A novel microfabrication technology on organic substrates - Application to a thermal flow sensor

G Kaltsas[2,1], A Petropoulos[1], K Tsougeni[1], D N Pagonis[1], T Speliotis[3], E Gogolides[1] and A G Nassiopoulou[1]

[1]Institute of Microelectronics, NCSR-"Demokritos", Athens, GREECE
[2]Department of Electronics, TEI of Athens, Aegaleo, Athens, GREECE
[3]Institute of Materials Science, NCSR-"Demokritos", Athens, GREECE

E-mail: G.Kaltsas@ee.teiath.gr

Abstract. A new technology that allows the formation of thermal sensors on organic substrates by combining the standard PCB technology with the well established microelectronic techniques, is proposed. The obtained structures consist of low thermal conductivity material, therefore the heat dissipation to the substrate is minimized, which result to the enhancement of the device sensitivity and the improvement of the corresponding response time. The proposed technology exhibits a series of advantageous characteristics such as significant cost reduction, elimination of both wire-die bonding and die cutting, direct integration with electronics and potential expansion on flexible substrates. Furthermore, the final structure provides a planar surface, which allows for further lithographic steps to take place, but is also a major advantage for specific type of applications such as non-invasive flow measurements. In the context of the proposed technology, a thermal gas flow sensor was fabricated and tested in a specially designed experimental set-up. The sensor consisted of three thin Pt strips directly connected to the copper tracks of the organic substrate. The middle Pt resistor act as a heater while the other two serve as temperature sensing elements.

1. Introduction

In general, a MEMS sensor device layout is based on structures formed by successive layers of patterned metal and insulating materials. A few attempts for the integration of MEMS structures onto printed circuit boards (PCBs) have been already reported by various groups. Merkel et al. [1] and Gassman et al. [2] realized fluidic devices using PCB technology. A PCB based capacitive sensor is presented in [3], while Enikov and Lazarov have demonstrated a fully PCB integrated thermal actuator [4]. A chemical sensor fabricated on a flexible printed circuit was presented by Y.S Kim [5]. A definite problem regarding the fabrication of any kind of structures on the PCB surface is the existing roughness of the FR4 substrate, as well as to the typical thickness of the copper structures, which is approximately 15-30μm. A way to encounter this issue was presented by B. Ghodsian *et al.* by using a polyimide planarization technique [6]. However until now there is no reported technology known to the authors, regarding the fabrication of fully PCB integrated thermal sensors, without the presence of silicon or wire bonding. A thermal flow sensor fabricated entirely by this new technology is demonstrated, alongside some preliminary operating data.

2. Technology description – Process layout

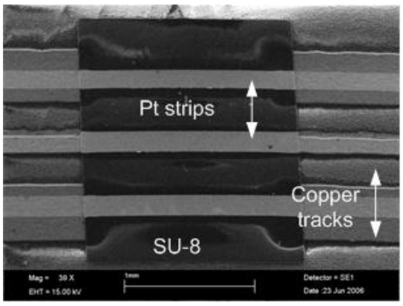

Figure 1. The rectangle-shaped SU-8 planarization layer, covering the ends of the Cu tracks. The Pt strips are also shown, which are on top of the SU8 layer. The Pt-Cu interconnections are located at the edges of the SU8 area.

Thermal sensors rely on the modified temperature distribution within a specified area in order to obtain correlated information regarding quantities such as flow velocity, pressure, acceleration etc. The aim of the proposed technology is to provide a new technique which allows the formation of MEMS structures on organic substrates. The basic device, which will be demonstrated, consists of a Pt thermistor integrated on top of a patterned FR4 substrate. In order to construct the thermistor, a straightforward metal deposition on the PCB does not lead to a functional structure, due to the anomalous topography of the surface. A planarization layer on top of the patterned PCB surface in order to smooth the existing height variations is then deemed necessary. This was utilized by the negative tone photoresist SU-8 which spans a wide variety of thickness values, exhibits high adhesion to both Cu and FR4 substrate, while it presents increased stability to etchants.

