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Development of a MEMS Multisensor Chip for Aerodynamic Pressure Measurements †

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Abstract: Existing instruments for aerodynamic pressure measurements are usually built around an array of discrete pressure sensors, placed in the same housing together with a few discrete temperature sensors. However, such approach is limiting, especially regarding miniaturization, sensor matching and thermal coupling. In this work, we intend to overcome these limitations by proposing a novel MEMS multisensor chip, which has a monolithically integrated matrix of four piezoresistive MEMS pressure sensing elements, and two resistive temperature sensing elements. After finishing the preliminary chip design, we performed computer simulations in order to assess its mechanical behavior when the measured pressure is applied. Subsequently, the final chip design was completed, and the first batch was fabricated. Technological processes included photolithography, thermal oxidation, diffusion, sputtering, micromachining (wet chemical etching), anodic bonding, and wafer dicing.

Keywords: MEMS multisensor; pressure sensing; chip fabrication

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1. Introduction

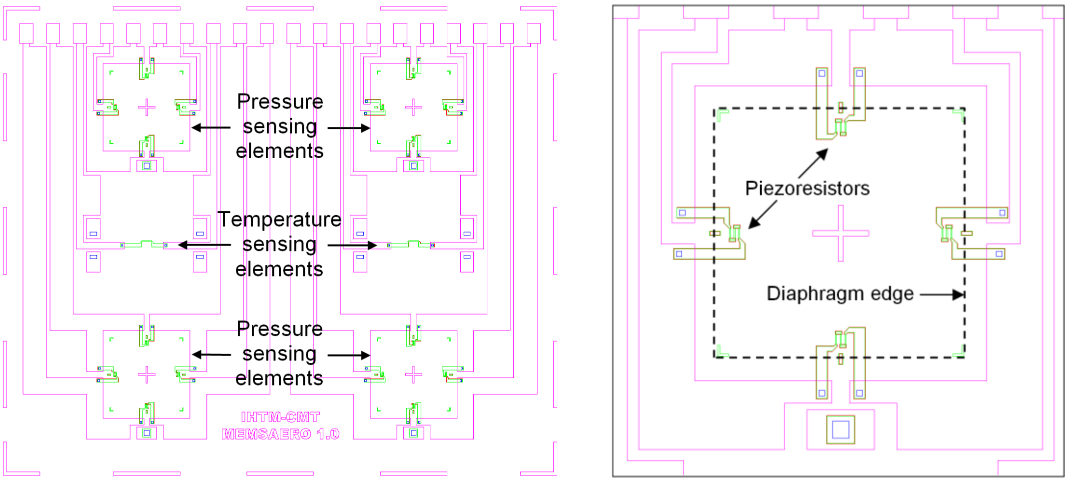
Sensors that belong to micro-electromechanical systems (MEMS) constitute one of the most popular and promising classes of sensors. MEMS sensors are miniature sensing devices, fabricated by using microelectronic and micromachining technologies. Appearing shortly after the development of monolithic integrated circuits in the 1960s, they have been adopted in a wide range of applications during the following decades. Today, they are indispensable in vehicles, medical devices, mobile phones and many other modern industrial and commercial applications. Piezoresistive MEMS pressure sensors constitute a large portion of the MEMS sensor market today, with the demand for them still growing. They have significant advantages over the other kinds of pressure sensors, including miniature dimensions, good measurement performance, high reliability, and low cost due to efficient mass production. Although piezoresistive MEMS pressure sensors may nowadays be considered as a mature technology, new applications continue to arise, and there are new scientific and technological challenges to be addressed [1,2].

Aerodynamic testing of various objects consists of pressure measurements at a multitude of points on aerodynamic surfaces or structural elements. Typically, the air pressure from the measurement points is transferred by flexible tubing to multichannel pressure sensing instruments. Such instruments are usually built around an array of discrete pressure sensors and a few discrete temperature sensors placed in the same housing. That approach has some limitations regarding miniaturization, sensor matching and thermal coupling. The goal of this work is to overcome these limitations by developing a novel MEMS multisensor chip with several monolithically integrated pressure and temperature sensing elements. Although reports on chips with multiple pressure sensing elements exist in the literature [3], their concept and design are not suitable for this application.

After finishing the preliminary multisensor chip design, we performed computer simulations of mechanical influences that the pressure applied to one sensing element can have on the whole chip structure. Subsequently, the final chip design was made, and the first batch of chips was manufactured and tested.

2. Materials and Methods

The concept of the proposed monolithically integrated multisensor structure is illustrated in Figure 1a. It is envisioned as a rectangular silicon chip with four piezoresistive MEMS pressure sensing elements, two resistive temperature sensing elements, as well as the necessary interconnects and wire bonding pads. The temperature sensing elements are intended for direct temperature sensing on the chip. The thermal coupling between the temperature and pressure sensing elements on the same chip is much better than it can be in the case of pressure and temperature sensors on separate substrates. This is important for temperature compensation of the pressure sensing elements. Another important advantage of the concept is that it enables better matching of characteristics of the pressure sensing elements on the same chip, because they are fabricated simultaneously in the same technological processes.



