Design of Microfabricated Strain Gauge Array to Monitor Bone Deformation

In Vitro and In Vivo

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Abstract

We present the design of a strain gauge embedded in polydimethylsiloxane (PDMS) that could be implanted and used for monitoring strain on surfaces of bones with high resolution. Our ultimate goal is to design and fabricate the device such that it could be used to provide real-time data of strain development in live subject. We have simulated the mechanical characteristics of thin-film metal strain gauges embedded in a flexible substrate made from polydimethyl-siloxane (PDMS) with various loading conditions using ANSYS® finite element analysis tool. Various gauge designs were subjected to stresses from several different directions. Linear relationships between fractional change of resistance and nominal resistance were found for both tensile and compressive stress applied on the gauges. Most significantly, the simulation demonstrated that external stresses were effectively transmitted through the PDMS layer to the thin-film metal, validating our approach.

1. Introduction

Monitoring strain (normalized deformation) at hundreds of sites on a bone surface, in vivo or in vitro, would be invaluable for studying bone with metastatic tumors, osteoporosis, and joint prostheses. However, currently available devices for measuring strain are too large (typically 2 × 5 mm) to provide measurements with suitable resolution. These gauges are also difficult to mount on bone surfaces because of their large size and the bone’s irregular surface topology. Furthermore, strain gradients and distributions in bones can be highly localized [1], [2], so mounting a gauge just a few mm from the peak or minimum strain can lead to grossly understated or overstated values.

Due to these limitations, off-the-shelf strain gauges are used infrequently [3]. There is a strong need for sensors that can provide a map of distributed strain data over the area of interest on the surfaces of bones.

An inexpensive, implantable microscale strain gauge array would have numerous clinical and research applications. For example, this device could be used to monitor the structural integrity of bones with metastatic lesions during medical treatment (e.g. with bisphosphonates). If strain during walking increased over time, fracture would be likely and more aggressive (surgical) treatment would be required. In contrast, decreasing strain over time would indicate successful medical treatment.

To evaluate a joint prosthesis, local changes in strain upon implantation would be measured (in vitro or in vivo). Such changes indicate that destructive bone remodeling would occur [4]. A common clinical problem occurs when strain decreases upon implantation of prosthesis, bone remodels to become less dense (bone resorption), the prosthesis loosens, and revision surgery must be performed. In contrast, if strain increases, the patient may experience pain and bone hypertrophy [2], [4]. A strain gauge array would greatly enhance our ability to evaluate prosthesis designs and to improve clinical results.

Furthermore, in osteoporosis studies, animals are sometimes oophorectomized to simulate menopause and the bone response is assessed, often by sacrificing animals at multiple time points and performing histological evaluation. However, if strain could be measured in vivo at many locations over time using an inexpensive, implantable microscale strain gauge array, a wealth of information about the bone response could be collected from each animal, thereby improving the quality and quantity of the data while using fewer animals.
2. Approach

We are currently developing a microscale strain gauge embedded in a flexible membrane. Micro Electromechanical Systems (MEMS) technology offers the ability to create microscale strain gauges that are orders of magnitude smaller than those currently available. Once these strain gauges have been developed, they could be fabricated in a two dimensional array that could be affixed to bone surfaces to facilitate comprehensive and accurate strain data acquisition, as shown in Figure 1. Large areas could be probed to monitor strain contours on both surfaces. Combined with signal processing electronics, real-time, high-fidelity resolution of strain development on the surface of bone in vivo or in vitro could be achieved.

![Figure 1. Diagram of an implantable, wireless, strain gauge array. The three-element gauge configuration at each recording site allows differential measurement of 2D stresses. The three elements can be superimposed on each other in different layers to further reduce the pixel size and localize the measurement.](image)

Through microfabrication technology, we can batch fabricate thousands of miniature strain gauges and offer orders of magnitude higher resolution than currently attainable. Ultimately we will develop a wireless, implantable array embedded in a flexible polymer membrane that can be attached to bone surfaces. To date, we have focused on designing a prototype strain gauge embedded in a flexible, biocompatible membrane. Our preliminary results are presented in the following sections.

