DEVELOPMENT OF WEIGHING SYSTEMS WITH IMPROVED DYNAMIC RANGE USING HIGH-RESOLUTION RESONANT MEMS STRAIN SENSORS

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ABSTRACT

The application of high-resolution MEMS strain sensors based on micromechanical resonators fabricated with wafer-level vacuum packaging to the construction of large dynamic range weighing systems is explored. Resonant sensors with sub-nano strain resolution are adopted to build a load cell prototype using a standard aluminum structure normally utilized in commercial weighing systems. A differential strain measurement configuration is implemented with two sensors oriented at 90° between them and fabricated on the same chip for temperature compensation. The load cell equipped with the resonant MEMS sensors shows an excellent dynamic range of 108 dB, effective temperature compensation and good weight measurement reproducibility.

KEYWORDS

Strain sensors, flexural resonators, SOI technology, MEMS, wafer-level vacuum packaging.

INTRODUCTION

Conventional strain sensors are widely employed in fabrication of weighing systems based on mechanical load cells. A load cell is a mechanical structure, normally manufactured in steel or aluminum, which is designed in order to be able to undergo a controlled mechanical deformation when subjected to a weight load. Such deformation is generally measured at some specific points in the structure, in which the measurable strain is in the correct order of magnitude for the weight measurements of interest. The load cells presently available on the market are generally based on metal strain gauge technology, which relies on the change in electrical resistance of a thin metal film patterned on a plastic foil.

The dynamic range of a weighing system m_{max}/m_{min} (maximum and minimum measurable mass ratio) can be expressed by

$$\frac{m_{max}}{m_{min}} = \frac{\varepsilon_{max}}{\varepsilon_n} \quad (1)$$

where ε_{max} and ε_n are respectively the maximum measurable strain and strain resolution limit of the sensor utilized in the load cell. In metal strain gauges, due to the electrical noise generated by the sensor itself and by the readout circuitry, ε_n is normally around 1 με or slightly lower. For these sensors, the maximum strain level, on the other side, is around a few mε. Consequently, the m_{max}/m_{min} ratio for such systems is typically in the order of 10^3.

In order to improve the dynamic range of the weighing system, a strain sensor with a higher $\varepsilon_{max}/\varepsilon_n$ ratio should be utilized in the load cell.

A possible technology that could fulfill this requirement may rely on MEMS strain sensors fabricated with electromechanical resonators. Compared to the resistive metal gauges, resonant strain sensors are based on a completely different operating principle, relying on the change in mechanical resonance frequency of a vibrating microstructure occurring upon application of strain [1-5]. A new fabrication technology that can be used to manufacture strain sensors based on wafer-level vacuum packaged silicon resonators demonstrating a strain resolution limit ε_n around 150 pε on steel was reported in [6]. Since such resolution is much higher than those achievable with conventional metal strain gauges, this technology can be used to build weighing systems with improved dynamic range.

In the present paper, we explore the potential application of high-resolution resonant MEMS strain sensors fabricated with vacuum packaging at wafer level to the manufacturing of weighing systems with improved dynamic range compared to that achievable with conventional metal strain gauges. To this purpose, the prototyping and testing of a load cell for weighing application equipped with resonant MEMS strain sensors with sub-nε resolution is presented and the results are compared with those obtained with commercial sensors.

LOAD CELL PROTOTYPING

The design of the load cell utilized to assemble the prototype of weighing system based on MEMS strain sensors is shown in Fig. 1. The cell, constructed in aluminum, was taken from a commercial weighing system from SunLife with a nominal measurement range 1g - 5kg. On the central part of the cell, which is the one producing the higher deformation under load, four commercial metal strain gauges are bonded on the two sides of the cell.

