Integrated Sensors for Health Monitoring in Advanced Electronic Systems

C. H. Wang, Y. Liu, M. Desmulliez and A. Richardson

Abstract—**This paper presents the development of integrated sensors for health monitoring applications in microsystems. Intelligent health monitoring is an emerging method for early diagnostic of the status or "health" of electronic systems and products under operation based on embedded tests. In this approach miniature sensors are used to monitor the key parameters of the package/system for example temperature, pressure, stress and humidity. Based on the outputs of the sensors stimuli are then used to test the responses of the system to determine its behavior. Thus early warning of system fault or failure can be obtained and measures taken for repair work or replacement of the system. We have been developing integrated sensors on a chip for heath monitoring applications in electronic systems. Integrated sensors on $LiNbO_3$ and silicon substrates are being investigated. In this paper we report the development of discrete sensors and the integration methods. Thin film temperature sensor arrays have been developed and tested as embedded sensors in substrate assemblies. SAW based low cost sensors have been designed and fabricated for humidity monitoring. Methods for sensor integration and the preliminary results are described.**

Index Terms—**Integrated sensors, System in Package (SiP), MEMS, health monitoring.**

I. INTRODUCTION

There is a growing interest in integrating health monitoring functions into advanced electronic systems in order to make a timely decision for system repair or replacement in safety critical applications. Health monitoring can also improve the cost-effectiveness of inspection and maintenance of the systems. With the increasing miniaturization and heterogeneous integration of electronic systems enabled by the system-in-package (SiP) technology [1-3], it is becoming difficult to conduct electrical test using the conventional methods because of limited access to the electrical contacts in stacked packages. Therefore it is necessary to use intelligent health monitoring approaches to determine the status of such a system. Health monitoring methods have already been developed for large systems such as airplanes and large structures such as bridges [4-9]. In these applications an array of sensors is used to continuously monitor the conditions of an airplane or a bridge to provide an early indication of problems such as damage to the structure from fatigue, corrosion or impact. The sensors and the monitor are used to transmit, analyze and visualize the functional data in order to produce an efficient system-wide view of the overall conditions of a monitored system. This information is then used to undertake corrective action before the damage develops to a stage where catastrophic failures can occur [4-9].

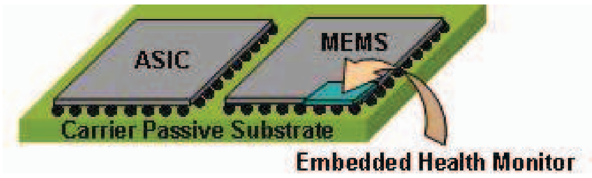

Fig. 1 Schematic illustration of an electronic system with a health monitoring chip.

For health monitoring in compact or miniaturized electronic systems, integrated sensors are essential. Fig. 1 shows a schematic illustration of an electronic system with integrated sensors for health monitoring. In this case an IC chip and a MEMS chip are integrated on a chip carrier. The health monitoring sensors are integrated with the MEMS chip. For 3D systems the health monitoring sensors or chip can be inserted in between the stacked chips. In this paper we present the development of miniature sensors and integration methods for health monitoring application in advanced electronic systems. Thin film resistive sensors and SAW (surface acoustic wave) sensors have been designed and fabricated for temperature and humidity monitoring respectively. Methods have been proposed for sensor integration on a singe chip.

II. DESIGN, FABRICATION AND TESTING OF DISCRETE SENSORS

A. *Thin film temperature sensor*

Thin film resistance sensors are highly desirable for temperature monitoring since they can be embedded into the SiP based Microsystems. They are low cost and can be fabricated by thin film deposition and wet or dry etching methods [10, 11]. The thin film sensors are designed in meander structures, as

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C. H. Wang is with the School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh EH14 4AS, UK. (Tel & Fax: +44 1314513903, Email: c.wang@hw.ac.uk).

Y. Liu is with the School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh EH14 4AS, UK. (Tel: +44 1314513321, Email: yl214@hw.ac.uk).

