Sensors and Actuators A 235 (2015) 1–13

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# Mems thermal film sensors for unsteady flow measurement

J.J. Miau[a,*], T.S. Leu[a], J.M. Yu[a], J.K. Tu[a], C.T. Wang[a], V. Lebiga[b], D. Mironov[b], A. Pak[b], V. Zinovyev[b], K.M. Chung[c]

[a] Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan, Taiwan
[b] Khristianovich Institute of Theoretical and Applied Mechanics, SB RAS, Novosibirsk, Russia
[c] Aerospace Science and Technology Research Center, National Cheng Kung University, Tainan, Taiwan

ARTICLE INFO

*Article history:*
Received 24 February 2015
Received in revised form
19 September 2015
Accepted 19 September 2015
Available online 25 September 2015

*Keywords:*
MEMS Sensors
Unsteady flow
Vortex shedding
Compressible cavity flow

ABSTRACT

Deposited on a flexible skin, self-made MEMS (Micro Electronically-Mechanical Systems) thermal film sensors were applied to a contoured wall surface for sensing unsteady flow behaviors. The sensors, each featuring a platinum sensing element 0.1 μm in thickness on a polyimide substrate 20 μm thick, were about 150–200 ohm at room temperature. The frequency response of the sensors could be up to 30 kHz when operating in constant temperature mode. In studying the unsteady flow behaviors, the flow information of interest was mainly the frequency contents of the real-time signals measured. In this paper, the three presented cases illustrate how the signals of the MEMS sensors could be used to explore the instantaneous behaviors of the unsteady flows.



## 1. Introduction

A pioneer work by Giedt [1] concerning thermal film sensors applied an electrically heated surface ribbon to a circular cylinder and measured the heat transfer rate as flow passed over the cylinder. The results obtained at different angular positions from the stagnation point were compared with the pressure and skin friction measurements, and the effect of free stream turbulence on the heat transfer rate was discussed. Since then, a thermal film sensor has been known for its application in shear stress measurement, for which a calibration based on the principle of heat transfer was required [2–4]. Because they have a high frequency response and are non-intrusive to the flow, the thermal film sensors were recommended as being advantageous over other conventional techniques such as Preston tube and hot-wire anemometry in shear stress measurement.

When the MEMS (Micro Mechanical and Electrical Systems) fabrication process was first introduced in 1980, the idea of making miniaturized thermal films for flow research caught people's attention immediately [5]. In the past decades, continuous efforts have been devoted to improving the fabrication process [6], understanding the heat-transfer characteristics of the sensors made [7,8] and finding applications for boundary-layer studies and aerodynamic flow control [9–13]. Nevertheless, the measurement of shear stress using thermal film sensors was considered an indirect method [14,15] since, in contrast to the direct method using a floating element or a fence, a calibration procedure is required. Breuer [15] commented that these two methods have their own merits and disadvantages. For instance, as far as the fabrication process is concerned, the former appears to be much more simplified than the latter.

This paper illustrates how to utilize the self-made MEMS thermal film sensors to gain a better understanding of unsteady flow behaviors near a wall surface. Unlike most of the MEMS thermal film sensors reported in the literature for wall shear stress measurement, the present interest is focused on exploiting the characteristics of the high frequency response of the self-made sensors. Therefore, the concerns associated with shear stress measurement, such as the calibration required prior to measurement and the drift issue due to heat conduction between the substrate and the film [7,8,13,16], are deemed unnecessary. The present thermal film sensors are characterized by a frequency response of up to 30 kHz when operating in constant temperature mode. Moreover, by using the advantage that the MEMS sensors can be densely patterned in a small area on a flexible skin, high spatial resolution measurement is possible. Therefore, as illustrated in this paper, the present sensors were utilized to resolve the unsteady flow behaviors in time and space. Moreover, with the assistance of the data

* Corresponding author. Fax: +886 6 2389940.
*E-mail address:* jjmiau@mail.ncku.edu.tw (J.J. Miau).

http://dx.doi.org/10.1016/j.sna.2015.09.030
0924-4247/

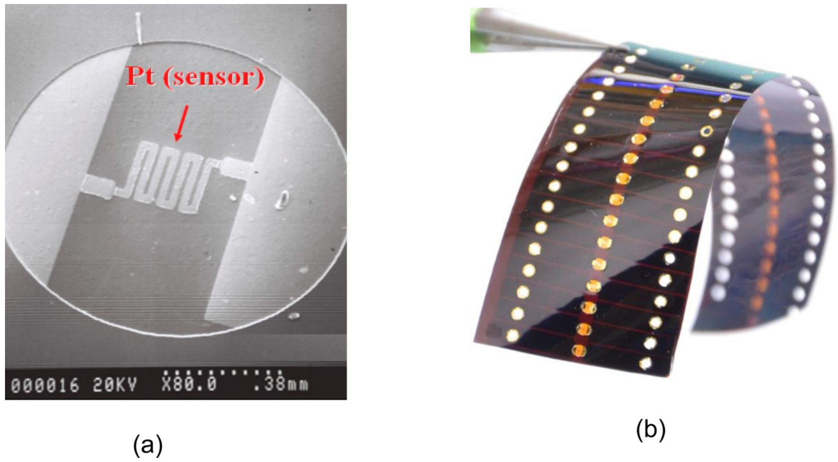


**Fig. 1.** (a) An SEM (Scanning Electronic Microscope) photo of a thermal film sensor. (b) A strip of the flexible skin with 35 sensors in array, with a distance of 2 mm between two neighboring sensors.

analysis techniques employed, the results obtained were able to shed light on the complicated flow phenomena of interest.