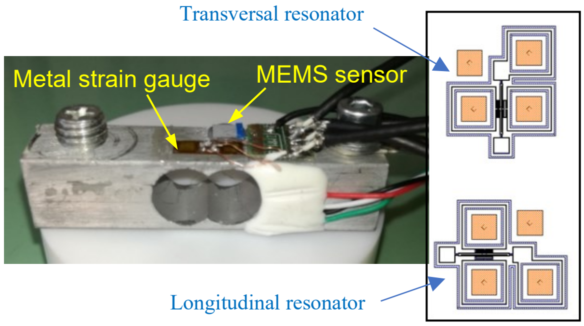

Figure 1: Load cell prototype (left) with detail of attached strain sensors (right).

In order to build a load cell prototype employing the MEMS strain sensors, a 5x5 mm^2 silicon chip containing several sensor prototypes was attached to the load cell using an epoxy glue LOCTITE EA 9461 from Henkel. the MEMS sensors chip was bonded beside the two upper metal strain gauges, in order to undergo a similar strain level during the cell load testing.

MEMS RESONANT STRAIN SENSORS

The MEMS strain sensors utilized in the system were designed according to the resonator structure reported in

Fig. 2 (unpackaged device). The strain sensors were fabricated from SOI substrates with 15 µm thick device layer, 2 µm thick buried oxide and 500 µm thick handle layer, following the process flow described in [6].

The resonator can be used as a strain sensor since the fundamental mechanical resonance frequency of the structure depends on the applied strain, so that, by operating the resonator in closed loop with a feedback circuit, a strain-dependent micromechanical oscillator locked at the fundamental mechanical resonance frequency of the microstructure can be obtained. The oscillation frequency of the closed-loop circuit containing the resonator can be then utilized as a sensing signal for strain.

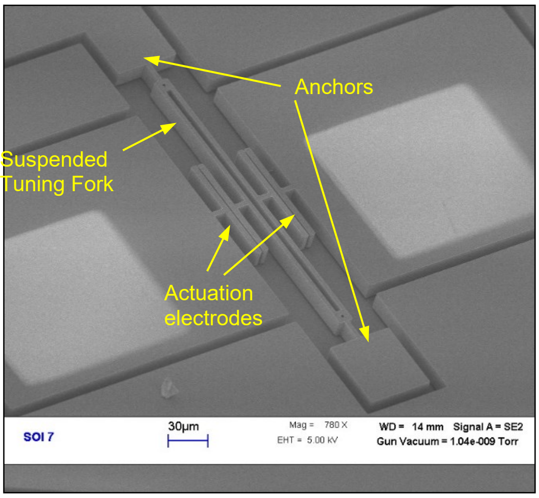

Figure 2: Strain sensor design (SEM image).

The strain sensor is built using a lateral flexural resonator with a Double-Ended Tuning Fork geometry (DETF), suspended at its two ends (see Fig. 2 showing the anchors of the micromachined structure).

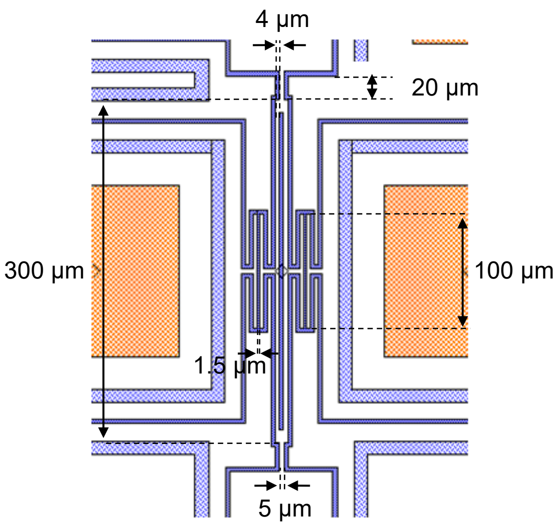

Figure 3: Design parameters of the MEMS.

The DETF resonator is micromachined on the 15 µm thick device layer of the SOI substrate and released by etching away the Buried Oxide (BOX) underneath in order to create a suspended structure that is free to vibrate. In particular, the structure is electrostatically actuated and put into vibration by using two capacitive parallel-plate electrodes. The design parameters of the MEMS strain sensors used in the weighing system prototype are schematically illustrated in Fig. 3. In order to increase the Quality factor (Q) of the resonators, a wafer-level vacuum packaging of the devices is adopted, based on thin-film encapsulation performed with a Low-Pressure Chemical Vapour (LPCVD) polycrystalline silicon deposition. The designed resonators have a measured resonance frequency of 350 kHz, strain sensitivity around 150 Hz/με and quality factor of 27000.

