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Novel Pressure Sensor for Aerospace Purposes

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Abstract: In this work, a novel silicon-based sensor for pressure and flow measurements is presented. To meet the special requirements of the aerospace industry a new piezoresistive pressure sensor with a flat surface has been developed, so that the flow is not affected by the sensor. To avoid bonding-wires on top of the sensor a special through-wafer connection is presented. By making other significant changes in the layout as well as in the micro fabrication process, a novel sensor has been created. It is robust enough to be laminated in fibre material, which opens new possibilities for measurements. With this sensor it is possible to characterize the condition of the flow near the separation point. This article describes the complete process from the development to the laminated sensor. *Copyright © 2009 IFSA.*

Keywords: piezoresistive pressure sensor for flow characterization; silicon membrane; micro fabrication; through-wafer connection

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1. Introduction

During tests on flow profiles novel sensor arrays are required to enable time-critical measurements of the conditions of the flow. Therefore the wall shear stress is an interesting physical value. The wall shear stress has a direct influence on the fuel consumption of all vehicles, planes and even ships. Thus it is necessary to analyse new models already in the development phase. The accelerated requirements of customers make these analyses even more important.
To date now the measurement of the wall shear stress in end-products is not necessary, because it is

non-influenceable. By eliminating this deficit new approaches are feasible. Controlling the flow makes it necessary to measure the conditions without influencing it through measurement. Up to now, a lot of sensors have components which rise in the streaming fluid. These sensors often have a surface fence [1] or a hot-wire [2] as a sensing element in the flow. Additional to the disadvantage of changing the flow, these components are very fragile against particles in the flow. Hence these sensors are just for scientific measurements in a lab.

The novel sensor has to determine two measurands. On one hand the pressure is required and on the other hand the flow velocity on the wall. In this article it is shown, how the micro fabrication process of a well-established piezoresistive force sensor [3] is modified to fabricate a pressure sensor. In the future, a hot-wire anemometer will be added. The combination of pressure sensor and a hot-wire sensor is considered as a promising development [2], [4], [5].

The sensor and its mounting have a totally flat surface in order to assure that the sensor does not affect the flow itself. It is essential to avoid bonding wires on the top. Hence an electrical through-wafer connection is necessary. A flexible polyimide foil with structured copper wires is used for improving the wiring, **Fig. 1** depicts all parts of the sensor in a sectional view. Also the electrical elements are labelled for a better understanding.

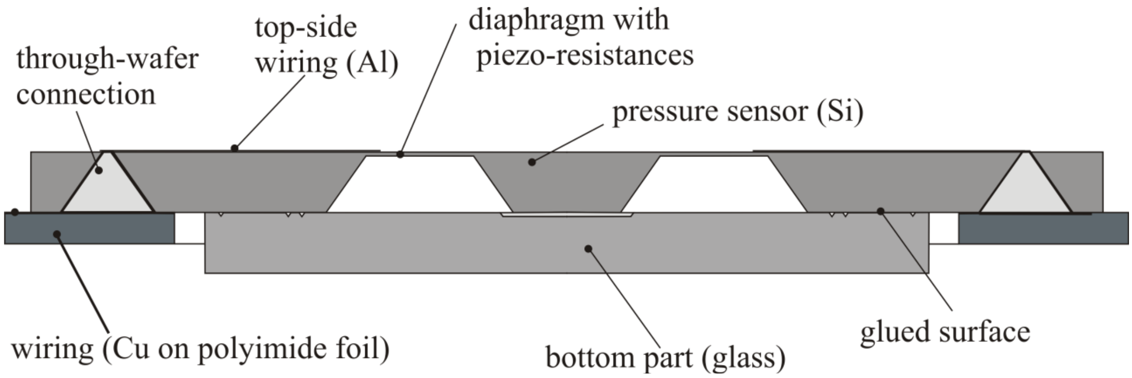

Fig. 1. Schematic of the pressure sensor with bottom part and polyimide foil

The whole sensor design is optimized for an easy and comfortable embedding in fibre composite. With this technique it is possible to create complex curved bodies for aerodynamic tests [6].

