Thick Film Heater for Sensor Application

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Abstract. A thick film microheater was elaborated. The microheater is intended for fast heating of small volume samples under measurement in optical based system. Thermal analysis of microheater was carried out using finite element method (FEM) for heat transfer calculation as a function of time and space. A nodal heat transfer function was calculated in classical form including all basics mechanisms of heat exchange - heat conduction, convection and radiation were considered. Work focuses on the influence of some construction parameters (ex. length, thermal conductivity of substrate, substrate thickness) on microheater performance. The results show that application of thin substrate of low thermal conductivity and low thickness for microheater construction and resistor of optimum dimensions leads to significant power consumption decrease and increase of overall optical measurement system performance.

1. Introduction

Optical sensing is one of the most emerging sensor technologies in recent decades. Increasing demand for various data collection is aligned with variety of parameters capable of being measured with the use of optical techniques. The unique optical based system for evaluation of organic liquids using optical capillaries as a sensing element has been developed at Institute of Micro- and Optoelectronics, Warsaw University of Technology. The system was successfully used for investigation of dairy products ex. milk [1] and petrochemical liquids ex. fuel [2]. The system is shown in figure 1. It consists of steel base, laser light source, short optical path part of which is optical capillary filled with investigated liquid, microheater, refracted, transmitted and scattered light detectors. The capillary is placed in shallow V graves on the surface of the steel base. The capillary is pressed to the steel base by two small pieces of magnetic rubber (shown as purple rectangles in figure 1). The heater is placed over the rectangle opening in the steel base (white rectangle in figure 1) on two steps below the surface of the base. The heater is attached to the base by two springs (not shown in figure 1). The dimensions of the heater substrate are 30 x 5 x 0.635 mm. Width of the resistor is 5 mm and length varies in the range from 1 mm to 10 mm. Thickness of the resistor is 20 µm. The level of the steps, the shape of the V graves and the diameter of the optical capillary ensure distance of 50 µm between the surface of the heater and the side wall of the capillary. The liquid placed in quartz capillary is heated over its boiling point by the thick film resistive microheater placed nearby and the bubble of the evaporated liquid is created. The phase change of the medium in capillary, that is a part of the optical path, causes the light transmission change. It is possible to determine many important physical properties of the sample by precise control of temperature of nano-liter volume liquid and transmission of the optical path. For example its purity, chemical composition or percentage of ingredients, can be found. More detailed description of the system was published in [3].
2. Simulation
Since a heat transmission to optical capillary is of great importance in described method the aim of this work was simulation and investigation of thermal properties of heating resistors manufactured using thick-film technology. Simulation was made using finite element method (FEM) for heat transfer calculation as a function of time and space. A nodal heat transfer function was calculated in classical form including all basics mechanisms of heat exchange. No heat transfer through the liquid in capillary was included since the volume of the liquid is negligible in comparison to capillary walls. Heat transfer through the liquid in the capillary is not important because the measurement in the system is carried out until the first bubble of vapour creates and the liquid is removed out of capillary. Al₂O₃ (96%) and ZrO₂ ceramics were used since this substrates have significantly different thermal conductivity with comparable other thermal parameters. First group of heaters was made of standard Al₂O₃ substrates of thickness 635 µm. Repeated measurements of organic liquid properties caused heating of the steel base which had influence on measurements result so the second group of heaters was prepared on ZrO₂ substrates of lower thickness – 150 µm. All important substrate parameters are shown in table 1.

Figure 1. Organic liquid analysis system incorporating optical capillary.

The resistive element was simulated using DuPont 2009 resistive paste with sheet resistance 10 Ω/□. Thermal conductivity, specific heat and emission coefficient of resistor material are not published by the manufacturer. Thermal conductivity of resistive layer was neglected due to its low thickness. The emission coefficient was assumed 0.9 the same as for ceramic substrate. Calculation focused on influence of resistor length on capillary temperature. Length varied from 1 mm to 10 mm. The 3D model of microheater was prepared. The model consists of 50 mm diameter and 5 mm thickness steel base with opening in the central part, 30 mm long and 5 mm wide ceramic heater substrate and 150 µm diameter quartz capillary. Thermal conductivity of resistor layer was neglected because of its low thickness. Distance between the thick film resistor surface and the capillary wall was 50 µm. The 3D model of microheater with steel base and optical capillary is presented in figure 2. Simulation of central area of resistor temperature growth was carried out. Applied power was 600 mW/mm² i.e. maximum power density for Du Pont 2009 resistive film [4] and power 5W, 4W, 3W, 2W, 1W per resistor. Simulations for maximum power density were carried out to assess
possibility of very fast heating of the object under measurement. Thermal destruction of materials was neglected during simulations. During normal operation power is lower and heating is stopped before the resistive layer reaches temperature of 350 °C. Steel base was the heat sink. Temperature of the steel base was 20 °C, and it was constant during the single experiment as time of heating was very short and amount of heat dissipated to the base did not cause growth of steel base temperature. The contact area between the substrate and the base was 10 mm\(^2\) at each end of the substrate. Convection was natural. The main aim of numerical analysis was reduction of the number of the experiments during resistor dimensions optimization. Figure 3 shows the heater central area temperature dependence for simulations with and without optical capillary for both substrates as a function of resistive element length.

