Miniaturized Wet-Wet Differential Pressure Sensor

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***Abstract*—We report a miniaturized wet-wet differential pressure sensor with applications in pressure and flow sensing in water networks and other harsh environments. The device is similar in concept to a conventional wet-wet differential pressure sensor in that the sensing element is protected from the external environment by oil-filled cavities closed off by corrugated diaphragms. However, with a package envelope of 11.0 x 4.8 x 3.4 mm^3, corresponding to a volume of only 0.18 cm^3, the device is considerably smaller than commercially available wet-wet differential pressure sensors. A high degree of miniaturization has been achieved by using micromachining to fabricate the corrugated diaphragms. Preliminary experimental results are presented showing operation of the device as a delta-pressure flow speed sensor in a water flow test rig.**

Keywords—wet-wet pressure sensor; delta-pressure flow sensor; corrugated diaphragm; micromachining

I. INTRODUCTION

Pressure sensors based on MEMS (micro-electro-mechanical systems) technology have become ubiquitous over the last few decades, providing low-cost, reliable pressure sensing in a wide range of applications [1]. The vast majority of these devices are based on a micromachined silicon membrane with piezoresistive readout. For absolute pressure sensing, a closed vacuum cavity is formed on one side of the device, while for differential or gauge pressure sensing both sides of the membrane are exposed to external pressures.

A variety of packaging options is available depending on the application requirements. For applications involving dry, non-corrosive gases, either side of the silicon chip may be coupled directly to a sensor port and hence exposed to the process fluid entering that port. The packaging requirements in this case are relatively simple. However, for applications involving fluids that are corrosive to the sensor materials and/or electrically conducting, more sophisticated packaging solutions are required. One important application in this category is differential pressure sensing in water or other aqueous media, for which a so-called “wet-wet” differential pressure sensor is required.

The traditional approach to packaging a wet-wet differential pressure sensor is to create an oil-filled cavity on either side of the sensing element, and to close off each cavity with a thin, corrugated metal diaphragm that acts as an interface to the process fluid [2]. The corrugated diaphragm allows pressure changes in the process fluid to be coupled to the oil in the adjacent cavity, and hence to the sensor element. It also provides some compliance to the cavity walls so as to accommodate thermal expansion of the oil.

Wet-wet pressure sensors with corrugated diaphragms are expensive to manufacture and tend to be relatively bulky. For example, the corrugated diaphragms are typically around 2 cm in diameter, and overall package volumes in the region of 10 cm^3 are common (see e.g. [3]). The minimum size of the diaphragms is dictated by the traditional fabrication processes used to form them. The high cost and relative complexity of such diaphragm-based packaging has led to the development of lower-cost solutions for liquids that are non-corrosive to silicon but electrically conducting. In this case the sensed media must be excluded from the front side of the sensor element where the electrical connections are located. One approach is to encapsulate two MEMS dies within the same package so that their back sides are connected to the sensor ports while their front sides face the interior of the package [4]. This is a simple solution, but it relies on close matching of the sensor elements for common-mode rejection; also, each sensing element must have a burst pressure that exceeds the highest expected common-mode pressure, and this inevitably leads to a trade-off between the differential pressure sensitivity and the maximum common-mode withstand pressure. Solutions employing a single sensor chip have also been proposed, where the electrical connections are isolated from the process fluid by a cap bonded to the top side of the chip [5].

In this paper we report a miniaturized wet-wet differential pressure sensor of the corrugate diaphragm type. The device consists of a MEMS sensor chip in a ceramic package with oil-filled cavities closed off by corrugated diaphragms fabricated by micromachining. Fig. 1 shows a photograph of the device with a US dime for scale. The overall package envelope is 11.0 × 4.8 × 3.4 mm^3, corresponding to a volume of only 0.18 cm^3. This is considerably smaller than other diaphragm-type wet-wet differential sensors. The sensor was designed to be compatible with the minimally invasive online water network monitor reported recently by us in [6]. This sensing platform enables the large-scale deployment of multi-parameter sensor nodes across a water network for network health and/or water quality monitoring.