M. Desmulliez is with the School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh EH14 4AS, UK.

A. Richardson is with Engineering Department, Lancaster University, Lancaster, LA1 4YW, UK.

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shown in Fig. 2, in order to minimize the footprint for the devices. Platinum based thin film sensors with different track widths have been designed and fabricated. The dimensions of the sensor designs are summarized in Table 1.

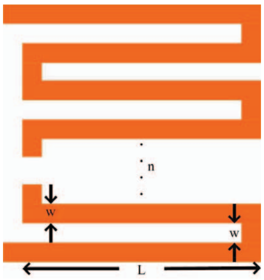


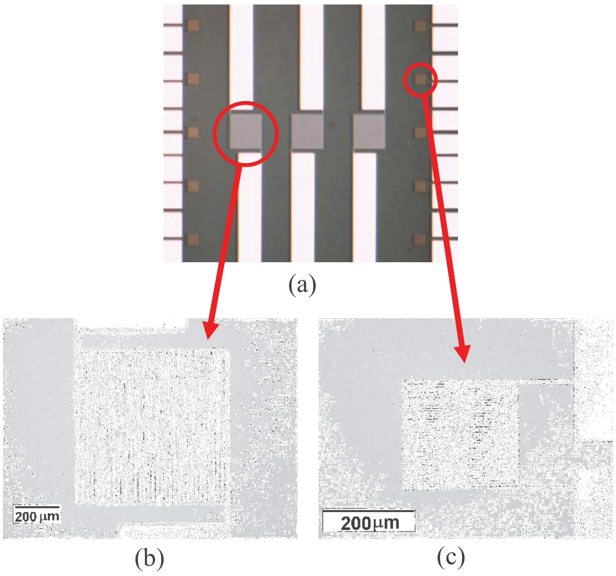
Fig. 2 Schematic of the meander design for thin film temperature sensors.

TABLE I
DESIGN PARAMETERS FOR THE TEMPERATURE SENSORS

Width (µm)	Length (µm)	Number of periods	Area of a single sensor (µm^2)
3	250	40	250×240
5	300	34	300×340
10	700	36	700×700

For sensor fabrication, a platinum film of ~100 nm of thickness was deposited onto a glass wafer or a silicon wafer by sputtering. The platinum film was then patterned using photolithography and ion beam etching methods. A patterned AZ6112 photoresist film was used to define the sensor structures in the etching process. The photoresist layer was then removed to obtain the meander sensors on the wafer. Individual sensor chips were obtained for testing and characterization after wafer dicing. Fig. 3 shows optical pictures of a microsensor array after fabrication. The sensor array was designed for temperature monitoring in a novel laser assisted polymer bonding process for MEMS packaging. As will be shown, the work also demonstrates successful integration of health monitoring sensors in a MEMS package. It can be seen from Fig. 3 that miniature temperature sensors were fabricated successfully with track width as narrow as 3 µm and a footprint of only 250µm × 240µm.

The temperature dependence of the resistance of the sensors was determined using a hotplate and a digital multimeter. The initial measurements showed a drift of resistance by about 7% after the first cycle of measurement between 25°C and 300°C. A stable resistance is required to obtain a reliable temperature for sensor applications. Therefore, an annealing process was conducted on the sensors to determine if the drift effect of the resistance could be eliminated. It was found that after annealing for 5 hours at 350°C, the resistance of the sensors over the above temperature range is stable at each temperature in the subsequent cycles of the measurement. Fig. 4 shows the linear behavior of the thermal responses of the platinum thin film sensors after annealing for sensors of track widths of 3, 5 and 10 µm respectively. The corresponding temperature coefficients of resistance (TCR) were determined to be in the range of 1.78×10-3 /°C to 2.26×10-3 /°C at 20°C.



(a)

(b) (c)

Fig. 3 (a) Fabricated temperature sensors; (b) Picture of a sensor with a track width of 10 µm; (c) Picture of a sensor with a track width of 3 µm.

