TRENCH-ISOLATED BULK-TYPE PRESSURE SENSOR ON SILICON-ON-INSULATOR FOR HIGH-TEMPERATURE AND HIGH-PRESSURE DOWNHOLE APPLICATIONS

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ABSTRACT

Presently reported is a dielectric-isolated bulk-type pressure sensor fabricated on silicon-on-insulator (SOI) that offers higher pressure capability than conventional diaphragm-type pressure sensors and wider temperature operating range than a recently reported junction-isolated bulk-type pressure sensor. The isolated piezoresistors are realized on the SOI device layer via trench etching and oxidation. Two types of trenches are formed: narrow ones that are completely filled with silicon dioxide and wide ones that are thermally oxidized on the sidewalls but partially filled. The pressure sensitivity is enhanced by relieving the transverse stress acting on selected piezoresistors isolated with the wide trenches.

INTRODUCTION

Resonant quartz pressure sensor (Fig. 1a) currently sets the benchmark for downhole pressure measurements. While MEMS pressure sensor with its relatively low cost and small size has the potential to replace the resonant quartz pressure sensor, it is still hindered by a number of limitations. A recent attempt [1] has been made to address some of the issues by replacing the conventional diaphragm-type with a bulk-type pressure sensor to handle the targeted high-pressure load (≥ 200 MPa), but the junction-isolation of the piezoresistors must be replaced by the presently demonstrated dielectric-isolation to handle the anticipated high operating temperature (≥ 200 °C).

Figure 1: (a) Schematic diagram of a resonant quartz pressure sensor package. (b) Schematic diagram showing the quartz crystals replaced by a MEMS pressure sensor. (c) Magnified schematic of the MEMS pressure sensor die suspended by bond wires.

A higher pressure sensitivity is desirable for reducing the electrical offset and its associated temperature coefficient. To achieve this, selective trenching of the piezoresistors to release specific stress components is explored. In addition, the package-induced stress that ultimately determines sensor repeatability, hence

compensability, must also be minimized. Presently proposed is a MEMS pressure sensor designed as a direct drop-in replacement of the quartz resonator capsule in an inconel package that is proven for downhole applications (Fig. 1b). The MEMS sensor die is suspended only by its bond wires, hence largely relieved of the package-induced stress (Fig. 1c). This potentially allows accurate temperature compensation, despite the temperature coefficient of a piezoresistive silicon sensor being intrinsically two orders of magnitude higher than that of a resonant quartz sensor.

PRINCIPLE OF OPERATION

The bulk-type pressure sensor is formed by eutectically bonding a [110]-oriented SOI sensor wafer and a cap wafer under vacuum (Fig. 2). Two orthogonal pairs of piezoresistors respectively aligned to the [001] and $[1\bar{1}0]$ orientations are realized in the center region on the sensor-side of the vacuum cavity and electrically configured to form a Wheatstone bridge.

Figure 2: Bulk-type pressure sensor schematically shown with the cap die separated from the SOI sensor die.

The relative change of the resistivity $\Delta\rho'_{11}/\rho$ along the longitudinal direction of a piezoresistor is given by [2]

$$\frac{\Delta\rho'_{11}}{\rho} = \pi'_{11}\sigma'_{11} + \pi'_{12}\sigma'_{22} + \pi'_{16}\sigma'_{12} \approx \pi'_{11}\sigma'_{11} + \pi'_{12}\sigma'_{22}, \quad (1)$$

where π'_{11} , π'_{12} and π'_{16} are the respective longitudinal, transverse and shear piezoresistive coefficients and σ'_{11} , σ'_{22} and σ'_{12} are the respective longitudinal, transverse, and shear stress components. Furthermore, σ'_{12} is small enough to be neglected under hydrostatic pressure loading conditions [2].

For the piezoresistors isolated and bound by the completely-filled narrow trenches, the relative change in the longitudinal resistivity is given by (1). For those isolated by the partially-filled wide trenches, σ'_{22} can be largely relieved by a proper design of the trench dimensions, thus reducing the biaxial stress field to a uniaxial stress field. In this case, the relative change in the longitudinal resistivity is given by

$$\frac{\Delta\rho'_{11}}{\rho} \approx \pi'_{11}\sigma'_{11}. \quad (2)$$

A 2-dimensional finite-element analysis was carried out to investigate the dependence of σ'_{22} on the dimensions of the trench and the piezoresistor (Fig. 3). It is concluded that the width w of the piezoresistor should be ≤ 3 times the depth h of the trench in order to effectively relieve the transverse stress σ'_{22} on the piezoresistor.