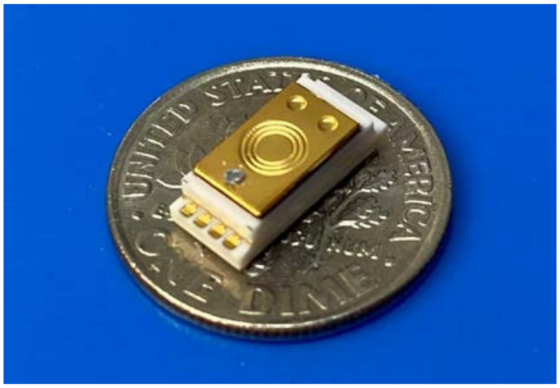

Fig. 1. Miniaturized wet-wet pressure sensor with US dime for scale.

II. SENSOR DESIGN AND FABRICATION

Fig. 2 shows an exploded view of the sensor, illustrating the package construction. The package body is built from a stack of four laser-cut ceramic plates, each 0.6 mm thick. Plates 1 and 2 sit beneath the MEMS chip and define the back-side cavity. Sputtered gold tracks on the top surface of Plate 2 provide electrical connections between wire bonding pads adjacent to the MEMS chip and contact pads at one end of the package. Plates 3 and 4 form the upper half of the package and define the front-side cavity. The cavities are closed off by 0.5 mm-thick metal top and bottom plates which incorporate the corrugated diaphragms. Each plate also has an oil-filling hole and a thinned region which may be plastically deformed for initial pressure balancing. The apertures in the ceramic plates are designed to ensure equal oil volumes top and bottom; this is necessary to minimise temperature dependent offsets due to thermal expansion of the oil.

To assemble the device, first the ceramic plates are bonded together in pairs (1-to-2 and 3-to-4). The MEMS chip is then attached to Plate 2 and wire-bonded to the adjacent gold pads. The two halves of the package body are bonded together, and finally the top and bottom plates are bonded to Plates 1 and 4. For initial prototyping, the high-temperature epoxy EPO-TEK 353 ND has been used for all bonding operations including the MEMS die attach step. However, it is anticipated that in future alternative bonding methods that can yield a fully hermetic package will be used. The reason for using four ceramic plates in the package construction, as opposed to just two, is that this makes it possible to use standard commercial laser cutting services which are generally limited to thicknesses <1 mm and do not extend to machining of blind holes.

A. *Fabrication of Corrugated Diaphragms*

The top and bottom plates are fabricated using a sequence of etching and electroplating steps which are applied to a 0.5 mm-thick copper substrate. The substrate is etched from both sides to define a template for the corrugations, the oil filling hole, the pressure balancing pad and a dicing channel around the perimeter. The sum of the front- and back-side etch depths is ~400 µm so that a finite thickness remains at all points. The substrate is then electroplated with the metal layers that will form the diaphragm. In the prototype sensors we have applied a thin (~0.2 µm) nickel layer as a diffusion barrier followed by a gold-nickel-gold stack with layer thicknesses of 0.5 µm, 3.0 µm and 0.5 µm respectively. Following the electroplating step, laser machining is used to strip the plated layers from behind the diaphragm. The copper substrate is then removed from behind the diaphragm with an ammonium persulphate etchant. The gold layers act as an etch stop for this etchant, whereas nickel does not, so the process results in a 4 µm-thick Au-Ni-Au diaphragm. Finally laser machining is used to singulate the part and open the oil filling hole.

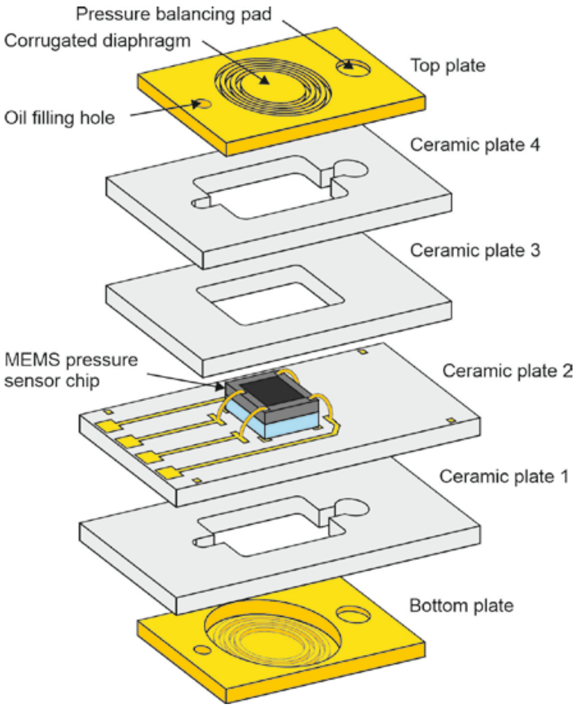

Fig. 2. Exploded view showing construction of miniaturised wet-wet differential pressure sensor.

