Surface Micromachined Electrostatically Actuated Double Bridge Digital Micromirror for Torsional and Piston Mode Operation

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Abstract— **This paper presents development of an electrostatically actuated double bridge micromirror platform for optical applications. The proposed double bridge micromirror structure is fabricated using a combination of surface micromachining and gold metal electroplating. Unlike single bridge micromirror, the constituent structural layers in fabricated micromirror are hidden below the top reflective plate, which prevents unwanted reflection of light from anchor and actuation electrodes. The Double bridge structure has the advantages of lower pull-in voltage and higher fill factor. The proposed micromirror platform is capable of producing both torsional and piston motion by bending of cantilever beams on application of voltage between actuation electrodes and cantilever actuators. With a top reflective mirror plate of dimension 200 x 200 μm^2, RMS roughness 25 nm and an actuation gap of 2.5 μm, maximum achievable tilt angle is 3 degrees at a pull-in voltage of 6.7 Volt DC in torsional motion. An axial displacement of 2.5 μm in piston motion is also achieved with this proposed structure .The micromirror is capable of torsional and axial scanning by application of AC voltages on selective actuation electrodes, at measured resonance frequencies of 35.23 KHz and 74.23 KHz respectively.**

Keywords—Digital Micromirror Devices, MEMS Actuator

I. INTRODUCTION

Micro-Electro Mechanical Systems (MEMS) devices have made rapid development in the field of communication, automobiles, medical and space applications in recent years. MEMS micromirrors in particular have found uses in various applications like optical projection display [1-2], multi-object spectroscopy [3], adaptive optics [4], optical cross-connects [5], maskless lithography [6] and optical scanning [7-8]. Owing to batch fabrication capability combined with high operational speed and low power consumption, MEMS micromirrors have huge market potential in fiber-optic interconnects and optical coherence tomography (OCT) [9]. Micromirrors are mostly rectangular or circular reflecting surfaces whose torsional motion is used for optical projection and scanning applications while piston motion is used in spatial light modulation and wave front shaping.

In optical Coherence Tomography (OCT), high resolution image of a biological tissue is generated by the use of Michelson interferometry where an optical delay is created by piston movement of a reference mirror using electrical motor. Replacing reference mirror in OCT by piston mode operational micromirror would significantly reduce interferometer size and improved imaging speed. Torsional and piston motions in micromirror is mostly achieved by twisting or bending of compliance structures by through electrostatic, thermal or piezoelectric actuation. The majority of these devices are driven by electrostatic actuation because of negligible power consumption, fast actuation speed and easy fabrication steps, however, actuation voltage increases non-linearly with requirement of large displacements. With exposed beams and anchors, reflection of light from unwanted regions during 'off state' of micromirror results in poor contrast and lower fill factor when arranged in an array.

In this paper, an electrostatically actuated double bridge digital micromirror device is fabricated and characterized. The fabricated micromirror is capable of both torsional and piston motion by bending of cantilever beams. Anchor, electrodes and cantilever beams are hidden under the top reflective plate for higher contrast compared to single bridge micromirrors. Hidden hinged micromirrors are available in literature, but the design and fabrication process is quite complex and majority of them are fabricated using Silicon-on-Insulator (SOI) and Deep Reactive Ion Etching (DRIE). In the current design, a simple fabrication approach of surface micromachining and gold electroplating with reduced complexity is proposed. The fabricated micromirror platform has potential to meet the requirements of axial scanning in OCT systems.

II. DEVICE DESIGN AND PROCESS FLOW

The schematic model of the proposed digital micromirror structure and its cross-section is shown in fig. 1 and fig. 2 respectively. A top reflective plate of dimension 200 x 200 μm^2 is attached to a set of cantilevers by four stubs and rigidly anchored to Silicon substrate. The actuation of cantilevers provide necessary spring action for deflection of micromirrors and four stubs provide a constant gap between actuating cantilevers and top reflective plate. The electrostatic force generated by application of voltage between one of the actuation electrode and cantilever beam attracts beam towards the actuation electrode due to electrostatic Pull-in. A restoring

