Metallic Microstructures Fabricated Using Photosensitive Polyimide Electroplating Molds

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***Abstract*—A polyimide-based process for the fabrication of thick (1–150 μm), sharp-sidewall, high-aspect-ratio electroplated microstructures is presented. In previous processes for the creation of electroplated microstructures, a photoresist material (typically PMMA-based) is deposited and patterned (typically using synchrotron radiation) into a sharp-sidewall "form" through which the desired structures are electroplated. The process presented in this paper exploits the sharp-sidewall characters of photosentitive polyimide to create the "form" through which the micromachined structures are electroplated. Although the achievable thicknesses and aspect ratios of this process are inferior to the synchrotron-based process described above, this process has several advantages: it is simple and can be carried out using commercially available materials and common clean room equipment; the excellent chemical and thermal resistance of polyimide allows plating to take place in a variety of environments; and multiple coats of polyimide can be used to fabricate "vertically integrated" structures which have variation in the third dimension. The process is completely compatible with surface micromachining sacrificial layer techniques to create released electroplated microstructures. In addition, it can also be performed upon substrates containing standard CMOS circuitry to create microstructures with no degredation of the underlying circuitry. Details of the process itself, structures fabricated using a variety of plating solutions, a demonstration of vertically integrated multilayer structures, and a demonstration of the release of structures including assembled structures fabricated using this method are presented.**

I. Introduction

THERE is application in the field of micromachining for metallic microstructures of relatively large (i.e., 10–1000 μm) thickness. For example, metallic microstructures offer the potential for reduced friction in sliding systems, or as essential components in micromagnetic actuators. Structures which are relatively thick offer structural rigidity in actuation systems. Finally, thick, high-aspect-ratio devices offer the possibility of compact production of high torque and/or actuation force. Thus, processes for the fabrication of thick, high-aspect-ratio, metallic microstructures are of interest.

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Several recent processes have been developed for the fabrication of thick metallic micromachined devices. One of the most well known processes is the so-called LIGA process [1]–[4] (lithography, electroplating, molding) for structure definition and fabrication. A schematic of the lithography and electroforming parts of the LIGA process is shown in Fig. 1. The process consists of depositing a thick (100–500 μm) layer of an X-ray sensitive photoresist, usually based in poly(methyl methacrylate), PMMA, on a metal-coated substrate. The resist is then exposed through an X-ray mask [5], [6] using a highly collimated and very bright X-ray source, such as a synchrotron. The use of a synchrotron-based lithography allows exposure of vertical sidewalls through the thickness of the resist. The resist in the exposed regions is then developed, revealing regions of the underlying metal layer. The photoresist now acts as a "form" for electroplating-based deposition of a metallic structural material. Once the deposition has been completed, the photoresist is removed, yielding the final electroplated structures. Stationary structures including arrays of pillars and honeycombs have been produced using this method [1], [2], as well as a variety of sensors [7]—[11]. In addition, movable microstructures such as turbines and micromotors have been fabricated using standard sacrificial layer/surface micromachining techniques [12]–[14]. Analogous methods, such as deep-UV lithography, have been developed for PMMA [3], [15]–[17], but are limited to single-step maximum thicknesses of approximately 5 μm owing to absorption of the photoresist. In addition to the use of positive photoresist systems, negative acting photoresist systems have also been used as electroplating molding materials [20], generally for the printed circuit board industry. Other techniques used to create molds for metallic structures include stenciling used in surface mount technology [18] and four-level VLSI bipolar metallization designs [19].

In-house operation of the LIGA process requires X-ray mask fabrication processes and synchrotron exposure, facilities which may not be available in many laboratories. Thus, if a fabrication technology using conventional equipment could be found which achieved results even partially comparable to the LIGA process, a variety of uses for the technology could be immediately envisioned.

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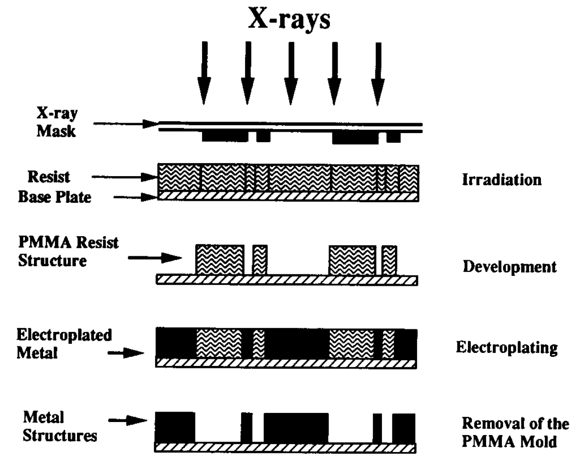

Fig. 1. Schematic representation of the lithography and electroforming processes for the LIGA method. The LIGA process utilizes X-ray masks and a synchrotron radiation source.