WEIGHING SYSTEM TESTING

After mounting the load cell equipped with the MEMS strain sensor and the commercial strain gauge, the complete weighing system prototype was obtained (Fig. 4).

A custom electronics readout was implemented on a Printed Circuit Board (PCB) [6] to drive the MEMS resonators in closed loop and digitally measure the oscillation frequencies of the two resonators oriented at 90 degrees with respect to each other (see Fig. 1). In the load tests, the shift of the mechanical resonance frequency of the two resonators used on the MEMS chip was observed after the application of variable weights on the balance.

Several measurements were taken in different weight ranges to estimate the load test reproducibility, linearity error and weight sensitivity.

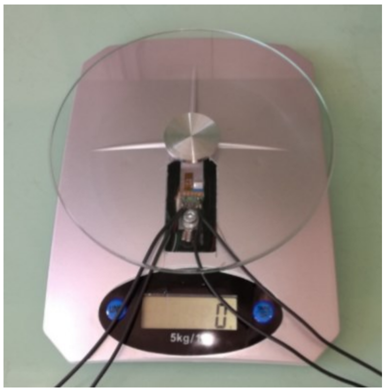

Figure 4: Weighing system prototype.

In Fig. 5, a typical result obtained in a medium-weight range (34.5-172.5 g) using the MEMS strain sensors is reported. As can be observed, the application of a mass load produces a positive resonance shift on the longitudinal resonator (the one oriented in horizontal direction in the schematic representation of the system reported in Fig. 1), whereas a negative shift of the resonance frequency is produced on the other resonator, oriented in transversal direction on the load cell.

When a load is applied on a mechanical structure like the one shown in Fig. 1, a tensile strain is generated in longitudinal direction on the region where the strain sensors are fixed. In transverse direction, instead, a compressive strain is produced on the silicon chip during bending, mainly for the Poisson effect produced on the structure by loading.

By plotting the difference between the longitudinal and transverse resonator frequencies, the result also reported in the plot can be obtained. On the differential signal, since the sign of the two frequency shifts is opposite, a slight increase of the overall load sensitivity is observed.

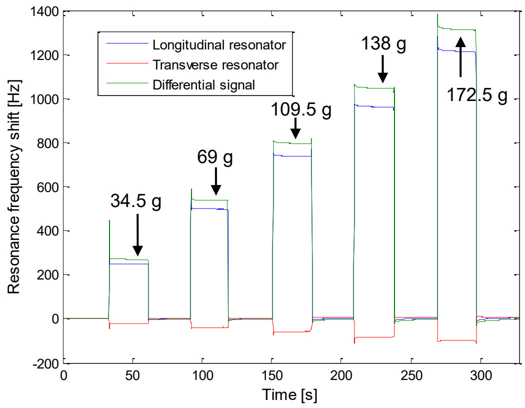

Figure 5: Load test results in a medium-weight.

Moreover, as can be hardly appreciated in the plot, a lower baseline drift is observed compared to the individual measurements. This happens because the thermal drift of the MEMS resonance frequency, mainly due to the difference in thermal expansion between silicon and aluminum, is roughly similar on the two resonators, despite the different orientation of the two microstructures.

In Fig. 6, the calibration curve on the differential frequency shift calculated by linearly fitting the experimental data acquired on a more extended weight range (up to 4 kg) is reported. As can be observed from the plot, a weight sensitivity of 7.3 Hz/g with a linearity error around 0.3 % is obtained with the differential measurement up to 3 kg. However, at the application of 4 kg, some loss in sensitivity is observed, probably due to sliding effects in the LOCTITE glue utilized to bond the MEMS sensors to the load cell. Anyway, this undesired effect could be avoided by using the chip thinning and gluing procedure described in [7], largely increasing the maximum measurable strain.

