Silicon on insulator pressure sensor based on a thermostable electrode for high temperature applications

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Published in Micro & Nano Letters; Received on 17th May 2015; Revised on 28th July 2015; Accepted on 28th July 2015

A high temperature silicon on insulator pressure sensor utilising a Ti/TiN/Pt/Au electrode is presented for improving the thermal stability of ohmic contacts, which can work stably at high temperatures of up to 500°C. To analyse the characteristics of the electrode at high temperatures, a special test structure is measured using the linear transmission line method and Auger electron spectroscopy. To solve the measurement problem, a novel calibration setup is designed to calibrate the absolute pressure sensor at extremely high temperatures. The measurement results have shown that the pressure sensor has a nonlinearity error of 0.17%FS and a sensitivity of 0.24 mV/kPa with a measurement range of 30–150 kPa at 500°C, indicating the good thermal stability of the ohmic contacts.

1. Introduction: High temperature pressure sensors have been widely applied in many fields, such as deep-drilling equipment, gas turbine engines and space exploration systems. To meet these requirements, various high temperature pressure sensors have been explored. Piezoresistive, capacitive or optical sensing can all be used for high temperature pressure sensors [1]. Among them, piezoresistive pressure sensors are more prevalent owing to their simple structures, as well as less complicated signal conditioning circuits. Owing to the degradation of p–n junction isolations at a temperature of more than 125°C [2], the most commonly used single-crystal silicon substrates cannot work for high temperature piezoresistive sensors. Instead, silicon on insulator (SOI), silicon carbide (SiC) or silicon on sapphire (SOS) can be used for the fabrication of high temperature pressure sensors [3–6]. Although SiC and SOS substrates show better high temperature characteristics, SOI-based high temperature pressure sensors still attract much attention for their relatively low cost and good performances up to 600°C, which meet most of the industrial requirements [7, 8].

Many efforts have been made to improve the performance of high temperature SOI pressure sensors. To withstand instantaneous ultra-high temperature impact, Zhao *et al.* [9] proposed a mechanical structure with a cantilever, diaphragm and transmitting beam. A Ti/Pt/Au beam-lead metallisation was fabricated to connect the piezoresistors. This pressure sensor can be used at 200°C and was able to endure an instantaneous impact of 2000°C. Li *et al.* [2] reported the high temperature piezoresistive effect of <110> oriented crystal silicon. The Cr/Ni/Au multilayer metallisation scheme and Corning 7740 glass were adopted to fabricate the sensor. The implemented device could work at high temperatures of up to 300°C. However, the development of SOI pressure sensors working up to 500°C is still challenging. The performance of high temperature SOI pressure sensors is largely dependent on the thermal stability of their ohmic contact electrodes. Owing to the interdiffusion between thin metal films and consequent silicon metal reactions at the elevated temperature [10, 11], the conventional ohmic contact electrodes such as Al, Cr/Au, Ti/Au and Ti/Pt/Au are not thermally stable above 450°C.

To solve the problems mentioned above, a $TiSi_2$/Ti/TiN/Pt/Au ohmic contact electrode with long-term thermal stability is proposed in this Letter. Auger electron spectroscopy (AES) and the linear transmission line method (TLM) are used to characterise the high temperature properties of the fabricated electrodes. Using the proposed electrodes, a high temperature SOI pressure sensor is designed and manufactured for verification.

2. Thermostable electrode: Instead of the commonly used metal–silicon contacts, silicide–silicon contacts are beneficial because of their superior thermal stability. In this Letter, titanium disilicide ($TiSi_2$) is particularly selected since it not only has excellent thermal and chemical characteristics but also can be fabricated using the self-aligned silicide process [12].

The electrode is a multilayer of Ti/TiN/Pt/Au. Titanium nitride (TiN) is inserted to inhibit intermetallic compound formation [13]. Experimental studies have revealed that a thin TiN layer can significantly prevent interdiffusion between Ti and Pt or Au at high temperatures (400–550°C) [10, 14]. The titanium thin film serves as an adhesion layer between the insulator and conductive metallic layers.

