Uses of Electroplated Aluminum for the Development of Microstructures and Micromachining Processes

A. Bruno Frazier, *Member, IEEE,* and Mark G. Allen, *Member, IEEE*

***Abstract*— In this paper, electroplated aluminum is explored as both a material for the fabrication of microstructures and use in the development of micromachining processes. A method for the fabrication of aluminum microstructures based on electrodeposition from organic solutions is presented. An extension of this process involving the use of plated aluminum structures as plating molds for subsequent electrodeposition of other materials is also discussed. Maximum structure aspect ratios of 21 : 1 have been demonstrated using this extended micromolding process. Finally, an aluminum-based process, in which the width of a metallic microstructure or the gap between metallic microstructures is achieved by controlling the plating time, is discussed. Using this process, vertical-gap aspect ratios between metallic microstructures of 25 : 1 have been demonstrated. Since the width of these features is controlled by the plating time and not by photolithography, gaps between metallic microstructures or widths of electroplated features ranging from submicron to tens of microns can be easily achieved using this process. [150]**

***Index Terms*—Aluminum, electroplating, micromolding.**

I. INTRODUCTION

MICROMACHINED devices are fabricated from a wide variety of materials. Some of the most common materials include, but are not limited to, single-crystal and polycrystalline silicon, silicon-based compounds, various electroplated and physical vapor deposited metals, as well as polymer materials. Each of these general classes of materials has specific electrical and mechanical properties that make them an attractive choice(s) for a given application. Fabrication of devices having aspect ratios (defined as height : width of the structure) and structural heights greater than achievable using standard microelectronics processes are needed for many applications. An example is high-torque electrostatic micromotors, in which case the torque generated depends on the aspect ratio of the gap between the rotor and stator electrodes. Another example is gas- and fluid-driven microturbines, where both the flow and output power depend on the size of the turbine rotor. Other examples where high-aspect ratios and large structural heights are advantageous include mechanical structures [1], [2] requiring stiffness out-of-plane of the substrate, gears/gear assemblies, high-flux magnetic microdevices, and interdigitated electrode structures driven electrostatically. Metallic microstructures are of interest for many of these applications. In addition to electrostatic [3], [4] and magnetic applications [5]–[10], metallic microstructures are of interest in dynamic micromachined systems, where system components are continually in contact with one another or some external material. In these cases, wear-resistant metals such as nickel can be utilized as structural elements or as surface finishes for structural elements so that the lifetime of the finished micromachined device is maximized.

Thick metallic microstructures have been under study for micromachining applications for many years. 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 is the LIGA (in German: Lithographie, Galvanoformung, Abformung, or in English: lithography, galvanoforming, and molding) process [1], [2], [4], [6], [7], [9], [11], the photosensitive polyimide process (PSPI) [3], [5], [8], [12]–[14], ultraviolet (UV)-based positive and negative photoresist processes [10], [15], [16], 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.

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 microheat sinks fabricated from aluminum would be completely compatible with the technology without the problems associated with intermetallic 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 that are explored in this work include the use of electroplated aluminum as a means of producing high-aspect-ratio metallic microstructures

---

Manuscript received April 5, 1995; revised February 2, 1996. Subject Editor, J. B. Warren. This work was supported in part by the National Science Foundation of the United States under Grant ECS-9117074 and by a grant from the Ford Motor Company.

A. B. Frazier is with the School of Electrical Engineering, University of Utah, Salt Lake City, UT 84112 USA.

M. G. Allen is with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250 USA.

Publisher Item Identifier S 1057-7157(97)04159-0.

and controllable small gaps (or, correspondingly, controllable small widths) in metallic microdevices.

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 compatible molding material for the process. First, the issue of selecting 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/width process for metallic microstructures.

II. ALUMINUM MICROSTRUCTURES

By utilizing the material properties of aluminum, such as high-thermal conductivity, high-corrosion resistance, low-neutron absorption, stable mechanical properties at cryogenic temperatures, and nonsparking 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], electrorefining [26], electroforming [27]–[30], and 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 the organic solvent, the aluminum chloride-lithium aluminum hydride-ethereal solution, originally developed by Couch and Brenner [35] and Connor and Brenner [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]. Several other recent studies have been performed on room-temperature high-purity aluminum electroplating baths [37]–[39].

Of the several electrodeposition processes having 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 versus 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 I. Additives can be introduced to the basic solution to reduce grain size and dendritic growth, particularly in thicker deposits [24], [28].

