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Advances in Silicon Resonant Pressure Transducers

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Abstract

This paper presents a MEMS Resonant Pressure Transducers (RPT) that is produced using a flexible fabrication route to allow pressure ranges from 1bar to 700bar in fully oil isolated hermetic packages without compromising sensor performance. The fabrication method makes use of silicon fusion bonding (SFB) and deep reactive ion etching (DRIE) to build up a three-layer die, with the middle layer consisting of a strain sensitive resonator. The key aspects of the fabrication process and sensor design that make this possible are presented, along with data showing long-term stability of better than 100ppm drift per year.

Keywords: Pressure Sensor; DRIE; Fusion Bonding; Resonant, Silicon

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1. Introduction

The stability of Piezoresistive pressure sensors is limited by drift of the piezoresistors with time. To overcome this limitation RPTs (Resonant Pressure Transducers) may be used. They are commercially available with total non-repeatable errors of less than 100ppm and stability of better than 100ppm per year. This is typically an order of magnitude better than Piezoresistive sensors. The majority of resonant pressure transducers are based on complex Quartz resonators, but for some limited applications more robust silicon MEMS (micro-electro-mechanical system) devices are available. This work presents a new silicon MEMS RPT designed to meet a wider range of challenging applications. When designing for such applications a main consideration is the required die packaging. In harsh environments this packaging should ensures the sensor die is hermetically isolated from the pressure media. This is typically done using a metallic isolation diaphragm and an oil-filled cavity to mount the die in.

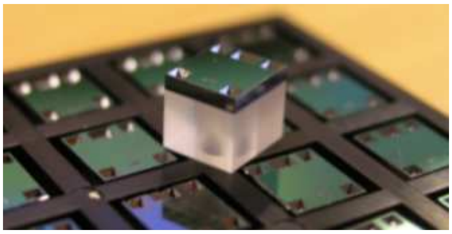

Fig. 1. Photograph of a resonant pressure transducer (RPT) die.

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The device presented in this work was designed to allow flexible manufacture of a MEMS RPT with packaging as a key consideration. The fabrication process developed will be explained together with the key design features that ensure the silicon die can successful packaged. Finally testing and charaterisation results will be presented that demonstrate the sensor performance.

2. Fabrication Process

The sensor die uses three technologies: silicon-on-insulator (SOI) wafers; direct silicon fusion bonding; and deep reactive ion etching (DRIE) to produce die as shown in Fig. 1. These technologies are commonplace in MEMS facilities and offer well defined processes. The use of these technologies makes a generic and configurable RPT design possible, the structure of which is shown in Fig. 2. The first stage in the process is to produce the diaphragm layer, which is done using conventional wet silicon etching. Once this is complete the resonator layer is fusion bonded to the diaphragm layer. The resonator structure is then defined in this layer by photolithography and DRIE. For optimum performance, robustness, and stability the resonator is then encapsulated on the wafer scale by bonding a third cap layer to the stack. This forms a hermetic seal encapsulating the resonator in a vacuum. At this stage the wafer stack may be customized to suit a range of particular applications. Electrical contact vias may be etched through either the cap or the diaphragm layer to suit the required package, and the diaphragm thickness may be reduced by a further etch to tailor sensitivity. The two main configurations are shown in Fig. 2, which allow die to be packaged with the silicon die exposed to the pressure media (type A), or in an isolated hermetic package (type B). Examples of the silicon exposed and hermitically isolated packages are also shown in Fig. 2.

3. Die Design

As previously stated the resonator has been specifically optimised such that it may be operated in a range of environments, each with specific package requirements. The sensor comprises a resonator that is fixed to two points on the diaphragm layer such that pressure induced deflection of the diaphragm induces strain in the resonator. This in turn causes a strain stiffening affect that increases the resonant frequency of the resonator. There are two key aspects of the resonator design that allow this. The first is the use of low impedance Piezoresistive outputs so the resonator can be operated in a closed loop with reduced influence from parasitic capacitances[1]. This is important as it allows electrical drive and pick-off signals to be delivered to the sensor die though the hermetic electrical interconnects that are required for the oil isolated (Type B) packaging.

