Fabrication of phosphorus doped polysilicon thin-film strain gauges using a 50 microns silicon substrate thickness

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Abstract. Strain gauges fabrication using phosphorus doped polysilicon thin-film resistors was performed. Strain gauges transducers were designed to measure the strain in load cells, using a Wheatstone bridge circuit configuration. The strain and sensitivity measurements results for load cells application are described. A linear response and excellent repeatability were obtained.

1. Introduction
Typical strain gauges are made from a heat-treated metallic foil bonded to a dielectric layer [1, 2], as showed in Figure 1. However, phosphorus doped polysilicon layer is often used as a piezo-resistive material, mainly because the temperature coefficient of resistance (TCR) can be set as zero by suitable adjustment of the doping concentration [3, 4], due to this convenient feature, these materials are used as sensor for precision mass measurement. Polysilicon thin films strain gauges have high accuracy, repeatability, reliability and low cost. These characteristics make this material particularly attractive in load cells elements applications.

An important issue in this application is the bonding method for the strain gauge with the deformation surface of the sensor element (usually aluminum). Usually the strain gauges are positioned onto the areas, where the highest deformation is located on the load cells. The strain gauges

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are connected to a Wheatstone bridge circuit configuration so when a load is applied in the load cell, the strain gauge detects the strain, and an unbalance in the Wheatstone bridge is observed. The resistance variation of the strain gauge is proportional to the mass of the load [3]. This paper shows the fabrication process for the phosphorus doped polysilicon thin film strain gauges and the optimization of phosphorous diffusion procedure as to enhance the sensor sensitivity. The fabricated devices were tested in load cells used in commercial mass measurement equipment.

1.1 Load Cells fundamentals

Nearly every electronic mass measurement equipment use load cells. These cells convert a force or mass into an electrical signal by transducing the strain into an electrical signal. As the surface of load cell becomes strained, the gauge stretches or compresses, changing its resistance proportionally to the applied load. Each strain gauge forms one leg of Wheatstone bridge, see Figure 2. When the excitation voltage $E$ is applied to the circuit (AD), the output (BC) is a differential voltage proportional to the force on the load cell [6].

![Figure 2. Electrical schematic of a Wheatstone bridge utilized in a load cell application [6].](image)

Most load cells are specified in terms of maximum capacity and output rating. Maximum capacity defines the maximum load (in kg) to which the load cell can be stressed. After this value, the output voltage no longer changes. The sensitivity (output rating) is given in mV/V. The differential output voltage varies in a linear relation to the mass applied load cell. [6].

2. Fabrication and bonding of phosphorus doped polysilicon thin film strain gauges

Polysilicon thin films have sensitivity in between that of a metal foil and crystalline Si. However, the temperature coefficient of resistance, (TCR), which represents the extent of the effect of temperature changes, is significantly lower than that of crystalline Si strain gauges; it is typically less than 500 ppm/°C [7]. TCR is influenced by two factors: difference in the thermal expansions of the metal surface and the silicon strain gauge, and thermionic emission of carriers. In this study, the resistance change due to the thermionic emission was more of a factor in the gauge output determination than that by thermal expansion in the silicon strain gauges. The temperature effect can be compensated using a Wheatstone bridge circuit or by optimizing the fabrication process. Moreover, the design of the polysilicon strain gauges is straightforward due to the isotropic characteristics of these types of gauges as a result of the random grain distribution [1].

2.1 The fabrication process for the thin polysilicon strain gauge

A 100 oriented, p type, 10-20 Ohm.cm, 50μm thick silicon wafer was used as substrate. It was processed with the following steps:

- Chemical cleaning: The wafers were cleaned by standard RCA cleaning procedure to make their surfaces hydrophilic.
Thermal oxidation: The wafers were thermally oxidized to grow a silicon oxide layer of 1 μm thick.

Polysilicon Deposition: A polysilicon thin film of 0.6 μm thickness was deposited by Low Pressure Chemical Vapour Deposition (LPCVD) technique at 630°C.

Phosphorus doping: A SOG (Spin on Glass) layer, with 1% or 3% phosphorus concentration, was deposited on the polysilicon film and the diffusion process temperature was carried out at 1150°C. The SOG layer was removed using a 1% HF solution.

Patterns definition: The patterns of the designed strain gauges were defined by optical lithography and the polysilicon film was etched by a SF₆ plasma process. The photoresist was removed by O₂ plasma etching process.

Metallization: An aluminum layer of 1 μm thick was deposited by thermal evaporation. This aluminum layer was annealed at 420°C in inert gas ambient for 2 hours to improve the electrical contacts.

Contacts definition: The contacts patterns were defined by optical lithography and etched in a H₃PO₄ solution. The photoresist was removed by acetone and 2-propanol solvents. Figure 3 shows an image of strain gauges with the electrical contacts patterns.

Strain gauges dicer: The silicon wafer was diced by a disco saw to detach the individual strain gauges.

