{-1} m^{-1}. This result agrees with literature data for the thermal conductivity of sulphuric acid alumina 0.85–1.0 W K^{-1} m^{-1} [9,10].

II. CONCLUSION

When the aluminum plate with nanoporous aluminum oxide was one-sidedly heated by a filament-like heater and the temperature of the back side of the plate was kept constant, the thermal field after 30 s of heating had a uniform temperature distribution over the surface.

Increasing the heating power of 2 times from 3.3 to 6.6 W results in 2 time increase in the temperature gradient between the carbon filament and the surface of the nanoporous anodic alumina, from 19.4 °C to 40.6 °C.

The thermal conductivity of the nanoporous anodic alumina layer formed in sulphuric acid was determined to be 1.0 W K^{-1} m^{-1}.

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