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Influence of substrate deformation on piezoelectric displacement measurement of piezoelectric film

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Abstract

In this work, effect of the substrate deformation on the measured displacement of piezoelectric films by laser interferometer was simulated using finite element analysis (FEA). The piezoelectric displacements measured by single-beam laser interferometer, laser scanning interferometer and double-beam interferometer were simulated. The results suggest that the substrate deformation may easily result in a large measurement error of effective piezoelectric coefficients if only calculating a ratio of the film thickness change obtained from the laser interferometer method over the applied voltage across the film. In order to measure exactly the piezoelectric responses of piezoelectric films, the size of the top electrode on the film should be larger than a critical electrode size and the bottom surface of the substrate should be perfectly clamped on a sample holder to inhabit the substrate bending and substrate deformation.

Keywords: A. Films; B. Surfaces; D. PZT; E. Substrates

1. Introduction

The promising applications of piezoelectric thin/thick films on silicon for various micro-electromechanical system (MEMS) devices have attracted considerable attention in recent years. The design and development of such miniature devices require comprehensive knowledge of the material properties, especially the longitudinal piezoelectric coefficient (d_{33}) of the piezoelectric films. Among various methods, laser interferometer method is the most important way to characterize piezoelectric responses of piezoelectric film because of its high resolution and non-destructive advantage.

It is well-known that effect of the substrate bending on the measured displacement is significant and must be deducted in order to obtain accurate piezoelectric responses. Single-beam laser interferometer [1], which detects the displacement of the piezoelectric film, has difficulty in separating the substrate bending from the thickness dilatation of the films. In order to eliminate the influence of the substrate bending, a double-beam interferometer and a laser scanning interferometer have been developed to compensate the bending of the substrate [2–7]. The converse piezoelectric response of piezoelectric film on a substrate without substrate bending was also investigated by the commercial software ANSYS [8,9]. For soft substrates, the substrate deformation which cannot be measured directly is also an important contribution to the film surface displacement. In this work, we report the study on the substrate deformation under the various substrate bending conditions and subsequently the effective piezoelectric coefficient of the piezoelectric films measured by laser interferometer systems.

2. Finite element simulation

In order to simulate different substrate bending conditions, an adhesive layer with the bottom surface perfect clamped was used below the silicon substrate and it caused the clamping effect which gave rise to the sample expansions and contractions due to the actuation of the transverse piezoelectric effect of the piezoelectric film and thus affects the measured strains. Different substrate bending conditions can be obtained by adjusting the Young's modulus of the adhesive layer. Simulation was performed with the commercial software ANSYS. The PZT film was modeled

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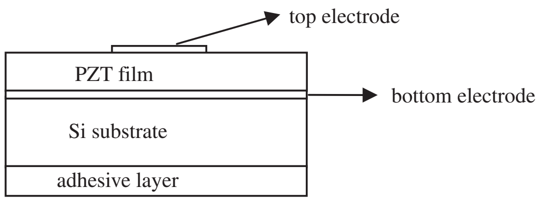

Fig. 1. Cross-sectional view of the structure for FEA.

with the piezoelectric element, SOLID98, the silicon substrate and the adhesive layer were modeled with SOLID187 elements.

Fig. 1 shows the cross-sectional view of the structure. The model considered has a silicon substrate with thickness of 500 μm, an electrode layer with negligible thickness but of various radii of 0.4 mm and 4 mm. Thicknesses of a piezoelectric film and an adhesive layer are 5 μm and 20 μm, respectively. The radii of the silicon substrate, adhesive layer and piezoelectric film are four times that of the top electrode. A voltage of 1 V or −1 V is applied along the polarization normally to the film. The scanning of the displacement distribution is simulated according to 200 grids. The material properties of PZT-5H [10] that we used in our simulation are as follows:

Elastic modulus (10^{10} N/m^2):

$C_{11}=12.6,\quad C_{12}=7.95,\quad C_{13}=8.41,$

$C_{33}=11.7,\quad C_{44}=2.3,\quad C_{66}=2.325,$

piezoelectric constant (C/m^2):

$e_{31}=-6.5,\quad e_{33}=23.3,\quad e_{15}=17.0,$

density (kg/m^3):

$\rho=7500$

relative dielectric constant:

$\varepsilon_{11}=1700\varepsilon_0,\quad \varepsilon_{33}=1470\varepsilon_0,\quad \varepsilon_0=8.854\times10^{-12}$ Farads/m

Young's modulus, Poisson's ratio and density of silicon are $E=130\times10^9$ N/m^2, $\upsilon=0.28$ and $\rho=2330$ kg/m^3, respectively. The adhesive layers with the Poisson's ratio $\upsilon=0.3$, density $\rho=3000$ kg/m^3 and different Young's modulus E ranging from 2×10^7 N/m^2 to infinite value are studied.

