A STUDY ON BIMETALLIC EFFECTS IN MICROCANTILEVER BIOSENSORS

Mohd. Zahid Ansari and Chongdu Cho
Department of Mechanical Engineering, Inha University, Incheon, Republic of Korea

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Abstract: This study investigates the bimetallic effects in a microcantilever biosensor induced due to change in ambient temperature. The cantilever is subject to both thermal and surface stresses. The biosensor exploits the surface-stress induced deflection to analyse the unknown molecules. However, due to bilayer structure of the cantilever thermal deflections are produced, which are a common source of noise in the deflection measurement. Thus, distinguishing surface-stress induced deflections from the thermal deflections is critical in accurate measurement by the biosensor. In this theoretical work, we show that both thermal stress and surface stress have linear effect on the cantilever deflections, and hence can be added algebraically to determine the absolute deflection produced entirely due to the surface stress variation.

1 INTRODUCTION

Microcantilever based sensors are getting increasingly popular in a variety of physical, chemical, and biological studies. They can be operated in both liquid and gaseous environments. They have been successfully used in many cases including calorimetric (Barness, 1994), rheometric (Hennemeyer, 2008), gas sensor (Qazi, 2008), DNA assaying (McKendry, 2002) and DNA hybridization (Mertens, 2008). Due to label-free, rapid and real-time detection abilities, microcantilever based biosensors are very attractive. The sensors normally use optical deflection readout techniques to measure the deflections generated due to the change in surface stress on the functionalized surface of the biosensor. By measuring the deflection, the target analytes are determined.

The overall accuracy of a microcantilever sensor depends on the design sensitivity of the cantilever and the measurement sensitivity of the deflection measurement system. An efficient cantilever design should convert the surface-stress induced stimulus into large deflection of the cantilever, whereas, an efficient measurement technique should ensure that the deflections measured are induced entirely because of the change in surface stress. Most of the noise in deflection signal is due to thermal drifting (Fritz, 2000). Thermal effects arise due to the bilayer structure of the cantilever and change in the ambient temperature. Microcantilever biosensor comprises gold-coated thin silicon or polymer substrate cantilever and laser-based optical deflection readout scheme. The gold film helps formation of monolayer of receptor molecules on the cantilever surface during functionalization. The presence of gold film coating on the cantilever, however, causes bimetallic effects in the biosensor. The temperature change can occur due to extrinsic or intrinsic sources. The extrinsic sources can be the bulk fluid temperature change in the fluidic cell during solution loading, whereas, the intrinsic reasons can be the exothermic or endothermic molecular reactions at the cantilever surface. Depending on the thermoelastic properties of film and substrate and the temperature change, thermal deflection can easily exceed the surface stress induced deflections, thus producing large noise in the deflection signal.

In this work, we show that by knowing the thermoelastic properties of the film and cantilever material, analytical and numerical approaches can be used to accurately predict the thermal-induced deflections in microcantilever biosensors. Thermal deflections induced due to variation in the ambient temperature are calculated using analytical and simulation results; and are then compared against available experimental result. Finally, the combined effect of thermal and adsorbate-induced surface stress changes on the cantilever deflection is

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investigated. A finite element analysis (FEA) code ANSYS Multiphysics is used in simulations.

2 THEORY AND SIMULATION

Bimetallic effects are common phenomena that arise in multilayered structures when subjected to temperature change. The mismatch in their coefficients of thermal expansion (CTEs) results in thermal strain, causing deflections in the structure. The amount and direction of motion depends on the CTEs of the layers. If the CTE of substrate is higher than that of film and the change in temperature is positive, the deflection will be upwards. Surface or film stresses are generated either due to the adsorbtion of foreign atoms onto a surface to saturate the dangling bonds or due to residual thermal stresses induced during fabrication and/or operation of the element.

Assuming the film thickness (t_f) is infinitesimal compared to the substrate thickness (t_s), Stoney expression (Stoney, 1909) relating the transverse deflection (Δz_{ss}) in a microcantilever to adsorbtion-induced surface stress change ($\Delta\sigma_{ss}$) can be given as

$$\Delta z_{ss} = \frac{4(1-\nu_s)\Delta\sigma_{ss}}{E_s}\left(\frac{L}{t_s}\right)^2 \quad (1)$$

where E_s and ν_s are elastic modulus and Poisson's ratio of the cantilever material, and L is cantilever length. Similarly, the Stoney relation between thermal deflection (Δz_{th}) and thermal-induced surface stress ($\Delta\sigma_{th}$) can be given as

$$\Delta z_{th} = \frac{4(1-\nu_s)\Delta\sigma_{th}}{E_s}\left(\frac{L}{t_s}\right)^2 \quad (2)$$

where $\Delta\sigma_{th} = t_f E_f (\alpha_s - \alpha_f)\Delta T$ (Hsueh, 2002) is the film stress induced due to temperature change ΔT; and α_s and α_f are the CTEs of the substrate and film. Equation (1) is used commonly in microcantilever biosensor applications to determine the analyte biomolecules and to measure their concentrations. Equation (2) is generally used in micro-electro-mechanical systems (MEMS) applications to determine the residual thermal stresses in thin film structures.

