

Wafer Level Encapsulation of Micromachined Pressure Sensors to Realize a Liquid Flow Sensor

Ali Shakir, Krishnaswami Srihari, Bob Murcko
*Systems Science and Industrial
 Engineering Department
 SUNY- Binghamton, NY, USA*

Changhan Yun, Bob Sulouff
*Analog Devices Inc
 Cambridge, MA, USA*

Abstract

A differential pressure flow sensor capable of measuring low flow rates 0.01 ml/hr to 100 ml/hr has been developed, using wafer level encapsulation. Glass frit was used as the bonding material to bond the cap and device wafers. The flow channel was created by combination of seal glass material and etch step carried out in the cap wafer fabrication process. This paper summarizes the research work carried out to realize a flow sensor with multiple sensing capabilities by utilizing the wafer level bonding technology. The realization of the flow channel was carried out in two phases in order to create a more uniform rectangular channel compared to the initial phase. This research activity demonstrates a very simple cap fabrication process that enabled the realization of a flow sensor with multiple sensing capabilities. Surface micromachined process was employed to fabricate the pressure sensors as well as the cap that defines the fluid channel. The flow sensor developed was capable of measuring flow rate, fluid type, fluid pressure, fluid presence, and flow direction. The sensor was configured in a way to successfully demonstrate two differential pressure sensing modes (i.e. sensors within the cavity and sensors in the flow channel). Both flow rate and viscosity measurements are based on the differential pressure sensing principle. Fluid presence is determined using an interdigitated structure which can also sense the fluid type based on permittivity of the fluid. The flow rate measured successfully has been as low as 0.01 ml/hr and showed very good linearity when compared to the theoretical model. The diameter of the pressure diaphragm utilized was as low as 100 microns and depends on the flow rate required to measure. The height and width of the fluidic channel realized was 12 microns and 380 microns respectively.

1.0 Introduction

Wafer level encapsulation so far has been considered as one of the promising solution to protect the device wafers and deal with space constraints in the electronics packaging industry [1]. Wafer level encapsulation traditionally has been used to provide protection and hermetic environment for the sensors. Various wafer bonding technologies have been demonstrated to solve this purpose. Literature review reveals successful wafer bonding technologies like direct wafer bonding, anodic bonding, and intermediate layer bonding used for this purpose [2]. Bonding technology has also been used to realize and make the cap as an integral and mechanical part of the sensor. Records indicate various wafer bonding technologies like direct wafer bonding, anodic wafer bonding has been used to demonstrate a differential pressure flow sensor [3, 4]. Research published so far identifies glass frit bonding as one of the successful bonding technology to protect and

provide hermetic containment for MEMS sensors. Glass frit bonding could also be applied to create a flow sensor and has not yet been recorded. Glass frit bonding also helps us overcome the limitations that exist in other bonding technologies listed earlier. The limitations in a broader perspective include maximum temperature the device could handle, surface topography issues due to metal lines and other fabrication process steps [2].

MEMS based flow sensors is an emerging topic and are employed to measure the movement of a fluid. This movement can be quantified as mass flow rate, velocity, or volumetric flow rate. The fluid could be either liquid or gas. Several techniques exist to translate the flow signal to an electrical signal. Some of the successfully developed MEMS based sensing principles include the Thermal sensing principle, the Differential pressure sensing principle, the Coriolis force sensing principle and the Vortex

flow sensing principle. The Thermal sensing principle has been the most predominant sensing technique both in the area of liquid and air flow sensing of all the techniques listed earlier. Hot film anemometry, Calorimetric and Time of flight are the three principle thermal sensing modes [3]. The Differential pressure sensing principle follows the thermal sensing principle in terms of commonality [4]. In differential pressure sensing, the pressure difference registered between two pressure sensors is related to the volumetric flow rate of the fluid.

