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A biocompatible Parylene thermal flow sensing array

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Abstract

A microelectromechanical systems (MEMS) thermal flow sensing array constructed of biocompatible materials has been designed, fabricated, and tested. In addition to the construction, the electronic biasing conditions were selected such that sensor operation was compatible with biological fluids. The device comprises several thin film platinum sensing elements sandwiched in a Parylene C membrane. The membrane is suspended over a bulk-micromachined silicon channel for improved thermal isolation. This sensing array layout permits, for the first time, operation in multiple flow sensing modes using a single device. Multi-mode testing was performed in hot-film, calorimetric, and time-of-flight modes at low overheat ratios. Furthermore, constant current (CC) and constant temperature (CT) biasing methods were explored in hot-film mode. The results of the various testing modes were compared and flow sensing down to $0.5 \,\mu$ L/min has been demonstrated.

Keywords: Thermal flow sensing; Parylene C; Hot film; Calorimetric; Time-of-flight

1. Introduction

Micromachined flow sensors have several decades of developmental history; the first silicon-based sensor was introduced in 1974 [1]. A variety of operational principles have been employed to realize flow sensors for diverse applications from home appliances [2] to medical diagnostics [3]. For a thorough review of micro-flow sensors, the reader is directed to articles by van Oudheusden [4] and Nguyen [5,6]. Of the many flow sensing methods, thermal flow sensors possess both simple structure and implementation thus offering a practical solution for integrated sensing in microfluidics applications. Although limited by drift and the need to calibrate for new fluid systems, interest continues to grow; recently, determination of the thermal properties (thermal diffusivity and conductivity) of the sensed fluid medium has been demonstrated using thermal flow sensors [7,8].

Flow control is vital in emerging applications in bioMEMS and micro-total analysis systems, demanding new flow sensing solutions designed specifically for use with biological fluids. A micromachined thermal flow sensing array constructed of biocompatible materials has been developed. The array layout permits flexible operation with the choice of several modes and measurement of multiple flow parameters. Packaging is simplified by integrating the flow sensors into the microchannel wall rather than having to bring the sensor into contact with the flowing medium. The most popular thermal flow sensing methods include hot film, calorimetric, and time-of-flight [4,5,9–14] which are all implemented and demonstrated in this single device. In addition, both constant current and constant temperature operation are examined in hot-film mode.

2. Theory

Thermal flow measurement relies on the detection of the convective heat transfer from an electrically heated resistive sensing element (wire or film) to fluid flow (Fig. 1). The wire or film will experience cooling due to heat transfer given that the sensor is at a temperature above that of the fluid. Heat transfer is related to the magnitude of the flow velocity and increases with increasing velocity (or flow rate). Thus sensing is accomplished without any moving parts and requires only resistive elements (heaters and temperature sensors). In some cases, the same element may

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Fig. 1. (Top) Schematic showing the thermal flow sensing principle. (Bottom) A three-dimensional exploded view of the sensing array layout and design.

serve as both the heater and sensor. Thus, thermal flow sensing is simple to implement and miniaturize.

The heat transfer variables available for flow measurement include temperature, temperature difference, heating power, and thermal signal transfer. These variables can be combined to yield a total of six possible operational modes detailed in [5]. Hot-film, calorimetric, and time-of-flight sensing modes are explored here.

In hot-film mode, sensors are located in or near a flow channel and experience heat loss when subjected to fluid flow. Sensing is accomplished by monitoring the resistance or voltage change with temperature. For many sensor materials, the resistance versus temperature relationship is expressed as

$$R(T) = R(T_0)[1 + \alpha(T - T_0)]$$
(1)

where R(T) denotes the resistance at temperature T and α is the temperature coefficient of resistivity (TCR). A hot-film sensor can be operated either in constant current or constant temperature modes [15]. In CC mode, the heating current, or power, is held constant and the decrease in sensor temperature in response to flow is detected. Conversely, in CT mode, the sensor temperature is held constant by feedback circuitry and the increase in heating power required to maintain constant temperature is measured in response to flow. Feedback provides electronic frequency compensation and can greatly improve the frequency response over CC mode.

Calorimetric flow measurement involves detecting changes in the temperature profile surrounding a heating element. At least three elements are required to implement calorimetric sensing: a heater and one upstream and one downstream sensor. Compared to the hot-film technique, this method is sensitive to small flows and allows for the detection of flow direction due to the presence of two sensors. For a detailed analysis of micro-calorimetric flow sensing, the reader is directed to [12].

