Heterogenous Integration of MEMS Gas Sensor using FOWLP : Personal Environment Monitors

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Abstract— *The exponentially increasing global population has led to environmental pollution which drastically affects human health; emphasizing the need for personal environmental monitoring. This demands the development of wearable devices capable of sensing the local environment and wirelessly transmitting data to cloud for spatial pollution tracking.*

In this paper, we have demonstrated the integration of MEMS gas sensors on flexible PDMS substrate using the fan out wafer packaging technique called FlexTrate™. One of the main issues in FOWLP involving the integration of MEMS sensors with a released membrane is the stability of the membrane during the molding process which results in poor yield. We have optimized the process for integrating released MEMS devices by protecting the membrane prior to the molding process and thus improving the stability of the released membranes and improving the yield by >80%. If the membrane is not protected, during curing the cavity which is filled by PDMS leads to membrane cracking due to generation of stresses. Simulation studies on the temperature profile of the microheater after protecting the membrane shows that the power consumption for 300ºC of heater temperature is 0.1W as compared to 0.091W where the PDMS fills the cavity of the membrane, which is <10% increase. Thus, this proves that the membrane protection process improves stability without affecting the thermal characteristics of the heater. Furthermore, there is an effort to integrate rechargeable flexible batteries to power the system wirelessly. Adding to this, is the capability of wireless communication achieved by integrating a Bluetooth die in the system to transmit data to a mobile phone.

The MEMS sensors along with the other electronic components such as transimpedance amplifiers, analog-to-digital converters and Bluetooth will be integrated on the same PDMS platform with interconnect pitches of 40 µm. This greatly reduces the form factor of the system and enables higher density of sensor arrays resulting in reliable and repeatable output. The intention of the work is to demonstrate a wearable gas sensor for local pollution monitoring with wireless communication capability using Bluetooth. This will provide a means to spatially map the pollution levels globally.

Keywords—FOWLP, MEMS sensor, FlexTrate™

I. Introduction

Internet of things (IoT) has driven the need for wearable interactive devices which are compact, multiple functionality enabled and user comfortable. The application of wearable devices spans a wide range all the way from military applications to health monitoring. The big picture is to enable wearables to wirelessly communicate to mobile phones and then to store the local environment conditions on the cloud for temporal and spatial monitoring of pollution levels globally (**Fig. 1**).

Fig. 1: Concept behind spatial resolution of global pollution monitoring.

However, there is a competing effort in the development of fixed environmental pollution monitoring stations which accumulate data on the pollution levels 24X7. The disadvantage of these stations is the cost and the installation of a large number of these stations for spatial monitoring and moreover it becomes very cumbersome for an individual to gain access on the local environment timely. The solution to this is mobile personal monitors which will not only give an individual immediate access to pollution levels in a particular vicinity but also help in spatially resolving the global pollution levels. Table 1 compares fixed monitoring stations with mobile personal monitors.

Fan out wafer level packaging (FOWLP) based heterogenous techniques which provide fine pitch interconnects help achieve small form factor systems. The aim of this work is the integration of MEMS gas sensor on flexible PDMS substrate using FOWLP technique. A lot of effort has been put in the development of mobile sensor systems. Gao *et al.* [1] has demonstrated a fibre gas sensor based smart face mask for distinguishing targeted gases. They fabricated these sensors using single and multi-walled CNTs for room temperature sensing of C_2H_5OH, HCHO and NH_3 (**Fig. 2(a)**). Singh *et al.* [2] have developed graphene based wearable chemical sensors for detection of CO_2, SO_2 and H_2S. They were able to integrate the sensor on a wearable band **(Fig. 2 (b)**). Swager *et al.* [3] have demonstrated a wireless gas detection system via a smartphone using rf communication. The system employs a chemiresponsive nanomaterials integrated into the circuitry of near field communication tags for detecting the presence of gases such as NH_3 and $C_6H_{10}O$ (**Fig. 2(c)**).

Table1: Comparison of mobile and fixed pollution monitors.

