ABSTRACT
In this paper, we presented a wafer-level encapsulated Thermoresistive Micro Calorimetric Flow (TMCF) sensor with the integrated packaging by using the proprietary InvenSense CMOS MEMS technology. For the nitrogen gas flow from -26m/s to 26m/s, the pulsed operated TMCF sensor (device size = 3.4mm²) under the Constant Temperature Difference (CTD) mode achieved a normalized sensitivity of 112.4µV/(m/s)/mW with respect to the input heating power. Besides, the measured TMCF sensor response time (τmax<3.63ms) shows good agreement with a theoretical model. With the pulsed operation, the proposed low-power TMCF sensor will be a promising digital CMOS MEMS flow sensor for the Internet of Things (IoT), especially for smart building/home.

INTRODUCTION
Measurement of fluids flow is crucial for industrial and biomedical applications. Many micro thermal flow sensors have been reported in recent years [1, 2]. To date, CMOS MEMS technologies have been steadily applied to fabricate different types of microsensors [3-6]. However, the essential packaging works in these monolithically integrated CMOS flow sensors were needed for the flow measurement, such as the flipping packaging design [4], the surface mounted adaptor on the chip [5], and the sealed flow channel with a chip or a part of chip inside [6]. Until now, there are very few reported wafer-level encapsulated CMOS MEMS flow sensors with the integrated packaging design. In this paper, based on a theoretical 1D model of micro calorimetric flow sensor, a compact TMCF sensor by using the proprietary InvenSense CMOS MEMS technology was designed, fabricated and characterized.

CONCEPT AND FABRICATION
As shown in Figure 1, the TMCF sensor consists of one 0.2µm thick molybdenum (Mo) micro heater at the center and two symmetrically located Mo thermoresistive sensors on a 5µm thick free-standing Si structure. In the absence of fluids flow, the temperature profile with respect to the micro heater is symmetrically distributed. While in the presence of fluid flow, the differential thermal output (ΔT) between the upstream and downstream Mo sensors can be related to the input flow velocity U via the convective heat transfer. The thermal output ΔT can be further converted to an electrical voltage signal (Vout) through a Wheatstone bridge. Thus the flow measurement is realized. For the more detailed working principle of this kind of TMCF sensor, readers are referred to [6].

The compact TMCF sensor in Figure 1 was fabricated by using proprietary InvenSense CMOS MEMS process: a SOI MEMS wafer bonded to a 0.18µm CMOS wafer through the Al-Ge eutectic bonding, where the sensor was wafer-level electrically interconnected and hermetically sealed [7]. The micrograph of the fabricated TMCF sensor is shown in Figure 1(b). Besides, FBAR gas sensor and ISFET were also implemented on the same die (4.5mm × 2.6mm) for the multi-sensors system-on-chip, as shown in Figure 1(c). To realize the tangible on-chip TMCF sensor, an integrated CMOS circuit with the function of signal conditioning (noise and offset reduction), amplification, and signal conversion into Pulse Width Modulation (PWM) was also implemented. The performance of this on-chip smart flow sensing platform will be reported later.

Figure 1. (a) Schematic of a wafer-level encapsulated Thermoresistive Micro Calorimetric Flow (TMCF) sensor with the integrated packaging design, (b) SEM micrograph of TMCF sensor with the serpentine structure, (c) photograph of a multi-sensors die, (d) key fabrication steps using the proprietary InvenSense CMOS MEMS process.
size of $350\mu m \times 62\mu m \times 6.2\mu m$ with the measured resistance of $304\Omega$. Similarly, two upstream and downstream sensors were constituted by $3.6\mu m$ wide Mo wires, each thermoresistive sensor has an overall size of $350\mu m \times 54\mu m \times 6.2\mu m$ with the measured resistance of $551\Omega$. In order to get high sensitivity to the input fluid flow, the optimal distance $D=32\mu m$ between the micro heater and sensors was determined from a modified 1D model according to Eq. (1). The details of the modified 1D model will be presented later. The MEMS wafer was then bonded to a CMOS wafer with the etched $2200\mu m \times 400\mu m \times 50\mu m$ (Length $\times$ Width $\times$ Height) bottom cavity for the internal fluids flow. Finally, the circular fluids inlet and outlet with the diameter of $510\mu m$ were opened on the MEMS wafer to realize the integrated packaging design which can significantly reduce the cost of MEMS packaging. In this compact TMCF sensor design, the effective device size is only around $3.4mm^2$.