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

Electrolytic Solution Components	Quantity (grams/liter of solution)
Aluminum Chloride, AlCl3	400 g/l
Lithium Aluminum Hydride, LiAlH4	15 g/l

Due to the nature of the bath, safety issues during electroplating are of primary concern. 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. Great care must be taken when mixing both the electrolytic solution and using the electrolytic solution due to the nature of the constituents. Since the electrolytic solution is ether based, it must be kept away from sources of ignition (e.g., flames and sparks). One common source of sparking is the anode/cathode connection to the source material/substrate, respectively. One way to minimize the possibility of sparking from the electrode(s) connections is to insure complete connection before turning on the power supply to the electrolytic cell. In addition, lithium aluminum hydride is a strong reducing agent. In the presence of water, the salt is reduced and accompanied by release of hydrogen gas. Therefore, the process begins with mixing of the electrolytic solution in the nitrogen-filled glove box. 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 cal per gram of heat. Cooling is recommended during mixing to minimize evaporation and to permit more rapid addition of $AlCl_3$ [34]. After the addition of the aluminum chloride, the lithium aluminum hydride $(LiAlH_4)$ is slowly added using good mixing. The first additions will produce considerable effervescence as the hydride reacts with traces of moisture from the diethyl ether and the HCl from the $AlCl_3$ in solution. Due to the addition of the LiAlH4, a precipitate of hydride-reduced impurities will be formed. The amount of precipitate is a function of the purity of the diethyl ether and the AlCl3. Pressure filtration is commonly recommended to remove the precipitate. As reported in the 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 0.8–1.2 μm/min. The resistivity of the electrolytic solution was 100-ohm cm. The electrolytic solution described in Table I has been operated from 15 °C to 60 °C. At lower temperatures, discontinuous deposits were observed with poor adhesion to the seed material. At higher temperatures, solution evaporation was a problem for structures requiring extended plating periods. For the experiments described in this work, the electroplating was carried out at room temperature with no external control of the electrolytic cell temperature. The temperature was allowed to stabilize after mixing and before the electroplating process. The effect of variations in the current density on the deposition rate and the material characteristics are comparable with those observed for nickel sulfate and copper sulfate electrolytic solutions (i.e., increased current density results in decreased grain size and increased deposition rate). The mechanical properties of the electrodeposited aluminum film are similar to those found in annealed commercially pure aluminum [34]. The residual stress in the electrodeposited aluminum films of similar thicknesses have been reported to be 80 lbf/in^2 tensile [24].

In order to realize micromolded electroplated aluminum microstructures, the forming material must have all the desirable properties associated with conventional electroforming materials (e.g., high-definition high-aspect-ratio molds, simple application, and removal processes) as well as have properties desirable for nonconventional electroplating processes (e.g., ability to withstand solvent-based electrolytic solutions and chemical resistance to preprocesses required for electroplating). For these reasons, standard 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 many photoresist systems. In contrast, polyimide materials are shown to have the properties necessary to withstand aluminum electroplating conditions. The micromolding processes used to create the aluminum microstructures use both photosensitive and nonphotosensitive polyimides [40]. The photosensitive materials are photo-crosslinked upon exposure, and the nonphotosensitive materials possess desirable characteristics such as high molecular weight and insolubility in ether. The nonphotosensitive polyimide process involves the use of plasma or reactive ion etching to produce molds with customized sidewall profiles. This process is covered in detail in [40]. For the case of the photosensitive polyimide, PSPI is used. The PSPI has many advantages, including chemical and thermal stability, the ability to electroplate a variety of metals or a combination of metals through the molds, microfabrication using common cleanroom equipment and materials, the ability to use the process as a postprocessing step to integrated circuit fabrication, as well as supplying an inexpensive technique for the realization of metallic microstructures. The basic process for fabrication of electroplated microstructures using photosensitive polyimide is analogous to the LIGA process, except that the photosensitive polyimide is used as the electroplating mask instead of polymethylmethacrylate (PMMA), and an ultraviolet exposure source is used instead of an X-ray synchrotron. Fig. 1 shows a schematic of the basic process. An electroplating metal system consisting of an adhesion layer, seed layer, and protective layer is deposited on a planar substrate. After the metal system is deposited on the substrate, an antireflective coating is spun on using a standard vacuum spinning station. Next, the photosensitive polyimide is spun on top of the antireflective coating. The photosensitive polyimide is then soft-baked in a conventional oven and imaged into the desired pattern using a standard microelectronic alignment and exposure station. The polyimide is developed and rinsed in solvent-based solutions to create the patterned molds in the thick polyimide films. After the polyimide molds are created, the antireflective coating is removed in oxygen plasma. Next, the protective metal layer overlying the electroplating seed layer is removed (chromium typically etched using HCl : H_2O 1 : 1 solution). At this point, two additional steps are required to prepare the seed-layer surface for aluminum electroplating. First, the sample must be rinsed in isopropyl alcohol or methanol to remove residual water vapor from the surface. Second, the sample is dipped in a solution of salicylic acid (100 g/L of solution) in ether. This solution prepares the surface of the metal seed layer for electrodeposition (e.g., removes residual metal oxides). The sample is immediately transferred to the electrolytic cell after removal from the salicylic acid solution. Electroplated aluminum is deposited to the surface of the mold. After completion of the electroplating process, the substrate is rinsed in alcohol to remove residues from the plating bath. At this point, the polyimide mold can be optionally removed using several methods. The most common techniques are wet etching of the polyimide using strippers provided by the manufacturer of the polyimide materials [41] or dry etching in oxygen-based plasmas.

