SURFACE MICROMACHINED PLATFORMS USING ELECTROPLATED SACRIFICIAL LAYERS

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Abstract

A technique for the surface micromachining of structures suspended many tens of microns above a substrate surface is presented. Electroplated metal sacrificial layers are used in a standard surface micromachining process to achieve the necessary sacrificial layer thickness. The process is demonstrated using copper as the sacrificial layer and polyimide as the structural material. Surface micromachined bridges 8 μm thick, 160 μm long, and 100 μm wide suspended over the surface from 10 to 50 μm have been fabricated in this manner. In addition, movable platforms suspended 15 μm above a surface over an area of 3x3 mm have also been demonstrated.

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.

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.

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. Two surface micromachined structures fabricated using these techniques, a 'bridge' test structure and a movable 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 150 Å 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).

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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/cm2 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 using a ferric chloride etch at room temperature to release the polyimide bridges (Figure 1d). The etch time for full release of the bridges was approximately one hour.

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 of high aspect ratio (Figure 3c) such as in the LIGA [5] or other [6,7] processes, causes the sacrificial layer edge profile to be straight. We have successfully fabricated all three types of bridges.

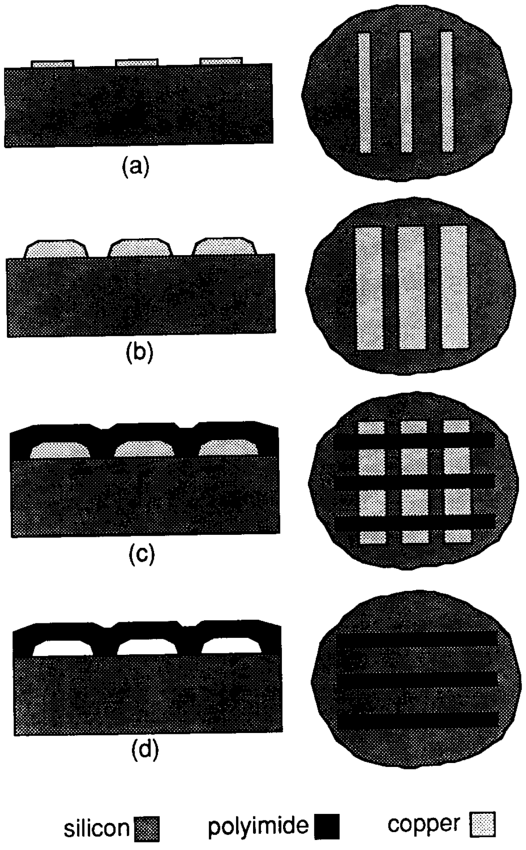

Figure 1. Fabrication sequence for bridge structures. (a) after deposition of electroplating seed layer; (b) after deposition of electroplated sacrificial layer; (c) after patterning of polyimide layer; (d) after etch of sacrificial layer.

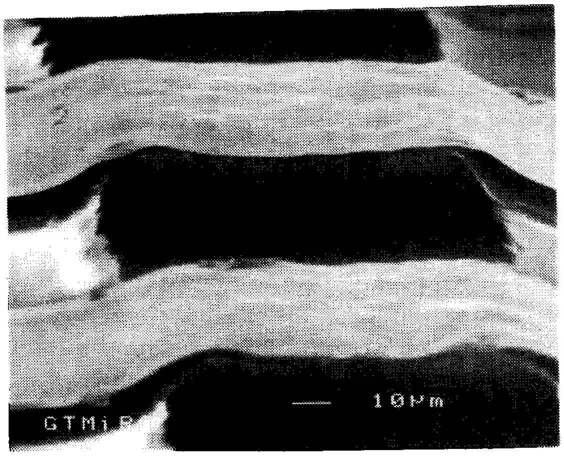

Figure 2. Scanning electron micrograph of gold-covered-polyimide, surface micromachined, bridge structures. The bridges are approximately 100 microns wide, 160 microns long, and 8 microns thick. They are suspended approximately 30 microns above the surface of the substrate.

