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SOI Pressure Sensors

Gwiy Sang Chung*, Makoto Ishida**, Tetsuro Nakamura**

SOI 壓力센서

鄭貴相, 石田誠, 中村哲郎

Abstract

This paper describes the characteristics of a piezoresistive pressure sensor fabricated on a SOI (Si-on-insulator) structure, in which the SOI structures of Si/SiO_2/Si and Si/Al_2O_3/Si were formed by SDB (Si-wafer direct bonding) technology and hetero-epitaxial growth, respectively. The SOI pressure sensors using the insulator of a SOI structure as the dielectrical isolation layer of piezoresistors, were operated at higher temperatures up to 300 ℃. In the case of pressure sensors using the insulator of a SOI structure as an etch-stop layer during the formation of thin Si diaphragms, the pressure sensitivity variation of the SOI pressure sensors was controlled to within a standard deviation of ±2.3% over 200 devices. Moreover, the pressure sensors fabricated on the double SOI (Si/Al_2O_3/Si/SiO_2/Si) structures formed by combining SDB technology with epitaxial growth also showed very excellent characteristics with high-temperature operation and high-resolution.

요 약

본 논문은 실리콘기판 직접접합기술과 에피택샬 성장법으로 각각 형성한 SOI구조, 즉 Si/SiO_2/Si 및 Si/Al_2O_3/Si 상에 제작한 압저항형 압력센서의 특성을 기술한다. SOI구조의 절연층을 압저항의 유전체 분리막으로 이용한 압력센서는 300℃ 까지 사용 가능했다. SOI구조의 절연층을 박막 실리콘 다이어프램 형성시 에칭 중지막으로 이용한 경우, 제작된 압력센서의 200개 소자들에 대한 압력감도의 변화는 ±2.3% 이내로 제어 가능했다. 더구나 실리콘기판 직접접합기술과 에피택샬 성장법의 결합으로 형성한 더블 SOI구조(Si/Al_2O_3/Si/SiO_2/Si)상에 제작된 압력센서는 고온분위기에서 사용 가능할 뿐만 아니라 고분해 능력을 갖는 특성을 보였다.

I. Introduction

As Si planar process and micromachining technologies advanced, monolithic Si pressure sensors offer many advantages such as small size, low manufacturing cost, high-sensitivity, no-hysteresis and reliability as compared with conventional metal strain-gauges. Among various solid-state pressure sensors such as (1) the piezoresistive effect of resistors, (2) the piezoelectric effect of films, (3) the stress effect on a pn junction, (4) an optical deflection or optical fiber and (5) the capacitive effect of a deformable diaphragm, the single-crystalline Si piezoresistive pressure sensor is currently one of the most widely used pressure sensors because of high-sensitivity, small nonlinearity and long-term stability over a wide pressure range, and suitable for batch-fabrication.[1] However, this device continues to suffer from various problems, in which the two most important problems are low yield and excessive tempera-

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* 正會員 : 東西工科大學校 電子工學科
(Dept. of Electronics, Dongseo Univ. of Technology)
** 日本 豊橋技術科學大學 電氣·電子工學科
(Dept. of Electrical and Electronic Eng., Toyohashi Univ. of Technology, Japan)
<접수일자 : 1993년 10월 7일>

ture drift.[2~3] Both of these factors have resulted in high-cost. The main cause of low yield is the lack of controllability and reproducibility in forming thin Si diaphragms by anisotropic etching. Temperature drift due to pn junction isolation is the largest single factor limiting the application such sensor to the automobile and to others demanding high-performance operating in high-temperature circumstances. Even though integrated pressure sensors with compensation circuits have been developed to overcome these problems,[4~6] they have not been utilized yet. The continuous optimization of the sensing-element itself demands not only improved fabrication process for the accurate thickness control of thin Si diaphragms but also alternative method to remove as many as possible the sources of the temperature drift.

As one of vehicle for solving of limitations mentioned above, a SOI(Si-on-insulator) structure is very attractive to because the insulator of a SOI structure can be used as either an etch-stop layer for the thickness controllability and surface smoothness of thin Si diaphragms or the dielectrical isolation layer of piezoresistors.[7]

This paper describes the characteristics of SOI pressure sensors using the insulator of a SOI structure as an etch-stop layer as well as the dielectrical isolation layer, respectively. Moreover, a novel pressure sensor with double SOI structures is proposed and its typical output characteristics is presented. The SOI structures of Si/SiO_2/Si and Si/Al_2O_3/Si utilized in this work were formed by SDB(Si-wafer direct bonding) technology and hetero-epitaxial growth, respectively.