A pressure drop can be created by constructing a restriction channel between the two pressure sensors. Pressure sensors can be either a piezoresistive or capacitive type. By using capacitive pressure sensors the system can be designed to consume less energy [4]. Silicon wafers bonded to glass wafers has been the common technique used in constructing differential pressure flow sensors [4, 5]. Current market demands more than just the ability to sense the basic flow rate of the fluid. Additional information such as fluid type, temperature, pressure, and any other possible information is always an added advantage. Sensors have been developed to individually sense each of the properties listed above but limited research has been carried out to collaboratively sense multiple properties embedded into one system. The primary aim of this research is to address that requirement and to use glass frit wafer bonding technology to realize the sensor. Hence this research summarizes the fabrication and assembly work behind developing a flow sensor by wafer level encapsulation. Sensors were developed in two phases, the first phase being the development of cap and bonding them with the pressure sensors. The second phase involved the inclusions of learnings from the flow sensor developed earlier and improvises the sensor channel and sensitivity. Results and conclusions arrived from testing these flow sensors with different fluids and at different flow rates will also be listed in this paper.

2.0 Sensing principle/Design

Sensor design was carried out in two phases. The first phase involves the development of basic flow sensor and the second phase involves the development of flow sensor with additional sensing capabilities. The differential pressure sensing principle was adopted for sensing the volumetric flow rate of a liquid. The

basic flow sensor developed in the initial phase had the capability to measure only the volumetric flow rate. Cap to match the geometrics of the available pressure sensor was developed and bonded with the pressure sensor to prove the initial concept of differential pressure flow sensors. In the second phase sensing structures to have multiple sensing capabilities were included with the basic flow sensor and the flow channel geometrics were improvised to have a more uniform flow channel. The additional sensing capabilities include sensing the type of fluid, fluid presence, flow direction and fluid pressure. Viscosity sensing to sense the type of fluid was also possible using the same differential pressure sensing principle. Capacitive type pressure sensors were utilized for sensing the flow rate, viscosity, fluid pressure and direction of flow. An interdigitated structure was integrated and fabricated along with pressure sensors to facilitate permittivity sensing and to register fluid presence. The parameters, notation, and their respective units are listed in Table 1. Figure 1 shows the schematic representation and working principle of the flow sensor. The schematic shown represents the flow sensor with additional sensing capabilities. The basic flow sensor developed in the initial phase had pressure sensors placed only in the cavity. Equation 1 explains the differential pressure sensing mode which utilizes the pressure sensors placed in the sensor cavity [6]. Equation 2 explains the sensing mode which utilizes pressure sensors in the restriction channel [7].

Parameter	Notation	Units
Differential pressure	ΔP	pa
Volumetric flow rate	Q	m ³
Dynamic viscosity	μ	Kg/m.s
Length of micro channel	L	m
Width of micro channel	w	m
Height of micro channel	h	m
Capacitance	C	Farads
Dielectric constant	k	-
Vacuum permittivity	ϵ_0	Farads/m ²
Area	A	m ²