Time-of-flight sensing (or pulsed-wire anemometry) also requires multiple elements; this is a thermal tracing technique in which a heat pulse is applied upstream and the thermal wake is detected by a temperature sensor downstream [16]. The top time (t) is the variable to be measured and is defined as the time at which the maximum temperature is detected by the sensor. At low flow rates, the top time is a function of the thermal diffusivity of the fluid and at higher flow rates, the heater–sensor distance ratio and average flow velocity. Thermal diffusion limits the minimum measurable velocity as it can smear the measured time-of-flight curve. If a second sensor is added on the upstream side of the heater element, reversed flows can also be measured. The theoretical analysis of time-of-flight micro-flow sensors can be found in [8].

3. Design

The flow sensing device consists of a linear array of seven Pt sensing elements suspended in a polymer membrane on one side of a bulk-micromachined channel (Fig. 1). The channel measures $1 \text{ mm} \times 0.5 \text{ mm} \times 8 \text{ mm} (w \times h \times l)$ and the sensors are arranged on 500 µm center-to-center spacing. Individual sensors possess a serpentine structure with 25 µm wide wires that wind back and forth within a 200 µm wide imaginary track. Four additional resistive elements are included, one in each corner of the device, for performing temperature compensation for hot-film mode measurements.

A sensing array layout permits operation in multiple modes, determination of flow direction, and enables thermal profiling of the fluid. Parylene C (Specialty Coating Systems, Indianapolis, IN) was selected as the membrane material. It is transparent to facilitate viewing of the microchannel contents, possesses excellent barrier properties and biocompatibility, and is compatible with microfabrication [17,18]. Platinum is well known as a stable thermal sensor material and is compatible with Parylene technology [19]. It possesses several properties favorable for its use in temperature sensing applications including excellent corrosion and oxidation resistance, a wide temperature range, a linear resistance versus temperature relationship, and high TCR (39.2 $\times 10^{-4}$ K⁻¹ for bulk Pt) [20–24].

The use of Parylene C dictates that the process temperature should not rise above 120 °C to prevent its thermally enhanced oxidative degradation. The Pt deposition process was carefully selected so as not to exceed the thermal budget. Although sputtered Pt has been noted to possess a lower TCR than the bulk material [23], it was chosen over electron-beam evaporation for its lower process temperature. Fortunately, it has been reported that Pt adheres quite well to Parylene C [19] eliminating the need for nitrogen annealing to improve adhesion. A thin Ti/W

adhesion layer was used to further reinforce metal-to-polymer adhesion.

4. Fabrication

The fabrication process flow was modified from the original [25] and is summarized in Fig. 2. A key feature of the process is that all steps are performed at low temperatures (<120 °C) so as to be compatible with Parylene technology.

Wafers were thermally oxidized (1.8 μ m thick) (Thermco 4104, Thermco Systems Inc., Orange, CA) and then coated with 2 μ m of Parylene C (PDS 2010 Labcoter, Specialty Coating Sys-



Fig. 2. Fabrication process flow for the thermal flow sensing arrays.

tems, Indianapolis, IN). AZ 4400 photoresist (AZ Electronic Materials, Branchburg, NJ) was applied (spun at 2 krpm, 6 μ m thick) and contact openings were etched in an oxygen plasma (400 mT, 400 W) (PEIIA, Technics Plasma, Kirchheim, Germany). The sensors were then patterned by using a dual-layer photoresist process to create an undercut to facilitate metal lift-off. First AZ 1518 (AZ Electronic Materials, Branchburg, NJ) was applied (4 krpm) and globally exposed. Then AZ 4400 was applied (4 krpm), exposed, and developed resulting in an undercut in the AZ 1518 layer and thus an appropriate sidewall profile for lift-off (total photoresist thickness of 4 μ m). Following a short photoresist descum, a 200 Å of Ti/W adhesion layer was sputter deposited followed by a 1000 Å thick Pt film (LGA Thin Films, Foster City, CA). The resistive sensing elements were defined by lift-off.