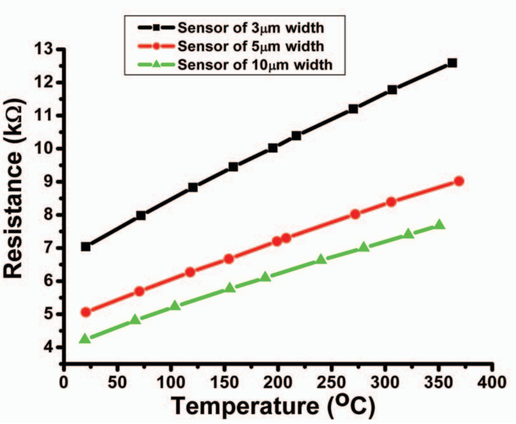


Fig. 4 Thermal response of platinum sensors

B. *SAW based sensors for humidity monitoring*

Surface acoustic wave devices have been well developed and widely used in both sensing and communication fields. SAW devices are based on inter-digitated transducers fabricated on a bulk piezoelectric substrate material such as $LiNbO_3$ or on a piezoelectric thin film such as AlN and ZnO deposited on a suitable substrate wafer. SAW resonator sensors have been developed previously for humidity monitoring using polymer films as the moisture absorption layers. The absorption of moisture in the polymer layer results in a mass loading on the surface of the piezoelectric material which leads to a shift in the resonant frequency and an associated change in the magnitude of the transmitted / reflected signal of the SAW resonator [12-15]. Fig. 5 shows the schematic layout of a typical SAW resonator sensor for humidity sensing applications.

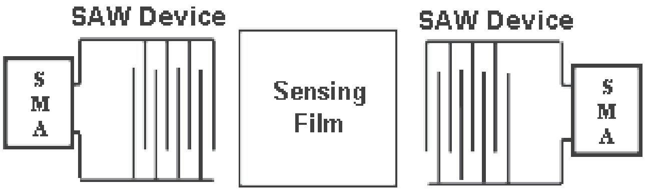
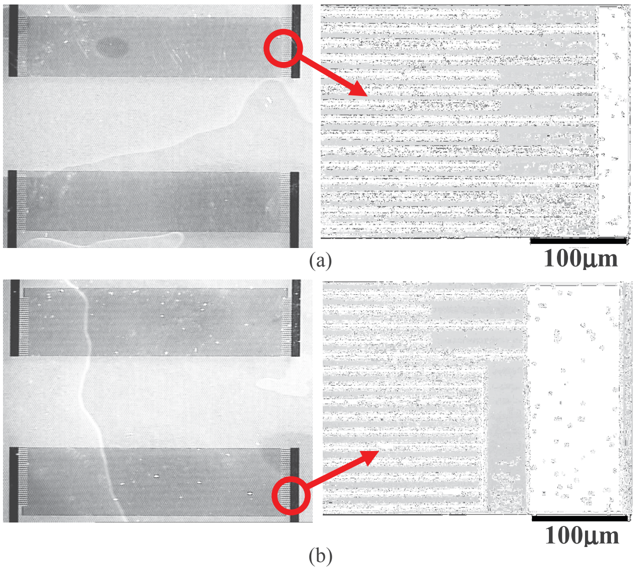


