Single and Multilayer Surface Micromachined Platforms Using Electroplated Sacrificial Layers

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Abstract

The use of electroplated sacrificial layers in the fabrication of surface micromachined structures is discussed. Electroplated sacrificial layers offer two benefits: first, structures suspended several tens of microns above a substrate can be fabricated due to the ability to deposit relatively thick electroplated layers; second, the selective deposition of electroplated material only on conductors allows the fabrication of multilayer three-dimensional structures in a self-aligned process. Single layer surface micromachined bridges and platforms suspended 10 to 50 μm above the surface have been fabricated in this manner. In addition, dual layer platforms with some portions suspended 2 to 3 μm above the surface and other portions 10 to 50 μm above the surface have also been fabricated. Both structures are demonstrated using copper as the sacrificial layer and polyimide as the structural material, although other material combinations can also be used. Electrostatic actuation of both types of platforms has been achieved.

Introduction

Over the past several years, advances in surface micromachining have yielded microstructures capable of a large variety of motion. In the standard surface micromachining process, a sacrificial layer is deposited on the surface of the wafer and patterned, a structural material is coated partly on top of the sacrificial layer and (usually) partly on the wafer, and the sacrificial layer is removed, creating a suspended structure of the structural material [1]. Using surface micromachining, structures moving laterally to the wafer plane, normal to the wafer plane, and unconstrained in a rotary direction have recently been realized [2-4].

One potential drawback of surface micromachining is the difficulty in achieving large gaps between the micromachined structure and the surface of the chip/wafer. As most sacrificial layers are evaporated, sputtered, or deposited by chemical vapor deposition techniques, the effective sacrificial layer thickness is usually limited to a few microns. This thickness limitation tends to restrict the vertical motion (normal to the wafer plane) which the micromachined structure can achieve. In contrast, electroplated metal layers tens or hundreds of microns in thickness can be easily realized. This phenomenon is exploited in the LIGA [5] and other similar processes [6,7] to achieve high-aspect-ratio microstructures. In this work, we discuss the use of electroplated sacrificial layers to achieve large gaps between surface micromachined structures and substrates. An additional advantage of using electroplated sacrificial layers is that electroplating is inherently a selective deposition process, with additional metal depositing only on exposed conductor layers. This allows the fabrication of a multilayer surface micromachined platform with well-defined edges using a self-aligned process. A simple example would be a square platform with a smaller protrusion underneath the platform, a structure which might be difficult to achieve using other methods. The fabrication of such a structure is also described in this paper.

Inherent in many surface micromachining processes is the problem of planarization. If the sacrificial layer is more than a few microns thick, the structural material may have difficulty in realizing good step coverage over the sacrificial material, resulting in failure of the device. For this reason, it is important that the structural material have good step coverage abilities. As polyimides [8] have been widely used in microelectronics due to their excellent planarizing and step coverage abilities, they will be investigated in the process described here. Other processes, e.g. chemical vapor deposition techniques, also offer this planarizing capability.

The use of polyimide as the structural material in a surface micromachined process was recently demonstrated by Schmidt [2]. In that work, an aluminum layer approximately 3 μm in thickness was used as the sacrificial layer and removed with a metal etchant (based on a mixture of phosphoric, acetic, and nitric acids) which did not attack the polyimide. In this work, polyimide will be used as the structural material to address the step-coverage issues discussed above. In addition, copper will be used as the sacrificial layer due to both the ease of deposition of this material through electroplating as well as the ability of the polyimide to withstand the standard copper etchants. Three surface micromachined structures fabricated using these techniques, a bridge test structure, a single-layer platform, and a multilayer platform are presented below.

Surface Micromachined Bridges

As a test vehicle for the fabrication of surface micromachined devices using electroplated sacrificial layers, a simple bridge structure was designed and fabricated. The structure consists of sets of parallel lines and spaces of sacrificial material, over which polyimide has been deposited. The polyimide is then patterned into a set of parallel lines orthogonal to the initial lines, forming an array of microbridges.