3. Design

The primary strain mechanism in our design is through piezoresistors. Piezoresistivity is a reversible phenomenon, in which a resistor exhibits a change in resistance when an external stress is applied. This fractional change in resistance is proportional to the applied strain and it persists as long as the applied stress remains. The piezoresistive effect is quantitatively expressed by a gauge factor, $G$, which is defined as the proportional change in resistance per unit strain:

$$ G = \frac{\Delta R}{R \varepsilon} $$

where $R = $ nominal resistance, $\varepsilon = $ strain, and $\Delta R = $ resulting change in resistance. This change in resistance arises from two important factors: (a) the change in the resistivity of the material, and (b) the change in the physical dimensions of the resistor as the material is deformed [5].

Strain is related to stress ($\sigma$) as expressed in Hooke's law:

$$ \sigma = E \varepsilon $$

where $E =$ Young's modulus or the modulus of elasticity of the material of interest. Stress and strain can be tensile, compressive, or shear. It is important to understand the interaction of stresses and strains on strain gauges so that their structural changes can be accounted for in the design process. Our goal is to develop a strain gauge design that maximizes sensitivity on a localized spot, and is amenable for embedding inside a flexible substrate.

There are three main categories for piezoresistive materials used for strain gauge applications. These are thin-metal films, thick-film resistors, and semiconductors. Although strain gauges made of semiconductors such as single-crystalline or polycrystalline silicon would have high gauge factors, they are non-flexible and brittle, and thus are not suitable for embedding in a flexible substrate. We chose thin-metal films for our purposes because of their compliance, ruggedness, and compatibility with microfabrication processes.

As an initial study, we intended to make several prototype thin-film metal strain gauges to characterize the performance as a function of fabrication process alternatives and variation in designs. The fabrication process was fairly straightforward. A thin-film metallic layer patterned into a serpentine resistor would
function as a strain gauge. The metal would be sandwiched between two layers of PDMS (Dow Corning 184 from K. R. Anderson, Inc., Morgan Hill, CA), which serve as the substrate. We chose PDMS because of its simple processing, flexibility, and biocompatibility. Also, metal films encapsulated in PDMS had been previously demonstrated [6]. In contrast to [6], we intended to use platinum or nickel-chromium alloy (NiCr) instead of gold for their higher resistivities, 10.6 µΩcm [7] and 130 µΩcm [8] respectively compared to 2.3 µΩcm for gold [9].

Various arrays of strain gauges were designed, in which the length (L), trace width (w), number of turns (n), and distance between turns (p) were varied systematically (Figure 2). A single-mask process is developed. The only masking step required to fabricate this device would be to define the metal thin film, and thus eliminating mask alignment problems.

A reference gauge with resistance of 500 Ω was included in every wafer. The dimensions of this reference gauge were w = 50 µm, L = 1 mm, and n = 18. Power consumption, physical dimension, sensitivity and noise were considered during the design phase. A trade-off existed between the signal-to-noise ratio (SNR) and the resolution of strain gauges. Increasing resistance would decrease SNR with higher Johnson noise [(σν)²_noise = 4kTRΔf]. However, larger resistance would provide greater resolution as ΔR would be increased. In addition, variance of resistance due to process variations would be reduced with larger dimensions (and thus higher resistances). An important factor affecting the sensitivity is the amount of stresses transmitted to the metal strain gauge through the PDMS substrate. The magnitude of this factor was not known a priori, and thus ANSYS® simulation was used as a design guide, which would be verified experimentally.

The relationship between each dimension and the sensitivity and noise of the strain gauges are determined with full-factorial analysis. The arrays were designed to vary one parameter while keeping the others constant. For instance, in wafer A, the width, length and the pitch between the turns remained constant while the number of turns varied from 3 to 42. In wafer B, only the lengths of the gauges were varied from 1 mm to 4 mm with an increment of 400 µm. In wafer C, there were two sets of strain gauges as shown in Fig. 3. In one set, only the widths of the gauges were varied from 25 µm to 100 µm, and in the other set, only the pitches of the turns were varied from 100 µm to 600 µm. Hence, from these strain gauge arrays, the relationship between sensitivity and the number of turns, pitch, length, and width of the strain gauges could be determined.

