Uses of Electroplated Aluminum in Micromachining Applications

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Abstract

In this paper, electroplated aluminum is explored as both a material for the fabrication of microstructures and for use in the development of micromachining processes. First, a method for the fabrication of aluminum microstructures is presented. Second, an extension of the basic photosensitive polyimide process is demonstrated for use in the fabrication of high aspect ratio microstructures. Third, electroplated aluminum is used as a sacrificial layer material in the development of a process for creation of controllable small gaps between metallic microstructural components.

Introduction

There are many uses of aluminum for the fabrication of microdevices and for generic micromachining technology. One important application of aluminum microstructures is in the fabrication of integrated circuits. Since aluminum is the predominant material used to define electrical conductors in integrated circuit technology, microstructures such as high aspect ratio current carrying traces and micro heat sinks fabricated from aluminum would be completely compatible with the technology without the problems associated withinter metallic alloys at junctions between dissimilar metals. In addition to the use of aluminum as a material for the fabrication of microstructures, it can also be used as a processing tool to develop fabrication technologies. Two examples of the use of aluminum as a processing tool which are explored in this work include the use of electroplated aluminum as a means of producing high aspect ratio metallic microstructures and for producing controllable small gaps in metallic microdevices.

Metallic microstructures have been under study for micromachining applications for many years. Some of the more prominent applications of metal-based microstructures have been as current conductors in both magnetically [1-6] and electrostatically [7,8] driven devices. In addition, there has been applications for metallic structures with selected mechanical properties [9,10]. Several different fabrication technologies have been developed to address the needs associated with the differing applications. Among the processes that have been developed for fabrication of metallic microstructures are the LIGA process [2,3,5,8-10,11], the photosensitive polyimide process (PSPI) [1,4,7,12-14], UV-based positive and negative photoresist processes [6,15,16], and stenciling [17-19] as well as others [20-23]. Electroplated microstructures of several different elemental metals and metal alloys have been demonstrated including gold, silver, copper, nickel, and nickel alloys. To this point, electroplated aluminum microstructures have not been investigated for use in micromachining technology.

The purpose of this research is to introduce the use of electroplated aluminum as a material for the fabrication of microstructures and micromachining processes. Since the majority of the electrolytic solutions used to electroplate aluminum are based on organic solvents, one of the major problems with implementing this technology is finding a non-compatible molding material for the process. First, the issue of a compatible molding material for the aluminum electroplating process is addressed, and aluminum microstructures are demonstrated. Second, the basic PSPI process is extended to using the aluminum microstructures as electroplated molds for the fabrication of high aspect ratio metallic microstructures from metals other than aluminum Third, electroplated aluminum is used as a sacrificial layer material in the development of a controlled small gap process for metallic microstructures.

Aluminum Microstructures

By utilizing the material properties of aluminum such as the high thermal conductivity, high corrosion resistance, low neutron absorption, electrochemical nobility, stable mechanical properties at cryogenic temperatures, and non-sparking characteristic, many micromachining applications can be envisioned including nuclear applications, and low temperature devices. Historically, the electrodeposition of aluminum has been investigated for use in coating steel strip [24,25], in electrorefining [26], in electroforming [27-30], and in the cladding of uranium [31,32]. Limited commercial applications of aluminum plating have been reported [29, 33]. Aluminum, because it is much more chemically active than hydrogen, probably cannot be electrodeposited from solutions that contain water or any other compound with an acidic hydrogen, for example, acids, alcohols, ammonia, and primary and secondary amines [34]. It can be electrodeposited from inorganic and organic fused salt mixtures and from solutions of aluminum compounds in certain organic solvents. The fused salt baths have proven unsuitable for electroforming because of inherent thermal distortion of the deposit due to residual stresses in the films [28]. Many other fused salt baths were found to yield only thin or mechanically inferior deposits, and were highly flammable, poisonous, and inconveniently moisture-sensitive.[28] For the case of aluminum compounds in organic solvent, the aluminum chloride-lithium aluminum hydride-ethereal solution, originally developed by [35,36], yielded satisfactory, low stress deposits. Low volatility, nonflammable derivatives of the aluminum chloride-lithium aluminum hydride-ethereal bath have been developed by replacing part of the ether with a quaternary ammonium salt such as 2-ethoxyethyl trimethylammonium chloride [24].