Various metals 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 was exceptionally sensitive to effects of oxidation.

Fig. 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. The aluminum gear is still attached to the substrate via the electroplating seed layer. It is also possible to use standard sacrificial layer technology to remove the final aluminum microstructures. For example, this can be accomplished by using a polyimide sacrificial layer under the electroplating seed layer.

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 using the electroplated aluminum as a processing tool are explored

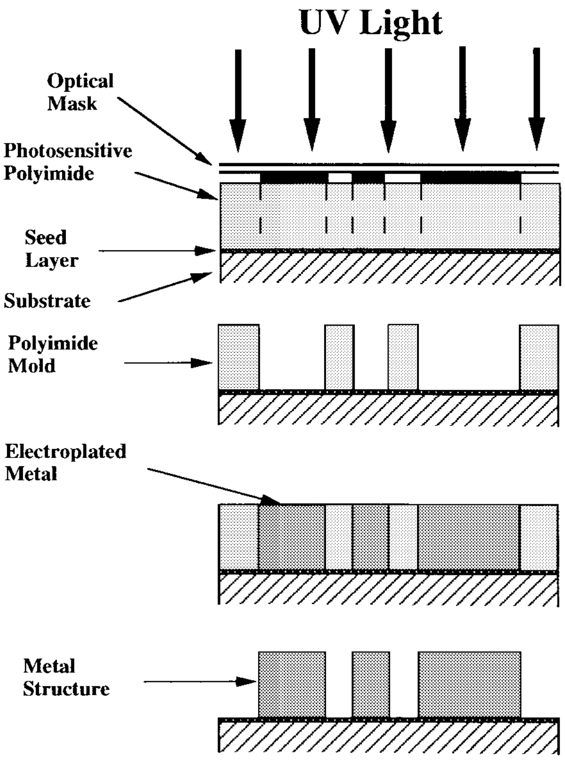

Fig. 1. The photosensitive polyimide process for the fabrication of high-aspect-ratio and/or thick metallic microstructures.

Fig. 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.

in this work. These include the use of electroplated aluminum as a molding material for producing high-aspect-ratio metallic microstructures and the use of electroplated aluminum for producing controllable small gaps in metallic microdevices.

III. 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. 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. Fig. 3 outlines the process used to create the high-aspect-ratio metallic microstructures. 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 (and similar negative-tone resist) processes. 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 given above. After removal of the polyimide, the seed-layer system is exposed in the regions initially covered by polyimide in the basic PSPI process. The overlying 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 W 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 gold.

Fig. 4 demonstrates the use of electroplated aluminum molds for the deposition of formed copper structures. For the

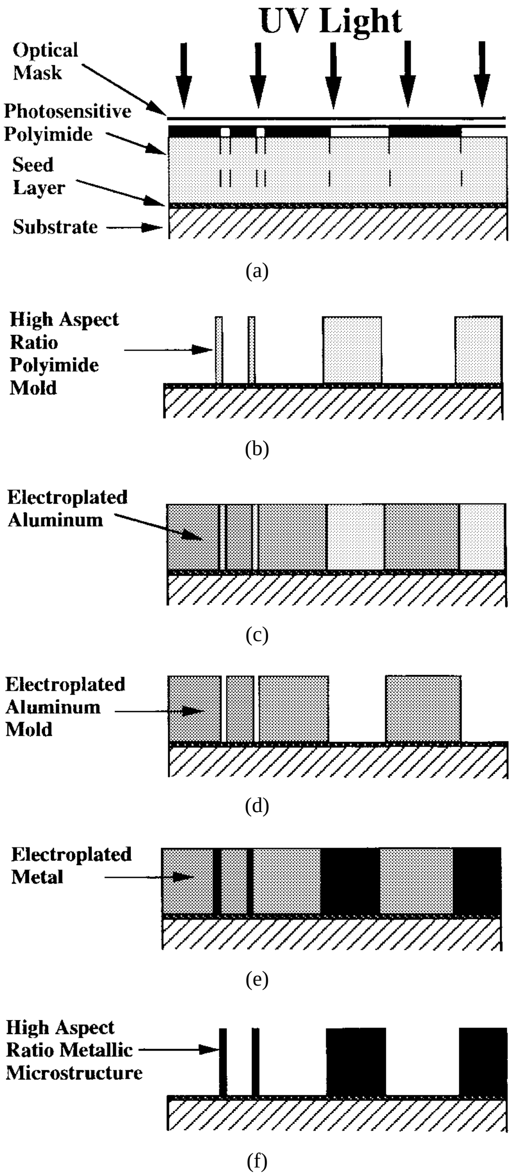

Fig. 3. The extended PSPI process for the fabrication of high-aspect-ratio metallic microstructures. Fabrication steps (a)–(d) are required for the basic PSPI process. Steps (e) and (f) utilize electroplated aluminum as a molding material to form high-aspect-ratio structures.

