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TPMS (tire-pressure monitoring system) sensors: Monolithic integration of surface-micromachined piezoresistive pressure sensor and self-testable accelerometer

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A novel surface-micromachining technology is developed to monolithically integrate piezoresistive pressure sensor and accelerometer for tire-pressure monitor system (TPMS) applications. A narrow rectangular diaphragm piezoresistive pressure sensor and a clamped beam-mass piezoresistive accelerometer compose the monolithic composite sensor that are on-chip integrated in a 1.6 mm × 1.6 mm single chip for low-cost production. With an electroplated Cu seismic-mass, the sensitivity of the accelerometer is much improved so that it can be compatibly fabricated with the pressure sensor by using surface-micromachining processes. For facilitating on-chip known-good-die and reliable TPMS application, the electroplated metal mass is used as a versatile structure to realize electrostatic self-testing function for the accelerometer. The fabricated TPMS sensors are characterized, resulting in 83.6 mV/MPa/3 V sensitivity and 0.34% FSO linearity for the 450 kPa-ranged pressure sensor, as well as, 15.6 μV/g/3 V sensitivity for the 125 g-ranged accelerometer. In addition, the on-chip electrostatic self-testing function is experimentally validated for the accelerometer.

1. Introduction

According to the analysis of automotive sensor market, the product requirement to tire pressure monitoring systems (TPMS) is rising rapidly [1,2]. More and more countries are planning to announce the transportation rules that require vehicles installing the TPMS sensors for every wheel. To fulfill the market demand, recently the researches on TPMS sensors have been intensively motivated. To make the product competitive in the market, the most TPMS sensors under development are required to feature low-cost, small-size and compatible batch fabrication with IC-foundry process.

In order to save the electric power from a battery for long-term working, the TPMS sensor would better be operated in a power-saving mode where the pressure sensor is wakened by an accelerometer. The accelerometer senses the vehicle movement by detecting the centrifugal acceleration of the rotating wheel. Therefore, the accelerometer would better be on-chip integrated with the pressure sensor. Featuring high output linearity and ease of signal processing, silicon piezoresistive pressure sensors and accelerometers [3] are quite suitable for the TPMS application. To achieve small size and low cost, surface-micromachining technique is a good candidate for fabricating the monolithic multi-functional sensors. Conducted from the front-side of the wafer, surface-micromachining technique normally employs thin-film deposition and sacrificial-layer etching that are quite compatible with standard semiconductor foundry processes. However, surface-micromachined piezoresistive sensors meet technical challenges in the following factors: (1) A very small diaphragm structure is needed for a surface-micromachined piezoresistive pressure sensor to avoid stiction of the diaphragm with the substrate that easily occurs during the sacrificial-layer release etching. (2) Surface-micromachined thin-film seismic mass is too light to secure an adequate acceleration sensitivity of a beam-mass structure accelerometer. Therefore, a heavier seismic-mass should be made for the accelerometer. (3) To secure the reliability of the acceleration that is used for waking up the pressure sensor, self-testing function should be on-chip integrated for the accelerometer. (4) The two sensors should be monolithically integrated with a compatible, miniaturizing and low-cost fabrication method.

To fulfill the above-mentioned technical requirements, this research presents a new sensor design and fabrication technique to develop monolithically integrated pressure sensor and self-testable accelerometer for low-cost and reliable TPMS applications. Surface micromachining processes plus metal electroplating technique are used to fabricate the integrated composite sensors. An odd-shaped narrow rectangular diaphragm structure is designed

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for the piezoresistive pressure sensor, with the designed absolute-pressure measure range as 450 kPa. By employing an electroplated Cu mass, the sensitivity of the accelerometer is significantly improved, where the acceleration measuring range is −25 g to +125 g and the pressure-monitoring waking-up threshold is set within 20–25 g according to the diameter of the vehicle wheel. The electroplated metal mass plate and the conductive silicon substrate are also employed as a couple of electrodes to realize electrostatic self-testing function for the accelerometer.

Differing from traditional surface-micromachining technologies [4,5], the electroplating process enclosed surface-micromachining fabrication method helps to gain a high inertial sensitivity of the accelerometer and still features good compatibility with standard IC-foundry process. There is no any double-sided aligning exposure needed for fabrication of the sensing structure chip. As will be shown in following sections, the on-chip composite sensor exhibits satisfactory testing results that are suitable for TPMS applications.