B. *Oil Filling Procedure*

For the prototype sensors fabricated to date we have used a low-viscosity (5 cSt) silicone oil to fill the cavities. When carrying out the filling process it is essential to exclude air pockets as any trapped air will compromise the coupling between the diaphragm and the sensing element. In this work the filling process was carried out using a custom rig consisting of a vacuum pump, a sample chamber with inlet and outlet valves and an oil reservoir. These three are connected in series via flexible pipes with the sample chamber between the oil reservoir and the pump. After placing the packaged sensor in the sample chamber, and with the reservoir full of oil, the system is pumped down to a base pressure of around 0.1 mbar. The reservoir is then raised above the sample chamber and tilted so that oil flows into the sample chamber under gravity. Once the sample chamber is full of oil, it is isolated from the vacuum pump by closing the outlet valve, and air is admitted to the oil reservoir so that both reservoir and sample chamber are brought back to atmospheric pressure. Finally the inlet valve on the sample chamber is closed, and the sample chamber is removed from the rig.

To seal off the oil filling holes, tapered metal pins are pushed into the holes with the aid of a tapered “punch” tool attached to a 3-axis micromanipulator. This procedure is carried out while the device is still submerged in the oil; the sides of the sample chamber can be removed for this purpose. Fig. 3 shows a schematic and a photograph of a prototype device undergoing the procedure. Once the pins are in place, the device is removed from the sample chamber and cleaned in MIBK (methyl-iso-butyl ketone), IPA (iso-propyl alcohol) and de-ionized water.

III. INITIAL TESTING OF PROTOTYPE SENSORS

Preliminary testing of prototype devices as delta-pressure flow sensors has been carried out on a recirculating flow rig. The rig has a 60 cm-long test section with an internal diameter of 28 mm and is equipped with a reference electromagnetic flow meter (ABB type FEP611). There is also a reference pressure sensor (WIKA DG-10) which is positioned just upstream of the test section. Fig. 4 shows a device that has been prepared for testing. The sensor has been mounted on a length of 6.0 mm-diameter stainless tube so that it can be inserted into the test section via an access port.

Fig. 5 shows the measured variation of differential pressure with flow velocity for a prototype device incorporating a MEMS chip from Merit Sensor (type S1C1-4000-B2T). The two data sets correspond to different orientations of the sensor, with the top plate facing either upstream or downstream. The quantity measured in the experiment was the output voltage of the piezoresistive bridge; this has been converted to differential pressure using the nominal sensitivity of the MEMS sensor [7]. The offset voltage measured before testing was subtracted from the raw data.

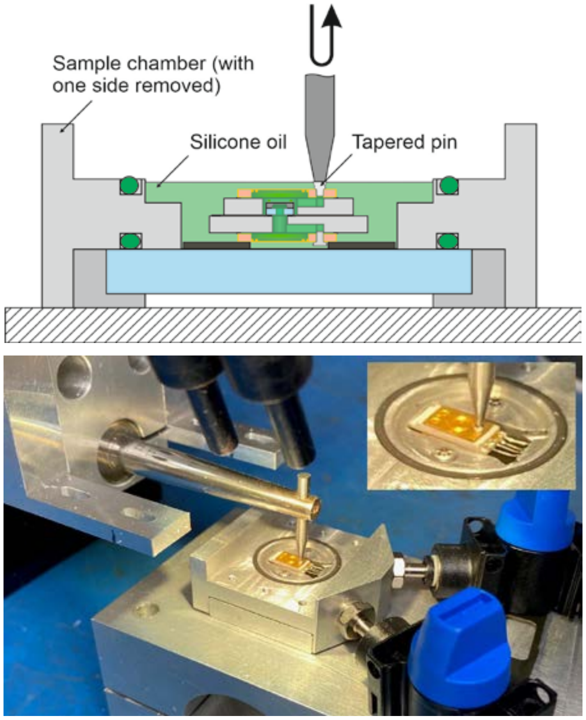

Fig. 3. Schematic (upper) and photograph (lower) illustrating oil fill hole plugging procedure.