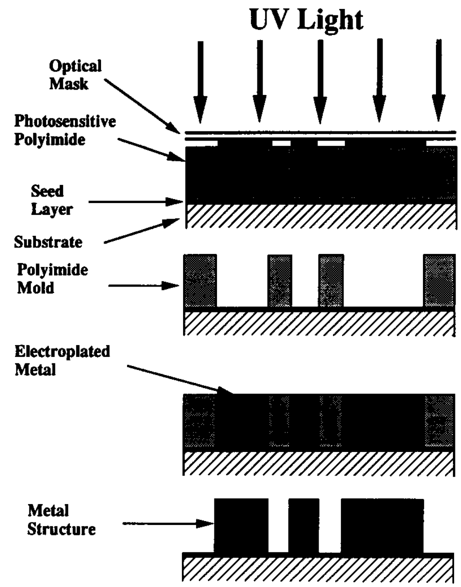

Fig. 2. Schematic representation of a generic process sequence for fabricating high-aspect ratio electroplated microstructures using photosentitive polyimide. The process utilizes standard optical masks and a standard UV radiation source.

For example, optical lithography has been used for fine pitch bumping as well as magnetic coils using high transparency and high-viscosity photoresist systems [21]. Our approach is the use of polyimides as electroplating forms to produce metallic microstructures.

Polyimides are commercially available materials which are widely used in various aspects of microelectronics. Present applications for polyimide/metal systems include multilevel interconnect technology (e.g. [22]–[24]) and multichip packaging (e.g. [25]–[27]). In addition, UV-exposable, negative-working, photosensitive polyimides which can have spun-on thicknesses in excess of 60 μm in a single coat are now commercially available, thus satisfying the thickness requirement. In addition, many of these systems have extremely sharp sidewalls upon developing, thus allowing the fabrication of relatively high aspect ratio structures. Finally, the additional properties such as compatibility with standard integrated circuit technology (allowing microstructures to be fabricated directly on top of foundry-processed CMOS or other silicon wafers), the option of using the chemically and thermally stable polyimide molding material as an integral part of the microsystem (as a dielectric material or structural component), the ability to electroplate in both acidic and alkaline solutions as well as some solvent-based solutions, and the ability to electroplate three dimensionally varying structures using multicoat procedures allows the realization of electroplated microstructures in an inexpensive and manufacturable fashion. Use of photosensitive polyimide in the fabrication of released and nonreleased micromachined structures made from a variety of metals is discussed below.

II. The Basic Process

The basic process for fabrication of electroplated microstructures using a photosensitive polyimide is analogous to the LIGA process shown in Fig. 1, except that photosensitive polyimide is used as the electroplating mask. Fig. 2 shows a schematic of the basic process. An electroplating seed layer is deposited on the substrate, and the photosensitive polyimide is spun on top of this layer. The photosensitive polyimide is then soft baked and imaged into the desired pattern. Electroplating and polyimide stripping are performed as shown in Fig. 2. Using these fabricating methods, electroplated structures of copper, nickel, gold, and silver, as well as other metals, can be realized.