(**a**) (**b**)

Figure 1. Topographic image of photolithographic masks used for the multisensor chip fabrication: (**a**) whole chip; (**b**) details of a pressure sensing element.

Silicon piezoresistive MEMS pressure sensor chips are typically fabricated on single crystal silicon wafers with the crystallographic orientation (100). In general, a pressure sensing element consists of a precisely defined mechanical structure (i.e., a diaphragm), and piezoresistors formed near the diaphragm's edges, in the crystallographic direction <110>. The piezoresistors are placed at locations where the highest mechanical stress occurs during the diaphragm deflection caused by the measured pressure. Usually four such piezoresistors are used, of which two are in the radial direction and the remaining two in the tangential direction relative to the diaphragm which is typically quadratic in shape. The four piezoresistors form a Wheatstone bridge, so that a differential voltage signal proportional to the measured pressure value is generated when sensor excitation is applied. The structure of a pressure sensing element is shown in more detail in Figure 1b.

2.1. Computer simulations

Computer simulations based on the finite element method (FEM) were performed with the main goal to investigate the parasitic influence the mechanical stress caused by the pressure applied to one of the pressure sensing elements may have on the other sensing elements on the same multisensor chip. In this case, the displacement profile and von Mises stress of the chip's surface were observed, and the applied pressure was 100 kPa. The results are shown graphically in Figure 2.

The simulations confirmed that the above-mentioned influence is negligible. Hence, the preliminary design of the multisensor chip was accepted. Based on it, the final design was made and subsequently used for chip fabrication.

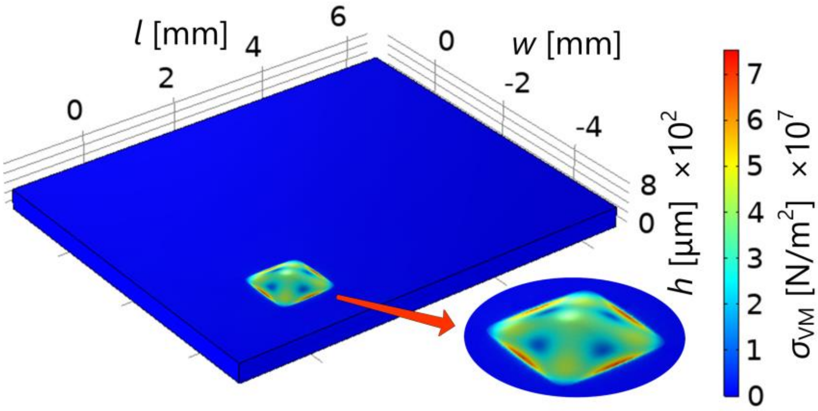


Figure 2. Graphical representation of the computer simulation results: the displacement of the multisensor chip's top surface caused by the pressure of 100 kPa applied to one pressure sensing element (in the bottom corner); color grading represents von Mises stress, according to the color scale on the right.