2. Requirements and environmental conditions

2.1 Requirements set by environment

The goal of this research is the application of the sensor on wings of airplanes. Because flight tests are very costly the first tests will take place in a wind tunnel. Therefore the design and the requirements have been adapted for use in a wind tunnel. This is relevant, because the maximum pressure is dependent on the maximum airspeed.

$$\Delta p = p - p_\infty = \frac{1}{2} c_p \rho V^2 \tag{1}$$

where Δp is the pressure difference between the local pressure p and the pressure in the free stream p_∞, c_p is the pressure coefficient, ρ the free stream fluid density and V the free stream velocity. During the first tests, the maximum airspeed in the wind tunnel is 55 *m/s*. The pressure coefficient depends on the location on the aerodynamic chord. In our case a typical value for c_p is -10 because of the location and the wing profile. Considering the density according to International Standard Atmosphere (ISA), the maximum pressure can be calculated as follows:

$$\Delta p = -\frac{1}{2} \cdot 10 \cdot 1{,}225 \; \frac{kg}{m^3} \cdot \left(55 \; \frac{m}{s} \right)^2 = -18528 \; Pa \tag{2}$$

To enable measurements up to the maximum pressure difference, the membrane has been simulated and optimized concerning its size and the placement of the piezoresistors (see section 3).

2.2 Requirements by purpose

According to the purpose of fixing the embedded sensor on a wing the mechanical and thermal stresses are not to be ignored. Because of the high speed, particles in the air such as dust or rain can cause major damage, if they hit the sensor directly, hence the sensor has to be designed very robust.
In aerospace applications a temperature range from -65 to 150°*C* is often assumed. Because water is changing its state and thereby changing its density, the sensor has to be hermetically sealed to avoid intrusion of water.

2.3 Requirements by embedding process

During the embedding process the mechanical and thermal stresses are completely different than those the sensor is designed for. **Figure 2** shows the basic set-up which is described in section 5 more detailed. However, during the laminating process a high pressure is applied to the sensor, which is mainly designed to resist negative pressures. A boss is added to the diaphragm in order to make the membrane robust. The glass cover has to have a reduction under the boss, so the maximum displacement can be set (see **fig. 2**). As shown in **figure 2** (right) the boss rests on the glass. This limits the mechanical stress and protects the membrane against damage during the embedding process. As shown on the left, during measuring where $p_a < p_0$, the boss is lifted up. Hence, the fragile diaphragm is deflected accordingly.

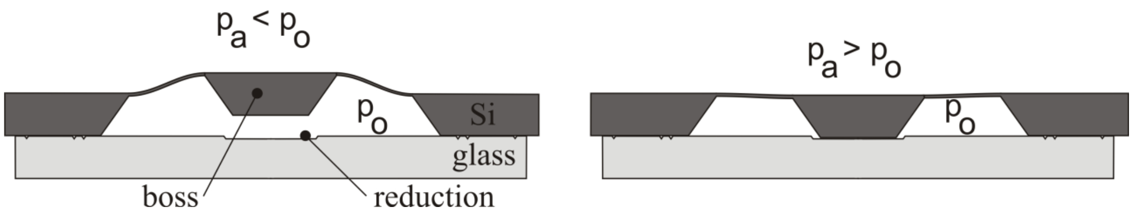

Fig. 2. Diaphragm during measurement (left) and during the laminating process (right)

The computerized simulation of the behaviour in both situations confirmed, that the fragile diaphragm can endure the laminating process and in parallel can lead to high sensitive measurements of negative pressures.

3. Simulation

A new design expanding the well-established and well-known 3D force sensor principle [3] allows to measure negative pressures.

