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A MEMS multi-sensor chip for gas flow sensing

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Abstract

This paper reports the development of a MEMS multi-sensor chip that enables the simultaneous measurements of shear stress, pressure, and temperature inside microchannels. On the multi-sensor chip, five sensor clusters, which consist of shear-stress, pressure, and temperature sensors, are arranged in a one-dimensional array. The multi-sensor chip has been characterized in a rectangular microchannel using both incompressible and compressible gas flows. A simple normalization method has proven to be effective in the reduction of the sensitivity variation of the shear-stress sensors. It has also been found out that the classical theory for conventional hot-film sensors needs to be modified for the MEMS thermal shear-stress sensors. Furthermore, flow rate measurements based on both differential pressure and thermal anemometry principles have been demonstrated using the multi-sensor chip.

Keywords: Flow sensor; Shear-stress sensor; Pressure sensor; Temperature sensor; Microchannel flow

1. Introduction

The measurement of wall shear-stress, pressure, and temperature distributions is of great interest for many fluidic applications. However, this is a very challenging task for the measurement of flows inside a microchannel. MEMS technology enables the fabrication of arrays of miniaturized shear-stress, pressure, and temperature sensors [1–3] and thus enables flow measurement inside microchannels. The first ever experimental data of the pressure distribution of gaseous flows in microchannels using MEMS technology were reported by Liu et al. [4]. Several groups have studied the temperature change/distribution inside microchannels [5,6]. For channels with uniform cross-sectional areas, the wall shear stress can be derived from the pressure gradient. But for channels with non-uniform cross-sectional areas, e.g., nozzles, it is highly desirable to measure both shear stress and pressure directly. This paper reports the first MEMS multi-sensor chip that enables the simultaneous measurement of shear-stress, pressure, and temperature distributions of microchannel flows. Compatible sensor designs have been implemented that simplifies the fabrication of the multi-sensor chip. The fabricated multi-sensor chip has been successfully tested with both incompressible and compressible channel flows. In addition, flow rate measurements have been demonstrated.

2. Sensor designs

Intuitively, the wall shear stress can be determined directly by measuring the force exerted on a small surface area. The micromachined versions of direct measurement have been realized by using floating elements [7–10]. The wall shear stress can be determined from the displacement of the floating element or the force it experiences. Alternatively, shear stress can be measured indirectly using the Stanton tube, Preston tube, sublayer fence, or techniques that are based on electrochemical or thermal principles [11]. Among these

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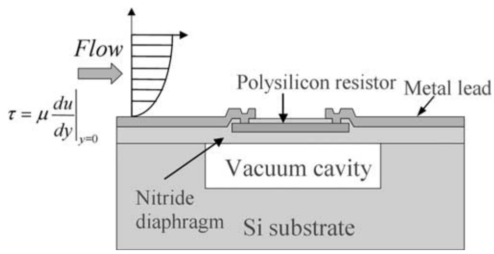

Fig. 1. The cross-section of the micromachined thermal shear-stress sensor.

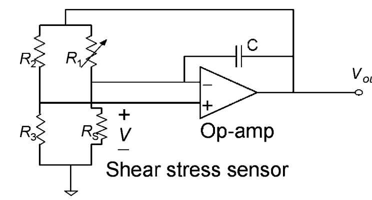

Fig. 2. Simplified constant temperature (CT) bias circuit. R_S is the shear-stress sensor; R_1, R_2 and R_3 are off-chip resistors.

approaches, the thermal method is most frequently used despite its non-linear output. This is mainly because the thermal method has the advantages that it can be used in a wide variety of flows, it does not interfere with the flow, and it offers the possibility of measuring time-varying flows. Additionally, thermal methods are well suited to micromachining, allowing for MEMS shear-stress sensors without moving parts.