To characterise the specific contact resistance of the proposed multilayer electrode, a test structure based on TLM is designed and fabricated on SOI substrate. Fig. 1*a* shows the schematic view of the TLM structure. The cross-sectional image of it obtained by a scanning electron microscope is given in Fig. 1*b*. The current–voltage (I–V) characteristics between two pads are measured at 500°C. The test results shown in Fig. 1*c* indicate that the $TiSi_2$–Si contact exhibits ohmic behaviour. With the linear TLM [15], the specific contact resistance ρ_c is evaluated to be 2.5×10^{-5} Ω cm^2.

After annealing at 500°C in nitrogen ambient for 3 h, an AES depth profile analysis of the specimen was carried out using a PHI-700 scanning Auger nanoprobe.

As shown in Fig. 2, the AES results indicate some interdiffusion at the Pt–Au interface has happened, but the remaining regions of Pt and Au maintain their integrity. Furthermore, both Ti–Pt interaction and Au–Si eutectic reaction are prevented by the TiN barrier layer. Consequently, the proposed multilayer electrode can be used for the fabrication of high temperature pressure sensors.

Micro & Nano Letters, 2015, Vol. 10, Iss. 10, pp. 496–499
doi: 10.1049/mnl.2015.0181

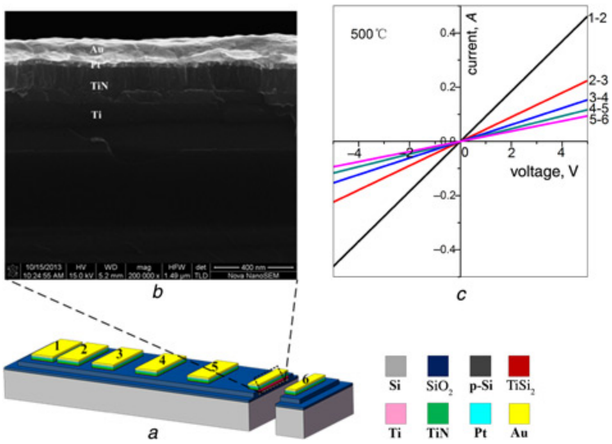

Figure 1 *TLM structure*
a Schematic view of the TLM structure
b Cross-sectional SEM image of the multilayer electrode
c Current–voltage (I–V) characteristics between two pads

3. Sensor design: The finite element analysis tool ANSYS has been used to analyse the stress distribution on the silicon diaphragm and to optimise the performance of the pressure sensor. In this simulation, the sensor chip has dimensions of 3600 µm × 3600 µm × 400 µm. The sensing diaphragm has dimensions of 800 µm × 800 µm. The stress distribution under the applied pressure of 150 kPa is shown in Fig. 3*a*. A path from point L to point R is set up and the stress distribution along this path is given in Fig. 3*b*.

The sensitivity and nonlinearity are affected by many factors [16, 17]. Fig. 4 shows the output voltage and nonlinearity change with the thickness of the diaphragm. The Wheatstone bridge is powered by a constant voltage of 5 V. The dimensions of the sensing diaphragm are fixed at 800 µm × 800 µm. The simulation results indicate that the sensitivity increases as the thickness of the diaphragm decreases. Considering both process deviation and performance, the thickness of the diaphragm is chosen to be 20–24 µm.

To optimise the performance of the high temperature pressure sensor, four kinds of piezoresistor structures are proposed as shown in Fig. 5. The dimensions of the sensing diaphragm are fixed at 800 µm × 800 µm × 22 µm. The total length of the piezoresistors is fixed at 480 µm. The meander-shaped piezoresistors with different turns are arranged near the centre of the diaphragm edges, where the stresses are large and concentrated [18, 19].

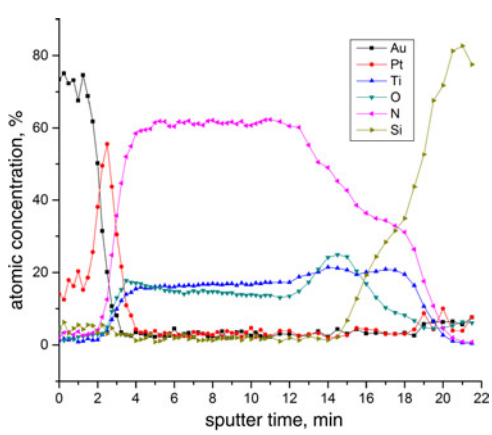

Figure 2 *AES depth profiles of the metallisation scheme: after annealing at 500°C for 3 h in N_2 ambient*