Prior to depositing the second layer of Parylene C (4 μ m thick), a brief oxygen plasma clean (200 mT, 200 W) was performed. The subsequent Parylene C coating was applied as a protective layer over the sensors. The contact pads were revealed by patterning (AZ 4400 at 1.5 krpm) and then etching in oxygen plasma (200 mT, 400 W). Electroless Au (autocatalytic Microgold Additive Deposition System, Stapleton Technologies Inc., Long Beach, CA) was plated on the Pt contact pads to facilitate wire bonding; the electroless plating process is summarized in Table 1. A protective layer of photoresist was applied to the front side of the wafer (AZ 4400 at 2 krpm) to conclude front side processing.

On the back side of the wafer, the flow channel was patterned (AZ 4400 at 2 krpm) followed by a descum in oxygen plasma (200 mT, 200 W). The oxide layer was then etched by buffered hydrofluoric acid to expose the underlying silicon. The channel was formed by etching the silicon substrate through to the oxide etch stop on the front side of the wafer by deep reactive ion etching (PlasmaTherm SLR-770B, Unaxis Corporation, St. Petersburg, FL). Then the oxide etch stop was removed by buffered hydrofluoric acid vapor etching and individual dies were obtained after dicing (K&S, Kulicke & Soffa Industries, Fort Washington, PA).

Table 1	
Flootrologo	Au plating

E.	ect	ro	less	Au	pla	itin	g	pro	oces	S

Process step	Description
1. Residue removal	Immerse in citric acid (20 g/L) at 40 °C for 10 min. Adding a few milliliters of MICRO 204 wetter to facilitate residue removal
2. Oxide removal	Immerse in a solution of 20% HCl at 40 $^\circ \text{C}$ for about 30 s
3. Ni plating	Plate an Ni adhesion layer to about 5000 Å or for a few minutes at 83 °C (1:1 ratio of deionized water to MICRO 282SX)
4. Immersion Au	Plate a monolayer of Au onto the Ni undercoat for 200 s at 88 °C (8.8:1.2 ratio of deionized water to MICRO 290B)
5. Autocatalytic Au	Plate Au to the desired thickness at 70 °C (4:5:1 ratio of deionized water to MICRO 294A to MICRO 294B. The optimal concentration of Au in the solution is 4 g/L. Stir solution for maximum uniformity



Fig. 3. Photographs of completely packaged thermal flow sensing arrays.

4.1. Packaging

Packaging the sensor entails providing both electrical and fluidic connections. Following the fabrication of the sensor chip, a glass backing plate was glued to the back side of each die to complete the microchannel. The glass plate contained inlet and outlet holes drilled using diamond mandrels (Wale Apparatus Co. Inc., Hellertown, PA). This chip was mounted to a customized printed circuit board (PCB) (Cartel Electronics Inc., Placentia, CA) in which a slot was milled to allow fluidic access connections to the inlet and outlet. In this manner, the electrical and fluidic connections are separated on opposite sides of the PCB. The chip was wirebonded and wires were soldered to the PCB. Custom bulk-micromachined silicon fluidic couplers [26] facilitated connection between the drilled glass ports and commercially available PEEK tubing (Upchurch Scientific Inc., Oak Harbor, WA). The connections were secured with epoxy. A fully packaged sensor is shown in Fig. 3.

5. Experimental methods

5.1. Sensor calibration

Each thermal sensor was calibrated to determine its TCR; sensor resistance values were recorded with data acquisition hardware (HP 34970A Data Acquisition Switch Unit, Agilent, Santa Clara, CA or LabVIEW 7.1 with PCI-6024E Multifunction Data Acquisition Card, National Instruments Corporation, Austin, TX) while being subjected to known temperatures in an oven (Environmental Test Chamber 9010, Delta Design, Inc., Poway, CA or ECOA Environmental Chamber, Sun Electronic Systems Inc., Titusville, FL) calibrated with a platinum resistance temperature detector (RTD) (RTD-2-F3105-36-T, Omega, Stamford, CT). The IV curve and the relationship between the applied current (2400 SourceMeter, Keithley Instruments Inc., Cleveland, OH) to the resistance for individual sensors were obtained. The resistance overheat ratio $(a_{\rm R})$, or ratio of the change in resistance to the original resistance, was calculated from Eq. (1) and can be expressed

as

$$a_{\rm R} = \frac{R(T) - R(T_0)}{R(T_0)} = \alpha(T - T_0) \quad \text{or} \quad \frac{\Delta R}{R} = \alpha \Delta T \qquad (2)$$

This relation was used to determine the relationship between the temperature rise of the resistive sensor, or overheat temperature, due to applied current. Note that there is also a temperature overheat ratio (α_T) which is related to a_R as follows:

$$a_{\rm T} = \frac{T - T_0}{T_0} = \frac{a_{\rm R}}{\alpha T_0} \tag{3}$$

A maximum overheat temperature of 25 °C was used to accommodate the lower temperatures required for biological applications and yield reasonable frequency response and sensitivity.

