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# Calculation of Stress And Deflection In Double Layer Microcantilever For Biosensor Application

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## Abstract
In microcantilever-based biosensor, a sensitive layer plays an important role as a place for the establishment of functional layer for detecting molecules target. When a sensitive layer is coated on the microcantilever surface, a surface stress change is induced as a consequence of adsorbate-surface interaction, resulting in a deflection of the microcantilever. However, the microcantilever with the sensitive layer of gold (Au) or 3-Aminopropyltriethoxysilane (aminosilane) which are commonly used in biosensor, has not been reported. In this paper, we study a dependence of the microcantilever deflection on the gold / aminosilane layers thickness in static mode operation. From a derivation of Stoney equation, it is found that the influence of material properties on the deflection of double layer microcantilever from the film stress and radius of curvature. Such relationship is important because the microcantilever deflection directly influences the sensor sensitivity. Our results indicate that the material and the thickness of sensitive layer should be considered to obtain a high sensitivity of microcantilever sensor.

**Keywords:** Microcantilever, double layer, deflection, stress, sensitive layer, thickness.

## 1. Introduction
Microcantilever-based sensors have attracted considerable interest for recognition of target analytes because of their fast, compact read-out, and high sensitivity [1-2]. Such sensor has been investigated in the fields of environment, medicine, chemistry, physics, and biology. In previous research, we have developed the microcantilever-based sensor for environmental monitoring, especially for humidity detection [3]. However, to act as biosensor, there are two important requirements for the microcantilever. First, the functional layer (usually antibody) must be coated on the microcantilever surface for detecting targeted object (antigen). Second, a sensitive layer (gold or 3-Aminopropyltriethoxysilane/aminosilane) is needed to provide a surface for attaching functional molecules. When the sensor operates in a static mode, the sensitivity is mainly determined by the microcantilever deflection, where, the deflection of the microcantilever depends on thickness coating of the sensitive layer [4]. The microcantilever with the sensitive layer (double layer structure) can be seen in Fig. 1.

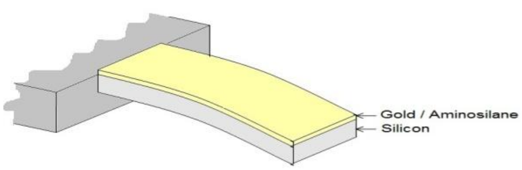


Figure 1. Double layer microcantilever

It is important to be noted that the sensitive layer coating on the microcantilever surface can induce a surface stress change as consequence of adsorbate-surface interaction. The surface stress can be obtained from the measurement of the curvature change by applying Stoney equation, which provides a linear relationship between surface stress change and the curvature change [5]. Stoney conducted the experiment of how glass substrates bent due to metal deposited on the surface [6]. However, the model does not contain any parameters related to coating film as shown in Fig. 1. Recently, Yoshikawa reported an analytical model for static deflection and optimization of a mechanical cantilever coated with a solid receptor film [7]. The model provides accurate values which are a good agreement with finite element analysis. However, to our knowledge, the microcantilever with the sensitive layer of gold (Au) or aminosilane which are commonly used, has not been reported. The gold is usually used as sensitive layer due to have a good corrosion resistance and biocompatible [8]. On the other hand, aminosilane is also widely used for the sensitive one because it is biocompatible and getting a covalent bind to immobilization layer [9]. In this paper, we investigate the dependence of the microcantilever deflection on the sensitive layer (gold and aminosilane) thickness in static mode operation. Such characteristic is important to be found because the microcantilever deflection directly influences the sensor sensitivity. Both gold and aminosilane have large diferences in their Young's moduli properties, therefore, the influence of material properties to sensitivity of double layer microcantilever via the film stress and radius of curvature is an interesting to be studied.

