Total dose radiation effects of pressure sensors fabricated on Unibond-SOI materials

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Abstract Piezoresistive pressure sensors with a twin-island structure were successfully fabricated using high quality Unibond-SOI (On Insulator) materials. Since the piezoresistors were structured by the single crystalline silicon overlayer of the SOI wafer and were totally isolated by the buried SiO_2, the sensors are radiation-hard. The sensitivity and the linearity of the pressure sensors keep their original values after being irradiated by ^{60}Co γ-rays up to 2.3×10^4 Gy (H_2O). However, the offset voltage of the sensor has a slight drift, increasing with the radiation dose. The absolute value of the offset voltage deviation depends on the pressure sensor itself. For comparison, corresponding polysilicon pressure sensors were fabricated using the similar process and irradiated at the same condition.

Keywords Total dose radiation, Pressure sensor, Silicon on insulator

CLC numbers TN386.1 A

1 INTRODUCTION

Silicon On Insulator (SOI) is used as an attractive substrate for modern submicrometer integrated circuits, especially for low voltage, low power integrated circuits. Moreover, SOI circuits are inherently tolerant to ionizing irradiations and high temperatures[1]. There has been an increasing tendency in recent years to apply SOI materials in the microelectromechanical systems (MEMS)[2,3]. Compared with bulk silicon, SOI wafer has a buried SiO_2 layer. It can be used as a dielectric isolation layer, an etching self-stopping layer or a sacrificial layer, which gives an additional freedom for design and fabrication of the micro-mechanical sensors and transducers.

In a traditional bulk silicon pressure sensor, the sensing elements are usually isolated from each other by PN junctions. The sensors cannot work at high temperature since a significant leakage current occurs at temperatures above about 100°C. On the other hand, polysilicon pressure sensors can work at high temperatures since their sensing elements are isolated from each other by SiO_2 layers. However, sensitivity of ploysilicon pressure sensors is much lower than that of bulk-Si pressure sensors[4] because the sensing elements are formed using a deposited polycrystalline silicon layer on a thermal oxidized silicon

Supported by Science and Technology Development Foundation of Shanghai under Grant (No. 98JC14004) and partly by National Natural Science Foundation of China (No. 69876007)

Manuscript received date:2001-01-07

wafer. It is well known that mechanical properties of the poly-Si are not as good as the single-crystalline Si[4]. The SOI materials combine both benefits of single crystalline Si elements with dielectric isolation. So the SOI pressure sensors have similar sensitivity as the bulk Si sensors and similar high temperature tolerance as the polysilicon sensors[5]. Moreover, an SOI pressure sensor is expected to be radiation-hard due to its totally dielectric isolation.

SOI pressure sensors have been fabricated using various SOI materials such as SIMOX (Separation by implanted oxygen)[2], BESOI (Bonding and Etching-back SOI)[3] and FIPOS (Fully Isolation by Porous Oxidized Silicon)[6] etc. Recently a new SOI material fabrication technology based on low temperature wafer bonding and layer-cutting induced by implanted hydrogen (also named as Unibond-SOI) was developed[7]. In this paper, high quality 3-inch Unibond-SOI wafers were fabricated by using a modified layer-cutting process. Piezoresistive pressure sensors were successfully fabricated on those Unibond-SOI wafers using similar layout as poly-Si pressure sensors. Total dose radiation and temperature effects are studied on the sensors.