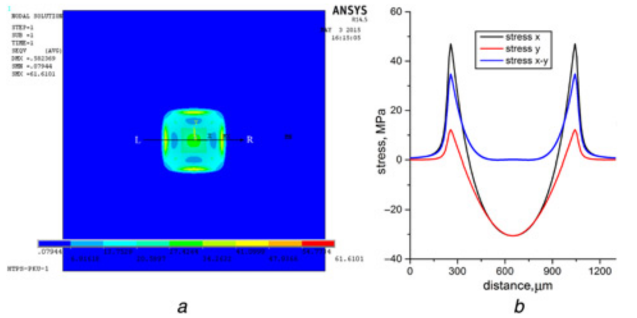

Figure 3 *FEM simulation results of sensing diaphragm*
a Stress distribution of a square diaphragm
b Stress distribution along the path from point L to point R

Fig. 6 shows the output voltage and nonlinearity change with the shape of the piezoresistor without considering the effect of the connecting arms. The FEM simulation results indicate that the sensitivity and nonlinearity of the piezoresistive pressure sensor are influenced both by the shape and the position of the piezoresistor.

4. Fabrication: A 4-inch double-side polished SOI wafer is used to fabricate the piezoresistive pressure sensor. The thickness of the wafer is 400 µm. The device layer is 0.34 µm and the buried oxide layer is 0.4 µm (Fig. 7*a*). First, the device layer of the SOI wafer is patterned (Fig. 7*b*) and doped to fabricate pressure sensing resistors (Fig. 7*c*). Then, the SiO_2/Si_3N_4 passivation layers are deposited by low pressure chemical vapour deposition.

Next, a $TiSi_2$–Si ohmic contact is fabricated using the self-aligned silicide process (Fig. 7*e*). Ti/TiN/Pt/Au multilayer films are then sputtered and patterned using lift-off to form electrodes and metal interconnects (Fig. 7*f*). The passivation layers SiO_2 and Si_3N_4 on the backside of the wafer are patterned to form masks of anisotropic etching.

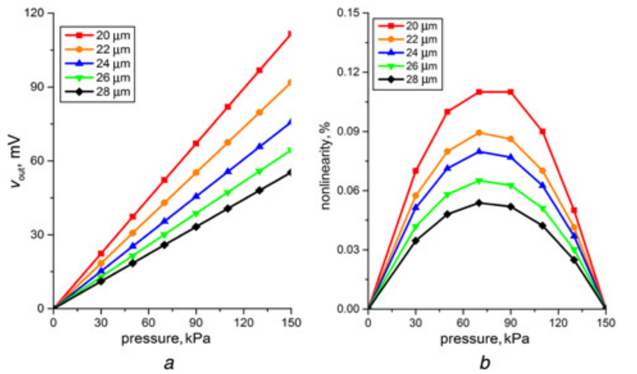

Figure 4 *Output voltage and nonlinearity change with the thickness of diaphragm*
a Output voltage plots for different diaphragm thicknesses
b Nonlinearity plots for different diaphragm thicknesses

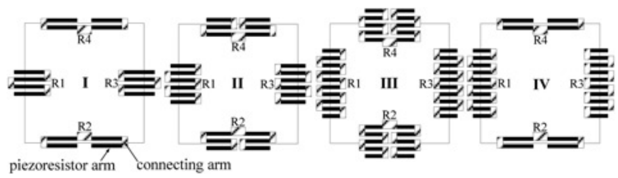

Figure 5 *Schematic view of the piezoresistor shapes*

doi: 10.1049/mnl.2015.0181

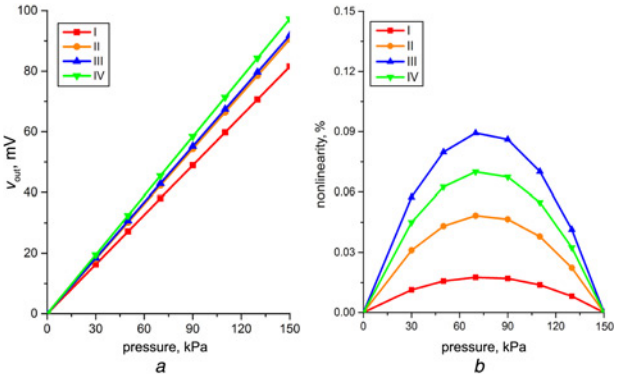

Figure 6 *Output voltage and nonlinearity change with the shape of the piezoresistor*
a Output voltage plots for different piezoresistor shapes
b Nonlinearity plots for different piezoresistor shapes

Subsequently, tetramethylammonium hydroxide (TMAH) solution (25wt. % at 80°C) is applied to fabricate the silicon diaphragm and cavity. The etching rate is ~0.33 μm/min (Fig. 7*g*).