	Mobile Sensors	Fixed Detectors
Form factor	Small	Large
Wearability	Light weight	Heavy
Cost	Low cost	expensive
Spatial resolution	Improved with location and time stamp	Requires a large number of them installed
Maintenance	No personnel needed	Requires personnel
Data accessibility	Real time data for immediate action	Data to be accessed over cloud

Though a lot of research has been done in this direction, most of them suffer for minimized flexibility, use of PCB technology for integration resulting in large form factor and sometimes requirement of monolithic integration methods. Hence, the aim of the project is to be able to heterogeneously integrate different sensor components on a very flexible PDMS substrate with file interconnect pitches to achieve low cost, light weight and small form factor system.

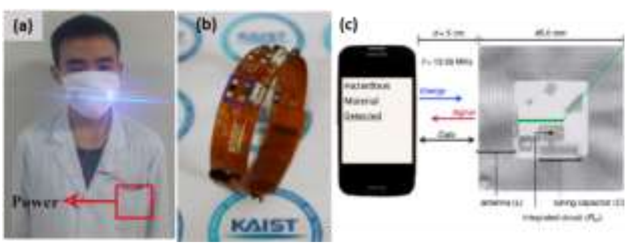

Fig. 2: Different sensor systems demonstrated for wearable applications.

The integration of MEMS devices using FOWLP comes with its own unique challenges. One the important packaging challenge is the fragile membrane which is sensitive to stress induced during polymer molding [4]. Another challenge is the need to maintain the pristine nature of the sensitive layers which play a key role in gas sensing. The process of face down die attach and removal after compression molding damage the sensor irreversibly.

A variety of methods have been investigated in order to integrate MEMS devices using FOWLP with high throughput. Theuss *et al.* [5] have demonstrated successful integration of MEMS devices by partial etching the membrane and protecting it using a silicon lid prior to die attach. The complete release is done after removal from adhesive tape. Braun *et al.* [6] have come up with multiple packaging solutions to keep the sensitive layer from contamination during packaging, one technique makes use of a cover layer for sensor protection and another uses channels over the sensor which are lithographically patterned which prevent contamination but also provide diffusion path for gas molecules. All these techniques are very successful but at the same time involve complicated lithographic processes. The aim of this work is to MEMS gas sensor using FOWLP on PDMS substrate using simple protection layer technique to protect the membrane as well as the sensitive layer.

A. Fabrication process flow

The MEMS gas sensor consists of a released microheater on which interdigitated electrodes (IDEs) are patterned atop the metal oxide sensing material. The cross-section schematic of the gas sensor and the top view is as shown in **Fig.3(a & b)** (Please refer [7] for more details on sensor device). One of the major roadblocks in the integration of MEMS devices using the conventional FOWLP technique is the poor reliability of released structures and the contamination of the sensitive layers, which require specialized lithographic processing steps to ensure high throughput [8].

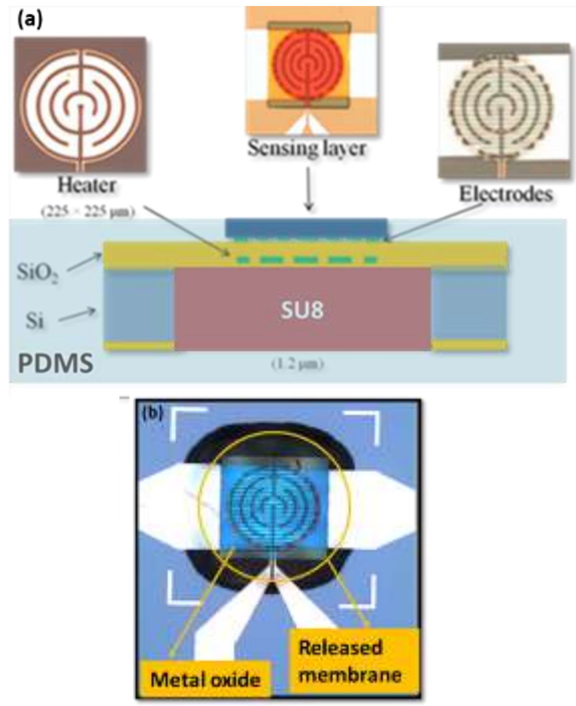

Fig.3: (a) Cross section of MEMS gas sensor device and **(b)** Optical micrograph of sensor.

