Computational Materials Science 85 (2014) 253–258

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Correlation between residual stresses and bending in functional electroceramic-based MEMS actuator

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ARTICLE INFO

Article history:
Received 20 April 2013
Received in revised form 3 December 2013
Accepted 3 January 2014
Available online 31 January 2014

Keywords:
FE modeling
Electroceramic
MEMS
Residual stress
Epitaxy
Thin films

ABSTRACT

Micro-electro-mechanical systems (MEMS) technology can offer a viable alternative to realize miniaturized and less expensive actuators for deformable mirror in adaptive optics to obtain high resolution retinal imaging. During fabrication of such devices, functional multilayered thin films are deposited at elevated temperatures. These films are therefore subjected to residual stresses which may result in bending of the structure. The bending thus occurred may lead to failure at interfaces between films. A successful fabrication of device therefore relies on the engineering justification of multi-structured device design and growth parameters used in fabrication. In this paper, we present the design of a piezoelectric (ceramic) thin film based MEMS actuator for deformable mirror used in retinal imaging. A proto-type piezoelectric thin film structure of Pt/PZT/SRO/Pt/γ-Al_2O_3 has been epitaxially fabricated on Si (1 1 1) substrate. Advanced 3D finite element simulations were conducted to correlate the bending of fabricated structure with residual stresses. A smart alternative design was also proposed employing an extra layer of Al–Si (1%) in the diaphragm region. Simulation results predict a failsafe structure when the thickness of extra Al–Si (1%) layer is tailored to an optimal thickness. The outcome of this research can be used to overcome the challenge encountered (bending due to residual stresses) to obtain a failsafe MEMS actuator for deformable mirror.

1. Introduction

In recent years, sensing architects have given profound attention to an important area of research on adaptive optics to develop smart tailor-made micro-electro-mechanical system (MEMS) actuators for deformable mirrors in vision science. It is propelled by ambitious goal to tantalize scientific community an ever glimpse of imaging retinal features in size scale of a single cell in human eye. Basically, human retina (a typical thickness of 200–400 μm) consists of multiple layers of neurons, which include nerve-fiber, bipolar, horizontal, amacrine cells and photoreceptors. Photoreceptors, a high density of cones (5 million) and rods (100 million) act as transducers to convert captured photons into electrical impulses. Cones with its three variants (depending on the response to wavelength of light) mediate high acuity color vision at the higher intensity of light (day-time). In contrast, rodes facilitate low acuity monochrome vision at the low intensity of light (at night) [1].

The optic nerve, a bundle of nerve fibers (about one million) transports the encoded signals from rodes/cones to the brain to assemble it into a perceived visual image. However, the quality of eye's optics is often defective due to aberrations (distortion of optical wavefront) and diffraction (limited by the finite size of pupil) which generates blurred retinal images and therefore, results in degraded vision. To collect quantitatively the extent of eye's optical imperfections, an aberrometer (Hartmann–Shack wavefront sensor) is generally used to place a point light source on the retina which refracts light back to the outer-world and the emerging wavefront is captured using a miniaturized lenslet array. Discrete aberrated wavefront from each lenslet is focused on its focal plane and imaged as a distorted collection of spots. The local slope of the aberrated wavefront can be deduced from its corresponding displacement from the optical axis. The shape of the distorted wavefront can easily be obtained by integration of these slopes. The next important step then remains to rectify them by using smart adaptive optics. Spectacles or contact lenses are used to correct optical defects of eye especially low order aberrations namely defocus (beyond simple sphere), astigmatism (cylinder) and prism (tilt) [2]. However, no substantial progress has been made to correct many higher order aberrations of eye. But, in vivo retinal imaging (in the scale of single photoreceptor) through the eye's optics is a fundamental need for noninvasive diagnosis of the development of normal eye and retinal diseases

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0927-0256/$ - see front matter
http://dx.doi.org/10.1016/j.commatsci.2014.01.005

such as cone-rod dystrophy (retinal disorders caused by a loss of functionalities higher in cone than rod), atrophy (a part of retina lacking in wave-guiding cones), retinal scaring, progressive retinal degeneration (loss of visual acuity). A substantial improvement in resolution and contrast (spatial details) of retinal imaging can be obtained with compensated aberrations by an appropriate tailoring of deformable mirrors by MEMS actuator.

Other prospective medical applications of adaptive optics include investigation of functionalities of various layers in retina and the detection of local pathological alterations including diagnosis and treatment of a wide range of retinal diseases. But these potential benefits pose a challenge to produce miniaturized and less expensive devices for adaptive optics. In this context, MEMS technology can offer an excellent alternative route to fabricate deformable mirror fulfilling the stringent requirements for retinal imaging.

Scientifically well established microelectromechanical systems (MEMS) are miniaturized sensors, actuators, devices and systems with a critical dimension in the order of micrometers. MEMS are used for applications in mechanical, electrical, chemical, biological and other disciplines. MEMS devices such as accelerometers, gyroscopes, high performance mirror displays, pressure sensors, micro motors, micro engines, RF switches, valves, pumps, ultra sensitive membranes, single-chip microfluidic systems such as chemical analyzers or synthesizers, single-chip micro total analysis systems (also referred to as lab-on-chip) and many more devices and systems have been designed and fabricated over the last two decades. MEMS technology has already been used in many industries (e.g., defense, aerospace, health care, etc.) even though a number of fundamental and practical challenges still remain unresolved [3].