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force is subsequently developed in the cantilever beam which opposes further bending and the micromirror attains a stable position when both forces are in equilibrium. Increase in actuation voltage beyond this point leads to snap down of cantilever beam on actuation electrodes. Since top reflective plate is attached to cantilevers using stubs as shown in fig. 2., a torsional motion of micromirror is achieved. Once applied voltage is removed, cantilever restores back to its normal position along with mirror plate. When voltage is applied to all four actuation electrodes simultaneously, all four cantilevers are attracted towards actuation electrodes and the mirror exhibits a piston mode movement. Both torsional and piston mode deflection is limited by the actuation gap between cantilevers and bottom electrodes. Micromirror reflective plate and actuation cantilevers are fabricated by gold electroplating while actuation electrodes are made using doped Poly-Silicon over a Silicon substrate. The proposed fabrication step of micromirror device is shown in fig. 3.

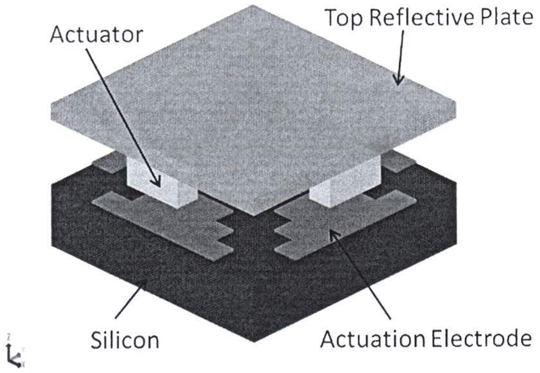

Fig. 1: Schematic model of the proposed double bridge digital micromirror device

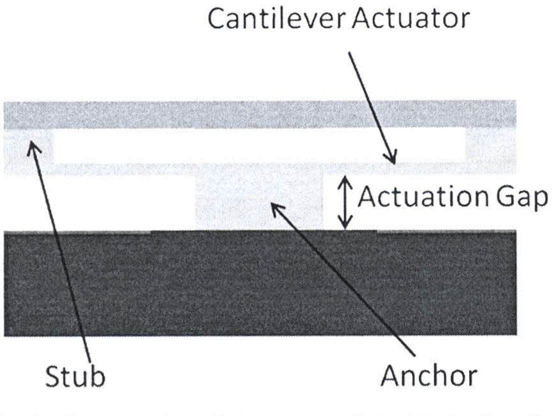

Fig. 2: Cross-section of the proposed double bridge digital micromirror device

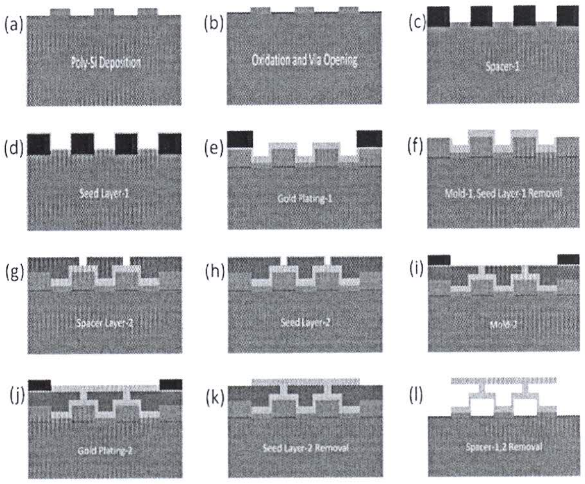

Fig. 3: Proposed fabrication flow of micromirror

III. DEVICE FABRICATION

The double bridge micromirror structure is fabricated using a combination of surface micromachining and gold electroplating. A three-step methodology of sacrificial deposition, mould formation and gold electroplating is adopted twice to realize double bridge structure configuration. The process begins with degreasing of 350 μm thick Silicon followed by RCA-1, RCA-2 and Piranha cleaning. A 1-μm thick Silicon dioxide is thermally grown at 1040^0C to provide electrical isolation between actuation electrodes. This is followed by deposition of 0.6 μm Poly-Silicon by Low Pressure Chemical Vapor Deposition (LPCVD) process. Poly-Silicon is patterned using optical lithography to form bottom actuation electrodes. Since Poly-Silicon is to act as electrode and interconnect lines, it is doped with Phosphorus to achieve low sheet resistance prior to patterning. Sheet resistance in the range of 1Ω/□ to 20 Ω/□ is found good enough for this role. A 0.2-μm layer of Silicon dioxide is deposited over actuation electrodes by Plasma Enhanced Chemical Vapor Deposition (PECVD) to prevent electrical short between actuation electrodes and cantilever actuators during the snap-down phenomenon. Contact holes are opened in PECVD oxide by optical lithography for electrical interconnects between actuation electrodes and contact pads. A sacrificial layer of thickness 2.5 μm is deposited using positive photoresist HIPR 6517 by spin coating. The photoresist is prebaked at 120^0C and patterned using optical lithography followed by deposition of Cr/Au seed layer