One of the first steps in ensuring that the metal oxide sensitive layer is not affected during the polymer molding process is to protect the metal oxide by spin coating a resist atop. AZ5214E is spin coated on the metal oxide to protect is from contamination during molding and release steps. The spin coated devices are then placed face down using a pick and place tool on a glass handler with alignment patterned thermal release tape (release temperature 110ºC). In order to protect the release membrane from experiencing the stresses of PDMS during curing, SU8 resist is spin coated and patterned in the sensor arear. PDMS is then compression molded using a silicon handler with a thermal release tape (release temperature 180ºC). After room temperature curing for 24 hours, the glass handler is released by heating to 110ºC. Parylene is then deposited to act as the dielectric layer and then SU8 is spin coated and patterned for creating corrugations on the metal lines to avoid interconnect cracking during bending [9]. Vias to contacts etched followed for interconnect patterning at 40um pitch and metal deposition. The metal oxide protection layer is then removed by etching the parylene and the AZ5214E protection layer. The process flow is as shown in **Fig. 4**. If the microheater was perforated during the MEMS sensor fabricated then an isotropic SU8 release process which help achieve a release membrane and thereby improving the thermal characteristics of the heater and reducing power consumption.

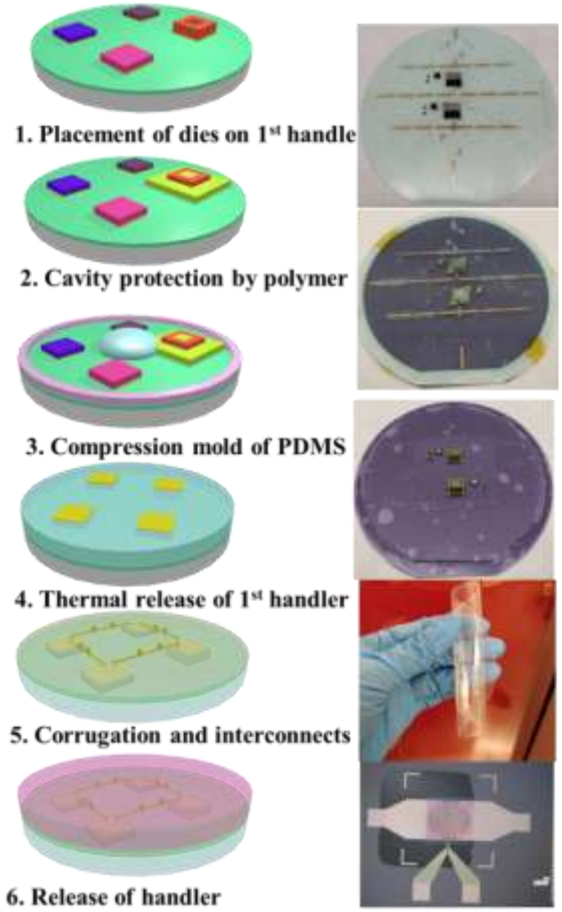

Fig. 4: Process for MEMS sensor integration in PDMS using FlexTrate™ technique.

A simple gas sensor system is designed with wireless communication capability. The system consists of the following components; i) MEMS gas sensor, which detects the presence of gas and performs the transduction of chemical reaction to electrical signals. ii) Transimpedance amplifier, for current to voltage conversion. The gain of the amplifier is controlled through the feedback resistor. The resistance value is decided depending on the input current range which spans from ~10 µA (without gas) to 1 mA (with gas). The TIA chosen has two channels which enables us to connect two sensor devices to a single TIA. The output of the TIA is then fed to the ADC input of the Bluetooth. The ADC is configured to function as a 14-bit converter with voltage resolution of 2 mV and an output range of 600 mV. The Bluetooth has 8 ADC input channels, 4 of which are configured for communication. The circuit diagram and final fabricated device is shown in **Fig.5**. The heterogenous dies are connected through fine 40 µm interconnects with a pitch of 40 µm.