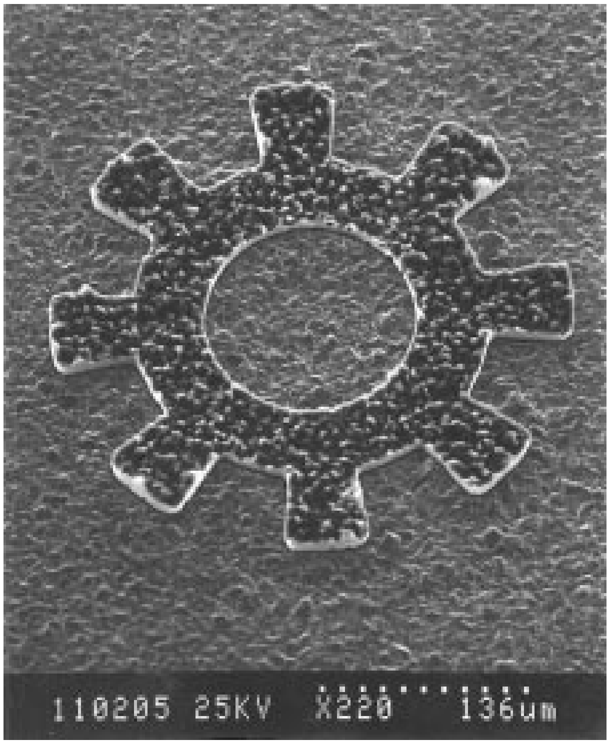

Fig. 4. Electroplated aluminum gear with a thickness of 45 μm serving as a mold for the electrodeposition of copper in the field.

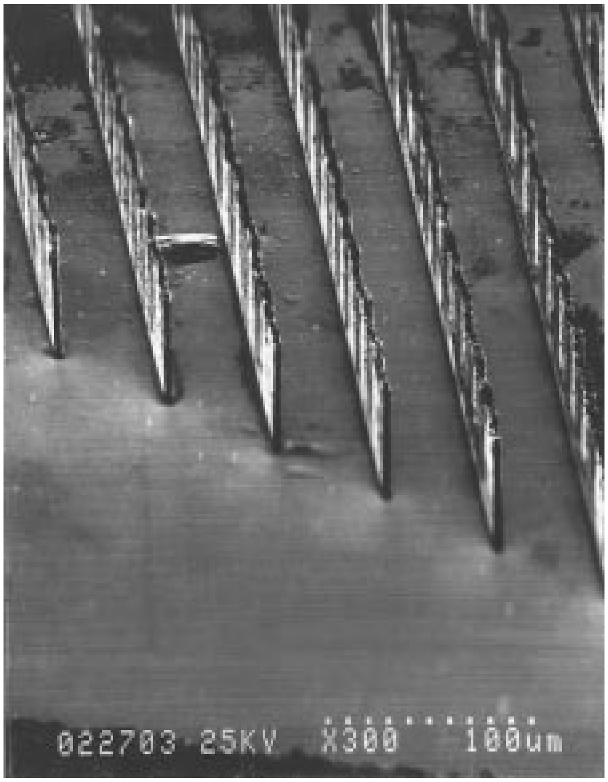

Fig. 5. An array of high-aspect-ratio copper beams fabricated using the extended PSPI process. The beams have a height of 42 μm and a width of 2 μm for an aspect ratio of 21 : 1.

case shown, the aluminum gear is formed 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. The electroplated copper formed in the field area by the aluminum gear is approximately 57 μm in thickness.

The use of this extended process for the realization of high-aspect-ratio metallic microstructures is shown in Fig. 5. In this case, beams of electroplated copper are formed using electroplated aluminum molds. The beams are 42 μm in height and have a width of 2 μm for an aspect ratio of 21 : 1. As can be seen from Fig. 5, the side walls of the microstructures remain smooth and act as a transfer of the side walls of the original polyimide micromolding material.

Other advantages of the extended 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.