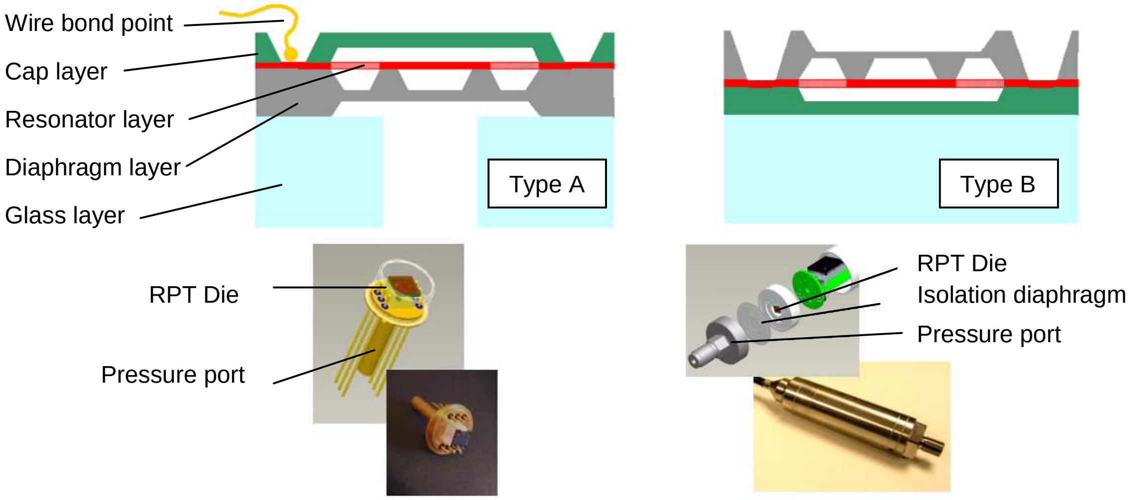
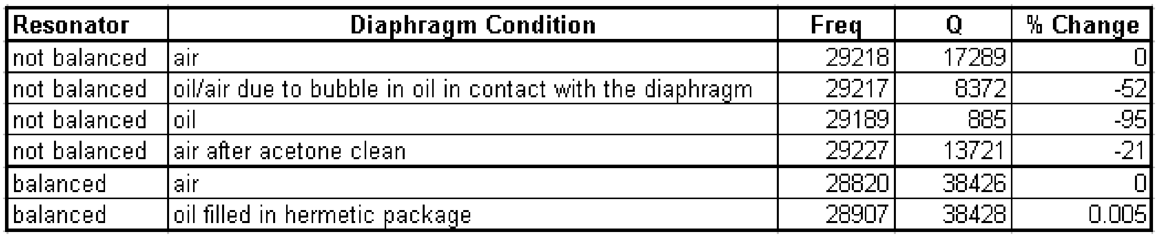


Fig. 2. Schematic of RPT die in two types, the type A die is configured for silicon exposed to pressure media, the type B die is configured for isolated hermetic packaging.



Resonator	Diaphragm Condition	Freq	Q	% Change
not balanced	air	29218	17289	0
not balanced	oil/air due to bubble in oil in contact with the diaphragm	29217	8372	-52
not balanced	oil	29189	885	-95
not balanced	air after acetone clean	29227	13721	-21
balanced	air	28820	38426	0
balanced	oil filled in hermetic package	28907	38428	0.005

Table 1. Comparison of balanced and un balanced resonator geometries, with sensor die subjected to a range of external media

The second key design aspect is the geometry of the resonator itself and in particular the mechanism by which the resonator is connected to the pressure diaphragm. The resonator geometry is designed to ensure the resonator is excited in a dynamically balanced lateral resonator mode shape. This mode shape ensure there is no net momentum change in the resonator that would impart a reaction force through the resonator fixing points to the diaphragm layer. The resonator fixing points have also been optimised to ensure that mechanical reaction forces generated by the resonator are balanced and not transferred to the diaphragm. As a result of balancing these reaction forces it is possible to minimise any transfer of energy from the resonator to the diaphragm. If this is not done then any transferred energy may then be lost to the environment external to the die. Loss of energy from the resonator will result in a lowering of the resonator quality factor. A high quality factor is important for the resonator as it allows for stable drive electronics with a good rejection of noise and therefore optimum sensor performance. It also indicates that there are minimal energy loss mechanisms from the resonator to the external environment, therefore the sensor must be well isolated from environmental affects that may limit sensor long-term stability.

To illustrate the dramatic impact of a non-balanced resonator two different resonator geometries were fabricated using the same generic process presented here. The resonators were both similar in overall dimensions, with closely matched natural frequencies of approximately 26kHz, and sensitivities of approximately 3Hz/mBar. One of the resonators was designed to be fully balanced and thus have minimal energy loss, while the other was unbalanced. The resonator quality factor was measured for each resonator using a Solartron 1255 frequency response analyser. Using this instrument a frequency response curve was obtained and this was then used to calculate quality factor using the half-power point method. The results of applying DC550 silicone oil to the diaphragm of both resonators can be seen in Table 1. With the unbalanced sensor although it had a reasonable quality factor of 17000 in air, once oil was placed on the diaphragm this dropped dramatically by 95%. With the balanced resonator there was no measurable change in quality factor allowing this device to hermetically sealed in a fully oil isolated package.