The passivation layers on the backside of the wafer are then removed using reactive ion etching, followed by the anodic bonding between the SOI wafer and the glass wafer (Fig. 8*h*). The strain points of the Corning 7740 glass and the Schott Borofloat 33 glass are ~510°C. Hence, these two commonly used glass wafers are not thermally stable above 450°C [20]. Compared with Corning 7740 glass and Schott Borofloat 33 glass, the strain point of the HOYA SD2 glass wafer is much higher (669°C), thus it has been selected in this work.

5. Characterisation: Normal pressure sensors are usually calibrated over a temperature range of −40 to 125°C. The pressure sensors are placed inside a metal testing container,

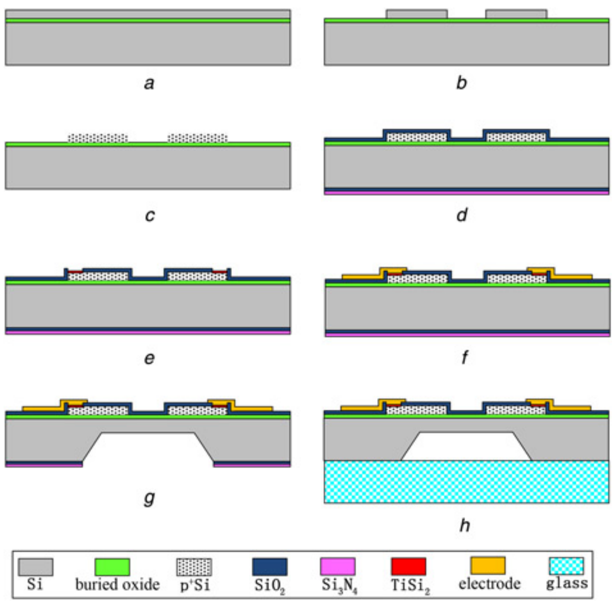

Figure 7 *Process flow for high temperature pressure sensor*
a Substrate is a 4-inch SOI wafer
b Device layer is patterned and etched
c Device layer is doped to fabricate piezoresistors
d SiO_2 and Si_3N_4 layers are deposited
e $TiSi_2$-Si ohmic contact is fabricated using self-aligned process
f Ti, TiN, Pt and Au films are sputtered and patterned using lift-off
g Wafer is etched in TMAH solution
h SOI-glass anodic bonding

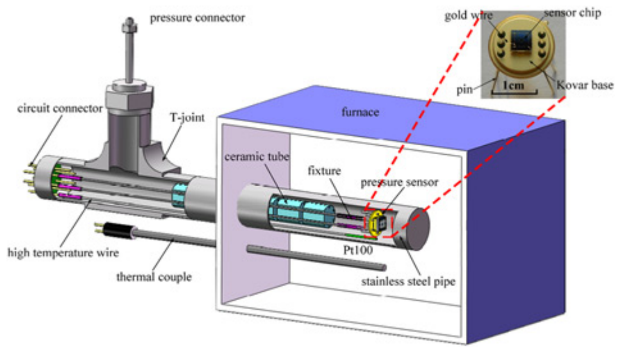

Figure 8 *Schematic view of the calibration device for high temperature pressure sensors*

which is commonly sealed using rubber sealing rings or epoxy sealants. However, the rubber sealing rings and epoxy sealants cannot keep the hermetic sealing above 300°C. Therefore it is a challenge to calibrate the pressure sensor in an ultra-high temperature and high pressure environment. Young *et al.* [21] proposed an apparatus for testing a SiC pressure sensor operating at 400°C. The pressure sensor was attached to a ceramic substrate and placed inside a sealed testing chamber equipped with a heater. A thermal couple was positioned near the pressure sensor for measuring the temperature. The testing apparatus can be applied to generate simultaneously high pressures and temperatures. However, the pressure sensor chip must be attached to the heater closely to heat the pressure sensor evenly. If the pressure sensor has been assembled on a Kovar base, it is difficult to heat the sensor chip evenly.