A typical fabrication process is described below. Oxidized silicon wafers are used as the initial substrate (oxide thickness 0.3–1.3 μm), and a suitable electroplating seed layer of metal (described in the following sections) is deposited on the substrate. Photosensitive polyimide (Ciba-Geigy Probimide 348 or 349, a photoimageable, thermally imidiziable material) is then spun on the wafer. Before coating the substrate, the polyimide is allowed to warm from a storage temperature of -5°C to 27°C over a 1.5–2.0 h period. The spinning is accomplished in two stages, with a spread stage of 600 rpm for 15 s, and a high-speed stage of 1100 rpm for 10 s, leading to a film thickness of approximately 40 μm. Thinner (or thicker) coats can also be achieved by increasing (decreasing) the speed of the high-speed spin stage. The wafers are then soft baked in a two-stage process, 15 min at 80°C, then 110°C for 20 min to drive off solvent, followed by contract imaging using a standard G-line (436 nm) mask aligner. The aligner used for experiments described in this paper has the following characteristics: the collimation is 2%; the uniformity is 5%; and the lowest power objective (2×) is used for maximum depth of field over a 10 cm diameter circular area. For a 40-μm-thick film, a typical exposure energy of 230 mJ/cm^2 is used. The exposure energy is a linear function of the polyimide thickness for films less than 60 μm. The patterns in the polyimide are then developed using Ciba-Geigy QZ 3301 developer and rinsed QZ 3312 rinse. Either spray or ultrasonic development and rinse have been found to be sufficient for film thicknesses less than 25 μm. Ultrasonic development is needed for films with thicknesses greater than approximately 25 μm. Although no exact measurements of the sidewall profile have been performed, SEM observations indicate nearly vertical sidewalls. Antireflection coatings and G-line filters have also been used in standard fashions and have been found to increase the process performance.

The polyimides can be optionally thermally cured (imidized) at this point to achieve increased resistance to solvents and basic solutions. Although the imidization leads to higher resistance of the polyimide to chemical attack, it also results in shrinkage of the film in-plane and orthogonal to the substrate. This shrinkage will substantially decrease the height of the film as well as compromise the sharpness of the sidewalls. The structures described in this work used polyimide which is not thermally imidized prior to electroplating; the detailed tradeoff between polyimide cure and feature distortion/shrinkage was not examined in this work.

To electroplate the microstructures, electrical contact is made to the activated seed layer, and the wafers are immersed in the suitable electroplating solution. As the uncured polyimides used in this work actually exist as polyamic acid esters instead of polyamic acids, acceptable resistance even to baths with pH $>$ 7 can be achieved if the bath is maintained at room temperature. Uncured films can also be used as electroplating forms in acidic plating baths at elevated temperature (typically 40–50°C for acid/copper solutions) with no discernible deterioration of the fill patterns. Because of the relatively large aspect ratios of some polyimide plating molds, it is often difficult to remove all entrapped air in the patterns. This can result in gross uniformity problems during the electroplating. In order to remove this entrapped air and to ensure intimate contact of the solution with the seed metal, the wafer is subjected to a short ultrasonic treatment in deionized H_2O prior to immersion in the solution. Electroplating is then carried out in the normal fashion, with the wafer at the cathode of the electroplating cell. When the electroplating is complete, the polyimide is removed. The polyimide, which has not been thermally imidized, can be removed by immersion in hot 70°C 30 wt% potassium hydroxide solution. Once the polyimide is removed, electrical isolation of the electroplated structures is optionally achieved by etching the seed layer. The detailed use of this technique to fabricate a variety of structures is illustrated in the following sections.

A. Nickel Structures

Nickel electroplating was accomplished using a nickel sulfate electrolytic solution buffered with boric acid [28]. The original solution composition is shown in Table I. The solution was mixed in a 2000 ml Pyrex breaker and the pH was then adjusted to 2.5 by the addition of H_2SO_4. A 7 cm × 10 cm nickel foil (99.9%) was used as the anode material. The electroplating was carried out with electrolytic solution at room temperature using a current density of approximately 10 mA/cm^2, corresponding to a plating rate of 0.2–0.3 μm/min. No attempt was made to optimize the above plating conditions.

Electroplated nickel microstructures were fabricated using the basic process in combination with a variety of seed layers deposited on the substrate. Three different seed layers for the nickel electroplating were investigated: copper, nickel, and chromium. To investigate copper seed layers, a three-layer metal system was deposited on oxidized silicon using a filament evaporator. The metals, in order of deposition, were 25 Å chromium (as an adhesion layer), 1500 Å copper, and 1000 Å chromium. The copper seed layer was of sufficient thickness to ensure uniform plating across a 3 in. wafer with minimal resistivity effects. The top layer of chromium was used to prevent oxidation of the seed film during subsequent processing leading up to nickel electroplating. The top layer of chromium was etched immediately before electroplating using 1 : 1 solution of $HCl:H_2O$ with aluminum depassivation to reveal a clean nonoxidized copper film. The chromium etch was followed by a distilled water rinse and electroplating.

