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Flip-chip packaging of piezoresistive pressure sensors

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Abstract

A packaging technology for piezoresistive silicon pressure sensors is presented which is based on the use of standard flip-chip bonding of the sensor die on a printed circuit board. The assessment of the packaging proposal has been carried out by using low-range, high-sensitivity relative pressure sensors. The characterization of the fabricated devices has shown the feasibility of the proposal in terms of stability and sensitivity although a higher dependence of the sensitivity on temperature than in the case of standard packaging. Since this drawback can readily be compensated for by the signal conditioning circuitry, the proposed packaging scheme can be of interest for cost-limited applications.

Keywords: Pressure sensor; Flip-chip; Packaging; Piezoresistive

1. Introduction

Much attention has been paid to the packaging of piezoresistive silicon pressure sensors since the performance and reliability of the device is greatly influenced by the encapsulation materials and packaging scheme used [1–3]. In addition, the need for a direct interaction between the silicon sensor and the medium makes protection against aggressive media compulsory [4]. All these constraints can lead to sensors in which the packaging represents more than half the cost of the device.

Among the different approaches proposed to tackle the packaging problem of microelectromechanical systems, flip-chip assembly has been considered of interest in terms of miniaturisation, reliability and cost [5,6]. This assembly technique has already been used in the case of accelerometers [7] and very recently for absolute silicon pressure sensors bonded to flexible substrates using conductive polymer bumps [8] or using anisotropic conductive films and stud bumping for the interconnects [9].

In this work a packaging technology based on the use of standard flip-chip assembly of piezoresistive silicon pressure sensors on common printed circuit boards is presented. The packaging proposal has been applied to low range, high-sensitivity relative pressure sensors with the aim of enhancing the effects that flip-chip soldering will certainly induce in the performance of the devices. The final purpose of this work is the assessment of an assembly and packaging proposal to fabricate hybrid pressure sensor systems of reduced dimensions for cost-limited applications.

2. Pressure sensor description

The piezoresistive pressure sensors used in this study have been in-house fabricated by means of a BESOI-based technology [10]. The sensor dice have a squared silicon diaphragm with a thickness of 15 μm and the chip dimensions are 5.38 mm × 5.88 mm. Two types of sensors have been used, their diaphragm dimensions being 1.46 mm × 1.46 mm and 2 mm × 2 mm, labelled Sensor S and Sensor L, respectively. In the standard fabrication technology the electrical connection pads are squares of 400 μm × 400 μm and made of aluminium. This metal, however, is not suitable for the flip-chip soldering process so an additional process module has been included in the fabrication technology in order to have the right metallization. This module, as described in [7], gives rise to a final metallization with gold and represents an additional lithographic mask in the technology. This specially designed mask leads to eight octagonal bump pads with a side of 300 μm, four corresponding to the electrical connection pads of the Wheatstone bridge of piezoresistors and four dummy pads included in order to symmetrically distribute the mechanical stresses that the soldering

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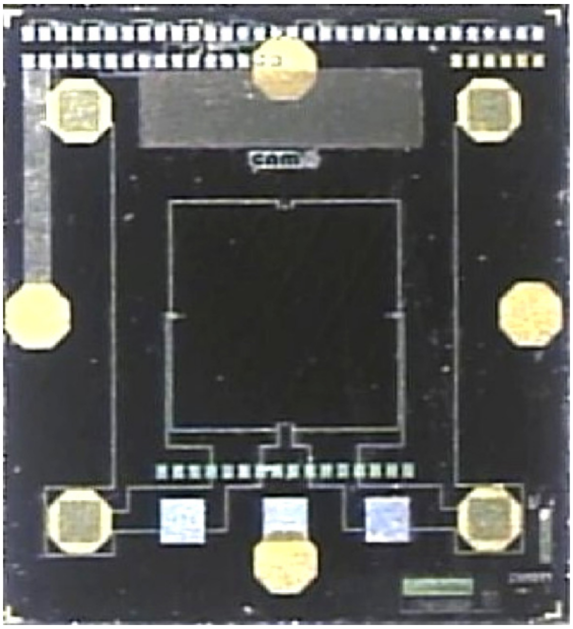

Fig. 1. Top view photograph of a type L pressure sensor showing the eight gold octagonal bump pads for flip-chip soldering.

process will certainly induce in the silicon diaphragm. The layout of the pads can be seen in Fig. 1.