5.2. Flow sensing methods

Flow sensing was performed using three distinct measurement techniques. The flow sensors and additional electronic components were housed in thermally isolating enclosures that minimized interference from ambient temperature fluctuations. When applicable, the sensor output was corrected to remove artifacts due to ambient temperature fluctuations. Precision syringes (Gastight Syringes, Hamilton Company, Reno, NV) driven by a syringe pump (KDS100, KD Scientific, Holliston, MA or PHD 2000, Harvard Apparatus Inc., Holliston, MA) provided precise flows of filtered deionized water to the sensors. The experimental testing apparatus for each sensing mode is depicted in Fig. 4.

5.3. Hot film

The hot-film method tracks the convective heat loss from a heated resistive sensor exposed to fluid flow. Two biasing schemes can be used: (1) constant heater current (or power) and (2) constant heater temperature; both methods were investigated. Sensors placed in a half bridge configuration to provide temperature compensation.



Fig. 4. Schematic of the experimental setup use for all operational modes. The interface circuitry is shown for hot-film mode constant current biasing, calorimetric mode, and time-of-flight mode.

5.3.1. Constant current

Sensor output versus flow rate was obtained at four different overheat ratios using a single sensing element and using multiple sensing elements (two or three) connected in series. The 2400 SourceMeter (Keithley Instruments Inc., Cleveland, OH) provided CC biasing and also recorded the voltage change in response to flow. Data at each flow rate was acquired (n = 60) and then averaged. No additional interface circuitry was required for this mode of operation. A platinum RTD monitored changes in ambient temperature and this information was used to manually compensate for the effects of temperature fluctuations during testing. Alternatively, it is also possible to perform temperature compensation by using bridge interface circuitry with the integrated temperature compensation elements at the periphery of the sensor chip [11].

5.3.2. Constant temperature

A feedback circuit was connected to the sensor bridge to maintain constant temperature in the sensing element (Fig. 5a). The Wheatstone bridge detects the imbalance in output voltage due to convective cooling of the sensing element. The output voltage is amplified and then fed back into the bridge to suppress resistance and temperature changes of the sensing element. The circuit output versus flow rate data for three different overheat ratios were automatically obtained by a LabVIEW program and recorded using the 2400 SourceMeter (Keithley Instruments Inc., Cleveland, OH). Data at each flow rate was acquired (n = 60) and then averaged. Prior to acquiring the data, R₄ was adjusted such that the voltage and thus the desired overheat ratio. Then, R₆ was adjusted to zero the circuit output.



Fig. 5. (a) Schematic of the constant temperature driving circuit, including the electronic test generator (V_t and R_t are used only for transient operation and obtaining the frequency response). (b) Schematic of the circuit used to for the sine wave test to obtain the frequency response in CC mode. R_s is the sensing element and R_1 is a 500 Ω precision resistor.

5.3.3. Frequency response

The frequency responses for constant current and constant temperature sensing methods were obtained. Ideally, an actual calibration in which velocity variations are applied over the frequency range of interest would be performed. However, as it is difficult to generate well-defined velocity variations, an electrical method was used whereby a variation in current is applied to the sensor or bridge circuit with a varying voltage [27]. The input signal frequency was varied and the corresponding amplitude of the output was recorded. For constant current mode, a sinusoidal current signal (4 mA peak-to-peak) was applied to the sensor using the circuit shown in Fig. 5b (PCI-5401 Function Generator, National Instruments Corporation, Austin, TX) and the output due to this disturbance signal was recorded with an oscilloscope (TDS 2024B Digital Storage Oscilloscope, Tektronix Inc., Beaverton, OR) [9]. For constant temperature mode, a sinusoidal input voltage (1 V peak-to-peak) was applied to the bridge (denoted by V_t in Fig. 5a) through a resistor and the output was recorded with an oscilloscope following the methods described in [28,29]. In both cases, the sensor current was initially set to 4 mA and a syringe pump supplied a constant flow rate of 200 µL/min. For CT mode, the frequency response was also acquired at flow rate of 10 µL/min. All data was obtained as mean \pm S.E. with n = 4.

