DEVELOPMENT OF LOAD CELL FOR FORCE MEASUREMENT USING MICRO-ELECTROMECHANICAL SENSOR (MEMS)

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ABSTRACT. MEMS piezoresistive strain sensors are more favorable and attractive due to a number of key advantages such as high sensitivity, low noise, better scaling characteristics, low cost and their ability to have the detection electronics circuit further away from the sensor or on the same sensing board. Moreover, they have high potential for monolithic integration with low-power CMOS electronics. Furthermore, piezoresistive strain sensors need less complicated conditioning circuit. The objective of this work is to develop a load cell for measure of a force using MEMS sensor. A decision of support platform for serving as the elastic transmission of the sensor system is presented. The integrated system design including a carrier platform and MEMS sensor is achieved using Finite Element Method (FEM). A computer simulation of the mechanism and the determination of the transfer function is provided.

KEY WORDS: MEMS load cell, silicon MEMS sensor, elastic transmission, computer simulation.

1. Introduction

A load cell is a transducer that converts load acting on it into an analog electrical signal. This conversion is achieved by the physical deformation of strain gages which are bonded into the load cell beam and wired into a Wheatstone bridge configuration. Strain gage load cells dominate the weighing industry [1].

Stresses due to thermal and mechanical loadings are often produced in integrated circuit (IC) chips that are incorporated into electronic packages. They typically occur due to nonuniform thermal expansions resulting from mismatches between the coefficients of thermal expansion of the materials comprising the package and the semiconductor die [2].

High-performance strain sensing systems, consisting of sensors and interface electronics, are highly desirable for advanced industrial applications, such as point-stress and torque sensing, and strain mapping. Conventional strain sensors made from metal foils suffer from limited sensitivity, large temperature dependence and high power consumption. Therefore, they are inadequate for high performance and
low power consumption applications [3] and hence other strain sensing methods, based on the Micro Electro Mechanical Systems (MEMS) technology, have been proposed [4, 5].

New advances in the field of Micro Electro Mechanical Systems (MEMS) have broadened considerably the applications of these devices. MEMS technology has also enabled the miniaturization of the devices, and a typical MEMS sensor is at least one order of magnitude smaller compared to a conventional sensor that is used to measure the same quantity. Consequently, MEMS devices can be patch-fabricated, which offers a high potential for cost reduction per unit. Moreover, proper design can solve some problems related to power consumption, while providing improved performance characteristics, such as accuracy, sensitivity and resolution. Finite Element Analysis (FEA) provides a reliable tool to carry out the required parametric studies in order to optimize the sensor performance [6].

For MEMS strain sensors, several physical sensing principles have been explored including the modulation of optical, capacitive, piezoelectric, frequency shift and piezoresistive properties [7, 8].

MEMS piezoresistive strain sensors are more favorable and attractive due to a number of key advantages such as high sensitivity [1], low noise, better scaling characteristics, low cost and their ability to have the detection electronics circuit further away from the sensor or on the same sensing board. Moreover, they have high potential for monolithic integration with low-power CMOS electronics. Furthermore, piezoresistive strain sensors need less complicated conditioning circuit [9].

The discovery of piezoresistive effects in silicon led to the development of classes of silicon-based electromechanical sensor technologies that are now in widespread use in various applications. Conventional metal-foil strain gauges offer flexibility and the potential for use in this format, but they suffer low sensitivity [i.e., gauge factor (GF)] and limited scalability to large areas due to lack of strategies for multiplexed addressing [10].

An example of a low-noise piezoresistive MEMS strain sensor is reported in [6]. The sensor is designed and verified using Finite Element (FE) Simulation. The simulation results showed high sensitivity, low-temperature dependence and high resolution. The sensor chip is composed of single crystal silicon, which has been through various microfabrication processes. The deformation of the silicon substrate is directly measured from the electrical resistivity change in the form of offset voltage caused by the bridge imbalance. The use of the full-bridge configuration will result in the cancellation of the temperature coefficients of resistance and the local thermal expansion coefficients based on the original values of piezoresistors electrical resistance, which will stabilize the output signal over the operating temperature range.

The force sensor presented in [1] is a compressive type load cell using polysilicon as a spring (sensing) element, which is deposited on patterned silicon dioxide grown on a silicon substrate. When the load is applied, the sensing element deforms and causes the change in resistance due to stresses and the piezo-resistive property change.
The operation of a DETF force sensor with unprecedented combinations of resolution and range is demonstrated. The MEMS sensing element was manufactured using a SOG process, with a device layer of 100 μm [11].