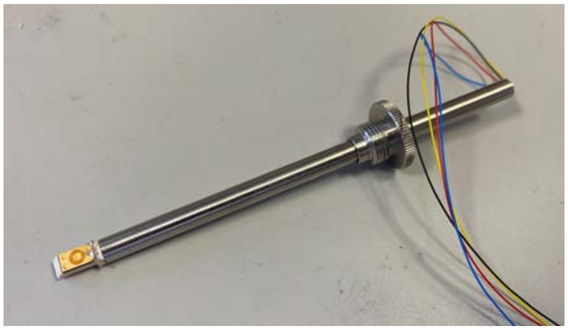

Fig. 4. Prototype delta-pressure flow sensor integrated into 6.0 mm-diameter probe for testing.

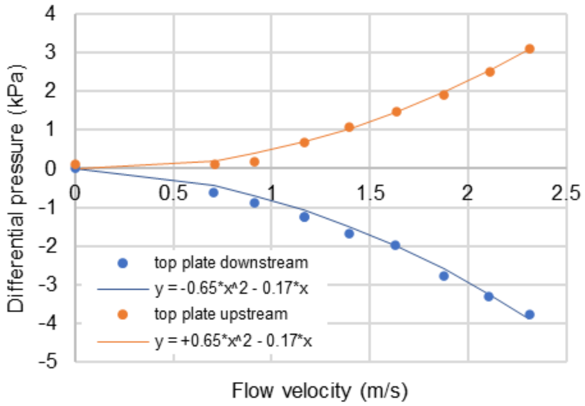

Fig. 5. Measured variations of differential pressure with flow velocity for prototype delta-pressure flow sensor.

From the fitted curves in Fig. 5 it is seen that the measured differential pressure is essentially quadratic in the flow velocity. This is as expected as the differential pressure across a bluff body scales in a similar manner to the stagnation pressure [8]. Also, the two curves should be mirror images of one another in the x-axis, but this is not the case; there is a small downward bias in both data sets which increases with flow speed. This is expressed in the linear components of the fitted curves in Fig. 5. We believe this is due to imperfect rejection of the common-mode pressure which varies with flow rate in the test rig.

IV. CONCLUSION

We have used microfabrication methods to realise a wet-wet differential pressure sensor that is more than an order of magnitude smaller in volume than typical commercial devices. Initial testing of the device as a delta-pressure flow sensor has yielded encouraging results and we are currently carrying out further tests to establish the performance of the device in terms of temperature stability, common-mode rejection and working pressure range.

ACKNOWLEDGMENT

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REFERENCES

[1] P. Song, Z. Ma, J. Ma, L. Yang, J. Wei, Y. Zhao, M. Zhang, F. Yang and X. Wang, “Recent progress of miniature MEMS pressure sensors”, Micromachines, vol. 11, no. 56, 2020, doi:10.3390/mi11010056, 38 pp.

[2] B. Li, G.Q. Zhang, D.G. Yang, F. Hou, Y. Hai, “The effect of diaphragm on performance of MEMS pressure sensor packaging”, Proc. 11th Int. Conf. Electron. Packaging & High Density Packaging, Xi’an, China, 16-19 Aug. 2010, pp. 601-606.

[3] Technical data sheet for Keller Druckmesstechnik AG differential pressure sensor type PD-10LHP, available at https://keller-druck.com/?d=o7S2QQDCqUfPgbyQQvz5NR.

[4] R. Werner, H. Schöpe, “Kostengünstige Nass/Nass - Differenzdruckmessung”, GMA/ITGFachtagung, Sensoren und Messsysteme 2019, 25 - 26 June 2019, doi: 10.5162/sensoren2019/P1.5.

[5] European Patent Application No. EP2189773A2, Honeywell International Inc, “Design of wet-wet differential pressure sensor based on microelectronic packaging process”, 2009.

[6] A.S. Holmes, M.E. Kiziroglou, S.K.E. Yang, C. Yuan, D.E. Boyle, D.M. Lincoln, J.D.J. McCabe, P. Szasz, S.C. Keeping, D.R. Williams, and E.M. Yeatman, “Minimally invasive online water monitor”, IEEE IoT Journal, (2021) doi: 10.1109/JIOT.2021.3074081.

[7] Technical data sheet for Merit Sensor S-series pressure sensors, available at https://meritsensor.com/assets/documents/pdf/S-series.pdf

[8] C. Norberg and B, Sundén, “Turbulence and Reynolds number effects on the flow and fluid forces on a single cylinder in cross flow”, J. Fluid Struct., vol. 1, 1987, pp. 337-357.