Comparative Study of Conventional and MEMS Flow Meters

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ABSTRACT
A flowmeter is a device used to measure the flow rate or quantity of a gas or liquid in a pipe. In the modern world, flowmeters are used in thousands of ways across all industries. The various technologies used to measure and control flow can be either simple as in the earlier uses but more often are complex. Microelctromechanical Systems (MEMS) has been identified as one of the most promising technologies for the 21st Century due to wide range of applications in various industries. The MEMS flowmeters offers several advantages over traditional meters such as wide turn- down rate, direct mass flow sensing, high accu-racy, very low power consumption, low pressure loss etc. The Design, fabrication, and response characteristics of few of the MEMS flow sensors were presented with introduction of MEMS technology, finally the comparison between conventional flowmeters and MEMS flowmeters. Also it includes a short analysis of future opportunities of MEMS flowsensors for industrial application.

Keywords
Flowmeters, MEMS, MEMS based flowmeters

1. INTRODUCTION
Over the past 60 years, the importance of flow measurement has grown, not only because of its widespread use for accounting purposes, such as the custody transfer of fluid from supplier to consumer but also because of its application in manufacturing processes. Flow meters are an integral tool for measuring the flow of liquid, gas or mixture of both in applications used in the food and beverage industry, oil and gas plants, and chemical/pharmaceutical factories [1]. Interest in MEMS has grown dramatically in last decade. Also MEMS technology have gain lot of interest in flow measurements these days. MEMS flow sensors based on conventional flow metering techniques such as micro thermal flow sensors, micro coriolis flow sensors, differential pressure based MEMS flow sensors have wide application in medical automotive and industrial devices [8]. A major reason is the need for accurate reliable and cost effective liquid and gas handling systems with increasing complexity and reduced size.

1.1 Basic of flow measurement
Industrial flow measurements include measuring of flow rate of solids, liquids and gases. There are two basic ways of measuring flow; one on volumetric basis and the other is on weight basis [2]. Solid materials are measured in terms of either volume per unit time or mass per unit time. Liquids are measured either in volume rate or in weight rate. Gases are normally measured in volume rate.

Need for flow measurement- There is of course no single answer for this. Flow measurement is normally concern with the question of how much-how much is produced or how much is used. Measuring the flow of liquids is a critical need in many industrial plants. In some operations, the ability to conduct accurate flow measurements is so important that it can make the difference between making a profit or taking a loss. In other cases, inaccurate flow measurements or failure to take measurements can cause serious (or even disastrous) results. Industries involved in flow measurement and control include [1].

i. Food and beverage
ii. Medical
iii. Mining and metallurgical
iv. Oil and gas transport
v. Petrochemical
vi. Pneumatic and hydraulic transport of solids
vii. Power generation
viii. Pulp and paper
ix. Distribution

Flowmeters – Flow meters widely used in various industries for flow measurements. Flow measurement applications are very diverse; consider these examples: water flow through an open channel, hydraulic valve leakage, fuel measurement through a fuel injector, or respiratory flow through a peak expiratory flow meter. Although there are many technologies used to measure flow, the positive displacement flow meter is unique as it is the only one to directly measure the actual volume. All other types infer the flow rate by making some other type of measurement and equating it to the flow rate. Flow meters are referred to by many names, such as flow gauge, flow indicator, liquid meter etc. dependent on a particular industry; however the function, to measure flow, remains the same. Numerous types of flow meters are available for closed-piping systems. In general, the equipment can be classified as differential pressure, positive displacement, velocity, and mass meters. Differential pressure devices include orifices, venturi tubes, flow tubes, flow nozzles, pitot tubes, and variable-area meters. Positive displacement meters include piston, oval gear, nutating-disk. Velocity meters consist of turbine, vortex shedding, electromagnetic, and sonic designs. Mass meters include Coriolis and thermal types [3].