2.1. Planarization layer

The most sophisticated step of the whole process is the formation of a functional planarization layer, for which the epoxy resist SU-8 25 was employed. The exact form of the planarization layer is mainly imposed by the thickness of the copper structures on the FR4 surface. In the specific case, the PCB is patterned using a double side vacuum UV exposure unit via the chemical etching method. This method allows for the definition of minimum Cu features of the order of 100μm. The aim of the planarization layer is to allow for subsequent lithographic steps to take place by providing a relatively smooth upper surface. Therefore, the certain anomalies of the patterned PCB surface must not be reproduced, while at the same time a path that provides feasible electrical contact between the copper tracks and the subsequently deposited second metal layer (Pt) should be established. Thus, the Pt strips should maintain two electrical contacts with the underneath Cu metal layer, through the intermediate electrical isolation material, which in this case is the SU8 layer. The initial pattern of the SU-8 was formed as a rectangular shaped area in order to cover the two adjacent ends of each copper track as shown in figure 1. Consequently, the Pt-Cu interconnections are formed at the edge of the SU-8 area. This approach induced several reliability problems due to a Pt line discontinuity that frequently occurs at the end of the SU-8 layer (figure 2a). A stress originated strain effect causes the SU-8 layer to be “lifted” upwards at the edges, which is a prohibiting factor regarding the continuity of the Pt line. This issue was addressed by altering the initial SU-8 pattern in a way that the Pt-Cu contact is made through holes (vias) that formed in the main body of the planarization layer (figure 2b), rather than the edge of the SU-8 layer.

It was experimentally found that an SU-8 layer of 15μm thickness exposed to UV radiation of 1700 mJ/cm^2 provides highly reliable results. The specific layer thickness is achieved by a double spinning stage at 300rpm and 3000rpm respectively, with an acceleration of 300rpm/s. Next to that, the PCB is baked at 65^{o}C for 2min followed by a 3min bake at 95^{o}C. The subsequent dip of the PCB into 1-Methoxy-2-propanol acetate (PGMEA) for 4 minutes results to the developing of the unexposed part of the SU-8. The remaining SU-8 layer exhibits high adhesion

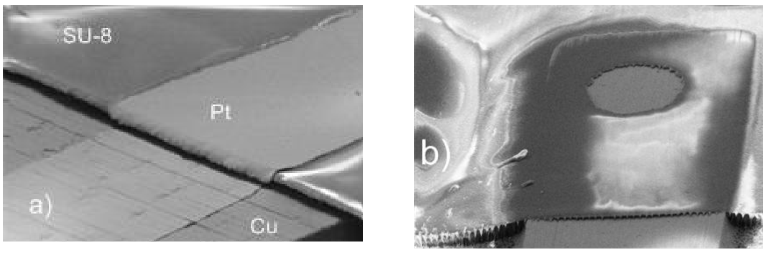

Figure 2. a) The Pt discontinuity at the edge of the SU-8 layer
b) A hole (via) at the SU-8 layer, offers a reliable way for the Pt line to establish contact with the copper tracks.

both to FR4 and Cu allowing enhanced mechanical and chemical stability.

2.2. Thermistor fabrication

The next process step is the formation of the Pt resistors by using the positive photoresist mA-p 1275 as a lift-off layer. The choice for the specific photoresist was made since it is easy to be removed and it spans a thickness range that is compatible with the rest of the process. The coating takes place with a spin speed of 400rpm at an acceleration of 300rpm/s, which results to a layer of approximately 20μm thickness. Then the board is baked at 100^0C for 10 minutes and exposed to a 2000 mJ/cm^2 UV dose. Thus the predefined pattern of the second metal layer is formed.