3. Results and discussion

Fig. 2 shows the displacement profiles of the top surface of the film, the substrate deformation and the film thickness change in response to a unit voltage of 1 V at the radii of 0.4 mm and 4 mm. The Young's modulus of the adhesive layer is infinite. Therefore, there is no substrate bending. The two contributions to the film surface displacement are the substrate deformation and the film thickness change. It can be seen clearly that the piezoelectric displacement measured at the top electrode is not always equal to the net thickness change of the film in response to an applied voltage, because the substrate deformation is not always zero at small radius because of the elastic substrate. The reason is that there exists a critical electrode size [8,9] for apparent piezoelectric coefficients, and if the electrode size is larger than the critical electrode size, the substrate deformation can be omitted and the surface displacement at the top electrode is equal to the film thickness change.

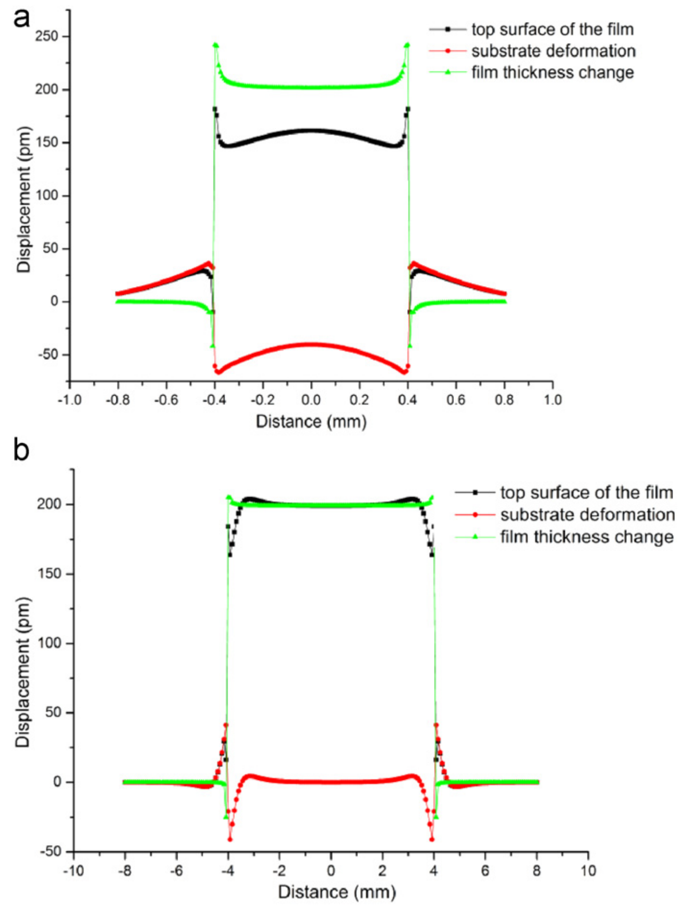

Fig. 2. Displacement profiles of top surface of the film, the substrate deformation and the film thickness change without substrate bending. The radius of top electrode is (a) 0.4 mm, smaller than the critical size; (b) 4 mm, larger than the critical electrode size.

Fig. 3 shows the displacement profiles of the top surface of the film under various Young's modulus of the adhesive layer in response to a unit voltage of −1 V at a radius of 0.4 mm. It can be seen that with the decreasing of Young's modulus of the adhesive layer, the bending effect becomes predominate and the displacement of the top electrode of the film varies from negative to positive. This result is similar to the piezoelectric displacement profiles measured by a laser scanning interferometer reported in Refs. [3–9]. As a result, while measuring the displacement near the center of top electrode using a single-beam laser interferometer, one may either underestimate or overestimate the effective piezoelectric coefficient of the piezoelectric film. The error is attributed to the substrate bending and the substrate deformation.

