Microfabricated heaters for thin films TCR characterization

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***Abstract*—In this paper two designs of heaters for thin films TCR characterization are presented. During this process, its thermoelectric behavior was simulated with Ansys Mechanical. In addition, they were microfabricated on two different substrates and then characterized. From the simulation, the temperature distribution on the sample was obtained. Moreover, from the experimental characterization, temperature outputs were measured as a function of the power supplied. Taking that into account, the influence of the substrate material on the performance was studied.**

Keywords—heater, NiCr, TCR, thin film, microfabrication, simulation and thermo-electric

I. Introduction

The materials study is fundamental in the MEMS design and application. Because of that, there are many researchers studying how the conditions of deposition and post deposition treatment influence the crystallinity and electrical properties of thin films [1-4]. More specifically, the resistivity and its variation with temperature and time are properties of interest to determine the suitability of a material for a certain application. Moreover, being capable of determining the dependence of these electrical properties with certain process variables could help to improve the microfabrication to have better results.

For these reasons, this paper reports the design, simulation, microfabrication and experimental characterization of NiCr heaters on alumina and glass substrates. Particularly, these heaters were designed to integrate a universal probe (Jandel, from Bridge Technology) for 4-point measurements of resistivity. The purpose is to heat thin films to study its resistivity dependence with temperature and calculate its TCR. The heaters have to be able to set at least a 30°C temperature difference over room temperature on the samples. One challenge was to restrict the thickness of the heating system to fit into the available space given by the needles travel. Another one was reducing the thermal loss to the probe chuck.

II. Design

The device must heat a thin film during resistivity tests. To be incorporated in the probe station, the total thickness of the system must not exceed 3 mm. It includes a thin film heating resistance, a substrate, a sample and an insulator. With the lumped model of Fig.1, the following relations were obtained

$$P_{total} = \varepsilon^{-1} h_{conv} A_{surf} \Delta T_{req} \quad (1)$$

$$\varepsilon = \left[1 + \left(\frac{e_s}{\lambda_s} + \frac{1}{h_{conv}}\right)\left(\frac{e_b}{\lambda_b} + \frac{e_i}{\lambda_i}\right)^{-1}\right]^{-1} \quad (2)$$

$$P_{total} = \frac{V^2}{R_h}, \quad (3)$$

where ε is the power efficiency, h_{conv} is the convection heat transfer coefficient, A_{surf} is the area exposed to convection, ΔT_{req} is the temperature difference required, P_{total} is the electrical power, V is the applied voltage, R_h is the electrical resistance of the heater, λ_x and e_x are the thermal conductivity and the thickness of an x material respectively (see Fig.1).

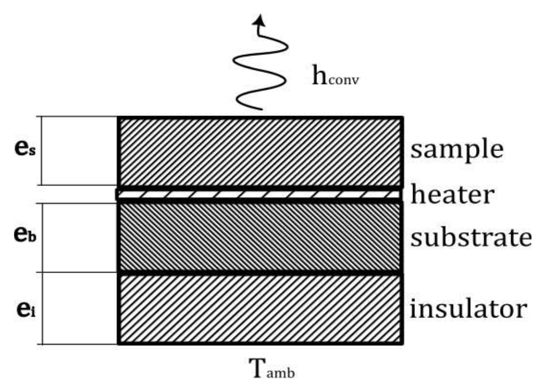

Fig.1. Diagram of the lumped model for the device design.

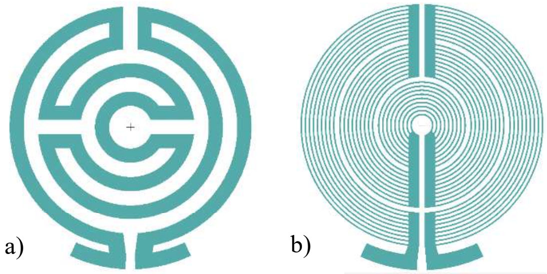

Fig.2. Masks designs for heaters refered as a) HJ-2400 and b) HJ-200 with 2400 µm and 200 µm trace width respectively.