Table 1: Definition of parameters

$$\Delta P = \frac{12\mu L Q}{wh^3} \quad \text{----1}$$

$$\Delta P = \frac{12\mu L Q(w + h)}{w^2 h^3} \quad \text{----2}$$

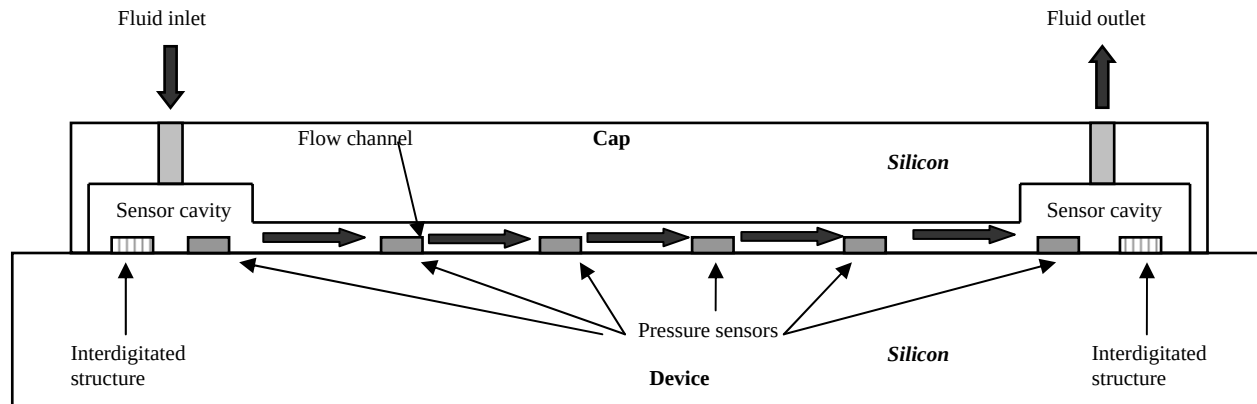


Figure 1 not to scale

Figure 1: Schematic representation of flow sensor

The basic flow sensor was designed to measure flow rates from 10 ml/hr to 100 ml/hr. Sensor design was primarily based on equation 1. Dimensional analysis was carried out to determine the dimensions of the flow channel. The diameter of the diaphragm varies from 107 microns to 119 microns. The diaphragm thickness is 2 microns and the dielectric gap is 1 micron between the ground plane and the diaphragm. Length, height, and width of the micro channel were 1175 microns, 375 microns and 12 microns respectively.

The flow sensor with additional sensing capabilities was designed to measure flow rates starting as low as 0.1 ml/hr to 100 ml/hr. Sensor design was primarily based on equations 1 and 2. Dimensional analysis was carried out to determine the dimensions of the flow channel. The pressure sensor geometrics were modified to suit the flow rate range being explored. The diameter of the diaphragm varies from 100 to 150 microns. The diaphragm thickness is 2 microns and the dielectric gap is 1 micron between the ground plane and the diaphragm. Length, height, and width of the micro channel were 6800 microns, 375 microns and 12 microns respectively. A fundamental capacitance based sensing mechanism was applied to sense the permittivity of the fluid. Equation 3 explains the sensing mechanism utilized to register the permittivity of the fluid based on their dielectric constant. An interdigitated polysilicon structure fabricated along with the pressure sensor device was utilized to meet the objective. The length of each rectangular beam ranges from 100 to 400

microns with a thickness of 4 microns and a gap of 4 microns between the beams. There were a total of 8 beams.

$$C = \frac{\epsilon_0 k A}{d} \quad \text{---3}$$

3.0 Fabrication and Assembly

Fabrication and assembly of both the basic flow sensor and the flow sensor with additional capabilities are very similar. The basic difference that exists between the two flow sensors is the additional sensing capability and achieving a more uniform rectangular channel. A surface micromachined circular pressure sensor designed for generic applications was utilized for the basic flow sensor. Learning's from the basic flow sensor were applied to the fabrication and assembly of flow sensor with additional sensing capabilities. Surface micromachined circular pressure sensor designed for generic applications and used in realizing the basic flow sensor was modified and utilized. Polysilicon was used as the diaphragm material for the pressure sensor on a P type silicon wafer substrate. The fabrication process for the pressure sensor involved alternate layers of polysilicon and oxide deposited to form a thin diaphragm that deflects based on the pressure experienced. A xenon difluoride etch process step etches the middle sacrificial polysilicon layer. The etch access holes used for etching the sacrificial layer is later plugged by depositing oxide and nitride. An open etch step followed by the plug off step realized the pressure sensor.

The processing steps until this stage were similar for basic flow sensor and flow sensor with additional sensing capability. The interdigitated structure was integrated at the diaphragm deposition step. Following the deposition and xenon difluoride etch step a layer of oxide and nitride as a passivation layer was deposited. A wet open etch process step common for both pressure sensor and the interdigitated structure was carried out to complete the processing and expose the pressure sensors and interdigitated structure. The focus of this research moving further was inclined more towards the cap fabrication and assembly process and has been explained in detail. Figure 2 highlights the critical processing steps of cap fabrication followed by the assembly to form the flow sensor.