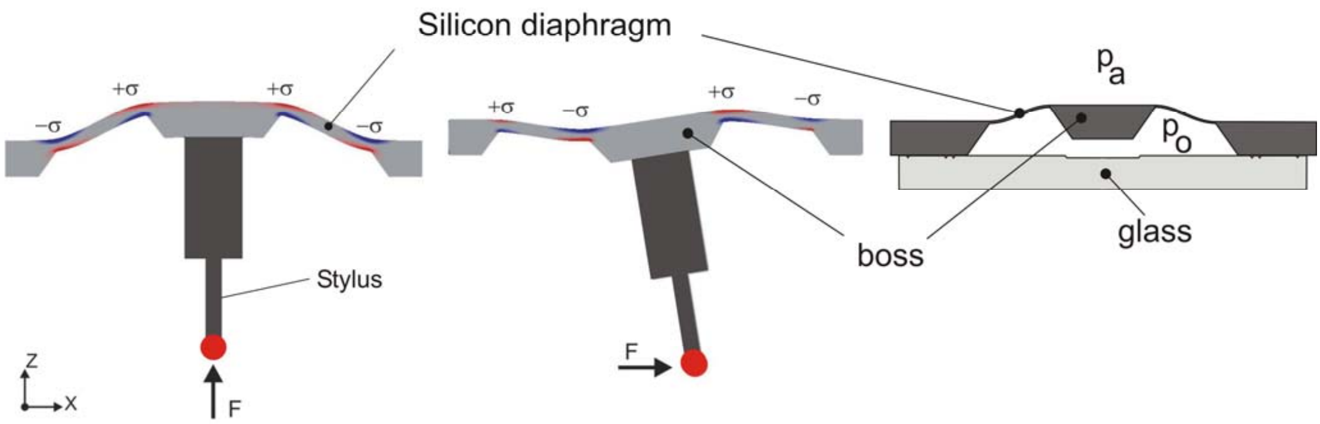

Fig. 3. 3D force sensor compared with pressure sensor

Figure 3 shows the comparison of the 3D force sensor and the pressure sensor. Instead of a stylus with its ruby spherical a cover is needed to create a cavity. During the simulation of the mechanical stresses the new through-wafer connections presented in section 4 is not needed.

3.1 Simulation of mechanical stresses

Figure 4 shows the results of the simulation. Because of the sensor symmetry, just a quarter was simulated. This reduces calculation time significantly. By changing the dimensions of the diaphragm (e.g. thickness, size of the boss, overall dimensions) the location of mechanical stress is influenced.

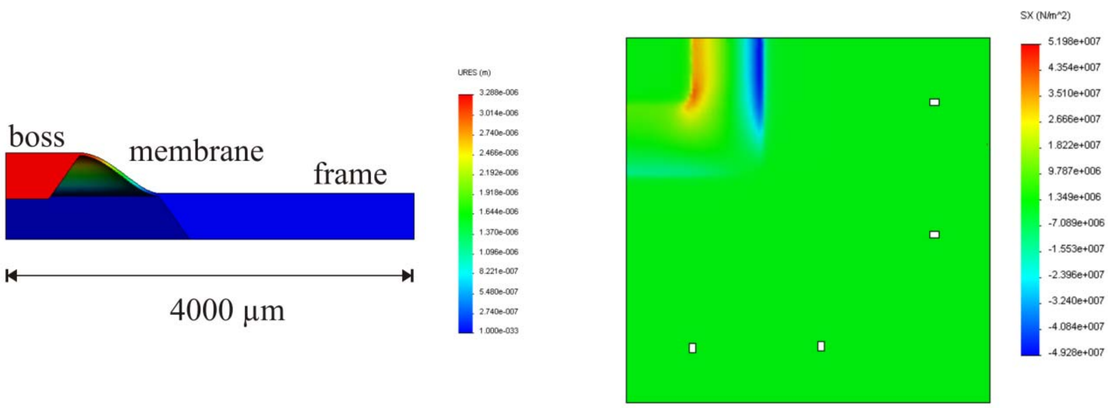

Fig. 4. Displacement (left) and mechanical stress (right) simulated in SolidWorks® Cosmos at $p_0 = 1\,bar$ and $p_a = 0.8\,bar$

It is advisable to place two piezoresistors on areas with strain and two on compression for maximum sensor sensitivity of four piezoresistors in a Wheatstone bridge configuration [7]. These areas are marked red and blue, respectively, in **figure 4** (right). Using the exact values of the simulation leads to concrete positions for the resistors.