of thickness 20/70 nm by RF magnetron sputtering at 300W power. Cr/Au seed layer provides adhesion and conductive surface for gold electroplating. A high aspect ratio mold is created by AZ 9260 positive photoresist and 1-μm thick gold is deposited by pulse electroplating using cyanide free thio-sulfite electroplating bath. Mold and seed layers are then chemically etched and a sacrificial layer of thickness 2 μm is deposited using positive photoresist HIPR 6517 by spin coating once again. The photoresist is patterned and Cr/Au seed layer of thickness 20/70 nm is sputter deposited. A high aspect ratio mold is created and 2-µm thick gold is deposited by pulse electroplating. Mold and seed layers are chemically etched away, but reflecting surface gets damaged due to Au etchants used for seed layer etching. To preserve the surface smoothness, a thin layer of copper is electroplated over gold prior to seed layer etching which is subsequently etched away after use of Au etchants. Several methods were used for the removal of sacrificial layer and release of micromirror e.g. boiling in acetone and oxygen plasma ashing were tried but traces of sacrificial photoresist remained under reflective plate. To ensure complete sacrificial removal, the structure is dipped in a mild piranha solution (H_2SO_4:H_2O_2::10:1) which completely dissolves photoresist. To prevent stiction, structure is immersed in Isopropyl alcohol (IPA) and the liquid is removed using Critical point Dryer (CPD). The completely released micromirror structure is shown in fig. 4.

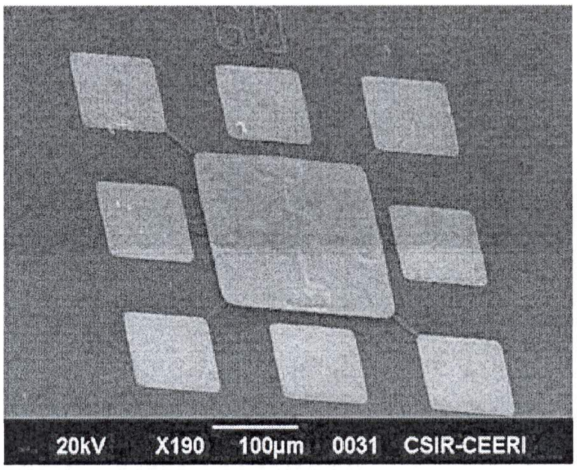

Fig. 4: Micromirror structure released using mild Piranha solution and CPD

IV. RESULTS AND DISCUSSION

The released micromirror device is evaluated for static and dynamic performance. Static measurements are done using Keithley CV measurement unit to measure change in capacitance between actuation electrode and top actuator. The cantilever and reflective plate are biased at ground potential and a DC voltage sweep is applied across one of the actuation electrodes. Fig. 5 shows minimal change in capacitance till 6.7 volt and an abrupt rise in capacitance from 252 fF to 1.16 pF beyond 6.7 Volt.. This micromirror showed small deflection up to 6.7 volt and snaps down abruptly afterward. The maximum achieved deflection for micromirror in torsion mode is 3 degrees. When a voltage is simultaneously applied to all bottom electrodes, micromirror operates in piston mode. To evaluate dynamic performance, the resonance frequency is measured using laser Doppler Vibrometer (LDV). Fig. 6 and fig. 7 shows two resonance modes of micromirrors with primary torsional mode at 35.23 KHz and piston mode at 74.23 KHz respectively. Higher order modes are beyond the scope of current work and hence not shown in paper. The surface roughness of reflective plate is measured using Zeta optical profiler and an average roughness of 25 nm is observed as shown in fig. 8. The measured roughness is found suitable for various optical applications.