II. Formation of a SOI structure

1. Formation process of a Si/SiO_2/Si structure by SDB technology

The formation process of a SOI structure by the developed SDB technology is briefly described. Starting materials were 2 or 4-inch Si (100) wafers with 110 nm thick thermal grown SiO_2. The bonding of the two wafers was performed *in situ* in the same oxidation furnace at 1000 ℃ and the bonded wafer was heated for 30 min. in a wet ambient. One side of the uncontacted areas or void-free bonded Si wafer was thus roughly thinned by a conventional polishing process to 10 μm thickness. Finally, the SOI layer of the desired thickness was obtained by a computer-controlled polishing system.[8] Polishing was repeated until a uniform SOI layer was achieved. Thus, we obtained the SOI layer with a mirrorlike surface, good flatness and uniformity of 30 % or better on area, This uniformity is adequate for most sensing-elements and MOS device application as shown in Fig. 1, and it could be improved with tighter process control.

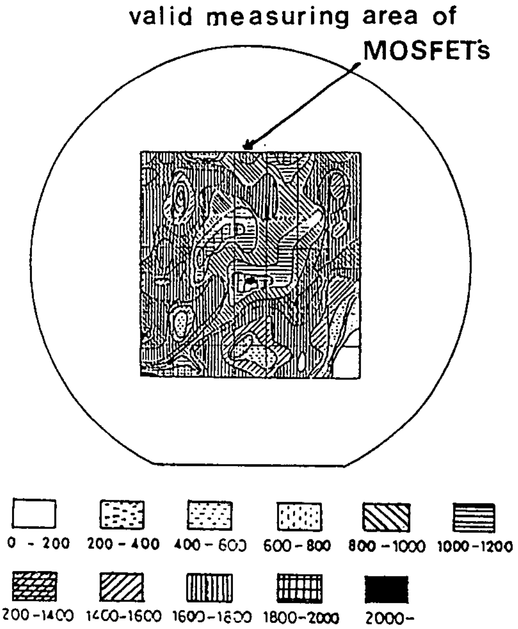
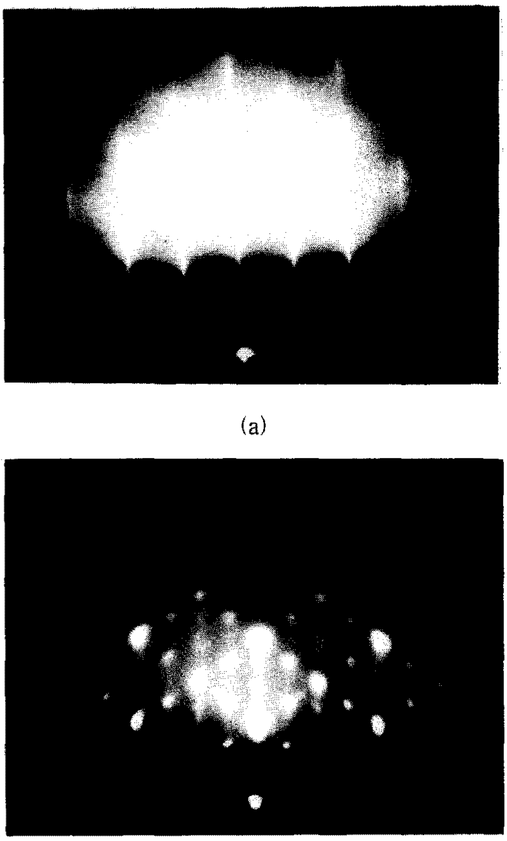


Fig. 1. Thickness contour plot showing SOI film thickness variation over a 2-inch Si wafer.

2. Formation process of epitaxially stacked Si/ Al_2O_3/Si structures

The formation process of epitaxially stacked Si/Al_2O_3/Si structures using Al_2O_3 films as an epitaxial insulator[9] is as following : The SOI structure was formed by the epitaxial growth of Al_2O_3 films on a 2-inch Si (100) substrate by LPCVD and then epitaxial Si films were sucessively grown on the epitaxial Al_2O_3 (100)/Si (100) substrate using CVD method. The epitaxial Al_2O_3 films were grown by pyrolysis of N_2-bubble $Al(CH_3)_3$(TMA) and N_2O at a pressure of 30 Torr. Gas flow rates of TMA and N_2O were 30 sccm and 20 sccm, respectively. N_2 gas for dilution was 1000 sccm. The growth temperature and the growth rate were 1050 ℃ and 72 Å/min., respectively. With this condtion, the epitaxial Al_2O_3 films of 0.1 μm thickness were grown on the Si substrate.