5.4. Calorimetric

Calorimetric flow sensing involves using at least two sensing elements to monitor the displacement of the temperature profile around a heating element in the presence of flow. One flow sensing element in the array was converted into a heater for this experiment. The responses of sensors on either side of the heater (one upstream and one downstream) were monitored by using a bridge for deflection measurements (HP 34970A Data Acquisition Switch Unit, Agilent, Santa Clara, CA). Data at each flow rate was acquired (n = 100) and then averaged. Both symmetrical and asymmetrical sensor arrangements can be used; an asymmetric arrangement of sensors around the heater was used here (upstream sensor 0.5 mm from heater and downstream sensor 1.0 mm from heater). The heater was biased at 5 mA (HP 3245A Universal Source, Agilent, Santa Clara, CA) yielding a local temperature rise of 15 °C.

5.5. Time-of-flight

Time-of-flight is a thermal tracing technique in which sensing is accomplished by injecting a heat pulse from an upstream heater that is detected as it passes a downstream sensor. Again, a sensing element was used as a heater in this operation mode. A single heat pulse (3 V in amplitude and having a duration of 1 s) (HP 33120A Function/Arbitrary Wave Generator, Agilent, Santa Clara, CA) corresponding to a local temperature rise of approximately 24 °C was used to detect a range of flow rates. The output of the sensor was monitored directly without the use of a bridge (HP 34970A Data Acquisition Switch Unit, Agilent, Santa Clara, CA). Four individual trials were performed at each flow rate and then averaged. The sensor-to-heater



Fig. 6. Representative temperature calibration curve for a flow sensing element. The slope of the curve corresponds to the empirically obtained TCR (α).

distance in these experiments was 1 mm measured center-tocenter.

6. Results and discussion

A typical sensor calibration curve is displayed in Fig. 6 (TCR curve) with a corresponding TCR of $1.0 \times 10^{-3} \,^{\circ}\text{C}^{-1}$ (or $0.1\% \,^{\circ}\text{C}^{-1}$). As expected, the TCR value of the thin film Pt was lower than that of the bulk material [23]. It has been well documented in the fabrication of Pt-wire RTDs, that the highest TCR values are obtained only when using the purest, unstrained Pt. A typical IV curve and overheat temperature (OHT) relationships are given in Figs. 7 and 8.

The flow rates detected in the various measurement modes ranged from 0.5 to 400 µL/min. For this flow rate range, the maximum Reynolds number, calculated from Re = UD/v, was 8.9 where U is the velocity, D is the hydraulic diameter, and v is the kinematic viscosity (1.004 × 10⁻⁶ m²/s for water at 20 °C). There is a 90° bend in the flow path located at the point where the external tubing meets the microchannel inlet and thus, secondary



Fig. 7. Representative IV characteristic for a flow sensing element.



Fig. 8. The resistance (\Box) and overheat temperature (\bigcirc) dependence on the applied sensor bias current.

flow, specifically Dean vortices, in which fluids experience centrifugal forces due to the flow trajectory should be considered [30]. The dimensionless Dean number ($K = Re(D/R)^{0.5}$, where D is the hydraulic diameter and R is the radius of curvature of the flow path) describes the relative importance of inertial and centrifugal forces to viscous forces. The Dean number (R = 0.5 mm) associated with this device geometry is 10.3, suggesting that the centrifugal effects are insufficient to perturb laminar flow and that secondary flow can be neglected; the critical Dean number associated with onset of secondary flow for rectangular channels is in the range of 140–200 [31–33].

Hot film results for both CC and CT mode exhibit the typical non-linear square root characteristic (Figs. 9 and 10). In CC mode, the responses of two and three sensors connected in series were also obtained (Figs. 11 and 12). Sensors in the array can be combined to obtain larger output signals which are especially useful for measuring smaller flow rates.