3.2 Simulation of the etching process

For optimal results of the microfabrication the etching process of silicon in KOH has been simulated. The tool SUZANA [8] has been used to check if the double-stage etching process and the used masks (with compensating structures) are leading to an optimum result [6].

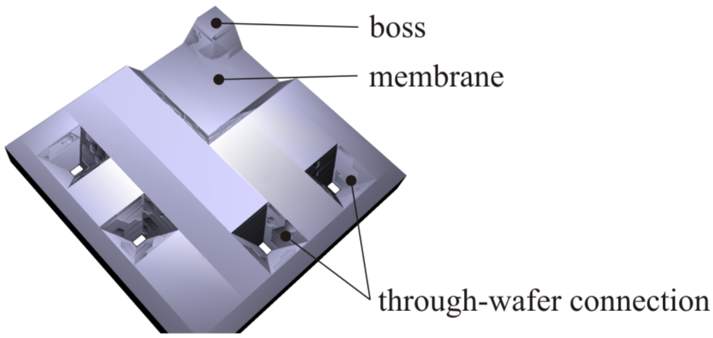

Fig. 5. Screenshot of the etching result in the software tool SUZANA

Figure 5 shows the result of the simulation. The through-wafer connections are visible, while the membrane still has a thickness of 25 *µm*. The shape of the boss is like expected. Because of the angle between the crystal plains and the size of the membrane, the minimum size of the sensor is fixed to 8x8 mm^2. Reducing the size even more will decrease the sensitivity and resolution [9].

4. Fabrication Process

The following fabrication process has been developed in order to realize the simulated design. The sensor has been fabricated on 4" Si wafers in a batch process using state-of- the art technologies. The below-mentioned figure shows a simplified scheme of the most significant states during the process [10].

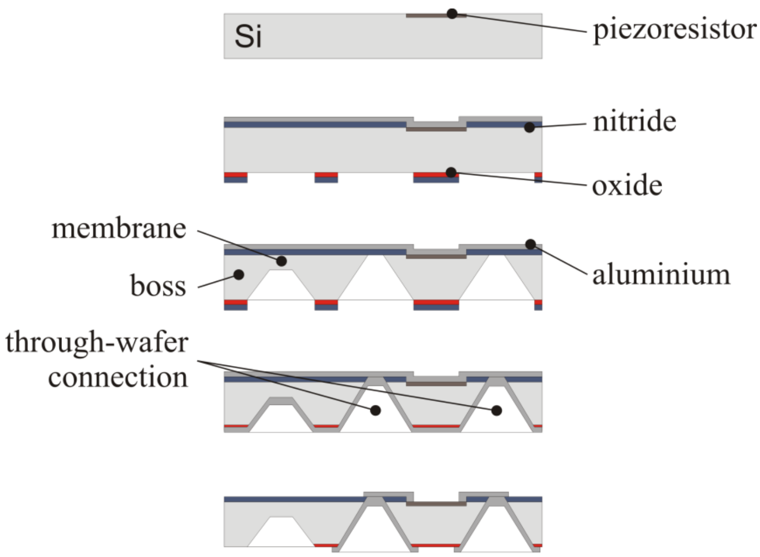

Fig. 6. Scheme of process steps during micro fabrication

First, the piezoresistors have been applied by diffusion of boron. Next, a Si_3N_4 layer is added as an etch stop layer for the through-wafer connection before sputtering aluminium. By structuring the aluminium the topside wiring is created. Then the bottom side is coated by several Si_3N_4 and SiO_2 layers as masking layers for the wet-etching processes in KOH. The first etching step creates an advance where the connections will be etched. During the second etching step the membrane and the connection are etched simultaneously until the membrane has its desired thickness and wafer is etched through for the connections. The nitride is then removed by dry-etching and the bottom side is sputtered with aluminium, so that an electrical connection is generated. Later the aluminium is structured on the bottom side.