A thin bilayer of Ti/Pt of 30/300nm thickness is then sputtered on top of the board. The final step of the entire process is the lift-off stage, whereby the board is inserted into acetone and put into an ultrasonic bath for 90 sec. The mA-p layer is removed from the board along with the Pt layer on top of it, while Pt remains at the lithographically defined open areas. The overall fabrication process is summarised in figure 3, while the resulting device is shown in figure 4. In essence, the electrical connection of this MEMS based structure to the macroworld is achieved without any intermediate elements such as electrical probes or wire-bonding.

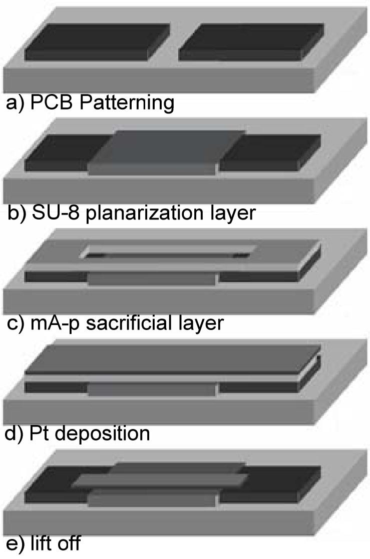

Figure 3. The fabrication process steps

3. Thermal Flow sensor

A direct product of the proposed technology is the fabricated thermal flow sensor which is shown in figure 4. Based on an operating principle that exploits the shift in the temperature distribution in the vicinity of a heating source as induced by convective heat transfer, the thermal flow sensors can extract the flow rate of a certain fluid. The resistor located in the middle acts as a heating element, while the two sensing elements, located at equal distance from the heater, detect the flow induced temperature field. A major advantage regarding the proposed device is the very low thermal conductivity of the SU-8 layer (0.2W/mK) which minimizes conductive heat transfer to the substrate and the associated noise. The sensor was mounted onto a 1.5m long tube with a rectangular cross sectional area of 25mm^2. A Brooks 5850 Mass Flow Controller (MFC) was used in order to form the reference flow of nitrogen in the region of 0-10 Standard Litres per Minute (SLPM). The sensor was wall-mounted 110cm away from the tube inlet, so as fully developed conditions to be assured within the whole flow range. The fabricated sensor is able to operate in both hot wire mode whereby the flow rate is determined by the cooling of the heating resistance and also in calorimetric mode by monitoring the temperature difference at the two resistors which lie symmetrically with respect to the heater.

The obtained results in calorimetric mode of operation are shown in figure 5. The resistance difference of the two thermistors as a function of flow for two different heater current values is illustrated. The sensor sensitivity increases with heating power as expected. The corresponding Reynolds numbers are also indicated on the top axis. A linear behaviour of the sensor response as a function of the square root of the flow velocity was obtained experimentally, with sensitivities of 18 and 39 mΩ/(m/s)$^{1/2}$ for 70 mA and 90 mA respectively. Figure 6 illustrates the sensor response in anemometry mode, where the heater resistance variation as a function of flow is presented. A linear response with a rate of 3.76 mΩ/(m/s) is extracted.

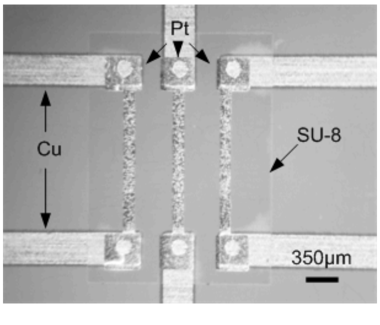

Figure 4 Optical picture of the final device, where the Cu tracks, the planarization layer and the Pt lines are illustrated.