To investigate nickel seed layers, a similar metal system was used: 25 Å chromium, 1500 Å nickel, and 1000 Å chromium. For the investigation of chromium as the seed layer, a single layer of chromium 1500 Å in thickness was used. The sample preparation leading up to electroplating remained the same for these seed layers as for the copper seed layer, except that for the chromium seed layer, an ultrasonic treatment in deionized water was used in place of a chromium etch.

The nickel and copper thin films proved to be adequate seed layers for the electroplating process. However, the adhesion between the chromium seed and nickel electroplated films was poor. For the structures fabricated in this work, uniform deposition was observed excluding the annular region from the wafer edge to approximately 10 mm in from the edge. In this region enhanced plating was observed, leading to overplating (mushrooming) of the microstructures. The area in which enhanced plating occurs is a strong function of the plating bath geometry and anode size. Based on existing technology in plating bath design and anode geometries, electroplating cells which minimize effects of nonuniform electric fields can be constructed. It is also possible to enhance uniformity by careful design of the areas to be electroplated (e.g., through the use of the thieving areas). Thieving areas are additional plating sites used to increase the current density in regions where there is insufficient surface plating area. These areas minimize local geometry effects which interfere with current density distribution and plating rate. After completion of plating, thieving formations can be

TABLE I
COMPOSITION OF THE NICKEL-IRON ELECTROPLATING SOLUTION (g/L REFERS TO GRAMS OF SUBSTITUENT ADDED PER LITER OF FINAL PLATING SOLUTION)

Component	g/L
$NiSO_4 \cdot 6H_2O$	200
$FeSO_4 \cdot 7H_2O$	8
$NiCl_2 \cdot 6H_2O$	5
H_3BO_3	25
saccharin	3

removed by preferentially releasing these structures using micromachining techniques.

Using concepts described above, it was possible in the center region to plate the metal to within a micron of the polyimide surface for the microstructure geometries illustrated. Fig. 3 shows a section of an electroplated gear structure prior to removal of the polyimide electroplating form. The height difference between metal and polyimide surfaces is on the order of 1 μm. Fig. 4 shows the same structure after the polyimide has been removed. As can be seen, an extremely sharp sidewall profile can be obtained. This gear structure is approximately 40 μm in height and 300 μm in diameter with a tooth width of approximately 40 μm.

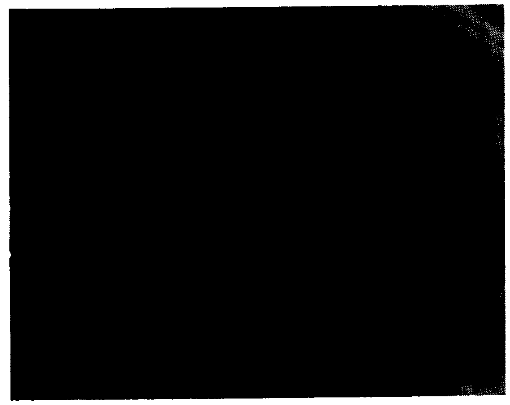

Fig. 3. Scanning electron micrograph of a nickel gear structure prior to the removal of the polyimide electroplating form. The nickel has been electroplated to within a micron of the top of the polyimide form.

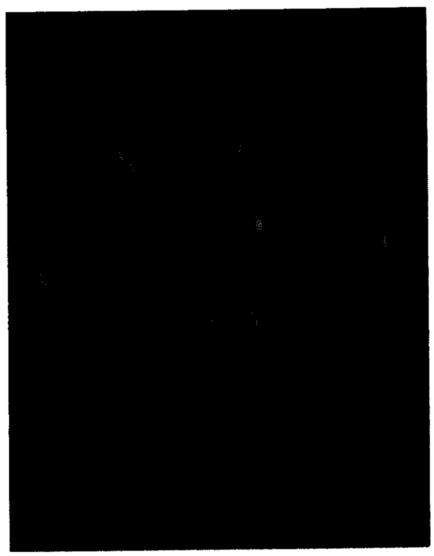

Fig. 4. Scanning electron micrograph of a nickel gear structure after removal of the polyimide form, illustrating the extremely sharp sidewall profiles which can be achieved using this process. The gear structure is approximately 40 μm in height and 300 μm in diameter with a tooth width of 40 μm.

