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Flexible flow sensor for large-scale air-conditioning network systems

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ABSTRACT

A patch-type flexible flow sensor was developed to precisely control the supply air in large-scale air-conditioning network systems in buildings. The proposed sensor enables us to reduce fruitless energy consumption in these systems. The flow sensor was produced by applying photolithography onto a 25-μm-thick polyimide film. The four sensors were attached at 90° angles inside the surface of an 8-in. duct, and the obtained outputs were averaged. The relationship between the sensor output and the flow rate followed the King equation under the 0–3000 $m^3 h^{-1}$ flow condition. The averaged sensor outputs depended on the distance of the sensor position from the bent duct, and their values were slightly higher than that obtained in a straight duct. Therefore, the conversion factor, which enables us to calculate the flow rate values from the obtained sensor outputs in a bent duct, was derived for this paper.

1. Introduction

Physical sensors, such as pressure, acceleration, and gyro sensors, have been miniaturized and integrated onto Si wafers by Micro Electro Mechanical Systems (MEMS) technologies since the 1970s [1–4]. They are now widely commercialized into the automotive and amusement industries. The flow sensor fabricated onto Si wafers also has a long history in MEMS miniaturization, and various types of MEMS flow sensors have been developed. C. Liu et al. developed a thermal type of flow sensor to detect shear stress [5]. Zhe et al. used a micro-machined cantilever structure for measuring the shear stress from the flow [6]. Generally, Si-MEMS flow sensors have excellent space and time resolutions, and therefore, they are used in semiconductor equipment and the fuel delivery systems in the automotive industry for precisely controlling the gas flow. Additionally, Unnikrishnan et al. proposed the MEMS-on-tube assembly to simplify the packaging process in Si-MEMS [7,8]. They integrated Si-MEMS devices directly onto a glass tube, which is compatible with a Swagelok® connector, by using a fusion bonding. These and other Si-based flow sensors are summarized in Refs. [9,10]. Si-MEMS flow sensors are normally assembled onto a rigid flat board in the packaging process, because of the brittleness of Si material. This means that difficulties arise when Si-MEMS flow sensors are applied to curved surfaces.

MEMS flow sensors need to be more flexible in order to be used in aero-space and medical equipment, and thus, resin material was used as a substrate. For example, Buder et al. fabricated double hot-wires suspended on a polyimide film. They mounted them onto a flat surface, and concluded it was able to detect the flow separation for a specific aerodynamic configuration [11]. Zhu et al. fabricated a flow sensor directly onto a flexible printed circuit board with electrical circuits, and mounted it onto the curved surface of a wing to control an aircraft [12]. For medical applications, Li et al. used Kapton film as a substrate, and they integrated pressure, temperature, glucose, and oxygen sensors onto it, for blood analysis [13]. Naito et al. fabricated a flow sensor on a 7.5-μm-thick flexible polyimide film, and they produced a miniaturized on-wall in-tube flow sensor [14]. They used it to fabricate a catheter-type flow sensor for the measurement of aspirated- and inspired-air characteristics in human beings [15,16]. Ma et al. produced a flexible flow sensor by using polyimide film for detecting the dynamic wave flow in water channels [17]. To improve the sensitivity of a flow sensor, Buchner et al. proposed a novel fabrication process, which enables us to produce flexible MEMS flow sensors using semiconductor materials [18,19]. As stated above, the MEMS flow came into use for medical, aircraft, and water channel applications, and the novel fabrication process for flexible MEMS flow sensors was also proposed.

The aim of this work is to extend the MEMS flow sensor applications into new application fields, and thus, we are currently introducing a flexible MEMS flow sensor into large-scale air-conditioning network systems. The advantage of a flexible MEMS flow sensor is that it can reduce the fruitless amount of energy consumption by precisely controlling the supplied air in the system.

2. Flow control in air-conditioning system in building

Generally, air-conditioned air is produced in a conditioning system located outside the building, and delivered to each room via

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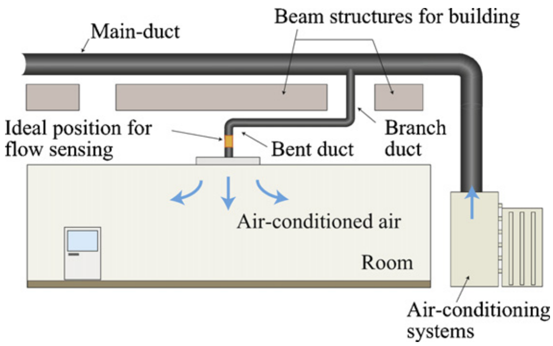

Fig. 1. Configuration of duct network and position for flow sensing in large-scale air-conditioning systems.

duct network systems. The duct configuration for supplying air to the necessary rooms is complicated and the system is composed of a several bent ducts (Fig. 1). This is because the beam structures are formed first in the building construction, and then the duct network is mounted by using the limited amount of empty space in the ceiling. The air supply to each room has to be controlled at the ideal sensing point near the outlet port in order to reduce the fruitless energy consumption of the air-conditioning system. This means that the flow rate must be precisely measured downstream of a bent duct.

