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A Study on Performance-driven Microfabrication Methods for MEMS Comb-drive Actuators

[1]M. Maheswaran and [2]HarNarayan Upadhyay
[1]School of Mechanical Engineering, SASTRA University, Thanjavur, 613 401, India
[2]School of Electrical and Electronics Engineering, SASTRA University, Thanjavur, 613 401, India

Abstract: Micro-electromechanical Systems (MEMS) comb-drive actuators are used to drive many micro-optical components such as switching mirror, scanning mirror applications. These actuators are electrostatically operated to obtain a tilting or rotational actuation. They have proven their capabilities for accomplishing extended travel ranges-of-movement reliably within the stable range. These actuators are fabricated by using different state of art fabrication techniques and methods with different materials. The residual stress developed during the deposition process, influences the electromechanical behavior of the fabricated actuator. Performance-driven criteria such as analog/binary mode, unidirectional/bidirectional and expected range of actuation for the comb-drives are realized in fabrication to achieve the expected specific requirements. In this study a study has been made on the critical steps in various microfabrication sequences by adopting a fabrication scheme of the actuator which precludes the generation of residual stress. The residual stress and stiction are the important parameters they are the limiting factors; but they are used in positive way to achieve specific structural behavior of the actuators. The causes and effects of residual stress formation during the microfabrication process are studied from the literatures. This knowledge can be used to correlate the performance of MEMS actuators with the microfabrication critical parameters.

Key words: MEMS, microfabrication, comb-drive, residual stress, stiction

INTRODUCTION

Comb-drive is an electromechanical actuator, having set of fixed and movable comb fingers which are interdigitated with each other and they are fixed and movable electrodes respectively as shown in Fig. 1. When external power supply is given to actuator, due to generated electrostatic attraction force, a micro-tilting movement occurs as shown in Fig. 2 and it is used to do switching or scanning functions. A reflective layer is deposited on the moving top plate electrode where the light path is getting tilted due the tilt movement of the actuator. Large aspect ratio provides large range of actuation motion; here aspect ratio, defined as the ratio between comb finger height and the finger separation gap. In the microfabrication process, substrate with functional layers are formed by a combination of deposition, lithographic patterning and etching operations. MEMS actuator elements are beams or trench/cavity structures. These thin film structures are made for applications requiring large flat surfaces and large actuation displacement. Uinn *et al.* (2006) discussed these fabricated micro structures which can be used as microactuators applications such as optical switches, scanning mirrors of micro-optical systems. In microfabrication process, substrate with functional layers are formed by a combination of deposition, lithographic patterning and etching operations. MEMS actuator elements are beams or trench/cavity structures. These thin film structures are made for applications requiring large flat surfaces and large actuation displacements. These fabricated micro structures can be used as microactuators applications such as optical switches, scanning mirrors of micro-optical systems.

Bhusan (2007a) discussed that, a structure under tension will contract and a under compression will expand. For all of these passive structures, the forces acting on them come from the internal residual stresses of the structural material. When a voltage is applied across either set of the interdigitated comb fingers shown an electrostatic attraction is generated due to the increase in capacitance as the overlap between the comb fingers increases. This tensile stress can be thought of as a tensile load being applied at the ends of the beam.

Corresponding Author: M. Maheswaran, School of Mechanical Engineering, SASTRA University, Thanjavur, 613 401, India

