Monolithic Integration of a Micromachined Flow Sensor Based on Post-CMOS

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Abstract

This paper investigates design, fabrication and testing of a monolithic piezoresistive flow sensor with on-chip signal conditioning circuit. Post-CMOS Processing of this flow sensor will be the focus of this paper, starting from theoretical analysis and numerical simulation, and moving to experimental verification. The flow sensor presented here is comprised of four symmetrically arranged silicon diaphragms with piezoresistors on them used to sense the drag force induced by the input gas flow. Piezoresistor fabrication has been merged into a conventional CMOS process and releasing of sensing part is conducted after CMOS processing. An integrated flow sensor with on-chip CMOS circuitry fabricated using this novel post-CMOS process was fabricated and tested. The integration method shows good compatibility of MEMS process with the state of art CMOS process. A quadratic relation between output voltage and flow rate was obtained within flow rate of 0-5L/min and the testing result was then compared with an Inter-CMOS based flow sensor.

Keywords: MEMS; flow sensor; Post-CMOS; Inter-CMOS

1. Introduction

CMOS micromachining has many attractive features for the fabrication of integrated inertial sensors due to the possibility to integrate high-performance on-chip signal conditioning circuits with digital readouts. The advantages of monolithic integrated sensors also include low cost, low power consumption and short production cycle. Besides, the close coupling between the sensing element and signal processing circuits can reduce the parasitic effect and noise pick-up. Nevertheless, the fundamental challenge of monolithic integration is the compatibility of MEMS and CMOS processes. Currently, many different approaches are taken to construct monolithic integration [1-3]. The first monolithic flow sensor was reported in 1992 [4]. Five masks in addition to the standard CMOS process are used to realize MEMS structure based on Inter-CMOS. The flow sensor presented in this paper was thermally based flow sensor.
sensor with 1.3-μm-thick LPCVD dielectric window to achieve high heating efficiency. Later, Robadey et al developed a two-crossed-dielectric-microbridge flow sensor and a dielectric-membrane flow sensor which are both compatible with the CMOS process [5]. The operation of these flow sensors is based on the flow dependent heat transport, which means additional thermal isolation is essential. Yet, most of the reported integrated flow sensors are based on Inter-CMOS and the modulated process of CMOS limits its fabrication in CMOS foundry. However, the add-on steps can follow the regular CMOS process for post-CMOS processing, leaving the CMOS layers untouched. And this could be the most effective way to pursue the advantages of low cost, short production cycle and high reliability based on CMOS foundry.

This paper demonstrates a post-CMOS integrated flow sensor and the operation is based on momentum transfer principles. The fabrication of piezoresistor has been merged into regular CMOS process and diaphragm releasing using backside wet etching and front side DRIE is implemented after CMOS process. In the following sections, details of the process will be described. A piezoresistive flow sensor fabricated using this post-CMOS process is tested. The testing results are then compared with an Inter-CMOS based flow sensor reported in authors' earlier study [6].

2. Design and theory

The flow sensor presented here is composed of the sensing element utilizing piezoresistive effect and on-chip signal conditioning circuits to amplify the output signal of the Wheatstone bridges. The schematic view of the sensing element is shown in figure 1, which is similar with normal piezoresistive pressure sensors except that four symmetrically arranged cantilever diaphragms are used instead of a whole diaphragm to minimize the output nonlinearity caused by the distortion of the diaphragms. Piezoresistors are fabricated on each of the diaphragms and connected as Wheatstone bridge to sense the pressure drop between top and bottom surface of the diaphragm induced by the input gas flow.

The output of the Wheatstone bridge can be written as [6]:

\[ \Delta V = \frac{3IR\pi C_D \rho V^2 L^2}{2h^2} \]  (1)

Eq.1 indicates the output voltage of the Wheatstone bridge is directly proportional to the square of the flow rate. In this study, the thickness of Si diaphragm of the flow sensor is chosen to be 30μm over a 370μm deep cavity and the flow channel is a 700μm wide square. The length and width of piezoresistor are 150μm and 25μm, respectively. All the other parameters are listed in table 1.