(a)

(b)

Fig. 2. RHEED patterns of epitaxial (a) 0.1 μm-thick Al_2O_3 films on a 2-inch (100) substrate and (b) 1.0 μm-thick Si (100) films on a Al_2O_3 (100)/Si(100) substrate.

To fabricate the SOI structure, the epitaxial growth of Si films on the Al_2O_3 (100)/Si (100) substrate was carried out using SiH_4 gas at substrate temperature range from 1030 ℃ to 1040 ℃. Gas flow rates of SiH_4 and H_2 were 90 sccm and 1000 sccm, respectively. The growth rate of the epitaxial Si films was 1.0 μm/min.

The crystalline quality of the epitaxially grown Al_2O_3 films was examined by RHEED, in which patterns were streaked and did not had twin spots as shown in Fig. 2(a). On the other hand, the epitaxially grown Si films on the Al_2O_3 layer had a mirrorlike surface and a smooth surface morphology was observed from the SEM image. The RHEED patterns were also streaks without twin spots as shown in Fig. 2(b), which indicated that single crystalline Si (100) films were grown epitaxially on the Al_2O_3 (100) layer.

III. Characteristics of pressure sensors

A piezoresistive pressure sensor was fabricated on the SOI structures prepared with the methods described above. In order to reduce the offset voltage and the nonlinearity due to mismatch among the piezoresistors in the form of a conventional Wheatstone bridge, we designed a single-element four-terminal piezoresistor utilizing a shear piezoresistive effect,[10] which was placed at the center of a rectangular diaphragm. The doping concentration of the piezoresisotr was $N_A = 3\times10^{18} cm^{-3}$. The formation of thin Si diaphragms and the dielectrical isolation of the piezoresistors were formed by wet etching in a KOH. The dimensions of the diaphragm and its thickness were 360 μm × 1140 μm and 5 μm, respectively.

1. Pressure sensors using the insulator of a SOI structure as the dielectrical isolation layer

In order to resolve the shortage of excess temperature drift mentioned previously, SOI pressure sensors were fabricated on the SOI structures, in which the insulator (interfacial SiO_2 or epitaxial Al_2O_3 films) of a SOI structure was used as the dielectrical isolation layer of piezoresistors as shown in Fig. 3.

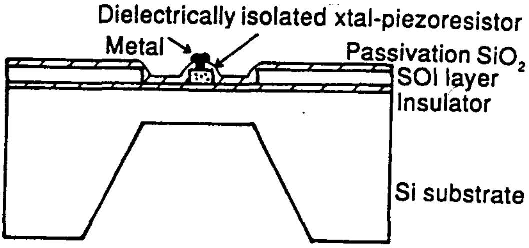


Fig. 3. Cros-section view of pressure sensors using interfacial SiO_2 or epitaxial Al_2O_3 films of a SOI structure as the dielectrical isolation layer of pizoresistors.

Stability of gauge resistance is very important factor in a high-temperature capability. The resistance instability of the dielectrically isolated piezoresistors on the $Si/SiO_2/Si$ structure formed by SDB technology was lower than 0.04 % error during thermal cycles over many hours at 200 ℃. On the other hand, the stability of dielectrically isolated piezoresistors on the $Si/Al_2O_3/Si$ structure prepared with epitaxial growth was measured under same conditions, in which the instability was lower than 0.05 %. These properties are reflected in a good long-term stability and reproducibility at elevated temperatures. Therefore, the dielectrically isolated single-element four-terminal piezoresistors as a sensing-element is very useful as a high-performance sensing-element of high-temperature operations, bearing out the potential suitability of a SOI structure for high-temperature devices.

Typical output characteristics of the fabricated SOI pressure sensors were as following : The pressure sensitivity of the pressure sensors implemented on the $Si/SiO_2/Si$ structure and the $Si/Al_2O_3/Si$ structure, respectively, was approximately 0.039 mV/V·mmHg and 0.035 mV/V·mmHg for 700 mmHg full-scale pressure range. In the case of pressure sensors implemented on the SOI structure formed by SDB technology, the magnitude of the pressure sensitivity is equal to the value of bulk Si pressure sensors, but the pressure sensitivity of pressure sensors fabricated on the epitaxiallly stacked SOI structure is somewhat lower than that of bulk Si pressure sensors.