2. Sensor design

2.1. Pressure sensor with narrow sensing diaphragm

Most bulk-micromachined piezoresistive pressure sensors use circular or square diaphragms for pressure sensing [6,7], where back-side isotropic or anisotropic etching is used to form the diaphragm. Square-shaped thin-film diaphragms were also formed for surface-micromachined pressure sensors [8,9]. However, our fabrication experiment has shown that, the relatively large area of the square-shaped diaphragm suffers from sticking effect that has been being a major problem in surface-micromachined structures for a long time. During or after wet release etching to the sacrificial layer that is just beneath the sensing diaphragm, the thin-film diaphragm easily sticks to the substrate that causes a low fabrication yield. To avoid the stiction, herein the TPMS pressure senor diaphragm is designed into a narrow rectangular shape that can be top-viewed in Fig. 1(a). We have experimentally found that the greatly narrowed low-stress SiN diaphragm can be free from the sticking failure. According to the analytical theory described in Ref. [10], such a narrow diaphragm (with the length-to-width aspect greater than 6) can be simplified treated as a clamped–clamped elastic beam structure, which is schematically shown in Fig. 2(a). When pressure is externally applied onto the diaphragm, compressive stress will occurs around the middle point of the beam [around Line A in Fig. 2(a)] while tensile stress will be induced near the clamps of the beam [around Lines B and B′ in Fig. 2(b)]. Ss is illustrated in Fig. 1(a), four poly-silicon piezoresistors are accordingly laid at the corresponding maximum stress locations (with two at the center and another two near the edges of the diaphragm) to form a fully sensitive Wheatstone-bridge that is demonstrated in Fig. 1(b).

For the narrow rectangular diaphragm, where the condition of $2b \gg 2a \gg 2h$ is satisfied [the definition of the diameters is denoted in Fig. 2(a)], the pressure induced stress distribution along x- and y-axis can be expressed as [10]

$$T_{xx}(x) = \frac{3p}{h^2}\left(x^2 - 2ax + \frac{2}{3}a^2\right) \tag{1}$$

and

$$T_{yy}(x) = \upsilon T_{xx}(x) \tag{2}$$

where p denotes pressure, υ is Poisson ratio of SiN. Here the mechanical influence from poly-silicon piezoresistors is ignored as the SiN film thickness is relatively larger. The analyzed stress distribution results are plotted in Fig. 2(b). When $x = a$, the difference between the compressive stress along x-axis and that along y-axis gets the maximum value. At the location of $x = 0$ or $x = 2a$, the difference between x-axis tensile stress and y-axis one is the highest. With the layout illustrated in Fig. 1(a), the piezoresistors are optimally designed to obtain the highest sensitivity to pressure. The designed diaphragm dimensions are: $2a = 44\ \mu m$, $2b = 365\ \mu m$, $h = 1.2\ \mu m$. Given the longitudinal piezoresistive coefficient (π_L) of polysilicon as $1.56 \times 10^{-10}\ Pa^{-1}$ and the transverse piezoresistive coefficient (π_T) as $-4.40 \times 10^{-11}\ Pa^{-1}$ [11,12], the sensitivity of the 450 kPa-ranged pressure sensor is designed as 75.9 mV/MPa under 3 V supply on the Wheatstone-bridge [10].

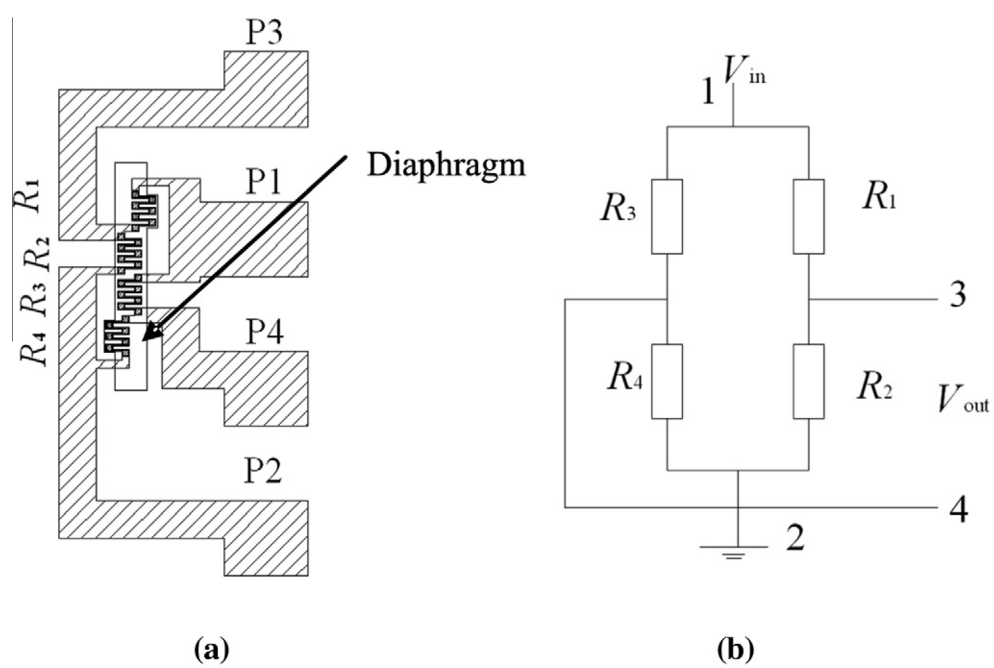

Fig. 1. (a) Top-view schematic of the pressure sensor, showing the narrow rectangular shape of the pressure sensing diaphragm and the layout of the piezoresistors. (b) Constructing diagram of the piezoresistive Wheatstong-bridge.