Fig. 5 Schematic layout of SAW resonator sensor for relative humidity monitoring

For humidity sensing in health monitoring applications, we have investigated SAW based sensors using the benzocyclobutene (BCB) photopolymer as the sensing medium. The BCB polymer is a well established material produced by Dow Chemical, which has already been used as the packaging adhesion and insulating layers in MEMS and IC packages. The equilibrium water absorption (wt%) in CYCLOTENE 4000 resin (Photo-BCB) at various relative humidity (RH) at 23°C is shown in Table II [16, 17]. The property of the conventionally processed BCB for humidity sensing can be enhanced by improving the water absorption capability in a subsequent surface treatment process in an oxygen plasma [18-20]. The IDT fingers of the SAW resonators were designed with widths of 4, 8 and 16 µm and fabricated on LiNbO3 wafers. The IDT fingers were fabricated using a sputtered aluminum layer and a wet etching method. Fig. 6 shows fabricated SAW resonator sensors with the IDT finger width of 8 µm on a 128-Y cut LiNbO3 substrate. Fig. 6(b) shows a sensor with a reflector for enhanced performance. Before deposition of the BCB polymer sensing film, the transmission and reflection characteristics of the sensors were measured using a HP8510 Network Analyzer. The results are shown in Figs. 7 and 8 for sensor designs without and with an additional reflector respectively. The results show that the central frequencies of two devices are identical at 124.8 MHz as predicted. However the resonant peak in Fig.8 is much sharper than that in Fig. 7 showing the enhanced response by the inclusion of the reflector in the sensor design. The BCB polymer, CYCLOTENE 4026-46, was then deposited on the SAW devices by spin coating. The spin speed and time were 3500 rpm and 100 s respectively for BCB deposition. After soft bake at 90^{o}C for 120 s, the thickness was measured to be 8.4 µm on a Zygo surface profilometer. After polymer coating, the central frequency of the SAW devices was measured and was found to have shifted from 124.8 MHz to 119.7 MHz because of the mass of the BCB polymer on the sensor surface. The detailed measurement of the response of the sensors to humidity change is being undertaken.

TABLE II
EQUILIBRIUM WT% WATER IN CYCLOTENE 4000 RESIN (PHOTO-BCB) AT VARIOUS RH AT 23°C

CYCLOTENE resin	Film thickness (µm)	Relative Humidity (%) 30	54	84
4024-40	5	0.061	0.075	0.14
4026-46	10	0.058	0.077	0.14
4026-46	20	0.050	0.082	0.14



(a)

(b)

Fig. 6 (a) SAW resonator with IDT width of 8 µm without reflector structure; (b) SAW resonator with IDT width of 8 µm with reflector structure.

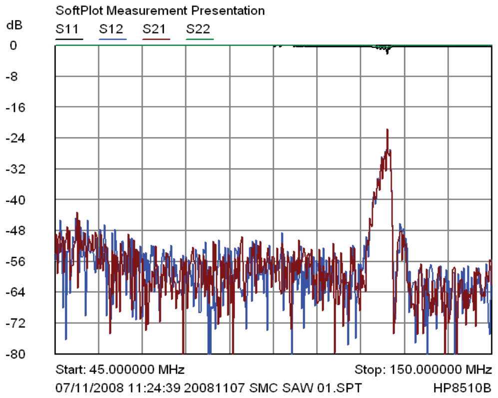


Fig. 7 Transmission (S12, S21) and reflection (S11, S22) responses of the SAW resonator with IDT width of 8µm without reflector structure

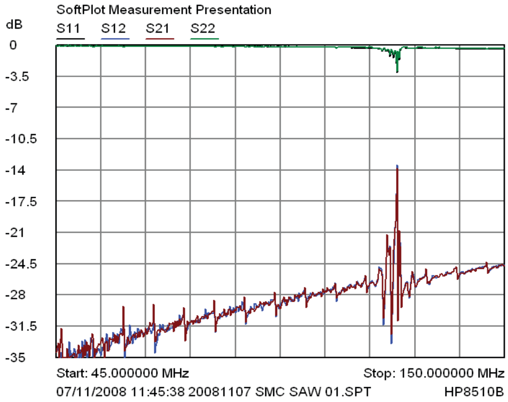


Fig. 8 Transmission (S12, S21) and reflection (S11, S22) responses of the resonator with IDT width of 8µm with reflector structure

C. Pressure sensor

MEMS pressure sensors have been well established and applied in many industrial applications. In this work we investigate hybrid integration of an un-packaged pressure sensor on a multi-sensor chip for health monitoring applications.

