3D Out-of-Plane Flow Sensor Array with Integrated Circuits

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Summary: A new type of thermal flow sensor has been constructed using a novel three-dimensional assembly process. Testing was performed in constant-temperature and time-of-flight operation. Arrays of sensors monolithically integrated with JFET signal conditioning circuit have been fabricated to demonstrate the robustness of the process and compatibility with integrated circuits.

Keywords: hot-wire, flow sensor, monolithic

Introduction

Micromachined resistors are thermal transducers that can be used to measure air and water flow rate. For the thermal resistor to function as a flow sensor, the electrical resistivity must be a strong function of temperature it must be sufficiently thermally isolated from the supports and substrate. The thermal resistor can be made of a metal or doped semiconductor and can thermally isolated by putting it on a thermally insulating substrate [1, 2]. However, the thermal mass of the substrate leads to a larger thermal time constant could have increased power requirement if there is insufficient thermal insulation. Another method is to selectively remove the material underneath[3, 4] to form membrane or beams, but this makes IC integration more difficult due to process incompatibility. Another group has incorporated bulk micromachining and a polyimide joint to create a three axis anemometer[5], however wiring across the polyimide joint complicates the process.

In this work, we apply a three-dimensional assembly process called Plastic Deformation Magnetic Assembly[6] developed here at the University of Illinois to create a new type of thermal flow sensor (Fig. 1). The device consists of an array of thermal resistors elevated from the substrate by composite support prongs made of metal and polyimide. The out-of-plane feature of the device structure provides the resistor thermal isolation and access to the flow beyond the fluid boundary layer.

We have tested this sensor array in both water and air using thermal anemometry and time-of-flight sensing modes. To verify the monolithic nature of the PDMA process, we have also integrated the sensor with a commercial operational amplifier for constant temperature (CT) operation.

Fabrication and Packaging

The fabrication process has been described in detail[7]. However, a brief description will be described here. The process is compatible as a back-end of a integrated circuit (IC) manufacturing process. A polyimide-metal-permalloy stack is deposited on a sacrificial layer using standard surface micromachining process. The main support is provided by a 3~5μm thick electroplated permalloy that also serves as the material for the magnetic actuation. The thermal resistor used is a nickel-chrome composite (100nm Ni, 10nm Cr) where the chrome is used as an adhesion layer.

Fig. 1. (a) Schematic of the out-of-plane flow sensor integrated with on-chip circuitry. (b) SEM micrograph of three thermal resistor used for flow measurement.
The sacrificial layer is subsequently removed and the entire structure is bent out of plane (at the gold hinge) by applying an external magnetic field. This will align permalloy, a ferromagnetic material, to the field and plastically deform a gold hinge at the base. This is immediately followed by a selective electroplating process to deposit nickel and reinforce the gold hinge (Fig. 1a). As an improvement to the previous design, the wiring for the Au hinge is separate from the wiring to the thermal resistor, and is connected throughout the chip so the selective hinge electroplating process is performed on all the devices simultaneously. An SEM of an array of three thermal resistor is shown in Fig 1b.

Fig. 1a: Schematic of the device with the sacrificial layer removed and the structure bent out of plane.

Fig. 1b: SEM image of an array of three thermal resistors.

For water flow measurement performed in this paper, an array of three thermal resistors is fabricated on a Si chip mounted and wire-bonded on a PC board. This is followed by a 5μm parylene coating to prevent electrical shorting. Parylene is a water repellent film that is conformably vapor deposited on all exposed surfaces. To form a flow channel, a PDMS block with a 2mm tall recess molded from an aluminum piece is epoxied onto the PC board to form a flow channel (Fig. 2). To permit adhesion between the PDMS block and epoxy, an O₂ plasma treatment of the PDMS surface is done prior to application of the epoxy. The thermal resistor is elevated 1mm from the chip surface and is located approximately at the midpoint of the channel.

Testing

Airflow testing has been performed on this device[7]. For liquid flow sensing, the thermal resistor can be configured in three modes[8]: by itself as an anemometer measuring convection loss to the medium, operate as a pair with a heater and temperature sensor downstream to measure the dynamic response, or in a calorimetric configuration with temperature sensors upstream and downstream. The first two modes have been preformed on this device. DI water is used as the fluid for all our testing. The volumetric flow rate is controlled using a Cole-Palmer 14900 syringe pump interfaced with a PC.