An on-chip instrumental amplifier is utilized to amplify the output signal of the Wheatstone bridge. Class AB output stage is designed for the instrumental amplifier in order to balance the need for excellent linearity, low noise, and low power consumption. The supply voltage of the Wheatstone is adjusted to be 2.7V.

![Fig. 1: Schematic of the sensing element. Piezoresistors are fabricated on the diaphragms to sense the drag force induced by fluid flow. The dimension of the flow channel is 700×700μm²](image)

| Parameters                          | Values     |
|-------------------------------------|------------|
| Density of air at room temperature, \( \rho \) | 1.118kg/m³ |
| Equivalent flow velocity, \( V \)   | 170m/s     |
| kinematic viscosity, \( \nu \)      | 14.8E-6m/s²|
| Length of the diaphragm, \( L \)    | 400μm      |
| Maximum width of the diaphragm      | 1500μm     |
| Young’s modulus, \( E \)            | 165GPa     |

Table 1. Parameters used in this paper
3. Post-CMOS micromachining process for flow sensor

The monolithic integration process is shown in figure 2. The process flow starts with n type (100) oriented silicon wafers. At first, p-well is formed (figure 2a) followed by the regular CMOS process till before PMOS source/drain implantation, including active area formation, threshold voltage implantation, LOCOS isolation, gate oxidation, poly gate pattern and NMOS source/drain implantation (figure 2b). After that, PMOS source/drain is formed using boron source at 40KeV energy with a dose of 3E13cm\(^{-2}\), followed by annealing at 950°C for 10 minutes. Piezoresistors are also formed at the same time (figure 2c). After that, the backside cavity is etched by KOH to get the sensor diaphragm (figure 2d). During this step, the front side of the wafer must be carefully protected to avoid the KOH etching and contaminations. A 0.6 \(\mu\)m-thick SiO\(_2\) film is deposited by LPCVD, followed by deposition of a 0.11 \(\mu\)m thick LPCVD low-stress Si\(_3\)N\(_4\) film, which is also the mask of KOH etching. Afterwards, metallization is carried out (figure 2e). At last, SiO\(_2\) and Si films are etched by DRIE (figure 2f).

![Fig. 2: Process flow of integrated flow sensor](image)

4. Test results and discussions

The SEM graph of sensing element and part of the on-chip circuit is shown in figure 3. Some special processes are needed for the flow sensor packaging to realize the flow channel. As shown in figure 4, the device is mounted on a PC board with a via on it and a metal cap with a hole in its head is mounted when packaging the device. The packaged device is then connected to a gas source of the diffusion furnace that can generate air velocities up to 5L/min together with a reference mass flow controller. As the read out circuits are integrated on chip, the output voltage of the sensor is directly measured by a voltmeter.

The flow sensor is tested for the flow rate ranging from 0L/min to 5L/min and the output voltage of the flow sensor tested is shown in figure 5. The test results indicate the output of the flow sensor has a quadratic relation to the flow rate which is the same as the simulation prediction. It also demonstrates that this post process is fully compatible with CMOS process. A possible explanation of the departure from
the simulation result observed is the impact of viscous force and process deviation. Output voltage comparison of post-CMOS based flow sensor with Inter-CMOS based flow sensor [6] is shown in figure 6. It is noted that inter-CMOS based flow sensor shows a better sensitivity than that of post-CMOS based sensor as predicted. However, post-CMOS based sensor has the advantage of low cost and simple process based on CMOS foundry.

### 5. Conclusion

This paper presents a monolithic integrated MEMS flow sensor based on post-CMOS. The prototype of a post-CMOS based micromachined flow sensor with on-chip signal conditioning circuitry has been successfully fabricated. The compatibility of this post-CMOS based process is verified. Compared with previous inter-CMOS based flow sensor, this post-CMOS based flow sensor shows lower sensitivity because of a trade-off for CMOS process. However, one important feature of this post-CMOS based sensor is that, this integration approach is compatible with a CMOS foundry, which demonstrates significant improvement for low cost and short production cycle.

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