Low-cost piezoresistive silicon load cell independent of force distribution

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SUMMARY
A silicon load cell (force sensor) is presented which is based on a new operating principle. The force is measured by compressing a meander like strain gage. A second strain gage which is not loaded, is used for temperature compensation and for compensation of bending and stretching stresses in the chip. Also, same changes in zero load resistor values are eliminated. It is shown that the output of the bridge is a linear function of the total force and independent of the force distribution on the silicon chip. Measurements up to 1000 kg show a linear response and a short term repeatability which is within 0.1 %. Creep after 30 minutes is within 1.2 %.

Keywords: load cell, creep, hysteresis

INTRODUCTION
In various industrial and technical fields there is a need for small force sensors. Silicon is a very suitable material for this, because it does not suffer from creep and hysteresis. Furthermore, batch fabrication offers the chance to fabricate these load cells for reasonable prices.

The basic structure of a silicon load cell is shown in figure 1. The silicon chip is put between two pressing blocks. The force which is to be measured is applied to these blocks. As silicon wafers are only about 0.5 mm thick, problems arise at the contact area of the silicon chip and the pressing blocks (see figure 1). Here the surface roughness of both parts and the limited height of the pressing blocks cause a non-homogeneous stress distribution [1]. In order to avoid that the stress distribution determines the output signal of the silicon force sensor, a sensor is needed that is capable of integrating the stress distribution so that the output signal is directly related to the total force ([2], [3]). The sensor described in [2] consists of a resistor made of a zeranin filament (metal) which is deposited on a hardened steel plate with a diameter of 72 mm. It was externally compensated for temperature changes.

In this paper a piezoresistive silicon force sensor is presented the output of which is also independent of the stress distribution. In addition, the sensor is able to locally (on chip) compensate for temperature changes and for bending and stretching stresses in the chip. Besides, same changes in zero load resistor values are eliminated. These statements are supported by a thorough mathematical analysis.

In figure 2 a top and cross-sectional view of the 1 by 1 cm silicon chip is shown. Two poly silicon strain gages are deposited on it. Gage 1 is placed on top of the chip and is directly loaded/compressed with pressing blocks which pass through the applied force. Gage 2 is situated in grooves in the substrate and is not directly loaded. To our knowledge, compression of silicon strain gages is only reported in [4].

CHARACTERIZATION
It is supposed that both strain gages are mainly subjected to three normal stresses and their corresponding

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**figure 1:** Contact area between silicon chip and pressing blocks.

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**figure 2:** Layout piezoresistive load cell. Strain gage 1 carries the load. Gage 2 is situated in grooves in the substrate.
strains (see figure 3 and compare the coordinate axes to those drawn in figure 2). $\sigma_{11}, \epsilon_{11}$ is the stress/strain in the direction of the force. $\sigma_{22}, \epsilon_{22}$ are in plane stresses/stains (perpendicular to the force). If resistance changes in the direction of the 11-stress/strain are considered, then the piezoresistance effect can be described in terms of strains $([5],[6])$:

$$\frac{dR}{R} = G_i \epsilon_{11} + G_s (\epsilon_{22} + \epsilon_{33}) + \beta T.$$ (1)

$G_i$ and $G_s$ are the longitudinal and transverse piezoresistive strain coefficients respectively. By combining (1) and (2), the relative change in resistance can be described in terms of stresses:

$$\frac{dR}{R} = \pi_i \sigma_{11} + \pi_s (\sigma_{22} + \sigma_{33}) + \beta T,$$ (3)

where

$$\pi_i = \frac{G_i}{E} - 2G_iv, \quad \pi_s = \frac{G_i (1-v) - G_s v}{E}.$$ (4)

$\pi_i$ and $\pi_s$ are the longitudinal and transverse piezoresistive stress coefficients respectively.

