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Pressure nonlinearity of micromachined piezoresistive pressure sensors with thin diaphragms under high residual stresses

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ABSTRACT

Thermal residual stress plays a significant role in the performance of microelectromechanical system (MEMS) pressure sensor devices. For example, the voltage span and pressure nonlinearity (PNL) on the voltage output of a pressure sensing element can be significantly affected by the residual stresses of passivation films on the silicon diaphragm. The objective of this study is to resolve a pressure nonlinearity problem in terms of silicon nitride residual stress and diaphragm thickness in order to meet the PNL design criteria within ±3% at 25 °C. The curvatures of wafers were measured and the film residual stresses were calculated. Finite element analyses (FEA) were conducted and correlated with the PNL experimental tests. To build a design window for optimization, a central composite design (CCD) method was utilized to significantly reduce the number of FEA runs. It is concluded that the residual stress of PECVD silicon nitride needs to be optimized and controlled in order to reduce the pressure nonlinearity.

1. Introduction and background

MEMS silicon pressure sensors have been in mass production for over two decades because of the attractive fabrication process [1–4]. These sensors are fabricated using bulk-micromachining or surface micromachining. Among them, many are made of piezoresistive transducer (PRT) sensors [1–20]. Although extensive research has been conducted on MEMS pressure sensors [5–24], challenges still exist in the scopes of cost reduction, die size shrinkage, manufacturing process simplifications, and control of process window. In order to reduce the die size without sacrificing sensitivity, we need to shrink the diaphragm area and make the diaphragm thinner. But a thinner diaphragm can cause a PNL performance problem due to the residual stresses from passivation films. Therefore, building a design window is very important for the design optimization for manufacturing robustness in the considerations of cost and performance.

Ishihara et al. [8] reported a PNL of 0.2% or lower could be achieved in their PRT sensing element with a 30-μm thick diaphragm. Matsuoka et al. [13] measured and analyzed the PNL within ±0.5% for high pressure sensors with a 1-mm thick diaphragm. Lin et al. [5,6] studied the linearity error or PNL problem even more thoroughly on the surface-micromachined pressure sensors by characterizing the diaphragm thickness and the length of sensing resistors. In these papers, the effect of passivation film residual stress was not considered either because of thick diaphragms or low residual stress. Unfortunately, the passivation film residual stress has a significant impact on the PNL of our bulk-micromachined pressure sensors, especially for the sensing elements with thin diaphragms. High passivation film residual stress [16,24–26] can easily cause wafer bow that deforms the diaphragms of PRT sensing elements. The pre-stressed deformed diaphragm affects voltage output and inevitably deteriorates pressure linearity due to geometry nonlinearity.

During the development of pressure sensors for diesel particle filter (DPF) applications with a new wafer supplier, a pressure nonlinearity problem was found and could not pass the design specification within ±3% at 25 °C. Fig. 1 shows a diesel particle filter sensor and an inside pressure sensing element with the filter pressure acting on the backside of diaphragm and the ambient pressure acting on the topside of diaphragm. The function of a DPF sensor is to detect the pressure difference between the ambient pressure and internal filter pressure and send a voltage signal to a control unit, which determines when the inside of diesel particle

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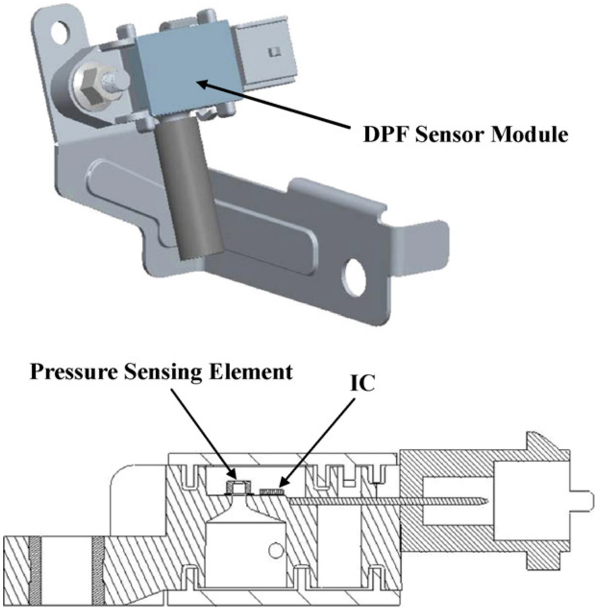

Fig. 1. Diesel particle filter sensor and its cross-section.

filter should be burned in order to remove the accumulated particles and prevent the filter from blockage. This is a backside pressure case because the internal filter pressure on the backside is always higher than the external ambient pressure on the topside. The layout of a sensing element is shown in Fig. 2 with a picture-frame transducer (or called micro Wheatstone-bridge) to sense pressure. By applying pressure on the diaphragm of a sensing element, the transducer senses the stress as the result of diaphragm bending, and thus provides electrical output voltage which is proportional to pressure.

