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A novel monolithic silicon sensor for measuring acceleration, pressure and temperature on a shock absorber

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Abstract

A fabricated micro-mechanical sensor to assess the condition of automotive shock absorbers is presented. The monolithic sensor, measures the oil temperature, acceleration and internal pressure of the shock absorber. A dual mass accelerometer with optimized beam geometry is used for acceleration readout. In addition, a 23.1 µm thickness square membrane and two buried resistors are used for pressure and temperature sensing respectively. The proposed miniaturized sensor can be effectively integrated with standard single- and dual-tube shock absorbers. The data acquired during normal vehicle operation can be continuously used to monitor the condition of the shock absorbers, allowing shock absorbers to be replaced before their degradation significantly reduce the comfort, performance and safety of the vehicle.

Keywords: Shock absorber; Embedded system; Smart sensor; Vehicle safety

1. Introduction

Shock absorbers, key components in a vehicle suspension system, play an important role in braking performance, maneuvering stability and onboard comfort. However, as any other mechanical system, suspension components are subjected to gradual wear, and shock absorbers in particular due to its physical working concept are more prone to deteriorate with time, distance driven and working conditions, resulting in excessive vehicle oscillations as a response to road disturbances, instability and increased breaking distances. Common diagnoses on ground suspension platforms give inaccurate results regarding the shock absorber condition [1,2]. More precise testing can be performed on a dedicated dynamometer, where a shock absorber velocity-force diagram can be collected [1,3]. Because shock absorbers must be removed from the vehicle in order to be tested, these analyses are seldom used. Insufficient examinations and because dampers are difficult to visually inspect are reasons why it is likely to have more vehicles with defective shock absorbers than worn tyres [4].

To address this issue, a monitoring system concept and an assessment method capable of continuously monitoring shock absorbers condition has been proposed in previous work [5,6]. The assessment method resulted

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from a theoretical analysis of the vehicle suspension and the shock absorbers internal working principles. The obtained suspension/shock absorber model was used to confirm the possibility of determining shock absorber condition by knowing wheel acceleration and shock absorber internal pressure (preferentially in the extension chamber). Trials done with shock absorbers, instrumented with macro sensors, under various known conditions validated the application of the proposed method [7]. Oil temperature is a key parameter, since it determines oil volume and density, and subsequently the damping force, making the temperature sensor needed for improved accuracy.

As all necessary physical quantities are available jointly in the shock absorber housing, this solution enables single point measurements which means a monolithic sensor is desirable. The added functionality to the vehicle diagnosis system of such a sensor system will make it possible to alert the driver when dampers replacement is required. Table 1 presents a summary of the sensor specifications.

Table 1. Specifications summary for a shock absorber integrated sensor.

Measurement	Working range	Max. frequency
Acceleration	-15 to 15 g	20 Hz
Pressure	0 to 60 bar	20 Hz
Temperature	-10 to 100 ºC	1 Hz

2. Proposed monolithic sensor

Micro-Electro-Mechanical Systems (MEMS) where mechanical sensing elements are integrated in the silicon substrate have the ability to measure acceleration, pressure, and temperature, which makes them suitable to meet the application requirements. The fabrication technologies, allowing batch fabrication of systems with small dimensions, high sensitivity, a high degree of manufacturability and reduced cost per unit are key factors for the success of MEMS in other and similar application such as automotive tyre pressure sensors.

The proposed micro-sensor has been fabricated in the SensoNor Multi-Project Wafer process (MultiMEMS) which was chosen because of its reliability, low cost and proven results in other applications. The MultiMEMS process is a bulk micromachining process with membranes of two thicknesses (3.1 µm and 23.1 µm) and a 10 µm frontside recess etch which can be used to etch through the thin membrane areas. Two types of piezoresistors are available for sensing: surface resistors for high sensitivity application and buried resistors for long term stability. Forming a triple stack of glass-silicon-glass, anodic bonding allows sealed cavities and pressure inlets.

