Manufacturing of 3D Optical and Micro-fluidic Structures Using Ultraprecision Self-Assembled Processes

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ABSTRACT

Micromachined structures produced using processes inherited from the IC industry are fundamentally two-dimensional. At Boston University, we have developed a new fabrication technique that combines ultra precision diamond cutting with microelectromechanical systems (MEMS) processes to produce self-assembled three-dimensional structures. The methodology adopted uses surface micromachining techniques such as sputtering for the deposition of structural and sacrificial layers in combination with ultra precision machining processes such as turning and milling. To demonstrate the feasibility of the manufacturing process, an actuator for a MEMS deformable mirror was fabricated. In this application, the three-dimensionality of the electrode enhances the performance of the device, by allowing for the first time, MEMS having multiple sculpted layers. By shaping the electrode to achieve the maximum deflection contour, one can increase the actuation range by an order of magnitude. Actuation deflection models comparing the standard micromachined electrode to a simple 3D one showed evidence of significantly increased electrostatic force, allowing larger stroke or lower required voltage. In this demonstration, materials such as electroless nickel, a machinable glass-ceramic (Macor®), and nonferrous metals were used where the previous devices were fabricated using conventional silicon-based MEMS materials. In addition to geometry flexibility and a broader choice of materials, the development time for a prototype was significantly reduced. Several combinations of structural/sacrificial materials are being explored and results will be reported. The design space and achievable tolerances are also being studied. To demonstrate the versatility of the fabrication, the design of a micro-fluidic device as well as the proposed fabrication scheme will be presented.

INTRODUCTION

Conventional MEMS fabrication typically utilizes processes inherited from the IC industry such as thin film deposition, oxidation, vapor deposition, photolithography, and etching. Although the silicon-based processes can be used to fabricate complex geometries, the number of steps required for the manufacturing can be exorbitant and the geometries remain limited, for example, by the etch depth. These limitations, combined with the goal of creating lower-cost production using a broad range of materials led to the development of alternative technologies such as Micro-Stereolithography. Micro-stereolithography allows the fabrication of small-size, high-resolution three-dimensional objects, by superimposing a certain number of layers obtained by selectively solidifying a photosensitive polymer using UV radiation [1]. A more advanced micro stereolithography [2] that breaks the layer-by-layer limitation of conventional stereo lithography is able to generate freely movable 3D structures with resolution less than 1 μm. This technique provides a better yield than the preceding stereolithography methods and the production speed is in the order of several minutes to tens of minutes. The main drawback of micro-stereolithography is related with the materials that can be used in this manufacturing process: only a few polymers such as acrylates or epoxies can be employed. Other techniques that are capable of producing truly 3D structures include Laser Chemical Vapor Deposition (LCVD) and Photo-Electroforming. Photo Electroforming uses a laser to locally heat a powder, creating a conductive pattern, and selectively joins an electrolytic or electroless metal only to the metallized region [3]. Using this method, planar resolution of 10-15μm and a 5μm layer thickness were reported. LCVD, which is also laser-assisted, can directly fabricate freestanding microstructure from vapor phase. This method has been used for the manufacturing of thin rods and fibers with small diameter (<10 μm). Using a two-beam setup, it is possible to create a 3D fiber growth process that permits the direct writing of complex freestanding microstructures [4]. However, the aspect ratios of both LCVD and Photo-Electroforming are limited. Also Photo-Electroforming is restricted to materials that can be processed with temperatures in the 200-300 ºC and the final surface finish is limited by the particle size of the precursor powder.

Additional solid freeform or rapid prototyping methods such as Selective Laser Sintering and PolyJet have also been used to fabricate 3D structures. The minimum feature size in these techniques is on the order of 100 μm, which limits their applications in MEMS manufacturing. The techniques just described are some of the main non-silicon/photolithography methods employed for fabricating MEMS devices. Each technique presents its limitation while offering significant advantages. For some, the material selection is very limited (micro stereolithography), others such as LCVD have limited aspect ratios. Other techniques combining several micromachining techniques such as LIGA eliminate several of the shortcomings of the traditional surface micromachining. LIGA is based on the combination of sacrificial wax molding with electro deposition and x-ray lithography [5]. This process is used to fabricate high aspect ratio microstructures and arbitrary shapes. However the combination of continuous three-dimensional profiles with large aspect ratios is not currently possible with lithographic techniques. LIGA is capable of producing accurate structures on a nanometer scale, but larger (micrometer scale) three-dimensional structures are not cost-effective [6].

