A WAFER-LEVEL ENCAPSULATED CMOS MEMS THERMORESISTIVE CALORIMETRIC FLOW SENSOR WITH INTEGRATED PACKAGING DESIGN

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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 = 3.4mm^2) 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 (τ_{max}<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 (V_{out}) 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.

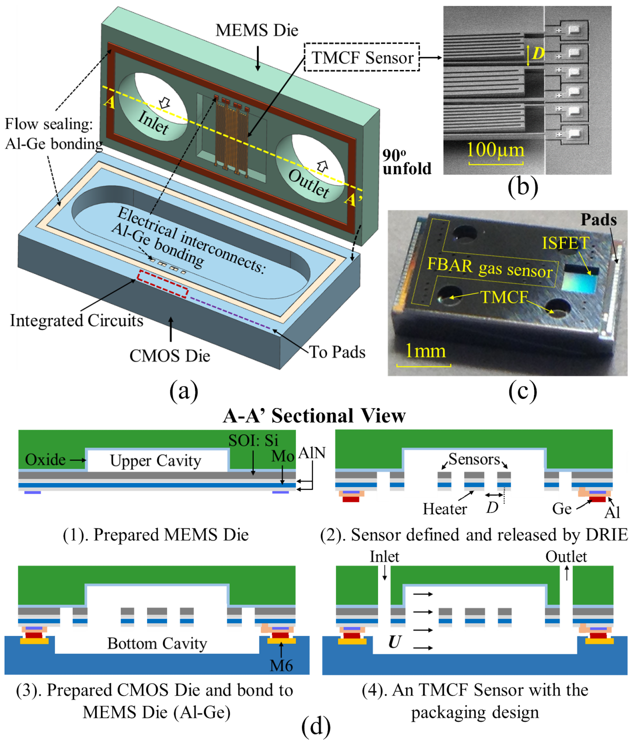


Figure 1. (a) Schematic of a wafer-level encapsulated Thermoresistive Micro Calorimetric Flow (TMCF) sensor with the integrated packaging design, (b) SEM micrograph of TMCF sensor with the serpentine structure, (c) photograph of a multi-sensors die, (d) key fabrication steps using the proprietary InvenSense CMOS MEMS process.

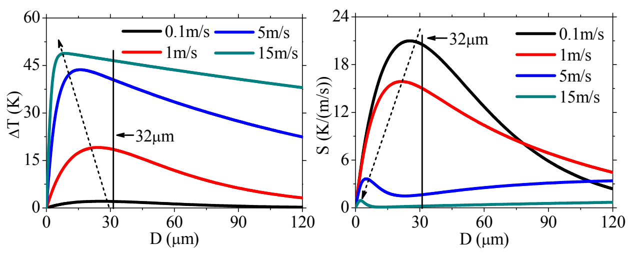
For the detailed design of TMCF sensor, firstly, the 400μm × 400μm × 22μm (Length × Width × Height) upper cavity on the MEMS wafer was fabricated to reduce the heat loss (Figure 1(d)). Then, the selective silicon DRIE was used to release the serpentine-shaped sensor structure from the prepared SOI MEMS die. The micro heater was constituted by 6μm wide Mo wire, which has an overall size of 350µm × 62µm × 6.2µm with the measured resistance of 304Ω. Similarly, two upstream and downstream sensors were constituted by 3.6µm wide Mo wires, each thermoresistive sensor has an overall size of 350µm × 54µm × 6.2µm with the measured resistance of 551Ω. In order to get high sensitivity to the input fluid flow, the optimal distance D=32µm 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 2200µm × 400µm × 50µm (Length × Width × Height) bottom cavity for the internal fluids flow. Finally, the circular fluids inlet and outlet with the diameter of 510µm 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.

$$\frac{1}{2}k_f(h_u+2t+h_d)\frac{d^2T(x)}{dx^2}-\frac{1}{2}\rho C_P U\frac{dT(x)}{dx}(h_u+2t+h_d)-k_f\left(\frac{1}{h_u}+\frac{1}{h_d}\right)T(x)=0 \quad (1)$$

The symbols in Eq. (1) are: h_u, h_d are the upper and bottom cavity height, t is the sensor thickness, k_f, ρ and C_p 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≈30µm 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 32µm.



(a) (b)

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=32µm was determined with the 1D model and CMOS MEMS process [7].