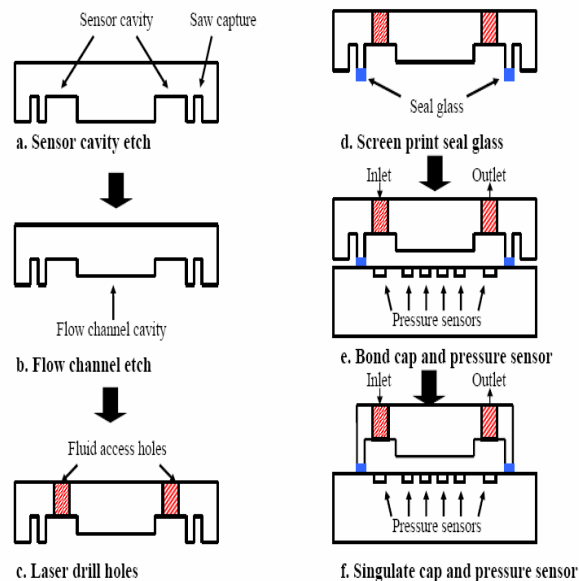


Figure 2: Cap fabrication and assembly process

The initial three steps involve the fabrication process followed by the next three which are part of the assembly process. As a first step, sensor cavity, and saw capture are patterned and etched using deep reactive ion etching (DRIE). Sensor cavity is the region where the pressure sensors are housed and used in one type of differential pressure sensing mode. Saw capture is a region in the cap that aids the singulation process. Saw capture basically prevents the saw blades from affecting the circuitry of the device during the cap singulation process. The flow channel is patterned and etched using the DRIE process in the next step.

Pressure sensors are also housed in the flow channel for the second differential pressure sensing mode. Fluid access holes in the cap were drilled using excimer laser technology. Seal glass was used as the bonding material to bond the device and cap wafers forming the final device. Screen printing technology was chosen to print the seal glass on the cap wafers. The seal glass forms the flow channel profile and also the boundary for the flow of fluid, thus preventing the fluid from getting into the circuitry. The screen printed wafers were then bonded at an elevated temperature and pressure to form a successful seal. Device singulation followed by cap singulation was carried out to finally form individual flow sensor chips. Figure 3 shows the SEM image of the basic flow sensor. Figure 4 shows the cross-sectional SEM image of the flow sensor chip after fabrication and assembly. The sensor cavity, flow channel, and fluid access holes that form the basic elements of the flow sensor are clearly marked and highlighted in Figure 4. Pressure sensors are housed both in the sensor cavity and in the flow channel.

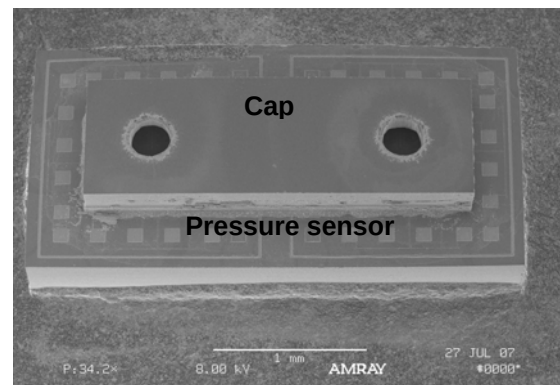


Figure 3: SEM image of assembled flow sensor

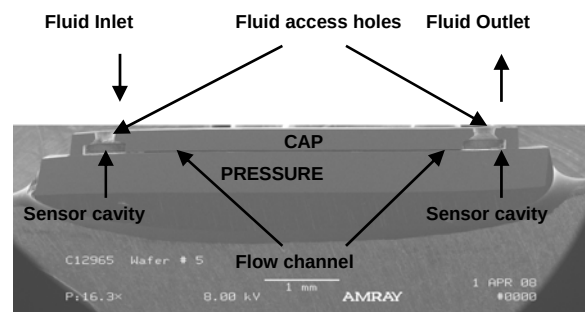


Figure 4: Cross sectional SEM image of assembled flow sensor

Figure 5 shows the pictorial representation of the pressure sensors utilized for the basic flow sensor. Both rectangular and circular diaphragms were evaluated to finally choose the circular diaphragms. Figure 6 is a pictorial representation of the pressure sensors and the interdigitated structure utilized for the flow sensor with additional sensing capabilities. The circular structures are the pressure sensors and the rectangular structure is the interdigitated structure.