MEMS load sensors capable of both steady-state and dynamic measurements are generally designed as compliant structures. The device geometry and operating voltages are optimized for maximum force resolution and range, subject to a number of manufacturing and electromechanical constraints [12].

In present paper the integrated system design including a supporting platform and silicon MEMS sensor is presented. Results found at development of millimetre-range monolithic travel sensor with complex layout [13], are reported.

The main objective of this work is to develop a load cell for measure of a force using MEMS sensor. Purpose of the article includes the development of a suitable carrier platform on which to be attached silicon MEMS sensors. Computer simulation of the mechanism and determination of the transfer function is intended to be developed using the commercial FE package.

2. Design of MEMS sensor for μm-range displacement.

The developed sensor for mm-range displacement shown in Fig. 1(a) comprises of rigid outer frame having size of 2.3 x 2.2 mm and a thickness of 270 μm and a central portion made of 12 μm thin membrane. The frame is done of thick silicon and it has two members defined by two pairs of additionally etched trenches, marked schematically with “X” in the Fig. 1(a). At stretching the frame, its breaking will be localized at the marked areas, thus the only connection between the both frame-members will be via compliant elements made of thin-membrane portion.

Two sets of symmetrical compliant micromechanical elements: in-plane actuated cantilevers having a length of 600 μm and pairs of differential springs have been combined in a single monolithic device. Each cantilever has two piezoresistors embedded into sidewalls of its base which are serially connected, thus providing differential voltage output, as shown schematically in Fig. 1(a). All four sidewall
piezoresistors, located on sidewalls of both cantilevers are connected in full bridge configuration, thus providing additional amplification of output voltage signal by a factor of two. The layout of the metal tracks on sensor surface is also shown in this figure. A detailed view of the base of the in-plane actuated microcantilever with sidewall embedded piezoresistors is shown in Fig. 1(b). The width of the cantilever is 20 µm and the width of its base is 5.4 µm, being a trade-off between its min value determined by the depth of the p-n junctions into the sidewalls and the value of the spring constant of the micromechanical elements to be implemented.

All compliant elements of the sensor are made of thin membrane portion by means of photolithographically patterned etch-mask layer.

For measuring of displacement between two macro parts/objects of interest, the both frame-members of the sensor have to be firmly attached to each part/object, first. Typical case of such assembly is shown in Fig. 2(a). The frame breaks predictably in two pieces at initial stretching are shown in Fig. 2(b). Any displacement between frame-members, between the parts/objects of interest respectively, will cause strain in both detecting cantilevers. The strain is transduced in proportional voltage output signal by sidewall piezoresistors’ bridge.

![Fig. 2. MEMS displacement sensor: (a) Plane view of the MEMS displacement sensor in initial state; (b) Plane view of the MEMS displacement sensor at 0.6 mm displacement](image)

3. Development of a device for force measurement using MEMS sensor.

3.1. CAD model of the measuring device

Inserted task is to develop a device for measuring the force based on the so designed silicon MEMS sensors. To measure the forces within specified limits it is necessary to develop a flexible transmission mechanism, which transforms the obtained elastic deformation to deformation of the MEMS sensor, and the stiffness of elastic transmission to determine the size of the measured force. Admissible deformations of MEMS sensor are determined – 0.6 mm, and the upper limit of the measured force is specified – 1500 N. A transmission mechanism is designed as illustrated by 3D CAD model shown in Fig.3.
The transmission mechanism is made of a solid steel plate drilled in a certain manner to obtain the elastic joints in the mechanism. Here is selected rectangular plate with dimensions 67x46 mm and thickness of 6.5 mm, drilled with 12 cylindrical holes. Two of the holes have a diameter of 15 mm and the other 10 have a diameter of 12 mm. All the holes are arranged symmetrically, so the distance between the central and lateral holes is 0.5 mm and the elastic joints are formed. By cutting of the plate at specific locations is received double symmetric mechanism as shown in Fig. 3. This design was chosen for easier and cheaper manufacturing of the device using conventional machine tools. MEMS sensor is located in the middle of the mechanism, connecting the two symmetrical zones.