The sensors are bulk silicon micromachined devices provided by SIMIT, Shanghai, China. Four piezoresistors fabricated on the membrane are arranged in a Wheatstone bridge configuration for producing output signals from the sensor. The devices were deigned to operate in the pressure range of 0 - 1.5 bar and 0 – 7 bar respectively. The dimensions of the pressure sensors are about 1mm x 1mm. Fig. 9 shows a picture of a pressure sensor after it is assembled on a substrate using the chip on board (CoB) method. This initial work is to demonstrate an assembly process for hybrid integration of a pressure sensor on a sensor chip. The pressure sensor was attached to the silicon substrate using a UV curing adhesive material. Wire bonding was then used to provide the interconnections between the bond pads on the sensor and the aluminium bond lines on the silicon substrate. The aluminium lines were fabricated using a sputtered aluminium film. The thickness of the film is about 400 nm. As will be discussed in Section IV, the aluminium bond lines and the IDT structures for SAW sensors will be fabricated in one process step for integration on LiNbO3 substrates.

III. Demonstration of In-Situ Condition Monitoring Using An Embedded Temperature Sensor Array

In order to demonstrate temperature monitoring in electronic packages using embedded sensors, we have developed thin film microsensor arrays for temperature monitoring in microsystem packages and in a novel laser assisted polymer bonding process for MEMS and microsystem packaging. The microsensor arrays shown in Fig.2 are embedded in between a polymer sealing ring that is used to bond two substrates together to form a microcavity for MEMS packaging. Fig. 10 shows a picture of a glass substrate bonded to a silicon substrate with an embedded microsensor array underneath the polymer ring. A photosensitive polymer, BCB (Dow Chemical), was used to fabricate the bonding ring. BCB is a stable polymer that produces a strong bond between the substrates for MEMS packaging applications. The substrates was bonded together in a pre-bonding step on a flip chip bonder at 100°C of temperature. This allows alignment of the polymer ring to the microsensor array. The outer dimensions of the polymer ring are 5.2mm x 5.2mm and the track width is 400 µm. The thickness of the polymer ring is about 9 µm. In order to produce a stable bond the BCB polymer is usually cured between 250°C and 350°C. A unique property of the BCB polymer is that the curing time is highly dependent on the curing temperature and it can be cured with in seconds above 300°C.

To demonstrate the fast curing time and successful temperature monitoring using the embedded temperature sensors, a laser based curing method using localized laser heating effect has been developed. A fiber coupled diode laser system with custom designed beam forming optics was used to carry out the temperature mintoring and binding experiments [21]. Fig. 11 shows the temperature profiles monitored by one of the peripheral sensors in the array for a tophat beam profile and a frame shaped beam profile respectively. The results show the potential of the temperature monitoring method using embedded sensors for health monitoring applications and for process control in the laser assisted polymer bonding technique. The embedded sensor approach allows provide more accurate temperature monitoring than the previous methods using a pyrometer and thermo-chromic paints respectively [22, 23].

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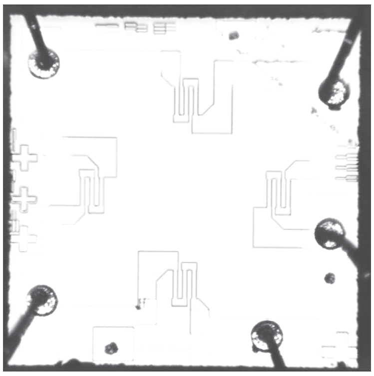