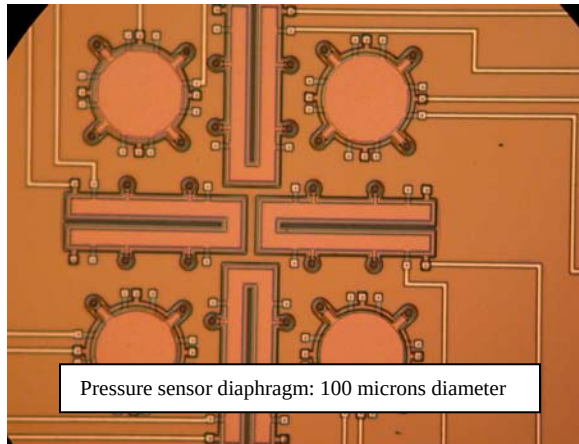


Figure 5: Pictorial representation of pressure sensor utilized for basic flow sensor

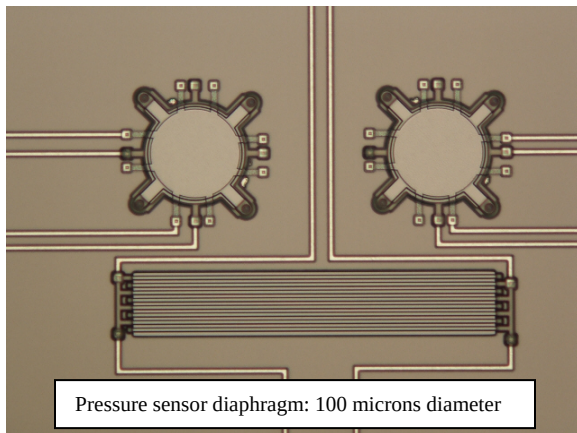


Figure 6: Pictorial representation of pressure sensor and interdigitated structure utilized for flow sensor with additional sensing capability

Figure 7 shows the packaged view of the flow sensor with a capacitance to digital converter (CDC) in a 44L JLCC package. This package was used as the prototype for test purposes.

CDC is an Analog product (AD7745) which monitors the capacitance and converts it to a digital output in the desired bit format.

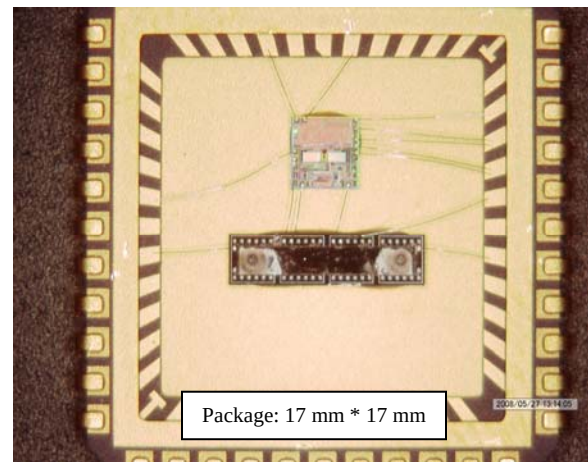


Figure 7: Pictorial representation of packaged flow sensor

4.0 Testing and Characterization

A test setup was established to evaluate these flow sensors at desired flow rates and with different fluids. Figure 8 shows the block diagram of the test setup. A syringe pump that delivers fluid at desired flow rates forms the integral part of the test setup. A weight scale was used to validate the flow rate delivered by the flow pump. Test boards to house and test the packaged flow sensors were built.