![Image of the polysilicon strain gauges (1.2 x 3.0mm) with the aluminum electrical contacts.](image)

**Figure 3.** Image of the polysilicon strain gauges (1.2 x 3.0mm) with the aluminum electrical contacts.

### 2.2 Bonding on a metal cantilever beam and electrical wiring

Bonding between various types of metals and silicon devices can be implemented using organic adhesives or glass frit bonders. Although the strain gauges that are bonded using glass frit, have low hysteresis and high level of repeatability, one major disadvantage exists [2, 8, 9], it is difficult to bond a silicon strain gauge onto a metal cantilever beam using glass frit because the high-temperature hardening process during the glass-bonding process causes cracking due to the CTE (coefficient of thermal expansion) mismatch between the silicon gauge and metal cantilever beam. For the organic adhesives, the curing temperature is lower than glass frit bonders to prevent the film from cracking. To avoid difficulties, a high-performance epoxy resin was used to bond the polysilicon strain gauges onto a metal cantilever beam as showed in Figure 4.
The metal and the cantilever beam dimensions (a x b x c) determine the maximum force (mass) that can be applied to the load as to avoid plastic behavior (not leading to hysteresis). The placement of four strain gauges in each load cell allows for the effective assembly of a Wheatstone bridge as shown in Figure 2. Notice that the strain gauges positioned at R_1 and R_3 have a positive resistance variation and R_2 and R_4 have a negative resistance variation [10].

The electrical contacts of the strain gauges can be made using a solder paste or wiring-bond processing. The Figure 5 shows an image of one strain gauge bonded using a high-performance epoxy resin and the electrical contacts were bonded using a silver conductive paste.

3. Experimental Results

3.1 Electrical characterization of the strain gauges.

3.1.1 Measurements of sheet resistance: The diffusion process changes the sheet resistance of the polysilicon film and it was characterized by a four-probe-meter. The main results of sheet resistance as a function of diffusion time and the concentration of the phosphorus dopant are shown in Table 1.
Table 1. Values of sheet resistance (Rsheet) of doped polysilicon film.

| Phosphorus Concentration | Processing Time (minutes) | Rsheet (Ohms/square) |
|--------------------------|---------------------------|----------------------|
| 1%                       | 20                        | 150 ± 16             |
| 1%                       | 30                        | 42 ± 7               |
| 1%                       | 40                        | 14.4 ± 0.5           |
| 3%                       | 70                        | 10.7 ± 0.2           |

The variation of sheet resistance depends mainly on the thickness and doping uniformity of the polysilicon film, but is within acceptable values for the strain gauge designed.

3.1.2 Measurements of electrical resistance: The electrical resistance of the fabricated strain gauges was measured using an I-V analyzer, where a voltage of 1V was applied to strain gauges distributed in the silicon wafer. The average values for the fabricated devices are shown in Table 2.

Table 2. Values of electrical resistance of fabricated strain gauges.

| Strain gauge identification | Resistance - Designed | Resistance - Measured |
|-----------------------------|-----------------------|-----------------------|
| A                           | 2 kΩ                  | 2.10 ± 0.03 kΩ       |
| B                           | 1.2 kΩ                | 1.27 ± 0.02 kΩ       |
| C                           | 1.3 kΩ                | 1.34 ± 0.02 kΩ       |

The electrical resistance values were close to the designed resistance values, indicating that the polysilicon film deposition and phosphorus SOG diffusion process results can be reproduced.

3.2 Electrical characterization of Wheatstone bridge in the load cell.
In the experimental arrangement, showed in Figure 4, an aluminum cantilever beam as a load cell was used. The arrangement was mounted on a stable and vibration free table. The input voltage was 5V and output voltage was monitored by a precision voltmeter as a function of the force (mass) applied on the structure. The results are shown in Figure 6.

![Figure 6. Wheatstone bridge output voltage in function of the force (mass) applied on the load cell.](image-url)
A linear variation of Wheatstone bridge output voltage as a function of the force applied to the structure was observed with good correlation ($R^2 > 0.996$). So, the resistance of each strain gauge increased linearly with the tensile stress while it decreased with the compressive stress. In all cases, the sensitivity (output rating) for loads of 1.6 kg was higher than 4.25 mV/V (2.41 µV/V.g). The design of strain gauge C had longer lines in the same device and it was doped with a high phosphorus concentration, resulting in a sensitivity of 5.06 mV/V (3.00 µV/V.g).

4. Conclusions

Strain gauges were designed and fabricated on 50 µm thick silicon wafers using conventional fabrication processes: thermal oxidation, chemical deposition of polycrystalline silicon (LPCVD), dopants diffusion, optical lithography, aluminum evaporation and wet and dry etching.

We demonstrated that the fabricated phosphorus doped polysilicon thin films strain gauges can be successfully used in a load cell sensor application.

The sheet resistivity of 10 ohms/square was adjusted in the phosphorus diffusion process and the strain gauges sensitivity depends on the length of the lines designed in the device.

The results of the electrical characterization of the Wheatstone bridges in the load cells show a linear variation of output voltage depending of the force (mass) applied to the structure with good correlations. The highest sensitivity (output rating) obtained was 5.06 mV/V (3.00 µV/V.g) for loads of 1.6 kg.

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