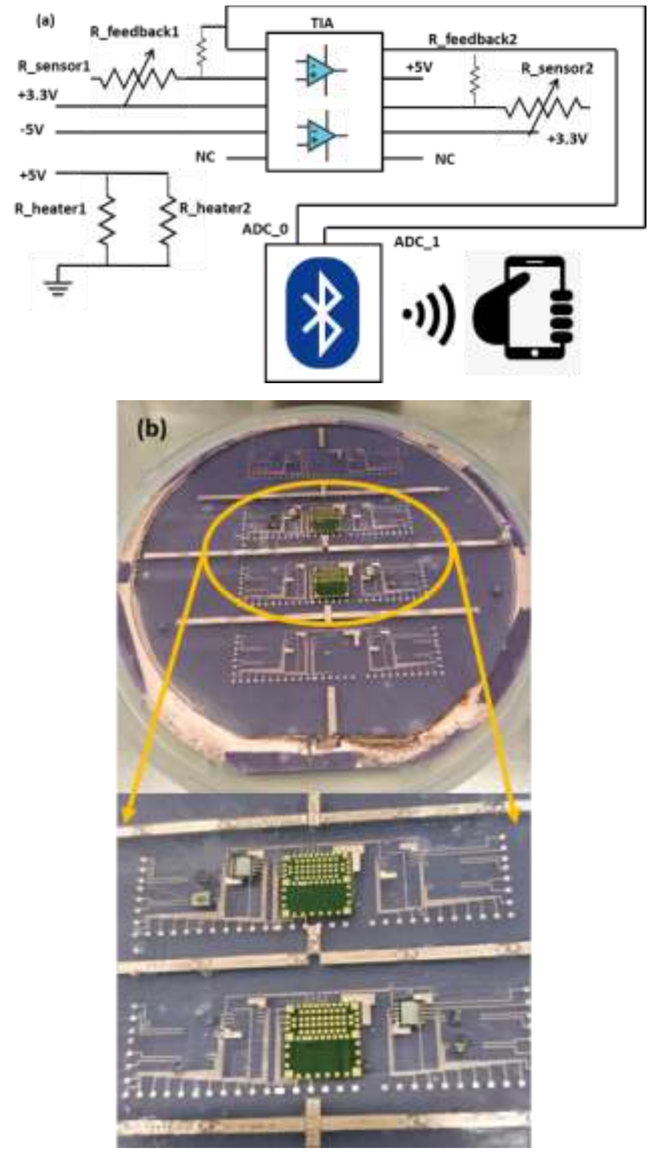

Fig. 5: (a) Circuit diagram of sensor system and **(b)** Final fabricated sensor system

B. Thermal Characterization of microheater

The throughput of devices integrated directly in PDMS without protecting the membrane is 10% and that after membrane protection is 90%. Though membrane protection is necessary for high yield it should not drastically affect the temperature profile of the microheater. COMSOL simulations are carried out for studying the temperature profile of the microheater for both cases; i) when the cavity is filled with PDMS and ii) when the cavity is filled with SU8 resist which is used to protect the membrane (**Fig.6(a)**). The similarities in the thermal properties of the two materials ensure a closely matched temperature profile of the microheater. The use of the SU8 resist as a membrane protection layer increases the reliability of the heater and boosts the throughput to about 90%.

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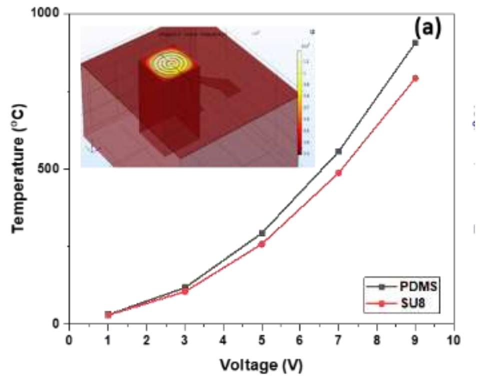
Furthermore, electrical characterization is done on the microheater after compression molding and release from the handler. The current of the microheater and that of the sensing material is recorded at different heater voltages.