B. Copper Structures

Electroplated copper microstructures were fabricated using the basic process in combination with copper, nickel, and chromium seed layers prepared as described above. The electroplated copper structures were fabricated using both a commercially available acid copper plating solution (LeaRonal Copper Gleam 125S-2) and an acid copper solution [29] consisting of 120 g/*l* $CuSO_4 \cdot 5H_2O$ and 100 g H_2SO_4 per liter of plating solution. A 2000 m*l* Pyrex breaker was used for both electrolytic copper solutions. During the electroplating process the baths were maintained at 45–50°C using a current density of approximately 10 mA/cm^2, yielding approximate deposition rate of 0.2–0.3 μm/min. A 7 cm × 10 cm copper foil was used as the anode material. No attempt was made to optimize the electroplating conditions to minimize surface roughness.

Using the seed layer preparation techniques for chromium described above, no evidence of copper plating was observed. As expected, the use of copper as the seed layer succeeded unless the seed layer was exceedingly thin. Very thin seed layers led to three significant problems: first, nonuniform plating across the wafer caused by the relatively large resistivity of the seed film; second, no plating due to breakdown at the point of electrical contact; third, oxidation of the seed film surface which could not be removed without removing the entire seed film. Nickel also provided an adequate seed layer for copper electroplating, subject to the same three constraints.

In Fig. 5 an electroplated copper structure is shown. The structure is approximately 45 μm tall and 300 μ in diameter with a tooth width approximately 40 μm. Fig. 6 reveals the sharp-sidewall characteristic achievable using this process. The surface of the electroplated copper structure is rough because the plating process was not optimized. Surface roughness can be reduced by appropriate adjustment of the plating current density and chemical composition of the electrolytic solutions.

III. SURFACE MICROMACHINED STRUCTRES

In order to achieve electroplated microactuators, provision must be made for release of the electroplated structures or parts of the structures. This release has been achieved in the LIGA process using titanium as a sacri-

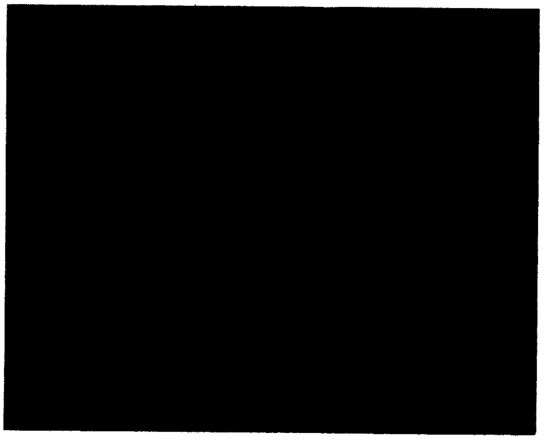

Fig. 5. Scanning electron micrograph image of a copper gear fabricated using the basic process. The gear is approximately 300 μm in diameter and 45 μm in height, with a tooth width of 40 μm.

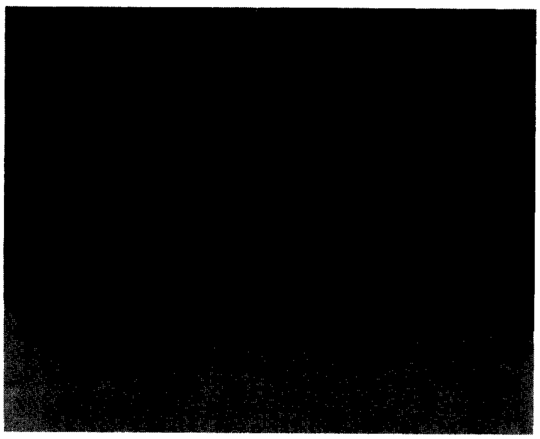

Fig. 6. Detailed scanning electron micrograph image of a copper gear, illustrating the extremely sharp sidewall profiles which can be achieved using this process. The tooth is approximately 40 μm in width and 45 μm in height.

ficial layer [9], [12], [13] as well as special forms of polyimide [10], [30], [31]. Released structures can also be achieved using the polyimide process described here using a wide variety of materials as the underlying sacrificial layer. In most applications of this process, the main criterion for determining if a material can be used as a sacrificial layer simply whether it can be preferentially etched with respect to the electroplated metal. If the sacrificial layer cannot be utilized as a seed layer for the electroplated metal, then a thin seed layer can be deposited before the photosensitive polyimide processing. To illustrate the release of microstructures, a process for forming gears and basic micromoter structures has been developed.