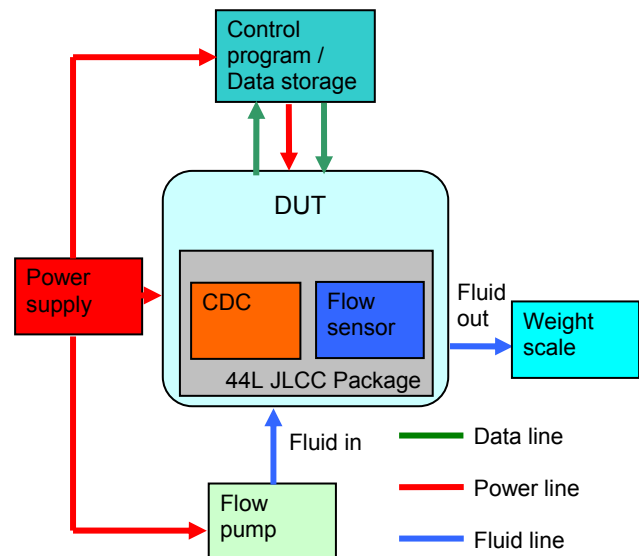


Figure 8: Block diagram of test setup

Initial calibration of the each individual pressure sensor was carried out by plotting the pressure Vs CDC output curves. Fluidic interconnection between the sensor and the test setup was accomplished by inserting steel tubes into the laser drilled holes and epoxying them. Figure 9 shows the pictorial representation of the flow sensor with fluidic interconnections ready to be tested in a test board.

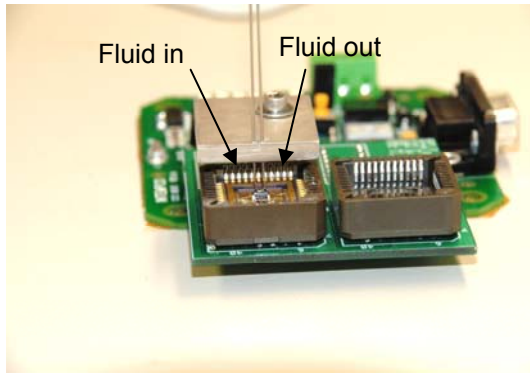


Figure 9: Photograph of flow sensor with fluid interconnections

Fluids of interest were introduced into the sensors at different flow rates and the pressure recorded by the sensors was used to calculate the differential pressure. Figure 10 shows a graph of a basic flow sensor tested at different flow rates and the corresponding differential pressure registered for a fluoro carbon liquid (FC-84). The theoretical values have also been plotted. It is obvious that the flow rate is directly proportional to the differential pressure.

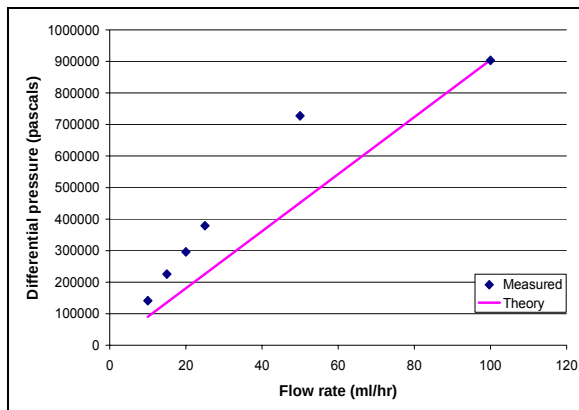


Figure 10: Test graph of basic flow sensor tested at different flow rates

Figure 11 shows the graph of flow sensor with additional sensing capabilities tested at different flow rates.