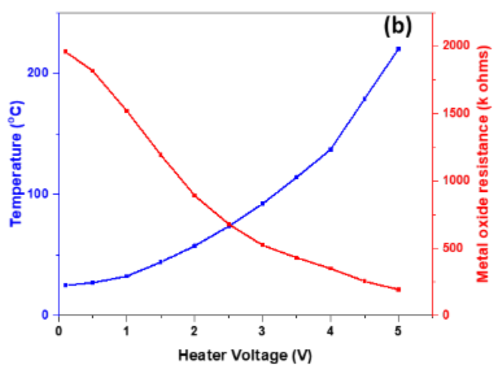


Fig. 6: (a) Comparison of temperature profile of PDMS and SU8 and **(b)** Heater temperature and sensor resistance as a function of heater voltage.

The microheater temperature increases with increase in voltage and the metal oxide current increases with increase in heater voltage confirming semiconducting behaviour as shown in **Fig. 6(b)**. This shows proper functioning of the MEMS gas sensor. IR imaging is done using a FLIR SCS2000. For this, the gas sensor integrated in PDMS is bonded on a PCB and voltage is applied to the microheater terminals. The images in **Fig. 7** clearly show the temperature profile of microheater and the temperatures at different heater voltages from 0.5V to 5V.

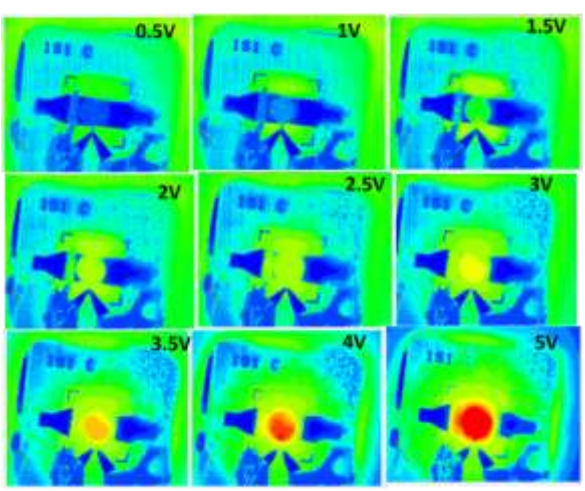


Fig. 7: IR images of microheater at different heater voltages.

C. Gas Sensing Characterization

The metal oxide used for the gas sensor fabrication is ZnO. ZnO is an n-type semiconductor. Gas sensing phenomenon is based on chemisorption of gaseous molecules. The temperature provided by the microheater causes ionic oxygen species to absorb on the metal oxide resulting in electron exchange. Owing to the n-type behaviour of ZnO, the oxygen adsorption creates a depletion layer causing the conductivity of ZnO to decrease. On exposure to H_2 (sensing gas), the adsorbed ionic oxygen species react with H_2 in accordance with the reaction below (**Equation 1**) increasing metal oxide conductivity which is the measured parameter.

$$H_2 + \ O^- \leftrightarrow H_2\,O + \ e^- \qquad \textbf{(1)}$$

In the experiments synthetic air (which is dry air containing 80% nitrogen and 20% oxygen) is used as the reference gas. The adsorption reactions are allowed to stabilize by monitoring the current using Keitheley 2450 source meter, after which H_2S of desired concentration is introduced through the mass flow controllers (MFCs). The sensor is placed on a chuck which is heated through an external source. The change in metal oxide resistance on exposure to H_2S is used to calculate the response using **Equation 2**

$$Response = (G_a - \ G_g)/G_a \text{ x } 100\ \% \qquad \textbf{(2)}$$

where G_a= Conductance of metal oxide in synthetic air and G_g= Conductance of metal oxide in presence of H_2S at the same temperature.

