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A BY-PASS SENSOR PACKAGE DESIGN ENABLING THE USE OF MICROFLUIDICS IN HIGH FLOW RATE APPLICATIONS

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ABSTRACT

The package design for microfluidic sensors is discussed. The MicroElectroMechanical Systems (MEMS) device covered in this paper requires a fluidic and electrical interface as well as vacuum packaging of the sensing element. By using a by-pass package design the limitations of low flow rate and high pressure drop often encountered with microfluidic products can be avoided. The MEMS device utilizes a resonating silicon microtube that is electrostatically driven and capacitively sensed. A platinum RTD is also integrated into the MEMS chip. To improve the Q of the resonator a thin-film getter has been integrated to lower the microcavity pressure. The microfluidic packaging technology lends itself to producing densitometers, chemical concentration meters and Coriolis mass flow sensors. The device has been applied to fuel cell concentration sensors for embedded Direct Methanol Fuel Cell (DMFC) systems. The DMFC systems require a methanol sensor to minimize crossover and hence optimize the water/methanol concentration over temperature and the life of the product. Other high flow rate applications include ethanol/gasoline concentration sensors for E85 vehicles and dialysis fluid monitoring. A microfluidic Coriolis mass flow sensor has been developed and applied to drug delivery to monitor the drug dose, total volume infused, drug type and concentration. Chemical and temperature compatibility of the MEMS chip and packaging materials must be considered when dealing with this wide range of applications and will be discussed in the paper.

INTRODUCTION

A variety of MEMS flow sensors have been developed including hot-wire, drag-force and pressure-based flow sensors [1,2]. Micromachined Coriolis mass flow sensors have also been developed in the last decade [3-6]. Coriolis mass flow sensors offer advantages over hot-wire and pressure-based flow sensors such as measuring true mass flow regardless of fluid, providing a density and temperature output and not heating the fluid under test.

This paper will primarily discuss the fluidic packaging of MEMS-based Coriolis mass flow meters and related resonant microfluidic devices such as density and chemical concentration meters [6]. The microfluidic flow sensor

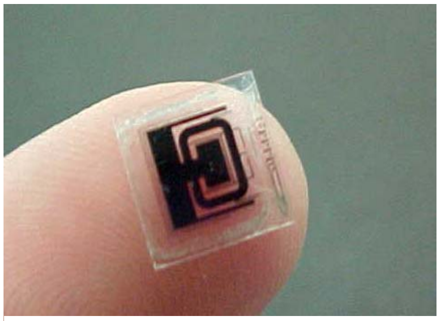

Fig. 1. The ISSYS micromachined silicon tube on a metallized glass substrate.

employs a plasma etched defined silicon tube, mounted to a metallized glass substrate with a very narrow capacitive gap [7]. At the core of the new sensor is a U or Ω - shaped, resonating silicon microtube, shown in Figure 1. The early work as well as one other MEMS study [3,6] entailed the development of an R&D micromachined chip only, and employed a laboratory vacuum chamber and instrumentation to both enable and sense resonance. Improved vacuum packaging of the technology was needed for the sensors to progress.

The MEMS fabrication process uses a combination of plasma and wet etching, photolithography, along with various types of wafer-to-wafer bonding to form the microfluidic chips [6-8]. To begin the tube fabrication process the inner channel is etched into a silicon wafer. Another silicon wafer is fusion bonded onto this. The outer shape of the tubes are next defined and this silicon slice is then anodically bonded to a metallized glass wafer. The glass wafer has holes drilled into it that will be the fluid inlet and outlet to the resonating tube. The glass wafer also is etched prior to metal deposition and patterning such that a gap is formed between the silicon tube and the metal capacitive electrodes present on the glass surface. The flow sensor microstructure now is in the form shown in Figure 1.