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_p, 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 1253Ω Mo-based R_3 and R_4 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_{NI} and V_h with the acquisition rate of 1MS/s were saved to the personal computer through a LabVIEW program.

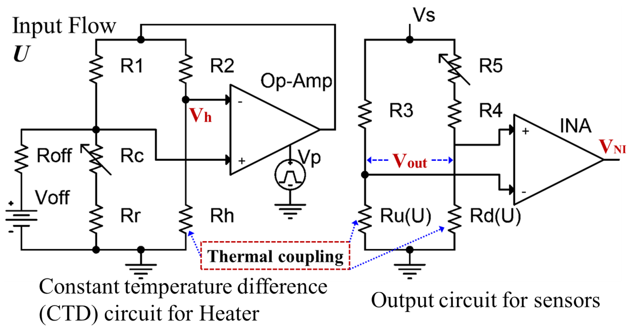


Figure 3. The pulsed operated CTD mode interface circuit for TMCF sensor with the on-chip temperature sensor R_r.

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™ HAFBLF0050CAAX5 (Honeywell, USA) was used as a reference flow meter.

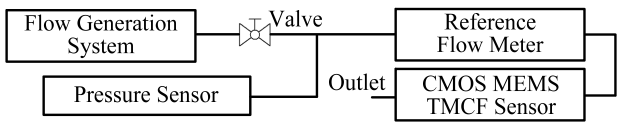


Figure 4. Experiment setup and testing of TMCF sensor

RESULTS AND DISCUSSION

Figure 5(a) shows the measured voltage signal V_h in the DC operated CTD mode. Due to the enhanced cooling effect of the gas flow, the required V_h 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 5µm 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.

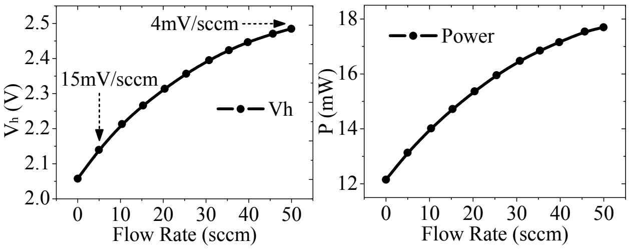


Figure 5. (a) Voltage signal and (b) Power consumption of micro heater under the DC operated CTD mode.

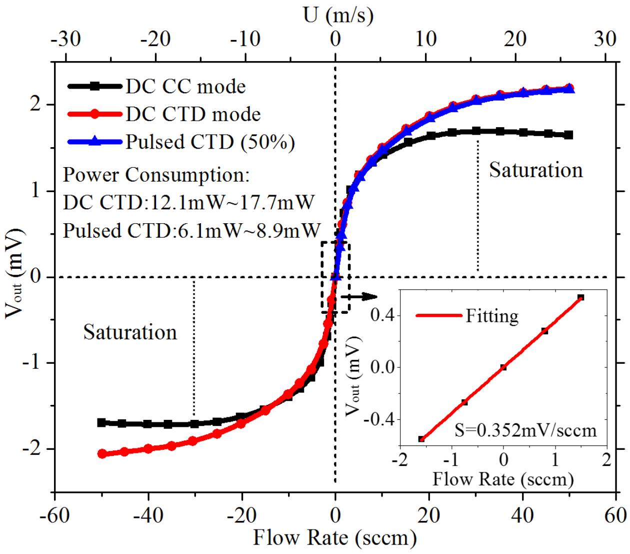


Figure 6. DC and pulsed operated TMCF sensor response to the nitrogen flow -50~50sccm (-26~26m/s). The sensitivity is 0.352mV/sccm and the minimum power consumption <9mW.

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 overlapped output response with the 20Hz square wave V_p operated counterpart. Note, the signal of V_{NI} is referred to the input terminal of the instrumentation amplifier, i.e. V_{out}. The power consumption of heater is almost 50% reduced (<9mW) with the pulsed operated (50% duty cycle) CTD mode as shown in Figure 7(a). Accordingly, the normalized sensitivity (112.4μV/(m/s)/mW) with respect to the input heating power and gain is better than those reported CMOS sensors [5, 9] and shows competitive performance to the monolithically released CMOS TMCF sensor [8] as listed in Table 1. Besides, it is worthwhile to claim that not only the ambient temperature compensation could be achieved in the CTD based TMCF sensor [6], but also a larger flow range is acquired as that compared to the Constant Current (CC) mode counterpart (-30~30sccm).