The temperature characteristics of the implemented SOI pressure sensors were measured at 5 V constant voltage for 700 mmHg pressure. The shifts in the pressure sensitivity and the offset voltage of pressure sensors fabricated on the $Si/SiO_2/Si$ structure were less than -0.2 % and +0.15 % in the temperature range of from -20 ℃ to +350 ℃. The result of this shift in the pressure sensitivity corresponded to less than 13 mV thermal offset voltage shift. A piezoresistive pressure sensor has several temperature drift mechanisms which contribute to this high-temperature coefficient.[2] The temperature coefficient of the pressure sensitivity in the implemented pressure sensors are comparable with dependence of the temperature coefficient of the piezoresistive coefficients ($TC\pi$). Therefore, the temperature drifts of the fabricated pressure sensors are dominated by the temperature dependence of the piezoresistive coefficient π_{44} due to the dielectrical isolation of piezoresistors.

On the other hand, the temperature characteristics of the pressure sensors implemented on the epitaxially stacked $Si/Al_2O_3/Si$ structure was as following : The shifts in the pressure sensitivity and the offset voltage were less than -0.3 % and +0.2 % in the temperature range of from -20 ℃ to +350 ℃, respectively. This pressure sensitivity shift corresponded to less than 16 mV thermal offset voltage shift. For the temperature drift of the fabricated pressure sensors, the temperature dependence of the piezoresistive coefficient π_{44}, the built-in stress and the crystalline defects are dominating due to the dielectrical isolation of the piezoresistors. A piezoresistive pressure sensors with conventional pn junction piezoresistors can be used up to 120℃. However, owing to the dielectrical isolation of the piezoresistors, the implemented pressure sensors can be operated up to at higher temperature ranges. Some part of the degradation of performance in the these devices results from the built-in stress and crystalline defects caused by epitaxial growth.

2. Pressure sensors using the insulator of a SOI structure as an etch-stop layer.

In order to realize a high-resolution pressure sensors with constant pressure sensitivity in mass production, accurate control of the diaphragm thickness is very important. Moreover, considering approaches to tactile imaging devices utilizing the array of piezoresistive pressure sensors cellls, it is required to fabricate cellls with the more constant pressure sensitivity on a large area.

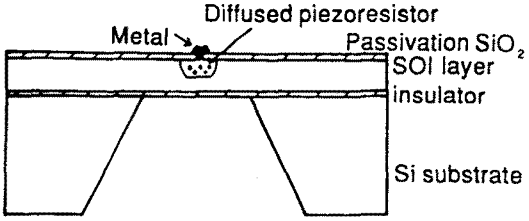


Fig. 4. Cros-section view of pressure sensors using interfacial SiO_2 or epitaxial Al_2O_3 films of a SOI structure as an etch-stop layer during the foramtion of thin Si diaphragms.

As the etch rate of SiO_2 is several Å per min. for the most anisotropic etchants and single-crystalline epitaxial Al_2O_3 films cannot be chemically etched,[11] the SiO_2 and Al_2O_3 films are the best etch-stop materials. In this section, the advantages of useful micromachined Si structural control are demonstrated by applying the insulator (interfacial SiO_2 or epitaxial Al_2O_3 films) of the SOI structures to an etch-stop layer during the formation of the thin Si diaphragms as shown Fig. 4, in which the diaphragm thickness corresponds to the thickness of the SOI layer.

Typical ouput characteristics of the fabricated SOI pressure sensors against pressure without any compensation were as following : The pressure sensitivity of the pressure sensors implemented on the SOI structures formed by SDB and epitaxial growth, respectively, was about 0.04 mV/V·mmHg and 0.037 mV/V·mmHg for 700 mmHg full-scale pressure range. The former is comparable to that of bulk Si, but the letter is somewhat (17.8 %) lower than that of bulk Si. The reason for this degraded pressure sensitivity is conjectured to be caused by crystalline defects such as the etch-pit density of $10^{18}cm^{-3}$, the lattice·mismatch of 2.4 %, built-in stress of $3.2 \times 10^9 dyn/cm^{-3}$ of the epitaxial Si films, and alignement error between the piezoresistor and the thin Si diaphragm center. These will be improved by formation of the epitaxial Si films at low temperature, resulting in reducing of built-in stress, and correct alignement of the piezoresistor on the center of the back-side etched diaphragm.