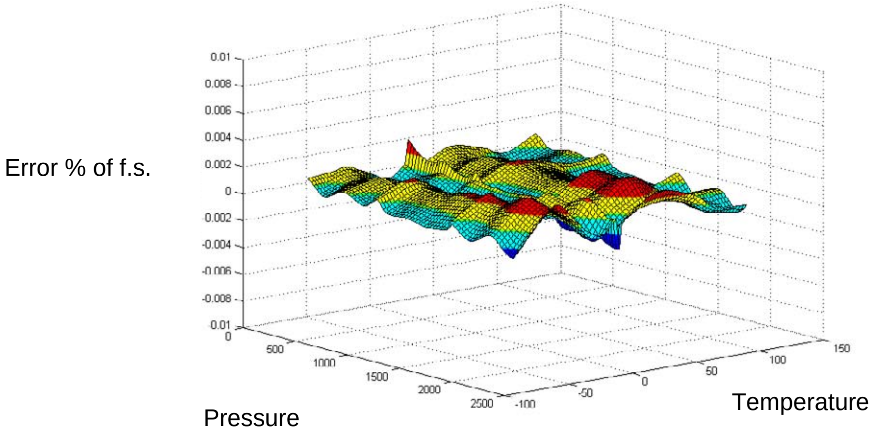


Fig. 3. Non-repeatable Pressure and Temperature Errors 0 – 2Bar and –54C to 125C.

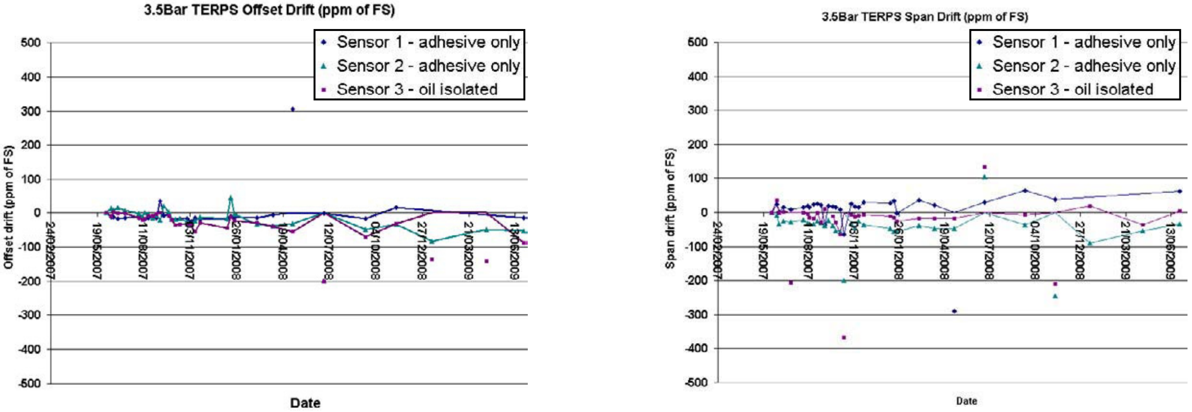


Fig. 4. (a) Resonant sensor off-set drift in ppm f.s. (b) Resonator span drift in ppm f.s.

4. Resonant Pressure Transducer Performance

To fully characterise the performance of the resonant sensor two tests were conducted to determine accuracy and stability of the device. To determine accuracy and non-repeatable errors a device was calibrated using a test rig comprising a GE Druck DPI515 pressure controller, a computer controlled oven, and a pressure reference system developed specially for this application. It comprised a high accuracy GE Druck RPT sensor held in a temperature-controlled environment for increased accuracy and stability. Data was collected over a range of temperatures from 125C to –54C with numerous returns to room temperature, and over a pressure range of 0 to 2Bar. This data can be seen in the surface plot shown in Fig. 3, with total errors of less than +/-40ppm of f.s. To determine the long term stability of the sensor three devices have be continuously tested versus a high stability dead weight in the in UKAS standards lab at GE Sensing, Leicestershire, UK. Results for offset and span of the devices is shown in Fig. 4 (a) and (b) respectively. This data shows the three sensors (one of which is full isolated in an oil filled hermetic package) have shown less than 100ppm f.s. drift over the two year period of testing.

5. Conclusion

The consideration of packaging at the die design stage has allowed RPT die to be packaged in isolated hermetic packages with no significant impact on resonator operation and long-term stability. The generic process that has been developed uses well established MEMS processing steps to produce a configurable die suitable for different packing requirements, with a range of pressures from 1bar to 700bar being made possible using the same technique. The fabricated die presented and have been successfully packed and tested over a two year period and show less than 100ppm drift.

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