Previously, we have successfully developed a general 1D model to predict the characteristics of a CMOS TMCF sensor considering the boundary layer effect on one side of the TMCF sensor [8]. In this paper, the fluid flow on both sides of TMCF sensor, validated by the CFD simulation, was sensed. Therefore, the 1D model in [8] is modified to Eq. (1) with the consideration of double-sided fluids flow.

$$
\frac{1}{2} k_s (h_s + 2t + h_d) \frac{d^2 T(x)}{dx^2} - \frac{1}{2} \rho C_s U \frac{dT(x)}{dx} (h_s + 2t + h_d) - k_s \left( \frac{1}{h_s} + \frac{1}{h_d} \right) T(x) = 0
$$

(1)

The symbols in Eq. (1) are: $h_s$, $h_d$ are the upper and bottom cavity height, $t$ is the sensor thickness, $k_s$, $\rho$ and $C_s$ are the thermal conductivity, density and heat capacity of the moving fluid, respectively.

As shown in Figure 2 (b), the TMCF sensor achieved the highest sensitivity $S$ with $D=30\mu m$ for the small input flow. Besides, to achieve a better sensor output and sensitivity for the detection of high-speed flow, it is suggested to place the Mo sensors close to the heater. In view of the proprietary InvenSense CMOS MEMS fabrication process [7], the final distance $D$ between the micro heater and sensors was determined to be $32\mu m$.

![Figure 2. The effect of distance (D) between the heater and sensing elements on the TMCF sensor’s (a) output and (b) sensitivity, an optimal distance $D=32\mu m$ was determined with the 1D model and CMOS MEMS process [7].](image)

**EXPERIMENTAL METHOD**

Previously, we reported a temperature-compensated interface circuit for the TMCF sensor with the micro heater working on Constant Temperature Difference (CTD) mode [6], where the issue of sensor output drifting due to the variation of ambient temperature could be compensated and minimized. The original CTD mode circuit [6] was modified with the replaced DC biased voltage source by a pulsed stimulated voltage source $V_s$, as shown in Figure 3. Therefore, the power consumption of the micro heater was reduced and the response time of TMCF sensor could be easily determined in the CTD mode. Note that, to minimize the self-heating of upstream and downstream sensors, $V_s$ was set to $0.5V$, and the on-chip $1253\Omega$ Mo-based $R_3$ and $R_t$ were used to reduce the current density over the Wheatstone bridge. The output signal $V_{out}$ was further amplified by an off-chip instrumentation amplifier (INA114) and then converted to a high-speed Data Acquisition (DAQ) card (National Instruments NI PCI-6110). The recorded data of $V_{sd}$ and $V_s$ with the acquisition rate of 1MS/s were saved to the personal computer through a LabVIEW program.

The TMCF sensor with the integrated micro flow channel was tested with nitrogen gas flow as shown in Figure 4. Therein, the Upchurch Scientific PEEK™ Tubing 1542 was directly inserted into the inlet and outlet of the TMCF sensor die and sealed with epoxy resin. The nitrogen tank was used as the gas source and a commercial flow sensor Zephyr™ HAFBFL0050CAAX5 (Honeywell, USA) was used as a reference flow meter.

![Figure 3. The pulsed operated CTD mode interface circuit for TMCF sensor with the on-chip temperature sensor $R_s$.](image)

**RESULTS AND DISCUSSION**

Figure 5(a) shows the measured voltage signal $V_s$ in the DC operated CTD mode. Due to the enhanced cooling effect of the gas flow, the required $V_s$ is increased with the enhanced joule heating to maintain a constantly overheated temperature of the micro heater. Accordingly, the power consumption of micro heater is increased from $12.1mW$ to $17.7mW$ as shown in Figure 5(b). Compare to the power loss of the monolithically released CMOS TMCF sensor [6]; this larger power consumption is mainly due to the conductive heat loss of $5\mu m$ thick silicon layer beneath the Mo resistors. Generally, silicon is an excellent thermal conductor with a better thermal conductivity (150W/m/K) than that of silicon oxide (1.4W/m/K). Therefore, more conductive heat loss through the support joints of TMCF sensor to the substrate (heat sink) can be expected. This
power loss can be significantly reduced with the pulsed operated CTD mode, which will be discussed later.

The micro heater in the TMCF sensor can be regarded as a type of hot-film sensor, where the voltage signal \( V_h \) could be used for the sensing of gas flow. As shown in Figure 5(a), the sensitivity of this hot-film sensor is 15mV/sccm with the 5sccm input gas flow, while its sensitivity decreased to 4mV/sccm with the 50sccm input gas flow.