The glass cover has been fabricated in a separate process. Here the glass is covered by a gold layer, which is structured. Then the glass is etched 25 *µm* by a hydrofluoric acid solution. Both wafers, the glass and the Si, are diced so that the single chips are available.

The glass chip is then glued onto the sensing chip, as shown in **figure 1**. An aligning tool is used to hold the glass part, where UV sensitive glue is applied. Then the Si part is aligned and then pressed on the glass chip. Exposing the sensor to UV light makes the glue harden. The advantage of using UV sensitive glue is that it is possible to visually control the alignment through the glass chip without having time limitations.

In the last step the sensor is fixed on the polyimide foil. Here a conductive adhesive, soldering paste, or balls of solder can be used to fix the sensor and guarantee the electrical connection as well. Some experiments have been made and are still going on to increase the pass rate.

5. Laminating process

The fibre material is stratified in several functional layers. As shown in **figure 7** a protection cover is placed on the bottom. Then a few fibre layers are administered (some with holes fitting to the lower sensor halves), before the polyimide foil with sensor is placed. Then another fibre layers are stacked to get a planar surface. Another protection cover protects the autoclave from resin.

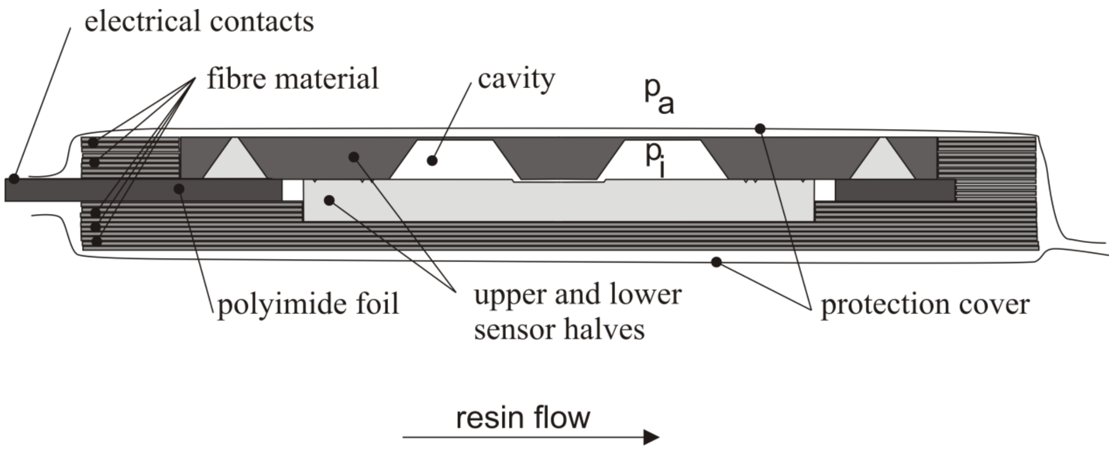

Fig. 7. Sectional view of the laminate with its different functional layers and the sensor

After closing the autoclave, a vacuum of 0.3 *mbar* is drawn between the two protection layers, so that no gas is remaining in the stack. Then the pressure p_a is set to 3 *bar* before the preheated resin is pressed with 2.8 *bar* from the left through the stack at 70 °*C*. When all the resin is within the autoclave the in- and outflow is closed properly for the 12 *h* baking process at 120 °*C*. After opening the autoclave and removing the protection layers the laminating process is finished.

In **figure 8** a sectional view of a laminated sensor is shown. The resin has flooded all spaces between the fibre material and the sensor. Also the through wafer connection is filled, while the cavity is free of resin.