2.1. Accelerometer

A dual beam and dual mass accelerometer design was chosen to reduce the cross axis sensitivity from accelerations in plane with the silicon wafer (longitudinal and transversal to the beams length). Fig. 1 shows a perspective view of the accelerometer structure with an inset showing the geometry used for the beams. The structures dimensions were obtained from a finite elements analysis and mainly came as a function of the sensing piezoresistors length (which forged the minimal width of the beams), process standard release etch depth (which forged the thickness of the beams) and the maximum stress allowed from the process specifications. Proof masses are made of the 23.1 µm thickness region.

While the maximum stress is located at the base of a beam with constant width and thickness, the given process results in a soft transition region between the thick (23.1 µm) and thin (3.1 µm) regions. The beams varying thickness resulted, for the presented design, in a stress peak 35 µm away from the beam base. To increase sensitivity the beams were strategically tapered to increase the extent of the high stress region in which the piezoresistors were positioned. The resulting stress profile, depicted in Fig. 2, is a smooth and larger high stress zone with more room to place the piezoresistors. And, for improved reproducibility, the location of maximum stress becomes geometrically forged by the mask alignment (tapered section).

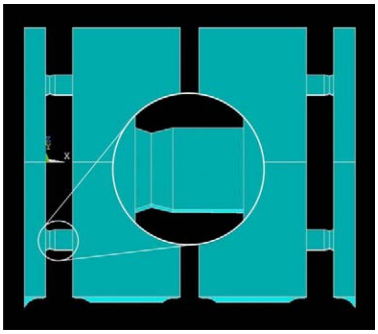

Fig. 1. Dual mass accelerometer with detail of the optimized beam geometry.

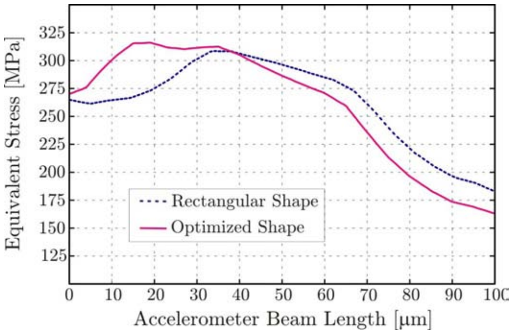

Fig. 2. Equivalent stress on the accelerometer beams surface, comparison between rectangular and optimized beam shapes.

2.2. Pressure and temperature sensors

To measure pressure, both simple flat membranes and bossed diaphragms designs were considered and studied. Bossed designs have improved linearity and even if theoretically designs with a membrane of 23.1 µm deep and central mass with wafer thickness deep (400 µm) are possible for the wanted pressure range, the necessary compensating structures for convex corners [8] have dimensions that exceed, by far, the required length for the membrane aperture mask, and therefore are impracticable. Also, as the tolerances of the back etch in the definition of the membrane dimension are quite big considering the needed membrane length, this could result in a membrane out of specifications with the consequent misalignment of the sensing elements. Therefore, a simple square 23.1 µm thickness membrane design with just concave corners was chosen.

Structural analysis was done to define the membrane area as function of the material properties, working load range and maximum stress allowed. As shown in Fig. 3, the equivalent stress over a membrane surface is maximum at its center, while the sensitivity, function of the difference between longitudinal and transversal stresses, is maximum at the membrane edges (Fig. 4). For that reason, piezoresistors should be placed at membrane edges, although care should be taken with the process tolerances for the membrane dimension. For improved sensitivity, piezoresistors transversal to the membrane edge were divided in two to maximize its exposure to the high stress area. The use of full Wheatstone bridges maximizes sensitivity while reducing the sensitivity to temperature.