NiCr was chosen for the heating resistor material because of its convenient properties for the application. It has a high electrical resistivity (1−1,5 Ωµm), high thermal conductivity (19 Wm^{-1} K^{-1}), low-temperature coefficient of resistance (TCR), high-temperature stability and high resistance to oxidation [5]. Two types of substrates were used, 75x50x1 mm^3 glass slides and 50 mm diameter alumina (96% Al_2O_3) discs with a thickness of 0,6 mm. A 0,5 mm air gap was used as the insulator. Given the properties of the materials and the temperature difference required, the resistance was calculated considering the power source limitations. Two geometries were proposed to meet the resistances required with a film thickness of 200 nm, referred as HJ2400 and HJ200 (Fig.2).

III. Simulation

Another relevant characteristic of the heater is the temperature distribution on a sample, which may affect the 4-point probe resistivity measurement. A uniform distribution around the centre of the sample is desired. To determine the performance of the designs proposed, a thermo-electric stationary model of the heaters was developed and solved with Ansys® Mechanical thermo-electric solver.

The domain considered includes the NiCr heater, the substrate (glass or alumina), an insulator layer (air) and a sample (a standard glass slide). The material properties used, thermal conductivity and electric resistance, are summarized in Table I.

The thermal boundary conditions were defined. At the base of the system, under the insulator, a uniform temperature condition is set to 22 ºC. At the top faces of the domain, convection condition is applied. The heat transfer coefficient was estimated with the natural convection correlation [6] using air, the exposed surface area and a temperature difference of 50 ºC resulting in h = 8,2 W/(m^2K). For the electrical boundary condition, an input voltage difference is set between the ends of the heater.

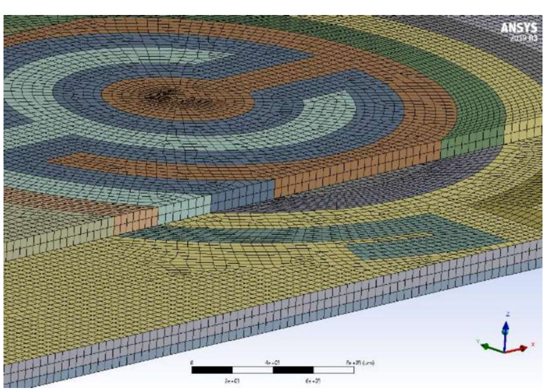

Fig. 3. Mesh for the numerical mode for the heaters simulation.

The model was meshed with a 500 µm and 200 µm side size on the plane of the heaters, for the HJ2400 and HJ200 designs respectively. In the normal direction the sizes of cells are 500 µm (Fig.3).

The numerical model was solved for different input voltages, ranging from 30V to 70V. Temperature, Joule heat and current density were extracted to characterize the temperature distributions and the resistances of the heaters.

TABLE I. Material properties set on simulations

Material	Properties	
	Thermal Conductivity [$Wm^{-1}K^{-1}$]	*Electric resistivity [Ωµm]*
Nichrome	19	1,07
Glass	1,3	10^{20}
Alumina	30	10^{20}
Air	0,026	10^{20}

IV. Microfabrication

The fabrication was performed in a cleanroom using thin-film microfabrication technology.

The process started with the cleaning of the substrates on piranha solution (98 wt % H_2SO_4 and 30 wt % H_2O_2, volume ratio of 2:1 for 10 minutes, at room temperature) to remove organic contamination.

Then, a conventional photolithography process was performed with a TI35E (Microchemicals) photoresist in image reversal mode to create the patterns from Fig.2. The substrates were spin coated, exposed with a flexible film photomask and soft baked (at 90°C for 20 minutes). Next, the flood exposure step (an exposure without mask) and the development were carried out.