![Figure 2: Diagram showing typical strain gauge and the parameters that were varied in the array.](image)

![Figure 3: Photomask of wafer C for strain gauge array where the number of turns was constant but the widths of the gauges varied from 25 µm to 100 µm in one set of gauges, and pitch was varied in another set of gauges.](image)

4. Simulation

Using ANSYS® finite element modeling tool, gauges with 3, 6, 10, 14, 18, 22, 26, 32, 34 and 38 turns were simulated each under compressive or tensile stress in the x and y directions as well as tensile stresses in both directions simultaneously. The other
parameters of the gauges were kept constant to \( L = 1 \) mm, \( w = 50 \) µm, and \( p = 450 \) µm. Thickness of the gauges was several hundreds of nanometers, which was at least 3 orders of magnitude less than the width of the traces. We assumed that the deformation of the gauge in the \( z \) direction would be negligible compared to those in the \( x \) and \( y \) directions. Therefore, a 2-D model was adopted for simulation. The gauge was embedded in a PDMS plane and properties of both materials were input into the program. Young’s modulus of the gauge was assumed to be the value of Platinum (170 GPa [10]). Poisson’s ratio of Platinum used was 0.35 [10]. Young’s modulus of PDMS was taken as 2.5 MPa [11] and Poisson’s ratio as 0.5 [12]. Density of PDMS used was 965 kg/m\(^3\) [13]. In all of the simulations, stress was applied to the PDMS edge, while the center of the gauge was fixed.

After appropriately meshing the area, force was applied in the form of stress. 10Pa compressive and tensile stresses along the \( x \)- and \( y \)-axes were separately simulated. Simulations with a uniform stress were also performed by imposing tension simultaneously along the \( x \)- and \( y \)-axes. From ANSYS®, the stress was calculated at each node. The corresponding strain at each node was separately calculated using Eq. (2). These values were used to calculate the average strain experienced by the entire gauge. The average strain was then used to determine the expected change in resistance (\( \Delta R \)) using Eq. (1) for each gauge configuration with a value of 2 for \( G \).

As stated previously, we intended to encapsulate the thin-film metal strain gauges within a flexible membrane. To resolve some initial design issues, we fabricated prototype membranes from a thin layer of PDMS and embedded mock foil “gauges” in the membranes. To create the membranes, shallow Petri dishes were first treated using silane vapor to prevent the PDMS from sticking to the dish. Degassed PDMS precursor was then poured into the dish, the foil gauges were placed in the PDMS, and the PDMS was cured at 70ºC for 2 hours. Once cured, the PDMS could be cut to the desired membrane dimensions and lifted from the mold. The final membrane thickness was varied from 1 – 2 mm. Two types of membranes were fabricated: those with staggered slits and those without. 2 cm long slits spaced 0.5 cm apart were cut into the membrane to allow it to cover a greater surface area without placing excessive strain on the gauges or the membrane.

5. Results and Discussions

Simulated values of resulting stresses from ANSYS® on all strain gauges for each loading condition were obtained. Expected changes of resistance (\( \Delta R \)) in the gauges were calculated from Eqs. (1) and (2) using a gauge factor of 2 for Platinum [14]. An example of the calculated \( \Delta R \) was shown in Table 1, in which compressive stress along \( x \)-axis was applied.