Of the several electrodeposition processes that have had some commercial success, only the National Bureau of Standards hydride process has achieved a modest degree of use. Aluminum electroplating has similar commercial applications to conventional electroplated metals such as copper and nickel, but due to the higher cost of the electrolyte (ether vs. water) and the higher initial facility cost (inert atmosphere and safety requirements), it can only compete with conventional processes where the material properties of aluminum are required.

The aluminum electroplating solution composition is shown in Table 1. Additives can be introduced to the basic solution to reduce grain size and treeing, particularly in thicker deposits. Since the bath contains strong reducing agents and is anhydrous, the electroplating must be carried out in an inert atmosphere. In this work, electroplating is carried out in a sealed glove box with dry nitrogen as the ambient gas. To mix the bath, aluminum chloride is slowly added to diethyl ether in order to avoid localized overheating of the solution. The reaction of the aluminum chloride with the ether is exothermic, producing 580 calories per gram of heat. For large scale aluminum electroplating, external cooling is required during mixing of the solution. After the addition of the aluminum chloride, the lithium aluminum hydride is slowly added to prevent excessive gas evolution. As reported in literature [28,29], the bath remains operational with no change in plating quality for baths utilized in excess of four weeks. A typical current density used for electroplating is 10 - 15 mA/cm^2 resulting in an electroplating rate of 0.4 μm/min to 0.8 μm/min.

In the hydride bath, diethyl ether is used as the solvent. For this reason, photoresist electroplating mold processes cannot be utilized for the fabrication of aluminum microstructures. The ether results in swelling and/or decomposition of the polymers used in photoresist systems. In this work, the photosensitive polyimide process (PSPI) is used as a basis to form the electroplated

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Table I. Composition of the aluminum electroplating solution (g / l refers to grams of substituent added per liter of final plating solution). The solvent-based electrolytic solution is based on diethyl ether.

Component		Quantity (g/l)
$AlCl_3$,	Aluminum Chloride	400
$LiAlH_4$,	Lithium Aluminum Hydride	15

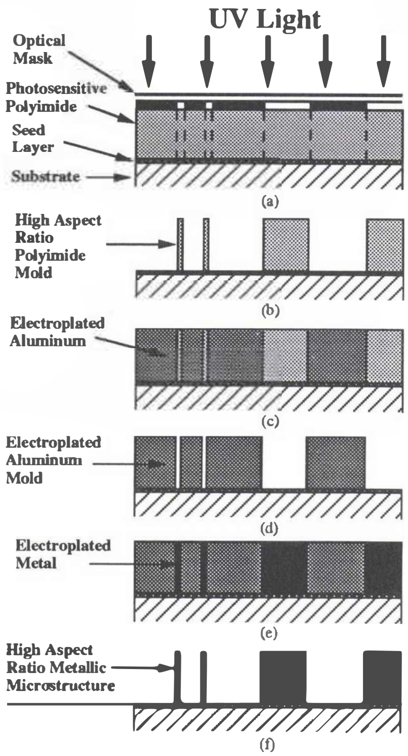

Figure 1. The extended PSPI process for the fabrication of high aspect ratio metallic microstructures. Fabrication steps 1a - 1d are required for the basic PSPI process. Steps 1e - 1f utilize electroplated aluminum as a molding material to form high aspect ratio structures.

aluminum microstructures [14]. The basic PSPI fabrication procedure, is shown in Figure 1a-1d. After the electroplating is complete, the substrate is rinsed in alcohol to remove residues from the plating bath and the polyimide mold is removed as in the basic process.