The sensing experiments are performed at different microheater voltages corresponding to different temperatures to establish the effect of heater temperature on sensing. The H2 concentration is varied from 0.1% to 1% at heater voltages of 3V, 4V and 5V. The transient sensor response at different heater temperatures is shown in **Fig. 8**. At 3V heater voltage corresponding to a temperature of 100ºC, the sensor response is 24% at 1% H_2, however the recovery of the sensor is very poor due to inability of the adsorbed gas molecules to desorb (**Fig. 8(a)**). At heater temperature of 150ºC (4V heater voltage), the sensor shows good response and fairly good recovery characteristics but a baseline shift is observed due to incomplete desorption phenomenon (**Fig. 8(b)**). At heater temperature of 220ºC, the response of the sensor is 565% which is highest. The response and recovery times of the sensor is 50 s and 300 s respectively and there is no baseline drift as observed from the transient analysis (**Fig. 8(c)**).

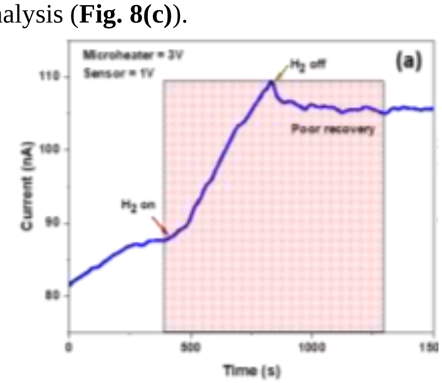


Fig. 8: (a) Transient sensor response at (a) 3V heater voltage

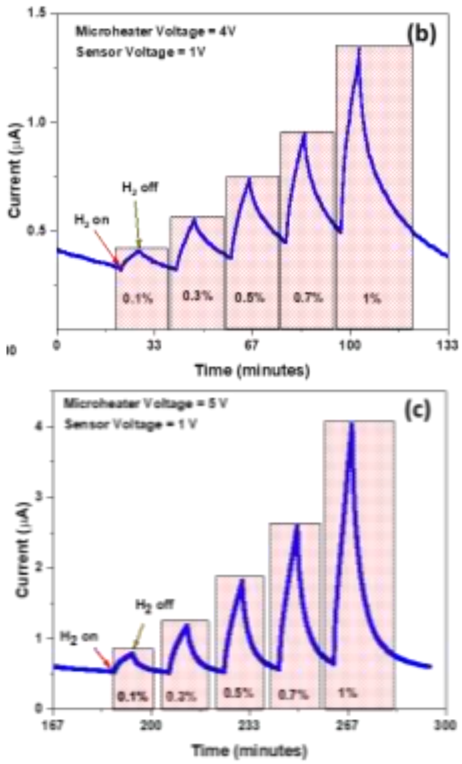


Fig. 8: Transient sensor response at **(b)** 4V heater voltage and **(c)** 5V.

The microheater collapses beyond 5V due to joule heating and electromigration. The optimum heater temperature for best response is hence 5V. The sensor response curve is obtained by plotting the sensor response as a function of H_2 concentration as shown in **Fig. 9**. It is clearly seen that the sensor response increases linearly with increase in temperature. The limit of detection of the sensor is ppm.

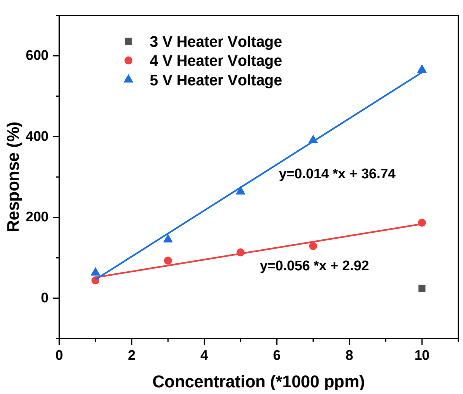


Fig. 9: Sensor response as a function of H_2 concentration at different heater voltages.

II. Conclusion and Future Work

We have demonstrated the successful integration of MEMS gas sensor using FOWLP technique. The process is optimized to increase the yield to about 90%. FlexTrate^{TM} based heterogenous methodology is utilized to integrate the sensor system including the transimpedance amplifier and Bluetooth for wireless communication on flexible PDMS substrate. Future aspects include the integration of flexible battery with wireless charging capability. These wearable systems demonstrate multi functionality capability with small form factor, light weight and low cost.

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