Design and Fabrication of Three Dimensional MEMS Actuators using Diamond Turning and Electroplating Processes

Greg Reimann and Thomas Bifano
Boston University College of Engineering

Diamond turning and electroplating processes have been used to fabricate MEMS structures. This new combination of processes frees MEMS design from the traditional stacks of two-dimensional layers that have constrained the geometry of devices. The devices described in this work consist of a thin film of metal suspended across a trench 500 microns wide and 20 microns deep. Actuation occurs when a voltage is supplied to the membrane while the trench is held at ground. The bottom of the trench is an asphere diamond turned into the substrate and designed to maximize the deflection to voltage ratio of the device without sacrificing stroke. Manufacturing a device with an asphere like this using exclusively traditional photolithography technology is not possible, but the hybrid process illustrated here allows for true three-dimensional structures to be fabricated.

Conventional micromachining consists of additive CVD and PVD processes, lithographic patterning, and chemical etching. Using these processes iteratively generates “extruded” shapes and can approximate three dimensional structures. However, these structures are really only stacks of two dimensional components. As 3D approximations get better and features get higher, the number of steps in the process increases dramatically.

An alternative to this method is to use electroplating for material addition and traditional mechanical machining for material patterning and removal, thereby allowing true 3D structures and reducing the number of process steps needed. This research focuses on using copper electroplating and diamond turning to create MEMS electrostatic actuators with a greater deflection per unit voltage than is achieved by their 2D counterparts.

The process described herein does not entirely eliminate conventional micromachining methods. It is a hybrid of traditional micromachining methods and traditional mechanical machining methods, each used where most appropriate. Future work will aim toward eliminating photolithography entirely, simplifying the process to a series of plating and machining steps. The actuators described in this paper are a first step toward that goal.

The process designed to fabricate this actuator requires four materials. The cross section of an unreleased device is shown below.
The process involves diamond turning the substrate, electroplating the sacrificial layer to fill the trench, turning the sacrificial material back, depositing the insulator and structural materials through PVD, patterning those layers with lithography and chemical etching, and finally, isotropically etching the sacrificial material to release the device.

The substrate material must be diamond turned and then plated. Aluminum was selected because of its machinability. Aluminum is somewhat difficult to electroplate because of the native oxide that forms upon its surface. However, this problem has been overcome by the electroplating industry by first displacing the oxide with a coating of zinc and then displacing the zinc with the plating material. A relatively pure alloy (1100) was chosen because silicon impurities impair the turning process and magnesium impurities complicate the zincting process.

Copper was selected as the sacrificial plating material because it is relatively easy and common material to plate, it is very easily diamond turned, and it does not require a cyanide plating solution. Many of the traditional copper etches, such as Ferric Chloride and Ammonia/Hydrogen Peroxide attack aluminum also. Transene APS-100 and some dilutions of nitric acid have selectivity of copper over aluminum of more than 1000:1.

Silicon Oxide was chosen as an insulating material. Its adhesion to other oxides (ie. Native aluminum oxide) is good, and it is easily sputtered or evaporated. It can be anisotropically etched in a reactive ion etcher and is resistant to all other chemical etches in the process. Aluminum was chosen as a structural layer because it is easily sputtered. Its thin film properties are well understood, and the release chemistry and adhesion properties have already been verified in the process since it is the substrate material.

The structural material choice of thin-film aluminum fixes the modulus of elasticity. Previous work has been done to successfully deposit one micron thick aluminum layers to form MEMS actuators, so one micron was chosen as a thickness to capitalize on that experience.
The diamond turning tool used to cut the trenches in the aluminum substrate rotates in a circular fashion, so the trenches were cut in a circular fashion. This leaves a curved trench on which to put the actuator. Therefore, the actuator size was chosen to be small enough to minimize effects of this curvature, yet large enough to be able to see elements and time etches with the naked eye. A value of 500 microns emerged as both length and width.

A maximum gap ($g_0$) of 20 microns was selected because it is a reasonable depth to diamond turn, yields reasonable a snap-through voltage of 103 volts, and will allow 6.6 microns of stroke.

With all of these parameters selected, the shape of the fully deflected actuator was modeled. The final shape looks like the following graph.

![Figure 2: Curve of trench bottom to match maximum deflection](image)

The final circular trench made in the aluminum substrate has 13.3 micron high vertical sidewalls, with a cross section matching Figure 2 at the base.

The multi-step manufacturing process outlined above will permit a new class of ultraprecision machined MEMS structures with improved electromechanical performance. Process integration is currently underway, and test devices should be produced soon.