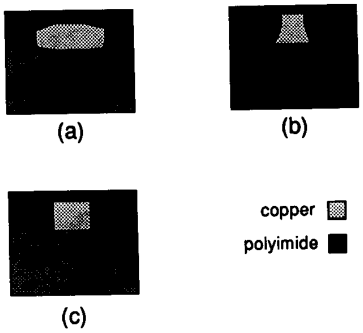

Figure 3. Dependence of bridge profile on etching technique used to define the sacrificial layer. The sacrificial layer is shown in light shade while the bridge material is shown in black. (a) etching of seed layer prior to electroplating, yielding a 'mushrooming' sidewall; (b) etching of sacrificial 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.

Surface Micromachined Platforms

In order to further demonstrate the utility of these structures, a relatively large surface micromachined platform was fabricated using electroplated sacrificial layers. The application of these platforms involves the positioning and motion in all three directions (x,y, and z) of objects supported on the platform for a variety of applications currently under development. Fabrication by using electroplated sacrificial layers allows substantial motion in the z-direction as well as x and y. The plates were designed to allow motions on the order of tens of microns in all three directions.

The platform is a movable square polyimide plate one millimeter on a side, suspended by four diagonally-oriented arms approximately 1.5 mm long. 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 a thermal 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 was 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 was 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 was removed using a ferric chloride etch at room temperature to free the polyimide plates (Figure 4d). The plates typically took approximately 2 hours to be released. 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 3x3 mm without sagging. We have mechanically deflected these plates as much as three hundred microns in the plane of the wafer, and 15 microns normal to the plane of the wafer. Electrostatic positioning of the plates as well as increasing the thickness of the sacrificial layers to achieve more z-directed motion is currently under investigation.

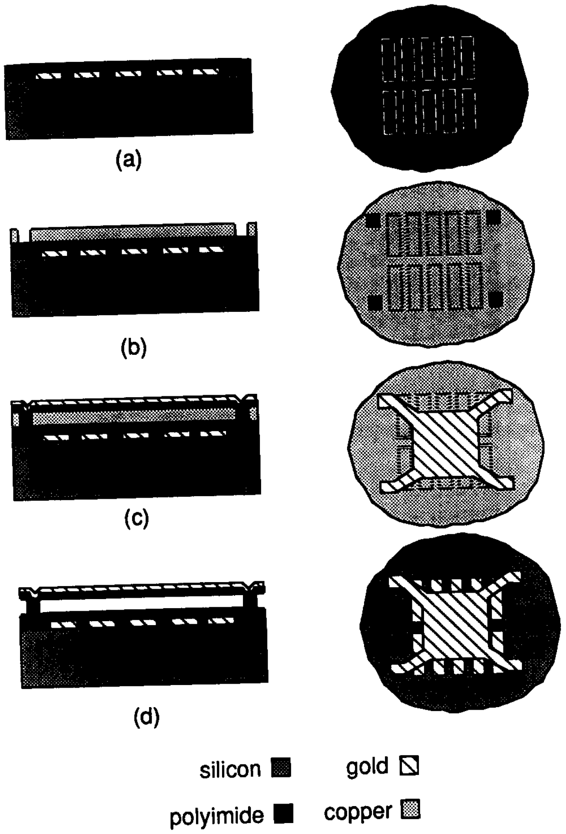

Figure 4. Fabrication sequence of surface micromachined platforms. (a) after deposition of polyimide over patterned electrodes; (b) after electroplating of sacrificial layer; (c) after deposition and patterning of structural polyimide layer; (d) after etch of sacrificial layer.