The detailed fabrication sequence for these microbridges is given below, and shown in Figure 1. The starting material was a single-side polished n-type <100> silicon wafer three inches in diameter. The wafers were cleaned using a standard RCA cleaning process, and a masking oxide of approximately 1 micron thickness was grown using steam oxidation. An adhesion layer of chromium 150Å in thickness followed by an electroplating seed layer of copper 1 μm in thickness were evaporated onto the wafer using a thermal evaporator. The metals were patterned into parallel 100 μm wide lines and spaces using standard metal etchants (Figure 1a). Additional copper (typically 15-50 μm) was then deposited onto these lines using standard electroplating techniques [9] to complete the sacrificial layer (Figure 1b). The effect of current density on surface roughness and deposition rate was assessed; it was determined that for our bath, a current density of approximately 10 mA/cm^2 yielded the best tradeoff between growth rate, surface roughness, and residual film stress.

The wafers were then cleaned in an acetone/methanol/water sequence, and polyimide (DuPont PI-2555) was deposited onto the wafers in three spin coats of 2750 rpm for 90 seconds each with a soft bake between coats of 130 °C for 18 minutes. After completion of the third spin coat, the polyimide was cured at 300 °C for one hour in air, yielding an after-cure thickness of approximately 7.5 μm In order to pattern the polyimide, a hard metal mask of 200 Å of chromium (as an adhesion layer) and 2500 Å of gold was evaporated onto the polyimide. This layer was patterned into 100 μm lines and spaces orthogonal to the sacrificial lines and spaces using a solution of iodine and potassium iodide in water as the gold etchant. The exposed polyimide was then etched in a 10% CF_4 - 90% O_2 plasma to form the polyimide bridges and expose the sacrificial layer (Figure 1c). Finally, the sacrificial layer of copper was removed from both between and underneath the polyimide using a ferric chloride etch at room temperature to free the polyimide bridges (Figure 1d). The bridges typically took approximately 1 hour to release. Figure 2 shows a scanning electron micrograph of a fabricated structure. The bridges are approximately 100 µm in width, 8 µm in thickness, and are suspended over the surface by 30 µm Structures as high as 50 µm over the surface have been successfully fabricated using this technique. This process takes advantage of several material properties: the excellent planarizing properties of polyimide, the large lateral etch rate of copper in ferric chloride solutions, and the residual tensile stress in the polyimide, which holds the bridges suspended over the wafer without sagging.

It should also be noted that the sidewall profile of the bridge can be altered by selecting the patterning method used for the sacrificial layer lines. Patterning the electroplating seed layer prior to electroplating (as done in the sequence described above) causes the sacrificial layer edge profile to mushroom outward (Figure 3a), yielding an after-release bridge profile as shown in Figure 2. Patterning of the sacrificial layer after electroplating (using an isotropic etch, Figure 3b) causes the sacrificial layer edge profile to take on a concave shape. Finally, electroplating of the sacrificial layer through a straight-sidewall electroplating form [5-7] (Figure 3c) causes the sacrificial layer edge profile to be straight. We have successfully fabricated all three types of bridges.