<table>
<thead>
<tr>
<th>No. of turns</th>
<th>Stress (N/ m(^2))</th>
<th>Strain</th>
<th>Resistance (Ohm)</th>
<th>( \Delta R ) (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1508</td>
<td>0.0006</td>
<td>80</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td>2136</td>
<td>0.0009</td>
<td>163</td>
<td>0.28</td>
</tr>
<tr>
<td>10</td>
<td>2332</td>
<td>0.0009</td>
<td>275</td>
<td>0.51</td>
</tr>
<tr>
<td>14</td>
<td>2567</td>
<td>0.0010</td>
<td>386</td>
<td>0.79</td>
</tr>
<tr>
<td>18</td>
<td>2640</td>
<td>0.0011</td>
<td>498</td>
<td>1.05</td>
</tr>
<tr>
<td>22</td>
<td>2687</td>
<td>0.0011</td>
<td>609</td>
<td>1.31</td>
</tr>
<tr>
<td>26</td>
<td>2349</td>
<td>0.0009</td>
<td>721</td>
<td>1.35</td>
</tr>
<tr>
<td>32</td>
<td>2541</td>
<td>0.0010</td>
<td>888</td>
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</tr>
<tr>
<td>34</td>
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<td>0.0010</td>
<td>944</td>
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</tr>
<tr>
<td>38</td>
<td>2578</td>
<td>0.0010</td>
<td>1055</td>
<td>2.18</td>
</tr>
</tbody>
</table>

The calculated \( \Delta R \) from simulated stress values were plotted against the nominal resistances for cases with compressive or tensile force applied along \( x \)-axis and \( y \)-axis as shown in Figs. 4 and 5, respectively. In each plot linear curve fitting was added.

As expected, the analytical results of \( \Delta R \) were equal in magnitude but opposite in direction for gauges subject to compressive and tensile stress of equal magnitude. As the number of turns of the strain gauges increased, we would expect the sensitivity of the strain gauges to remain the same. Since each turn experienced the same amount of stress which was 10 Pa when stress was applied in the \( x \)-direction, increasing or decreasing the number of turns had no effect on the overall sensitivity of the strain gauges. However, when stress was applied in the \( y \)-direction, it was distributed across the whole gauge, and hence each turn only experienced a stress that was equivalent to 10 Pa divided by the number of turns. Thus, the calculated \( \Delta R \) values were smaller in \( y \)-direction than those measured along the \( x \)-direction as expected.

In addition, a plot of calculated \( \Delta R \) versus the nominal resistances for the case with a tensile stress applied along \( x \)- and \( y \)-axes simultaneously was shown in Figure 6. The analytical results of \( \Delta R \) showed a linear relationship.
An example plot of an undeformed strain gauge drawn in ANSYS® was shown in Fig. 7. The plots of the undeformed and resulting deformed gauges were also captured. Examples of these plots were shown in Figs. 8 – 10 for an 18-turn strain gauge with stress applied along x- and y-axis and along both directions simultaneously, respectively. The nominal resistance of this gauge was 500 Ω.

Figure 4: (a) With a compressive stress of 10 Pa applied along x-axis, the calculated $\Delta R$ from simulated stress values were plotted versus the nominal resistances; similarly for (b) but instead, a tensile stress of 10 Pa was applied.

Figure 5: (a) With a compressive stress of 10 Pa applied along y-axis, the calculated $\Delta R$ from simulated stress values were plotted versus the nominal resistances; similarly for (b) but instead, a tensile stress of 10 Pa was applied.

Figure 6: (a) A tensile stress of 10 Pa was applied along positive x- and y- axes
simultaneously. The $\Delta R$ was calculated and plotted against the nominal resistances.

![Figure 7](image)

**Figure 7:** Undeformed 18 turn gauge embedded in PDMS. The black regions represented the metal while the red was the PDMS within which the metal gauge was embedded.

![Figure 8](image)

**Figure 8:** Simulated plots of the reference strain gauge by ANSYS® (a) with a compressive stress of 10 Pa and (b) with a tensile stress of 10 Pa applied along y-axis.

Figure 8: Simulated plots of the reference strain gauge by ANSYS® (a) with a compressive stress of 10 Pa and (b) with a tensile stress of 10 Pa applied along x-axis.

The dotted-line rectangle was the strain gauge with PDMS when no stress was applied. The solid line and yellow region represented the deformed strain gauge when 10 Pa stress was applied.

![Figure 9](image)

**Figure 9:** Simulated plots of the reference strain gauge by ANSYS® (a) with a compressive stress of 10 Pa applied along $x$-axis.