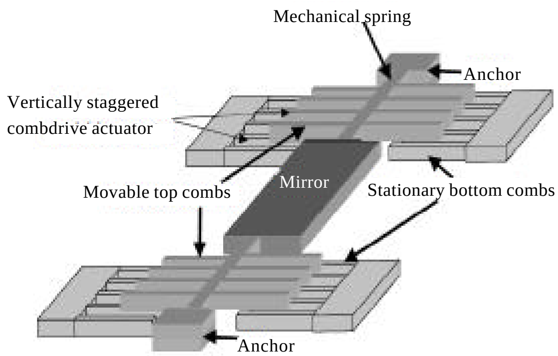

Fig. 1: Micro mirror driven by vertically staggered comb-drive actuator

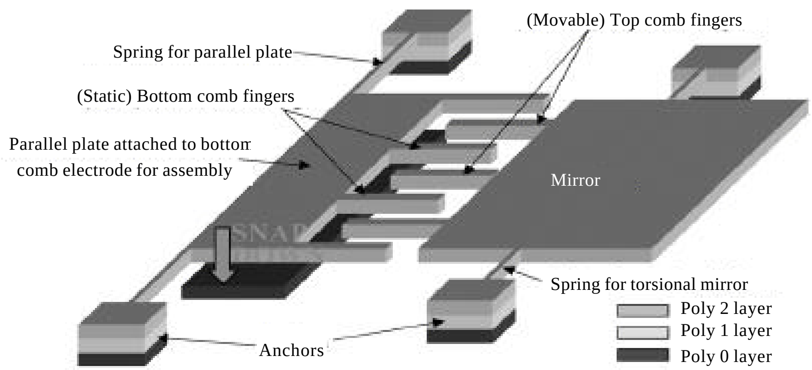

Fig. 2: A vertically staggered comb driven micromirror implemented in the surface micromachined MUMPS process

Microfabrication techniques and comb-drive types: The state of art of technologies available for the microfabrication are PolyMUMPs (Poly-Multi-User-MEMS-Process), DRIE (Deep Reactive ion beam etching, SOI (silicon On Insulator), Soft-lithographic Lift-off and Grafting (SLLOG), LIGA, Nano-imprint lithography (NIL), SUMMiT (Sandia Ultra-planar, Multi-level MEMS Technology). The X-Ray and UV-LIGA fabrication techniques are used to realize three dimensional structures.

Different types of comb-drive systems such as vertical comb-drive, angular vertical comb-drive, pre-stress comb-drive, self-aligned vertical comb-drive, staggered vertical comb-drive.

Chiou and Lin (2005) discussed that it is highly desirable to fabricate an actuator with no pull-in and no hysteresis characteristics. It is realized through Pre-stress comb-drive Actuator (PCA) which consists of a set of comb fingers fabricated along the laminated beam and substrate. One end of the laminated beam is fixed to the anchor and the other end is raised vertically by the residual stress. The fringe field induces electrostatic actuation force which in turn pulls the laminated beam towards the base substrate. To obtain large stroke of the PCA by increasing the initial lift height, post annealing process was carried out.

Edwin *et al*. (2005) discussed that high aspect ratio comb-drives need optimization in their fabrication steps. Various fabrication steps are followed according to the actuator-specific requirements. Anisotropic etching is controlled selectively in fabricating self-aligned comb-drives. The offset type comb-drive generates actuation forces five times stronger than self-aligned type. Self aligned comb-drive type is fabricated from SOI multiple layers.

Kwon *et al*. (2004) discussed that in order to achieve the bidirectional actuation with larger actuation range can be realized through defining static and movable comb

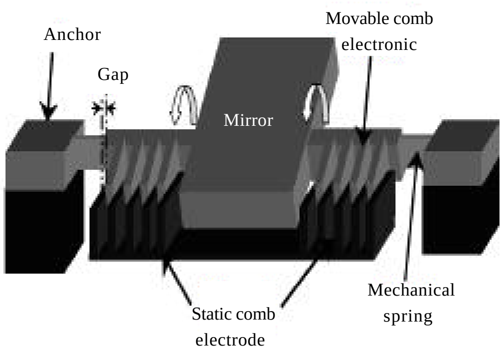

Fig. 3: Micromirror with single-sided actuations

fingers in the SOI layer and they are isolated by trenches. With low voltage the high-aspect SOI structures are capable of generating high force density for larger actuation displacement.

Stress related issues in microfabrication: Thermally induced stress and intrinsic film stress are two main sources of residual stress. The first one is due to the mismatch of thermal expansion coefficients between the thin-film layer and the substrate. The second one is originating from nucleation, grain growth and impurities added to the thin-film during deposition step. The stable deflection range can be significantly improved if the suspension structures are fabricated in a pre-bent configuration.