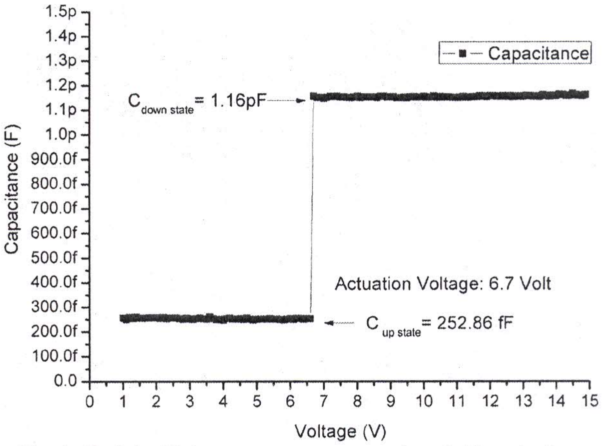

Fig. 5: Pull-in Voltage measurement using C-V analysis

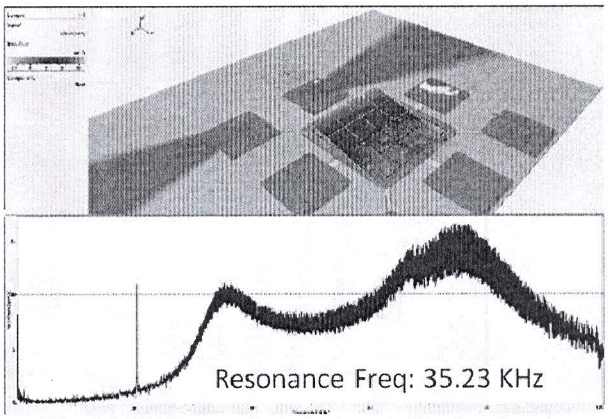

Fig. 6: LDV image of micromirror in Torsional mode

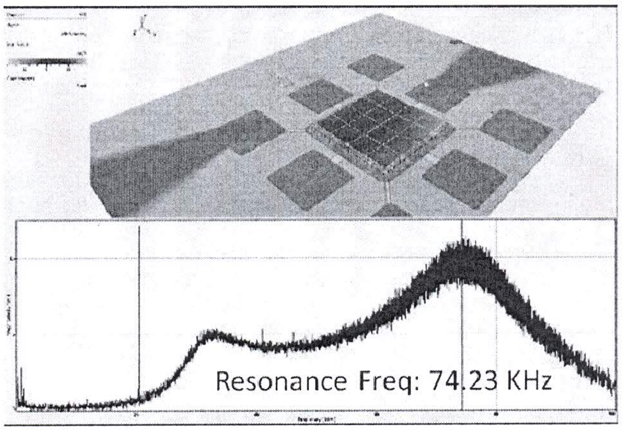

Fig. 7: LDV image of micromirror in piston mode

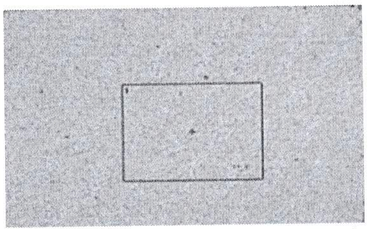

Fig. 8: Surface roughness measurement using Zeta Optical Profiler

In this paper, a simple process for development of electrostatically actuated double bridge digital micromirror is presented. To illustrate the fabrication methodology, the micromirrors are designed, fabricated and characterized. A 2 micron thick reflective plate of gold is suspended at 2.5 micron height has been released successfully without stiction. The actuation cantilevers and anchors are hidden below the reflective plate for higher contrast and high fill factor. The fabricated micromirror exhibit a pull-in voltage of 6.7 V for 3 degree tilt. The resonance frequencies of micromirror is observed at 35.23 KHz in torsional mode and 74.23 KHz in piston mode respectively.

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