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 τ as a function of flow rate both with and without feedback can be determined.

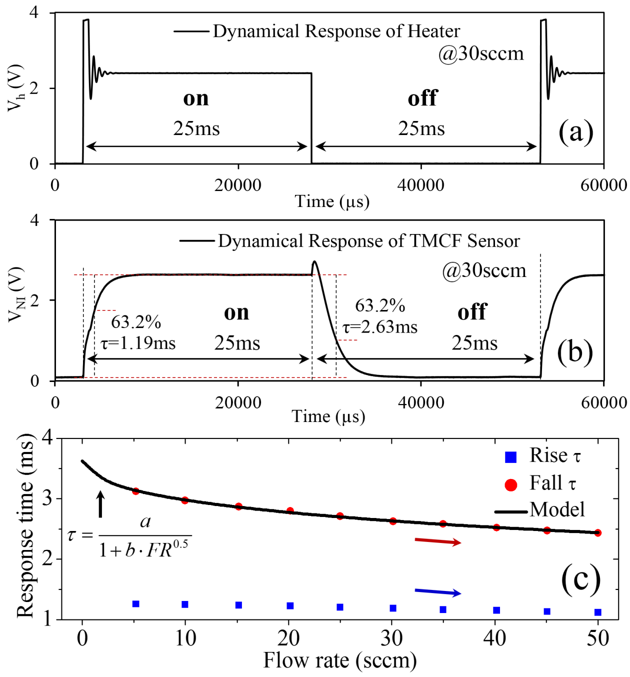


Figure 7. Pulsed operated TMCF sensor (20Hz square wave) in CTD mode with (a) 50% reduced power and (b) time constant τ at 30sccm, (c) τ vs. flow rates, τ_{max}<3.63ms.

Figure 7(a) shows the dynamical response of the micro heater V_h under the input N_2 flow of 30sccm, where the CTD circuit in Figure 3 shows the quick electrical response to the 20Hz square wave pulsed V_p with the effective *on* and *off* (The high and low voltage periods keep 25ms long, respectively). Due to the introduction of feedback in the CTD mode, the rise time constant (τ=1.19ms) of TMCF sensor is much faster than the fall time constant (τ=2.63ms) as shown in Figure 7(b). Both the rise and fall τ were decreased with the increased flow due to the enhanced heat

Table 1. Comparison between the previous CMOS flow sensor and current work.

References	Device Size, mm^2	Packaging	Fluids	Flow Range, m/s	Power, mW	S^*, μV/(m/s)/mW	Response time (ms)
Wu [a] [4]	16	Flip to Ceramic	Air	1~25	25	N/A	N/A
Bruschi [a] [5]	16	PMMA adaptor	N_2	-3.33~3.33	4	23	N/A
Xu [b] [8]	2.25	PMMA Channel	N_2	-11~11	2.36~2.77	154.4	N/A
Dong [b] [9]	36	Flip to Ceramic	Air	0.5~40	2~452.6	39.3	<1400
Current work [b]	**3.4**	**Wafer-Level**	$\mathbf{N_2}$	**-26~26**	**(6.1~8.9)/ε**	**112.4×ε**	**<3.63**

[a] thermopile transduction principle, [b] thermoresistive transduction principle, S^* =sensitivity normalized with respect to input power and gain. ε=0.5 for DC-operated TMCF sensor, ε=1 for pulsed operated TMCF sensor.

convection, and the maximum response time of TMCF sensor τ_{max}<3.63ms. The response time of INA114 in this off-chip TMCF sensor configuration is around 160μs, which can be ignored in comparison to the measured fall time constant of the sensor system (*ca.* several milliseconds). Therefore, the fall τ 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).

$$\tau = R_t C_t;\ R_t = 1/(Q_{cond} + Q_{conv}), C_t = \rho C_p V \qquad (2)$$

where C_t is thermal capacitance, R_t is thermal resistance donated by heat conduction loss of Q_{cond} and heat convection loss of Q_{conv}. The heat convection loss over a plate with the double-sided fluid flow is $Q_{conv}=2hA$, where the heat transfer coefficient h is [13]:

$$Nu = hL/k_f = 0.664\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3} \qquad (3)$$

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

$$\tau = a/(1 + b\cdot FR^{0.5}) \qquad (4)$$

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 τ 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 112.4μV/(m/s)/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 τ can be easily determined both with and without feedback. The measured TMCF sensor response time (τ_{max}<3.63ms) 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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