Various seed layers were investigated as seed layers for aluminum electroplated microstructures. Among the metallic seed layers investigated were gold, copper, nickel, chromium and aluminum. With the exception of chromium, all the seed metals chosen proved to be adequate as electroplating bases if the metals were protected from oxidation and contamination prior to the electrodeposition process. Electroplating using both aluminum and nickel seed layers were exceptionally sensitive to effects of oxidation.

Figure 2 shows an electroplated aluminum gear fabricated using the above process and electroplating bath. The aluminum gear has a thickness of 45 µm, an outer diameter of 300 µm, an inner diameter of 50 µm, and a tooth width of 40 µm. The surface of the microstructure is representative of the grain sizes obtained using the basic aluminum electroplating solution without the addition of additives at a plating rate of 0.4 µm/min.

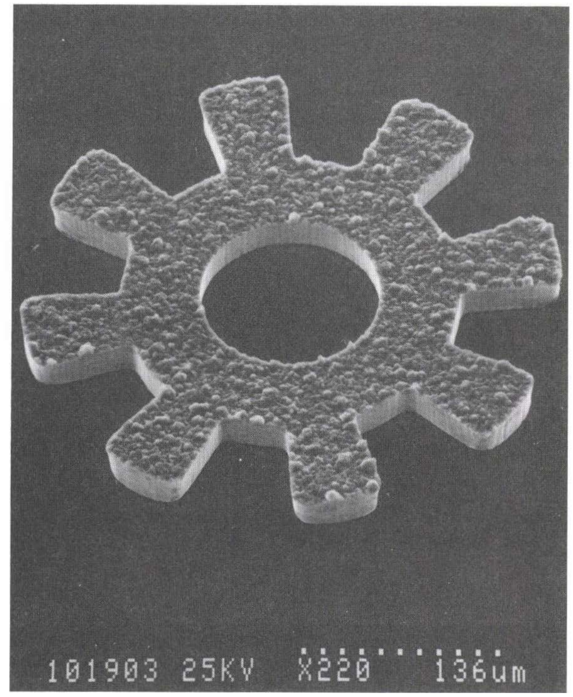

Figure 2. An electroplated aluminum gear with a thickness of 45 µm, an inner / outer diameter of 50 µm / 300 µm, and a tooth width of 40 µm.

High Aspect Ratio Microstructures Using Electroplated Aluminum Molds

High aspect ratio metallic microstructures have been a subject of interest for many years. As mentioned above, several processes have been demonstrated for the fabrication of high aspect ratio metallic microstructures. Of these techniques, electroplating of metals through polymer micromolds is the primary method of forming the structures. Using micromolding technologies, maximum aspects ratios of beam structures have been limited to approximately 4:1 (height:width) by non x-ray based technologies.

In this section, metallic microstructures with aspect ratios as large as 20:1 are demonstrated using an extension of the basic PSPI process [14]. This process differs from other available techniques in that electroplated aluminum micromolds have been used to form the metallic microstructures instead of polymer molding materials. The necessary extension of the PSPI process is shown in Figure 1d-1e. The process could be referred to as an inversion process in which the final metallic microstructures are of the same dimensions as the polyimide used as the initial molding material in the process. High aspect ratio microstructures have been achieved by utilizing the inversion characteristic of the process and the fact that high aspect ratio polyimide microstructures are simpler to fabricate than high aspect ratio trenches using the PSPI process. To outline the extended PSPI process, fabrication began with the basic process using photosensitive polyimide as the molding material through which aluminum was electroplated. For this study, the electroplating metal system consisted of a 300 Å titanium adhesion layer between the silicon (or ceramic) substrate and the electroplating seed layer, 1000 Å of either gold or copper as the electroplating seed layer, and an overlying layer of 1000 Å chromium to protect the electroplating seed layer during processes leading up to the electroplating step. The polyimide material used in the molding process was spun on at the desired thickness and photolithographically defined into the pattern required for the final metallic microstructure. After the aluminum has been electroplated to the top of the polyimide molds, the polyimide is removed leaving free standing aluminum microstructures (or micromolds in this case). The polyimide can be removed by several standard techniques. After removal of the polyimide, the chromium protective layer of the metal system is removed using reactive ion etching with a gas mixture consisting of 25 sccm O_2 and 25 sccm CHF_3 at a pressure of 50 mtorr and 300 watts of power (approximate etch rate: 55 Å/min). At this point in the process, the seed layer is exposed in the regions initially covered by polyimide in the basic PSPI process and the electroplated aluminum can be used as a mold for further electrodeposition of other metals including copper and nickel.