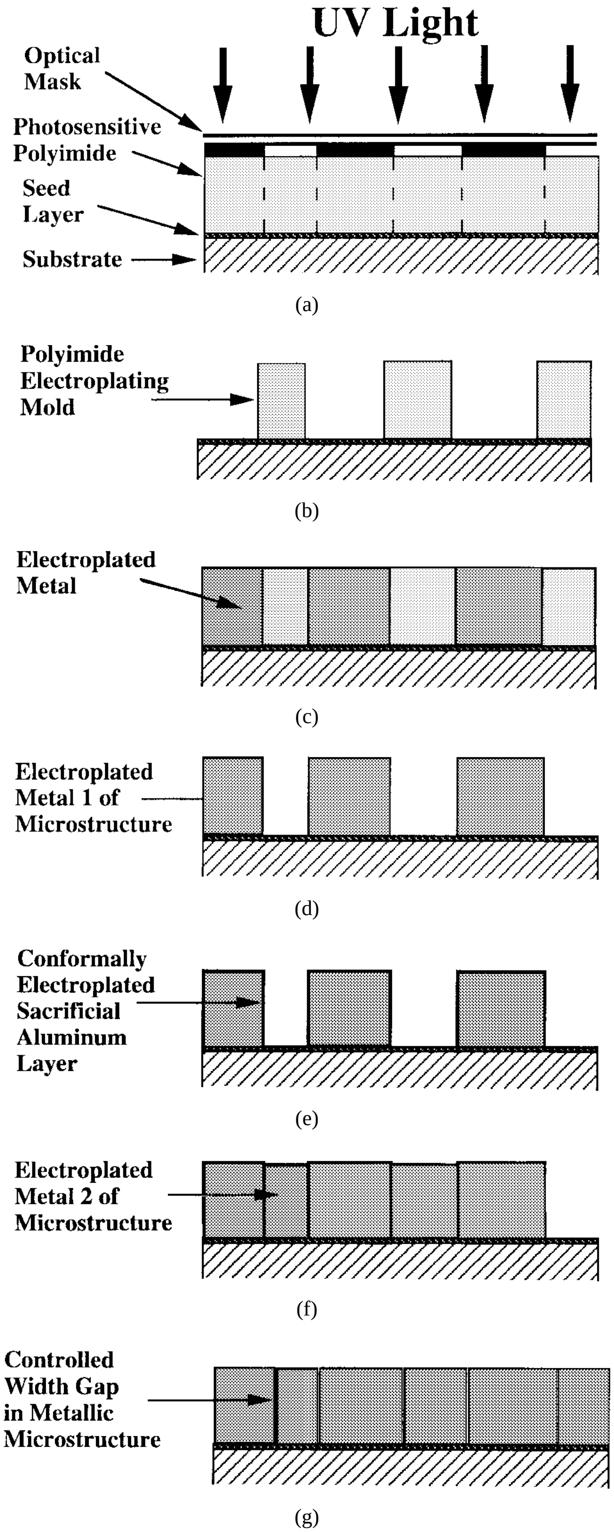

Fig. 6. The process developed for the realization of controlled gaps between metallic microsystem components. Gaps of $<1\,\mu$m to $>10\,\mu$m can be realized with submicron precision. The process can be extended to create metallic shell structures for packaging applications.

IV. SMALL-GAP/WIDTH PROCESS FOR METALLIC MICROSTRUCTURES

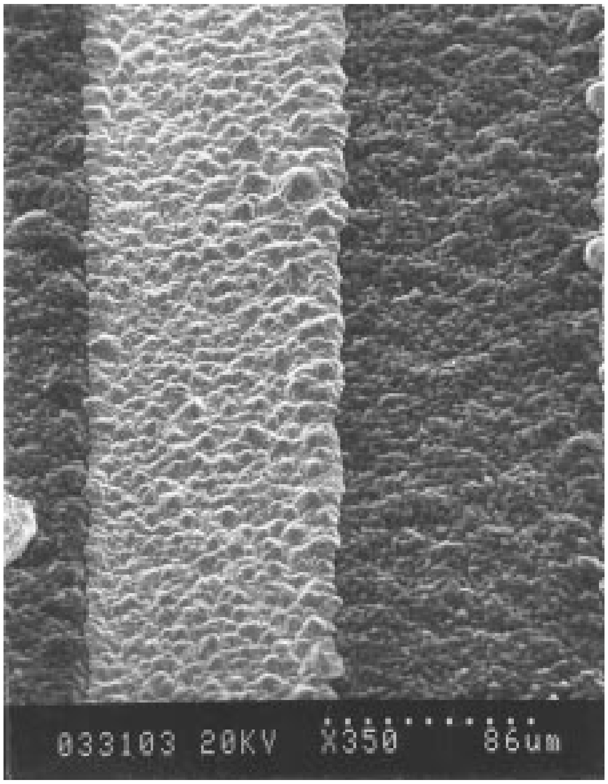

Fig. 7. Demonstration of the use of electroplated aluminum as a sacrificial layer material for producing controllable small gaps between metallic microstructures.

In addition to using aluminum as a processing tool for the fabrication of high-aspect-ratio metallic microstructures, it can be used as a processing tool for the fabrication of controlled thickness gaps between, or controlled widths of, metallic microstructures. In the controlled width process, electroplated aluminum is deposited on the side walls of previously defined metallic structures, which are subsequently selectively removed to yield aluminum structures the width of which is defined by the plating time of the aluminum. Alternatively, the electroplated aluminum can be deposited in the same fashion (i.e., width controlled by plating time by plating on side walls) and used as a sacrificial layer between microstructures of metal other than aluminum. The end result is the development of a controllable small-gap process for metallic microstructures, shown in Fig. 6. This method is analogous to a previously reported silicon-based process for obtaining small gaps [42].