Figure 3: 2-dimensional finite-element analysis of a trenched piezoresistor under 200-MPa lateral compression. (a) The transverse compressive stress is plotted along the dotted path from the top and (b) the dependence of the transverse stress on w/h at the top of a piezoresistor defined by two wide trenches.

Under an applied hydrostatic pressure P of 200 MPa, the simulated values of $\sigma_{[1\bar{1}0]}$ and $\sigma_{[001]}$ are respectively -126 and -100 MPa around the center of the die where the piezoresistors are located [2]. The relative sensitivity of the pressure sensor, estimated and summarized in Table I, is proportional to the magnitude of the difference $\left|\Delta\left(\frac{\Delta\rho}{\rho}\right)\right|$ between the $\frac{\Delta\rho}{\rho}$ of the two orthogonal pairs of piezoresistors: R_1 and R_3 aligned to the $[001]$ orientation, and R_2 and R_4 aligned to the $[1\bar{1}0]$ orientation.

Table I: Relative pressure sensitivity $\left|\Delta\left(\frac{\Delta\rho}{\rho}\right)\right|$ for all combinations of wide and narrow trenches in both p- and n-type piezoresistors.

R_1, R_3	R_2, R_4	$\left \Delta\left(\frac{\Delta\rho}{\rho}\right)\right $ (%) (p-Type)	$\left \Delta\left(\frac{\Delta\rho}{\rho}\right)\right $ (%) (n-Type)
Wide	Wide	8.4	6.3
Narrow	Narrow	8.4	4.9
Narrow	Wide	8.5	0.4
Wide	Narrow	8.3	11.6

It can be seen that wide and narrow trenches have little impact on the pressure sensitivity for an implementation with p-type piezoresistors. The impact is, however, significant for an implementation with n-type piezoresistors for which the highest sensitivity is obtained by having wide trenches on R_1 and R_3 , and narrow trenches on R_2 and R_4 . With this configuration the sensitivity of an implementation using n-type piezoresistors can be ~ 1.4 times higher than that of an implementation using p-type piezoresistors.

A schematic layout of the sensor and trench designs for the best n-type piezoresistor configuration is shown in Fig. 4. Implemented are R_1 and R_3 defined by 10- μm wide trenches, and R_2 and R_4 by 1- μm narrow trenches.

Figure 4: Sensor layout showing piezoresistors R_2 and R_4 defined by completely-filled narrow trenches and piezoresistors R_1 and R_3 defined by partially-filled wide trenches for the relief of the transverse stress.

FABRICATION

Sensor fabrication started with an SOI wafer with a 3- μm thick $[110]$ -oriented device layer. 1- μm and 10- μm wide trenches were etched on the device layer reaching the buried oxide layer (Fig. 5a). These were subsequently oxidized to define the piezoresistor active areas. Incidentally, a small notch (Fig. 6) was formed on the top of the oxide-filled narrow trenches resulting from the oxidation process. A blanket boron implantation at an energy of 27 keV and dose of $2.6 \times 10^{15} \text{ cm}^{-2}$, and a second selective boron implantation at the same energy but a higher dose of $2 \times 10^{16} \text{ cm}^{-2}$ were performed, respectively to adjust the doping level of the p-type piezoresistors and to form the P+ electrical leads (Fig. 5b). A 200-nm thick cover silicon dioxide was then deposited by low-pressure chemical vapor deposition, prior to the activation of the implanted dopants at 1000 $^{\circ}\text{C}$ for 30 min. Contact holes were opened through the cover oxide layer and a 1.5- μm aluminum-silicon (Al-Si) alloy was deposited and patterned to form the contact pads and the bond ring for the subsequent aluminum-germanium (Al-Ge) eutectic bonding.

A separate silicon cap wafer was prepared, on which 200- μm deep cavities were formed using deep reactive-ion etching and subsequently covered with a 500-nm thick evaporated Ge (Fig. 5c). Eutectic bonding of the device and cap wafers (Fig. 5d) was carried out under a force load of 40 kN at 430 $^{\circ}\text{C}$ for 5 min in vacuum. The eutectic melt was able to overcome the topography of the small notch, thus resulting in hermetic sealing of the cavity. The $2.5 \times 2.5 \text{ mm}^2$ sensor die (Fig. 7) was packaged after dicing and tested in a custom setup [2].