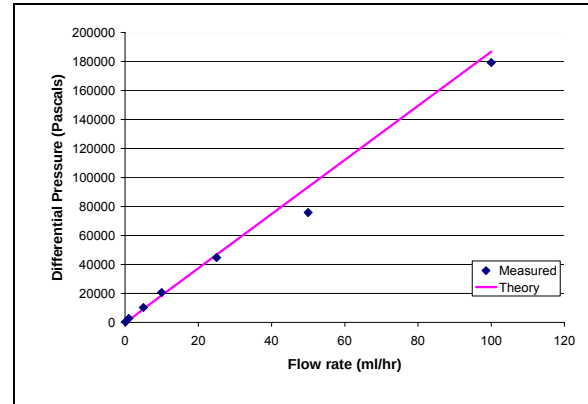


Figure 11: Test graph of flow sensor with additional sensing capabilities tested at different flow rates

It can be observed from Figure 11 that flow rate is proportional to the differential pressure. Also flow rates as low as 0.01 ml/hr has been successfully measured with different fluids. Comparing the results obtained from the basic flow sensor and the flow sensor with additional sensing capabilities the basic flow sensor has more deviation from the model. Further investigation of the flow channel led to the conclusion that there was non uniformity in the flow channel. Figure 12 shows the IR image of the flow channel in the basic flow sensor. It is clearly evident that the flow channel is non uniform due to the squish out of the seal glass into the flow channel. The squish out registered was 40 to 50 microns on either side of the channel.

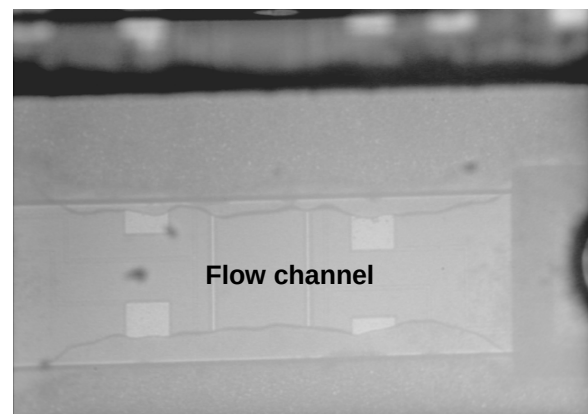


Figure 12: IR image of the flow channel in the basic flow sensor

As part of the improvisation process to reduce the variation of the flow channel, various factors that lead to the squish out of seal glass was studied. The length, width, and height of the seal glass printed on the cap wafer were the prominent factors that could possibly lead to squish out. Recordings of different widths of seal glass and their respective squish out was studied. It was understood that the current width of 150 microns in the flow channel region makes the seal glass to squish out in the middle region of the flow channel. Hence the width of the seal glass was modified to 100 microns for the flow sensor with additional sensing capabilities. At the same time the modification of the length of the flow channel to accommodate pressure sensors in the flow channel helped reducing the squish out to a very great extent. Figure 13 shows the IR image of the flow sensor with additional sensing capabilities.

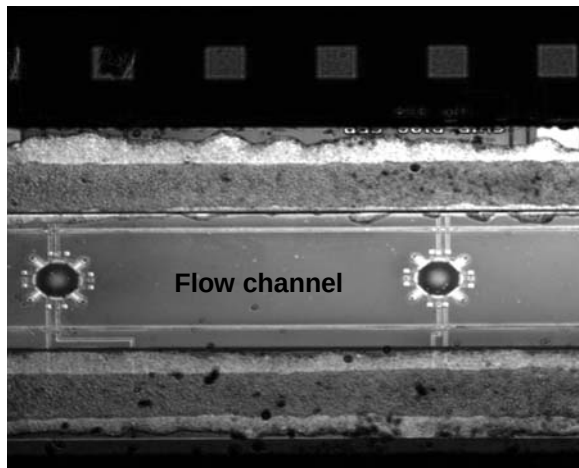


Figure 13: IR image of the flow channel in the flow sensor with additional sensing capabilities

It can be observed that the squish out of the seal glass has been reduced to a very great extent. The squish out registered was less than 15 microns and the flow channel is very uniform compared to the earlier one. Also the squish out recorded is not uniform right through out the channel but only in few sections of the flow channel. Flow sensors with additional sensing capabilities were further evaluated for the sensing capabilities in addition to the flow rate. Figure 14 shows the in channel differential pressure registered for different fluids at 1 ml/hr which can be used to sense the viscosity. Fluids tested were de-ionized water, FC-84, saline and glucose. It must be noted that there are shifts when compared to the theoretical values. The