Figure 3 demonstrates the use of electroplated aluminum molds for the deposition of formed copper structures. For the case shown, the aluminum gear is formed initially using the process described in the previous section, followed by the deposition of copper in the pin and field area. The aluminum gear is approximately 60 µm in thickness with a tooth width of 40 µm, an outer diameter of 300 µm, and an inner diameter of 50 µm.

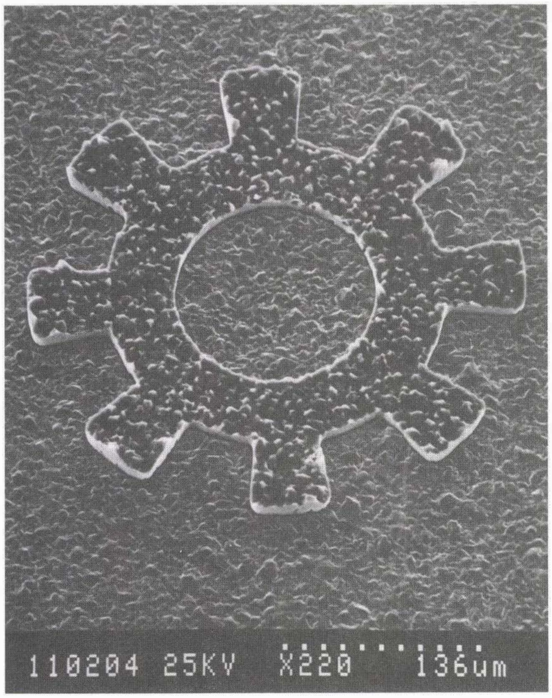

Figure 3. Electroplated aluminum gear with a thickness of 45 µm serving as a mold for the electrodeposition of copper in the field.

The use of this extended process for the realization of high aspect ratio metallic microstructures is shown in Figure 4. In this case, beams of electroplated copper are formed using aluminum molds. The beams are 42 µm in height and have a width of 2 µm for an aspect ratio of 21:1. Figure 5 is a close-up of a copper beam showing the smooth sidewall of the microstructure.

Other advantages of this process include the ability to fabricate metallic bimorphs for high current carrying applications, as well as using the electroplated aluminum as a thick sacrificial release layer for surface micromachining applications.

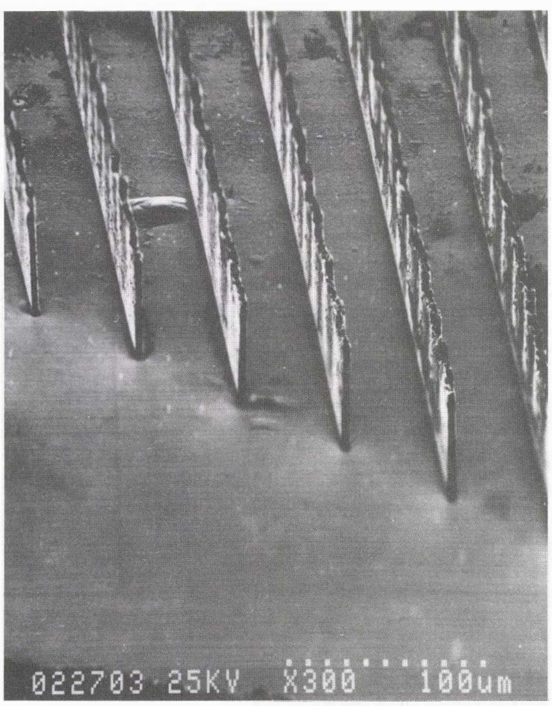

Figure 4. An array of high aspect ratio copper beams fabricated using the extended PSPI process. The beams have a height of 42 µm and a width of 2 µm for an aspect ratio of 21:1.