Single Layer Surface Micromachined Platforms

In order to further demonstrate the utility of these structures, surface micromachined movable platforms were fabricated using electroplated sacrificial layers. The platforms are designed to be electrostatically positionable(in x,y, and z) polyimide plates of varying sizes and supports; typical platform sizes are squares ranging from 50-1000 µm on a side, suspended by four diagonally-oriented arms ranging from 50-1000 µm in length. The structure is fabricated using surface micromachining techniques as shown in Figure 4. An oxidized silicon wafer prepared as described in the previous section is used as the starting material. An adhesion layer of chromium 100 Å in thickness followed by a gold layer 4000 Å in thickness is evaporated onto the wafer using an E-beam evaporator and patterned into an electrode pattern for use in electrostatic plate positioning. The wafer and electrodes are then coated with an insulating layer of polyimide (DuPont PI-2555) deposited in one spin coat of 5000 rpm for 30 seconds, followed by a prebake of 130 °C for 20 minutes in air and a final cure of 300 °C for one hour in air (Figure 4a). Layers of chromium (for adhesion) and copper (as electroplating seed layer) are then deposited as described above and patterned to form anchors for the arms of the movable plate, and additional copper (the sacrificial layer) is electroplated to a final thickness of approximately 15 microns (Figure 4b). A second layer of polyimide (the structural material) with an after-cure thickness of approximately 7.5 microns is deposited in an identical manner to that described in the previous section. In order to pattern the polyimide, a hard metal mask of 200 Å of chromium (as an adhesion layer) and 2500 Å of gold is evaporated onto the polyimide and patterned to form the platforms using a solution of iodine and potassium iodide in water as the gold etchant. The exposed polyimide is then etched in a 10% CF_4 - 90% O_2 plasma to form the gold-covered polyimide platforms and expose the sacrificial layer (Figure 4c). Finally, the copper sacrificial layer is removed using a ferric chloride etch at room temperature to free the polyimide plates (Figure 4d). The plates typically took 1 - 2 hours to release depending on their size.

A photomicrograph of the fabricated structure is shown in Figure 5, and a scanning electron micrograph of a typical beam support is shown in Figure 6. It should be noted that in Figures 5 and 6, the polyimide platform is suspended 15 µm above the surface of the wafer over an area of approximately 1.1 x 1.1 mm without sagging. We have mechanically deflected the largest plate as much as three hundred microns in the plane of the wafer, and 15 microns normal to the plane of the wafer. The qualitative electrostatic actuation of these devices was also investigated, and successful actuation was achieved. For example, for a 100 x 100 µm square platform suspended 15 µm from the surface of the wafer, application of 50 V between the platform was sufficient to attract the plate 15 μm down to the surface. Application of approximately 65 volts between the platform and an electrode laterally displaced on the surface was sufficient to laterally deflect the platform approximately 5 μm. Thus, this process can be used to fabricate electrostatically actuatable structures suspended several tens of microns above the surface of the wafer.

Multilayer Surface Micromachined Platforms

The selective deposition nature of electroplating (i.e., electroplating will only occur on exposed conductors which are electrically connected to the electroplating cathode) allows the fabrication of multilayer structures in a planar, self-aligned fashion. This is described schematically in Figure 7. A sacrificial layer suitable for electroplating is deposited (or itself electroplated), and a first structural layer which is electrically insulating is deposited and patterned on top of it. The device is then immersed (or re-immersed) in the electroplating solution and a second sacrificial layer is deposited. Since the patterned structural layer is electrically insulating, deposition only occurs around the structural layer. The height of this layer can then be varied; for example, the layer can be plated up so that the sacrificial and structural layers are coplanar, as shown in Figure 7. A second structural layer is then deposited, and the sacrificial layer is removed in the normal fashion, resulting in multilayer platforms. It should be noted that not only is there variation in the third dimension, but the top layer can be made larger than the bottom layer using this process. Thus, platforms with integral features attached underneath can easily be fabricated.

The structures are fabricated in a similar fashion to the single-layer structures described in the previous section, along with the modifications described in Figure 7. An oxidized silicon wafer prepared as described in the previous section is used as the starting material. An adhesion layer of chromium 200 Å in thickness followed by a gold layer 4000 Å in thickness is evaporated onto the wafer using an electron beam evaporator and patterned into an electrode pattern for use in electrostatic plate positioning. A copper layer approximately 3 μm in thickness (the first sacrificial layer) is then evaporated on the wafer using an electron beam evaporator and patterned to form anchors for the arms of the movable plate. The thickness of this layer could be optionally increased by electroplating, but this was not done for the platforms described here. The first structural layer is then deposited. DuPont PI-2611 is spin-cast in four coats of 2750 rpm for 90 seconds, with a soft bake of 130 °C for 20 minutes between coats. Upon deposition of the four coats, the polyimide is cured at 300 °C for 60 minutes in air, yielding an after-cure thickness of approximately 12 μm This polyimide is patterned using 100% oxygen plasma to form the first structural layer. The wafer is then immersed in a copper electroplating solution as described above and the second sacrificial layer is deposited in a self-aligned manner. Deposition is stopped when the second sacrificial layer reaches the top of the first structural layer, yielding a sacrificial layer thickness of 12 μm A second polyimide layer (second structural layer) is deposited identically to the first structural layer. A hard metal mask of 200 Å of chromium (as an adhesion layer) and 4000 Å of gold is evaporated onto the polyimide and patterned to form the platforms using a solution of iodine and potassium iodide in water as the gold etchant. The exposed polyimide is then etched in a 100% oxygen plasma to form the gold-covered polyimide platforms and expose the sacrificial layer. Finally, the copper sacrificial layer is removed using a ferric chloride etch at room temperature to free the multilayer platforms. These relatively small platforms typically took approximately 1 hour to release.