2 EXPERIMENTAL

Starting materials are 3-inch, n-type, (100)-oriented Si wafers with a resistivity of $5\sim8\,\Omega$cm. The total thickness variation (TTV) is better than 2μm and the surface roughness is less than 0.5 nm. After thermal oxidation, the wafers were implanted with H^+ ions to a dose of 6×10^{16} cm^{-2} at 70 keV. Immediately after cleaning using an improved RCA process, the implanted wafer and another oxidized wafer (substrate wafer) were bonded together in a microcleanroom set-up at room temperature. The bonding strength was increased by annealing the pairs at low temperatures ($\leq$200°C) for several days. Then the pairs were annealed in a furnace in N_2 ambient. At about 500°C, the hydrogen-implanted Si was delaminated along an interface near the projected range. A thin single crystalline silicon layer was transferred to the substrate wafer and an SOI structure was formed. The SOI structure was re-annealed at 1100°C for 2 hours in order to increase the bond strength and to remove the implantation-induced-damages in the Si overlayer. Detailed process for the Unibond-SOI technique was reported in our previous papers[8,9].

The backside of the SOI wafer was ground and polished to form a both-side polished SOI wafer with a thickness of 240μm. A twin-island-beam-membrane structure was designed for the sensor chip, which is shown in Fig.1 schematically. The backside of the SOI wafer was anisotropically etched in a KOH solution to form back islands and beams. In the front side of the SOI wafer, using both-side alignment technique and boron diffusion process, four piezoresistors were formed in the single crystalline Si overlayer. Two of them were located between islands and the other two were placed between the boundary and the island symmetrically, as shown in Fig.1(c). The resistance is about $9.2\sim9.5$ kΩ. These four resistors were connected as a Wheatstone bridge and were isolated each other by the buried SiO_2 layer. The chip was sealed on a glass using an electrostatic bonding technique and was packaged in a steel pedestal[5].

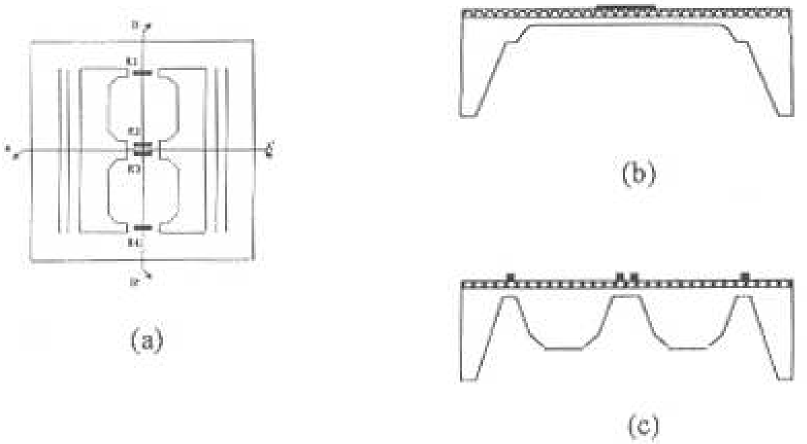

Fig.1 Schematic views of the pressure sensor with a twin-island-beam-membrane structure
(a) top view, (b) cross-section view of AA', (c) cross-section view of BB'

The pressure sensors were irradiated by ^{60}Co γ-rays. An applied voltage (5 V) was put on or off during the irradiation. The dose rate was 2.3×10^4 Gy (H_2O)/h. After one hour irradiation, the sensors were measured. For comparison, some polysilicon sensors that were made using the same layout design and process parameters were also irradiated and measured.

3 RESULTS AND DISCUSSION

The quality of the Unibond-SOI depends to a great extent on the bonding quality. Small voids in the bonding interface can cause large defects during the splitting of the bonded wafer. Moreover, even though no defects in the bonding interface are detected by an infrared (IR) transmission camera, small babbles of high density may exist in the SOI overlayer. If so, the device fabrication will be impossible. Such babbles have been attributed to the contamination of carbon-related trace impurities before bonding[9]. We were able to reduce the density of the babbles dramatically using an improved RCA cleaning process in our experiments. Fig.2 shows the topography of the as-formed SOI surface by a magic mirror. There are