The same process could be applied to fabricate sensors with n-type piezoresistors by changing the implanted species from boron to phosphorus, energy to 50 keV, and implant doses to 10^{15} and 10^{16} cm^{-2} , respectively, for the piezoresistors and the N+ electrical leads.

Figure 5: Schematic cross-sections illustrating the fabrication of the SOI pressure sensor having piezoresistors with narrow and wide trenches. (a), (b) SOI wafer, (c) cap wafer, and (d) Al-Ge bonding.

Figure 6: SEM micrograph of the oxide-filled narrow trench.

Figure 7: Photomicrograph of the fabricated SOI pressure sensor die.

TEST RESULTS

SOI pressure sensor with p-type piezoresistors was first realized. The pressure sensor was subjected to an applied hydrostatic pressure P and the dependence of the resistance of individual piezoresistors on P was characterized at room temperature. The test

results shown in Fig. 8 are from a pressure sensor in which all four p-type piezoresistors are defined by wide trenches. Consistent with the theory [2], R_1 and R_3 aligned with the $[001]$ orientation are almost independent of P , whereas R_2 and R_4 aligned with the $[1\bar{1}0]$ orientation are sensitive to P . The resistance of R_2 and R_4 decreases by $\sim 2.8\%$ over the 200 MPa range of applied P .

Figure 8: Dependence of the resistance of individual piezoresistors on the applied pressure at room temperature for the SOI pressure sensor with p-type piezoresistors all defined by wide trenches.

The measured Wheatstone bridge output voltage V_{OUT} of the SOI pressure sensor versus P and temperature is shown in Fig. 9. The discontinued plot at 225 °C was due to a pressure seal failure of the test-package beyond 100 MPa at which point the pressure sensor die was still functional. A room-temperature sensitivity of 66 $\mu\text{V/V/MPa}$ over 200 MPa and a temperature coefficient of sensitivity of -1000 ppm/°C over 200 °C were obtained. On the other hand, the leakage current of the present dielectric-isolated pressure sensor remained low, reaching only 0.1 nA at 175 °C (Fig. 10a). This is less than one thousandth of the leakage current of a junction-isolated pressure sensor (Fig. 10b). A comparison of the sensor characteristics of this work and others is shown in Table II.

Figure 9: Wheatstone bridge output voltage of the SOI pressure sensor with p-type piezoresistors all defined by wide trenches.

Figure 10: Leakage current of (a) dielectric- and (b) junction-isolated pressure sensors.

Table II: MEMS piezoresistive high-pressure sensor comparison.

Ref.	Type	P_{max} (MPa)	ΔV_{out} (mV)	Power Supply	Temp. (°C)
[1]	All-Si Bulk	120	58	5 V	25~125
[2]	All-Si Bulk	200	79	5 V	25~175
[3]	Si-Glass Diaphragm	150	50	5 V	20~150
[4]	Si-Glass Diaphragm	150	167	1.5 mA	≤ 200
[5]	Si-Glass Bulk	200	22	5 V	N/A
[6]	Si-Glass Bulk	60	62	5V	-40~125
This Work	SOI Bulk	200	66	5 V	25~225

DISCUSSION AND CONCLUSION

A dielectric-isolated bulk-type pressure sensor on SOI with the piezoresistors defined by isolation trenches was designed and fabricated. Theoretical analysis shows that selective trenching on p- or n-type piezoresistors should result in appreciable difference in the pressure sensitivity, with n-type piezoresistors having better performance. Finite-element analysis shows that the applied stress acting on the piezoresistors could be biaxial or uniaxial, depending on the design of the trenches.

The fabricated sensor with p-type piezoresistors was characterized with pressure loading up to 200 MPa and temperature up to 225 °C. The respective sensitivity and temperature coefficient of sensitivity are $\sim 66 \mu\text{V/V/MPa}$ and $-1000 \text{ ppm/}^\circ\text{C}$. The high temperature performance of the SOI pressure sensor was experimentally demonstrated. The leakage current of the present dielectric-isolated pressure sensor was 0.1 nA at 175 °C, which is less than one thousandth of the leakage current of a junction-isolated pressure sensor.

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