Fig. 4 shows the top surface displacement of the film, the top and the bottom surface displacements of the substrate,

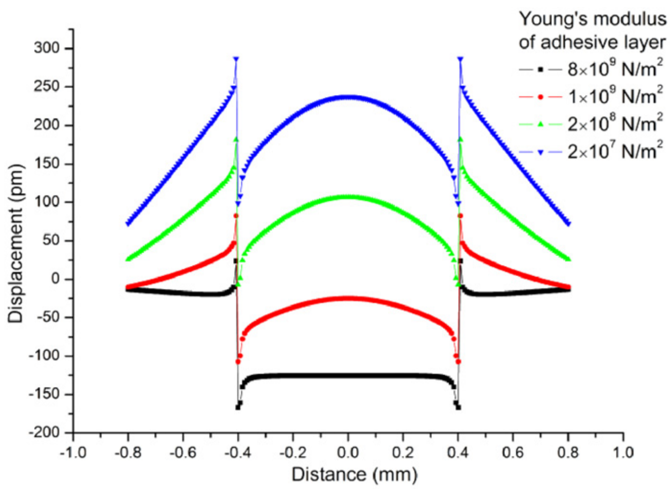

Fig. 3. The displacement profiles the top surface of the film under the various Young's modulus of the adhesive layer. The radius of the top electrode is 0.4 mm.

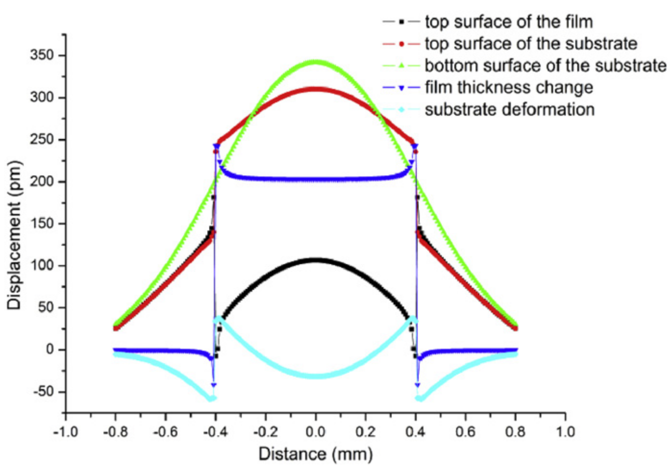

Fig. 4. Displacement profiles of the top surface of the film, bottom and top surface of the substrate, film thickness change and substrate deformation. The Young's modulus of adhesive layer is 2×10^8 N/m^2. The radius of the top electrode is 0.4 mm.

the film thickness change and the substrate deformation in response to a unit voltage of -1 V when the Young's modulus of the adhesive layer is 2×10^8 N/m^2 at a radius of 0.4 mm. The film thickness change of 200 pm can be obtained by calculating the relative displacement between the top surface of the film and the top surface of the substrate. It almost has no change under the different substrate bending conditions. However, if we use a laser scanning interferometer to measure piezoelectric displacement of the film and regard the displacement difference between the top electrode and its surrounding passive part of the film as the film thickness change, the result obtained is not accurate. The reason is that the displacement outside the top electrode is the sum of substrate bending and substrate deformation while the displacement on the top electrode is the sum of substrate bending, substrate deformation and film thickness change. Hence, the error is the relative substrate deformation between the active part and the surrounding passive part.

The influence of the substrate deformation on the displacement measured by a double-beam interferometer can also be simulated. By calculating the relative displacement between the top surface of the PZT film and the bottom surface of the substrate, we can simulate the piezoelectric displacement measured by the double-beam interferometer. The result is the sum of substrate deformation and film thickness change. The displacement profiles obtained by the double-beam interferometer and the substrate deformation under the different substrate bending conditions at the applied voltage of 1 V and at a radius of 0.4 mm and 4 mm are shown in Fig. 5. With increasing substrate bending, the substrate deformation and the displacement will also increase. This result indicates that the piezoelectric displacement measured by the double-beam interferometer is not accurate because of the effect of the substrate deformation. It also suggests that the film thickness change obtained from a laser