Conventional thermal shear-stress sensors are typically made by depositing thin metal film resistors, mostly platinum or nickel, on flat substrates. With the MEMS technology, novel thermal shear-stress sensors have been successfully developed [12–14]. As shown in Fig. 1, the sensor consists of a polysilicon resistor embedded in a nitride diaphragm with a vacuum cavity underneath. Heat loss to substrate is significantly reduced and the heated area is confined to a small area, leading to a much better spatial resolution. The input power of the resistor is a function of the wall shear stress of the ambient fluid, which is defined by:

$$\tau = \mu \frac{\mathrm{d}U}{\mathrm{d}y}\bigg|_{y=0} \quad (1)$$

where μ is the fluid viscosity, U the streamwise velocity and y-axis is normal to and originates at the sensor surface. The relationship between τ and the input power P to the sensor is typically described by [15]:

$$P = \frac{V^2}{R_S} = \Delta T(A(\rho\tau)^{1/3} + B) \quad (2)$$

where V and R_S are the voltage and electrical resistance of the shear-stress sensor, respectively, ΔT the average temperature difference between the heated resistor and ambient, $A \propto C_p^{1/3} k_T^{2/3}/\mu^{1/3}$ (C_p and k_T are the heat capacity and thermal conductivity of the fluid, respectively), ρ the density of the fluid and the term B represents the heat loss to the substrate and is a function of the dimension and thermal conductivity of the diaphragm. The physical interpretation of Eq. (2) is that the Joule heating generated dissipates in two ways: the convection loss to ambient fluid and the conduction loss to the substrate. Radiation loss is negligible at the typical operating temperature. Note that Eq. (2) is derived for conventional hot-film sensors. As will be shown later, the exponent of τ is not 1/3 for our micromachined shear-stress sensors. Thus, we will use the empirical formula

$$P = \frac{V^2}{R_S} = \Delta T(A_t(\rho\tau)^{1/n} + B_t) \quad (3)$$

where A_t, B_t, and n are determined experimentally.

The shear-stress sensor can operate in either constant temperature (CT) mode or constant current (CC) mode. CT mode is chosen in this work because of its high sensitivity. Fig. 2 shows the simplified CT biasing circuits, where R_S is the shear-stress sensor, R_1, R_2, and R_3 are off-chip resistors that have nearly zero temperature coefficient of resistance (TCR). Here, the resistance of R_2 is chosen to be equal to the resistance of R_3. R_S, R_1, R_2, and R_3, together with the operational amplifier, form a negative feedback loop, which requires that R_S must be equal to R_1 when steady state is reached. An important parameter for the operation of shear-stress sensor is the (resistive) over-heat ratio, which is defined as

$$a_R = \frac{R_S - R_{S0}}{R_{S0}} \quad (4)$$

where R_S is the resistance of the shear-stress sensor at the operating temperature and R_{S0} is the resistance at a reference temperature. For example, if an over-heat ratio of 10% is desired, we then set $R_1 = (1 + 10\%)R_{S0}$. The Joule heating will increase the temperature of shear-stress sensor and thus its resistance (positive TCR). Finally the Wheatstone bridge is balanced and $R_S = R_1 = (1 + 10\%)R_{S0}$. By measuring V_{out} or V ($V_{out} = 2V$), we know how much power is dissipated through fluid and hence the shear stress.

The temperature sensor is a polysilicon thermistor, taking advantage of the temperature dependence of polysilicon's electrical resistivity [16]. The resistance R at temperature T is given by:

$$R = R_0[1 + \alpha_T(T - T_0)] \quad (5)$$

where R_0 is the resistance at a reference temperature T_0 and α_T is the temperature coefficient of resistance of polysilicon.

The pressure sensor is also constructed by embedding polysilicon resistors in a vacuum-sealed nitride diaphragm. In this case, the polysilicon thin films are employed as piezoresistors and are placed at the edge and central areas of the diaphragm where the maximum stress occurs [17]. The pressure is detected by measuring the resistance change of the piezoresistors in the form of a Wheatstone bridge. The resis-