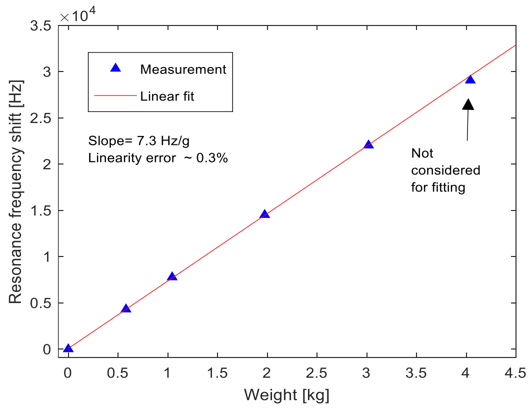

Figure 6: Load test results in a large-weight range (0.6-4 kg): calibration curve of the differential signal.

In order to investigate the temperature drift of the weighing system, further measurements were carried out in a temperature-controlled environment as shown in Fig. 7, where the result of a temperature drift measurement is reported by way of example. The temperature drift test was executed by first heating the system at 55 °C and subsequently decreasing the chamber set point to lower temperatures. As may be observed, the temperature increase with respect to the room temperature produces a positive resonance frequency shift on the two resonators. Although this shift is of the same order of magnitude on the two resonators, it shows a different linear dependence on temperature for the two devices and a lower thermal dependence than expected by considering the large thermal expansion mismatch between silicon and aluminum. This effect could be explained by the different position of the two resonators on the chip and the effect of the not-negligible chip thickness on the load cell strain distribution

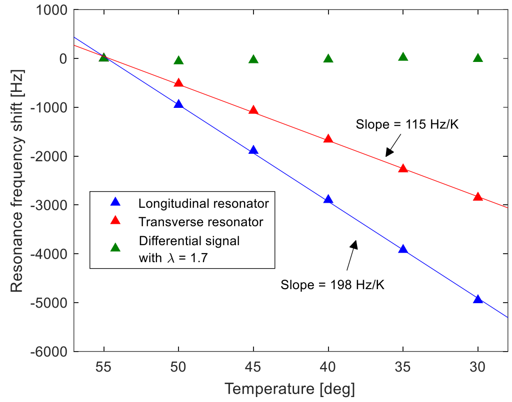

Figure 7: Temperature drift test in the range 30-55 °C.

In order to compensate the temperature drift, a numerical coefficient was then introduced defining the sensing signal f_w as:

$$f_w = f_l - \lambda f_t \quad (2)$$

in which f_l, f_t are the frequencies of the longitudinal and transverse resonators, respectively, whereas λ is a numerical coefficient that can be adjusted to find the best temperature drift compensation. Despite the different temperature dependence, the use of the differential frequency defined by Eq. (2) with $\lambda = 1.7$ gives rise to the optimal temperature compensation in the range 30-55 °C, which markedly reduces the drift of the individual MEMS sensors, anyway leaving a residual drift on the baseline around 50 Hz over the temperature range considered.

The typical noise level of the MEMS strain sensors, considering for example an acquisition time of 170 msec, is around 0.1 Hz (Fig. 8).

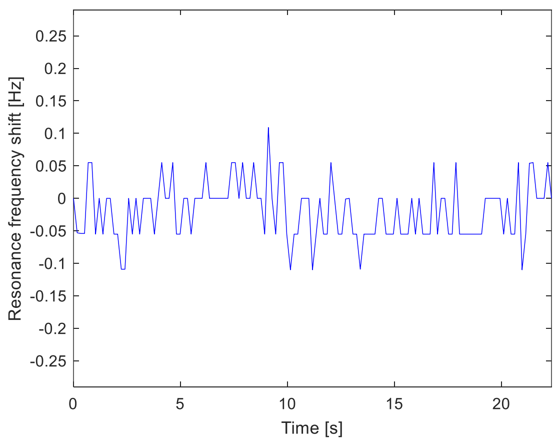

Figure 8: Noise level on the differential frequency output of the system.