## 2. Analytical Model For Stress And Deflection

The stoney equation, shown in equation (1), is commonly used for relating substrate curvature to film stress. From the equation, the deflection (Δz) induced by surface stress (σ) can be estimated. Here, *v* is Poisson's ratio, *E* is Young's moduli, *l* and *t* are respectively the length and thickness of microcantilever. It is noted that this equation does not contain any parameters relating with a coating film inducing the surface stress.

$$\Delta z = \frac{3(1-v)l^2}{Et^2}\sigma \qquad (1)$$

In this section, the stoney equation is derived for suitable analytical model of static deflection a microcantilever sensor coated with sensitive layer. When the sensitive layer is coated on the microcantilever surface, stress (σ) is set up in the top and bottom of each layer, as shown in Fig. 2(a). As a result, the composite will bend in response to these stresses. Here, we define the numbers of 1 and 2 in Fig. 2(b) as a substrate layer (first layer) and a coating film or sensitive layer (second layer), respectivelly.

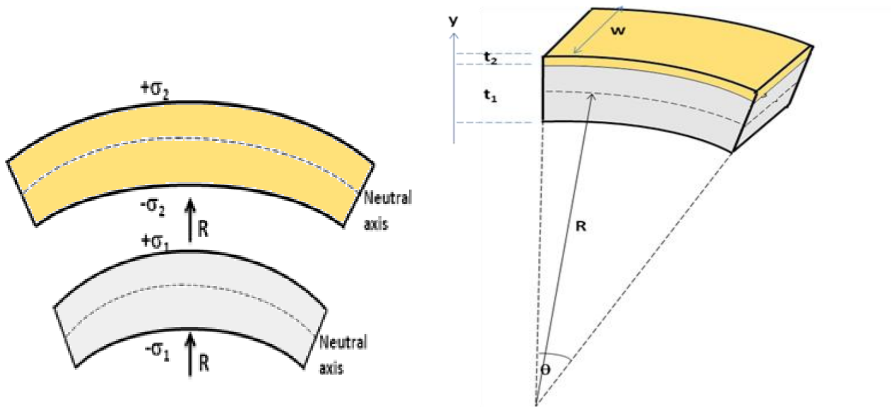


Figure 2. (a) Stress in each layer, (b) Radius of curvature

The radius of curvature, *R*, can be calculated from the mechanical equilibrium condition, where both force and moment must be in balance, as described in equation (2). It is noted that the radius of the curvature can be shown in Fig. 2(b).

$$\frac{E_1 w t_1^3}{12R} + \frac{E_2 w t_2^3}{12R} + F_1\frac{t_1}{2} + F_2\left(t_1 + \frac{t_2}{2}\right) = 0 \qquad (2)$$

Here, $F_i$ is internal force distributed throughout the *i*-th layer. Since $F_2 = -F_1$ in the case of equilibrium, and $F_1 = -\frac{E_1 E_2 t_1 t_2 w}{(E_1 t_1 + E_2 t_2)}\left(\epsilon_{21} + \frac{(t_1 + t_2)}{2R}\right)$, the radius of curvature can be described as,

$$R = \frac{(E_1 w t_1^3 + E_2 w t_2^3)(E_1 t_1 + E_2 t_2) + 3(t_1 + t_2)^2 E_1 E_2 t_1 t_2 w}{12(E_1 t_1 + E_2 t_2) - 6(t_1 + t_2) E_1 E_2 t_1 t_2 w \epsilon_{21}}. \qquad (3)$$

The joined two layers also generate strain in each layer. The strain which exists in the composite, $\epsilon_{21}$, is the difference of total strain in the bottom of second layer, $\epsilon_2$, and total strain in the top of first layer, $\epsilon_1$, as described below,

$$\epsilon_{21} = \epsilon_2 - \epsilon_1 \qquad (4)$$

The radius of curvature is needed to calculate sensitive layer stress as a function of position within the layer, $\sigma(y)$. Noted that the stress in each layer varies and may change sign over its entire thickness. The stress in any layer, $\sigma_i(y)$ consists of stress due to internal force and stress due to bending stress. The stress in the sensitive layer is shown in equation (5) [10],

$$\sigma_2(y) = \frac{F_2}{w t_2} + \frac{E_2}{2R}\left(y - \frac{t_2}{2}\right) \qquad (5).$$