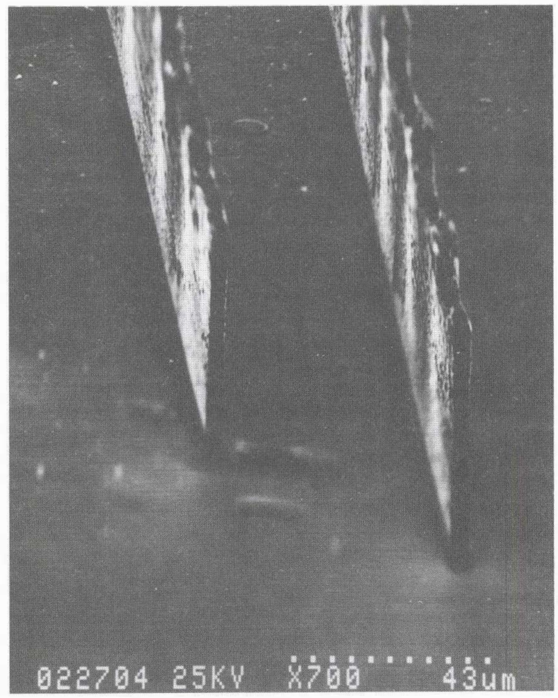

Figure 5. Close-up of the copper beam revealing the smooth sidewalls obtained with the process.

Small Gap Process for Metallic Microstructures

In addition to using aluminum as a processing tool for the fabrication of high aspect ratio metallic microstructures, it can also be used as a sacrificial layer in the development of a controllable small gap process for metallic microstructures. Development of a silicon based process for obtaining small gaps has already been reported [37]. In this process, metallic microstructures (other than aluminum) are fabricated using the basic PSPI process. The free standing microstructures are then conformally electroplated with aluminum, thus covering the entire microstructure with a thin layer of aluminum. The thickness of the aluminum "shell" is controlled by the electroplating current density and time duration of the electroplating cycle. The aluminum plating is followed by a second electroplating cycle in which a metal other than aluminum is deposited in the regions surrounding the existing structure. The second electroplating step uses the original seed layer as an electroplating base, and as in the case of the process for the fabrication of high aspect ratio microstructures, the metal deposited during the second cycle does not plate onto the aluminum encompassing the initial microstructure. The second metal is deposited to the desired height with respect to the initial microstructure.

Figure 6 demonstrated the use of aluminum in the controllable gap process. In this figure, the initial microstructures of copper with the thin film of electroplated aluminum are shown on either side of the metal (copper) deposited second. In the next step the