Fig. 9 Picture of wire bonded pressure sensor based on piezoresistance effect

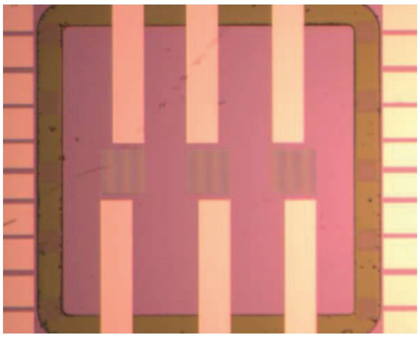

Fig. 10 Picture of sample for temperature monitoring in laser assisted bonding

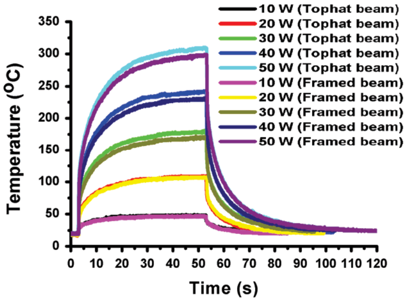

Fig. 11 Temperature rise of laser bonding between glass cap and silicon substrate.

IV. Methods for Sensor Integration

For healthing monitoring in electronic systems, it may be necessary to monitor multiple parameters inside a package in order to assess the condition of a sytemand under operation. It may be necessary to monitor the environmental paramters within a system package such as temperature, humidity and pressure. Two methods for sensor integration on a single chip are proposed. Fig. 12 shows a schematic layout of integrated sensors on a $LiNbO_3$ substrate. In this case platinum based temperature sensors and SAW based humidty sensors are fabrocated on the substarte. A micromachined pressure sensor is assembled onto the same chip in order to obtain integrated sensors on the same substrate. In the second method all of the sensors are fabricated on a silicon substarate as illustrated in Fig. 13. The temperature sensors are fabricated using a sputtered platinum thin film on the silicon substarte. The pressure sensor is produced on the substarte using the bulk silicon micromachining technique. The SAW based humidity sensor is fabricated on a piezoelectric thin film such as ZnO or AlN that can be deposited on the silicon substrate by the sputtering method. The work on sensor integration on a $LiNbO_3$ substrate is being conducted.

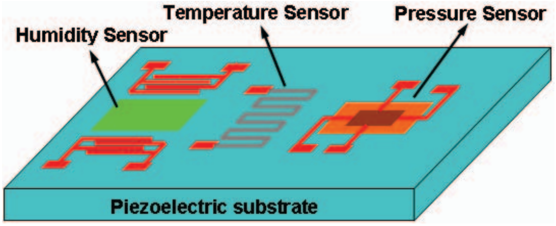

Fig. 12 Schematic layout of integrated sensors on a piezoelectric substrate for health monitoring in electronic systems.

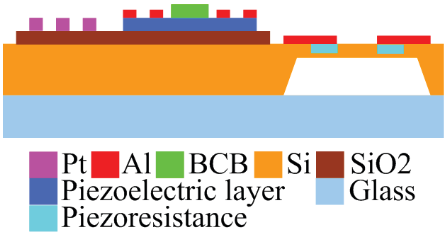

Fig. 13 Cross sectional view of the proposed sensor integration method on a silicon chip.

V. CONCLUSION

The development of microsensors for health monitoring in advanced microsystems has been described. Miniature temperature sensors and SAW based humidity sensors have been fabricated. The temperature sensors have been integrated in a package assembly to demonstrate temperature/condition monitoring using embedded sensors. The embedded sensors have been used for accurate temperature monitoring in a laser assisted polymer bonding method for MEMS packaging. The results show the successful monitoring of temperature in a package using embedded sensors. The SAW devices for humidity monitoring showed good characteristics for sensor applications. The detailed measurement of the response of the sensors to humidity is in progress. Two methods for sensor integration have been proposed. For $LiNbO_3$ based sensor chips, the temperature and humidity sensors can be fabricated on the sensor substrate utilizing the piezoelectric property of the substrate for SAW devices. The other sensors such as pressure sensor can be assembled onto substrate through hybrid integration. In the second approach, the temperature, humidity and pressure sensors are all fabricated on a silicon substrate. A piezoelectric film is deposited on the silicon substrate for fabrication of SAW based humidity sensors. The sensors and integration methods will find potential applications in heath monitoring in miniature electronic systems.

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