## 2. The self-made mems thermal film sensors

The fabrication process of the present MEMS thermal film sensors was first reported by Tu and Miau [17] and later repeated by Mr. Jui-Ming Yu: one of the co-authors of this study. The process is described below.

Basically, the MEMS thermal sensors were patterned on a flexible skin using the methods of photo mask and thin-film deposition. The fabrication process was started with a 4″ diameter silicon wafer that was deposited with a 0.6 μm aluminum layer by the physical vapor deposition (PVD) process. This layer served as the sacrificial layer for the purpose of lift-off after the completion of the fabrication process. Subsequently, a polyimide thin film was applied by a spinning method for a thickness of 10 μm and cured at 330 °C. This layer served as the substrate on which the package holes were defined before the curing process. Then, a positive-type photoresist mask was applied to define the pattern of the thermal sensors. Next, the PVD process was applied to deposit chromium andplatinum, which served as the sensing materials. The thickness of the chromium and platinum were 0.02 μm and 0.1 μm, respectively. Subsequently, another mask was applied to define the pattern of the electrical lead, after which chromium and gold were deposited by the PVD process. In this process, the thickness of the chromium and gold were 0.02 μm and 0.4 μm, respectively. This was followed by a spin coating process to cover a second polyimide layer on the film sensors. This layer served as the protecting layer above the sensing element and the electrical lead. Subsequently, one more mask was applied to define the pattern of the bonding pads, which were connected to film sensors. Finally, a flexible skin with the thermal film sensors was lifted from the silicon wafer by applying HCl solution to etch out the aluminum layer.

Fig. 1 presents an SEM (Scanning Electronic Microscope) photo of a thermal film sensor and a picture of the final product. The dimensions of the sensing element were 200 μm × 260 μm, which had a resistance of about 200 Ω after annealing, shown in Fig. 1a. A sample of the final product shown in Fig. 1b is a strip 16 mm wide and 70 mm long on which 35 sensors were patterned. The spacing between two adjacent sensors was 2 mm.

Additional remarks regarding the present sensors are given below. First, the sensors described above have a cold resistance about 200 Ω, which is slightly higher than that reported in Tu and Miau [17]: about 150 Ω. The discrepancy could be due to variations of the parameter settings between the two fabricating processes. Nevertheless, in either case the resistances of the sensors after annealing only varied within a small range: less than 10 Ω. Taking advantage of the sensors' narrow range of resistance, the amplifier circuits for these sensors made were identical. Second, the frequency response of the present sensors when operating in a constant current mode was at least 1 kHz. This was confirmed by a simple method: dropping a water particle on a film sensor in operation for an abrupt change of temperature and examining the signal output for the time response. A higher frequency response could be achieved if operating in constant temperature mode [19]. This will be described later in this paper. Third, the present fabrication process is much more simplified than those designed for shear stress measurement. For the latter, to minimize the heat loss to the substrate, a design with a cavity beneath the sensing element [13,18] was recommended. However, such a design would limit the choices of the substrate material, such as the silicon-based substrate. Each sensing element was patterned on the silicon substrate, called a silicon island [13,18,20], which was rigid. In order to be applied to a contoured surface, these silicon islands needed to be patterned on a flexible skin [20,21]. In contrast to such a design, the present sensors were patterned directly onto a polyimide substrate.

## 3. Cases of applications

Three cases of the self-made MEMS thermal film sensors applied to unsteady flow studies are given below, serving the purpose of illustrating the usefulness of the sensors in experimental research.

### 3.1. Three-dimensionality of vortex shedding

Tu et al. [22] and Miau et al. [23] reported on applying a spanwise array of MEMS sensors on the surface of a circular cylinder for studying the three-dimensionality of vortex shedding from the cylinder. The experimental model is shown in Fig. 2. An array of sensors on a flexible skin was applied to a circular cylinder 32 mm in diameter, denoted as D. The experiment was performed in a closed-loop low speed wind tunnel that had a test section 160 mm wide and 150 mm high in the cross section. The sensors were operated in constant-current mode.

Fig. 3 presents the real-time signals obtained by seven of the sensors in the array over one second at the sampling rate of 10 KHz per channel and Re = $2.7 \times 10^4$, where Re denotes the Reynolds number based on D and the incoming freestream velocity. The locations of the sensors are marked in Fig. 2 for reference. Note that the