Fabrication and packaging of a miniature sensor array for harsh environments

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Abstract—This paper describes the fabrication of devices to be used in harsh environments. The devices should operate under extreme conditions: high temperature (180°C), high pressure (200 bar) and in a chemically aggressive environment. Therefore, packaging is a major concern. Sensor fabrication and packaging is described. Two devices were made and tested at the temperature and pressure mentioned above.

I. INTRODUCTION

A schematic overview of the exploration and production (E&P) of gas and oil is depicted in fig. 1. From an oil platform a hole is drilled to an oil well (upstream). The produced oil or gas is delivered to the shore by a pipeline (downstream). Due to a variable composition of the fluid (a mixture of oil and water) flowing through the pipeline the condition of the pipeline changes unpredictably. To react to these changes the pipelines must be inspected. The currently used inspection methods are time consuming, very expensive and there are many interfaces where data transfer can be very difficult. Therefore, an oil-spore, i.e. an autonomous miniature system for upstream and downstream measurements, is being developed to investigate the fluid composition.

The oil-spore consists of a shell that contains a temperature and conductivity sensor, a data-logger and a battery. The oil-spore should operate under extreme conditions, i.e. high temperature (180°C), high pressure (200 bar) and in a chemically aggressive environment; therefore packaging of the sensors is a major concern. Sensor fabrication and packaging is described in this paper.

Fig. 1. Schematic diagram of an oil platform and oil well.

II. SENSOR DESIGN CRITERIA & CONCEPT

A device was made consisting of a temperature and a conductivity sensor. Design rules for the temperature and conductivity are not presented here, but can be found in [1-3]. A conductivity sensor consists of two metal electrodes that are immersed in a solution. The resistive path of solution can be obtained by measuring with an AC signal. In general, the area of a conductivity sensor should be as large as possible for a wide sensing range. The temperature sensor is a resistive sensor [4]. The size of the temperature sensor is small compared to the conductivity sensor.

The conceptual idea of the sensor packaging is depicted in fig. 2. The sensor must fit, for compatibility reasons, in a stainless steel tube with an outer diameter of 2.5 mm. This implies an inner diameter of 2.1 mm, leaving the sensor area to be 2.0 mm. A disc shaped sensor substrate with a diameter of 2.0 mm is made in which four holes are made to connect the temperature and conductivity sensor. Wires are put through the holes and connected to the sensors. The sensor is sealed on its topside with epoxy. The other side of the sensor housing is filled with epoxy to ensure pressure resistivity.

The sensors are made on a glass substrate. The disc shape and the holes can be made using powder blasting [5-7]. Powder blasting or abrasive jet machining is an etching technique for brittle materials, in which a particle jet is directed towards a target for mechanical removal as shown in fig. 3. A schematic hole profile is also shown in this figure. The boundary slope is approximately 60 degrees. The minimum required hole diameter depends on the wire that must fit through the hole (200 µm). To obtain a large sensor area two

Fig. 2. Conceptual idea of the sensor packaging (cross sectional view).

Fig. 3. A schematic diagram of the powder blast process.

things can be done to achieve a minimal hole diameter on the outside:

- use a thin substrate;
- powder blast from both sides.

The latter will cause the holes to be diablo shaped.

Another important issue is that epoxy will run out when it is applied. A margin of 200 μm is required between the area of application and the area where no epoxy is allowed. Fig. 4 shows a schematical top view of the sensor to be realized with the epoxy margins indicated by the dotted lines. The light gray area indicates the non-covered area where the temperature and conductivity sensor are made.

III. SENSOR FABRICATION

The device fabrication can be divided in two phases, subdivided in several steps as shown in fig. 5. Phase A consists of standard clean room processing, and phase B consisting of powder blasting, which is used to make holes and dice the devices. Phase A consists of 3 steps:

1. A 500 μm thick Pyrex wafer is etched back to 190 μm using HF.
2. Platinum (100 nm thick) is deposited and photo lithographically patterned for the temperature and conductivity sensor and a pad around the holes to be made, so a connection with the wires can be made.
3. Polyimide, that is inert to most substances, is applied to cover the temperature sensor and the interconnections.

In phase B photo foil, as a mask for powder blasting, is added to both sides of the wafer, exposed and developed.