Fabrication of lifted-off micromachined gears can be achieved by applying the basic process to a substrate which contains a chromium release layer. Fabrication began with a three-layer metal system: 1500 Å of chro-

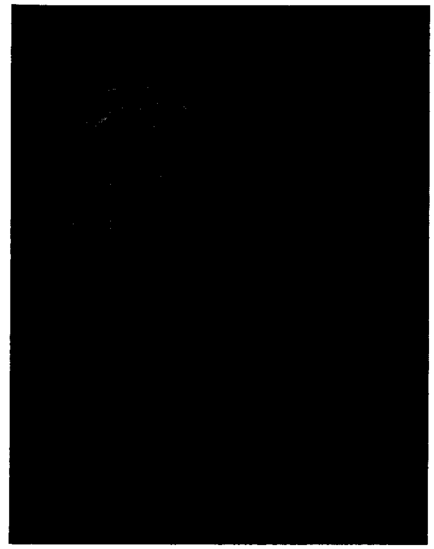

Fig. 7. An interlocking configuration constructed of four copper structures which have been completely released from the substrate. The lower-left and upper-right structures have been turned over, revealing the original copper seed layer used for the electroplating process. The gear structures are 300 μm in diameter and 45 μm in height.

mium (which is used as both an adhesion layer and a sacrificial layer); 2000 Å of copper (seed layer); and 1250 Å of chromium (to protect the seed layer prior to plating). All metal layers were deposited in a filament evaporator without breaking vacuum between evaporations. The photosensitive polyimide was spun, baked, and imaged, and the top layer of chromium was etched as in the basic process. The copper gears were then electroplated and the polyimide was removed. The exposed chromium in the fields was removed, and the exposed copper seed layer was removed using the chromium and copper etchants previously described. Finally, the lower (sacrificial) chromium layer was underetched in $HCl:H_2O$ 1 : 1 to completely release the gears.

Fig. 7 shows four copper structures which have been released and subsequently mechanically positioned into an interlocking gear configuration. The lower-left and upper-right structures have been turned over, revealing the original copper seed layer used for the electroplating process. The lateral underetch rate of the chromium sacrificial layer was observed to be approximately 25–35 μm/h in $HCl:H_2O$ 1 : 1. Negligible attack on the copper gears was observed during the chromium underetch. The use of this process to create released nickel structures was also achieved.

It has also been possible to achieve selective release (as opposed to blanket release) of electroplated structures using polyimide electroplated forms. For example, micromotor structures involving electroplated copper and nickel can be achieved by arranging the seed and sacrificial layers such that rotor structures can be selectively released without simultaneously releasing stator structures. Full details of this process have been discussed in [32].

IV. Assembled Structures

Assembly of structures fabricated using the photosensitive polyimide process has been realized by using sacrificial layer surface micromachining. Using optical subtraction strategies, gaps in micromachined structures can be greatly reduced. For example, a gear with a hole inner diameter of 64 μm can be fabricated independently of a pin with an outer diameter of 60 μm. These two structures can then be assembled, yielding a gear/pin combination with a gap of 2 μm. Fig. 8 shows such an assembled structure. A gear was fabricated using the basic process and released using a chromium sacrificial layer. The released gear was then mechanically placed onto a pin. The resulting gap between the gear and the pin in the assembled structure is approximately 2 μm. A similar procedure has been developed for the three-dimensional integration of LIGA microstructures [30].

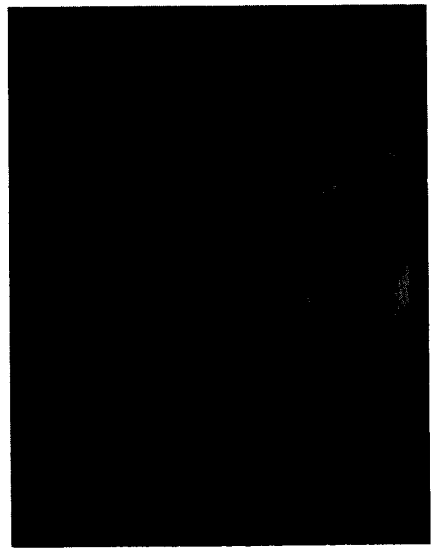

Fig. 8. A gear/pin structure using the combination of surface micromachining and postassembly techniques. The gear and pin height are 50 μm and the gear/pin gap is less than 2 μm. The gear is free to spin around the pin.