Regarding the full characterization of the sensor operation, a special measurement setup has been designed, in order to provide the means to control the resistance of the heater under varying flow conditions. This way the device is able to operate in the constant

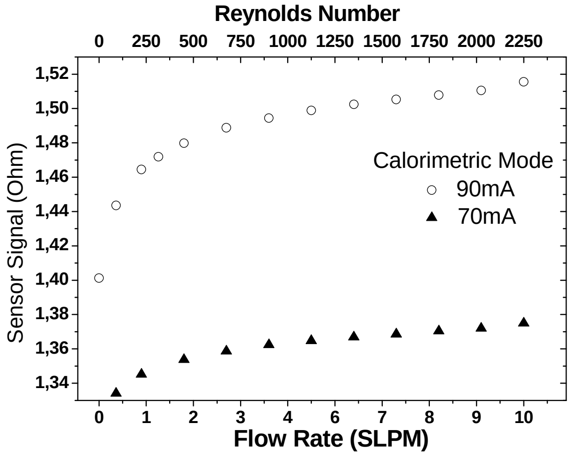

Figure 5. The sensor response in calorimetric mode of operation. The extracted sensitivity is increased with the applied current.

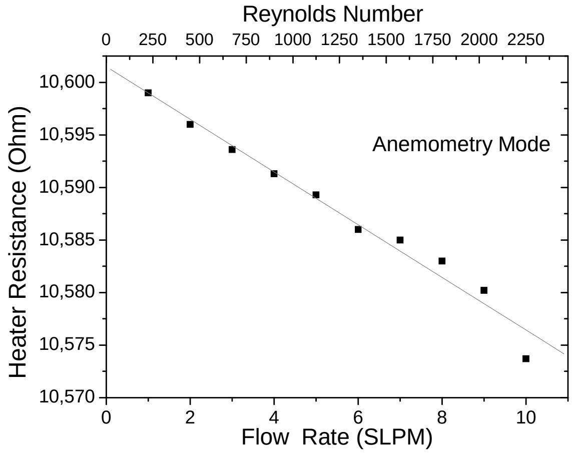

Figure 6. The sensor response in anemometry mode of operation.

temperature mode, whereby the conduction effects in the detected resistance difference of the sensing elements is minimised. Preliminary device characterization in the specific operating mode reveals a higher degree of reproducibility of the results, as well as an improved flow rate resolution.

4. Conclusions

A new sensor fabrication technology that combines printed circuit and MEMS technology is presented. Quite a few of the drawbacks existing in the standard microelectronic fabrication process are addressed. The sensing elements are inherently connected to the macrowrold, overcoming the necessity for wire bonding, with immediate benefits in device complexity, mechanical reliability, process time and cost. The planar surface that is obtained with the proposed technology allows for further lithographic steps to take place, while it poses minimal obstacle to fluid flow. There is no need for die cutting or die bonding, while the whole technology concept can be expanded to flexible substrates. The fact that no high conductivity material such as silicon is present in the fabricated structures, significantly minimises heat diffusion to the substrate with an immediate gain in sensor sensitivity and response time. Within the context of the aforementioned technology, a thermal flow sensor was fabricated and tested. The preliminary data presented here, are a manifestation of a reliable sensor, with high sensitivity and highly reproducible results. The specific technology is rendering as an effective candidate for sensor fabrication, since it presents significant advantages comparing to existing microfabrication methods.

Acknowledgements

This work is co-funded by 75% from the E.U. and 25% from the Greek Government under the framework of the Education and Initial Vocational Training Program Archimedes and PENED.

References

[1] Merkel T, Grasser M and Pagel L 1999 *Sensor Actuator A-Phys* **77** 98–105
[2] Gassmann S, Ibendorf I and Pagel L 2007 *Sensor Actuator A-Phys* **133** 231–235
[3] Zagnoni M, Golfarelli A, Callegari S, Talamelli A,V. Bonora, E. Sangiorgi and M Tartagni 2005 *Sensor Actuator A-Phys* **123–124** 240–248
[4] Enikov T E and Lazarov K 2003 *Sensor Actuator A-Phys* **105** 76–82
[5] Kim Y S 2006 *Sensor Actuator B-Chem* **114** 410–417
[6] Ghodsian B, Jung C W, Cetiner B A and De Flaviis F 2005 *IEEE Sens. J.* **5** (5) 950-955