After the complete wafer containing the pressure sensors is fabricated, a first-level packaging is made by anodically bonding a 1 mm-thick Pyrex#7740 glass wafer with the appropriate array of holes, for relative pressure measurement.

Some samples from the same batch were packaged on metal TO8 and using the standard wire-bonding technique. The characteristics of these pressure sensors will be used as a reference and will be compared with the results obtained when using the flip-chip packaging proposal. Measurement of the output voltage as a function of applied pressure has been carried out in the pressure range 0–50 mbar at different temperatures. The results obtained are shown in Fig. 2 for a temperature of 24 °C from which the sensitivities for each type of sensor are calculated, resulting in the following values: 347 (mV/bar)/V for Sensor L and 169 (mV/bar)/V for Sensor S. The dependence of the sensitivity on the temperature is shown in Fig. 3, indicating a linear dependence in the temperature range studied.

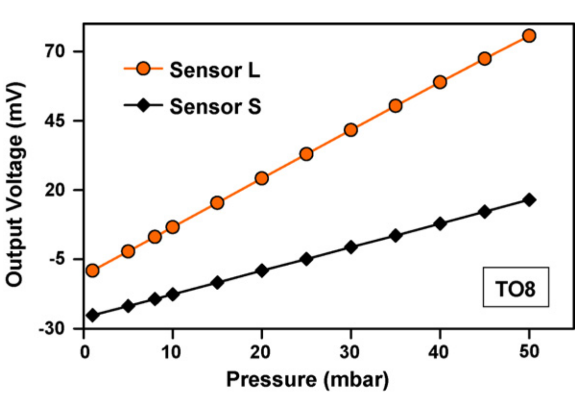

Fig. 2. Output voltage signal of TO8-packaged pressure sensors as a function of the applied pressure, at a temperature of 24 °C and with 5 V of supply voltage. The solid lines correspond to a linear fitting of the experimental results.

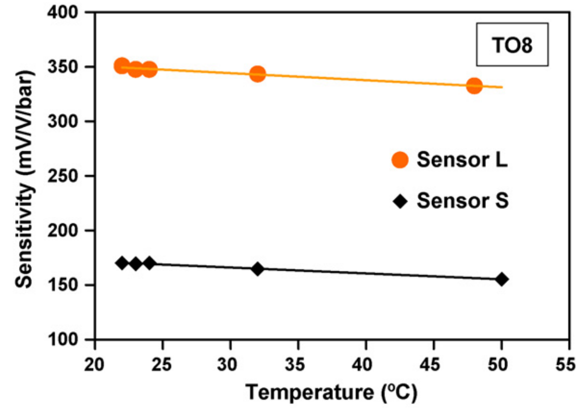

Fig. 3. Sensitivity of TO8-packaged pressure sensors as a function of the temperature.

3. Packaging process

The pressure sensor packaging proposal to be evaluated is schematically drawn in Fig. 4. It consists of a printed circuit board (PCB), with a central drilled hole, on which the sensor is to be soldered in flip-chip configuration. In the case of relative pressure sensors, once the pressure sensor chip is soldered onto the PCB, the assembly flow follows with the sealing of the gap between the chip and the PCB. Finally, the package is completed with the adhesion of a sensor cap on the opposite side of the PCB that will allow pressure application on the top side of the silicon diaphragm of the sensor die.

In the present work, the PCB has been designed with octagonal connection pads with similar dimensions as the ones on the pressure sensor and has been fabricated of laminated FR-4 and gold for the metal pads and connections. With respect to the flip-chip soldering process between the gold pads on the sensor and the gold pads on the PCB substrate, it starts with a screen-printing step using a 100 μm-thick steel stencil and Sn/Pb (63/37) solder paste performed in a DEK248 automatic machine. The sensors are then placed upside down by means of a manual pick-and-place machine. An ambient controlled hot plate is then used to perform a reflow process which melts down the solder paste and links the flip-chip to the FR-4 board.