The utility of this approach is illustrated through the small-gap process. In this process, metallic microstructures (other than aluminum) are fabricated using the basic PSPI or other polymer mold processes. 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

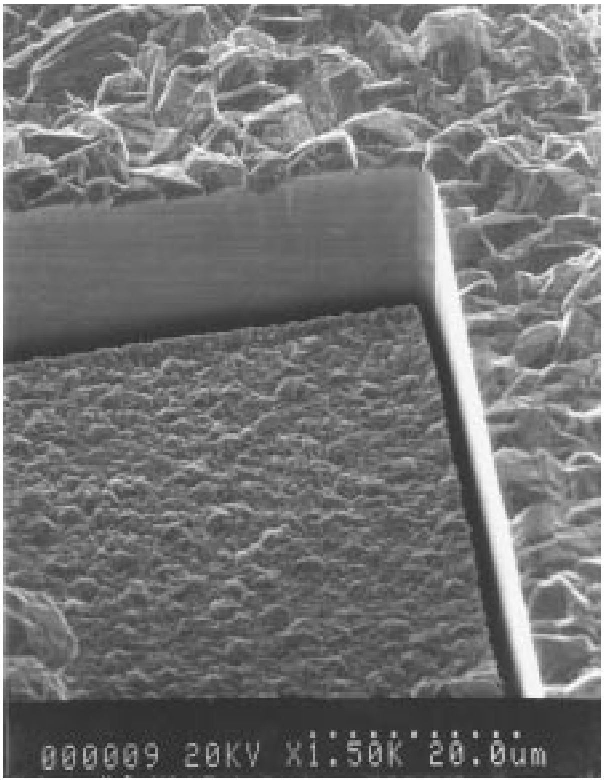

Fig. 8. A high-aspect-ratio gap produced using the small-gap process. The gap is 2 μm, and the structural heights are 60 and 55 μm.

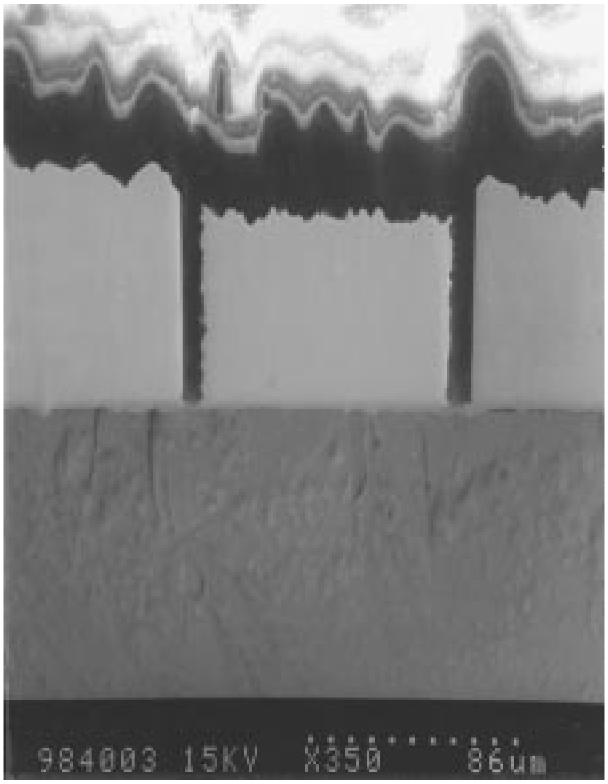

Fig. 9. A cross section of two copper microstructures to study the side-wall characteristics of the process. The microstructures are 55 μm in height, and the gap is 5 μm.

the initial microstructure. Selective removal of the aluminum results in a narrow gap between the other microstructures, the width of which is defined by the aluminum deposition time.

Fig. 7 demonstrates the use of aluminum in the controllable gap process. In this figure, the initial microstructure of copper with the thin shell of electroplated aluminum (center of micrograph) is shown. On either side of the initial structure is the secondary metallic structure (copper) deposited after the aluminum sacrifical shell layer. In the next step, the aluminum is removed using a 1 vol% HF solution, leaving a small gap between the copper microstructures. Fig. 8 shows a gap of 2 μm between copper structures that are 60 and 55 μm in height for a gap aspect ratio of 27.5 : 1, illustrating that both narrow gaps and multilayer structures can be achieved. Fig. 9 shows a cross section of the gap and the side walls obtained using this process. In Fig. 9, the microstructures are 55 μm in height, and the gap is 5 μm.

V. 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 in the development of a fabrication technique for obtaining metallic shells and controllable small gaps between metallic microstructural components.

ACKNOWLEDGMENT

Donation of the materials used in this work by OCG Microelectronic Materials, DuPont Electronics, Olin Hunt Microelectronics, and Brewer Science are gratefully acknowledged by the authors.

