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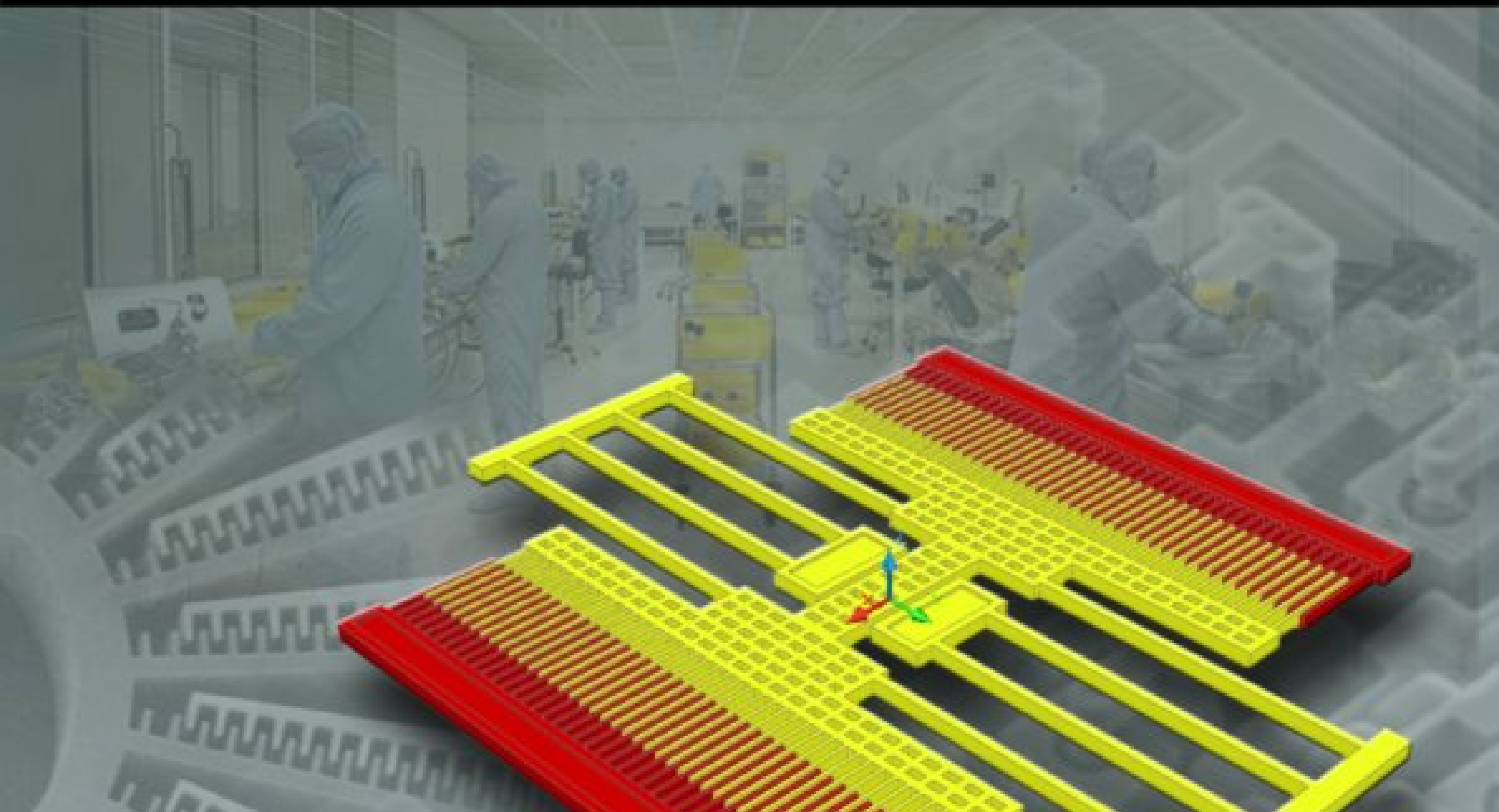

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Design and Development of Polysilicon-based Microhotplate for Gas Sensing Application