![Figure 10](image)

**Figure 10:** Simulated plot of the reference strain gauge by ANSYS® with a tensile stress of 10 Pa applied along $x$- and $y$-axes simultaneously.

As seen in Figs. 8 – 10, the simulations showed the resulting deformation of the gauge embedded in the PDMS. In cases of compression along the $x$-direction, the spacing between each turn of the gauge decreased in response to the compressive stress. Since there was an equal compressive stress from both sides of the gauge along the $x$-axis, the length of the gauge was shortened while the height increased, as expected. The opposite occurred for gauges subject to tensile stress.

Similar results were seen when tensile and compressive stress was applied along the $y$-axis.

Close-up contour plots showed the stress gradients within the gauge. Examples of these plots were shown in Fig. 11 - 13 for the reference gauge with 18 turns. Corners and edges and regions perpendicular to where the stress was applied were regions of high stress concentration, as expected.

Most significantly, from the contour plots, we demonstrated that the stress applied on the PDMS was mostly transmitted to the embedded metal gauge. Since the metal gauge was embedded, the resulting strain on both materials would be the same. In addition, the metal gauge had larger Young’s modulus value than PDMS. Hence, the stress experienced by the metal gauge would be higher than the PDMS, as shown in the simulated results. This indicated the feasibility of our strain gauge design in PDMS.
Figure 11: Simulated contour plots of the reference strain gauge by ANSYS (a) with a compressive stress of 10 Pa and (b) with a tensile stress of 10 Pa applied along x-axis. The color scale shows the stress value ranged from -12083 Pa (dark blue) to 14719 Pa (red) for (a). The stress value ranged from -14719 Pa (dark blue) to 12083 Pa (red) for (b). The green background indicated the value of stress acting on the PDMS to be -171 Pa for (a) and -2807 Pa for (b).

Figure 12: Simulated contour plots of the reference strain gauge by ANSYS® (a) with a compressive stress of 10 Pa and (b) with a tensile stress of 10 Pa applied along y-axis. The color scale shows the stress value ranged from -4069 Pa (dark blue) to 2516 Pa (red) for (a). The stress value ranged from -2516 Pa (dark blue) to 4069 Pa (red) for (b). The colored background indicated the value of stress acting on the PDMS to be -418 Pa for (a) and -321 Pa for (b).

Figure 13: Simulated plot of the reference strain gauge by ANSYS® with tensile stress of 10 Pa applied along x- and y-axes simultaneously. The color scale shows the stress values ranged from -4063 Pa (dark blue) to 4010 Pa (red). The colored background indicated the value of stress acting on the PDMS to be -474 Pa.

As mentioned previously, PDMS prototype membranes were fabricated. The membranes with staggered slits facilitated close membrane coverage of a foam model femur (Pacific Research Laboratories, Vashon, WA), as illustrated in Fig. 14. Without slits, the membrane would have to be stretched to achieve close contact with the bone surface. Stretching the membrane may produce excessive strain on the gauges. The slits would thus prevent excessive strain and facilitate proper device positioning.

Figure 14: (A) Slotted prototype membrane with mock gauges, as fabricated (5 cm x 7 cm, 1 mm thick). (B) Membrane in (A) fully expanded. (C) Membrane along boney ridge
on posterior aspect of femur. (D) Membrane shows good conformation to bone surface.

In the future, we will design 2-D gauge arrays with gauges positioned between slits. The immediate step is to fabricate the strain gauges as drawn in the mask (Fig. 3) and conduct comprehensive full-factorial tests. Further, reduction in strain gauge array will be pursued with higher resolution photomask.

6. Conclusion

We have designed the first version of micro strain gauges to be embedded in PDMS for monitoring the deformation on bone surfaces. We have simulated these gauges with ANSYS® to find the fractional changes in resistances with various loading conditions and verified their performances. We have also tested several prototype membranes with mock strain gauges and conceived the first slitted membranes that can be used to monitor strain (normalized deformation) at hundreds of sites on a bone surface, in vivo or in vitro, with much better anticipated resolution.

7. Acknowledgements

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8. References