1.2 MEMS and MEMS based flowmeters
Interest in MEMS has grown dramatically in the last decade because of a wide range of applications. These include the automotive industry, process control and automation, scientific and medical instrumentation, telecommunication, commodity products, environmental monitoring etc. As a result, MEMS technology has become one of the most rapidly changing fields today [5].Flow measurement is an indispensable component in areas of medical instrumentation, process control, mechanics, chemistry, environmental

monitoring etc. as MEMS technology matures, along with the rapid development of applications in total analysis systems, the demand for fluid flow measurement and control has been increasing. MEMS flow sensors have advantages such as high repeatability, fast response, low power consumption, high sensitivity, high resolution, and batch production. MEMS flow sensors are classified either thermal or non thermal. Most of the MEMS flow sensors are thermal flow sensors which are based on thermal measurement principle. These thermal sensors are less expensive, more reliable, more accurate, and smaller than competitive approaches.

2. INTRODUCTION TO MEMS

MEMS promises to revolutionize nearly every product category by bringing together silicon based microelectronics with micro machining technology, making possible the realization of complete systems on a chip. MEMS is a technology of miniaturization that has been largely adopted from the integrated circuit (IC) industry and applied to the miniaturization of all systems not only electrical systems but also mechanical, optical, fluid, magnetic etc [6]. MEMS represent an extraordinary technology that promises to transform whole industries and drive the next technological revolution.

2.1 MEMS Fabrication methods-

MEMS fabrication uses high volume IC style batch processing that involves the addition or subtraction of two dimensional layers on a substrate (usually silicon) based on photolithography and chemical etching. Additional layers can be added using a variety of thin-film deposition and bonding techniques as well as by etching through sacrificial spacer layers. In MEMS fabrication photolithography, materials, micromachining (bulk micromachining, surface micromachining, HAR micromachining) are important factors. MEMS fabrication fall into three general classifications [7].

1. Bulk micromachining.
2. Surface micromachining.
3. High-aspect-ratio micromachining (HARM).

Bulk Micromachining- The purpose of bulk micromachining is to selectively remove significant amounts of silicon from a substrate. It is a subtractive process that uses wet anisotropic etching or a dry etching method. such as reactive ion etching (RIE), to create large pits, grooves and channels. Materials typically used for wet etching include silicon and quartz, while dry etching is typically used with silicon, metals, plastics and ceramics [7].

Surface Micromachining- Surface micromachining is a fabrication technology where by the micromechanical structures or devices are made entirely on the surface of the wafer without ever penetrating the wafer surface [8]. Material is added to the substrate in the form of layers of thin films. The process usually involves films of two different materials: a structural material out of which the free standing structure is made (generally polycrystalline silicon or polysilicon, silicon nitride or aluminium) and a sacrificial material, deposited wherever either an open area or a free standing mechanical structure is required (usually an oxide, but also resist or metals are used).

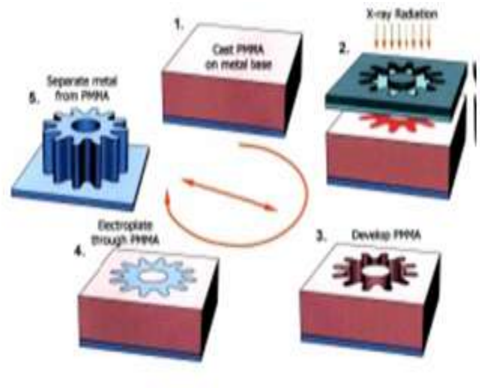

Fig -1: LIGA Micromachining.

High-Aspect-Ratio Micromachining- This technique uses a photolithographic process, but the photoresists are thick compared to the in bulk and surface micromachining. The expose source for the photoresist is a synchrotron (X-rays) rather than the standard ultra violet and deep ultraviolet Sources used in semiconductor fabrication. High-aspect-ratio micromachining (HARM) is a process that involves micromachining as a tooling step followed by injection moulding or embossing and, if required, by electroforming to replicate microstructures in metal from moulded parts. It is one of the most attractive technologies for replicating microstructures at a high performance-to-cost ratio and includes techniques known as LIGA [7] shown in figure 1.