Due to the continuous miniaturization of device, the micromechanics of deformation and stress induced in thin films structure has been of great concern. Therefore, the reliability of MEMS based devices has become a more challenging task. However, multilayered functional thin films are ubiquitous in all microelectronic systems including MEMS. During fabrication of MEMS devices residual stresses may evolve in the course of processing steps that may result in the bending of thin films structure. The bending thus occurred may lead to delamination and/or peeling off the film(s) at the film/(substrate) film interface. An understanding of the correlation between induced residual stress and bending of such thin films structure is therefore essential to realize a successful device guarding against such technological failures. A successful fabrication of device therefore relies on the engineering justification of device design and used parameters during fabrication to obtain a successful device. There had already been some attempts [4,5] to fabricate piezoelectric MEMS actuator for mirror but no systematic research has yet been done to correlate the bending of epitaxial thin films structure with finite element simulations.

Now-a-days, $Pb(Zr_{0.52}, Ti_{0.48})O_3$ henceforth termed as PZT is one of the most widely used functional electro-ceramic materials. PZT ceramic with composition at morphotropic phase boundary (MPB) provides a high capacity of load storage, low coercive field and large thermal stability. PZT films have shown a wide range of applications in adaptive optics, pyroelectric sensors, infrared thermal imaging devices, micro-electromechanical devices, and ferroelectric random-access memories (FeRAM)[6–11]. The fabrication of epitaxial PZT thin film for MEMS actuator 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 precise control, thereby, justifying the added complexity of micro-fabrication.

In this paper, we report mainly on the design of a electrocermic based MEMS actuator used in micromirror for retinal imaging, fabrication of actuator with PZT functional ceramic using Pt/PZT (1 1 1)/SRO (1 1 1)/Pt (1 1 1)/γ-Al_2O_3(1 1 1)/Si (1 1 1) structure, the progress towards to the goal, challenges encountered (bending due to stresses), and probable solutions to obtain an optimal structure.

The paper is organized in the following way. The next Section 2 briefly describes the micromechanics of bending of structure. The design and fabrication of actuator device are provided in Section 3. Section 4 describes results and discussion. Details on characterization of polarization hysteresis are highlighted in Section 4.1. Section 4.2 describes the finite element model used for the optimization of the structure of actuator device. Correlation between residual stress and bending is given in Section 5. Finally, Section 6 summarizes the conclusions.

2. Micromechanics of bending

In most of the cases, thin films are grown at elevated temperatures followed by cooling it down to room temperature. In the subsequent deposition of each thin film, thermal cycling is repeated. Due to such processing steps, bending may occur in the structure due to induced thermal stresses. In addition, intrinsic stress may develop from the film growth process [12]. However, intrinsic stresses maybe suppressed during high temperature annealing process for crystallization purpose. Thermal stresses are generated due mainly to the difference in thermal expansion coefficients of

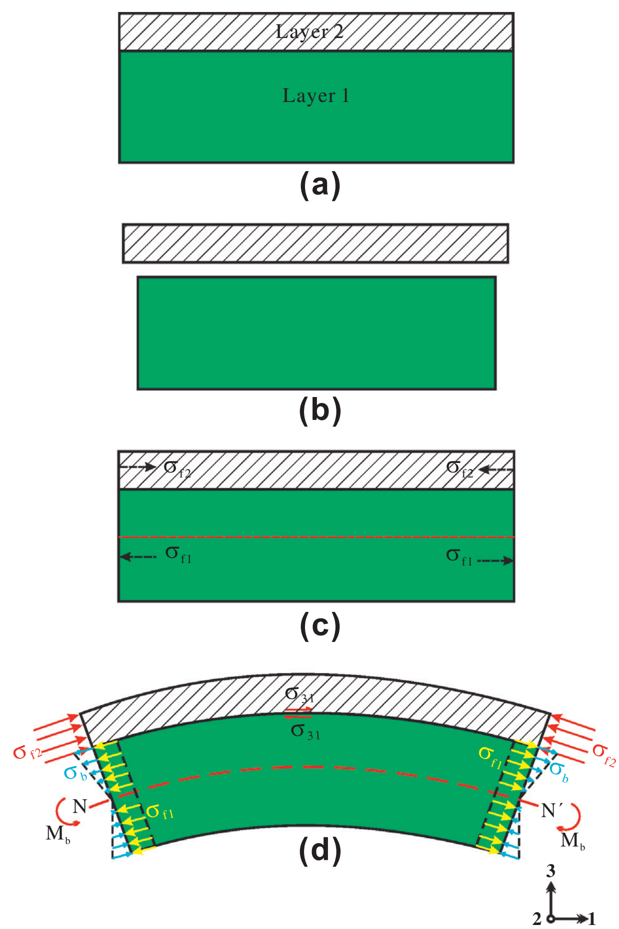

Fig. 1. Schematic diagrams showing the bending of a bi-layer structure due to thermal stress: (a) stress free state (at deposition temperature, Θ_0), (b) unconstrained state while cooling it down (to ambient temperature, Θ), (c) constrained state to maintain strain compatibility (with film stresses, σ_{f1} and σ_{f2}), and (d) bending of the structure due to asymmetric stresses resulting from tensile stress, σ_{f1}, bending stress, σ_b and bending moment, M_b (with respect to neutral axis NN′) in the substrate.