Here, $y$ is position in $i$-th layer measured from bottom of the $i$-th layer (see Fig. 2(b)). The stress in first layer (substrate) is determined by similar formula of equation (5). For two-dimensional nature of the stress and bending problem, $E_i$ is replaced by $E_i/(1-v_i)$, which includes the Poisson ratio, $v_i$, of any material. For the microcantilever with the assumption of the deflection $\Delta z = l^2/2R$, $\Delta z$ is described in the equation below [7],

$$\Delta z = \frac{3l^2(t_2-t_1)}{(A+4)t_2^2+(A^{-1}+A)t_2^2+6t_2t_1} \in_2 \qquad (6)$$

where $A = [E_2w_2t_2(1-v_1)]/[E_1w_1t_1(1-v_2)]$, $t_1$ is thickness of microcantilever, $t_2$ is film thickness, and $\in_2$ is a strain of a coating film, shown as

$$\in_2 = \frac{\sigma_2(1-v_2)}{E_2}. \qquad (7)$$

## 3. Result and Discussion

First, we investigaed the dependence of the curvature radius on thickness of the coating film (sensitive layer) for gold and aminosilane using the equation (3). The simulation was run by using MATLAB Programming with detail parameters listed in Table 1.

Table 1. The parameters used in the calculation

| No. | Parameters | Value |
|---|---|---|
| 1 | Thickness of Microcantilever, $t$ | 3 [μm] |
| 2 | Length of Microcantilever, $l$ | 100 [μm] |
| 3 | Width of Microcantilever, $w$ | 50 [μm] |
| 5 | Silicon Young's moduli, $E_1$ | 190 [GPa] |
| 6 | Silicon Poisson Ratio, $v_1$ | 0.27 |
| 8 | Gold Young's moduli, $E_2$ | 79 [GPa] |
| 9 | Gold Poisson Ratio, $v_2$ | 0.44 |
| 10 | Aminosilane Young's moduli, $E_3$ | 5 [GPa] |
| 11 | Aminosilane Poisson Ratio, $v_3$ | 0.31 |
| 12 | Surface stress | 0.1 [N/m] |

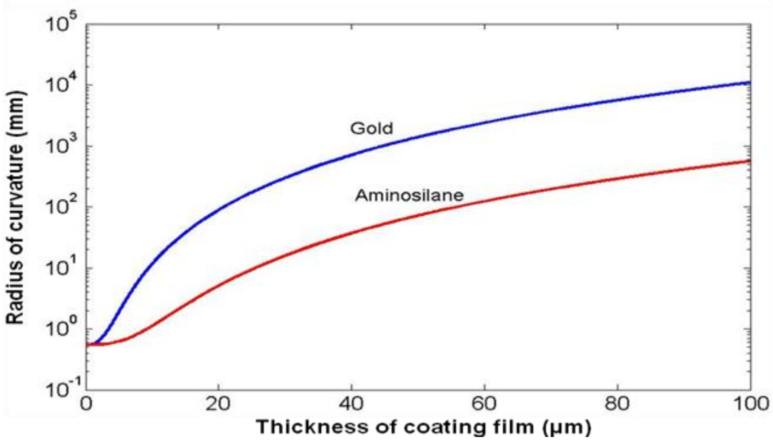


Figure 3. Dependence of curvature radius on the thickness of coating film for gold and aminosilane

Figure 3 shows the calculated radius of the curvature as a function of the various thickness of gold and aminosilane coating film. It can be seen in equation (3) that the radius of curvature is influenced by Young's moduli, thickness of each layer, and strain at the interface of double layers. As results, the higher Young's moduli of gold generates the higher radius of curvature on gold layer than aminosilane layer as shown in the figure. The radius of curvature increases exponentially with the increasing thickness of coating film for both gold and aminosilane layer. Previously, Olsen and Ettenberg reported the stress distribution in the multilayer structures [10], where they found that the layer thickness influenced the radius of curvature. Our result agrees with their result.