REFERENCES

[1] R. Rapp, P. Bley, W. Menz, and W. K. Schomburg, "Micropump fabricated with the LIGA process," in *1993 IEEE Micro Electro Mechanical Systems Conf.*, Fort Lauderdale, FL, Feb. 7–10, p. 123.
[2] A. B. Frazier, D. P. O'Brien, and M. G. Allen, "Two dimensional metallic microelectrode arrays for extracellular stimulation and recording of neurons," in *1993 IEEE Micro Electro Mechanical Systems Conf.*, Fort Lauderdale, FL, Feb. 7–10, p. 195–200.
[3] A. B. Frazier, J. W. Babb, M. G. Allen, and D. G. Taylor, "Design and fabrication of electroplated micromotor structures," in *Proc. ASME Winter Annu. Meet.*, Atlanta, GA, Dec., pp. DSC135–DSC146.
[4] U. Wallrabe, P. Bley, B. Krevet, W. Menz, and J. Mohr, "Theoretical and experimental results of an electrostatic micro motor with large gear ratio fabricated by the LIGA process," in *1992 IEEE Micro Electro Mechanical Systems Conf.*, Travemunde, Germany, Feb. 4–7, pp. 139–140.
[5] C. H. Ahn, Y. J. Kim, and M. G. Allen, "A planar variable reluctance magnetic micromotor with integrated stator and wrapped coils," in *1993 IEEE Micro Electro Mechanical Systems Conf.*, Fort Lauderdale, FL, Feb. 7–10, pp. 1–6.
[6] H. Guckel, T. R. Christenson, K. J. Scrobis, T. S. Jung, J. Klein, K. V. Hartojo, and L. Widjaja, "A first functional current excited planar rotational magnetic micromotor," in *1993 IEEE Micro Electro Mechanical Systems Conf.*, Fort Lauderdale, FL, Feb. 7–10, pp. 7–11.
[7] H. Guckel, J. Klein, T. Christenson, K. Skrobis, M. Laudon, and E. G. Lovell, "Thermo-magnetic metal flexure actuators," in *1992 IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, June 22–25, pp. 73–75.

[8] C. H. Ahn, Y. J. Kim, and M. G. Allen, "A fully integrated micromachined toroidal inductor with a nickel-iron magnetic core (the switched dc/dc boost converter application," in *7th Int. Conf. Solid-State Sensors and Actuators*, Yokohama, Japan, June 7–10, 1993, pp. 70–75.

[9] H. Guckel, T. R. Christenson, K. J. Skrobis, and J. Klein, "Design and testing of planar magnetic micromotors fabricated by deep x-ray lithography and electroplating," in *7th Int. Conf. Solid-State Sensors and Actuators*, Yokohama, Japan, June 7–10, 1993, pp. 76–79.

[10] T. Hirano and T. Furuhata, "Dry released nickel micromotors and their friction characteristics," in *7th Int. Conf. Solid-State Sensors and Actuators*, Yokohama, Japan, June 7–10, 1993, pp. 80–83.

[11] M. Harmening, W. Bacher, P. Bley, A. El-Kholi, H. Kalb, B. Kowanz, W. Menz, A. Michel, and J. Mohr, "Molding of three dimensional microstructures by the LIGA process," in *1992 IEEE Micro Electro Mechanical Systems Conf.*, Travemunde, Germany, Feb. 4–7, pp. 202–207.

[12] A. B. Frazier and M. G. Allen, "High aspect ratio electroplated microstructures using a photosensitive polyimide process," in *1992 IEEE Micro Electro Mechanical Systems Conf.*, Travemunde, Germany, Feb. 4–7, pp. 87–92.

[13] M. G. Allen, "Polyimide-based processes for the fabrication of thick electroplated microstructures," in *The 7th Int. Conf. Solid-State Sensors and Actuators*, Yokohama, Japan, June 7–10, 1993, pp. 60–65.

[14] A. B. Frazier and M. G. Allen, "Metallic microstructures fabricated using photosensitive polyimide electroplating molds," *IEEE J. Microelectromech. Syst.*, vol. 2, pp. 87–94, 1993.

[15] S. G. Mearing, "Thick liquid photoresist for improving image and plating resolution," *Solid State Technol.*, Sept. 1986.

[16] T. Hirano, T. Furuhata, and H. Fujita, "Dry releasing of electroplated rotational and overhang structures," in *1993 IEEE Micro Electro Mechanical Systems Conf.*, Fort Lauderdale, FL, Feb. 7–10, pp. 278–283.

[17] H. Snakenborg, "A new development in electroformed nickel screens," in *Proc. Symp. Electroforming/Deposition Forming*, Mar. 1983.

[18] W. L. Guthrie, W. J. Patrick, E. Levine, H. C. Jones, E. A. Mehter, T. F. Houghton, G. T. Chiu, M. A. Fury, "A four-level VLSI bipolar metallization design with chemical-mechanical planarization," *IBM J. Res. Dev.*, vol. 36, no. 5, pp. 845–857, 1992.

