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Characterization of embedded microheater of a CMOS–MEMS gravimetric sensor device

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ABSTRACT

A CMOS–MEMS device for mass detection has been designed using 2008 CoventorWare software and fabricated using 0.35 μm CMOS technology. This paper reports the characterization of the microheater and the temperature sensor embedded in the device. The measured resistances of the microheater and the temperature sensor were found to be close to the modeled values within ~4.2% error. The average temperature coefficient of resistance (TCR) of the temperature sensor of five dies was determined by increasing or decreasing the temperature in a range of 25 °C–100 °C. The resistance of the temperature sensor was found to increase with either an increase in ambient temperature or the voltage applied to the microheater, with a correlation factor of 0.99. The average TCR was found to be 0.0034/°C for the increasing temperature and 0.0036/°C for the decreasing temperature as compared to 0.0037 °C reported in the literature, indicating an error of 8.1% and 3.5%, respectively. These differences between the measured and reported values are believed to be due to fabrication tolerances in the design dimensions or the material properties. The humidity was found to have a negligible effect on the resistance of the temperature sensor for increasing humidity levels from 40% to 90%. The repeatability of the measurements has shown low standard errors, which gives confidence in the reliability of the fabricated device.

1. Introduction

Microelectromechanical systems (MEMS) technology has been extensively used in the automotive, aerospace, medical and consumer electronics industries [1]. Applications of MEMS include the fabrication of gyroscopes, accelerometers and seismographs [2], and sensors for mass detection [3]. In recent years, gas and chemical sensors based on MEMS technology have been developed and applied for bio-sensing to detect biomolecules [1] for different purposes. Gravimetric sensing is a technique used to detect change of mass due to bio-chemical processes like antigen–antibody interaction [4]. MEMS sensors have many advantages over sensors fabricated using other technologies. MEMS sensors are small in size, and thus they have very high mass sensitivity [5], which makes them suitable for gravimetric sensing. Besides, this technology has an advantage of mass production and batch processing; hence the sensors are fabricated in large numbers which reduce the cost tremendously [1]. In addition, this technology provides the ability to incorporate actuation, sensing and signal conditioning circuits in the same fabricated chip, which results in high functional performance (increased sensitivity, resolution, etc.) [6]. Furthermore, MEMS technology is easily interfaced with Complementary-Metal-Oxide-Semiconductor (CMOS) electronics [1], which enables the use of multiple sensors in the same device to detect different analytes. This feature is very good and important for human breath analysis.

Expired human air has been known for disease recognition since the early time of the ancient Greeks. For example, the sweet smell of acetone was linked to diabetes, a fish-like smell to liver disease, and breath that smells like urine was described for kidney failure [7]. Since then, exhaled breath (EB) has been studied and developed over time, and it has been recognized to contain potential and useful biomarkers for diagnosis of some diseases [8]. Inflammatory lung diseases like asthma are diagnosed by measuring the elevation of exhaled nitric oxide; exhaled ammonia rises due to kidney failure and acetone due to diabetes. Exhaled acetone has gained a lot of attention and became among the most studied biomarkers. It is related to glucose concentration in blood, and can thus be used for diabetes screening. According to the recent and latest report (2015) of the International Diabetes

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Federation (IDF), one in every 11 adults has diabetes, and one in two adults with diabetes is undiagnosed. The total number of people who are aged 20–79 and living with diabetes is estimated to be 8.2–11.4% (135–188 million) [9]. Diabetes causes serious health problems such as blindness, kidney failure, heart disease, premature death, limb amputation and gangrene [10]. The common practice to diagnose diabetes is by invasive means which involves withdrawal of blood and then glucose measurement and analysis. Thus, researchers have been studying and developing different methodologies for breath analysis to measure exhaled acetone instead of the blood glucose as a non-invasive way of diabetes screening [8,11]. The concentration of acetone in the diabetic subjects was reported to be higher than 1.71 parts per million (ppm) [11,12].

The most commonly used methods to detect acetone in exhaled breath are gas chromatography (GC), mass spectroscopy (MS) and their combinations (GC–MS) [13], proton transfer reaction–mass spectroscopy (PTR-MS) and selected ion flow tube mass spectroscopy (SIFT-MS) [14,15]. Although the above methods are sensitive and can detect a low level of acetone concentration, nevertheless, they have practical limitations such as high cost, bulky and bench-top equipments, and require a longer time for sample preparation [15]. Electrochemical sensors and especially semiconductor metal oxides (SMOs) have been well reported by many researchers to replace GC–MS techniques for acetone detection in exhaled breath [16–20]. These SMOs sensors have a low cost, are portable and easy to operate. However, they do not have satisfactory sensitivity to low concentrations of acetone and have cross-sensitivity to other gases in the exhaled breath [18,21]. In addition, SMOs normally work at temperatures above 200 °C and thus consume high power [22]. Using MEMS technologies enables researchers to fabricate SMOs with ultra-low power consumption due to the features of MEMS [23,24]. This paper reports the characterization of an embedded microheater and temperature sensor of a CMOS–MEMS device proposed for gravimetric detection of acetone vapor in exhaled breath for non-invasive screening of diabetes.