Scanning electron micrographs of the fabricated structures are shown in Figure 8. Figure 8a is a top view of the fabricated structure, while Figures 8b and 8c (a close view of 8b) are angular views. The multilayer aspect of the platform is evident in the angular views. The arms of the platform are suspended 15 μm above the surface, while the lowest part of the platform is only 3 μm above the surface. Electrostatic actuation of the platform in the vertical direction could be achieved by application of approximately 80 volts between platform and lower electrodes. This structure will be useful in optomechanical applications currently under investigation where intimate contact between platform and substrate is necessary with no intervening electrostatic electrodes shielding or otherwise interfering with the contact.

Conclusions

The use of electroplated sacrificial layers in surface micromachining allows the fabrication of electrostatically actuatable, three-dimensional structures suspended several tens of microns above the surface of a substrate. Three test structures, a series of microbridges, a single-layer movable platform, and a multilayer movable platform, were fabricated in order to demonstrate the utility of this technique. Although a sacrificial layer of copper and a structural material of polyimide were used in this work to demonstrate the technique, any set of complimentary micromachining materials can be used providing the sacrificial material can be electroplated and the structural material has relatively good step coverage.

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Biographies

Young W. Kim received his B.S. and M.S. degrees in Department of Electrical Engineering from the University of Inha, Korea, in 1981 and 1983, respectively. He worked as a researcher at Samsung Electron Devices Research Center from 1984 to 1985 on modeling, design and testing electrooptic devices and sensors. He is currently pursuing graduate studies in School of Electrical Engineering at Georgia Institute of Technology. His research interests include design, fabrication and characterization of surface micromachined devices and their application to integrated optic devices. He is a member of the IEEE and a member of Korean Institute of Electrical Engineers.

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Figure Captions

Figure 1. Fabrication sequence for bridge structures. (a) after deposition of electroplating seed layer; (b) after deposition of electroplated sacrificial layer; (c) after patterning of polyimide layer; (d) after etch of sacrificial layer.

Figure 2. Scanning electron micrograph of gold-covered-polyimide, surface micromachined, bridge structures. The bridges are approximately 100 microns wide, 160 microns long, and 8 microns thick. They are suspended approximately 30 microns above the surface of the substrate.

Figure 3. Dependence of bridge profile on etching technique used to define the sacrificial layer. The sacrificial layer is shown in light shade while the bridge material is shown in black. (a) etching of seed layer prior to electroplating, yielding a 'mushrooming' sidewall; (b) etching of sacrificial layer after electroplating, yielding a standard isotropic etch sidewall; (c) electroplating of sacrificial material through a straight-sidewall form (e.g., as formed by LIGA or other processes), yielding a straight sidewall.

Figure 4. Fabrication sequence of surface micromachined platforms. (a) after deposition of polyimide over patterned electrodes; (b) after electroplating of sacrificial layer; (c) after deposition and patterning of structural polyimide layer; (d) after etch of sacrificial layer.

Figure 5. Photomicrograph of fabricated platform. The platform is approximately 360 micron on a side and 7.5 micron thick, and is suspended by arms approximately 540 micron long, 25 micron wide, and 7.5 micron thick. The platform is suspended approximately 15 micron above the surface of the substrate.