The first fabrication process combining precision machining with sacrificial/structural layer deposition is UPSAMS (Ultra-Precision Self-Assembled Micro-Systems [7]. With UPSAMS, a material is deposited onto a milled cavity or negative of the structural layer. The structural is then milled down to its final shape and the entire 3D structure is then released from the sacrificial layer. In the demonstrated device fabrication only one sacrificial layer and one structural layer were deposited. Therefore this fabrication yields a stand-alone part and problems related to multi-layer adhesion and related stresses during service are not encountered. However the limitations faced in this fabrication process are similar to those that our approach will face. One being the minimum feature size is limited by the tool size, which is an order of magnitude larger than obtained with photolithographic techniques.

FABRICATION PROCESSES

Demonstration of the Fabrication Process

A MEMS actuator for a deformable mirror [8] is being used to demonstrate this fabrication technology. In this application, the three-dimensionality of the electrode enhances the performances of the device. By shaping the electrode to mimic the maximum deflection contour, one can increase the actuation range by an order of magnitude. Actuation deflection models comparing the standard Micromachined electrode to a simple 3D one showed evidence of better electrostatic force usage by obtaining better stroke or identical stroke with less power.

Figure 1 shows the fabrication sequence that is currently being used to fabricate the actuators. The first and second layers currently used are Ti and Al layers, which were deposited via sputtering. Electroless plating of a thick layer on Ni followed and the shaping of the electrodes are depicted in steps 2 and 3 of the process. Steps 4 and 5 are the deposition and machining of the copper sacrificial layer, which upon release, acts as the electrostatic air gap for the actuators. This Cu is machined to define the geometry of the mirror membrane that consists of the nickel deposited in step 6 and machined in step 7. The sacrificial copper layer is augmented to serve as substrate for the mirror membrane and post, which comprised another Ni layer. The fabrication is completed with a machining step (mirror post; step 10), the use of the third sacrificial layer (step 11), the deposition of the mirror layer, and finally the release of the entire structure.