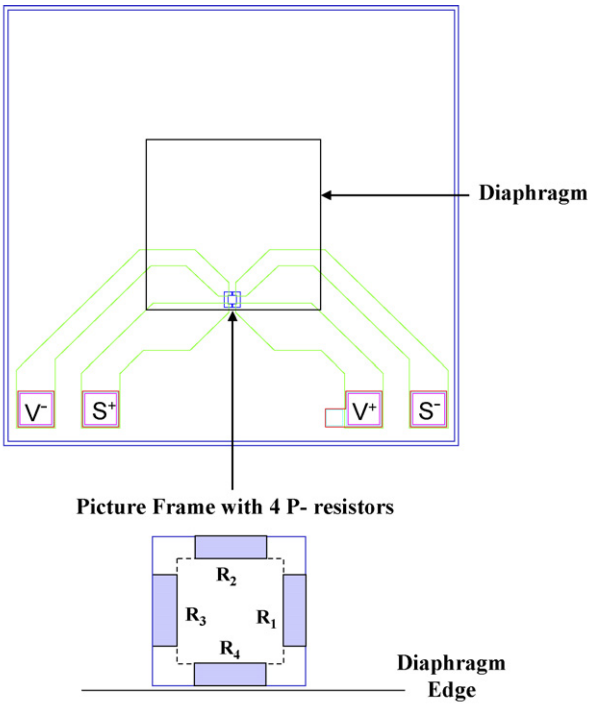

Fig. 2. Layout of a DPF sensing element with a picture-frame transducer.

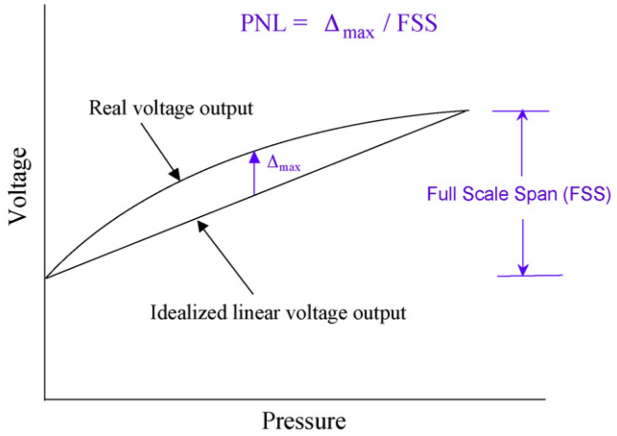

Fig. 3. Definition of pressure nonlinearity (PNL).

Piezoresistive silicon pressure sensors have to be sensitive, accurate, and stable during pressure measurement and maintain a linear relationship between the voltage and pressure. The definition of pressure nonlinearity (PNL) is described in Fig. 3 at 25 °C. The full-scale span (FSS) is the voltage range that the sensing element detects in the pressure range. The $\Delta_{\max}$ is the maximum voltage output difference between the real voltage output and the idealized linear voltage output. The PNL is the ratio of $\Delta_{\max}$ to FSS. The requirement for PNL is within ±3%. Usually the $\Delta_{\max}$ and PNL occur at the center point in the pressure range. In order to reduce tremendous time and work, we can use three voltage output data at the initial, center, and final pressure points for an approximate PNL calculation. Passivation layers including plasma enhanced chemical vapor deposition (PECVD) silicon nitride and silicon dioxide (SiO_2) as shown in Fig. 4 are used to protect the surface of the sensing element and circuitry. However, the severe residual stresses on passivation films can induce a PNL problem. For the sensing elements from a manufacturing source, we found a severe PNL problem with thinner diaphragms as shown in Fig. 5. These sensing elements are diced from different wafers and different lots. For the sensing elements with diaphragms thicker than 11 μm as indicated in Fig. 5, the PNL is drastically reduced and improved. We also found that the PNL dropped significantly if the silicon nitride layer was removed. For some sensing elements with diaphragms thinner than 9 μm, the magnitudes of PNLs do not consistently follow the exact trend: the thicker the diaphragm, the lower the PNL. That is presumably due to that a thinner diaphragm is more susceptible to variability of the residual stress of silicon nitride. Some other parameters can

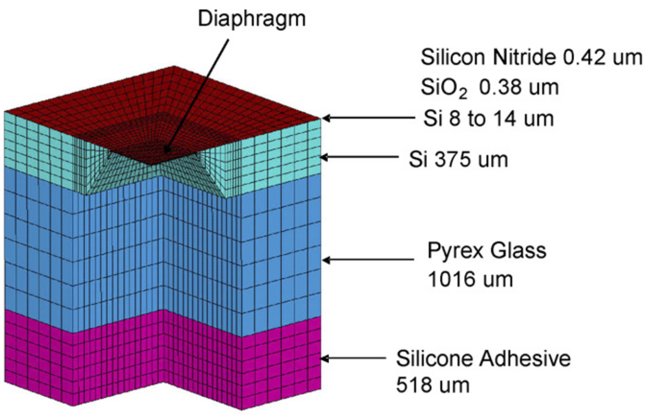

Fig. 4. A quarter finite element model of pressure sensing element packaging.