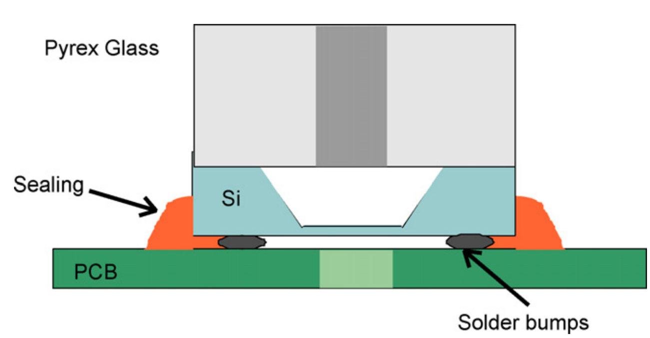

Fig. 4. Cross-sectional drawing of a flip-chip soldered piezoresistive pressure sensor.

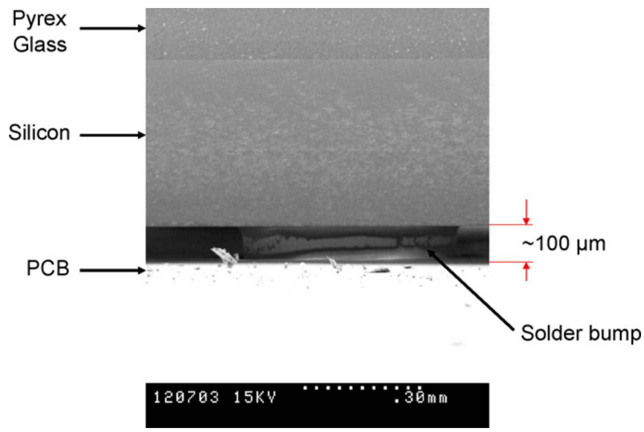

Fig. 5. SEM image of a solder bump of a flip-chip packaged pressure sensor.

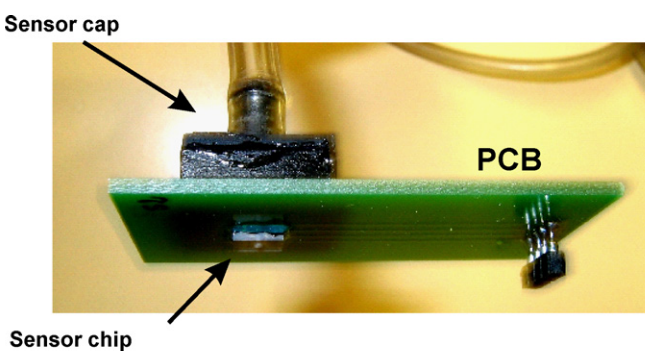

Fig. 6. Photograph of the pressure sensor after complete packaging.

Lead-free solders cannot be used together with FR-4 because of their higher melting point which would require higher reflow peak temperatures. In case of using lead-free solders, other intermediate solutions have been explored for other MEMS devices [7]. An image of one solder bump in a flip-chip assembled sensor is shown in Fig. 5 from which the height of the bump is estimated to be 100 μm.

After flip-chip soldering, the packaging of the pressure sensors under study follows with the sealing using the epoxy OG147-7 from Epotek, which is cured by UV radiation, thus preventing the use of high temperatures. Finally, a polyurethane sensor cap is adhered to the PCB. An image of the complete device is shown in Fig. 6.