Fig. 4. Top view of the sensor with epoxy margin (dotted line), the sensor area (light gray) for the temperature (meander) and conductivity sensor (two rectangles) (to scale).

Fig. 5. Sensor processing steps (1) 500 μm thick Pyrex wafer is etched back to 190 μm using HF; (2) platinum is deposited; (3) polyimide is added; (4) front side holes are made using powder blasting; (5) back side holes are made using powder blasting.

Subsequently, powder blasting is used to make the holes and to separate the sensors from the wafer. For the powder blasting process 29 μm alumina particles were used.

4. For the front side the depth was set to 80 μm , the pressure was set to 4.5 bar. A total of 56 g of alumina powder was used for an area of approximately 56 cm^2 .
5. For the backside the depth was set to 120 μm , (pressure equal to that of step 4). Now, 78 gr of alumina powder was used for an area of approximately 56 cm^2 .

Acetone was used to remove the photo foil from the sensor. A photograph of the processed chip is shown in fig. 6.

Fig. 6. Photograph of a processed sensor.

IV. SENSOR PACKAGING

The next step is to put the chip in its stainless steel 321 housing. This is done in 5 steps as depicted in fig. 7:

1. A special tool (see fig. 8) was made to attach four insulated wires, stripped at the end, to the sensor.
2. The wires and the contacts on the chip were connected on the front side by applying conductive epoxy (Epotek H20E). Subsequently, the chip is put in an oven at 80°C for 10 minutes.
3. After curing, small drops epoxy (Hysol C-8) were added on the other side of the chip to strengthen the connection between the wires and the sensor. The epoxy was cured at 60°C for 1 hour.
4. Next the chip is put in its housing and little epoxy (Epikote LEVEL 828) is used to cover the contacts and to fix the chip to the housing.
5. Finally, on the tube is filled with epoxy (Epikote LEVEL 828) using a syringe to give the device its pressure strength.

Two packaged sensors were realized and tested. A photograph of a packaged device is shown in fig. 9.

Fig. 7. Sensor packaging steps (1) attach chip on the tool and add wires; (2) connect the wires with conductive epoxy to the chip; (3) make a solid connection between the chip and the wires by adding small drops of epoxy to the other side; (4) put the chip with wires in the package and cover the contacts with epoxy; (5) fill the tube with epoxy.

Fig. 8. Sensor packaging tool with a sensor and four wires. Inset: enlargement of the chip.

V. PRESSURE AND TEMPERATURE TESTS

The two packaged sensors should be able to withstand a pressure difference of 200 bar and a temperature of 180°C. Initially, helium tests were performed. In these tests a differential pressure of 1 bar is applied and the amount of He-atoms that pass the device under test is being recorded. The leakage rate of two samples was less than the detection limit ($5 \cdot 10^{-9}$ ml/s) of the system.

Subsequently, the sensors were subjected to a temperature test. The sensors were immersed in a silicone oil bath at a temperature of 180°C for several minutes. After the test the sensors did not show any damage.

Thereafter, the sensor was clamped in a special holder and a water pressure test was performed. The applied pressure was slowly increased at the top, whereas the inside of the device was kept at atmospheric pressure (1 bar). The first sensor broke down at pressure of 150 bar. The other sensor was able to withstand a pressure of 250 bar for at least 3 minutes. From these results we conclude that the sensors are able to withstand high pressure. In the packaging process a cleaning step should be included to remove dirt and grease from the inside of the housing. The inside should also be sanded to get a rougher surface. Also primer should be applied to the wires and the inside of the housing to improve the adherence of the epoxy.

Fig. 9. Sensor packaged in a 321 stainless steel housing.

VI. CONCLUSIONS

A sensor for measuring temperature and conductivity has been fabricated using standard clean room techniques. Powder blasting was used to make holes through the devices and to separate the sensors from the wafer. Packaging was done in 5 steps. Both sensors withstood a temperature of 180°C.

One of the packaged sensors broke down when the pressure difference was 150 bar, but the other sensor was able to withstand a pressure difference of at least 250 bar. By improving the packaging process, especially when applying the pressure resistive epoxy, the sensors should have an improved pressure resistivity.

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