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Abstract: The paper presents the design and development of a polysilicon-based microhotplate (MHP) on a SiO_2 membrane formed by bulk micromachining in <100> orientation *P*-type silicon. The chip comprises four microheater cells, which can be used separately or in series combination. The chip size is 2.1 × 2.1 sq. mm. The design and simulation of a single-cell microhotplate is carried out using ANSYS. The complete fabrication process is described in this paper. The temperature coefficient of resistance (TCR) of polysilicon resistors of values 5.7 kΩ and 3.36 kΩ has been measured as 0.69×10^{-3} and 0.5×10^{-3} per °C respectively. These values are used to estimate the temperature of the polysilicon heater by measuring the change in resistance value of the resistor on applying a voltage to it. Temperatures up to 367 °C have been calculated at low bias voltages. As the sensitivity of the gas sensing film is temperature dependent, the developed hotplate will be used as a platform for fabricating the gas sensors. *Copyright © 2009 IFSA.*

Keywords: Polysilicon heater, Bulk micromachining, MHP, Gas sensor, TCR

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1. Introduction

Semiconductor metal-oxide gas sensors normally require high power consumption of several watts because of the elevated operating temperature requirement. In modern applications including wireless sensor networks and portable sensors, low power consumption is essential. Conventional sensors use a nichrome coil or thick-film heating element for their operation. As these gas sensors have to be continuously operated for gas monitoring, a lot of power is unnecessarily wasted. MEMS technology-based microhotplate provides a solution to this problem because temperature can be locally confined in a small area with minimal heat conduction losses [1]. Several researchers have fabricated MEMS hotplates using polysilicon [1] or platinum [2] spirals as heating elements.

In MEMS, there are two main technologies for hotplate development, viz., surface and bulk micromachining. In the former, the suspended membrane has a higher mechanical strength but it provides poor thermal isolation. The latter technique gives superior thermal isolation but the membrane is mechanically weaker. The bulk micromachining process was used in the present work.

To monitor the environmentally relevant gases like carbon monoxide (CO), methane (CH_4) and ozone (O_3), the semiconductor-based gas sensors are widely used [3, 9]. Commonly used chemically sensitive materials for these target gases are wide-bandgap semiconducting oxides such as tin oxide, tungsten oxide or indium oxide, which are operated at elevated temperatures of 200–400 °C. At the high temperatures, these oxides show considerable resistance changes upon exposure to a multitude of inorganic gases and volatile organics. The most prominent example is tin oxide (SnO_2), which shows large electrical resistance changes upon exposure to the above-mentioned gases at operating temperatures between 250 °C–350 °C, and has been engineered to provide sufficient long-term stability. The polysilicon layer deposited by low-pressure chemical vapor deposition (LPCVD) process has been used to fabricate the microheater, which can create this temperature range by applying a small DC voltage.

2. Design and Simulation

A four-element polysilicon-based microhotplate array has been designed by using L-Edit. The complete die has the dimensions 2.1 mm × 2.1 mm. The detailed specifications are given in the Table 1. The single-cell microhotplate is a $100 \times 100\ \mu m^2$ membrane of thickness 1.0 micron (silicon dioxide) over which a polysilicon heater of 2 kΩ is laid out. The designed chip consists of four trapezoidal openings to allow post-process etching of exposed silicon, forming a pit so that the microhotplate can be suspended in the air. There are four supporting beams for each MHP membrane which give the mechanical strength to the membrane and provide electrical connections for heaters. The layout of the hotplate consists of five photomasks: MHP-1 for polysilicon resistor definition, MHP-2 for contact holes, MHP-3 for cavity etching, MHP-4 for metal lift-off and MHP-5 for protection.

Table 1. Dimensions used in mask layout.

Die Size	$2.1 \times 2.1\ mm^2$
Heater finger width	10 μm
Gap between fingers	5 μm
Interdigitated electrode width	10 μm
Gap between interdigitated fingers	5 μm
Metal pad size	$200 \times 200\ \mu m^2$
Hotplate size	$100 \times 100\ \mu m^2$

