Thermal Drift and Chip Size in Capacitive Pressure Sensors

G Blasquez, X Chauffleur, Patrick Pons, C Douziech, P Favaro, Philippe Menini

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G. Blasquez, X. Chauffleur, P. Pons, C. Douziech, P. Favaro, Ph. Menini
CNRS - LAAS, 7 Avenue du Colonel Roche, 31 077 Toulouse cedex 4, France
E-mail : blasquez@laas.fr, http : //www.laas.fr

SUMMARY

Anodic bonding and anisotropic etching have been used to fabricate silicon / Pyrex capacitive pressure sensors. Their thermal behaviour has been evaluated by 3D finite element structural analysis and measured from - 30ºC to 180ºC. Experimental and modelling results have revealed that the thermal coefficient is a strong function of dimensions. In order to minimise the thermal drift due to thermo-mechanical deformations it has been shown that the ratio of the chip and internal cavity widths should be approximately equal to 3/2. Based on this exemplary case, it has been inferred that the best metrological characteristics can be reached by effecting an in-depth structural analysis taking into account not only the active parts of micro devices but also their passive parts.

Keywords : *Thermal drift, capacitive pressure sensors, thermo-mechanical deformations, structural analysis.*

INTRODUCTION

During the last decade the feasibility of miniature hybrid or integrated capacitive sensors has been demonstrated [1 to 12]. Generally speaking these sensors are characterized by their very high sensitivities, their low power consumption and their easy connections with MOS and CMOS integrated circuits. Nevertheless their thermal behaviour remains to a large extend unpredictable and sometimes disappointing because they can display unexpected thermal drifts.
The basic solution to reduce these thermal drifts is to design ratiometric or differential architectures [13, 14]. Ultimate minimization implies an accurate identification of the thermal drift mechanisms and the optimization of the sensing cell parameters.

From a design point of view, devices exhibit active and passive parts. In micro electronics devices, the passive part (i. e. the substrate), is most often disregarded by designers. Its lateral dimensions are reduced to place as many chips as possible per wafer. Correspondingly design models and tools only simulate the behaviour of the active part. These practices are often followed unconsciously to design and fabricate Silicon sensors and micro-devices.

In the following, it is shown that the passive parts can significantly influence the thermal behaviour of sensors and that they should be designed properly to reach the best metrological characteristics.

SENSOR DEFINITION

Let us consider the capacitive pressure sensor shown in Fig. 1. It comprises a metal plate deposited on a rigid insulating substrate of thickness h_p, and a deformable plate of thickness h_s. The substrate and cavity have square shapes. Let a_{ch} and a_c, be the respective sides of the chip and the cavity. The fixed and the deformable plates can be assimilated to the active part of the device. In the following, C denotes the capacitance.The remaining part of the structure is the passive part.

To assess the influence of this part, it was assumed that h_p and h_s were invariant and a_{ch} and a_c were variables chosen by the designer.

The conventional optimisation, consists of maximising a_c and minimising a_{ch} - a_c. Within the framework of this study, we assigned a fixed value to a_c while a_{ch} was taken as the variable. This solution offers the advantage of being simple to implement.

To support and refine the estimation given by modelling, we designed and investigated the behaviour of three Silicon / Pyrex sensors whose main characteristics are as follows : (deformable plate : Silicon, h_s = 0.3 mm) ; (cavity : a_c = 3.5 mm) ; (substrate : Pyrex 7740 ; h_p = 1.5 mm ; a_{ch} = 4 mm, 4.5 mm and 5.5 mm). From these data, it is easy to see that the surfaces used to bond the deformable plate have a width $(a_{ch} - a_c) / 2$ equal to 0.25 mm, 0.5 mm and 1 mm respectively.

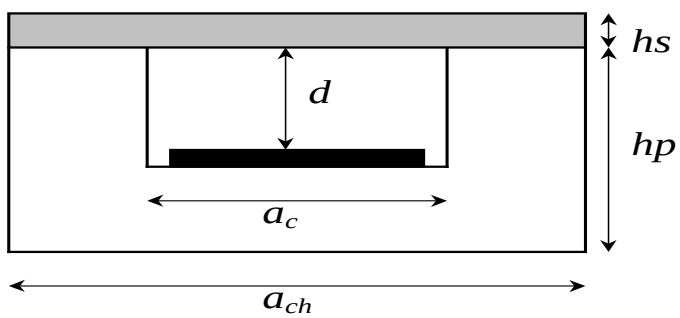

Fig. 1 : Sensor Model and Symbol Definitions Substrate : Pyrex 7740, Membrane : Silicon.

THERMAL DRIFT SIMULATION

The sensor behaviour as a function of pressure was modelled in [6, 15, 16]. In this study, only the behaviour versus temperature *T* is considered, and more precisely that of the thermal drift of capacitance *C* with no applied pressure.