Edwin *et al*. (2005) discussed that, stress gradient is equally important as the stress itself. Due to stress gradients in the layer structure, they try to bend upward or downward which is not desirable; since the structures are designed to be completely planar. High aspect ratio comb-drives need optimization in their fabrication steps. Various fabrication steps are followed according to the actuator-specific requirements. Anisotropic etching is controlled selectively in fabricating self-aligned comb-drives. The offset type comb-drive generates actuation forces five times stronger than self-aligned type (Fig. 3). Self aligned comb-drive type is fabricated from SOI multiple layers.

Kim *et al*. (2006a) discussed that, in a stress-strain curve of silicon it is shown that where σ_m is maximum yield stress, σ_f is flow stress, the stress needed to continue plastic deformation as shown in Fig. 4. At higher temperature (900° C) annealing step changes the initial elastic deformations of the torsion hinges that join the two comb finger electrode sets into permanent plastic deformations.

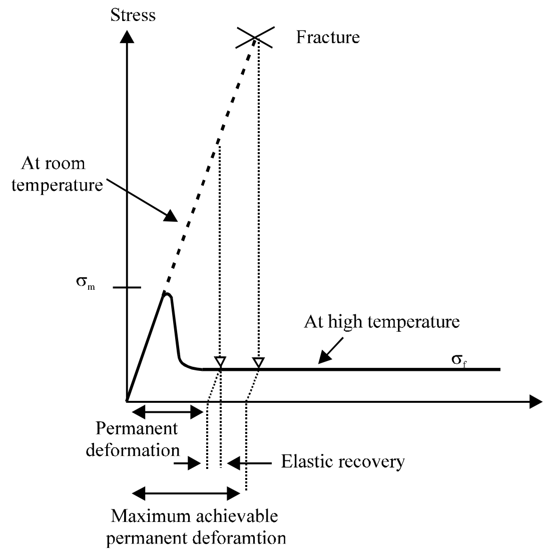

Fig. 4: The permanent plastic deformation and elastic recovery

Tabata *et al*. (2008) discussed that, the actuator performance is influenced by the elastic properties such as Young's modulus, Poisson's ratio and shear modulus. The stiffness of laminated thin-film structural layer is proportional to the above elastic properties and further it depends on the internal stress.

Pull-in, hysteresis, stiction are the limiting parameters and they are the causes for instability of the performance of the actuators and these parameters can be prior-controlled by managing the stress level during the fabrication process.

Edwin *et al*. (2005) discussed that, vertical comb-drive actuation is generated parallel to the displacement direction and the lateral pull-in instability causes misalignment in finger gap results in poor performance of the vertical comb-drive. Vertical actuation which is generated parallel to the direction as it moves towards.

John *et al*. (2003) discussed that, the side suspension spring stiffness is nonlinear. The spring constant is a combined value of the axial stiffness of the individual suspension beams and the geometric stiffness of the suspension as a whole. The side spring constant of the suspension is found to decrease with the square of the forward movement. The stiffness in the side direction decreases initially and it goes up as the suspension beams becoming straight with forward deflection and when side stiffness increases in tune with side forces increase.

A brief summary of the different fabrication process

Gimbaled comb-drive: Kim *et al*. (2002) discussed that, the

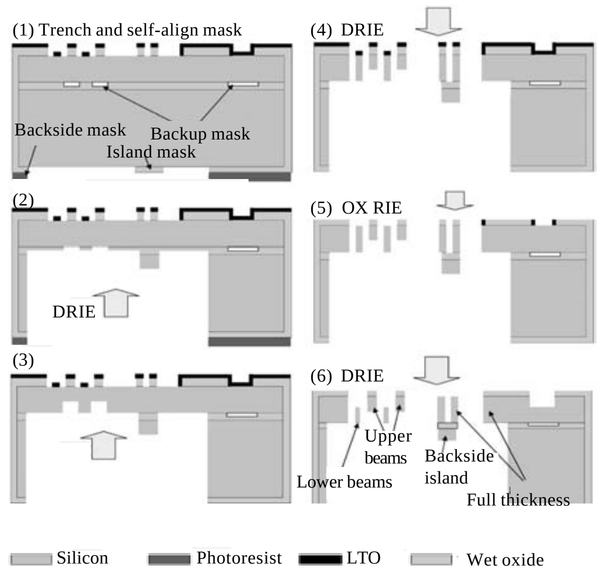

Fig. 5: The fabrication process of the vertical comb-based gimbaled micromirror. The backside island is incorporated into the fabrication process for the vertical comb drives