Figure 6. Scanning electron micrograph detailing the separation of a platform support arm above the surface of the wafer. The arm is suspended approximately 15 micron above the surface of the wafer.

Figure 7. Schematic representation of multilayer platform fabrication. The sacrificial layer is shown in light shade while the bridge material is shown in black. (a) after deposition of first sacrificial layer; (b) after deposition and patterning of first structural material; (c) after selective deposition of second sacrificial layer; (d) after deposition and patterning of second structural material; (e) after removal of sacrificial layer.

Figure 8. Scanning electron micrographs of multilayer surface micromachined platform. (a) Top view; (b) side view; (c) close-up of side view. The upper platform is approximately 400 microns on a side, and is suspended by arms approximately 500 μm long, 40 μm wide, and 12 μm thick. The lower platform is approximately 400 μm long, 70 μm wide, and 12 μm thick, and is integrally attached to the upper platform. The lower platform is approximately 3 μm above the surface, while the upper platform is approximately 15 μm above the surface.

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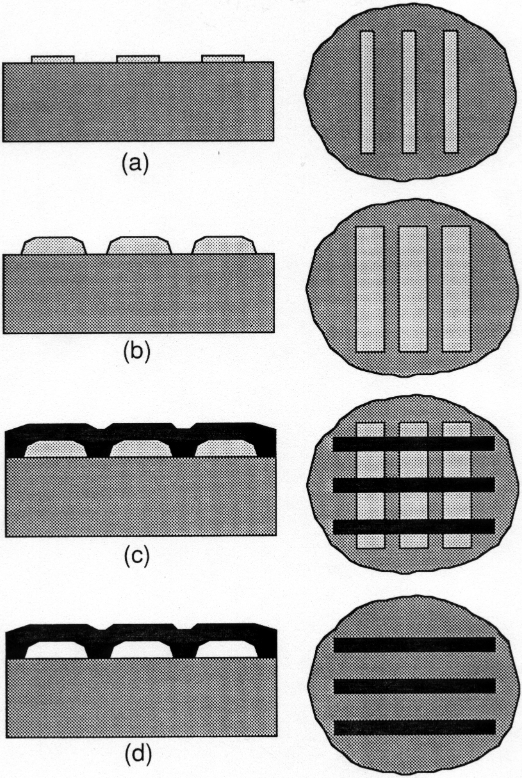

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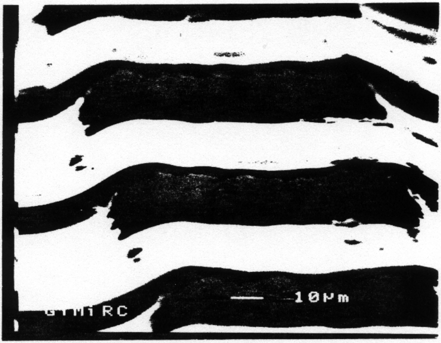

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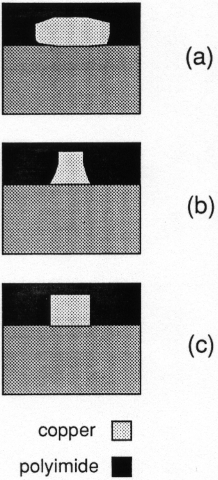
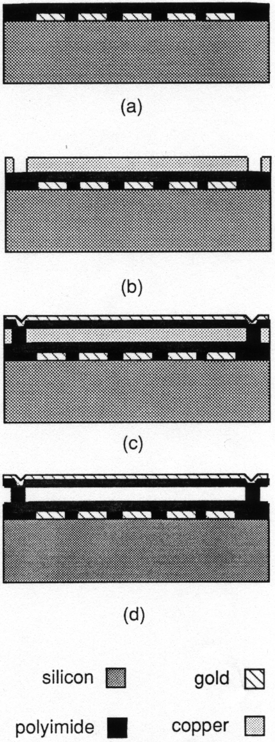


Figure 4. Fabrication sequence of surface micromachined platforms. (a) after deposition of polyimide over patterned electrodes; (b) after electroplating of sacrificial layer; (c) after deposition and patterning of structural polyimide layer; (d) after etch of sacrificial layer.