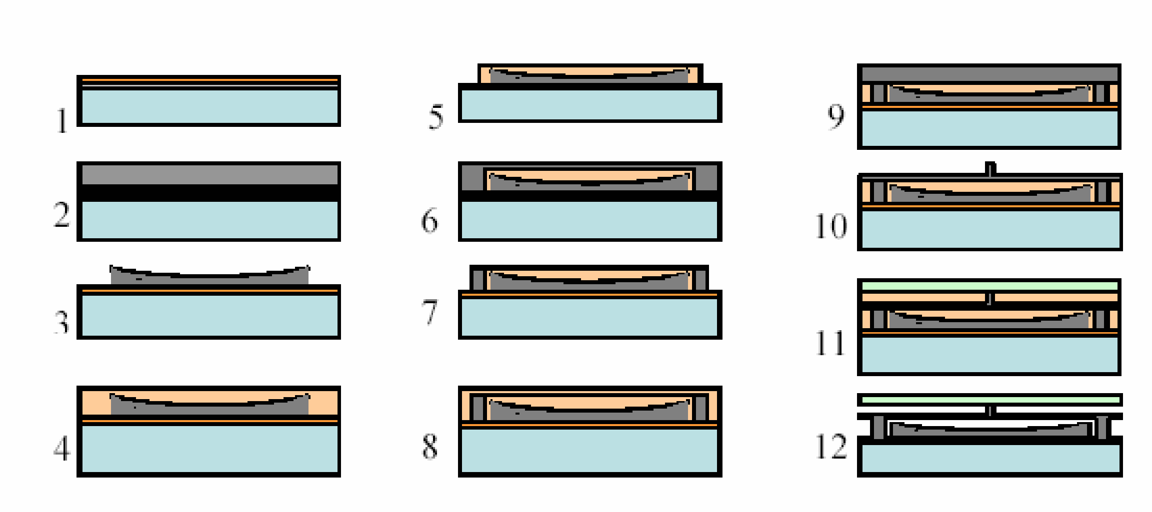
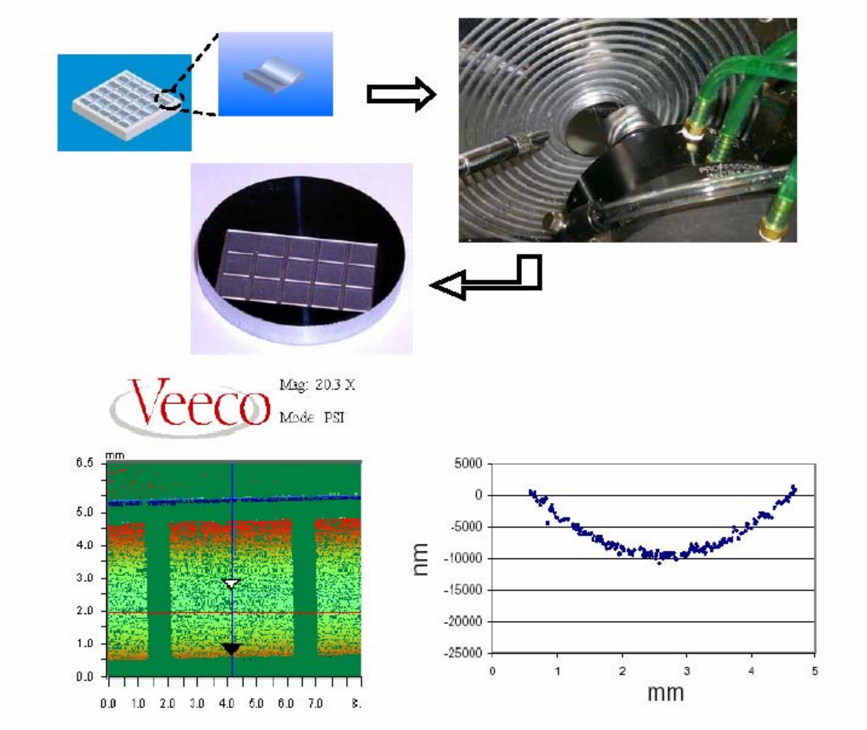


Figure 1: Fabrication Process of a MEMS Deformable Mirror with a 3-D Electrostatic Actuator. 1 – Sputter adhesion and seed layers. 2 – Electroless deposition of nickel. 3 – Define electrode geometry. 4 – Electroplate copper (sacrificial). 5 – Mill Cu surface. 6 - Deposit Nickel and turn. 7- Machine anchors. 8 – Deposit copper and turn. 9 – Deposit Nifor mirror post. 10 – Define mirror post geometry. 11 – Deposit Cu Ni mirror and diamond turn. 12– Release structure.

High Speed Micromilling

To produce complex 3D micro structures on nickel layer, ultraprecision diamond milling is utilized. To achieve an adequate cutting speed, a ISO 2000 Professional Instrument airbearing is selected. This spindle can reach a speed up to 60,000 rpm while maintaining asynchronized error motion to be less than 100 nm. We have cutting tools size (tool nose radius) range from a few microns to a few hundreds microns. First, the 3D solid model of the MEMS device can be constructed using commercial solid modeling software and then transported to FeatureCAM®, a program that converts a 3D model into G-code. The G-code file is then uploaded to the ultraprecision machine for device fabrication. Initial test indicated that the machine 3D curve match the design with a high accuracy.



	Trench Height (µm)	Electrode Max Depth (µm)	Surface Finish (µm)
Modeled	36	10	1
Measured	37	10.1	1.29

Figure 2: 3D electrode machined on a aluminum substrate. Prototype fabrication using carbide tools provided the information needed to machine thin layers of EN using a milling tool.

Material Selection

One of the main criteria guiding the choice of a substrate is machinability. Also, the substrate has to be an insulator so that electronics can be possibly embedded onto it if needed. In addition to these requirements, adhesion to other metallic layers has to be possible without extensive preprocessing. Last, it should be able to withstand high temperatures processing, up to 300 °C without any deformation or failure.

