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Sensitivity Enhancement of Polysilicon Piezo-resistive Pressure Sensors with Phosphorous Diffused Resistors

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Abstract. It is generally accepted that the piezo-resistive coefficient in single crystal silicon is higher when P-type impurities such as boron are used for doping the resistors. In this paper we demonstrate that the sensitivity of polycrystalline silicon piezo-resistive pressure sensors can be enhanced considerably when phosphorus diffusion source is used instead of boron dopant for realizing the piezo-resistors. Pressure sensors have been designed and fabricated with the polycrystalline piezo-resistors connected in the form of a Wheatstone bridge and laid out on thermal oxide grown on membranes obtained with a Silicon On Insulator (SOI) approach. The SOI wafers required for this purpose have been realized in-house by Silicon Fusion Bonding (SFB) and etch back technique in our laboratory. This approach provides excellent isolation between the resistors and enables zero temperature coefficient of the polysilicon resistor. The results obtained in our laboratory have clearly demonstrated that by optimizing the phosphorus diffusion temperature and duration, it is possible to achieve sensitivities in excess of 20mV /Bar for bridge input voltage of 10V, with linearity within 1% over a differential pressure range up to 10Bar (10^6 Pascal), and burst pressure in excess of 50 Bar as compared to the 10mV /Bar sensitivity obtained with boron doped polysilicon piezo-resistors. This enhancement is attributed to grain boundary passivation by phosphorous atoms.

Key words: Polysilicon, piezoresistive pressure sensor, SOI, Silicon Fusion Bonding.

1. Introduction

Piezo-resistive pressure sensors are easy to fabricate and do not require any complicated electronics. Conventional piezo-resistive pressure sensors are fabricated by implanting P-type resistors on N-type membrane. These sensors, however suffer from the disadvantage that the PN junction isolation of piezo-resistors becomes leaky at temperatures higher than 100 ºC. This problem can be overcome by fabricating the pressure sensors on the SOI substrate as the oxide isolation between piezo-resistors can withstand high temperatures[1]. Polysilicon is used as a piezo-resistive material because of the advantage that temperature coefficient of resistivity (TCR) can be made zero by suitably adjusting the doping concentration[2]. However, the sensitivity of the polysilicon piezo-resistive pressure sensors is always lower compared to the single crystalline piezo-resistive pressure sensor because of the lower gauge factor of polysilicon than that of single crystalline silicon[3].

This paper discusses the fabrication of SOI polysilicon piezo-resistive pressure sensor. The optimization of phosphorous diffusion schedule to enhance the sensitivity of the sensors is also presented. The fabricated devices are packaged and tested at various temperature and pressure. The sensitivity of the pressure sensors fabricated with phosphorous diffused resistors and boron implanted resistors are compared.

2. Fabrication of SOI polysilicon piezoresistive pressure sensors

2.1. Realization of SOI wafer

The SOI wafer has been realized by Bonded and Etch back SOI (BESOI) technique and this consists of the following steps:

(1) Chemical treatment: Two 200 µm double side polished wafers were cleaned by standard cleaning procedure. One of the wafers was thermally oxidized to grow an oxide thickness of 2000Å. Both these wafers were given standard RCA1 and RCA2 cleaning to make their surfaces hydrophilic.

(2) Pre Bonding: The wafers were brought into contact in the Substrate Bonder (Karl-Suss SB6) at 450 ºC in vacuum.

(3) Annealing: The pre bonded wafer was annealed at 1050 ºC in wet oxygen ambient for 2 hours to increase the bond strength.

(4) Etching: The bonded wafer was etched from the top side by 80 % KOH at 75 ºC while protecting the bottom side of the wafer by SiO_2 as masking layer. The etching was carried out till a membrane thickness of 15µm was achieved.

These process steps are shown in the following diagram.

