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CMOS-MEMS piezoresistive force sensor with scanning signal process circuit for vertical probe card

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ABSTRACT

In response to the essential role probe cards play in the semiconductor testing industry, a CMOS-MEMS force sensing devices capable of simultaneously monitoring the probe reacting force and electrical test signals is designed for probe cards. The probe reacting force can assist operators immediately to identify a broken, deformed, or worn-out probe and recognize that the measured electrical signals are erroneous. The debug time and cost of the IC test can therefore be effectively reduced. Array-type CMOS-MEMS force sensors are capable of monitoring the status of vertical probe cards on-line in the case of both die-level and wafer-level applications. The force sensor essentially is a Wheatstone-bridge-based piezoresistive force sensor with a small surface area and can be easily fabricated. It consists of a membrane composed of metal, silicon oxide, and a piezoresistive layer made of polycrystalline silicon. Moreover, as the conventional back-etch process can barely handle the increasingly smaller probe pitch, we use front etching to etch out a cavity under the membrane on the silicon substrate in order to deform the membrane during the post-process. For measuring the output signals of the sensors, on-chip circuits to scan and amplify the output signals of the sensors are integrated in the design process. Furthermore, a finite element method is adopted to analyze the structure of the sensors and to find the optimal piezoresistive sensor design. The TSMC 0.35 μm 2P4M process is used to fabricate the force sensors and the circuits. According to the measurement results, the designed sensor reports a sensitivity of 3.114 mV/N/V while a load-bearing force is 0.0294 N.

1. Introduction

The constant advancement of semiconductor technology has prompted a further reduction in size and an increase in the density of integrated circuits. In order to satisfy the various requirements of the industry, higher accuracy, longer fatigue life, and a greater capability to withstand temperature extremes have become important criteria in the design of probe cards [1,2]. After a certain period of use, probe cards must be calibrated by a professional machine; several properties need to be verified, such as the probe's maximum current, resistivity (contact resistance), and reaction force. This verification procedure may influence the efficiency of production lines, since it is performed off-line. One crucial step in this procedure is monitoring the reaction force exerted by the probes on test plane to ensure the efficient operation of the probe cards. To expedite this procedure, we designed an array-type CMOS-MEMS force sensor that is capable of monitoring the contact status of vertical probe cards on-line in both die-level and wafer-level applications.

In the past, the fabrication of pressure sensors typically involved an MEMS post-process with backside etching [3,4]. However, in recent years, more and more researchers had proposed to combine the standard CMOS process with the MEMS front-side etching process to manufacture both microsensors and integrated circuits [5–7]. The combined process also has additional advantages, such as a reduction in the noise and number of pads. Our design also adopted the combined CMOS-MEMS process to fabricate force sensors and their signal conditioning circuits. Moreover, as the conventional backside etching process (wet etching, KOH) could barely handle the higher density of sensors to match the increasingly smaller pitch between the probes [8], we employed front etching to etch out a cavity on the silicon substrate to release the membrane in the post-process (RIE and ICP).

2. Design principle

The main structure of a piezoresistive pressure sensor is made from a material that has a piezoresistance effect. As a pressure or force is exerted upon the membrane, the membrane is deformed; the piezoresistance value or resistance of the piezoresistive material alters with the stress; this is referred as the piezoresistance effect. The resistive materials of the sensor are connected to a

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Wheatstone bridge in order to enhance their sensitivity and alleviate the temperature disturbance. Thus, with the assistance of the Wheatstone bridge, the value of ΔV will be obtained when the resistance values alters. The resistance and ΔV values vary greatly when the pressure increases. The pressure can be measured on the basis of the output value of ΔV once the relation between the pressure and ΔV is established.

The formula and architecture of a piezoresistive pressure sensor is as shown below [9–11]:

$$\Delta P \Rightarrow \omega \Rightarrow \varepsilon \Rightarrow \sigma \Rightarrow \frac{\Delta R}{R} \Rightarrow \Delta V \tag{1}$$

In this formula, the ΔP is the change in the pressure; ω, the membrane deformation; ε, strain; σ, stress; $\Delta R/R$, ratio of piezoresistance variation and ΔV, potential difference.

The change ratio of the resistance is

$$\frac{\Delta R}{R} = \varepsilon(1+2\nu) + \frac{\Delta\rho}{\rho} \tag{2}$$

In this equation, $(1+2\nu)$ is the deformation of the material by the external pressure, ν is Poisson's ratio, and $\Delta\rho/\rho$ is the relative change of resistivity.