[19] H. D. Goldberg, D. P. Liu, R. W. Hower, M. E. Poplawski, and R. B. Brown, "Screen printing: A technology for partitioning integrated microsensor processing," in *1992 IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, June 22–25, pp. 140–143.

[20] K. Ikuta and K. Hirowatari, " Real three dimensional micro fabrication using stereo lithography and metal molding," in *1993 IEEE Micro Electro Mechanical Systems Conf.*, Fort Lauderdale, FL, Feb. 7–10, pp. 42–47.

[21] M. Boman, H. Westberg, S. Johansson, and J.-A. Schweitz, "Helical microstructures grown by laser assisted chemical vapor deposition," in *1992 IEEE Micro Electro Mechanical Systems Conf.*, Travemunde, Germany, Feb. 4–7, pp. 162–167.

[22] W. H. Brunger and K. T. Kohlmann, "E-beam induced fabrication of microstructures," in *1992 IEEE Micro Electro Mechanical Systems Conf.*, Travemunde, Germany, Feb. 4–7, pp. 168–170

[23] C. C. Liu, "Electroless plating of metals for micromechanical structures," in *7th Int. Conf. Solid-State Sensors and Actuators*, Yokohama, Japan, June 7–10, 1993, pp. 66–69.

[24] J. G. Beach, L. D. McGraw, and C. L. Faust, "A low-volatility nonflammable bath for electrodepositing aluminum," *Plating*, vol. 55, pp. 936–940, 1968.

[25] B. O. Holland, "The electrodeposition of aluminum upon steel strip from.some organic solutions," *J. Aust. Inst. Met.*, vol. 6, pp. 212–219, 1961.

[26] V. K. Ziegler and H. Lemkuhl, "Die elektroltische abscheidung von aluminum aus organizchen komplexverbindungen," *Zeitschrift fuer Anorganizche und Allgemeine Chemie*, vol. 283, pp. 414–424, 1956.

[27] F. J. Schmidt and I. J. Hess, "Electroforming aluminum for solar energy concentrators," NASA Rep. CR-197, Apr. 1965.

[28] F. J. Schmidt and I. J. Hess, "Properties of electroformed aluminum," *Plating*, vol. 53, pp. 229–235, 1966.

[29] A. G. Buschow and C. H. Esola, "Commercial applications of the aluminum electroplating process," *Plating*, vol. 55, pp. 931–940, 1968.

[30] F. J. Schmidt, I. J. Hess, C. H. Esola, and A. G. Buschow, "Electroforming of aluminum composite structures by codeposition of high-strength, high modulus fibers," in *15th Nat. SAMPE Symp. Exposition*, Los Angeles, CA, Apr. 29–May 1, 1969, pp. 117–124.

[31] G. V. Alm and M. J. Binstock, "Aluminum electrocladding studies for proposed OMR fuel elements," U.S. Dept. Commerce Rep. NAA-SR-274, Oct. 1, 1958.

[32] J. G. Beach and C. L. Faust, *J. Electrochem. Soc.*, vol. 106, pp. 654–662, 1959.

[33] I. J. Hess and J. F. Betz, *Metal Finishing*, vol. 69, pp. 38–51, 1971.

[34] W. B. Harding, "Aluminum," in *Modern Electroplating*, Ed. F. A. Lowenheim. Plainfield, NJ: 1974, pp. 63–70.

[35] D. E. Couch and A. Brenner, "A hydride bath for the electrodeposition of aluminum," *J. Electrochem. Soc.*, vol. 96, pp. 234–44, 1952.

[36] J. H. Connor and A. Brenner, "Electrodeposition of metals from organic solutions," *J. Electrochem. Soc.*, vol. 103, pp. 657–62, 1958.

[37] W. Fromberg and F. A. Donaldson, "Electroplating with aluminum," *Adv. Mater. Process.*, vol. 149, pp. 33–35, 1996.

[38] E. Gileadi and G. Capuano, "High purity aluminum electroplating," *Adv. Mater. Process.*, vol. 135, pp. 14–18, 1989.

[39] J. F. Van de Berg, G. A. Van Dijk, and R. E. Van de Leest, "Room temperature electroplating of aluminum," *Metal Finishing*, vol. 83, pp. 15–18, 1985.

[40] A. B. Frazier, C. H. Ahn, and M. G. Allen, "Development of micromachined devices using polyimide-based processes," *Sens. Actuators*, vol. 45, pp. 47–55, 1994.

[41] *Technical Information on QZ3322 Polyimide Stripper, OCG Microelectronic Materials*, 1994.

[42] T. Furuhata, T. Hirano, K. J. Gabriel, and H. Fujita, "Sub-micron gaps without sub-micron etching," in *Proc. IEEE Micro Electro Mechanical Systems Conf.*, Nara, Japan, Jan. 30, 1991, pp. 57–62.

A. Bruno Frazier (S'85–M'85), photograph and biography not available at the time of publication.

Mark G. Allen (M'89), photograph and biography not available at the time of publication.