The NiCr alloy (Ni-Cr 80/20 wt %) thin film was deposited through DC magnetron sputtering. A Boc Edwards Auto 500 physical vapour deposition system was used with the following conditions: 5,07.10^{-3} mbar of working pressure, 20 sccm of Ar, 200 W of DC power and 30 minutes of deposition time. The final step was a lift off process.

V. Characterization

After the fabrication, the heaters were tested in the setup presented in Fig.4. The temperature was registered on the

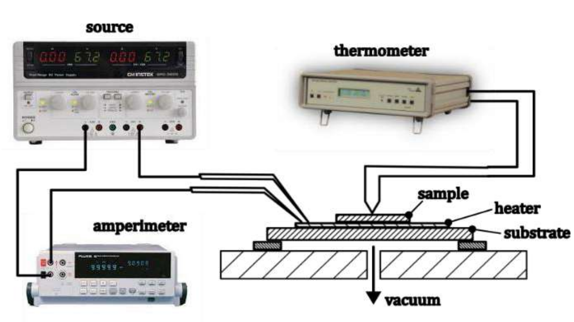

Fig. 4. Diagram of the experimental characterization.

centre of upper side of a glass slide. This was acquired with a Tek Now SM-300 precision thermometer and a type K thermocouple. The substrates were placed on a rubber sheet with a ring shape to generate vacuum under the substrates to thermally isolate them from the chuck.

The power was supplied by an SPD-3606 DC power source between 30 V and 70 V. Also, the circulating current was registered for each tension value with a Fluke 45 multimeter. All measurements were made after 20 minutes to let the system to reach thermal steady state.

VI. RESULTS

From the characterization and simulations, the resistance of the different designs with the relation of voltage and current was obtained, see Table II. It should be noted that for the simulation there is no distinction between substrate as the model is not able to consider that interaction. Giving that, there is a difference between simulation and experimental results, this could be caused by the thin film thickness or roughness of the substrate.

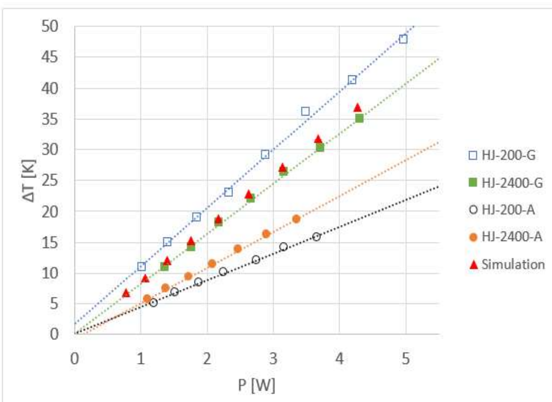

Fig.5. Curves showing the difference of temperature as a function of power and voltage supplied for both designs and substrates.

TABLE II. ELECTRICAL RESISTANCES OF THE HEATERS

Material	Resistance [kΩ]		
	Glass	*Alumina*	*Simulation*
HJ2400	1,11	1,50	1,16
HJ200	0,85	1,33	1,01

Another relevant result is the relationship between input power and temperature difference obtained on the sample respect to ambient temperature. Fig.5 shows the results from the characterization and the simulations. Simulations do not vary greatly between designs, so they are represented as a unique set of points. Then designs with alumina as substrate show less temperature response as function of input power.