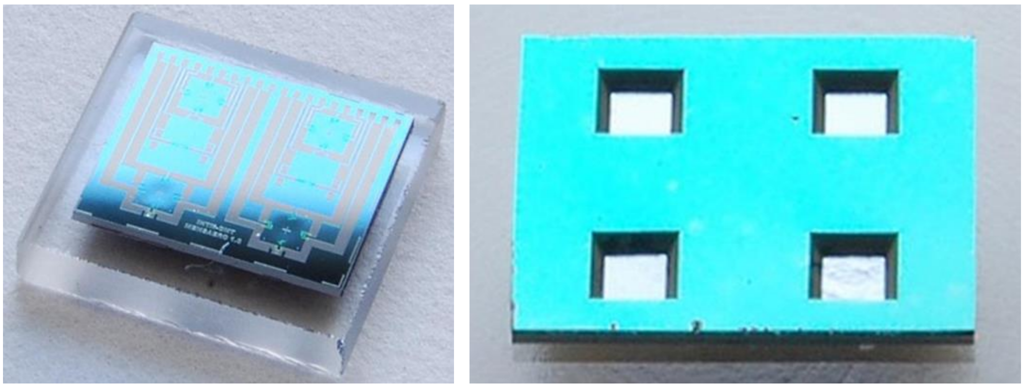
2.2. Multisensor Chip Fabrication

The MEMS multisensor chip is developed based on the extensive ICTM's experience in the field [4–6], including the ICTM SP-12 pressure sensor chip intended for measurement of medium pressures. The multisensor chip is realized using the 1 μm technology. The photolithographic masks were made by using the following equipment: EVG 620 double sided mask aligner, Microtech LaserWriter LW405, and AML AWB-04 aligner wafer bonder (for anodic bonding). The fabrication started from silicon wafers of the following characteristics: n-type (resistivity from 3 Ωcm to 5 Ωcm), polished on both sides, 76.2 mm (3″) in diameter, (100) orientation. The piezoresistors were formed by diffusion of p-type impurities (boron), resulting in the electrical resistance in the range from 2 kΩ to 4 kΩ. Metallic interconnects and bonding pads were formed by the deposition of aluminum (high vacuum sputtering at ≈$2 \cdot 10^{-4}$ Pa). The diaphragms of the pressure sensing elements were made by anisotropic wet chemical etching in 30% KOH water solution.

3. Results and Discussion

Photographs of the realized multisensor chip are shown in Figure 3. For the purposes of testing and characterization, the chip is anodically bonded to a flat Pyrex glass plate. As the bonding is performed in a vacuum, the pressure sensing elements' diaphragms are deflected by the atmospheric pressure, which is noticeable in Figure 3a for the lower two pressure sensing elements. The photograph of the bottom side of the chip, showing the etched MEMS diaphragms, is given in Figure 3b.

Three silicon wafers were processed, each with 30 chips. Electrical tests have been carried out by using a probing station and a semiconductor parameter analyzer.



(**a**) (**b**)

Figure 3. Photographs of the realized MEMS multisensor chip: (**a**) top side; (**b**) bottom side (four etched MEMS diaphragms).

A preliminary characterization of the chip was performed by connecting the pressure sensing elements to a constant voltage excitation of 2.5 V, and measuring their output voltages at several pressure and temperature values. The applied relative pressure was in the range from −700 hPa to 700 hPa (set by using the Mensor APC 600 automated pressure calibrator), and the temperature was from 2 °C to 50 °C (set by using the Heraeus Vötsch VMT 04/140 temperature chamber). The results are presented graphically in Figure 4. They indicate that the chip performs as expected.

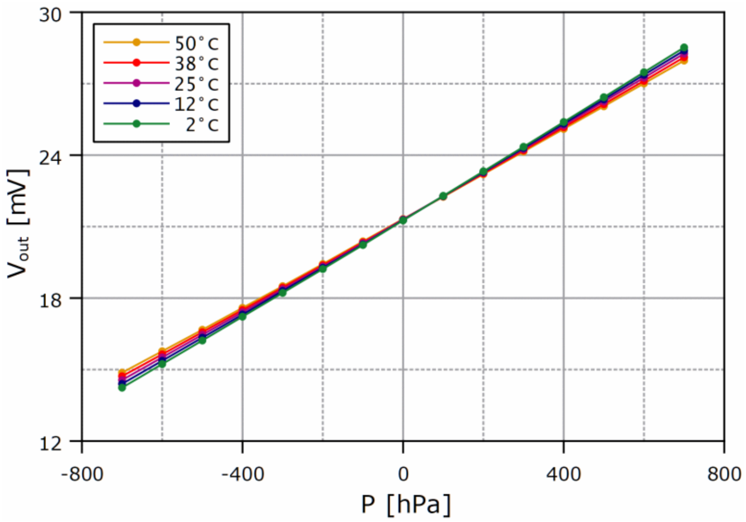


Figure 4. Results of the preliminary characterization of the realized multisensor chip: the dependence of the output voltage of a tested pressure sensing element on the applied pressure, with temperature as a parameter.

4. Conclusions

In this paper we presented the development of the MEMS multisensor chip intended for aerodynamic pressure measurements. We briefly explained the concept and the methodology, which includes the chip design, computer simulations and, finally, the fabrication processes that resulted in the finished chip. We also performed the preliminary characterization of the chip.

The development of the multisensor chip is an important step towards higher integration, higher performance, and further miniaturization of aerodynamic pressure measurement devices. Our future work in this field will include a detailed characterization of the developed multisensor chip, and the development of signal processing methods in order to optimize the pressure measurement performance. Also, the possibility of increasing the number of sensing elements on the chip will be considered.

Author Contributions: Conceptualization, M.F. and Ž.L.; methodology, Ž.L., M.M.S., D.T., M.R.-R., K.C., E.M., M.V.B. and S.A.; validation, Ž.L., D.T. and P.P.; formal analysis, Ž.L. and M.F.; investigation, Ž.L., M.M.S. and D.T.; resources, M.F.; writing—original draft preparation, M.F., Ž.L. and D.T.; writing—review and editing, P.P.; visualization, Ž.L. and D.T.; supervision, M.F.; project administration, M.F.; funding acquisition, M.F. All authors have read and agreed to the published version of the manuscript.

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