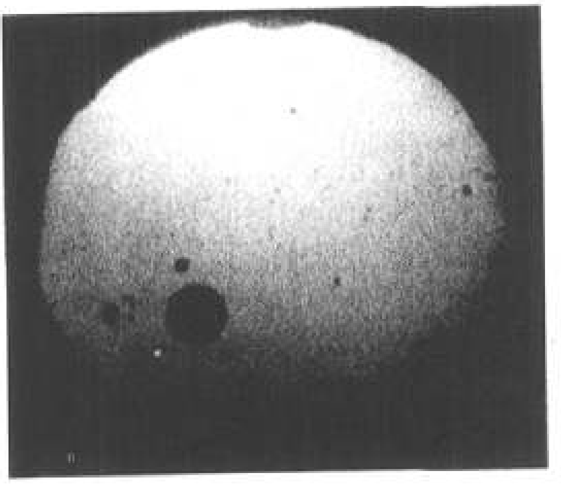

Fig.2 Magic mirror image of the SOI surface using an improved RCA cleaning process

only several babbles in the whole wafer. The quality is good enough for the pressure sensor fabrication.

The surface of the as-split SOI wafer is bright and mirror-like. Atomic force microscopy (AFM) measurements show that the roughness $< R_a >$ is about 7 nm. Fig.3 shows an AFM topography of the SOI surface. Such a surface roughness is too large for VLSI applications and wafers will have to be treated by CMP (chemical mechanical polishing) procedure. However, the roughness is acceptable for the micro-sensors and the CMP procedure is not necessary, hence reducing of the cost.

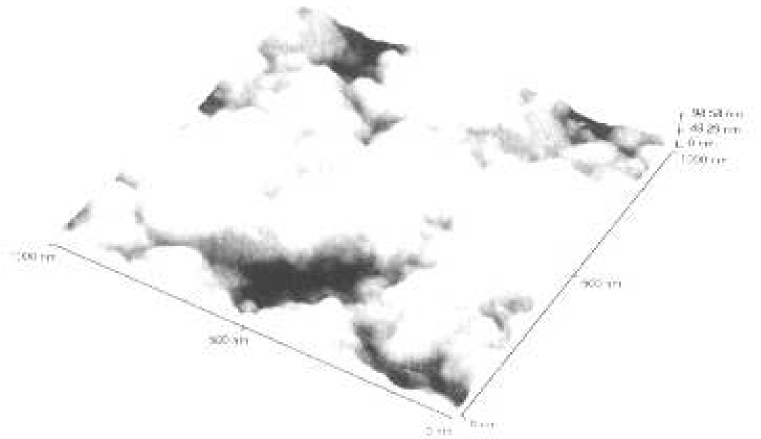

Fig.3 AFM image of the as-spilt SOI surface

As expected, the SOI pressure sensor has better properties than those of the polysilicon sensor. Its sensitivity is 65 mV/(MPa·5V), about 7 times higher than that of the polysilicon sensor. The SOI pressure sensor works at 200°C. The temperature coefficients of the sensitivity and the offset voltage are 2.0×10^{-3}Fs/°C and 2.18×10^{-4} Fs/°C, respectively.

Fig.4 (a), (b) show the output voltage of the SOI pressure sensor in an applied voltage of 5 V as a function of applied pressure before and after irradiation, respectively. The results of a polysilicon sensor are also shown for comparison. After 2.3×10^4 Gy(H_2O) γ-ray irradiation, the sensitivity and the linearity of both types of pressure sensors does not degenerated, either the applied voltage is put on or off during irradiation. All the other sensors measured in our experiment have the similar property. For the twin-island structure, the output of the pressure sensor can be approximated by[4] $V_{\rm out} \approx 1.5P\frac{c^2}{h^2}(1-\nu)\frac{1}{2}\pi_{44}V_{\rm s}$, where P is the input pressure, $V_{\rm s}$ is the applied voltage, c is the sensor chip size, h is the membrane thickness, ν and π_{44} are the Poisson's ratio and piezoresistive coefficient of silicon, respectively. Since the mechanical properties of silicon (ν and μ)

are not sensitive to ionizing radiation[10], the output of the sensors is inherent tolerance to ionizing radiation.