With the simulations, the temperature distribution of the different designs was estimated. Fig.6 shows how the longitudinal and horizontal section of the profile changes with input power. To characterize the uniformity, the relative temperature profile θ was calculated as

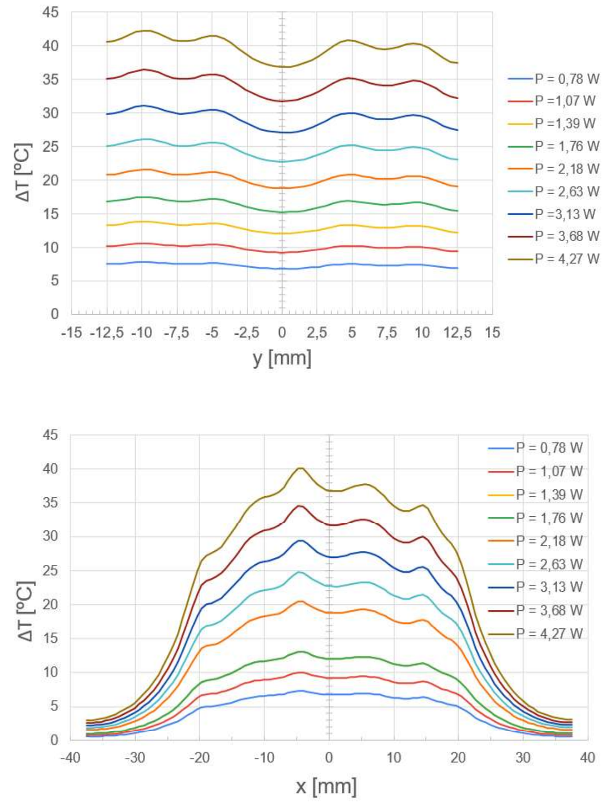

Fig.6. Temperature profiles simulated for HJ-2400 on glass substrate across x=0 and y=0.

$$\theta = \frac{T(x,y) - T_{amb}}{T(0,0) - T_{amb}} \tag{4}$$

On Fig.7, it is compared and showed that the temperature is more uniform for the simulations with alumina as the substrate, that is explained by the higher thermal conduction. The 2D distributions for all cases are presented on Fig.8.

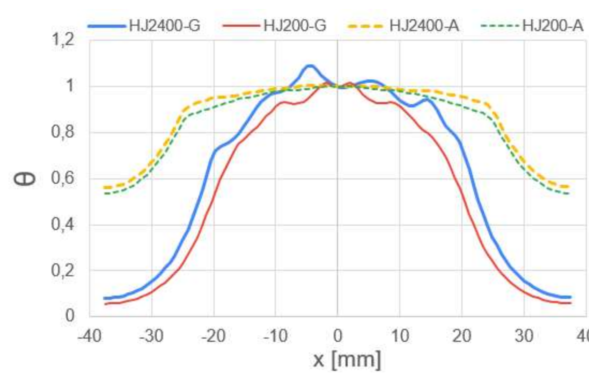

Fig.7. Comparison of relative temperature simulated profiles at y=0.