speculation is that the cause of the shift from the theory could be due to the characteristic behavior of the fluid or due to localized change in channel geometries. Flow direction was measured by comparing the pressure observed at each of the sensor cavities. As part of the permittivity sensing mechanism, different fluids were introduced into the interdigitated structure and changes in capacitance was noted. Fluids of different dielectric constant showed a very significant change in capacitance. The sensitivity of the CDC chip is 30.5 attofarad and any shift registered by fluids of different dielectric constant higher than this value could be successfully measured. Fluid presence was also registered using these structures. There was an initial speculation to compare and contrast the output of sensors placed in cavity and sensors placed in channel. Subsequently a comparative study conducted between sensors placed in cavity as opposed to sensors placed in channel revealed no significant difference between them.

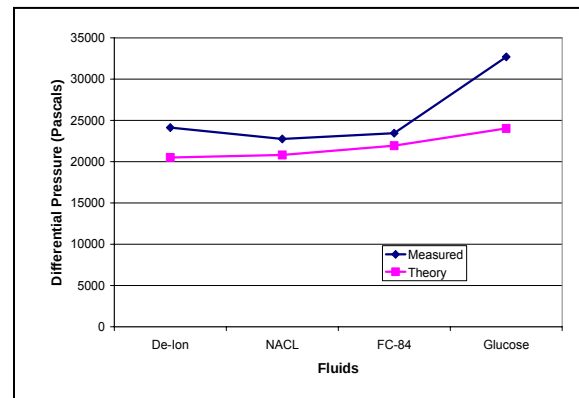


Figure 14: Test graph of fluids with different viscosity registering different differential pressure tested at different flow rates

5.0 Conclusions

Wafer level encapsulation of micromachined pressure sensors realized a liquid flow sensor. A simple cap fabrication process fulfilled the realization of a differential pressure based flow sensor. Flow rates ranging from 0.01 ml/hr to 100 ml/hr has been successfully measured. Seal glass was utilized as the bonding material to bond the cap and device wafers and successfully realize a flow sensor. A two step learning process of achieving a more uniform channel to help reduce the variation is also recorded. This sensor is also capable of

measuring fluid pressure, viscosity, permittivity, flow direction and fluid presence. Significant achievement of this research included embedding multiple sensing structures to sense different fluid properties. Future work includes increasing flow rate range, exploring temperature effects, manufacturability, design/process optimization, flow channel variation and fluidic packaging.

6.0 References

1. L.E. Felton, M. Duffy, N. Hablutzet, P.W. Farrell, W.A. Webster., "Low cost packaging of inertial MEMS devices", Proceedings- International Symposium on Microelectronics, 2003, pp. 402 – 406.
2. R. Knechtel., "Glass frit bonding: an universal technology for wafer level encapsulation and wafer bonding", Microsystems Technology, Vol. 12, October 2005, pp. 63-68.
3. M. Elwenspoek., "Thermal flow micro sensors", Proceedings- International semiconductor conference, Sinaia, Romania, Vol. 2, October 1999, pp. 423-435.
4. R.E. Oosterbroek, T.S.J. Lammerink, J.W. Berenschot, A. van den Berg, and M.C. Elwenspoek, "Designing realization and characterization of a novel capacitive pressure/ flow sensor", Proceedings- Transducers- International conference on Solid State Sensors and Actuators, Chicago, IL, June 1997, pp. 151-154.
5. M.A. Boillat, A.J. van der Wiel, A.C. Hoogerwerf, N.P. de Rooij., "A differential pressure liquid flow sensor for flow regulation and dosing systems", Proceedings – Micro electro mechanical systems, January 1995, pp.350-352.
6. S. Wu, J. Mai, Y. Zohar, Y.C. Tai, and C.M. Ho, "A suspended microchannel with integrated temperature sensors for high-pressure flow studies", Proceedings- Annual International Workshop on Micro Electro Mechanical Systems, Germany, January 1998, pp. 87-92.
7. K. Walters, Rheometry, Chapman and Hall, London, 1975. [www.rheosense.com]