Next, the stress distribution in position $y$ in the sensitive layer, $\sigma_2(y)$ was calculated using equation (5). Since strain is induced by adsorption analytes on the sensitive layer, we can assume that the strain is not generated in the microcantilever during this process ($\in_1 = 0$). Therefore, the strain which exists in the composite ($\in_{21}$) is only the strain in the second layer or sensitive layer ($\in_2$), defined as equation (7). Figure 4 shows the stress distribution for both sensitive layers as a function of position $y$ within the layer. Here, the thickness of the sensitive layers is fixed to be 6 nm. As results, for both gold and aminosilane, the stress distribution throughout the coating films increases with the increasing its position from the bottom. The change sign on thickness reflects the tension ($+\sigma$) and compression ($-\sigma$). The maximum tension and maximum compression for both sensitive layers are about 20000 N/m$^2$ and -20000 N/m$^2$, respectively. On the position of a half thickness of sensitive layer (3 nm), the stress distribution for gold and aminosilane layers is 1187 N/m$^2$ and 94 N/m$^2$, respectively. Such stress distribution on this position is only determined by stress due to internal force, where the internal force is influenced by the strain at the interface of two layers. Since the strain is determined by Young's moduli of a material, the higher Young's moduli of gold layer produces the higher stress distribution than that of the aminosilane layer. The stress on the top surface layer for gold and aminosilane is 21000 N/m$^2$ and 19900 N/m$^2$, respectively, whereas the stress on the bottom of gold and aminosilane layers is -19000 N/m$^2$ and -20000 N/m$^2$, respectively.

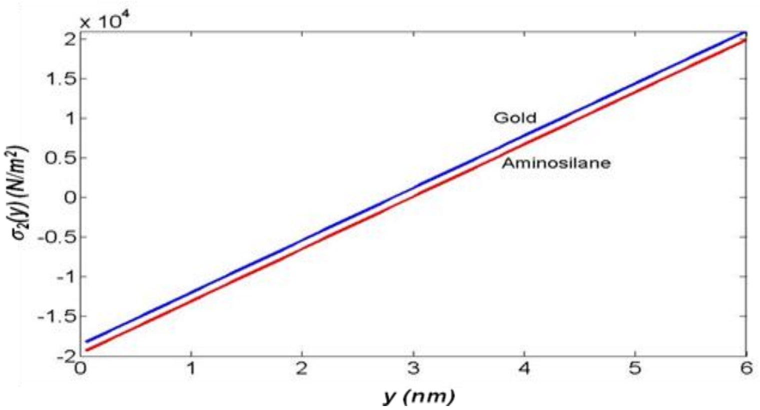


Figure 4. Stress on the film $\sigma_2(y)$, where the position $y$ is measured from the bottom of coating film

Next, we calculated the total stress of the coating film as a function of its thickness, as shown in Fig. 5. The calculated stress is a total of the stress distribution on all positions of thickness layer. In this calculation, it is assumed that all values of the stress are positive. We can see that, for both the sensitive layers, the stress increases with increasing the thickness the stress until a certain value and then decreases thereafter. The maximum stresses of 1.249 x 10$^{10}$ N/m$^2$ and 1.728 x 10$^9$ N/m$^2$ are obtained at the thickness of 2900 nm and 7800 nm for gold and aminosilane, respectively. This result agrees with Fig. 4, where the stress of higher Young's moduli (gold) generates the higher stress than one (aminosilane). It indicates that the peak of maximum stress is reduced in lower Young's moduli.