2.2 Photolithography

Photolithography is the photographic technique to transfer copies of a master pattern, usually, onto the surface of a substrate of some material (usually a silicon wafer) [8]. For example, the substrate is covered with a thin film of some material, usually silicon dioxide (SiO2), in the case of silicon wafers, on which a pattern of holes will be formed. A thin layer of an organic polymer, which is sensitive to ultraviolet radiation, is then deposited on the oxide layer; this is called a photoresist. A photo mask, consisting of a glass plate (transparent) coated with a chromium pattern (opaque), is then placed in contact with the photoresist coated surface. Ultraviolet light is then shone through the mask onto the photo resist. The radiation causes a chemical reaction in the exposed areas of the photoresist. A special chemical is used to attack and remove the uncovered oxide from the exposed areas of the photoresist. The remaining photoresist is subsequently removed, leaving a pattern of oxide on the silicon surface.

2.3 Materials

MEMS devices are fabricated using a number of materials, depending on the application requirements. One popular material is polycrystalline silicon, also called poly silicon or poly [9]. This material is sculpted with techniques such as bulk or surface micromachining, and Deep Reactive Ion Etching (DRIE), proving to be fairly durable for many mechanical operations. Another is nickel, which can be shaped by PMMA (a form of plexiglass) mask plating (LIGA), as well as by conventional photolithographic techniques Frequently, poly-crystalline silicon is doped with other materials like germanium or phosphate to enhance the materials properties. Sometimes, copper or aluminium is plated onto the polycrystalline silicon to allow electrical conduction between different parts of the MEMS devices [9].

3. MEMS BASED FLOWMETERS

Many studies have demonstrated the successful application of MEMS techniques to the fabrication of variety of flow sensors capable of detecting the flowrate. MEMS flow sensors have advantages such as high repeatability, fast response, low power consumption, high sensitivity, high resolution, and batch production. Their are many flowmeters which are fabricated based on MEMS technology such as

a. Themal flow meter.
b. Coriolis flow meter.
c. Differential pressure.
d. Doppler flow meter.
e. Ultrasonic flow meter.
f. Hot wire anemometer.
g. Turbine flow meter.
h. And more

The most common classification for MEMS flow sensors, based on the working principles, that distinguishes two groups

1. Themal flow sensors.
2. Non-thermal flow sensors

Most of the MEMS flow sensors are thermal flow sensors which are based on thermal measurement principle. These thermal sensors are less expensive, more reliable, more accurate, and smaller than competitive approaches. And also MEMS based coriolis flow sensors, differential pressure flow sensors have wide applications in industry. Also their are many other flow sensors such as doppler flow meter, hot wire anemometer, ultrasonic flow meter, turbine flow meter based on MEMS technology but they dont give too much application like coriolis flow meter and thermal flow meter.

Here, the operating principle, design, fabrication and working of micro coriolis flow sensor and micro thermal flow sensor is briefly discussed.

3.1 Micro coriolis mass flow sensor (with integrated capacitance readout)

Sensor is based on the Coriolis force which acts on a fluid (mass) flowing in a vibrating channel [10]. Here micro Coriolis mass flow sensor with integrated capacitive readout is presented to detect the extremely small Coriolis vibration of the sensor tube.

Operating principle- A Coriolis type flow sensor consists of a vibrating tube, by an externally imposed vibration moving mass inside the tube is forced to change its velocity. Which forms coriolis forces that can be detected [11]. That can be expressed by

$$F = -2L\omega\times\Phi \quad (1)$$

Where F is coriolis force, L is length of the tube, ω is the frequency of vibration, Φ is the mass flow.

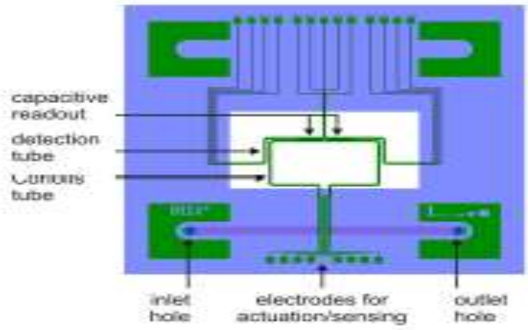

Fig 2- Layout of sensor chip(size 15 × 15mm) .