4. Devices characterization

Before the complete packaging of the devices was carried out, the measurement of the offset voltage of the sensor after the flip-chip soldering step was done. Since this magnitude is related to the mechanical stresses on the silicon diaphragm, this measurement will give an indication of the effect of the flip-chip solder bumps on the diaphragm. In addition, the aim of these tests was also to check whether the anodically bonding of the Pyrex glass could be avoided. The results of the stability of the offset voltage during a period of almost 66 h in which the devices were continuously biased at 5 V are given in Fig. 7, for type L sensors with and without Pyrex glass. In view of these

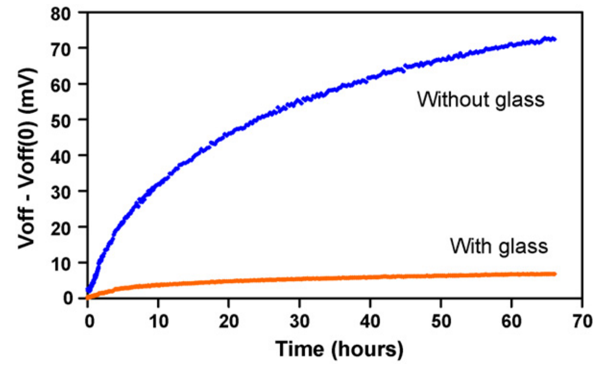

Fig. 7. Offset voltage shift as a function of time of flip-chip soldered pressure sensor chips, with and without Pyrex glass anodically bonded to the sensor die. Measurements are made at 25 °C and continuously biasing the sensors at 5 V.

results, we concluded that the anodically bonded glass makes the sensor more robust and that, under these conditions, the stability is acceptable for many applications. As a consequence, we have restricted the assessment of the packaging proposal to the case of chips with bonded glass.

The characterization of the pressure sensor devices has been carried out by means of a DPI515 Pressure Controller/Calibrator from Druck at fixed and controlled temperature, for a pressure range of 0–50 mbar. An example of the calibration curves for both types of sensors is shown in Fig. 8. The sensitivity of the resulting pressure sensor devices is 376 and 167 (mV/bar)/V for Sensor L and Sensor S, respectively. These sensitivity values are analogous to the results obtained when the pressure sensor dice are assembled and packaged using the standard scheme and TO8 packages (Fig. 2). The analysis of the results as a function of the temperature shows a rather different behaviour of the flip-chip packaged devices as compared to the reference ones. Fig. 9 shows the sensitivity results up to 50 °C. The dependence on temperature is slightly non-linear and the results can be best fitted with a second-order polynomial, so that the sensitivity S can be put in the form:

$$S = S_0[(1 - \beta T_D) + \rho T_D^2] \quad (1)$$

where $T_D = T - 25\,°C$, S_0 is the sensitivity at 25 °C and β and ρ are fitting parameters. Using this equation, the values of the

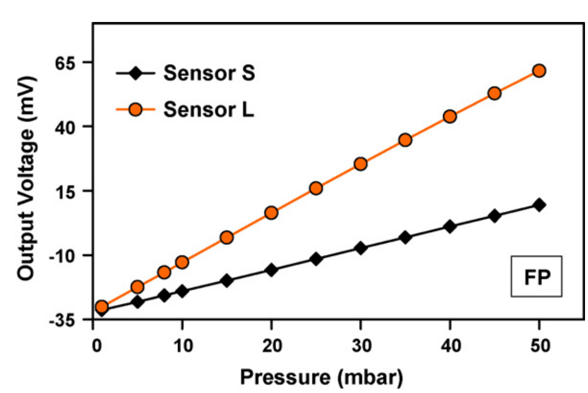

Fig. 8. Output voltage signal flip-chip packaged pressure sensors as a function of the applied pressure, at a temperature of 27 °C and with 5 V of supply voltage.

Table 1
Fitting parameters values of the sensitivity dependence on temperature

Package	Sensor L			Sensor S		
	S_0 (mV/bar)/V	β (°C^{-1})	ρ (°C^{-2})	S_0 (mV/bar)/V	β (°C^{-1})	ρ (°C^{-2})
TO8	347	1.86×10^{-3}	0	169	3.23×10^{-3}	0
Flip-chip	404	24.6×10^{-3}	0.4×10^{-3}	177	15.2×10^{-3}	0.3×10^{-3}