The stress components $\sigma_{11}$ and $\sigma_{22}$ consist of different contributions. First of all of the stresses due to bending and stretching of the chip, $\sigma_{11}^{st}$ and $\sigma_{22}^{st}$ respectively (see figure 4). In this paper both stresses are called global stresses, because it is assumed that they are the same in the gages which are situated next to each other. The other contributions are called local stresses, because they are only caused by the material deformation due to the forces in the neighbourhood of that location (see ref. [8] for theory on local stresses caused by a point force). These stresses are not the same in both strain gages which are located next to each other. It is defined that $\sigma_{11}^{lt}$ is the local 11-stress in gage 1 which is caused by $\sigma_{33}$ in the same gage (stress in direction of force). $\sigma_{22}^{lt}$ is the local 11-stress in gage 2 which is caused by $\sigma_{33}$ in gage 1.

Local stress $\sigma_{11}^{lt} (\sigma_{33}, \sigma_{23})$ is the 11-stress in gage 1 which is caused by the shear stresses $\sigma_{13}$ and $\sigma_{23}$ on top of gage 1. $\sigma_{22}^{lt} (\sigma_{13}, \sigma_{23})$ is the 11-stress in gage 2 which is caused by the same shear stresses. Stresses $\sigma_{11}^{lt} (\sigma_{13}, \sigma_{23})$ and $\sigma_{22}^{lt} (\sigma_{13}, \sigma_{23})$ have similar explanations. Now, the relative change of resistance for gage 1 and 2 can be written as

$$\frac{dR_1}{R_1} = \pi_i [\sigma_{11}^{lt} + \sigma_{11}^{st}] + \pi_s [\sigma_{22}^{lt} + \sigma_{22}^{st}] + \beta T,$$

$$\frac{dR_2}{R_2} = \pi_i [\sigma_{11}^{lt} + \sigma_{11}^{st}] + \pi_s [\sigma_{22}^{lt} + \sigma_{22}^{st}] + \beta T.$$ (5)

As poly silicon behaves linearly (5) can be written as

$$\frac{dR_1}{R_1} = \pi_i [\sigma_{11}^{lt} + k_1 \sigma_{33}^{st}] + \pi_s [\sigma_{22}^{lt} + k_2 \sigma_{33}^{st}] + \beta T,$$

$$\frac{dR_2}{R_2} = \pi_i [\sigma_{11}^{lt} + k_1 \sigma_{33}^{st}] + \pi_s [\sigma_{22}^{lt} + k_2 \sigma_{33}^{st}] + \beta T.$$ (6)

$k_1, k_2$ are constants which depend on the Poisson's ratio and the geometry [8]. By subtracting both relative changes of resistance the next equation results:

$$\frac{dR_1}{R_1} - \frac{dR_2}{R_2} = \pi_i [(k_1 - k_2) \sigma_{33}^{st} + \sigma_{11}^{lt} (\sigma_{13}, \sigma_{23}) - \sigma_{11}^{st} (\sigma_{13}, \sigma_{23})] + \pi_s [(k_2 - k_1 + 1) \sigma_{33}^{st} + \sigma_{22}^{lt} (\sigma_{13}, \sigma_{23}) - \sigma_{22}^{st} (\sigma_{13}, \sigma_{23})].$$ (7)

From (7) it follows that the difference is independent of temperature and independent of the global stretching and bending stresses. As gage 1 is loaded with another silicon chip which is also glued on the pressing block (see figure 5), it follows that the force sensor assembly is (almost) symmetric with respect to a plane going through gage 1. This implies that shear stresses in this plane are zero. Therefore, in equation (7), the terms which contain shear stress coefficients $\sigma_{13}$ and $\sigma_{23}$ can be put zero.

By integration of (7) it then follows that

$$\frac{R_1 - R_2}{R_1} = \frac{\pi_i (k_1 - k_2) + \pi_s (1 + k_2 - k_1)}{aL} F,$$ (8)

where
\[ F = - \int_{0}^{L} \sigma_{33} \, dl \, . \] (9)

\( L \) is the total length of a gage, \( a \) its width and \( R_{0} \) the resistance of a gage at zero load. \( F \) is the total force which equals the integral of the \( 33 \)-stress distribution along gage 1. Therefore, it is shown that the difference in resistance values is independent of the force distribution.