Since the weight sensitivity obtained in the cell load testing was around 7.3 Hz/g, the weight resolution limit of the system used with the MEMS sensors in differential configuration may be calculated as the weight that generates a frequency shift equal to the maximum noise of

0.1 Hz on the differential output of the system, which yields a resolution limit around 13.7 mg for the weighing system operated with the MEMS strain sensors.

In order to compare the performance obtained with the MEMS sensors with those actually achievable with the commercial metal foil gauges, parallel measurements with the MEMS sensors in differential configuration and the commercial 4 strain gauges in full Wheatstone bridge configuration were carried out. In these measurements, the output of the Wheatstone bridge was read using a HP34578A Multimeter from Keysight with 3V bridge polarization. The data were simultaneously acquired with a LabVIEW PC interface during the weighing experiments and a comparable integration time for the two types of sensors was adopted (170 ms). Several weighing experiments were carried out, progressively decreasing the weight of the samples utilized to individuate the resolution limit of the commercial sensor, as can be seen from the comparative test reported in Fig. 9, where the acquired signals are reported for a small weight testing range.

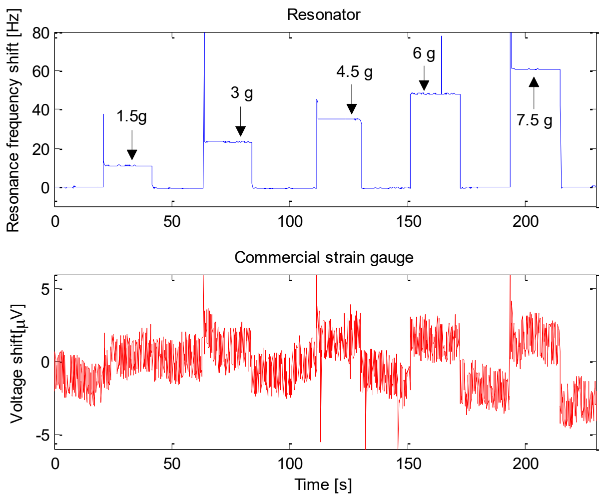

Figure 9: Load testing in a small-weight range (1.5-7.5 g).

As can be observed in these plots, the noise on the commercial strain gauge is around 1 μV, whereas the strain sensitivity is 0.5 μV/g, leading to a weight resolution of 2 g. From the results obtained in the comparative test, it is clear that a much lower weight resolution limit is obtained by using the MEMS strain sensors instead of the commercial metal strain gauges. In particular, with the measurement time adopted in the experiments presented above, the system presents a dynamic range m_{max}/m_{min} of 107 dB if used with the MEMS sensors, whereas a reduced range of rough 68 dB with the commercial metal strain gauges. In these calculations, a full scale range of 3 and 5 kg was considered for the MEMS and the commercial sensors respectively. Moreover, it is worth noticing that by using the procedure described in [7], the dynamic range could be further increased.

CONCLUSION

The use of strain sensing technology based on wafer-level vacuum packaged MEMS resonators can be a promising solution for the development of weighing systems with enhanced performance, which may find application in many industrial fields, such as automatic packaging and biomedical engineering, in which high-performance weight measurements are often needed. In particular, an enhancement of almost two orders of magnitude of the dynamic range m_{max}/m_{min} of the system, from 68 to 115 dB, was obtained using the MEMS sensors in place of the traditional metal foil gauges.

Moreover, differently than the traditional technology based on resistive metal strain gauges, the MEMS technology could be suitable for the development of very low power IC-based readout circuits, as recently reported in [8], which would ideally suited for battery-supplied weighing systems operating in wireless mode.

ACKNOWLEDGMENT

The contribution of Mr. Filippo Bonafè, Mr. Fabrizio Tamarri, Mr. Michele Sanmartin and Mr. Giulio Pizzochero in clean room processing is acknowledged. The contribution of Dr. Michele Bellettato in sample preparation is also acknowledged.

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