Sensor design- Silicon nitride used as the tube material to fabricate a micro coriolis mass flow sensor. This results in a sensor with very thin tube wall, so mass of the tube is small compared to mass of the moving fluid. This fabricated sensor incorporates capacitance readout structures, which are used to measure the very small coriolis vibrations. The coriolis tube dimensions: a low stress silicon-rich nitride (Si,Ny) tube with an effective diameter of approximately 40 µ*m* and a wall thickness of approximately 1.2 *µm*. The Coriolis tube has a rectangular shape with dimensions 2.5x4 mm [11].

Fabrication- Starting with a highly doped wafer, a 500 nm thick low stress LPCVD silicon-rich silicon nitride (SixNy) layer is deposited. Then the fluidic inlet/outlet holes are etched from the backside of the wafer using the SixNy layer at the top side as etch stop (Figure 3a), then 1 mm thick TEOS (tetraethyl orthosilicate) oxide layer is deposited and removed from the front side of the wafer. Then a 50 nm layer of chromium is sputtered on the front side of the substrate. This chromium layer is patterned using a mask containing arrays of 5x2 µm holes, spaced 3 µm apart. This pattern forms the centerline of the channel. The pattern is then transferred into the nitride layer by reactive ion etching and subsequently the channels are etched in the silicon using isotropic plasma etching (Figure 3b). The TEOS layer and chromium mask are then removed and another SixNy layer is grown with a thickness of 1.8 µm to form the channel walls and seals the etch holes in the first nitride layer (Figure 3c).

A 10/200 nm layer of chromium and gold is sputtered (chromium serving as the adhesion layer for the gold) and pre-patterned using wet etching, followed by a short dip in chromium etchant (figure 3d) to create the metal tracks on top of the tube which will facilitate Lorentz force actuation and capacitive sensing of the structure. Then a second lithography step is performed, in which the comb-like structures are defined, as well as the windows which are used to release the tube from the substrate [17]. The Cr/Au layer is then patterned using ion beam etching, because wet etching makes it extremely hard to precisely control the width of the teeth of the comb structures. Directly after the metal patterning the release windows are opened by reactive ion etching of the SixNy layer (Figure 3e). Then the structure is released by an isotropic silicon plasma etch step followed by resist removal using stripper (Figure 3f).

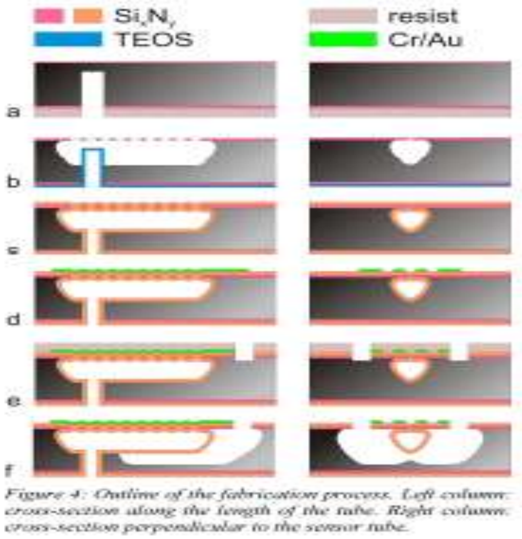

Fig -3: Outline of the fabrication process. Left column: cross-section along the length of the tube. Right column: cross-section perpendicular to the sensor tube.

Working- As shown in figure-2 flow inters in inlet holes of the chip and leaves from outlet hole. The sensor was connected to electronics which deliver the actuation signal and process the detection signal. These two signals are in counter-phase to eliminate the influence of parasitic capacitance to the substrate. The counter electrodes are kept at virtual ground by two charge amplifiers. As coriolis form due to flow, it affect comb position which generated and detected by capacitors C1 and C2 at outside of the loop. These output signals of the charge amplifiers are amplitude modulated signals of 1.4 MHz, where the amplitude is proportional to the sensor capacitance. Even smallest coriolis displace in the comb structure which generate a signals. These signals are demodulated using standard integrated analog multipliers and an op-amp based second-order low pass filter at 3 kHz. Summation of the two output signals gives a measure for the difference in capacitance (C1-C2), i.e. the actuation amplitude. The difference between the output signals is a measure for the common variation in the capacitors due to the Coriolis effect which is used to measure the flowrate.