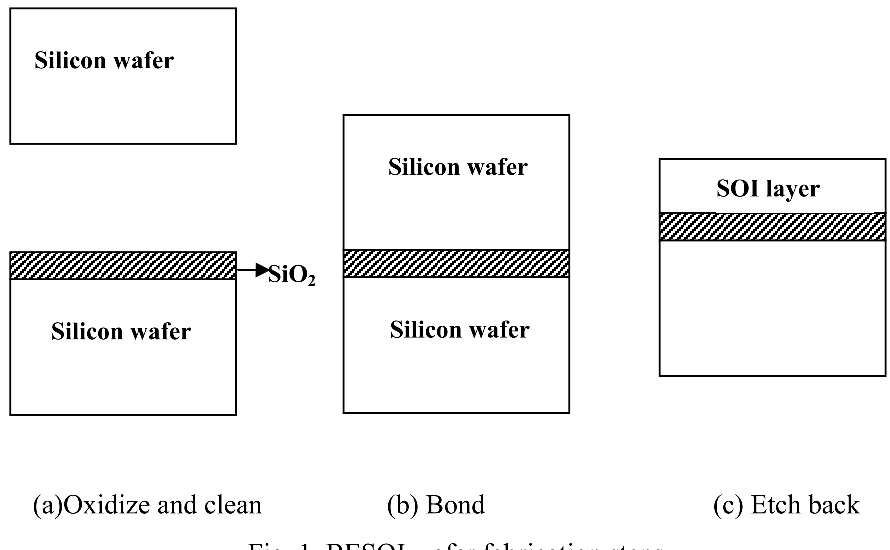

Fig. 1. BESOI wafer fabrication steps.

2.2. Fabrication of Pressure sensor

The front surface of the SOI substrate was protected by growing a thermal oxide. KOH etching was carried out through a window opened on the bottom surface of the substrate to realize the membrane. Buried oxide layer (BOX) in the SOI wafer was used as etch stop layer.SiO_2 layer of 2000 Å was grown thermally on SOI layer and polysilicon of thickness 0.6um was deposited by Low Pressure Chemical Vapour Deposition (LPCVD) technique. The polysilicon layer was annealed at 1000 ºC for 1 hour in N_2 ambient to relieve the stress. Polysilicon was doped with boron in one set of wafers and with phosphorous for another set of wafers. In case of boron doping, implantation dose of 1.5x 10^{15} cm^{-2} with an energy of 80 keV was used. Implanted devices were annealed at 950 ˚C for 20 minutes. In the case of phosphorous doping, optimized diffusion schedule explained in section 3 is used. Then polysilicon was patterned. Aluminum metallization was carried out to connect the polysilicon resistors in Wheatstone bridge. The schematic diagram of the pressure sensor is shown in fig.2.

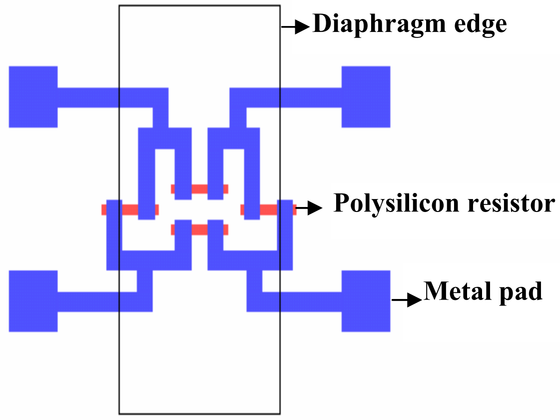

Fig. 2. Schematic diagram of the pressure sensor.