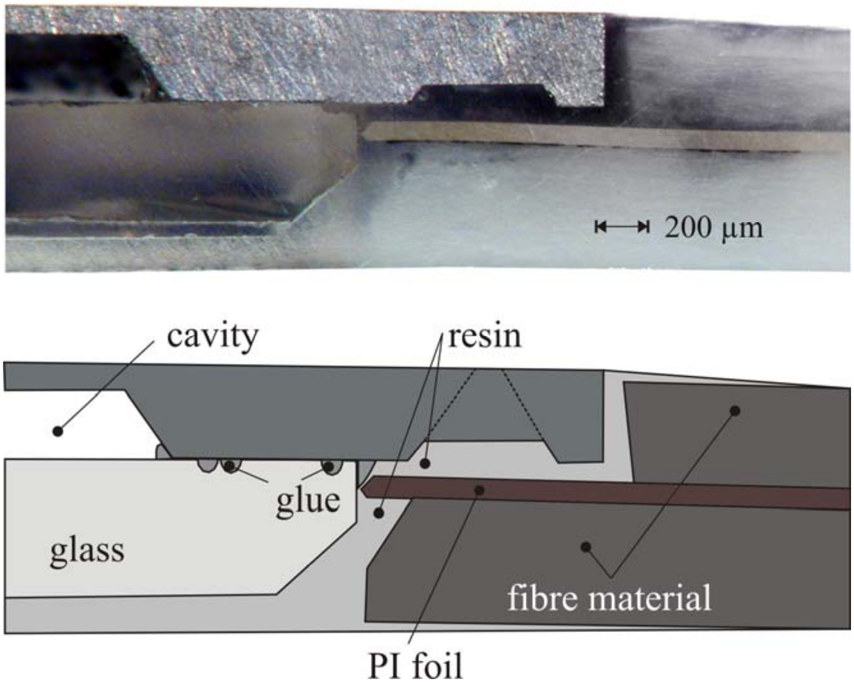

Fig. 8. top: photo of sensor, who has been cut for a better view; bottom: map of materials

Figure 8 also shows that the UV sensitive glue is suitable for the process. The etched channels in the glass buffer all the glue which was applied excessively in order to avoid that the boss does not stick to the glass cover.

Figure 9 shows a topview of the embedded sensor. The sensor is on the right, while the connection point for the external electric devices is on the left. The stack has an overall height of 1.1 mm and is very flexible. In the future, the PI foil will be led through the fibre material. The circuit is designed for a FPC connector with a spacing of 1 mm.

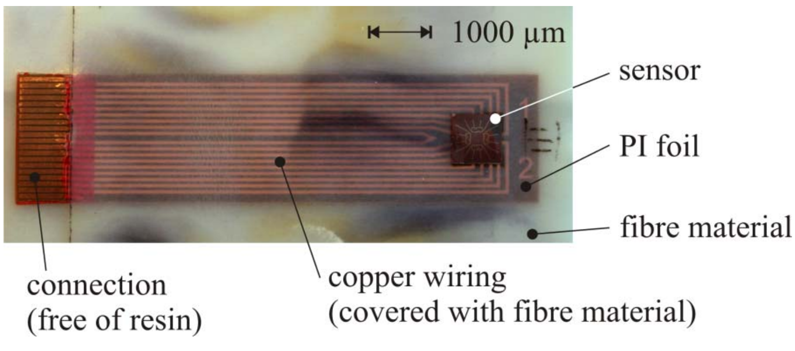

Fig. 9. Topview of the embedded sensor

On the other manufactured probes the planarity has been checked. The amount of fibre layers and therefore the thickness of the fibre material under and above the polyimide foil have to be validated in future, since in these first tests they were too thin.

6. Summary and perspectives

A novel pressure sensor and its manufacturing process has been presented. It is very robust, but sufficiently sensitive. It consists of a piezoresistive element and a glass cover. Via a through-wafer connection, all the wiring has been relocated to the bottom side, so that the top surface of the sensor does not influence the flow. The wiring to the external electric devices for the analyses has been made of a polyimide foil with a copper layer.

In the future the embedding process has to be improved to get an even flatter surface. Since all basic process steps work, it should be feasible to implement more functionalities e.g. hot-film anemometer [12] on the sensor surface. Also arrays of sensors will be produced.

Because the sensors are robust enough, they enable new measurements e.g. by implementing them in large composite parts, like airplane bodies, to monitor the process parameters within the material. After hardening the sensors can stay in the material.

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