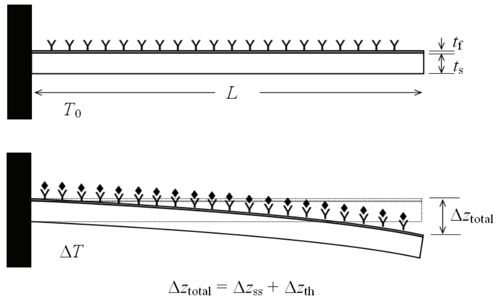

Figure 1: Schematic showing functionalized cantilever (top) and total deflection due to thermal and adsorbtion-induced surface stress (below).

A commonly used expression for predicting the transverse deflection in a layered beam due to bimetallic effect is (Finot, 2008)

$$\Delta z_{th} = \frac{3(\alpha_s - \alpha_f)(t_s + t_f)}{K_1}\left(\frac{L}{t_s}\right)^2 \Delta T \quad (3)$$

where,

$$K_1 = 4 + 6\left(\frac{t_f}{t_s}\right) + 4\left(\frac{t_f}{t_s}\right)^2 + \left(\frac{E_f}{E_s}\right)\left(\frac{t_f}{t_s}\right)^3 + \left(\frac{E_s}{E_f}\right)\left(\frac{t_s}{t_f}\right)$$

This study used all the above models to investigate the thermal and adsorbtion-induced deflections in a microcantilever biosensor. By taking advantage of the cantilever geometry, 2-D FE model was used. The model was meshed by 8-node coupled-field PLANE223 elements. Solution convergence and mesh-size effects were analysed before the final simulations. First we performed thermal analysis and then a coupled thermal-structural analysis involving both thermal- and adsorbtion-induced stresses. In the first case, the microcantilever was subjected to temperature change alone, whereas, in the other, it was subjected to a constant surface stress as well as increased temperature. The cantilever was coated with a 20-nm-thick film of gold. The cantilever size was 500×100×1 µm; and an adsorbtion-induced surface stress of 0.05 N/m was applied on its top surface. The surface stress was modelled as a tensile force applied to the top, free edge of the cantilever (Ansari, 2009). The applied tensile force was $F = \Delta\sigma_{ss} \times b = 0.05 \times 100\times10^{-6} = 5\times10^{-6}$ N, where b is the cantilever width. The geometric and thermoelastic properties of film and substrate are $L = 500$ µm, $t_s = 1$ µm, $t_f = 0.02$ µm, $E_s = 130$ GPa, $E_f = 78$ GPa, $\alpha_s = 2.6\times10^{-6}$ /°C, $\alpha_f = 14.2\times10^{-6}$ /°C, $\nu_s = 0.28$, $\nu_f = 0.44$, $k_s = 149$ W/m°C and $k_f = 315$ W/m°C.

3 RESULTS AND DISCUSSION

Table 1 compares the analytical and simulation results against the experimental result in (Ramos, 2007). The thermoelastic material and geometric properties were adopted from it. In the experiment, a 20-nm gold coated silicon microcantilever of size 400×100×1 μm was subjected to a temperature change of −12 °C. The analytical study used (2) and (3), and FEA result is from ANSYS. It is obvious in the table that the experimental and the analytical and simulation results have good accord in predicting the thermal deflection, indicating the conformity of analytical and simulation analysis.

Table 1: Comparison between experimental, analytical, and FEA results.

ΔT (°C)	Thermal deflection, Δz_{th} (μm)			
	Exp.	Stoney (2)	Beam (3)	FEA
-12	0.56	0.60	0.61	0.62

Figure 2 shows a comparison between Stoney model (2), beam model (3) and simulation results for the deflections in the cantilever biosensor with and without adsorbtion surface stress. Figure 2 (a) shows the effect of temperature variation on the cantilever deflection. All the three curves show good accord in predicting the thermal deflections. Furthermore, the simulations results corroborate the linear relation between deflection and temperature, which is suggested in the analytical models (2) and (3).