To verify the design, the transient and steady-state electro-thermal simulation of the unit cell has been carried out by ANSYS, a widely used finite-element based software for simulation of MEMS devices. In this simulation, the SOLID69 element has been used, which supports the basic thermoelectric analysis taking the joule heating effect into consideration. SOLID69 has 3-D thermal and electrical conduction capability. Standard values of physical constants and material properties have been taken from Table 2. In this analysis, a Si substrate has been taken on which there is a 1.0 micron thick SiO_2

layer for supporting the membrane. Above the oxide layer there is a 1.0-micron thick polysilicon layer for microheater and 0.2 micron gold layer to take out the connections. For simulating the effect of cavity below the hotplate, the Si layer underlying the hotplate has been extruded. The temperature of Si substrate surrounding the hotplate was fixed at 20 °C as the boundary condition. The typical ANSYS plots of temperature distribution at 5 V with and without Si inside the cavity are shown in Fig. 1 and Fig. 2 respectively. It is seen from Fig. 1 that a temperature of 21-23.4 °C was achieved, i.e., there was negligible heating of hotplate when Si was present inside the cavity, as expected. In Fig. 2, the temperature of 139°C was achieved at the edges of the heater while at its centre, the mean temperature was 526.8 °C. This represents the case in which there is no conducting medium inside the cavity and is compared with the practical situation in which air fills the cavity (see Fig. 3). From this ANSYS plot, at the edges of the heater, the mean temperature was 112°C, and the temperature at its centre was 412°C.

Table 2. Material properties used in simulation.

Material Properties (in MKS)	Si	SiO_2	Gold	Polysilicon	Air
Thermal Conductivity (W/m/K)	149	1.4	310	150	0.027
Resistivity (ohm-m)	1.0×10^{-1}	5.05×10^{13}	2.2×10^{-8}	5.1×10^{-5}	10^{9}
Specific Heat (J/kg/K)	0.7×10^{3}	710	129	753	1000
Density (kg/m^3)	2.33×10^{3}	2200	19300	2330	1.205

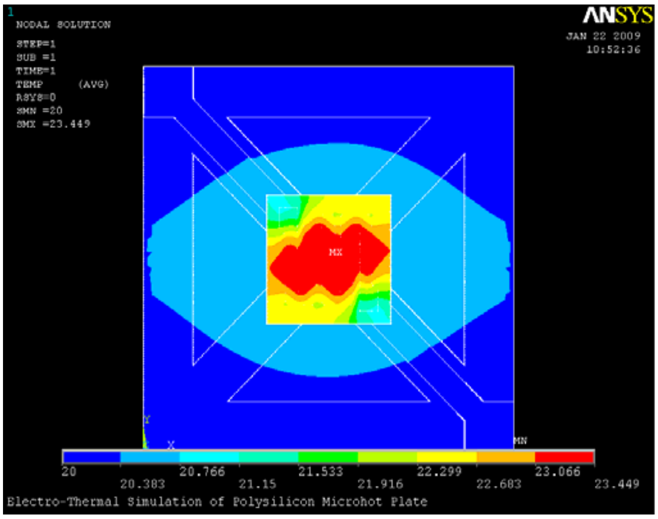


Fig. 1. Temperature distribution at 5 V with Si inside cavity.

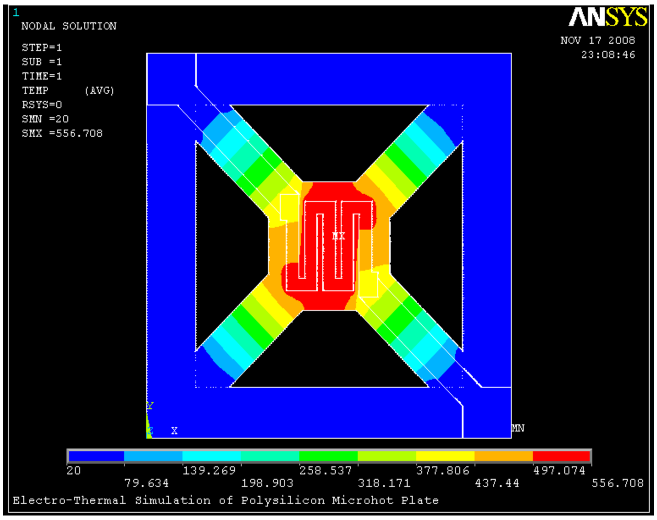


Fig. 2. Temperature distribution at 5 V without Si inside cavity.

The reason for the temperature differences between Figs. 2 and 3 is as follows: When air inside the cavity was included in the analysis, the heat losses by convection were also taken into account. As a result, the maximum temperature at the centre of the hotplate was reduced. The temperature distributions in the central zone of the heater obtained from ANSYS simulation for bias voltages of 2, 3 and 4 V were 117-129 °C, 218.3-243.1 °C, and 338.3-378.1 °C respectively. Thus by varying the supply voltage to the heater terminals, the required temperature of the platform was reachable. The thermal time constant of the simulated heater at 5V was 3.2 ms, which is shown in Fig. 4; this simulation has been done without taking air medium into consideration.