Since silicon has a square structure, the relationship between the change rate of resistivity and the stress can be simply shown in a matrix equation:

$$\frac{1}{\Delta\rho}\begin{pmatrix}\Delta\rho_1\\ \Delta\rho_2\\ \Delta\rho_3\\ \Delta\rho_4\\ \Delta\rho_5\\ \Delta\rho_6\end{pmatrix} = \begin{pmatrix}\pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0\\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0\\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0\\ 0 & 0 & 0 & \pi_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & \pi_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & \pi_{44}\end{pmatrix}\begin{pmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_1\\ \tau_2\\ \tau_3\end{pmatrix} \tag{3}$$

For the function, (π) is the coefficient for the piezoresistance matrix. The material characteristics and coefficient for the piezoresistance matrix can be simply converted by Euler coordinates into

$$\pi_T = \pi_{11} + (\pi_{11} - \pi_{12} - \pi_{44})[l_1^2 l_2^2 + m_1^2 m_1^2 + n_1^2 n_2^2] \tag{4}$$

$$\pi_L = \pi_{11} - 2(\pi_{11} - \pi_{12} - \pi_{44})[l_1^2 m_1^2 + m_1^2 n_1^2 + l_1^2 n_1^2] \tag{5}$$

where l_1, m_1, n_1, l_2, m_2, and n_2 are the transverse direction cosine and longitudinal direction cosine, respectively [12].

The relationship between the change ratio of the resistance and the stress is

$$\frac{\Delta R}{R} = \frac{\Delta\rho}{\rho} = \pi_L\sigma_L + \pi_T\sigma_T \tag{6}$$

where σ_L and σ_T are the longitudinal stress and transverse stress, and π_L and π_T are the longitudinal piezoresistance coefficient and transverse piezoresistance coefficient, respectively.

2.1. The Wheatstone-bridge principle

Piezoresistive pressure sensors use piezoresistive materials embedded in the membrane of the sensor, and adopt the Wheatstone-bridge principle. Four piezoresistors are placed at the edge of a square membrane (two transverse piezoresistors; two longitudinal piezoresistors). The transverse and longitudinal piezoresistors are influenced by stress when the membrane deforms. The transverse piezoresistors are widened and thus their resistances reduced, while the other piezoresistors are lengthened and thus their resistances increased.

The relationship between the output and input voltage is

$$\frac{V_{out}}{V_{in}} = \frac{R_2}{R_1+R_2} - \frac{R_4}{R_3+R_4} \tag{7}$$

When the resistances do not alter, the output voltage is zero.

$$R_1 = R_2 = R_3 = R_4 = R, \quad V_{out} = 0 \tag{8}$$

Table 1
The properties of materials utilized in the TSMC standard CMOS process.

Property			
Material	Yield stress (GPa)	Young's modulus (GPa)	Poisson ratio
Silicon dioxide	8.4	73	0.17
Silicon	7.0	190	0.23
Polysilicon	2.7	140	0.2
Nitride	14.0	260	0.27
Tungsten	4.0	410	0.28
Aluminum	0.17	70	0.35

When pressure is exerted upon the sensor, the resistances will alter in an ideal situation:

$$R_2 = R_3 = R + \Delta R; \quad R_1 = R_4 = R - \Delta R \tag{9}$$

Thus, the relationship between the output voltage and exerted pressure (formula (1)) can be established:

$$\frac{V_{out}}{V_{in}} = \frac{\Delta R}{R} = kP \tag{10}$$

where k is a constant.

As shown in the above equation, the change ratio of the output voltage can be utilized to evaluate the change ratio of the resistances and thus obtain a pressure measurement.

3. Design and fabrication

First, sensor loading and other properties were simulated. If the simulated properties of the sensor conformed to our requests, then the photo mask for the sensor would be designed with a layout accordingly. Then, the TSMC standard process was adopted through the project with Chip Implementation Center (CIC, Taiwan). The last step was post-process and measurement.

The force range of a normal vertical probe card is about 0.0098–0.0294 N [2]. Table 1 summarizes the properties of the main materials used in the IC fabrication process for the design, based on the limits of the TSMC 0.35 2P4M process. The optimal membrane area could be determined based on the probe pitch and membrane thickness.

The simulation parameter settings include:

(a) Force: The force range for the simulation was set at 0–0.098 N.
(b) Boundary condition: The edge of the sensor membrane was firmly fixed.

3.1. Simulation of membrane structure

In the TSMC 0.35 2P4M process, the membrane consists of four aluminum layers and five silicon dioxide layers. The average thickness of aluminum layer is 0.7 μm and the average thickness of silicon dioxide layer is 1.05 μm. Among these materials, silicon dioxide is the best membrane material because its Young's modulus and yield stresses are better. For this reason, the more silicon dioxide layers are employed the less deformation will be anticipated. Or, the more metal layers are employed the weaker strength will be obtained. For a trade-off between the strength of the membrane structure and the sensitivity of the piezoresistance, a membrane structure was designed of four metal layers and five silicon dioxide layers. In addition, the probe tip cross-sectional area designed in the vertical probe card was 40 μm × 40 μm [13], so the membrane area of sensor was designed to be 100 μm × 100 μm. Figs. 1 and 2 showed a distribution map for von-Mises stress and displacement respectively when the membrane was compressed by an external force. In Fig. 3, the black line represents the von-Mises stress line, and the red line represents the displacement line, respectively. The