3. Phosphorous diffusion schedule optimization for sensitivity enhancement

The polysilicon doping with phosphorous was carried out at various diffusion temperatures varying from 800 ºC to 900 ºC and pressure sensors were fabricated for all cases of diffusion temperatures by following the steps explained in the section 2.2. Devices were tested at the wafer level by mounting them on a vacuum chuck of the probe station. The membrane is thus subjected to a differential pressure of 1 Bar by creating vacuum on the bottom side of the membrane using a vacuum pump connected to the chuck. The sensitivities of all the devices were thus measured initially at 1 bar, prior to the packaging. The results obtained on the sensors fabricated using polysilicon piezo-resistors doped by phosphorous diffusion in the temperature range 800 ºC to 900 ºC are shown in fig.3. It can be seen that phosphorous incorporation at higher diffusion temperature results in considerably higher sensitivity. However temperatures above 900 ºC were not preferred because the values of the piezo-resistors reduced well below the designed value of 1kΩ. Also in those cases significant improvement in the sensitivity was not achieved. Therefore phosphorous diffusion at 900 ºC for 30 minutes was chosen as optimum process schedule to achieve best sensitivity and for further packaging and Testing.

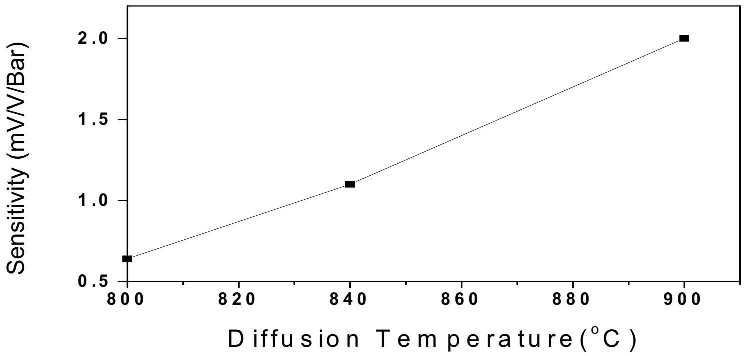

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Fig.3. Sensitivity of pressure sensor versus Phosphorous diffusion temperature .

4. Results and Discussions

The individual devices pressure sensors were diced from the wafer form and packaged in TO39 headers. Devices were mounted in specially designed jig and tested up to 10 bar pressure using N_2 gas from the cylinder. The results comparing bridge output voltage versus pressure characteristics of boron implanted devices and phosphorous diffused device are shown in the fig.4. Devices were also tested at various temperatures ranging from 30 ºC to 80 ºC with various pressures. These results are shown in fig.5 and in fig.6.

It may be noted from the fig.4 that both phosphorous diffused and boron implanted pressure sensors with 15 µm diaphragm thickness showed a linear variation of output voltage with change in pressure up to 10 bar. Phosphorous diffused devices showed higher sensitivity of 2mV/V/Bar as compared to the sensitivity of 1mV/V/Bar obtained on the devices with boron implanted piezo-resistors. The enhancement in the sensitivity obtained with phosphorous diffused piezo-resistors is attributed to the polysilicon grain boundary passivation by phosphorous atoms[4]. The probability of grain boundary segregation is higher in the case of phosphorous whereas it is not significant in the case of boron[5]. When devices were tested at temperatures from 30ºC up to 80 ºC, only marginal change in the output voltage at various pressures was observed due to negligibly small TCR of optimally doped polysilicon piezo-resistors.

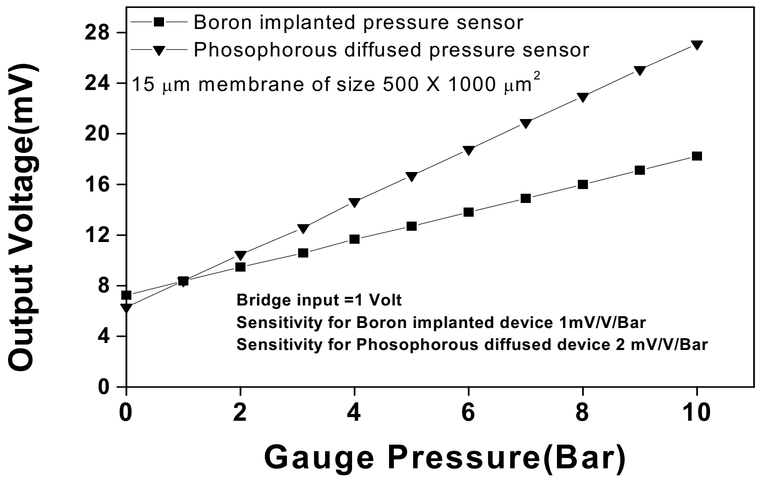

Fig. 4. Comparison of boron implanted device and phosphorous doped device characteristics.