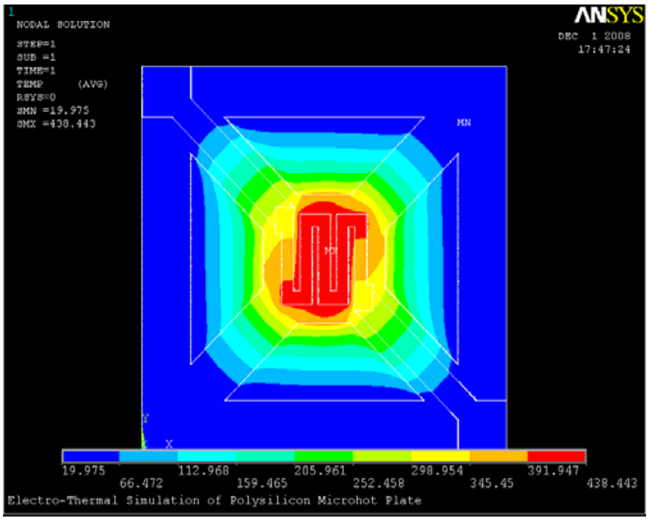


Fig. 3. Temperature distribution at 5 V with air inside Si cavity.

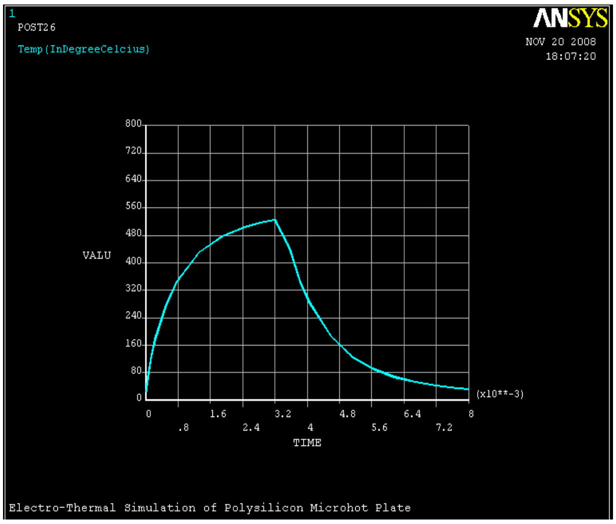


Fig. 4. Transient response of Microhotplate at 5 V.

3. Experimental Details

3.1. Microhotplate Fabrication Process

Fig. 5 illustrates the different stages of the microhotplate process. The starting wafer was *P*-type silicon having resistivity 1-10 Ω-cm and orientation <100> (Fig. 5a). The first step was to grow a thermal oxide layer of thickness 1 μm to provide a mechanically strong substrate for the base layer over which the microheater will be made (Fig. 5b). Then 1 μm-thick polysilicon layer was deposited by LPCVD technique (Fig. 5c) on the oxidized silicon wafer at 630 ^{o}C to form the heating element. In this process, the gas flow used was 115 sccm SiH_4 on front side and 35 sccm SiH_4 on backside. The deposition time and the vacuum were 1 hour 20 minutes and 250 mtorr respectively. Phosphorous diffusion in polysilicon layer was performed at 950 °C to achieve the desired sheet resistance (50-70 Ω/sq) for controlling the resistance of the microheater. Then a thin thermal oxide layer was grown over it (Fig. 5d). The polysilicon layer was selectively etched to form the spiral-shaped microheater element (Fig. 5e). After the resistance adjustment step, insulating protective oxide layer of 0.5 μm thick was formed by plasma-enhanced chemical vapour deposition (PECVD) at 300 ^{o}C (Fig. 5f). The necessity of PECVD oxide arose because growth of thermal oxide results in consumption of underlying polysilicon, thereby altering the polysilicon film thickness. Contact holes were made in this layer to provide electrical connections formed on the PECVD oxide layer. The gold layer of thickness 0.2 μm was deposited by sputtering technique to form the interdigitated electrode geometry (Fig. 5g) and electrical connection for heater. Lift-off process was used for gold pattern definition. To avoid any shorting of the interdigitated fingers during metallization, negative profile of the positive photoresist S1818 has been created by giving the chlorobenzene soak for 10 minutes before developing. As the sensing film was deposited over the gold layer, the interdigitated electrodes helped in decreasing the resistance of the sensing film, making it easy for measurement because higher resistance values in the mega ohm range are more susceptible to noise. The cavities were etched from the trapezoidal-shaped regions so that the microhotplate was suspended in the air through the thin bridges attached to the four corners (Fig. 5h).