It can be seen that lower heat transfer from the resistor through the substrate to the steel base can cause quicker heating to higher temperature. Lower heat transfer is caused by the use the substrate of lower thickness and lower thermal conductivity.

Presence of capillary in short distance over the resistor reduces temperature growth of central part of the heating resistor.

Table 1. Substrate parameters.

| Parameter                          | \(\text{Al}_2\text{O}_3\) | \(\text{ZrO}_2\) |
|------------------------------------|---------------------------|-----------------|
| Density \([\text{g/cm}^3]\)        | 3.72                      | 6.0             |
| Max. working temperature \([\text{K}]\) | 1700                      | 1500            |
| Th. conductivity \([\text{W/mK}]\) | 25                        | 2               |
| Th. Expansion coeff. \([10^{-6} \text{ K}^{-1}]\) | 8.2                       | 10.3            |
| Specific heat \([\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}]\) | 880                       | 400             |
| Emissivity                        | 0.9                       | 0.91            |
| Thickness \([\mu\text{m}]\)       | 635                       | 150             |
Figure 3. Maximum temperature of heating element as a function of time for ZrO$_2$ substrate (a) and Al$_2$O$_3$ substrate (b). Length of the resistor is the parameter. Solid lines – without optical capillary (NC), dashed lines – with optical capillary (CP).

3. Experimental

For the experiment the microheaters of various resistor length were prepared on alumina and zirconia substrates. Both experiments of heating microheater with and without capillary presence were carried out. Various values of heating power were applied. Temperature of the resistor and capillary surfaces was measured with thermovision camera R300.

The results of temperature distribution measurements over microheater surface with and without capillary presence are presented in figure 4. Microheater was prepared on alumina substrate. Applied power was 5W. Such level of power causes heating the microheater central area up to temperature of 300 °C during about 30 seconds. Quicker heating was possible however the optical measurement setup needed moderate temperature growth. The resistor length was 5 mm. Such resistor length on alumina substrate ensures reasonable balance of radiated power and power dissipated by the substrate to the steel base. Results of simulations and results of measurements are consistent. It can be seen that large amount of power is dissipated through the alumina substrate to the base (see temperature distribution in figure 4c and 4d). Please note higher temperature region of the side surface of the substrate in neighborhood of the resistor (figure 4c). The reason of higher temperature of the side surface of the substrate is low heat transfer through surrounding air in direction perpendicular to the side surface. The two-wedge shape of this region is caused by combination of two heat transfer mechanisms: conduction along the substrate and radiation perpendicular to the substrate surface. As a matter of fact this high temperature region shows the temperature distribution in a cross section of the substrate to some extent. Application of zirconia substrates of low thickness is reasonable. Both simulations and measurements show that capillary presence reduces temperature of the central part of the resistor in proximity of the capillary. It is hard to see, especially at thermal image of the device, because the capillary covers the resistor.
Figure 4. Temperature distribution over microheater surface. Substrate – alumina, resistor length – 5 mm, power - 5 W, time - 30s.: (a) simulation without optical capillary, (b) simulation with optical capillary, (c) thermovision camera image without optical capillary, (d) thermovision camera image with optical capillary.

Figure 5. Temperature growth of microheater central area surface. Substrate – alumina, resistor length – 5 mm, power - 5 W. Solid lines – simulation, dashed lines – measurement.

Results of microheater central area temperature growth simulations and measurements for various heating power values are presented in figure 5. Simulations and measurements results are consistent. The good agreement is caused by proper choice of heat transfer mechanisms (conduction through substrate to the steel base, radiation and convection) and parameters for simulation.
Figure 6 presents measured time of reaching temperature of 100°C by the water in the capillary as a function of the resistor length. The experiment was carried out in optical system. Power density applied to the resistor was 600 mW/mm² i.e. maximum power density for Du Pont 2009 resistive film. The moment of reaching boiling point was determined by optical measurement. It can be seen that time of heating to T = 100°C is dependent on resistor length. This time increases for resistors shorter than 5 mm for alumina substrate and 2 mm for zirconia substrate. The reason of heating time reduction is cooling of central area of the resistor by heat transfer through ceramic substrate to surrounding air and to the steel base. Optimum lengths of heating resistors are 5 mm and 2 mm for alumina and zirconia substrates respectively. Resistors of such lengths allow for heating the liquid in the capillary quickly and with minimum power expense.

4. Conclusions
The simulations of temperature growth and temperature distribution over surface of thick film resistive microheater for sensor applications were carried out. The test microheaters were prepared on alumina and zirconia substrates and the heating experiments were executed. The results of performed measurements show that temperature growth and temperature distribution are consistent with simulation results. The best performance was reached for 2 mm long resistor on zirconia substrate. Such construction of thick film resistive microheater allowed to quickly heat the measured liquid sample in the capillary and at the lowest power expense.

5. References
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