V. Vertically Integrated Structures

Consider an application where it is desirable to have projected structures vertically integrated ("stacked") and attached by means of electroplating to form one continuous structure. An example of such an application might be the attachment of a vertical rotor shaft to an electroplated motor to vertically couple mechanical power out of the motor. One way to achieve this vertical integration is to cast a first layer of resist, pattern, and electroplate, yielding a metal structure imbedded in the resist as in Fig. 3. If the plating is carefully controlled so that the metal structure is coplanar with the resist, a second layer of resist can be spun, a different pattern exposed, and a second metal structure plated to yield a single continuous metal structure with three-dimensional variation. The use of photosensitive polyimide in this application is ideal since the photocrosslinking and/or cure of the first layer of the polyimide induces sufficient solvent stability in the first layer that a second layer can be spun on without dissolving the first. Thus, vertically integrated structures can be achieved using the polyimide process. It should be noted that, at all times, lithography is done on surfaces which are nearly planar. In theory, if the second pattern is identical to the first and is well-aligned, a continuous projection of the original structure to high aspect ratios can be achieved.

This effect is illustrated by vertically integrated "platform-pin" structures in which an electroplated "pin" of approximately 1 : 1 aspect ratio is fabricated on top of a relatively flat and thin electroplated "platform" using a multilayer process. The structures described here were all fabricated from nickel, although nickel-on-copper structures have also been fabricated.

A square platform approximately 120 μm in diameter and 10 μm high is fabricated on a silicon substrate using the basic process with nickel as the structural material and copper as the seed layer, except that the first layer of polyimide is not removed at the completion of the electroplating. The first layer of polyimide is then partially cured at 200°C for 60 min. A layer of chromium 1200 Å thick is sputter-deposited. A second layer polyimide is then spun and patterned using the basic process to form pin electroplating forms 45 μm in diameter and 45 μm in height aligned over the underlying platforms. The exposed chromium is then removed using HCl/H_2O 1 : 1, and the pin is electroplated to the surface of the second polyimide structure. The polyimide structure is then removed to yield the final vertically integrated structure.

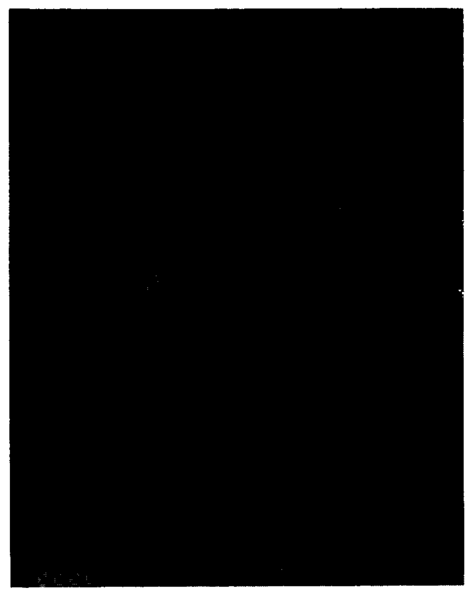

Fig. 9. A vertically integrated electroplated nickel "platform-pin" structure fabricated utilizing a multicoat polyimide procedure. The platform is 120 μm on a side and has a height of 10 μm. The pin is 45 μm in diameter and has a height of 45 μm.

Figure 9 shows a scanning electron micrograph of a vertically integrated "platform-pin" structure. The height of the pin is approximately 45 μm, and the aspect ratio of the pin is approximately 1. There are no theoretical limitations on the numbers of layers which can be applied in this fashion, although no more than two were fabricated in this initial work. The inversion of this structure, i.e., with the "small" (in diameter) component on the bottom and the "large" (in diameter) component on top has also been fabricated using this technique. In order to realize overhanging structures such as the inverted "platform-pin" structure the complete metal system must be deposited prior to the application of the second polyimide layer. Extensions of this technique to beams and platforms resting on pillars of columns can easily be envisioned.

VI. Conclusions

A process for the fabrication of electroplated microstructures using photosensitive polyimide has been described. This process is a low-cost alternative to the LIGA process for microstructure fabrication. Although this process cannot match the performance of the LIGA process, it uses ordinary optical masks and ultraviolet light exposure, resulting in simple and inexpensive equipment requirements. Using this technology, structures made of a variety of electroplated metals can be fabricated. Vertically integrated structures which exploit the multilayer ability of the polyimides used can also be realized. Finally, processes for surface micromachining using this process for the fabrication of movable electroplated microactuators can be achieved.

Acknowledgment

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