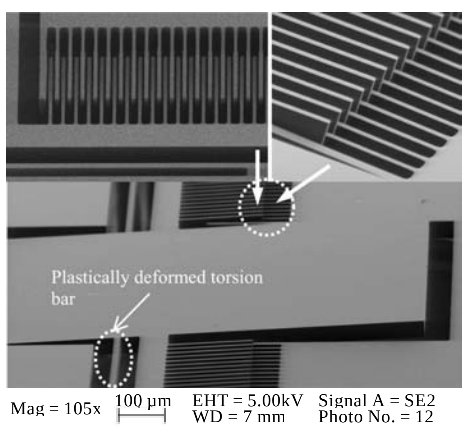

Fig. 6: Plastically deformed and tilted mirror and precisely aligned vertical combs

new idea in this fabrication by introducing built-in air gap and large rotation angle for gimbal structure self aligned comb-drive is achieved. DRIE technique is used to fabricate these structures as shown in Fig. 5. Over etching of Silicon Nitride (Si_3N_4) and Aluminum (Al) took place during releasing process. High degree of flatness and high optical reflectivity on the top surface of the actuator is achieved through a low-stress Si_3N_4/Al bimorph.

It is suggested that the cross-coupling effect between the gimbals can be minimized by controlling the stress level around the inner and outer hinges.

Pre bent multilayered comb-drive: Chiou *et al.* (2007) discussed that, a pre-stress comb-drive system fabricated using PolyMUMPs fabrication sequence summarizes as follows. Starting with nitride isolation layer, three polysilicon structural layers (Poly0-2), two phosphosilicate glass sacrificial layers (PSG1 and PSG2) and a gold metal layer (Au) for optical reflection and electronic circuit interconnection embedded in between layers.

Edwin *et al.* (2005) discussed that, the internal stress of the hinge decides the height of the upper finger of the pre-stress hinge comb-drives.

Self aligned vertical comb-drive: Vertical comb-drive actuators are suitable for requirement smaller actuator size, low driving voltage and large vertical displacements. A single step lithography fabrication technology which employs multiple thin layers of conductors separated by thin layers of dielectrics. This technology is used to achieve the high aspect ratio self-aligned vertical comb-drives with smaller gaps between finger electrodes. Small finger gaps resulting in high force densities.

Edwin *et al.* (2005) discussed that, when surface micromachining technique is used to fabricate vertical comb-drive, normally it yields a small self-aligned finger gaps and due to low aspect ratio larger displacement can not be obtained from it.

Angular vertical comb-drive: The torsion bars are permanently deformed and actuated. the precisely aligned vertical-comb sets. Figure 6 is a close-up view of