CHIP-SCALE VACUUM PACKAGING

A quality factor or Q value of the resonator above 1000 was desired to obtain sufficient signal to noise ratio and frequency / density resolution with the sensor. From the data taken in the laboratory system it was observed that a pressure of under 100mTorr would be needed to obtain a useful signal. Chip-scale vacuum packaging is most often accomplished using wafer-to-wafer vacuum bonding. Figure 2 shows an example of a bonded wafer stack. After wafer bonding the individual chips are singulated by sawing the wafer. The MEMS chips are then wirebonded to an adjacent circuit board or IC.

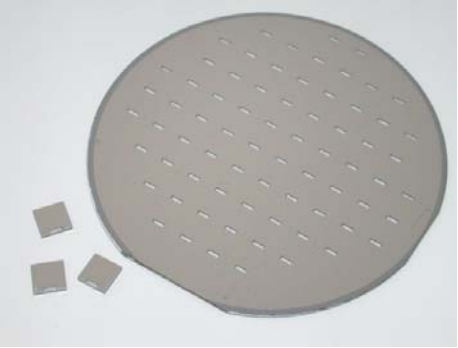

Fig. 2. A micromachined wafer stack, enabling chip-scale vacuum packaging.

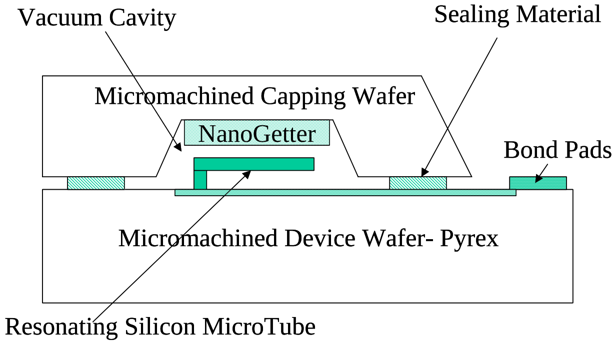

Fig. 3. Cross-sectional illustration of the vacuum packaging and gettering approach.

Conventional anodic wafer bonding produces cavity pressures in the 100 - 400 Torr range [9], while glass frit and solder sealing produces cavity pressures of 1-2 Torr [10]. For this microfluidic flow device, a cavity pressure of 1.4 Torr was obtained with glass frit sealing and due to squeeze-film damping and molecular interaction, the Q value was limited to 40 for this wide vertical resonator and narrow gap. To overcome the pressure limitation of conventional vacuum wafer bonding a reactive gettering material was developed and integrated into the wafer fabrication process. This getter, called a NanoGetter^{TM}, reduces the package pressure by more than four orders of magnitude and has been applied to other devices such as gyroscopes, RF-MEMS, pressure sensors and optical/IR devices. A capping wafer, generally either silicon or glass is patterned and etched to form both a cavity that encloses the active micromachine and opens up access to the electrical bond pads. At this point a thin film metal getter [8,11], is applied and patterned on the top portion of the cavity, as shown in Figure 3.

Through wafer-to-wafer bonding with getters, the vacuum level obtained was found to be under a milliTorr, resulting in Q values ranging from 2,000 to 62,000 for various silicon tube resonator designs. Extensive life testing of the hermetic glass frit seal and getter has been performed to insure

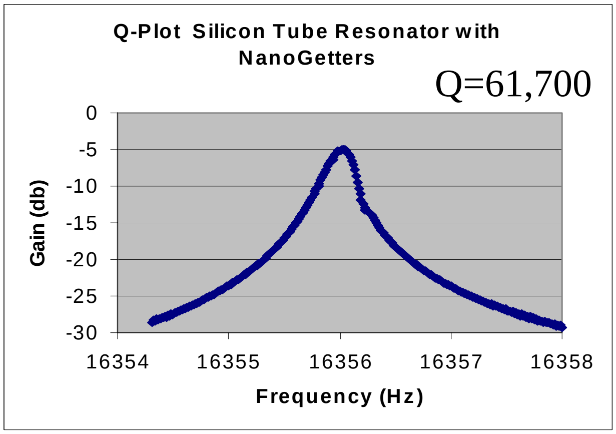

Fig. 4. A Q-plot for a silicon micromachined tube resonator used in a small Coriolis mass flow meter.

that the basic MEMS device is reliable. Figure 4 shows a signal gain versus frequency or Q plot for a MEMS resonator. These high Q values for resonant systems are rarely seen in the macroscopic world of steel tube Coriolis mass flow meters.