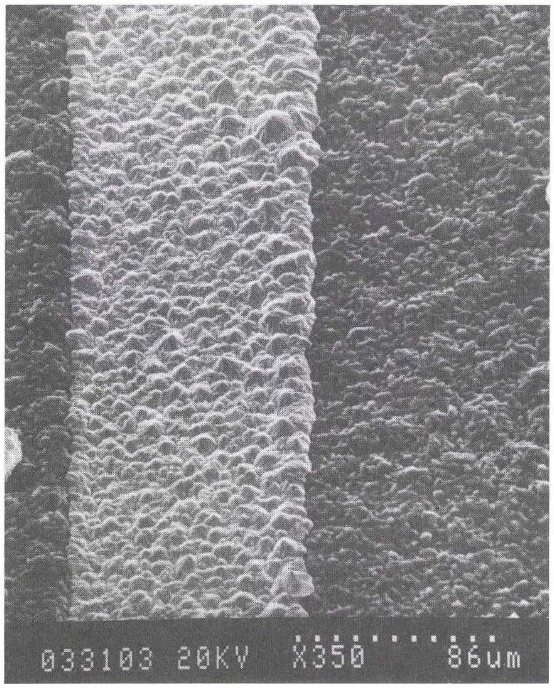

Figure 6. Demonstration of the use of electroplated aluminum as a sacrificial layer material for producing controllable small gaps between metallic microstructures.

aluminum is removed using a 1 vol% HF solution, leaving a small gap between the copper microstructures. Figure 7 shows a gap of 2 µm between copper structures which are 60 µm and 55 µm in height for a gap aspect ratio of 27.5:1. Figure 8 shows a cross section of the gap and the sidewalls obtained using this process. In Figure 8, the microstructures are 55 µm in height and the gap is 5 µm.

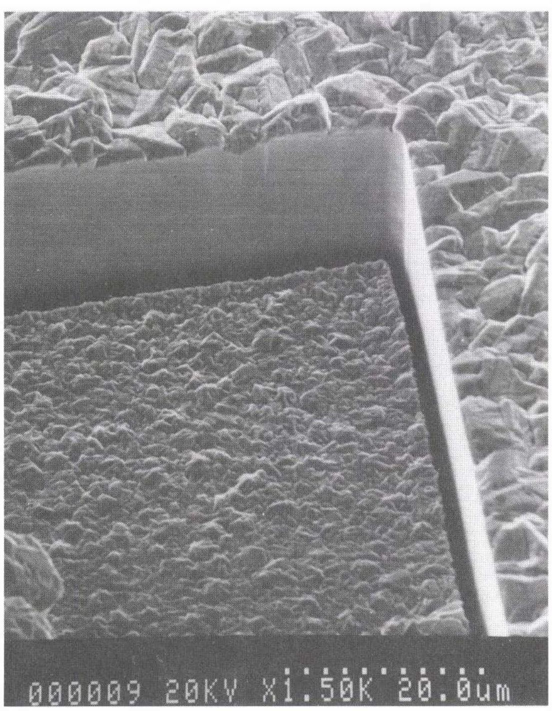

Figure 7. A high aspect ratio gap produced using the small gap process. The gap is 2 µm and the structural heights are 60 and 55 µm.

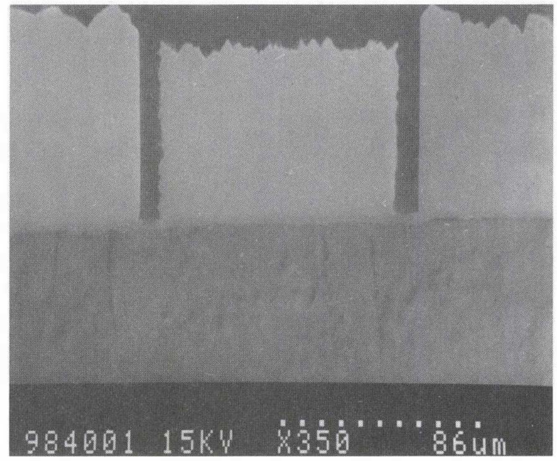

Figure 8. A cross section of two copper microstructures to study the sidewall characteristics of the process. The microstructures are 55 µm in height and the gap is 5 µm.

Conclusion

Electroplated aluminum has been demonstrated to be of use in both the realization of microstructures and as a processing tool for micromachining processes. Electroplated aluminum microstructures have been demonstrated using a slightly modified version of the PSPI process. The use of aluminum as a processing tool for the fabrication of high aspect ratio metallic microstructures was demonstrated. Also, electroplated aluminum has been used as a sacrificial layer in the development of a fabrication technique for obtaining controllable small gaps between metallic microstructural components.

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