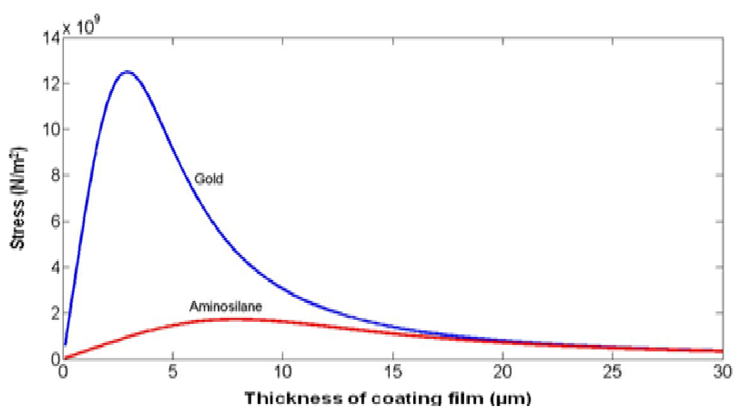


Figure 5. Relationship of the stress and the thickness of coating film

Figure 6 shows the simulation result of the microcantilever deflection as a function of sensitive layer thickness for both gold and aminosilane. The deflection increases with increasing the thickness until a certain value and then the value decreases. For microcantilever with aminosilane layer, the maximum deflection of 141.8 µm is reached at the layer thickness of 7300 nm, while for gold layer, the maximum deflection of 111 µm is obtained at the layer thickness of 2600 nm.

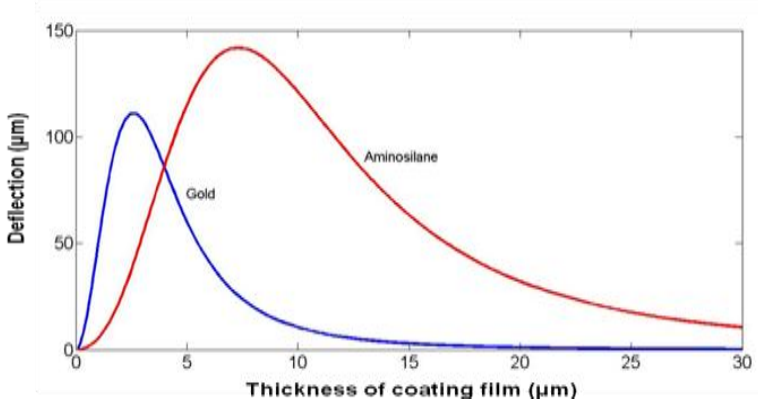


Figure 6. Dependence of the sensor sensitivity on the thickness of coating film for gold and aminosilane

By comparing Fig. 5 and Fig. 6, we can see that the maximum deflection is reached at the thickness of coating film which generates a maximum stress. However, the material with the lower Young's moduli does not always induce the higher deflection value. At the lower thickness, it is possible to obtain the higher deflection value on a material with the higher Young's moduli. These results indicate that the material properties and the thickness of sensitive layer should be considered to obtain a high sensitivity of microcantilever sensor. Therefore, the radius of curvature, strain, and stress distribution are important parameters to study a deflection mechanism of the microcantilever sensor.

## 4. Conclusion

We have investigated the influence of the material properties and the thickness on deflection of double layer microcantilever via the film stress and the radius of curvature. The film stress distribution is calculated as a function of a position within the film. On the position of a half thickness of sensitive layer (3 nm for layer thickness of 6 nm), the stress distribution for gold and aminosilane layers is 1187 $N/m^2$ and 94 $N/m^2$, respectively. The stress on the top surface layer for gold and aminosilane is 21000 $N/m^2$ and 19900 $N/m^2$, whereas the stress on the bottom of gold and aminosilane layers is -19000 $N/m^2$ and -20000 $N/m^2$, respectively. From the relationship between stress and microcantilever deflection, it is found that, for gold layer, the maximum stress of $1.249 \times 10^{10}$ $N/m^2$ is reached at the thickness of 2500~2900 nm, resulting in the maximum deflection of 111 µm. For aminosilane layer, the maximum stress of $1.728 \times 10^{9}$ $N/m^2$ is obtained at the thickness of 7300~7800 nm and the maximum deflection of 141.8 µm is found. These result indicate that stress induces the maximum deflection of the microcantilever and influences the sensor sensitivity.

## 5. Acknowledgement

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