This drift has been characterised by means of its differential thermal coefficient *TC* which is defined by the following relationship :

$$TC\ [\ C(T)\ ] = \frac{1}{C}\frac{\delta C}{\delta T}$$

In order to estimate *TC [C(T)]*, it was assumed that thermo-mechanical deformations of the sensor structure are the main source of thermal drift. The thermo-mechanical simulation has been done using the finite elements method and the ANSYS software.

Figures 2 to 4 give the results obtained for the three sensors. In the three cases, it was assumed that the thermo-electrical bond of Silicon and Pyrex [17, 18] was made at 400 °C. Figure 2 shows the shape of one quarter of a sensor at ambient temperature.

At 400 °C, the sensor is almost flat. The deformations appearing in Fig. 2 are due to cooling to ambient temperature. They originate from the difference in the thermal expansion coefficient of Pyrex and Silicon [19, 20]. Therefore thermo-mechanical deformations occur irrespective of the sensor size.

These structural deformations provoke very small variations of the distance, d, separating the plates. Their amplitude is maximum at the centre. Simulations of d(400ºC) - d(T) as a function of temperature are given in Fig.3. In the range - 50ºC, + 150ºC the distance between the plates decreases. From 150ºC to 400ºC this distance increases and tends to the initial plate separation i.e. the separation without structural deformations.

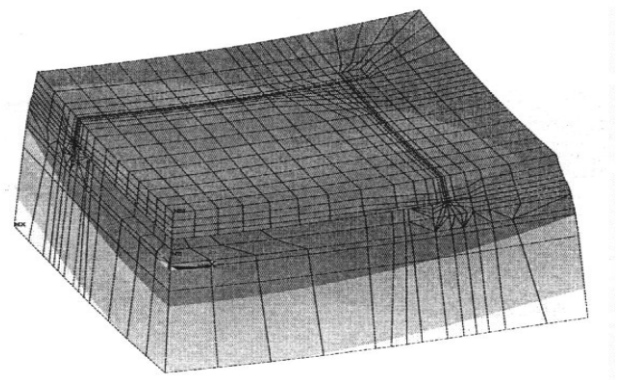

Fig.2 : Thermo-mechanical deformation evaluation given by finite element analysis. Representation of one quarter of the sensor model.

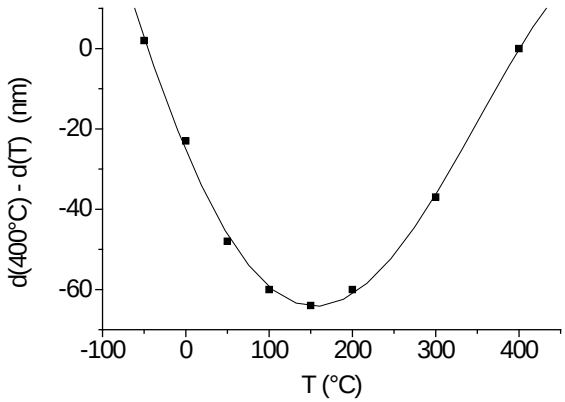

Fig.3 : Thermal variation evaluation of the plate separation at the centre.

The thermal drift of the capacitance is shown in Fig. 4. In the range - 30 °C, + 125 °C the *TC [C(T)]* exhibits a positive sign. The thermo-mechanical deformations of the sensor structure cause a monotonous increase in capacitance as a function of temperature. Also, it appears in Fig. 4 that *TC [C(T)]* decreases if *T* increases. This behaviour implies that the thermal drift is mainly determined by the evolution of the plate separation.

Finally and most importantly, it can be seen in Fig. 4 that the thermal coefficient is a highly decreasing function of the chip size. To optimise the thermal drift, one has to increase a_{ch} and more precisely a_{ch} - a_c. In other words, one has to increase the relative weight of the passive parts with respect to the active ones. This induces an extra cost since the total number of chips that can be produced per wafer diminishes. Cost and thermal drift optimisations are more or less incompatible. The designer has therefore to determine an acceptable compromise.

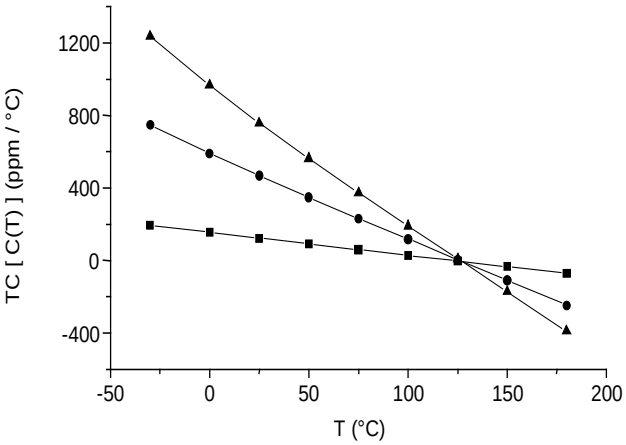

Fig. 4 : 3D Simulation of the influence of (a_{ch} - a_c) / 2 on the thermal drift induced by thermo-mechanical deformations : σ 0.25 mm, λ 0.5 mm, ν 1 mm.