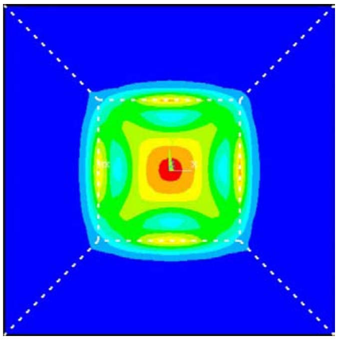

Fig. 3. Equivalent stress over the membrane top surface.

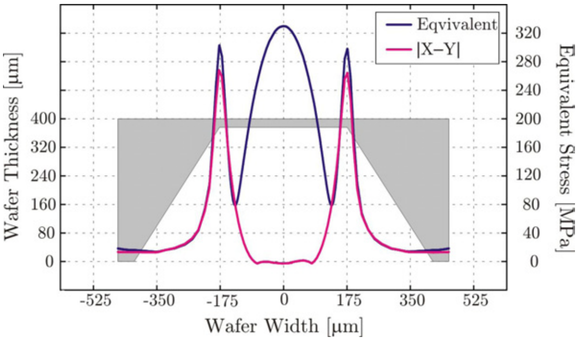

Fig. 4. Equivalent and |X-Y| stress profiles over the membrane surface.

Temperature is measured with buried resistors, because they have a higher temperature coefficient than surface resistors. Two buried resistors are used, placed strategically near the pressure port, one with a terminal grounded and the other as a terminal connected to the sensor power supply pad. This configuration enhances the device temperature sensitivity while minimizing the number of output pads required (when both sensing resistors are used together with two external fixed resistors in a full Wheatstone bridge configuration).

3. Results

The presented device has been fabricated and is currently being characterized. Fig. 5 shows the sensor installed in a TO8 package. The proof masses, metal connections and sealed glass cavity are visible on the right side of the sensor, while on the left side only the top glass cavity (over the pressure diaphragm) is visible.

The developed accelerometer was characterized using a Brüel & Kjær vibration exciter type 4809 and a Silicon Designs, Inc. analog accelerometer model 1210 for reference. A chirp vibrating waveform up to 35 Hz was applied to both accelerometers and data acquired with a NI USB6009 acquisition board and signal amplifying/conditioning electronics connected to a laptop running LabView. Results obtained for sensitivity without output amplification, shown in Fig. 6, are close to the maximum theoretical value of 84 µV/V/g.

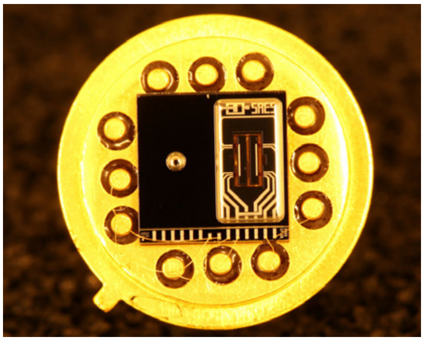

Fig. 5. Shock absorber monolithic sensor installed in a TO8 package.

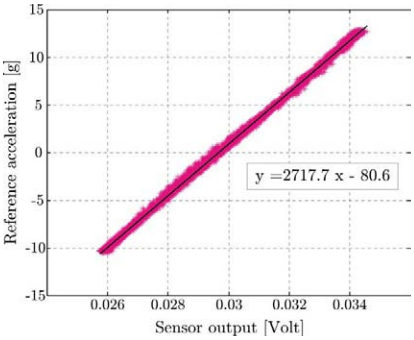

Fig. 6. Accelerometer characterization results (supplied with 5 Volt).

4. Conclusion

This paper describes a monolithic silicon sensor concept, fabricated using the SensoNor MultiMEMS process, capable of measuring shock absorber acceleration, internal pressure and temperature.

Preliminary characterization results confirmed the accelerometer sensitivity, validating the structural study and reliability of optimized geometries.

The integration of such a monitoring system in the shock absorbers allows near real time assessment of its condition and performance and will represent a major improvement to vehicle safety.

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