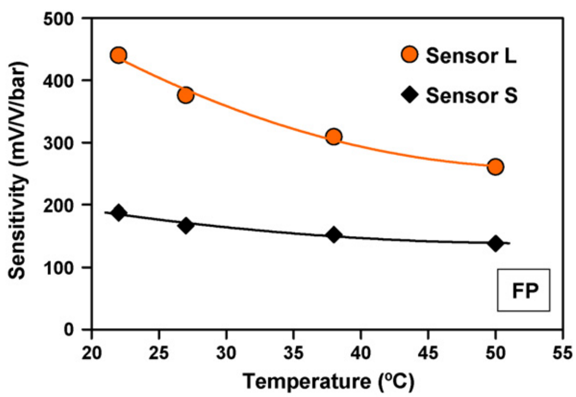

Fig. 9. Sensitivity of flip-chip packaged pressure sensors as a function of the temperature. The solid lines correspond to a second-order polynomial fitting of the experimental results.

parameters for the two types of packaging are summarized in Table 1. The differences between the two types of packaging schemes and the two types of sensors are best revealed analysing the relative variation of the sensitivity with temperature, which is plotted in Fig. 10. As shown, for a temperature variation of 30 °C, in the case of TO8-packaged sensors the sensitivity varies less than 10% the value at 25 °C whereas for flip-chip packaged sensors the variation is roughly 30% for Sensor S and 50% for Sensor L. As expected, the flip-chip configuration does exert stress on the sensor diaphragm and the difference in coefficient of thermal expansion of the used materials gives rise to a significant effect that is more important for higher sensitivity sensors.

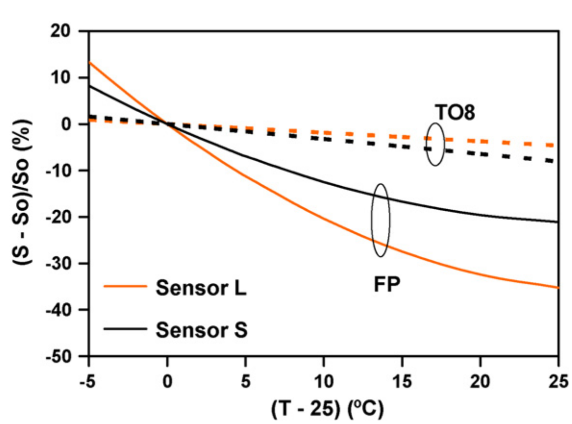

Fig. 10. Percentage variation of the sensitivity with respect to its value at 25 °C as a function of the temperature for sensors packaged on TO8 and flip-chip packaged (FP) sensors.

5. Conclusions

The characterization results of the highly sensitive pressure sensor devices shows that flip-chip soldering on common PCB substrates has a deleterious effect on the performance of the devices in terms of their dependence on temperature. This drawback however can be compensated for by means of an appropriate signal conditioning circuitry, which will certainly be used in real applications. On the other hand, our packaging proposal can be an adequate solution for not so sensitive pressure sensors as long as anodically bonded Pyrex glass is used in a first-level packaging of the sensor dice, since it has been shown to guarantee output stability. As a conclusion, standard, low cost flip-chip packaging of piezoresistive pressure sensors has been demonstrated feasible and of interest for cost-limited applications, since it may lead to compact pressure sensor systems.

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Biographies

Francesca Campabadal was born in Sabadell, Spain, in 1959. She received the PhD degree in Physics in 1986 from the Universitat Autònoma de Barcelona. In 1987 she joined the CNM as a senior researcher, working on thin oxide technology and characterization. Since 1992, her research activities have been also in the field of technologies for silicon sensors and microsystems and in the monolithic integration of mechanical sensors and CMOS circuitry.

Josep Lluís Carreras was born in Sant Lluís, Minorca, Spain, in 1971. He received the Bachelor's degree in Physics in 2000 and the Master's degree in Electronic Engineering in 2002, both from the Universitat Autònoma de Barcelona. He worked in the CNM from 2001 up to 2004 developing and characterizing silicon pressure sensors and systems.

Enric Cabruja was born in Girona, Catalunya, in 1962. He received his PhD degree in Physics from the Universitat Autònoma de Barcelona in 1990. He was dry-etching process engineer till 1993 when he became a senior researcher at CNM. From 1995 he is responsible of the Multichip Modules group at CNM and is interested in special processes for high density packaging.