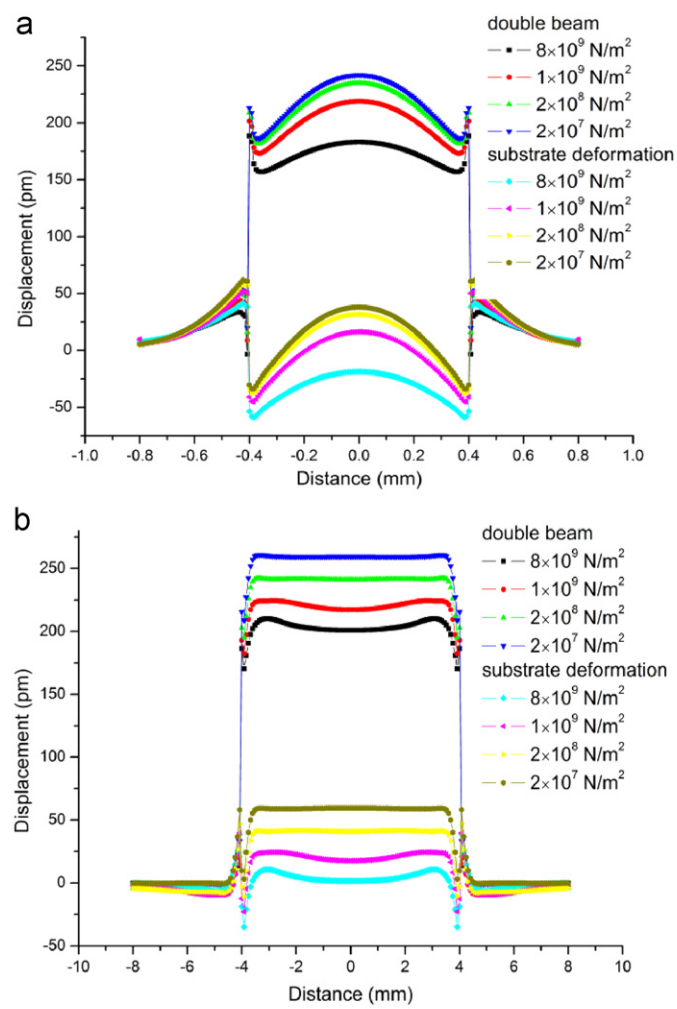

Fig. 5. The displacement profiles obtained by a double-beam interferometer and the substrate deformation under the different substrate bending conditions. The radii of the top electrode are (a) 0.4 mm and (b) 4 mm.

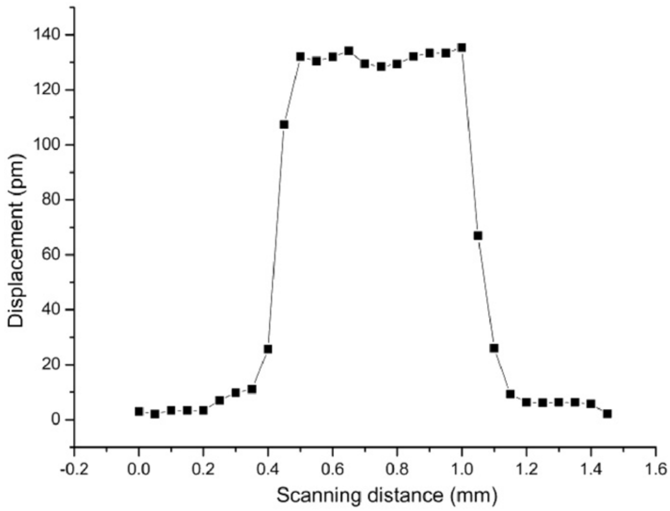

Fig. 6. Experimental result of the displacement profile of a PZT film along a line that crosses the top electrode in response to an ac voltage of 1 V on the film. The diameter of the top electrode is 0.5 mm. The testing frequency is 8 kHz. The film was poled with a bias of 50 V for 10 min at room temperature before the measurement.

scanning interferometer will also change under the different substrate deformation.

Therefore, in order to measure exactly the effective piezoelectric coefficient of a film, the top electrode of the film should be larger than the critical electrode size and the sample should be perfectly fixed on the sample holder to minimize the substrate bending and substrate deformation. Fig. 6 shows a piezoelectric response of a 5 μm-thick PZT film measured with a scanning Mach–Zehnder interferometer. With this plateau-like profile, the size of the top electrode of the film can be considered to be larger than the critical one. The substrate bending is almost inhabited. Hence, the substrate deformation can also be neglected. One can thus measure the relative motion between the activated film and its non-active surroundings, which can well reflect the effective piezoelectric coefficient d_{33}.

4. Conclusions

The substrate deformation under various substrate bending conditions has been simulated using the finite element analysis. With increasing the substrate bending, the substrate deformation increases so as to result in a large measurement error of the effective piezoelectric coefficient. Our results indicate that the laser scanning interferometer and the double-beam interferometer which are developed to compensate the substrate bending might not be accurate without considering the substrate deformation. In order to measure exactly the effective piezoelectric coefficient of a film, the top electrode of the film should be larger than the critical electrode size and the sample should be perfectly fixed on the sample holder to minimize the substrate bending and substrate deformation.

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