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Characterization of the deflection of a new epitaxial piezoelectric micro-mirror: Modeling and experiment

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ABSTRACT

Advanced 3D finite element analysis of a newly designed piezoelectric micro-mirror device was conducted to assess a priori the attainable deflection of micro-mirror. The deflection of micro-mirror has shown to vary with the competitions and/or cooperative interactions among deposited layers. The device was successfully fabricated using a heteroepitaxial growth process with Pt/PZT(1 1 1)/Pt(1 1 1)/γ-Al_2O_3(1 1 1)/Si(1 1 1) structure. Material anisotropy and technologically induced residual stress have shown to play a significant role on the deflection of micro-mirror. A good correlation was found between simulation results and experimentally measured deflection of fabricated micro-mirror.

1. Introduction

Micro-mirror can be classified into two broad categories: continuous micro-mirror and segmented micro-mirror. The continuous micro-mirror has a single continuous reflective surface. The potential drawbacks of this type of micro-mirror are: (1) it requires comparatively large driving force and the resulting mirror stroke is generally less than 5 μm, (2) the precise control of mirror deflection is difficult as the induced deformation is not confined only to the mirror area directly connected to it, (3) the large in size precludes its application in many adaptive optics systems, and (4) the fabrication methods do not allow an easy integration of control electronics into mirror structure. In contrast, a segmented micro-mirror is comprised of a number of segments, each of which is driven independently to form a piecewise approximation of the required deformation to rectify the aberrations of incoming wavefront. This results in a low driving force to obtain high-stroke required for many potential applications in adaptive optics. There are still escalating demands to develop optimized miniaturized micro-mirror for adaptive optics [1,2].

Piezoelectric materials used for micro-mirror can be subdivided into three categories: (a) single crystals, e.g. quartz, (b) piezoelectric ceramics, e.g. $BaTiO_3$, $PbZrO_3$ and (c) polymers, e.g. polyvinylidenfluoride (PVDF). The most widely used piezoelectric material today is lead zirconate titanate, $Pb(Zr_xTi_{1-x})O_3$ (PZT), that induces strains in the order of 0.1–0.2 %. PZT films have a wide range of applications such as wavefront correctors in adaptive optics, pyroelectric sensors, infrared thermal imaging devices, micro-electromechanical devices, and ferroelectric random-access memories (FeRAM) [3–7]. These applications are made possible due to its high capacity of load storage, low coercive field and large thermal stability with compositions near the morphotrophic phase boundary (at Zr to Ti ratio of 52/48). The fabrication of epitaxial $Pb(Zr_{0.52},Ti_{0.48})O_3$ film for the segmented micro-mirror is promising due to its ability to achieve high strains with a significantly low driving force. Additionally, PZT actuation approach fulfils the stringent requirements for precision control, thereby, justifying the added complexity of micro-fabrication.

Basically, a PZT micro-mirror actuator consists of a piezoelectric film sandwiched between two electrodes. An electric field is applied parallel to the poling direction of the film, that results in strain proportional to the applied field. The induced mechanical strain results in out-of-plane structural deformation of the film allowing the deflection of micro-mirror.

An intrinsic coupling occurs during piezoelectric actuation between the mechanical variables (stress, σ_{kl} and strain, ε_{ij} of 2nd rank tensors) and electrical variables (field, E_k and displacement, D_i) of PZT material. With strain and electric field as independent variables, a piezoelectric continuum can be represented by the constitutive equations employing the standard Cartesian tensor

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notations in stress-charge form as [8]:

$$\sigma_{ij} = c^{E}_{ijkl}\varepsilon_{kl} - e_{kij}E_k \quad (1a)$$

$$D_i = e_{ijk}\varepsilon_{jk} + \xi^{\varepsilon}_{ij}E_j \quad (1b)$$

where $E_k = \nabla\Phi$ (Φ is the electric potential), c^{E}_{ijkl} denotes the 4th rank elastic stiffness tensor at constant E, e_{kij} represents the 3rd rank piezoelectric coupling tensor, ξ^{ε}_{ij} is the 2nd rank dielectric tensor at constant ε.

The symmetry in the first two suffixes (i, j) and the last two suffixes (k, l) of C_{ijkl} allows to use stiffness matrix C_{mn} with i, j, k, l = 1–3 and m, n = 1–6.

Therefore, by employing the single subscript contracted Voigt's notations for stress and strain components and the double subscript notations for elastic constants, Eqs. (1a) and (1b) can be re-written in matrix-vector form as [9]:

$$\sigma_m = c^{E}_{mn}\varepsilon_n - e_{km}E_k \quad (2a)$$

$$D_i = e_{in}\varepsilon_n + \xi^{\varepsilon}_{ik}E_k \quad (2b)$$

The mechanical and electrical constants in the above equations are dependent on the orientation of crystals.

The parameters e, ξ, and C are also dependent on type of PZT materials including deposition techniques (film quality), thickness of the PZT film, crystal types (single crystal or polycrystal), and crystallographic symmetry. Therefore, it is essential to use the correct material parameters for PZT material in the model for FE simulations.