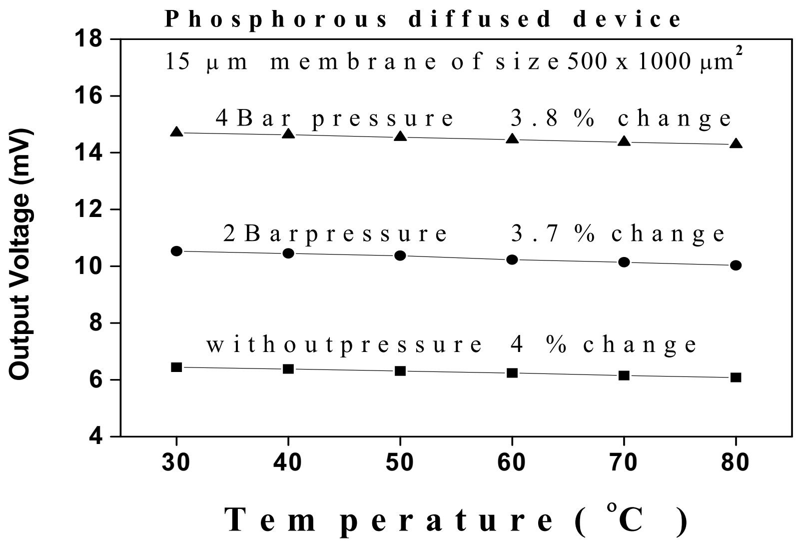

Fig .5. Characteristics of phosphorous diffused device with respect to temperature at various pressures.

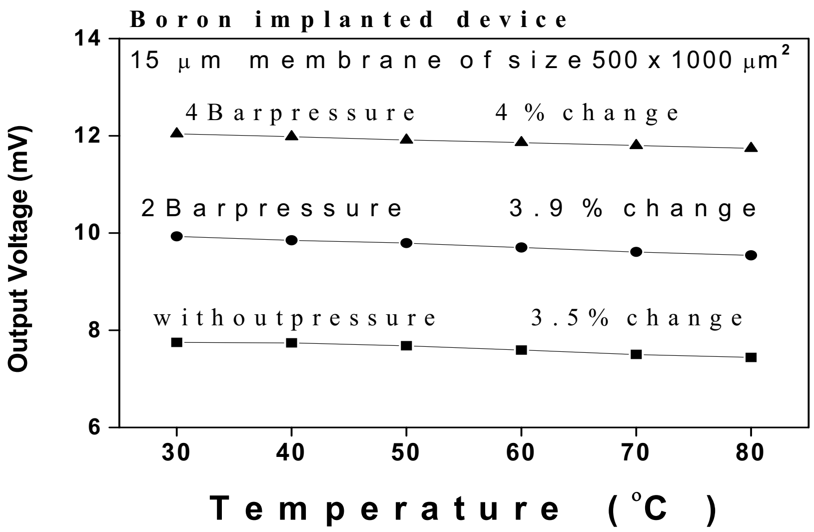

Fig .6. Characteristics of Boron implanted device with respect to temperature at various pressures.

5. Summary and conclusions

In this paper fabrication of SOI polysilicon piezo-resistive pressure sensor is presented. Phosphorous diffusion schedule optimization for achieving better performance of the sensors is discussed. The results comparing characteristics of pressure sensors fabricated in our laboratory with polysilicon piezo-resistors doped (a) with phosphorous by diffusion (b) with boron by ion implantation are presented. The results obtained have clearly demonstrated that phosphorous diffused piezo-resistors lead to considerably higher values of sensitivity in the pressure sensors. These results have been achieved with excellent linearity and at the same time maintaining output voltage which is practically invariant with temperature in the measured range of 30º C to 80 ºC.

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