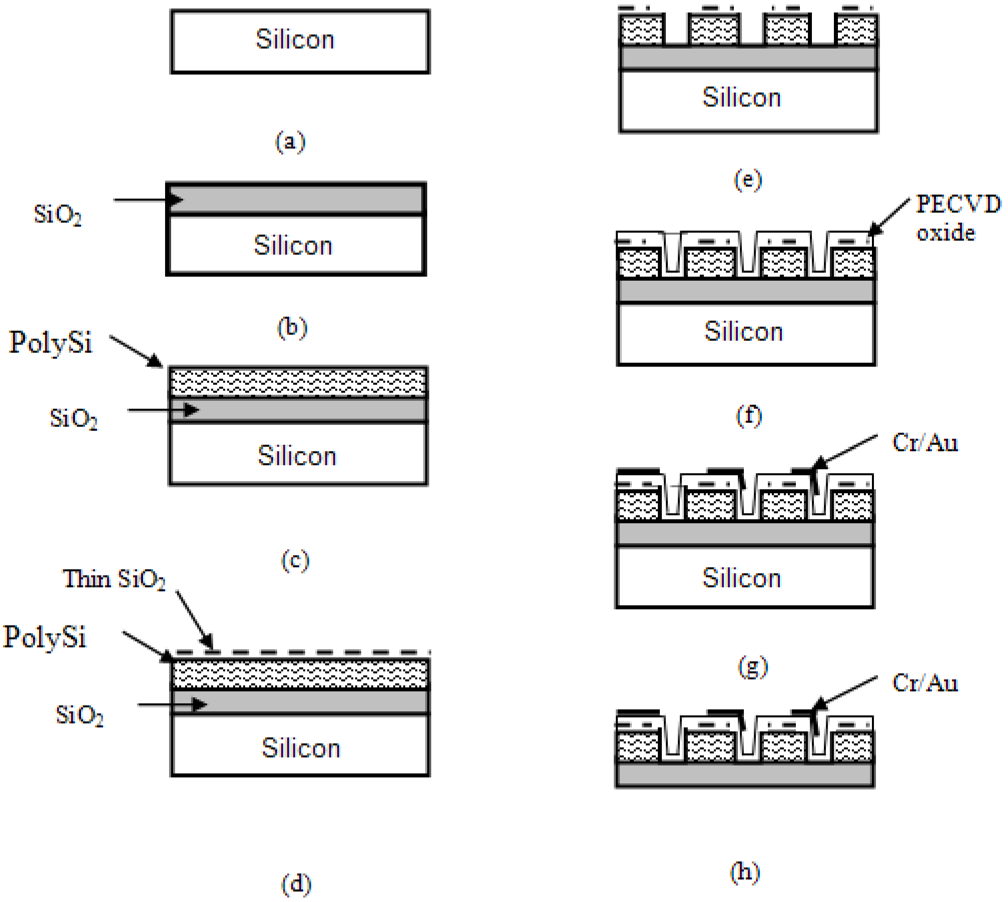


Fig. 5. Schematic process flow of the microhotplate.

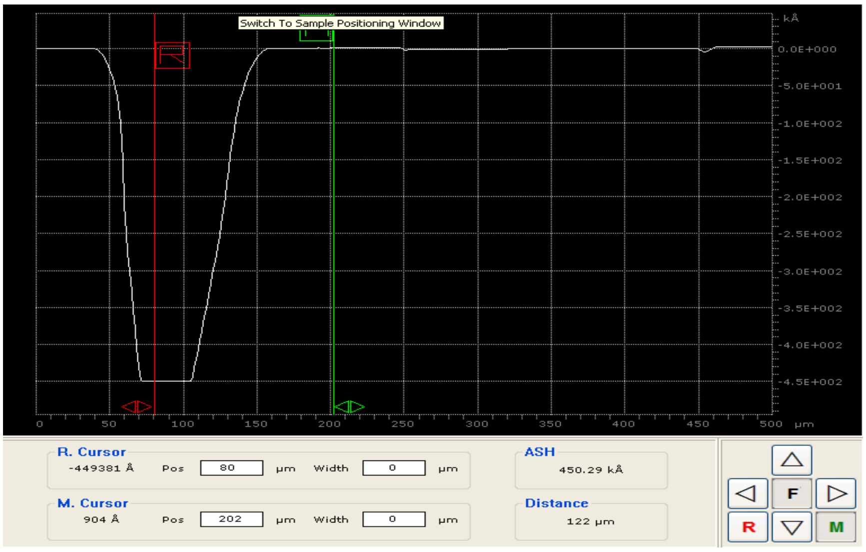
Bulk micromachining was carried out at the end of the process using tetra-methyl ammonium hydroxide (TMAH) to form a 45.0-micron deep cavity below the hotplate. The etching was done at 65 °C, after protecting the top surface with PECVD silicon nitride and SU-8 photoresist.