Figure 2 (b) shows the combined effect of temperature variation and adsorbate-induced surface stress on the cantilever deflection. The total deflection (Δz_{total}) is sum of thermal and adsorbate-induced deflections. Equation (1) was used in calculating the adsorbate-induced deflection. The Stoney models used (1) and (2), whereas, the Stoney + beam models used (1) and (3). As can be seen in the figure, at ΔT = 0 the cantilever shows a deflection of about 0.28 μm, which is induced entirely due to the surface stress of 0.05 N/m. In the figure, for ΔT > 3°C, thermal deflections exceed the surface-stress induced deflections. In Figure 2, we also observe that as the temperature increases, the deflection curves show deviation, which suggests the analytical and simulation results are accurate for ΔT < 10°C. The higher the temperature change, the higher the thermal noise will be. However, by knowing the thermoelastic and geometric properties of the cantilever, thermal deflection can be readily calculated from analytical relations (2) or (3). Since both the thermal and surface-stress deflections show linear and additive characteristics, thermal noise can be isolated easily by deducting the thermal deflection from the total deflection.

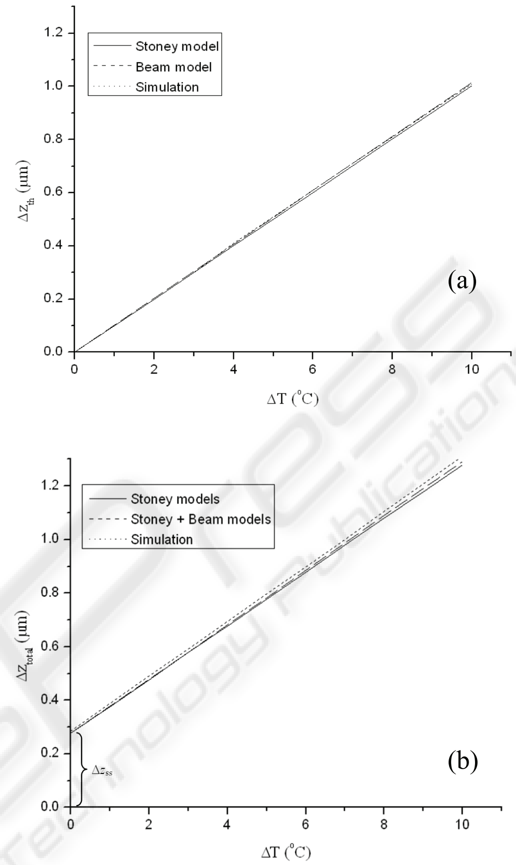

Figure 2: Cantilever deflection due to (a) thermal and (b) thermal and adsorbtion-induced deflections.

Thermal noise problem is more pronounced in liquid medium than in gaseous. In microcantilever biosensor system, the cantilevers array is immersed in a fluidic cell chamber and solution stream containing the analyte molecules is flowed across it. During purging the chamber and/or changing solution samples, the fluid filling the chamber alters the ambient temperature around the cantilever array. It induces thermal strain in the cantilever, which eventually produces thermal deflections. Bimetallic effects present more serious problems in SU8 polymer microcantilever biosensors, mainly due to the large mismatch between the thermoelastic properties of SU8 substrate and gold film. The CTE and elastic modulus of SU8 and gold are about 52×10^{-6}/°C and 2 GPa, and 14.2×10^{-6}/°C and 78 GPa, respectively. Since the CTE of SU8 is considerably higher than that of gold, the cantilever will bend upwards when the temperature is increased. In addition, the large difference between the elastic moduli will generate substantial shear strain at the gold-SU8 interface, which may lead to de-lamination of the film from the substrate.

If the film thickness is significant, (2) and (3) can still be used for predicting deflections by replacing the substrate modulus (E_s) with the effective substrate modulus (E_{eff}) given as (Yi, 2002)

$$E_{eff} = \frac{E_f^2 a^4 + E_s^2 b^4 + 2E_f E_s ab(2a^2 + 2b^2 + 3ab)}{E_f a + E_s b} \quad (4)$$

where $a = t_f/t$ and $b = t_s/t$, and t is total thickness of the cantilever. To elucidate (4), consider the geometric and material properties of the gold coated cantilever analysed in this study. Though E_s is 130 GPa, the E_{eff} is about 127 GPa.

4 CONCLUSIONS

Microcantilever biosensors provide a universal, rapid, and highly sensitive mean to many applications. The measurement accuracy of the sensor depends on its ability to isolate and eliminate the noise from the signal. Since bimetallic effects are a major source of noise in the signal, we investigated the effect of temperature on the deflection characteristics of the cantilever. The results indicated that thermal deflections can be determined accurately using analytical and simulation models. By studying the combined effect of thermal- and adsorbate-induced surface stresses on the cantilever deflection, we found that the two stresses act linearly and additively. We found that even for small temperature variation, the thermal deflections can easily exceed the adsorbate-induced deflections, and hence produce noise in the deflection signal. However, by deducting the thermal deflection from the total deflection amount, the exact adsorbate-induced deflection or stress can be determined. Further, the large mismatch in the thermoelastic properties makes SU8 microcantilever biosensors more susceptible to bimetallic effects.

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