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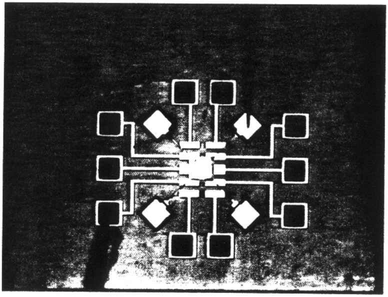

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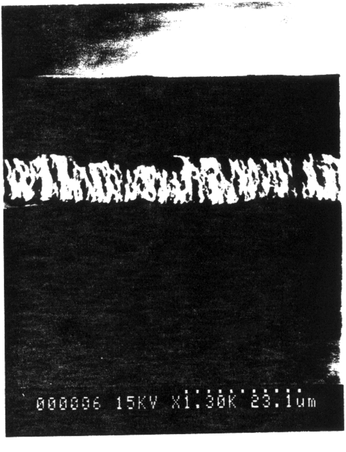
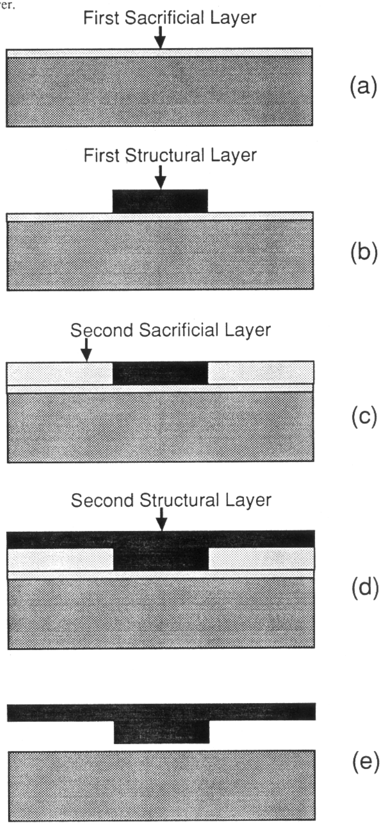


Figure 7. Schematic representation of multilayer platform fabrication. The sacrificial layer is shown in light shade while the bridge material is shown in black. (a) after deposition of first sacrificial layer; (b) after deposition and patterning of first structural material; (c) after selective deposition of second sacrificial layer; (d) after deposition and patterning of second structural material; (e) after removal of sacrificial layer.



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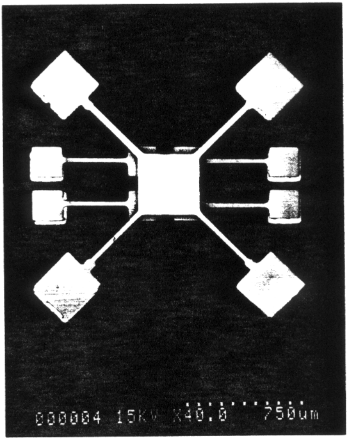
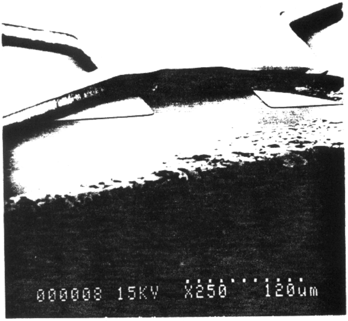


(a)

Figure 8(b)



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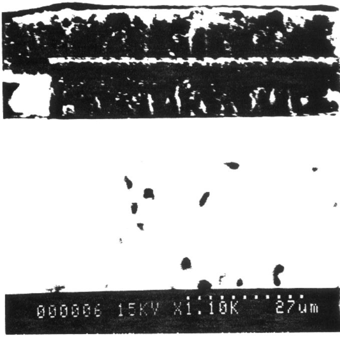

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