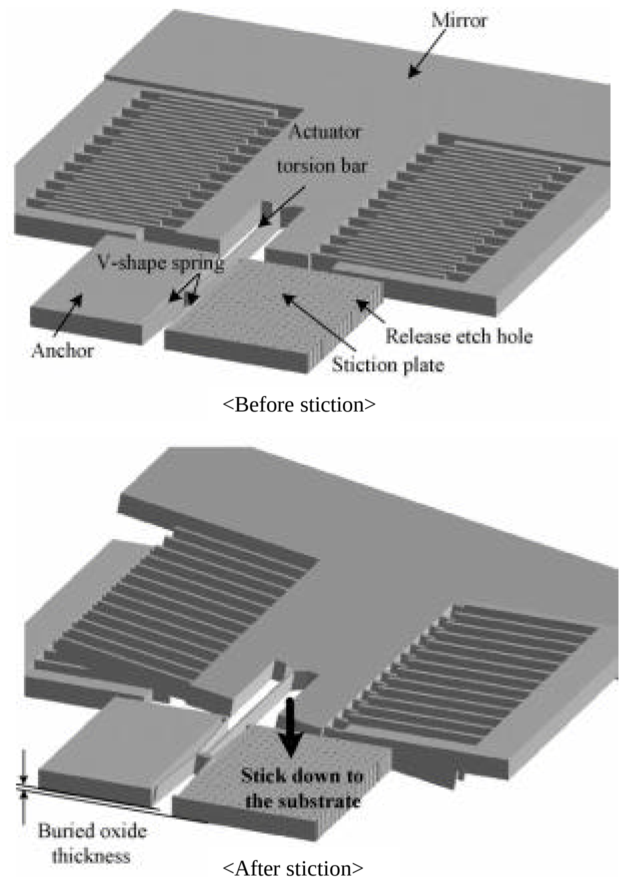

Fig. 7: Working principle of vertical comb actuators

a plastically deformed torsion bar showing that the deformation appears to be uniform along the torsion bar. By using the method of plastic deformation, the maximum value of initial tilt angle is limited by the fracture strength of the Silicon at room temperature.

Stiction related Performance issues of comb-drives: Stiction selectively used in positive way to fabricate self -aligned angular vertical comb-drive made of single-crystal silicon as shown in Fig. 7. A new structure called stiction plate with mechanical spring used to reduce the unwanted compliances on the actuators there by the uncontrolled motion is prevented and stability is ensured during operation.

Kim *et al.* (2006b) discussed that, the critical fabrication step is summarized as follows as shown in the Fig. 8. The critical point CO_2 drying process involves two important steps. In the first step solvent such as methanol or isopropyl alcohol is dispensed with high-pressure liquid CO_2. In the next step temperature is raised above the critical point of CO_2. During releasing of the structure there is no liquid-solid interface is formed during the process. This step is used to prevent the stiction which is not desirable during releasing of the structures.

Kim *et al.* (2006a) discussed that, the moving- combs and static-combs are coplanar provided they are fabricated in the same device layer of SOI wafer. Coplanar configuration cannot induce vertical displacement, when voltages applied between the comb fingers. In the next step, the combs attached to mirror top are deformed from their default orientations. It is done by pressing on them with a separately formed silicon substrate. This substrate is processed separately so that it has a precisely located array of pillar structures. The pillar structures are located such that each of them deforms one pair of torsion bars. It is done by pushing the corresponding mirror edge towards down from its initial default position. In the next step high-temperature at 900°C annealing process changes the initial elastic deformations of the torsion bars. These bars connect the two comb finger sets into

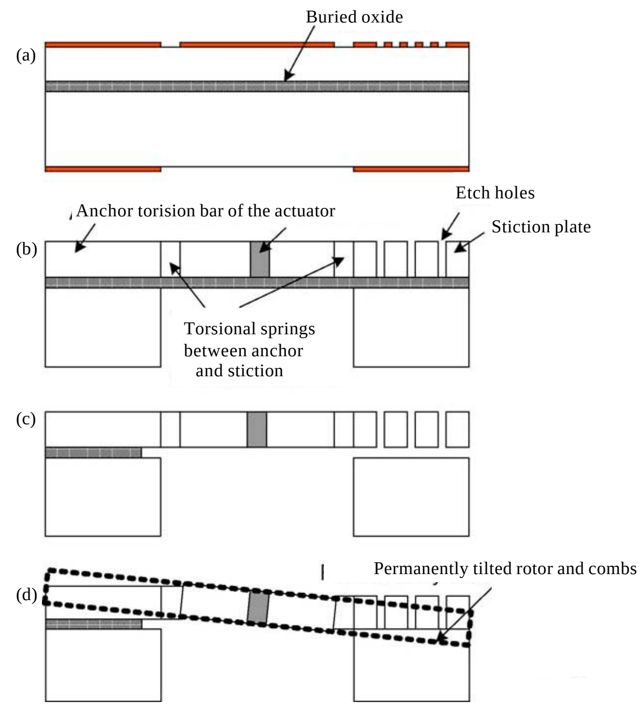

Fig. 8(a-d): The fabrication sequence of comb-drive, (a) Pattern on front and back side of SOL (50 μm device layer), (b) DRIE on front and back side, (c) Oxide wet etching in HF to release Si structures, (d) Drying and annealing

permanent plastic deformation portions. With the comb pairs in this angled configuration, driving voltages applied between them there by inducing torque in the torsion-bar support structure that connect them.