The frequency response curves obtained by using the sine wave test for CC and CT modes are given in Figs. 13 and 14. The cutoff frequency at the -3 dB point was measured to be 890 Hz for CC mode following which the output dropped by 15 dB/decade. For CT mode, the -3 dB points were 3200 Hz



Fig. 10. Single sensor response for constant temperature biasing and hot-film mode operation at three different overheat ratios and over the flow rate range of $0-400 \ \mu L/min$ (mean \pm S.E. with n = 60).

at 10 µL/min and 4000 Hz at 200 µL/min. Beyond the cutoff frequency, the output dropped by 20 and 25 dB/decade, respectively. The insets in Fig. 14 show the sensor time constant measured using the square wave disturbance technique described in [27]. The relationship between the time constant, τ , and the cutoff frequency, f_c , is $f_c = 1/1.3\tau$. Cutoff frequencies obtained using both methods show close agreement. As expected, CT operation increased the frequency response and the cutoff frequency increased slightly with flow rate in this mode. It is possible to further increase the frequency response by optimizing the characteristics of the bridge, amplifier, sensor, and its environment [29]. Specifically, reducing the sensor's thermal capacity and increasing the overheat ratio will increase the cutoff frequency. However, the overheat ratio is necessarily kept low to accommodate biological materials which may degrade if exposed to higher sensor operation temperatures.



Fig. 9. Single sensor response for constant current biasing and hot-film mode operation at four different overheat ratios and over the flow rate range of $0-400 \,\mu$ L/min (mean ± S.E. with *n* = 60).



Fig. 11. Response of two sensors connected in series for constant current biasing and hot-film mode operation at four different overheat ratios and over the flow rate range of 0–400 μ L/min (mean ± S.E. with *n* = 60). The predicted response, or sum of the individual sensor responses, is also plotted for comparison.



Fig. 12. Response of three sensors connected in series for constant current biasing and hot-film mode operation at four different overheat ratios and over the flow rate range of 0–400 μ L/min (mean ± S.E. with *n* = 60). The predicted response, or sum of the individual sensor responses, is also plotted for comparison.

It is important to note that the frequency response of the sensor is governed by the thermal responses of the supporting insulating membrane, silicon substrate, and Pt sensing element; these factors contribute to the CC response obtained in Fig. 13. The presence of the Parylene C insulation increases the time constant, decreases the frequency response, and results in a second order response [34,35]. In addition, due to the non-trivial thermal conductivity of the underlying Parylene C membrane and the silicon substrate supporting it, side losses due to thermal conduction through the sensor leads to the surrounding cool zones can be significant. It has been shown that the second order output response in the CT case is attributed to case where the sensor possesses only one time constant and the operational amplifier has a single pole [10].



Fig. 13. Frequency response for constant current biasing with a sinusoidal input (mean \pm S.E. with *n*=4). The cutoff frequency is 890 Hz and after which the output drops off at 15 dB/decade.

Flow data for calorimetric operation is shown in Fig. 15. Constant heating power is responsible for the characteristic curve in which the signal linearly increases up to a maximum temperature difference (above 50 μ L/min) and then decreases for higher flow rates. The latter portion of the curve is called the cooling part and can also be used for measuring flow, thereby extending the effective flow rate measurement range. However, the cooling portion is associated with reduced sensitivity in comparison to the linear portion [36,37].

The detected heat pulses for each flow rate monitored in timeof-flight mode are plotted together in Fig. 16. Differences in heat dissipation over the flow rate range are apparent. The top time for each flow rate was obtained from the raw data then plotted in Fig. 17 showing the expected inverse relationship. The sensed maximum temperature was calculated and is also displayed in the graph.



Fig. 14. Frequency responses for constant temperature biasing with a sinusoidal disturbance input at a flow rate of (a) 10 μ L/min and (b) 200 μ L/min (in both cases, mean \pm S.E. with *n* = 4). The cutoff frequencies are 3200 and 4000 Hz, respectively. The inset in each figure shows the time constant measured with a square wave disturbance.



Fig. 15. Flow sensing performance for calorimetric mode testing for flow rates between 0 and 300 μ L/min. The inset displays in detail the performance a low flow rates (0–20 μ L/min). The heater is initially set to impose a local temperature increase of 15 °C (5 mA). Data is presented as mean ± S.E. with *n* = 100.







Fig. 17. The time-of-flight response displayed as the measured top time (t, \blacksquare) and corresponding temperature increase at the thermal sensor $(\Delta T, \bullet)$ for flow rates between 0 and 30 µL/min (mean ± S.E. with n = 4).