3.2 Micro thermal flow sensor

Most of MEMS flow sensors are based on thermal measurement principle due to simple in both structures and implementation. This micro thermal flow sensor which is explained here is based on the principle of thermo transfer method which uses simple tempreture distribution technique to measure flowrate.

Principle of operation- The operating principle of the micro thermal flow sensor is three sensing resistors whose resistance varies with temperature are located on the outside surface of the flow channel across the flow direction. The center resistor is used as a heater, and the resistors on both sides are temperature sensors. The temperature of the heater is controlled at a certain level higher than that of the flowing fluid to generate a temperature distribution. This temperature distribution generated by the heater depends on the flow velocity [13].

Fabrication- The micro flow sensor is fabricated as follows.

1. Semicircular flow channels and holes for inlet/outlet are sandblasted on one glass substrate while only semicircular flow channels are sandblasted on another glass substrate. The channel length of downsized flow sensor is 12mm while that of original flow sensor is 50mm. Channel width of both is 1mm.

2. These two glass substrates are thermal compression bonded to configure circular flow channels.
3. Thin film resistors are deposited on the surface of the thin cover glass by the MEMS process.

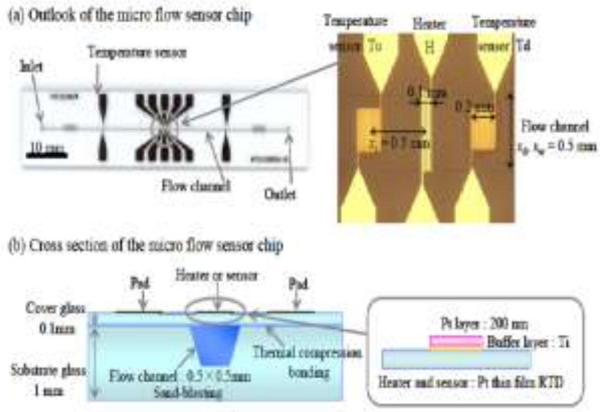

Fig 4: Micro thermal sensor chip.

These resistors are resistance temperature detector (RTD) made of platinum thin film. Platinum thin film is sputter deposited and the patterns of RTD are fabricated by the lift-off technique.

Working- Three sensing resistors that change its resistance with temperature are located on the outside surface along the flow channel, so these are non-wetted to the liquid to be measured. The center resistor (H) heats the liquid, and the resistors on both sides (Td and Tu) measure the temperature of the fluid. H is controlled at constant temperature to make temperature distribution around the heater. This temperature distribution profile depends on flow velocity. Flow velocity becomes faster, more heat transfers from upstream to downstream and the temperature at downstream becomes higher. Consequently, flow velocity can be determined from the measured difference in temperature between Td and Tu [15].

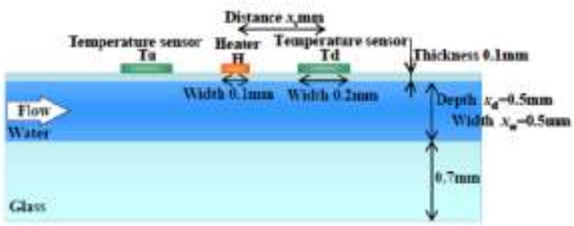

Fig 5: FEM model of micro thermal flow sensor.

4. COMPARATIVE STUDY OF FLOWMETERS

The MEMS flow meters offers several advantages over traditional meters such as low cost, small size, wide turn-down rate, direct mass flow sensing, high accuracy, very low power consumption, low pressure loss etc. Based on these parameters related to flowmeter we have compared few of the conventional flowmeters and MEMS flowmeters.