A special feature of SOI pressure sensors describing in this section is the development of a high-resolution pressure sensor with invariant pressure sensitivity on a large area. The output voltage was measured at constant voltage of 5 V over 200 devices, relative to the average value. The average pressure sensitivity of the pressure sensors implemented on the $Si/SiO_2/Si$ structures formed by SDB technology is 133 mV and the standard deviation of the pressure sensitivity is only ± 2.3 %. On the other hand, in the case of pressure sensors fabricated on the epitaxially stacked $Si/Al_2O_3/Si$ structure, the average pressure sensitivity and the standard deviation of the pressure sensitivity were 131 mV and ± 2.0 % over 200 devices, respectively. These results verify that the control method of a thin Si diaphragm thickness using a SOI structure is extremely distinguished than ± 4% of that of electrochemical pn junction etch-stop method[3] widely used currently.

3. Pressure sensors fabircated on double SOI structures

As seen in section previously, the implemented pressure sensors using only the single SOI structure can not solve the drawbacks of both low yield and exessive temperature drift at the same time. This section describes a novel pressure sensor with double SOI structures, i.e., Si (100)/Al_2O_3 (100)/Si (100)/SiO_2/Si (100) substrate as shown in Fig. 5, which were formed by combining SDB technology with epitaxial growth. The interfacial SiO_2 of the first SOI layer made by bonding two oxidized Si wafers together, were used as an etch-stop layer to control the thin Si diaphragm thickness during an anisotropic etching. On the other hand, hetero-epitaxially grown insulating Al_2O_3 films on the first SOI layer and epitaxial Si films on the Al_2O_3/Si were used as the dielectrical isolation of the piezoresistors and the piezoresistors themseleves, respectively.

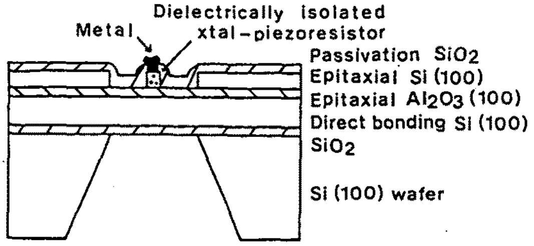


Fig. 5. Cros-section view of pressure sensors using double SOI ($Si/Al_2O_3/Si/SiO_2/Si$) SOI structures.

The pressure sensors fabricated on the double SOI structures without any compensation were capable of very accurate operation at temperature as high as 300 ℃, and had high-sensitivity (0.04 mV/V·mmHg) for 700 mmHg full-scale pressure range. Moreover, the pressure sensitivity variation of the implemented pressure sensors was controlled to within a standard deviation of ± 2.4% over 32 devices.

IV. Conclusion

The results obtained from this work should be a significant step in the development of high-performance and low cost pressure sensors needed for a wide variety of pressure sensors applications : Firstly, as it is possible to integrate a signal conditional circuitry taking advantages of the thin SOI MOS devices, the developed pressure sensors using the insulator of a SOI structure as the dielectrical isolation of piezoresistors are very suitable for the development of high-temperature integrated pressure sensors. Secondly, using the insulator of a SOI structure as an etch-stop layer for the formation of accurate thin Si diaphragms, the SOI structure is very promising materials for the development of high-resolution pressure sensors with no -variation pressure sensitivity on a large area. Therefore, this device seems to be especially attractive to application such as tactile imaging devices to enable them to measure not only force but also force distribution. Finally, pressure sensors implemented on double SOI structures will receives a particular attention as a high-performance pressure sensing-element because the inherent limitations of both low yield and exessive temperature drift can be eliminated completely.

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著者紹介

Gwiy Sang Chung

『센서학회지 제1권 제1호』 논문 92-16 p. 145 참조.
현재 동서공과대학교 전자공학과 전임강사.

Tetsuro Nakamura

『센서학회지 제1권 제1호』 논문 92-16, p. 145 참조.
현재 일본 豊橋技術科學大學 전기전자공학과 교수.

Makoto Ishida

『센서학회지 제1권 제1호』 논문 92-16, p. 145 참조.
현재 일본 豊橋技術科學大學 전기전자공학과 조교수.