Fig. 18. Flow velocity vs. time-of-flight calibration laws for the pulsed thin film sensor.

In the absence of the viscous wake and thermal diffusion, the time-of-flight is simply x/U. However, these effects and the finite thermal response time of the sensor results in the following general form of the relationship between the measured time-of-flight and velocity:

$$U = \frac{x}{t} + f(t) \tag{4}$$

where *U* is the velocity, *x* is the distance between the heater and sensor, *t* is the time-of-flight, and f(t) is some function. It has been demonstrated that integer power laws were adequate for calibrating the relationship; the following calibration laws are typically used [16,38]:

$$U = \begin{cases} \frac{A}{t} + \frac{B}{t^2} \\ \frac{A}{t} + \frac{B}{t^3} \end{cases}$$
(5)

The fitted top time versus flow rate results are shown in Fig. 18. For $f(T) = Bt^{-2}$, *A* and *B* were found to be -7.38×10^{-3} and 1.14×10^{-2} , respectively. For $f(T) = Bt^{-3}$, *A* and *B* were found to be -3.36×10^{-3} and 8.03×10^{-2} , respectively. For our sensor, the $f(T) = Bt^{-2}$ calibration law provided a slightly better fit.

The sensitivity of each method can be compared where sensitivity is defined as the derivative of sensor signal with respect to flow rate or flow velocity. For non-linear flow responses, the sensitivity at zero flow (S_0) is used

$$S_0 = \left. \frac{\mathrm{d}V}{\mathrm{d}Q} \right|_{Q \to 0} \tag{6}$$

where V is the sensor voltage output and Q is the volumetric flow rate. Table 2 compares the performance of the various sensing modes investigated.

All modes exhibited reasonable resolution over a wide range of flow rates relevant to microfluidic applications. Calorimetric sensing, in particular, has good resolution in the low flow range (<10 μ L/min). Hot-film sensing in CC mode tends to lack res-

olution at lower flow rates, however, this can be overcome by increasing the overheat ratio or concatenating multiple sensors in series to increase the output signal at the cost of losing spatial resolution. Increasing the overheat ratio, however, may degrade biological materials present in the flow and also increase the thermal noise present in the sensing element(s). For a 400 Ω sensing element at a temperature of 310 K and a bandwidth of 500 Hz, the thermal noise, or Johnson noise, is $0.06 \,\mu$ V. Thus, under the current operating conditions, the noise can be neglected compared to the signal level. Another alternative is to operate the hot film under CT biasing which leads to increases in both the frequency response and the output signal. Time-of-flight sensing requires a large applied heat pulse to provide an adequate signalto-noise ratio and is useful over large ranges. At lower flow rates, the signal can be masked by thermal diffusion effects.

7. Conclusion

A thermal flow sensing array having biocompatible construction and multiple operational modes has been designed and developed. The sensors were fabricated using a low temperature process so as to be compatible with Parylene C. Pt flow sensing elements are suspended in a freestanding Parylene C membrane and integrated into the wall of a bulk-micromachined channel. This layout affords an efficient packaging scheme for making both electrical and fluidic connections.

The array format allows flexibility in sensing both flow and direction. Here, two heater control methods (CC and CT) were used with three different types of flow sensing (hot film, calorimetric, and time-of-flight) to yield a total four operational modes examined in a single device. The sensor array was systematically characterized and flow rates down to 0.5 µL/min have been detected with operation at low overheat ratios and minimal heating of the sensed medium.

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Hot film—si	-single (I	cc)	Hot filn	n—doubl	e (CC)	Hot filr	n—triple	(CC)	Hot film (CT)			Calorimetric	TOF
Power (mW) 3.3 6.	6.4	10.0	6.9	12.3	19.2	10.5	18.6	29.1	N/A	N/A	N/A	9.2	23.5
Overheat temperature (°C) 3.2 5.8	5.8	9.1	4.3	7.5	11.5	5.1	8.5	13	3.2	5.8	9.1	15	24
Overheat ratio (%) $0.32 0.32$	0.58	0.91	0.43	0.75	1.15	0.51	0.85	1.30	0.32	0.58	0.91	1.5	2.4
Sensitivity (µV/(µL min)) 29.75 62	62.3	89.4	25.1	62.4	110.4	39.6	74.3	155.6	3.14×10^{3}	1.41×10^{4}	3.92×10^4	71.26	N/A

Table 2

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