We took into consideration the following points in the development of a flow sensor for measuring the flow rate downstream of a bent duct.

(1) We developed a patch-type flexible flow sensor to fit onto the rounded inside surface of a duct. As shown in Fig. 2, it consists of heaters on a thin polyimide film that can detect the flow velocity and a flexible printed circuit. The film is supported by silicone rubber with a hole in it to form a cavity under the heater element to improve the responsibility.
(2) We decreased the thickness of the sensor structure to less than 525 μm to reduce the air flow resistance caused by the sensor itself, and also put it on the inside surface of the duct. This is because the flow velocity in the duct is minimized on the inside surface.
(3) The air flow downstream of a bent duct is generally complicated, because of the secondary flow caused in the bent duct [20]. As a result, it is difficult to detect the flow rate by conducting only a single-point measurement. We attached four sensors on the inside surface of the ducts to overcome this problem, and averaged the flow rate at these four points to reduce the effect of the secondary flow (Fig. 2).

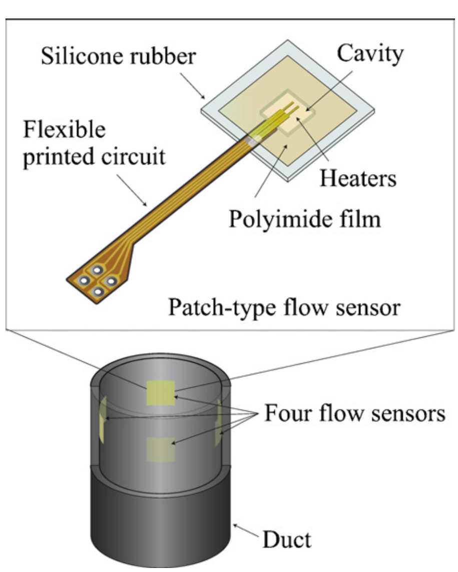

Fig. 2. Patch-type flow sensors and their in duct mounting position.

Three different types of detection mechanisms, thermal anemometry, calorimetric flow sensing, and time-of-flight sensing, are normally used in a miniaturized MEMS flow sensor [9,10]. Thermal anemometry detects the flow rate by determining the cooling effect on a heated element. It is used in this study, because it has a relatively large measurement range and the simplest of structures. The relationship between the electrical energy supplied to the heater in a constant temperature mode and the flow velocity U in a low Reynolds number flow can be expressed as [21]

$$\frac{V_h^2}{R_h} = (A + BU^n) \cdot (T_h - T_0), \tag{1}$$

where V_h and R_h are the voltage difference and electrical resistance of the heater, respectively. A, B, and n are the constants depending on the geometry of the heater element. If the heater were infinitely long, n would be 0.5. However, n differs by 0.5 when a heater with a finite length [9] is used. T_h and T_0 are the temperatures of the heater and the body of fluid, respectively. Here, the square of the voltage at the heater is proportional to the nth power of the flow velocity. The details are explained in Refs. [9,10,21].

3. Fabrication

We fabricated the film-based sensor structure with polyimide film (25-μm thick) by using photolithography and thin-film deposition. The details are as follows (Fig. 3):

(a) A polyimide (PI) Upilex film (produced by Ube Industries Ltd.) was used as the substrate. The film thickness affects the length of the response time. The heat capacity increases with the increase in film thickness, and as a result, the length of the response time increases with the increase in film thickness. To shorten the response time, we chose a film thickness of about 25 μm for the fabrication process.
(b) The film was at first fixed on a glass wafer with thin silicone rubber at a thickness of 0.5 mm to enable it to be handled in the process that followed (Fig. 3(a)). A negative-type photoresist (ZPN1150-90 produced by Zeon Corporation), which was specially developed for the lift-off process, was applied to the film surface (Fig. 3(b)), and patterned with UV light to define the shape of the thermal sensor (Fig. 3(c)). Then, sputtering was used to deposit an Au/Cr film (Fig. 3(d) and (e)), and was patterned by selectively removing the photoresist (lift-off process). The Au and Cr thicknesses were 250 nm for the former and 10 nm for the latter. Cr film deposited by sputtering generally induces tensile stress into thin PI film.
(c) The flexible film was manually peeled from the silicone rubber on the glass wafer in an acetone solution (Fig. 3(f)). The flexible film sensors fabricated on a 3-in. wafer are shown in the images on the right in Fig. 3. The film sensor was 10 mm × 10 mm. Two heaters were formed on one film sensor. One was for the flow measurement and the other was for a backup. The typical electrical resistance of a heater is 55.6 Ω. Each film sensor was manually cut with a knife.
(d) A flexible printed circuit was used as the electrical connection from the film sensor (Fig. 4). At first, the film sensor was placed on the printed circuit, and bonded using an adhesive. Then, the electrical connection was manually made by using a silver