The etching time was 4 hours, 30 minutes. SU8 2025 photoresist of thickness 19 micron was used to give the extra protection to polysilicon resistors during bulk micromachining. The prebake and hard bake times of SU8 2025 were 24 min (12 min at 65 °C and 12 min at 95 °C) and 30 min (at 95 °C) respectively. In this process, the exposure time and intensity of UV light were 9 sec and 32 mW/cm^2 respectively. The depth of the cavity was measured by Dektak 6M surface profiler (see Fig. 6).

Fig. 7 shows the SEM photograph of the complete chip after bulk micromachining. It is clear from this photograph that the hotplate is isolated from the silicon wafer and remains suspended by its four supporting beams at the corners.

3.2. Packaging and Measurements

The complete chip was wire bonded (see Fig. 8) and packaged. In this process the microheater dies were mounted on TO type 14-pin header using EPO-TEK H20E silver epoxy with curing temperature 120 °C for duration of 40 minutes. Thereafter, one mil diameter gold wires were bonded for external connection of individual heating elements and interdigitated electrodes of the device. These wires were bonded by using WestBond Bonder thermosonically at 120 °C. The resulting hotplate was a 2.5-micron thick membrane suspended in air. As the heat losses were minimized, it could achieve the required high temperature with low power consumption in milliwatt range.



R. Cursor
-449381 Å Pos 80 µm Width 0 µm

M. Cursor
904 Å Pos 202 µm Width 0 µm

ASH
450.29 kÅ

Distance
122 µm

Fig. 6. Depth of cavity.

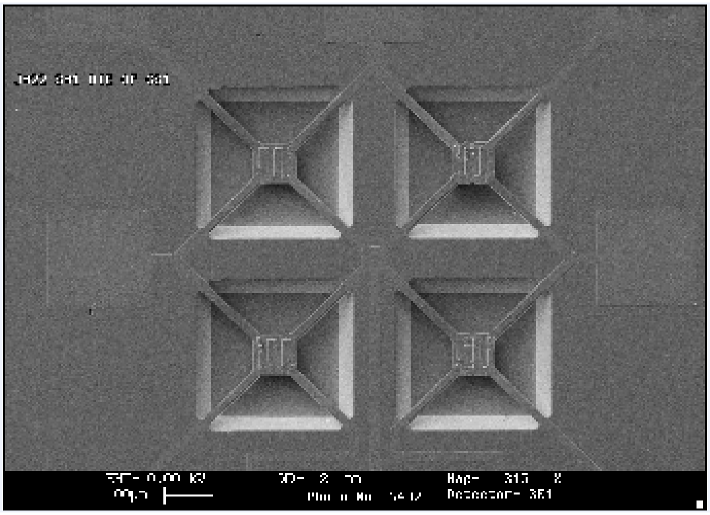


Fig. 7. SEM photograph of the complete chip after bulk micromachining.