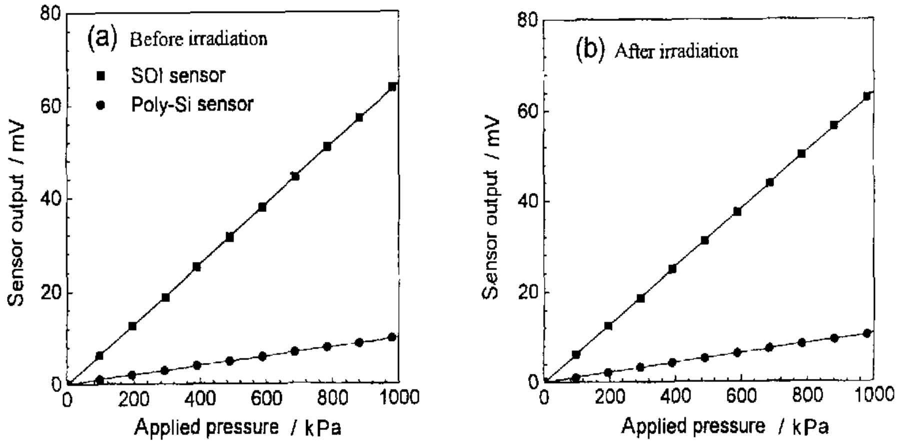

Fig.4 Sensor output voltage vs. applied pressure for the applied voltage of 5 V
(a) before and (b) after irradiation by 2.3×10^4 Gy(H_2O) γ-rays

However, we found that the offset voltages of the pressure sensors had changed after irradiation. Table 1 lists the offset voltages for two SOI sensors and one polysilicon sensor before and after irradiation.

Table 1 Offset voltages of the pressure sensors before and after radiation

Pressure sensor	Offset voltage/mV	
	Before irradiation	2.3×10^4 Gy(H_2O)
SOI(#1)	48.6	42.2
SOI(#2)	15.8	14.3
Ploysilicon(1)	0.0	0.1

(1)This sensor has a compensation resistor, so that the original value is zero

The offset voltage is mainly caused by the deviation of the geometries of the sensing elements and the stresses in the chip induced by a mismatch of the coefficient of thermal expansion between the silicon and the packaging materials. The second factor is insensitive to ionizing irradiation. The first factor, however, causes non-identical resistors for the Wheatstone bridge. Then, the offset voltage V_{OS} is given as: $V_{os} = V_s(R_2R_3 - R_1R_4)/[(R_1 + R_2)(R_3 + R_4)]$, where R_i is the resistance. The resistivity of Si may be affected by the radiation-induced damage[10]. Another factor that may cause the variation of the resistance can be attributed to the positive trapped-oxide charge in the buried SiO_2 and the Si/SiO_2 interface traps[11,12]. It can cause the accumulation or depletion of the charge in the Si overlayer near the Si/SiO_2 interface and hence change the resistance of the Si resistors. However, as the offset voltage is related to the detail of the geometry of the sensing elements and may be affected by many other factors (such as the measurement temperature), a quantitative analysis of the offset voltage variation with the radiation dose is difficult.

4 Summary

High quality Unibond-SOI materials are fabricated using the layer-cutting techniques with an improved RCA cleaning process. The final CMP procedure is not necessary for the sensor fabrication. Piezoresistive pressure sensors with a twin-island-beam-membrane structure are successfully fabricated using those Unibond-SOI wafers. The sensitivity of the sensor is 65 mV/(MPa·5V), 7 times larger than that of the polysilicon sensor. After 2.3×10^4 Gy(H_2O) irradiation, the sensitivity and the linearity of the output property do not degenerated. However, the offset voltage has a slight shift. The polysilicon pressure sensor has a similar radiation behavior.

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