Materials evaluated for these requirements were ceramics such as Macor®, and thermoplastic polymers such as polypropylene. These are insulating materials and can be machined. However expansion and swelling in a high temperature environment is possible with polypropylene. Polypropylene was successfully coated with various compounds such as Ti and Cu but their adhesion failed when immersed into an acidic solution (sulfuric acid). Among many ceramics Macor® was chosen because it is an insulating material, has a low thermal conductivity, can be cleaned with a variety of acids, adheres well to many metals and can be used at 800 °C continuous or 1000°C peak (Corning Product data sheet). In addition to those properties, Macor®'s coefficient of thermal expansion matches most metals and sealing glasses, which eliminates potential residual stress problems.

In order to enhance adhesion between the substrate material and other layers, a thin coating of a material that provides excellent bonding to the substrate can be deposited onto it. The superior adhesion requirement stems from the cutting forces the machined surface will be subject during turning or milling. In the fabrication process that will be demonstrated later, a thin layer of titanium was used for this purpose. Also chromium is a common adhesive layer used in microfabrication. The choice of this adhesion enhancer also depends on the type of material or process that will follow. Titanium happens to be a versatile material since it can stick to a variety of metals. In addition to adhering to many metals it can be sputtered or evaporated, two depositions processes that are common in many labs or facilities. Sputter deposition provides better adhesion than evaporation thus was retained for the deposition of all inter-metallic layers.

Besides the layer that will enhance the adhesion of other material to the substrate, another thin conductive layer is needed for the electroless deposition of nickel. Among many choices copper, gold, and aluminum stood out. Copper is the most common material used for electroless plating and was initially selected for this task. Despite obtaining very satisfactory results using copper, it will be evident from the following fabrication process that we had to replace it with another material because the sacrificial layer was made of the same material.

The insertion of sacrificial layers in this fabrication process opens up its application to assembled MEMS devices where partially attached and free structures are common.

The best material for a sacrificial layer would be one that could be etched rapidly while leaving the permanent structures undamaged. With a wet chemical etching in mind for the removal of the spacer layer, copper was selected as sacrificial material in the demonstrated fabrication process since it can be etched with high selectivity to nickel, the material used in the structures. Different application-specific structural layers can be used in conjunction with suitable fabrication technology. Again, since ultra precision diamond machining is used for material removal, the materials of the structural layers have to be diamond turnable. Therefore various combinations of structural/sacrificial materials can be used as long as the diamond-turnability requirement is met and the material can be selectively etched to the other one. In this fabrication, wet-chemical etching is chosen because of it simplicity and inexpensiveness, which can restrict the choice of structural/sacrificial layers. The diamond turnable metals are: electroless nickel, aluminum, copper, gold and silver. The second group of materials considered is the plastics such as polymethylmethacrylate (PMMA), which is commonly used in the industry. Starting with Nickel as a structural layer, possible combinations include Ni/Cu (the proposed method), Ni/Al, Ni/Au, and Ni/PMMA. Gold is extremely difficult to etch, therefore will not be retained in most designs. Ni/PMMA has been previously used to fabricate Ni switches. If we start with the most used sacrificial metal, Cu could also be combined with gold, aluminum, and epoxy, in addition to nickel. Ductile materials like Al and Cu are most commonly used in diamond turning. The diamond turnability of ductile materials is well understood and has been the subject of many investigations [9, 10]. It has been reported that the slip in crystals on surface roughness must be considered. Brittle materials have also been used in diamond turning by keeping the depth of cut and the feed rate below certain values [11].

SUMMARY

A novel fabrication process integrating ultraprecision diamond turning and conventional MEMS fabrication processes has been presented. The fabrication process overcomes several limitations of conventional microfabrication techniques such as lithographic based deposition as well as restriction from precision machining such as the inability to machine sacrificial gaps. Real 3D structured electrode fabrication process has been demonstrated using a high speed milling process with micro size diamond tools. Ultraprecision diamond turning and milling provides adequate position accuracy for the multiple process steps required for MEMS device fabrication. Several materials that could be incorporated in this fabrication have identified and experimental studies to fabricate a prototype are currently underway. The investigation and optimization of the micro machining of the materials will greatly benefit the fabrication technology by expanding the material selection beyond the binary classification of diamond turnable materials. Finally, a second prototype from a different application will be fabricated to demonstrate the versatility of the fabrication process. In the meantime a set of design rules and the limitation of this fabrication will be identified.

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