To solve this problem, a novel calibration setup is designed for calibrating pressure sensors at extremely high temperatures. After dicing, the absolute pressure sensor has been assembled on a Kovar base. The sensor chip and the pins of the Kovar base are connected using the wire bonding process.

As shown in Fig. 8, the absolute pressure sensor is positioned in a closed end stainless steel pipe. The pins of the Kovar base and the high temperature wires are connected by special fixtures. To improve the reliability of the device, both the pins and the high temperature wires are wrapped around ceramic tubes. One end of a T-joint is connected to the opening end of the stainless steel pipe. The other ends are connected to a pressure connector and a circuit connector. Then, the closed end of the stainless steel pipe is inserted into a furnace through a thermometer hole. In this way, only the stainless steel pipe and the pressure sensor are in the furnace, while the pressure connector and the circuit connector

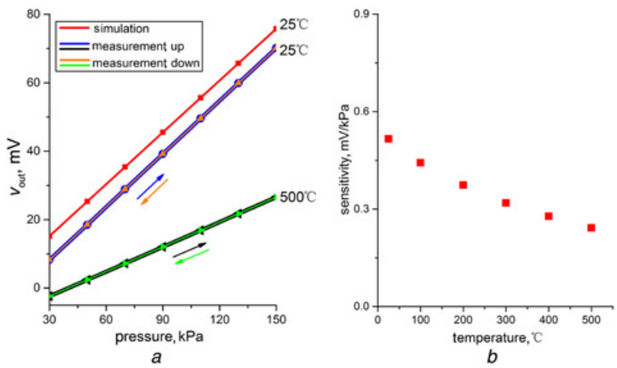

Figure 9 *Experimental results and temperature sensitivity drift*
a Measurement results of the pressure sensor
b Temperature sensitivity drift of the pressure sensor

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Table 1 Main performances of the pressure sensor

temperature, °C	25	500
pressure range, kPa	30–150	30–150
supply voltage, V	5	5
full scale output, mV	70.2	26.6
zero output, mV	−7.2	−9.7
sensitivity, mV/kPa	0.51	0.24
nonlinearity error, %FS	0.08	0.17

are placed outside the furnace. As a result, the connectors can be sealed using ordinary sealants at room temperature.

With the homemade calibration setup, the performance of the pressure sensor is tested. It is powered by a constant voltage of 5 V. The pressure range is 30–150 kPa, which is controlled by a gas pressure controller. The temperature range is 25–500°C.

The experimental results are depicted in Fig. 9*a*. The test results demonstrate that the nonlinearity error is 0.17%FS and the sensitivity is 0.24 mV/kPa at 500°C. The main performances of the pressure sensor are presented in Table 1.

Fig. 9*b* shows the sensitivity variation with temperature, which is mainly caused by the thermal drift of the silicon's piezoresistive coefficient. The thermal drift can be reduced by increasing the dopant concentration or applying special temperature compensation circuits.

6. Conclusion: This Letter presents an SOI high temperature pressure sensor using a thermostable ohmic contact electrode of $TiSi_2$/Ti/TiN/ Pt/Au. Linear TLM and AES have been used to analyse the properties of the electrode at high temperatures. The test results show that the multilayer electrode can be used for the fabrication of high temperature pressure sensors. Moreover, an SOI high temperature pressure sensor is designed and fabricated using this multilayer electrode structure. A novel calibration setup is designed to calibrate the pressure sensor at extremely high temperatures. The experimental results demonstrate a nonlinearity error of 0.17%FS and sensitivity of 0.24 mV/kPa at 500°C with a measurement range of 30–150 kPa. The pressure sensor can be applied in extremely high temperature environments. More work will be devoted to reducing thermal drift and improving package reliability.

7. Acknowledgments: This work was supported by the National High Technology Research and Development Program of China (grant no. 2012AA041201). The authors acknowledge support from the National Key Laboratory of Science and Technology on Micro/Nano Fabrication, Peking University. They also thank Z. Yang, W. Wang, C. Yang, Q. Zhao and K. Xu for technical discussion.

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