In addition, since the structure of micro-mirror device is fabricated epitaxially it is composed of monocrystal layers, therefore it is also necessary to take into account material anisotropy. Taking thermal effect into account the thermomechanical behavior of a linearly elastic solid can be described completely by the following constitutive equation [10]:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} - C_{ijkl}\alpha_{ij}\Delta\Theta \quad (3)$$

where σ_{ij} is the second Piola–Kirchhoff stress tensor, ε_{kl} the Lagrangian strain tensor, C_{ijkl} is elastic tensor of the solid, α_{ij} denotes the thermal expansion tensor and $\Delta\Theta = \Theta - \Theta_0$ represents the temperature difference (where Θ_0 is the stress free temperature state and Θ is the final temperature state).

The above constitutive equation represents a physical relation with respect to a given reference configuration. If one rotates the elastic body from the laboratory reference frame to a new one by a rotation R and reapplies the same strain on the rotated body, one will obtain the constitutive relation as follows:

$$\sigma^{FE}_{mn} = C^{FE}_{mnop}\varepsilon_{op} - C^{FE}_{mnop}\alpha^{FE}_{mn}\Delta\Theta \quad (4)$$

where $C^{FE}_{mnop} = R_{mi}R_{nj}R_{ok}R_{pl}C_{ijkl}$ and $\alpha^{FE}_{mn} = R_{mi}R_{nj}\alpha_{ij}$.

The difference of the stresses of the elastic solid before and after the rotation is accounted for in the above relations. If the rotation R is not a symmetry rotation of the solid, the material will be sensitive to such rotation. Moreover, the differences will differ from each other for different solids involved in micro-mirror device even though, they may possess the same material symmetry group. Therefore, in FE simulations material anisotropy has to be taken into consideration.

However, in the most of the publications addressing piezoelectric simulations, material anisotropy was not properly accounted for [11,12]. But in reality, due to the orientation of single crystal with respect to device structure, the anisotropic behavior is expected [13]. However, no attempt has yet been taken to study the effects of material anisotropy and technologically induced residual stress on the deflection of micro-mirror. In this paper, we therefore studied the deflection of segmented micro-mirror taking the influences of these factors into account. The competitions and/or cooperative interactions of deposited layers to induce deflection of micro-mirror device were also highlighted. The micro-mirror device was successfully fabricated with Pt/PZT(1 1 1)/Pt(1 1 1)/γ-Al_2O_3(1 1 1)/Si(1 1 1) structure. The obtained simulation results were validated with experimental findings.

The paper is organized in the following way. The next Section 2 introduces the design of micro-mirror device. Section 3 presents details on the finite element modeling of the device. Section 4 describes the fabrication processing steps of the device. Section 5 contains the calculation of technologically induced residual stress. Section 6 highlights on the correlation between simulations and experiment. Finally, Section 7 summarizes the conclusions.

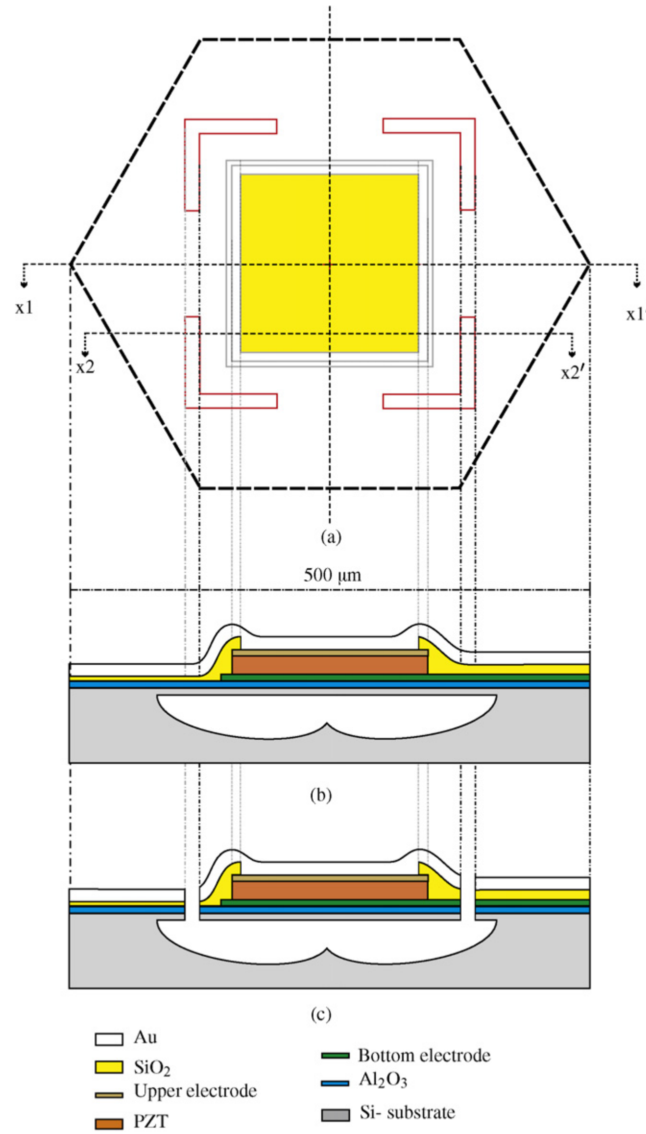

Fig. 1. Schematic drawings of micro-mirror device (not to scale): (a) planar view, (b) cross-section along line (x1–x1′), and (c) cross-section along line (x2–x2′).

2. Design of micro-mirror device

To obtain higher deflections, the design of micro-mirror can be tailored to amplify the dimensional changes of PZT material. In this context, a new design of PZT-actuated micro-mirror is shown in Fig. 1. Only one segment of the micro-mirror is presented in the figure.