Output response to flow rate for a single 400μm long thermal resistor operating at CT in anemometer mode is plotted in Fig. 3 at various overheat $a$. Overheat is defined as the resistance increase from room temperature ($a=\frac{R_{T0}}{R_{T0}+\Delta T}$) due to heating. In CT mode, the average temperature (resistance) is held constant by a feedback amplifier control circuit. The power input to the circuit ($Q$) should follow the following relation derived from King’s law[9],

$$Q = (A + BU^n)(\Delta T)$$

where $A$ is a constant relating to the conduction loss to the support and the fluid, and $B$ is a constant that corresponds to the convective heat loss to liquid flow, and $\Delta T$ is the average change in temperature along the thermal resistor.

Fig. 3. Output response of hot-wire in CT operation at various overheat with a DC gain of 2.2.

At higher overheat the output sensitivity (slope) is slightly higher. For example, the sensitivity is 15% higher for the 0.13 overheat versus 0.06 at 6 ml/m flow rate.
Fig. 4. Power supplied to the resistor at 5 ml/m flow rate, the abrupt spike above $a=0.15$ leads to air bubble formation.

The power consumption is plotted in Fig 4. The power loss should increase linearly to the overheat ratio, as is shown at overheat below 0.15. Due to excellent thermal isolation by having the resistor out-of-plane, the power required to maintain a high overheat is only on the order of tens of mW. In comparison, a poorly insulated thick film flow sensor[10] require 2W of power. Beyond an overheat ratio of 0.15 (corresponding to an average $\Delta T=50$ K), air bubbles start to form on hot-spots at the center of the thermal resistor and can disrupt the flow measurement. This leads to an abrupt spike in power supplied as shown by the last two points.

Fig. 5. Oscilloscope output overlay for sensor response at 4, 8, and 15 ml/m flow rate for time-of-flight measurement. A 0.5 Hz heat pulse (400ms) is generated by a heater operating in CT mode with $a=0.15$ overheat.

Time-of-flight is the second mode we tested the device in, where a three thermal resistor array is operating in a dynamic mode (Fig 2b). A large resistor with a meander structure used as a heater in the middle of the array. The heater operating in CT mode (to prevent overheating) generates a 0.5 Hz heat pulse with 20% duty cycle. Two smaller resistors without the meander pattern are placed 1.6mm up/downstream at the same elevation. The two resistors operate as RTDs to the heater to capture the temperature profile of the heat pulse, and its output is amplified and filtered. Dynamic response taken with a digital scope with time averaging is shown in Fig. 5. The square wave corresponds to the 400ms square wave pulse, with a small notch at the beginning that corresponds to the response time of the circuit used to control the heater temperature. The response captured by the RTD at three flow rate is time averaged by the oscilloscope and are overlaid onto the same plot. The response shows that for higher flow rates, the heat pulse arrvies at the RTD more quickly, and has less time to disperse. Lower flow rates leads to a wide pulse with lower amplitude.

Fig. 6. Plot of delay time versus flow rate. The delay time is measured from the high-low edge of the heat pulse to the peak of the RTD response.

The delay time of the peak to the edge of the pulse is plotted in Fig 6. The delay time of flight should be inversely proportional to the flow velocity, as it is roughly represented in the above figure. The advantage of using the time-of-flight method is the relative independence to the fluid property.

Circuit integration

By using surface micromachining and capping the fabrication temperature to below 350°C, this new type of sensor is well suited to be integrated with commercial ICs.

Fig. 6. Array of hot-wire sensors integrated with commercial JFET Op-Amps for CT operation. Backside Si etch allows the array to be flexible.
To demonstrate the compatibility of this new type of sensor, we have fabricated a sensor array directly on top of a National Semiconductor LF347 JFET operational amplifiers (Fig. 6) as an additional back-end process. The operational amplifier is used to perform on-chip signal conditioning. The chip was selected for its relative large die size to accommodate the sensors, as well as for its relatively large gain-bandwidth. To fabricate the sensor on the commercial wafer, a 5 μm thick polyimide layer is first spun on and patterned to expose the aluminum bonding pads. This layer serves to planarize the surface and to electrically and chemically insulate the circuit from the subsequent process. The remaining fabrication process is mainly identical to what was described earlier, except the addition of a gold layer for wiring.

The device consists of an array of 8 nodes. At each node there are sensors with different sensing modality: a hot-wire anemometer with integrated CT circuit for flow airflow measurement, as well as an artificial haircell [11] with strain gauge signal amplified for collecting directional flow data. Testing of these new arrays is ongoing, but preliminary tests of the hot-wire show that functionality is comparable to those with external CT circuitry.

![Fig. 7. Air flow response of a thermal resistor with integrated constant temperature circuit.](image)

**Conclusion**

Array of surface Micromachined, out-of-plane thermal resistors have been fabricated and tested as a liquid flow sensor. The sensor can operate both in anemometric mode as well as time-of-flight mode. To demonstrate the compatibility of this process with ICs, we integrate an array of sensors directly on a commercial operational amplifier.

**References**