![Figure 5. (a) Voltage signal and (b) Power consumption of micro heater under the DC operated CTD mode.](image)

The measured output of the TMCF sensor is plotted against the N\(_2\) gas flow within a flow range of -50~50sccm (-26~26m/s) as shown in Figure 6. Unlike the hot-film sensor, our TMCF sensor is capable of detecting the bidirectional fluids flow. With the DC operated CTD mode, the TMCF sensor shows a high sensitivity (0.352mV/sccm) and the minimum power consumption <9mW.

![Figure 6. DC and pulsed operated TMCF sensor response to the nitrogen flow -50~50sccm (-26~26m/s). The sensitivity is 0.352mV/sccm and the minimum power consumption <9mW.](image)

In addition to the merits of sensitivity, power consumption, and flow range, another merit of TMCF sensor is the response time. The capability of a flow sensor system to accurately and quickly respond to the changes in fluid flow depends on different factors, including biasing conditions, construction materials, and sensor geometry. The response time of flow system can be defined as the time required for the output voltage fall to 36.8% (1/e) or rise to 63.2% (1-1/e) from its final amplitude. However, it is hard to measure the sensor response time due to the difficulties of realizing the well-defined fluidic step input [10]. Currently, the experiment for the response time measurement is usually based on an electric impulse heating that directly applies to the micro heater with the step input (jump) of temperature [11], or the complicated experiment setup with the sudden step of velocity made by a membrane burst [12]. In this paper, the measurement of the response time for our TMCF sensor is performed on the pulsed operated CTD mode with the relative system on and off. Therefore, the response time as a function of flow rate both with and without feedback can be determined.

![Figure 7. Pulsed operated TMCF sensor (20Hz square wave) in CTD mode with (a) 50% reduced power and (b) time constant \( \tau \) at 30sccm, (c) \( \tau \) vs. flow rates, \( \tau_{\text{max}} < 3.63 \text{ms} \).](image)
convection, and the maximum response time of TMCF sensor \( t_{max} \approx 3.63\text{ms} \). The response time of INA114 in this off-chip TMCF sensor configuration is around 160\(\mu\text{s} \), which can be ignored in comparison to the measured fall time constant of the sensor system (ca. several milliseconds). Therefore, the fall time measured can be regarded as the thermal time constant of TMCF sensor. For simplicity, the suspended TMCF sensor structure is treated as an isothermal plate; therefore, the dynamical behavior of this TMCF sensor can be predicted from a thermal RC model as shown in Eq. (2).

\[
\tau = R C R C = 1/(Q_{conv} + Q_{conv}), C = \rho C_{p} V
\]

where \( C_{t} \) is thermal capacitance, \( R_{t} \) is thermal resistance due to conduction loss of \( Q_{conv} \) and heat convection loss of \( Q_{conv} \). The heat convection loss over a plate with the double-sided fluid flow is \( Q_{conv} = 2 h A \), where the heat transfer coefficient \( h \) is [13]:

\[
Nu = hL/k_f = 0.664Re^{1/2}Pr^{1/3}
\]

Therefore, the response time of this TMCF sensor can be semi-empirically determined as:

\[
\tau = \sqrt{(1 + b \cdot FR^{0.5})}
\]

where \( FR \) is the input flow rate. Figure 7(c) shows that the proposed model could successfully predict the TMCF sensor’s dynamical behavior, which is in good agreement with the experimental data. The determination of this time constant \( \tau \) will enable the low-cost energy-efficient pulsed operated digital CMOS MEMS flow sensors with the on-chip integrated electronics in the future.

CONCLUSION

In summary, based on the 1D TMCF sensor model, we successfully design and fabricate a wafer-level encapsulated TMCF sensor by using the proprietary InvenSense CMOS MEMS technology. The fabricated TMCF sensor achieved an excellent normalized sensitivity of 112.4\(\mu\text{V}/(\text{m/s})/\text{mW} \) with the bidirectional detection of nitrogen flow (-26–26 m/s). With the pulsed operated CTD mode for our TMCF sensor, the heating power was significantly reduced and the response time \( \tau \) can be easily determined both with and without feedback. The measured TMCF sensor response time (\( t_{max} \approx 3.63\text{ms} \)) shows good agreement with the proposed theoretical thermal RC model. With the pulsed CTD operation, this low-power TMCF sensor will be a promising digital CMOS MEMS flow sensor for the Internet of Things (IoT), especially for smart building/home.

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