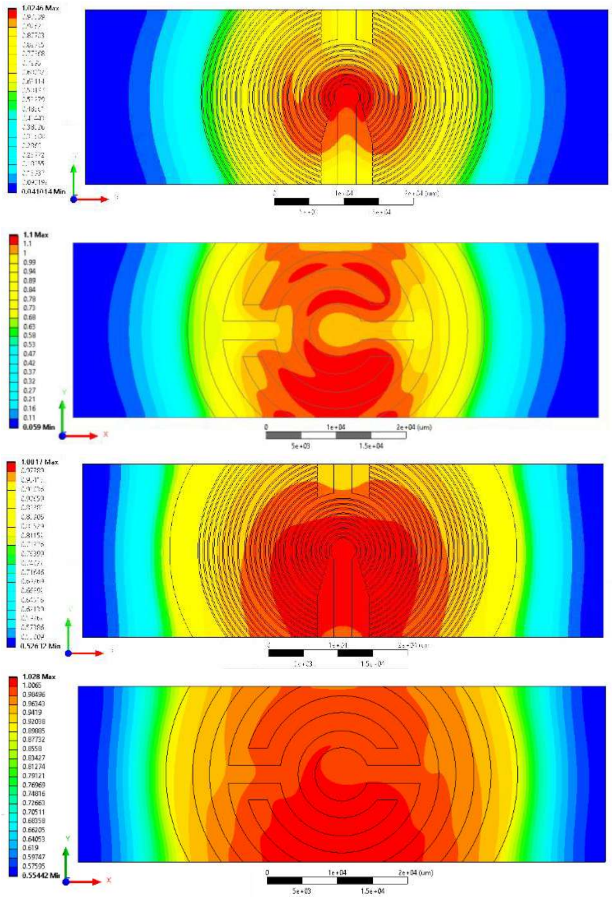

Fig.8. Relative temperature level maps (from the top to the botton): HJ-200-G, HJ-2400-G, HJ-200-A and HJ-2400-A.

Additionally, a thermographic camera FLYR T 400 was used to evaluate the thermal distribution on a sample on top of the heater (Fig.9). It is important to note that the color scale seen in the images is different between materials because of its different thermal emissivity.

VII. CONCLUSIONS

In this work, four different heaters were designed, simulated, microfabricated and characterized successfully for TCR evaluation of thin films.

It was noted that our model requires an experimental value of resistivity to adjust to the measurements as this property can vary with the material of the substrate, deposition and post processing conditions (e.g. an annealing).

In addition, it was observed that the temperature profiles are more uniform on the devices with the alumina substrates due to its higher thermal conductivity. On the other hand, the

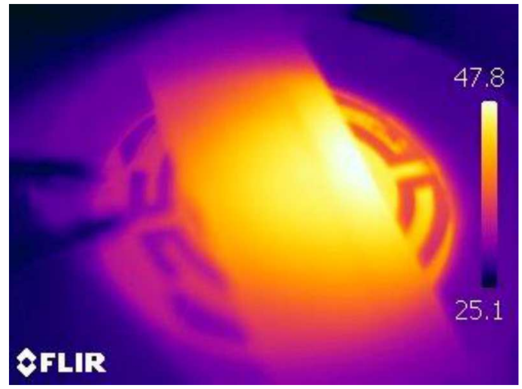

Fig.9. Thermographic image of the HJ-2400-A heater with a sample (a glass slide) on top of it.

characterization showed major heat loss in the designs with the same substrates. This indicates a trade-off between temperature uniformity and power efficiency. This could be addressed introducing a highly thermal conductive layer over the heater

However, all the designs reached the temperature difference required so the devices can be used for the intended application.

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REFERENCES

[1] Das, S., Akhtar, J. Comparative Study on Temperature Coefficient of Resistance (TCR) of the E-beam and Sputter Deposited Nichrome Thin Film for Precise Temperature Control of Microheater for MEMS Gas Sensor. In: Jain, V., Verma, A. (eds) Physics of Semiconductor Devices. Environmental Science and Engineering. Springer, Cham. 2014

[2] Ting-Ting Wu et al., "Electrical properties of micro-heaters using sputtered NiCr thin film," The 8th Annual IEEE International Conference on Nano/Micro Engineered and Molecular Systems, Suzhou, 2013, pp. 466-469.

[3] Lifei Lai, Xianzhu Fu, Rong Sun, Ruxu Du, Comparison of microstructure and electrical properties of NiCr alloy thin film deposited on different substrates, Surface and Coatings Technology, Volume 235, 2013, pp 552-560.

[4] Imam H. Kazi, P.M. Wild, T.N. Moore, M. Sayer, The electromechanical behavior of nichrome (80/20 wt.%) film, Thin Solid Films, Volume 433, Issues 1–2, 2003, pp 337-343

[5] Jeroish, Z.E., Bhuvaneshwari, K.S., Samsuri, F. et al. Microheater:material, design, fabrication, temperature control, and applications—a role in COVID-19. Biomed Microdevices 24, 3 2022.

[6] Jack Philip Holman. Heat Transfer. McGraw-Hill Companies, 2002, pp. 342–344.M.