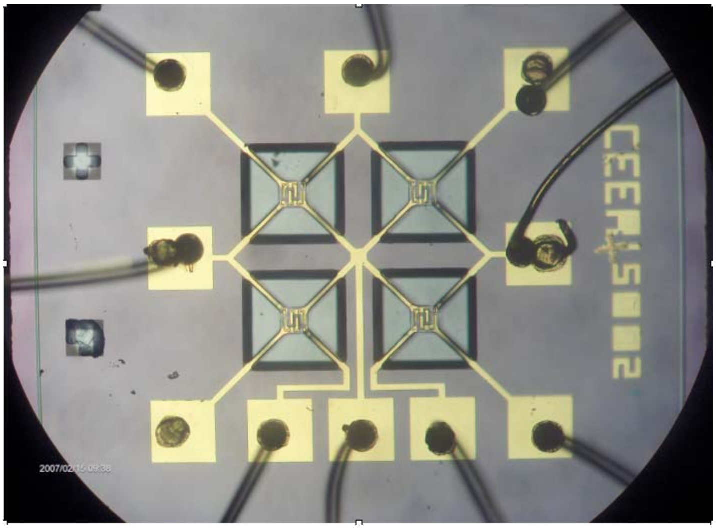


Fig. 8. Final chip with wire bonding.

The TCR of polysilicon microheater was obtained by electrically heating the device in a temperature-controlled oven in 20-degree steps to 160 °C. The resistance was measured by an ohmmeter at each 20-degree step. TCR value for polysilicon is obtained by using the equation

$$(\Delta R/R_o) = \alpha\,(\Delta T) \tag{1}$$

where ΔR is the change in resistance, ΔT is the change in temperature, and R_o is the resistance at 20 °C.

4. Results and Discussion

Figs. 9(a) and (b) show the variation of resistance of polysilicon heater with increasing temperature. By using equation (1), the values of α have been calculated as 0.5×10^{-3}/ °C and 0.69×10^{-3}/°C for polysilicon resistors 3.36 kΩ and 5.7 kΩ respectively. It is clear from the figure that the polysilicon resistor value varies linearly with temperature. The value of α was used to estimate the temperature of the microhotplate.

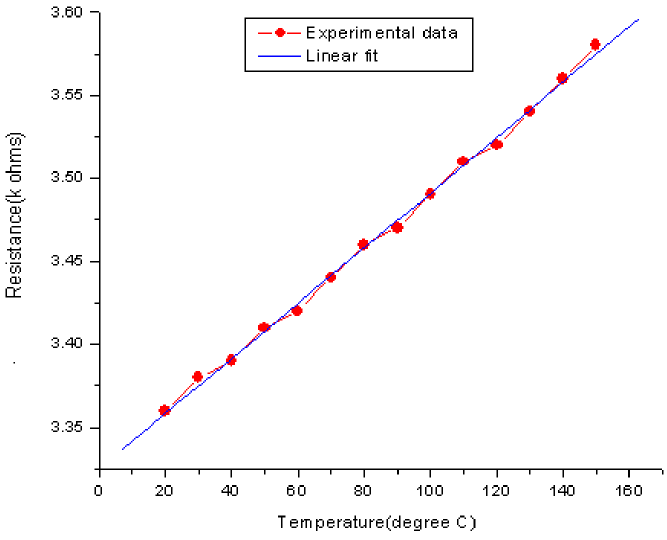


Fig. 9 (a). TCR measurement of polysilicon for 3.36 kΩ.

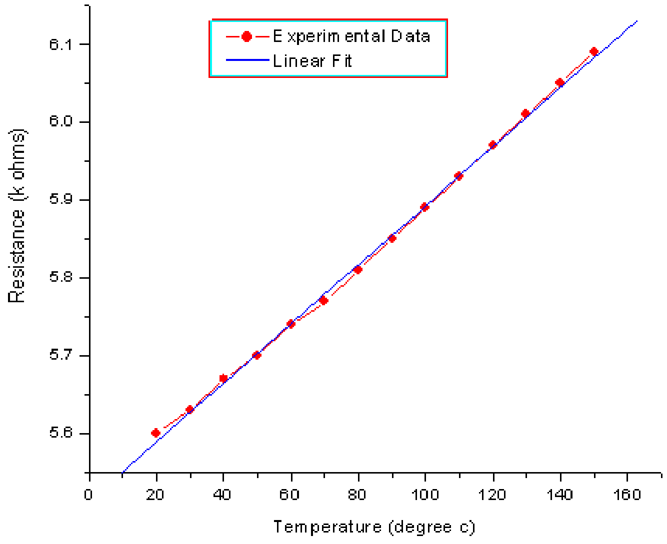


Fig. 9 (b). TCR measurement of polysilicon for 5.7 kΩ resistor.

5. Conclusions

A polysilicon microhotplate containing four unit cells has been designed and fabricated. Hotplate operation has been studied, both by theoretical simulations and by actual measurements. Temperatures up to 367°C have been attained with gold metallization.

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