The frequency of vibration is another major difference between conventional and micromachined Coriolis mass flow meters. While conventional metal tube Coriolis mass flow meter resonate at 100 to 1500 Hz, the microresonant tubes have resonant frequencies ranging from 10KHz to 30KHz depending of microtube design and size. The microtube data shown in Figure 4 has a resonant peak at 16,356 Hz.

FLUIDIC PACKAGING

The ISSYS micro Coriolis mass flow sensors have measured both gas and liquid flows [8]. For liquid flows, flow rate ranging from 0.5 mg/hr to 1500 mg/hr have been measured with this microfluidic system.

A platinum resistive temperature sensor has also been integrated onto the microfluidic chip to improve density and flow measurement accuracy [8]. This element is located just a few microns from the silicon fluid conduit and so gives the chip a very quick temperature response. The microfluidic device, like conventional Coriolis mass flow meter, can measure the mass flow, density and temperature. The technology has been used to produce standalone density and chemical concentration meters [12].

With an accurate density and Coriolis mass flow sensor available, a number of new flow applications were found for this microfluidic technology. Drug infusion is an area where low flow rates are delivered, generally in the range of 1 mL/hr to 1000 mL/hr. These flow rates are compatible with those used in microtubes. A new micromachined sensing system has been developed that can accurately measure the specific gravity, chemical concentration, flow rate, dose and dose rate of a fluid or liquid drug [13]. This chip-based, safety tool offers a cost effective means of detecting both air bubbles, occlusions and when the wrong medication or concentration is being administered to a patient during common drug delivery procedures. Any materials that come into contact with the human body or with a fluid going into the human body must be nontoxic, biocompatible and not leach any hazardous material into the fluid stream. Saline solutions whole blood and blood products are somewhat corrosive so material selection and testing are important steps in developing a medical related system. With recent FDA approval this new technology is ready to enter the US drug pump market [14]. Figure 5 shows a photograph of this MEMS-based drug infusion monitor.

Fig. 5. A MEMS-based drug flow monitoring system.

HIGH FLOW RATE BY-PASS SYSTEM

Microfluidic devices are excellent at monitoring small fluid streams, however they have a problem with high-pressure drops when the flow rate increase. This pressure drop problem limits the use of microfluidic devices in more conventional flow rate regimes. Microchannels can be increased in diameter to increase the applicable flow rate range of the device, but eventually a practical limit is reached as to how large the microchannel can become before the size and cost benefits of MEMS technology is lost. To further extend the applicability of microfluidics to higher flow rate ranges a bypass packaging design can be employed. Figure 6 illustrates a bypass design that is employed in chemical concentration, density and DMFC sensors. Note that the main flow stream has a slight restriction in the bypass area to locally raise the pressure and force a parallel flow stream into the microsensor. This restricted

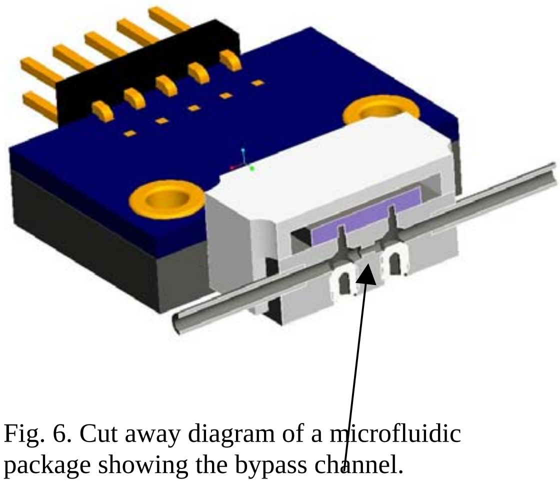

Fig. 6. Cut away diagram of a microfluidic package showing the bypass channel.