Edwin *et al.* (2005) discussed that, with a single DRIE step where the upper and lower finger-electrodes are separated by the internal stress of an attached hinge part. Angular vertical comb structures can be etched from an SOI layer which are capable of producing high aspect ratio comb finger-electrodes. The offset comb finger-electrodes are formed using a combination of Deep Reactive Ion beam Etching (DRIE), growth of barrier layer oxide and a dry isotropic selective etch of the upper comb finger electrode layer.

Compound comb-drive: By using a bulk-and-surface mixed silicon micromachining process the compound comb-drive is fabricated in SOI substrate. The compound driving structure is combination of a planar plate drive and a vertical comb drive. This structure can actuate the mirror to achieve large-range analog rotation as well as binary 90° rotation induced by the pull-in effect where this effect is used in positive way in a voltage control fashion for its actuation.

VCD section is used in analog mode of operation where rotational movement is obtained and the PPD section is used in binary mode of actuation where spontaneous 90° rotation induced by the pull-in effect.

Wu *et al.* (2007) discussed that the elastic torsion springs were fabricated thinner than the micromirrors for low driving voltage. The length of movable comb fingers and the thickness of fixed comb fingers are the deciding factors of actual maximum rotation angle.

Elman *et al.* (2008) discussed that the MASIS process (Multiple aspect ratio structural integration in single-crystal-silicon) a novel fabrication process was especially introduced for fabrication of MOEMS (Micro-Opto-Electro-Mechanical-Systems) actuators which are driven by long-stroke comb-drive actuators. This process is implemented for the fabrication of single crystal silicon structures having distinct aspect ratios in the same actuator layer.

DISCUSSION

Residual stresses in polysilicon: The formation of residual stresses of LPCVD polysilicon summarized here and the residual stress as a function of deposition

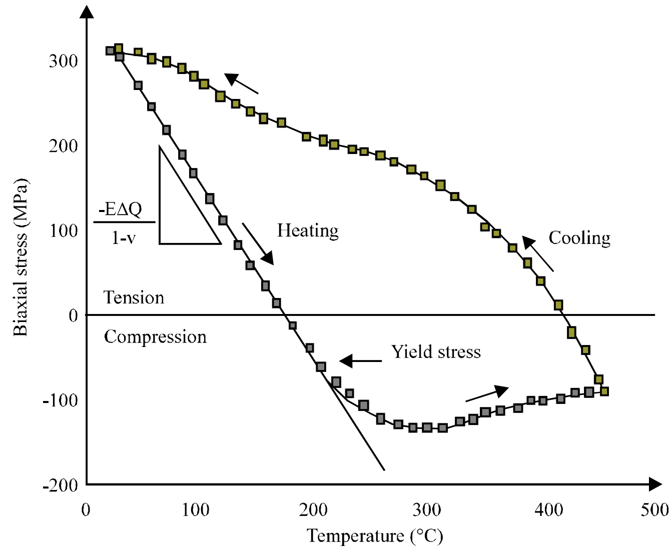

Fig. 9: Typical results for residual stress as a function of temperature for an aluminum film on a silicon substrate, Thickness 590 nm

temperature taken from five different investigations from literatures. All five sets of data show the same trend. The stress undergoes a change from compressive nature at the lower deposition temperature to tensile nature at intermediate temperature and returning back to compressive nature at the higher temperature. In each data set the transitions are easily perceptible. The microstructure of the LPCVD polysilicon films influences the origin of these residual stress changes. Deposition conditions dictate the microstructure of LPCVD polysilicon films. The thin films are grown at temperature slightly lower than 570°C are in amorphous nature and they show fine grain structure at the temperature range of 570 to 610°C. The grain structure is columnar at the 610 to 700°C and also a fine-grained layer is formed at substrate and layer interface.