3.2. Model of the transmission mechanisms

A model of double symmetric transmission mechanism as a linkage is created. Monolith areas of the mechanism form the rigid links and thin areas form the mechanism elastic joints. Rigid links are connected each other by rotating joints as it is shown in Fig. 4. The number of rigid links is 8 and the number of the rotating joints is 8. The mechanism has more than one degree of freedom, but with a load on the axis of symmetry it can be assumed that the mechanism has one degree of freedom. The height of the device is denoted by H, and the width of the device in the sensor area is denoted by N (Fig. 4). Each symmetric branch of the transmission is considered as a rectangle with two sides n and h, hypotenuse l and one leg angle α. Then the next equations are valid:

\[ \frac{n}{h} = \tan \alpha \]

\[ n^2 = l^2 - h^2 \]

After differentiation of (2), the transmission ratio is found as follows:

\[ \frac{\dot{n}}{\dot{h}} = -h \sqrt{l^2 - h^2} = -h / n \]

or
For symmetrical linkage exists relationship between the parameters

\[ H = 2h + a_1 \]  
\[ N = 2n + a_2 \]

where \( a_1 \) and \( a_2 \) are constant geometric parameters defined by the design.

After differentiation of (4) and (5) and taking into account of (3) we find the gear ratio of double symmetric transmission mechanism

\[ k = \frac{\partial N}{\partial H} = \frac{\partial n}{\partial h} = \frac{-h}{n} \]

3.3. Numeric evaluations

According to the constructed model of the transmission mechanism according Fig.4 and the scheme of Fig.4, the following values of the parameters of an experimental device for force measurement were accepted as follows: \( h = 15 \text{ mm} \), and \( n = 1.5 \text{ mm} \).

According to (6) the following transmission ratio of the mechanism was calculated: \( k = \partial N / \partial H = 10 \).

An experiment of the static load was carried out using the finite element modelling (FEM) as function of a commercial CAD system (Fig. 5). Fig. 5 shows the screen with effective displacements. The screen with effective stresses is not shown, but normal stresses in the most loaded areas did not exceed the admissible for the material.

Some simulations were carried out using the constructed 3D CAD model of the measuring device shown in Fig.3. All the system bodies were simulated by means of stainless steel (X2CrNi18-9) with Young’s modulus \( E = 190 \text{ GPa} \) and Yield strength \( \sigma = 0.465 \text{ GPa} \).
Simulations were conducted, when the forces are attached at the upper end of the load platform. The lower end of the platform is rigidly immobilized. A load on the platform with a static force 1000 N was simulated, using a model with varying thickness of the steel plate. Here are reported displacements of the force application points and deflections of the MEMS sensor points, accepted as $\partial H \partial N$. Reported displacements and calculated transmission ratio are shown in Table 1.

<table>
<thead>
<tr>
<th>Plate thickness</th>
<th>5.0 [mm]</th>
<th>5.5 [mm]</th>
<th>6.0 [mm]</th>
<th>6.5 [mm]</th>
<th>7.0 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\partial H$ [mm]</td>
<td>0.0405</td>
<td>0.0364</td>
<td>0.0335</td>
<td>0.0295</td>
<td>0.0273</td>
</tr>
<tr>
<td>$\partial N$ [mm]</td>
<td>0.4490</td>
<td>0.3940</td>
<td>0.3580</td>
<td>0.2990</td>
<td>0.2660</td>
</tr>
<tr>
<td>$k$</td>
<td>11.08</td>
<td>10.82</td>
<td>10.68</td>
<td>10.13</td>
<td>9.74</td>
</tr>
</tbody>
</table>

Reported results of the simulation show an effect of the plate thickness on the gear ratio of the elastic mechanism. For prototyping of a measuring device is selected plate thickness $t = 6.5$ mm, for which additional simulations during load changes were carried out. A load respectively 500 N, 1000 N, 1500 N and 2000 N is attached. Reported displacements and calculated transmission ratios are shown in Table 2.

<table>
<thead>
<tr>
<th>Load</th>
<th>500 [N]</th>
<th>1000[N]</th>
<th>1500[N]</th>
<th>2000[N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\partial H$ [mm]</td>
<td>0.0148</td>
<td>0.0295</td>
<td>0.0443</td>
<td>0.0590</td>
</tr>
<tr>
<td>$\partial N$ [mm]</td>
<td>0.1495</td>
<td>0.2990</td>
<td>0.4480</td>
<td>0.5990</td>
</tr>
<tr>
<td>$k$</td>
<td>10.10</td>
<td>10.13</td>
<td>10.11</td>
<td>10.15</td>
</tr>
</tbody>
</table>

As a result of the experiment it appears that the transmission ratio is maintained constant. The deformations of the sensor are in the admissible limits ($\partial N < 600 \mu m$). The upper limit of the measured force specified as 1500 N provides reserve of damaging the sensor.

4. Conclusion

The results obtained using the FEM function of the CAD system are similar to those obtained by the simple model of solids, but these results reflect the influence of more parameters. The results are useful for assessing the behavior of the measuring device under static loading. The calculated transmission ratio may be used in the design and prototyping of the device, but for measurements it must be determined experimentally.

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REFERENCES