**FABRICATION AND MEASUREMENTS**

For the fabrication process only two masks are needed. The 4 \( \mu \)m deep grooves are made by reactive ion etching. Hereafter, 1.5 \( \mu \)m thermal oxide is grown at 1150 \( \degree \)C. Then, a 1 \( \mu \)m thick poly silicon layer is grown which is given piezoresistive properties by doping it with boron [9]. Finally, the poly silicon strain gages are formed by patterning and reactive ion etching the poly silicon. The top wafer has a thermal oxide of 1.0 \( \mu \)m. The parameters of the realized load cell are given in table 1. The force sensor assembly is shown in figure 5. Both silicon chips are glued to the pressing blocks. The thin membrane takes care of the lateral forces.

The value of \( (R_{a} - R_{b})/R_{0} \) can accurately be determined in a Wheatstone bridge (see figure 6). \( V_{\text{supply}} \) is the power supply voltage, \( \Delta V_{\text{out}} \) the change in output voltage after amplification. A potentiometer is used to balance the bridge. The voltage-force relation is given by

\[ \Delta V_{\text{out}} = \frac{2R_{a}V_{\text{supply}}}{R_{a} - R_{b}} \left( \frac{R_{b}V_{\text{supply}}}{R_{a}} \right) K F \, , \] (10)

where

\[ K = \pi_{r}(k_{1} - k_{3}) + \pi_{r}(1 + k_{2} - k_{4}) \, . \] (11)

From (10) it also follows that it is compensated for same changes in zero load resistance \( R_{0} \) of both strain gages.

Instant repeatability of the load cell was tested by loading the load cell twice with some specific weight. During one minute, 60 measurements were done. Weights were available in steps of 100 kg (±2 kg) up to 1000 kg. The mean output of the first and second loading for different masses is shown in figure 7. The signal is linear which is expected from the theory (see equation (10)). The experimental measured value of \( K \) follows from (10) and table 1, giving \( K = 5.51 \cdot 10^{-11} \text{Pa}^{-1} \). As the local in plane stresses due to stress \( \sigma_{33} \) are smaller than \( \sigma_{33} \) itself, it follows from (11) that \( K = \pi_{r} \, . \) (12)

In [6] it was measured that \( G_{r} = 25 \) and \( G_{r} = -6 \). With these values it can from (4) and table 1 be derived that the experimental value of \( \pi_{r} \) in [6] would be \( \pi_{r} = 6.48 \cdot 10^{-11} \text{Pa}^{-1} \) which is in good agreement with our measurement.

The short term repeatability error as a percentage of the difference in output at maximum load (1000 kg) is shown in figure 8. It is seen that this error is within 0.1 %. Creep is tested by applying a load of 1000 kg for 30 minutes (see figure 9). It is concluded that the creep is within 1.2 %. For smaller loads creep is also smaller. Probably, creep is caused by slipping of the top silicon chip over the gage which carries the load.

![figure 5: Force sensor assembly.](image)

**Table 1: Parameter values.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a ) [( \mu )m]</td>
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<tr>
<td>( L ) [( \mu )m]</td>
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</tr>
<tr>
<td>( R_{0} ) [k( \Omega )]</td>
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</tr>
<tr>
<td>( V_{\text{supply}} ) [V]</td>
<td>10.12</td>
</tr>
<tr>
<td>( E ) [GPa]</td>
<td>166</td>
</tr>
</tbody>
</table>

| \( R_{a} \) [k\( \Omega \)] | 4.72  |
| \( R_{b} \) [k\( \Omega \)] | 272   |
| \( C_{1} \) [nF]           | 100   |
| \( C_{2} \) [nF]           | 100   |
| \( \nu \) [-]              | 0.25  |

![figure 6: Layout electronic circuit.](image)

![figure 7: Change in output of Wheatstone bridge.](image)
CONCLUSIONS

A piezoresistive silicon load cell is designed, analysed and tested. Two meander like strain gages are used to measure the load and to compensate for temperature changes and for bending and stretching stresses in the chip. Besides, it is compensated for changes in zero load resistance of both strain gages. The load cell can be made by using only two masks. Short term repeatability of the load cell is within 0.1 %, Its behaviour is linear. The creep after 30 minutes is maximum 1.2 %. Probably, this creep is mainly caused by slipping of the top silicon chip over gage 1. This slipping can be prevented by bonding a silicon wafer on top of strain gage 1. Then, a polishing step will have to be added which increases the fabrication costs of the silicon chip.

ACKNOWLEDGEMENTS

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REFERENCES