The slope of the heating curve for an aluminum film on a silicon substrate. gives the difference in thermal expansion between the film and the substrate. When the heating curve changes slope and becomes nearly horizontal, the yield strength of the film is reached as shown in the Fig. 9. The deposition rate is faster than crystallization rate during the homogeneous nucleation and growth of grains within the regime as-deposited film which is amorphous in nature and results in fine-grained microstructure. The as-deposited films are crystalline at the substrate interface and amorphous at the free surface. The amorphous part can be crystallized by annealing process which is done at above 610°C.

At higher growth temperature the columnar grain structure is formed and the growth rate is faster in <110> directions. The crystallization of the as-deposited amorphous material is accompanied with the formation of tensile stress due to volume decrease in fine-grained structure. During the film growth in amorphous and columnar films can increase the surface chemical potential. It occurs due to increase in surface chemical potential which is caused by the atoms deposited from the vapor. The increase in surface chemical potential further promotes atoms to flow into newly generated grain boundaries, inducing a compressive stress in the film.

Bhusan (2007b) discussed that the perfect bonding between the two films and the total strain must be continuous across the interface. The elastic moduli are different for the two films, so the stresses are not continuous at the interface.

The PECVD oxide (on a silicon substrate) curvature stress measurement result for a temperature cycling. It is also easy to distinct the thermal and non-thermal stresses from the stress-temperature diagram as shown in Fig. 10. As the substrate thickness increases, the stress present in the layer decreases with the higher value occurring at the interface. The stress in the substrate increases at the interface but decreases on the bottom surface. The stress distribution in the substrate that is compressive nature on the bottom surface and tensile nature at the substrate-interface. Depending on thickness, the stresses in the layer are either tensile in whole or partly tensile on the interface and partly compressive on the free surface. With the increase of thickness, the stress difference between the interface and the surface also increases and it is a measure of stress gradient in each thin-film as shown in Fig. 11. It is suggested that in order to reduce the residual

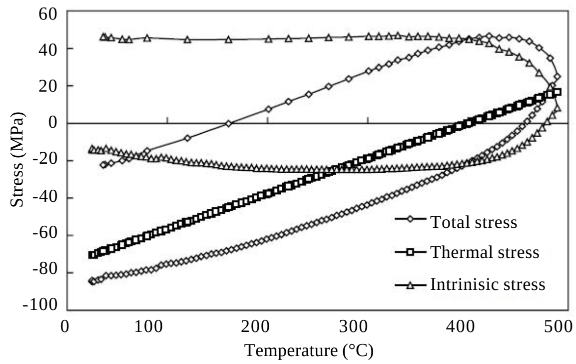

Fig. 10: Decomposition of thin-film stress into its components

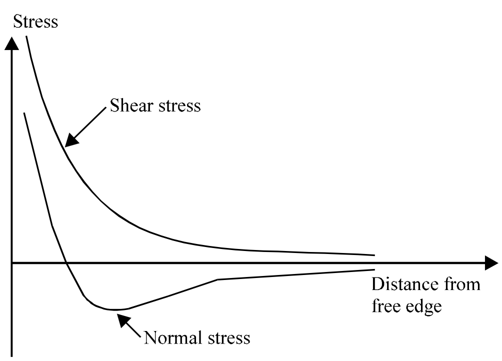

Fig. 11: Characteristics of the normal and shear stress distribution at the film/substrate interface near the free edge

stress the Radio Frequency plasma enhanced chemical vapor deposition (RF-PECVD) which supports the processing temperature in the range of 100-250°C can be considered.

CONCLUSION

The causes and effect of residual stress formation during the microfabrication process is studied from the literatures. This knowledge can be used to correlate the performance of MEMS actuators with the fabrication critical parameters. The critical steps that are followed to control the residual stress are presented from literatures. Pull-in and stiction phenomena are positively used to achieve the featured actuations in comb-drive system. Application and performance specific fabrication methods for MEMS comb-drive actuators are briefly summarized.

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