tubing are is at the end of the arrow in Figure 6. This design approach has been used in DMFC application to enable relatively small electric pumps to move fluid through a portable fuel cell system [15]. Figure 6 is actually a mechanical drawing of a DMFC methanol concentration sensor. Since the density of alcohol and water are significantly different and vary in a consistent manner over temperature, a fluid density and temperature measurement can be employed to monitor the methanol to water concentration in a fuel cell. By using a control loop an optimum concentration of methanol can be maintained which reduces membrane cross-over [16] and keeps the efficiency of the fuel cell high. Since the sensor is density based, it can also be used for measuring concentrations in ethanol, ethylene glycol and formic acid-based direct fuel cells. Figure 7 shows a density versus concentration plot for ethylene glycol and water. The same design approach can be scaled up to higher flow rate ranges.

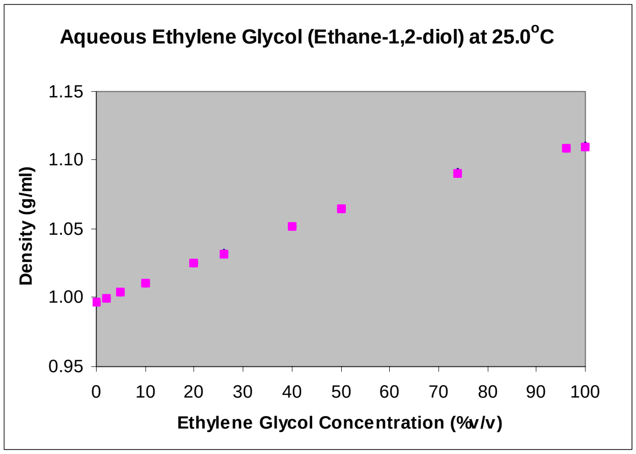

Fig. 7. A density versus concentration plot for ethylene glycol (antifreeze) in water.

Figure 9 shows a by-pass system used for industrial density and chemical concentration measurements. This type of by-pass configuration also enables microfluidic chemical sensors to be coupled with conventional, large volume flow meters such as turbine, hot-wire and paddle wheel meters. This offers added functionality and improve the accuracy of lower-cost high-flow rate meters. Wide temperature ranges of use in the industrial environment require closer matching of thermal expansion coefficients between the MEMS chip and packaging material. Corrosion of the packaging material can also be an issue when handling acids, bases and solvents. Reliability testing must be undertaken before launching industrial products. A by-pass design opens up many high flow rate applications such as industrial chemical processing/monitoring, flex-fuel vehicles using ethanol-gasoline [17], dialysis, petrochemical analysis and chemical mixing.

Fig. 8. A high flow rate by-pass, MEMS-based, resonant density meter.

CONCLUSIONS

The packaging of microfluidic sensors was discussed. The MEMS device utilizes a resonating silicon microtube that is electrostatically driven and capacitively sensed. To improve the Q of the resonator a thin-film getter has been integrated to lower the microcavity pressure. This getter, called a NanoGetter^{TM}, reduces the package pressure by more than four orders of magnitude and has been applied to other devices such as gyroscopes, RF-MEMS, pressure sensors and optical/IR devices. A platinum RTD is also integrated into the MEMS chip. The microfluidic packaging technology lends itself to producing densitometers, chemical concentration meters and Coriolis mass flow sensors. The microfluidic Coriolis mass flow sensor has also been applied to drug delivery to monitor the drug dose, total volume infused and drug type and concentration. By using a by-pass package design the limitations of low flow rate and high pressure drop often encountered with microfluidic products can be avoided. The by-pass device has been applied to fuel cell concentration sensors for embedded DMFC systems. The sensor can also be used for ethanol and formic acid-based direct fuel cells. The by-pass design opens up many high flow rate applications such as industrial chemical processing/monitoring, dialysis, fuel cells, flex-fuel concentration, petrochemical analysis and chemical mixing.

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