Table 1. Comparison between Conventional and MEMS flow meters

	Conven-tional coriolis flowme-ter	Conventi-onal thermal flowmet-er	MEMS coriolis flowmeter	MEMS thermal flowmeter
Power consum-ption	Good	Good	Excellent	Excellent
Size	Good	Good	Excellent	Excellent
Cost	Bad	Good	Good	Excellent
Accuracy	Bad	Good	Excellent	Excellent
Turndow n ratio	Good	Excellent	Excellent	Excellent
Time response	Good	Good	Excellent	Excellent
Pressure loss	Good	Excellent	Excellent	Excellent

Table 1 shows the comparison between the Conventional coriolis flowmeter and MEMS coriolis flowmeter also Conventional thermal flowmeter and MEMS thermal flow-meter. Flowmeters are compared based on power consum-ption, size, cost, accuracy, turndown ration, time response, pressure loss etc on these parameters.The Conventional coriolis flowmeters generally employ large diameter stainless steel tubes, expensive to purchase and install and pressure loss is also there. MEMS based sensors employ wafer fabrication, which enables hundreds of micromachined silicon coriolis mass flow tubes and even assembled subsystems to be produced with one wafer stack. This batch fabrication method reduces the manufacturing costs, enabling a wider use coriolis mass flow technology. Also with ±0.5% of accuracy and turndown ratio, pressure loss, time response in these parameters the MEMS coriolis flow meters shows superiority against the Conventional coriolis flow meters.MEMS thermal mass flow sensors have been explored extensively for their simple structure and implementation. MEMS technology is amenable to creating micro-heaters and thermal sensors with no moving parts, thus simplifying fabrication and operational requirements. Other advantages of thermal mass flow sensors is small size, short response time, low power consumption, higher sensitivity to low flow rates over conventional flow meters.There are MEMS flow sensors based on technologies such as doppler flow meter, ultrasonic flow meter, hot wire anemometer, turbine flow meter which have better accuracy, low cost, small size, low power consumption, wide turn down ratio, better time response, very low pressure loss compared with conventional flow meters. But they dont have much applications in industries compared with the conventional flow meters.

5. MICRO CORIOLIS FLOWMETER FOR DRUG INFUSION MONITORING

MEMS-based Coriolis mass flow sensors have been applied to the medical field in the area of drug infusion monitoring shown in the figure 6. If the mass flow of the liquid or drug in such a tube changes, the vibrating tube twists as a result of the Coriolis force. This twisting motion is sensed capacitively by the micro sensor. By measuring the true mass flow of a liquid with respect to time, the dose volume and dose rate can be monitored and occlusions detected [23]. Recently FDA-approved drug flow monitor that uses such a chip to measure drug flow rates and the total volume of infused drugs into a 4 patient in the 5 mL/hr to 200 mL/hr flow rate range. The IV line from gravity-fed IV bags are connected in series with the small flow sensor to provide an extra layer of protection to the patient and reduce the incidence of drug infusion errors.

Fig 6: Drug infusion monitoring using micro coriolis flow sensor.

The Micro-Coriolis Mass Flow Sensor offers improvements in drug delivery safety by:

- Improving drug delivery accuracy.
- Monitoring the dose, dose rate and total infused volume
- .• Detecting air bubbles and occlusions.
- Offering controlled retrograde infusion capability and a temperature measurement option.ISSYS is initially applying this technology to monitoring and controlling IV drug delivery. Unlike hot-wire flow sensors a Coriolis meter can measure mass flow of virtually any liquid without recalibration between fluids. Different IV solution can be distingushed from each other based on the simple freque- ncy output. It can also detect occlusions or blockages in the IV line and sense air bubbles. Single microsensor been able to provide the patient with so much protection.

6. CONCLUSIONS

Conventional flowmeters does not give accurate flow measurement to very low flow rates. MEMS flow sensor are used for accurate low flow measurement in areas of medical instrumentation, process control, mechanics, chemistry, environmental monitoring etc. where accurate low flow measurement is very important. Also with accurate low flow measurement MEMS flow sensors gives high repeatability, fast response, low power consumption, high sensitivity, low cost, wide turndown ratio and very low pressure loss. Although there are many applications of MEMS flow sensors, MEMS technology will soon find its way into the industrial flow sensor market for low mass flow rate applications, MEMS technology will offer industrial markets, cost and size improvements and extend the lower end of fluid flowrates and volumes that can be precisely monitored.

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