2. Design and simulation of the device

The 3D model of the proposed device is shown in Fig. 1. It consists of two parts. They are the upper part (vibrating plate) and the lower part (stator). The vibrating plate is a square plate supported by four flexible beams and suspended on top of the stator plate with a certain gap Z_0 maintained. It is a thin film made from aluminum and silicon dioxide layers with a total thickness of 6.15 μm. However, the stator is a thick layer of approximately 305.15 μm. Both the vibrating plate and stator contain three rectangular plates used for sensing and actuation purposes. The rectangular plates on the sides are used as actuation plates for the electrostatic actuation, while the middle rectangular plate is used as a sensing plate for the capacitive sensing. The details of the actuation and sensing have been reported elsewhere in [25]. As shown in Fig. 1, polymer is coated on the device on top of the vibrating plate and modeled as a sensitive layer to acetone vapor. Fig. 2 shows the cross (A–A) section view of the device showing the CMOS layers.

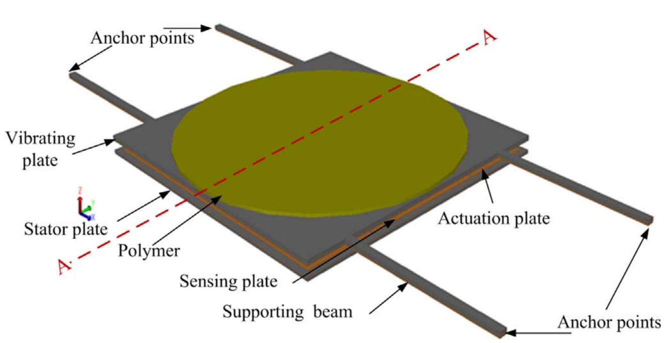

Fig. 1. Schematic of the proposed device.

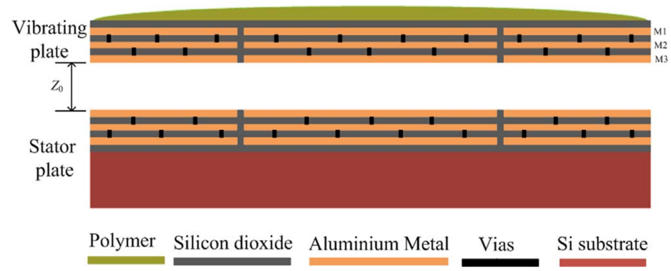

Fig. 2. Cross section view (A–A) of the CMOS–MEMS device with polymer coating on top of the vibrating plate.

The vibrating plate also consists of an embedded microheater and a temperature sensor. The heater and temperature sensor are made of the aluminum metal 1 (M1). Aluminum is good for temperature sensing [26] due to its low cost, low corrosion and thermal stability [27]. The purpose of using the microheater is to accelerate the desorption process when the acetone vapor is adsorbed/absorbed by the polymer for the subsequent acetone measurement [28]. The desorption process is important for the reversibility of the sensitive layer in the detection and sensing applications. On the other hand, the temperature sensor is needed to estimate the surface temperature of the device plate.

The device is designed using CoventorWare 2008 software according to 0.35 μm fabrication technology. This technology uses two polysilicon layers, three metal (aluminum) layers, silicon dioxide between layers as an insulator and tungsten layer as vias for interconnection of different layers. The dimensions of the CMOS–MEMS device are given in Table 1and the material properties of the layers used are in Table 2.

The resonance frequency and maximum displacement of the vibrating plate when the gap between the vibrating plate and stator is set to 10 μm with a coated polymer of 4 μm thickness were found and are shown in Figs. 3 and 4.

3. Microheater and temperature sensor design

The microheater was designed in a meander shape using aluminum metal 1 (M1) with the 0.35 μm CMOS technology, while the temperature sensor was designed to surround the heater. Fig. 5 shows the layout of the vibrating plate with the microheater and the temperature sensor.

Table 3 shows the dimensions and resistance values of the heater and the temperature sensor that are designed using M1 from the fabrication foundry used. The calculation steps to obtain the resistances of the microheater and the temperature sensor were given in our previously reported paper [29].

Table 1
Dimensions of the CMOS–MEMS device.

Dimension	Value
Total thickness (μm)	~321.30
Beam width (μm)	10
Beam length (μm)	210
Plate area (μm^2)	376 × 376