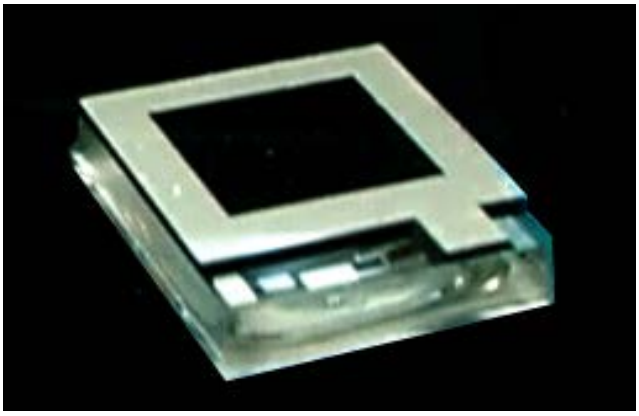

Fig. 5 : Silicon / Pyrex capacitive sensor photograph.

MEASUREMENTS

In a real sensor, there may exist numerous other sources of thermal drift. Their order of magnitude has to be known so as to predict from which stage the increase in chip size would no longer significantly diminish the total thermal drift.

In order to reach an effective trade-off, we have made the three sensors whose dimensions are given in the preceding sections. A photograph of one of them is given as an illustration in Fig.5.

The capacitance variations in the range - 30ºC, + 180ºC are plotted in Fig.6. Their general evolution follows approximately the features derived from the numerical model. From these data, the incremental thermal coefficient *TC [C(T)]* has been computed. Results are shown in Fig.7

Clearly, for small size chips (i.e., a_{ch} = 4 mm), measurements and simulation give consistent results. This means that the thermal drift chiefly originates from the thermo-mechanical deformations of the chip.

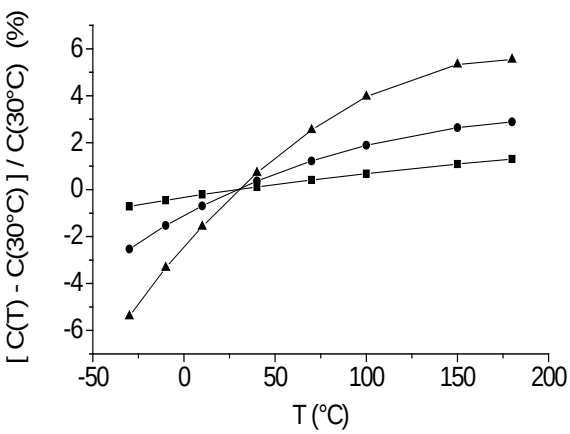

Fig.6 : Normalised thermal variations of the capacitance with the bonding width as a parameter : σ 0.25 mm, λ 0.5 mm, ν 1 mm.

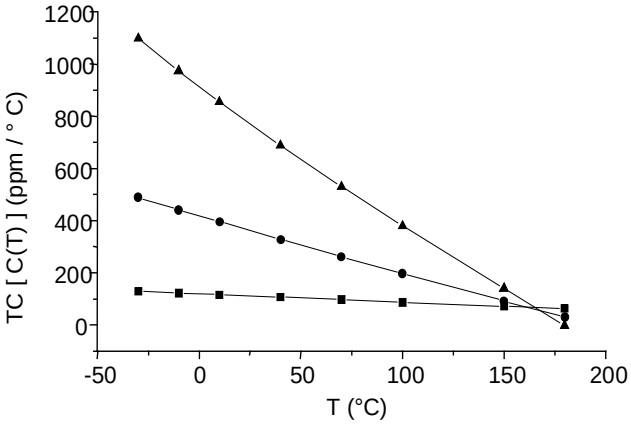

Fig. 7 : Differential thermal coefficient measurements vs temperature and with the bonding width as a parameter : σ 0.25 mm, λ 0.5 mm, ν 1 mm.

On the other hand, for large size chips (i.e., a_{ch} = 5 mm), the drift is roughly independent of temperature. The decreasing nature of the drift due to the chip deformation is less clearly apparent. In this case, it is likely that the behaviour is influenced by other sources of drift and possibly by parasitic capacitors, adhesive used to mount the chip in the package and edges effects, ... The threshold beyond which the increase in size is less beneficial seems to be an a_{ch} / a_c ratio greater than 3 / 2.

CONCLUSION

In capacitive pressure sensors fabricated by bonding Pyrex and Silicon, the thermo-mechanical deformations can induce large thermal drifts. Their amplitude estimation requires 3D numerical simulation. They can be minimised simply by designing the bonded part with a sufficient width.

Starting from this particular example, we infer that in order to obtain the best metrological performances, one has to take into account not only the active parts of microstructures but also to design carefully their so-called passive parts. Size reduction of these passive parts should not be systematically made. It must be supported by an in-depth comparative evaluation of the economic and metrological advantages and drawbacks.

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