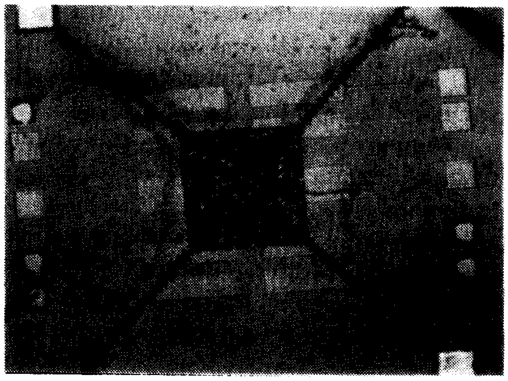

Figure 5. Photomicrograph of fabricated platform. The platform is approximately one millimeter on a side and 7.5 μm thick, and is suspended by arms approximately 1.5 mm long, 25 μm wide, and 7.5 μm thick. The platform is suspended approximately 15 μm above the surface of the substrate.

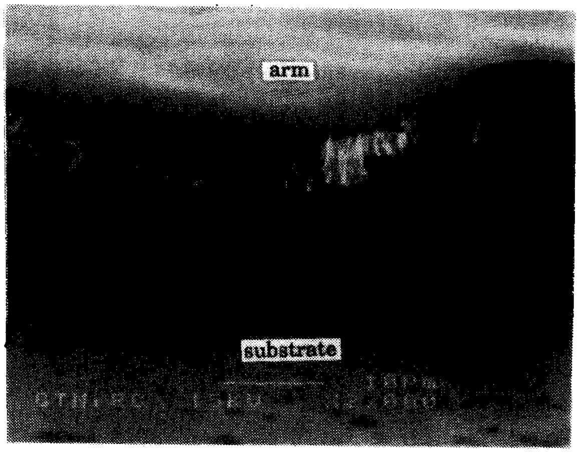

Figure 6. Scanning electron micrograph detailing the separation of a platform support arm above the surface of the wafer. The arm is suspended approximately 15 μm above the surface of the wafer.

Conclusions

The use of electroplated sacrificial layers in surface micromachining allows the fabrication of structures many tens of microns above the surface of a substrate. Two test structures, a series of microbridges and a 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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References

[1] R.T. Howe and R.S. Muller, "Polycrystalline Silicon Micromechanical Beams", J. Electrochem. Soc., vol. 130, p. 1420, 1983.

[2] M.A. Schmidt, R.T. Howe, S.D. Senturia, and J.H. Haritonidis, "Design and Calibration of a Microfabricated Floating Element Shear-Stress Sensor", IEEE Transactions on Electron Devices, vol. 35, no. 6, pp. 750-757, 1988.

[3] L.S. Fan, Y.C. Tai, and R.S. Muller, "IC-processed Electrostatic Micromotors", Proceedings of the 1988 IEEE International Electron Devices Meeting, San Francisco, CA,December 1988, pp. 666-669.

[4] W. C. Tang et. al., "Electrostatic-Comb Drive of Lateral Polysilicon Resonators", Sensors and Actuators, A21-A23, pp. 328-331, 1990.

[5] W. Ehrfeld et al., "Fabrication of Microstructures Using the LIGA Process", Proceedings of the IEEE Microrobots and Teleoperators Workshop, Hyannis, MA, February 1987.

[6] H. Guckel et al., "Deep X-Ray and UV Lithographies for Micromechanics", Proceedings of the IEEE Sensor and Actuator Workshop, Hilton Head, SC, June, 1990, pp.118-122.

[7] B. Frazier, J.W. Babb, and M.G. Allen, "Design and Fabrication of Electroplated Micromotor Structures", Proceedings of the 1991 American Society of Mechanical Engineers Symposium on Microelectromechanical Systems, Atlanta, GA, December, 1991.

[8] R.J. Jensen, J.P. Cummings, and H. Vora, "Copper/Polyimide Materials System for High Performance Packaging", IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol.CHMT-7, no. 4, pp.384-393, 1984.

[9] J.P. Cummings, R.J. Jensen, D.J. Kompelien, and T.J. Moravec, "Technology Base for High Performance Packaging", Proceedings of the Electronic Components Conference, pp. 465-478, 1982.