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Development of micromachined devices using polyimide-based processes

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Abstract

Currently there are several techniques under investigation for the fabrication of metallic microstructures, including photoresist-based technologies, stencil-based technologies and photoelectroforming-based technologies. In this paper, high aspect ratio and thick metallic microstructures are investigated using polyimide-based technologies. The use of polyimide processes offers several advantages, including compatibility with conventional integrated circuit fabrication techniques, chemical and thermal stability for electroplating in a wide variety of acidic, basic and solvent-based solutions, the ability to fabricate devices using conventional cleanroom equipment and materials, and the flexibility to integrate the polyimide into the final micromachined system as a dielectric or structural material. After a review of the polyimide-based processes, selected applications utilizing this technology will be discussed.

Keywords: Micromachined devices; Polyimide-based processes

1. Introduction

There is application in the field of micromachining for metallic microstructures of relatively large (i.e., 10–1000 μm) thickness. Some examples of applications include high-current metallic bimorphs, dynamic microsystems with the potential for reduced friction and longer life using wear-resistant metal components and micromagnetic actuators. Also, structures that 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 and/or high-aspect-ratio metallic microstructures are of interest.

Several processes have been developed recently 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. Stationary structures, including arrays of pillars and honeycombs, have been produced using this method [1,2], as well as a variety of sensors [5–9]. In addition, movable microstructures such as turbines and micromotors have been fabricated using standard sacrificial layer/surface micromachining techniques [10,11]. However, 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, alternative processing schemes for realization of high-aspect-ratio metallic structures that can be realized in-house are useful even if the full performance of the LIGA process cannot be matched by these alternative processing schemes. The purpose of this paper is to discuss the use of the polyimide-based processes to realize thick electroplated microstructures.

2. Polyimide materials

Polyimides are commercially available materials that are widely used in various aspects of microelectronics. Present applications for polyimide/metal systems include multilevel interconnect technology [12–14] and multichip packaging [15–17]. Processes have been developed for patterning these films using wet-etching techniques, dry-etching techniques, or developing photosensitive versions of the polyimides. Much work has gone into tailoring the sidewall profiles of these polyimides, so that sidewall profiles ranging from vertical to 45° slopes to completely isotropic have been achieved. Additional polyimide properties such as compatibility with standard

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integrated circuit technology (allowing microstructures to be fabricated directly on top of foundry-processed CMOS or other silicon wafers), electroplating in both acidic and some alkaline solutions, and the ability to electroplate structures that vary three dimensionally using multicoat procedures, allow the realization of a number of vertical and sloped-sidewall electroplated microstructures in an inexpensive and manufacturable fashion. Use of polyimides in the fabrication of released and nonreleased micromachined structures made from a variety of metals is discussed below.

3. Photosensitive-polyimide-based processes

UV-exposable, negative-working, photosensitive polyimides which can have spun-on thicknesses ranging from 3 to 150 μm in a single coat depending on the processing conditions are now commercially available, thus allowing the simple fabrication of thick electroplated microstructures. In addition, many of these systems have extremely sharp sidewalls upon developing, thus allowing the fabrication of relatively high aspect ratio structures. The basic process (Fig. 1) is very similar to ordinary photolithography, with the exception of the large resist thickness used. Initially, an electroplating

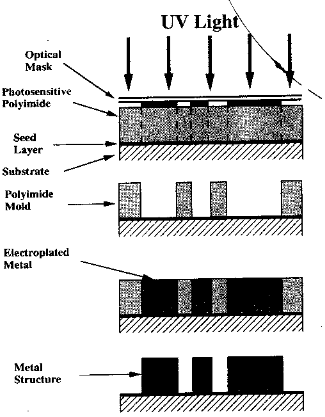

Fig. 1. Schematic representation of the process sequence for fabricating metallic electroplated microstructures using photosensitive polyimide. The process utilizes standard optical masks and a standard UV radiation source.

seed layer as well as an adhesion layer (if needed) is deposited on the substrate. This is followed by application of the photosensitive polyimide on top of these layers. The photosensitive polyimide is then soft baked and imaged into the desired pattern using a conventional UV exposure source to form the electroplating mold. Electroplating and (optionally) polyimide stripping are then performed. Electroplated structures of copper, nickel, nickel–iron alloys, gold, silver and other metals can be realized using this technology.

3.1. The PSPI-based process

A typical fabrication process [18,19] is described in some detail below. Planar silicon, ceramic or compound semiconductor surfaces can be used as the initial substrate upon which a suitable electroplating seed layer of metal is deposited. Photosensitive polyimide (e.g., Ciba-Geigy Probimide 348, a photoimageable, thermally imidizable material) is then spun on the substrate. The spinning is accomplished in two stages, 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 the low-temperature solvent, followed by imaging using a standard G-line (436 nm) mask aligner. For a 40-μm-thick film, a typical exposure energy of 275 mJ cm^{-2} is used. The unexposed polyimide material is then developed and rinsed, resulting in a polyimide mold through which metal can be electroplated. Development and rinse using a pressurized spray or submersion in a conventional ultrasonic bath 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. Scanning electron microscopy (SEM) measurements of the sidewall profile for a 50-μm-thick film indicate typical sidewall variations of 2 μm horizontally. Antireflection coatings and G-line filters are options that can be used to increase the process performance.

The polyimides can optionally be 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 procedure we have followed is: if the polyimide is not to be used as an integral part of the final device, but only as an electroplating mold, do not thermally cure; if the polyimide is to be used as an integral structural part of the final device (such as in the micromagnetic applications discussed below), thermal curing is necessary.

To electroplate the microstructures, electrical contact is made to the activated seed layer, and the wafers are immersed in a suitable electroplating solution. As the uncured polyimide described in this paper actually exists as a polyamic acid ester instead of a polyamic acid, 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 film patterns. Electroplating is 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. Polyimide that has not been thermally imidized can be removed at this point by immersion in hot (70 °C) 30 wt.% potassium hydroxide solution, or by oxygen plasma. If the polyimide is removed, electrical isolation of the electroplated structures can optionally be achieved by etching the underlying seed layer.

3.2. Results

Fig. 2 shows a cross test pattern of electroplated nickel that has been fabricated using the above process. The structure is approximately 35 μm wide and 50 μm thick. In Fig. 3 an electroplated copper gear structure is shown. The gear is approximately 45 μm tall and 300 μm in diameter, with a tooth width of approximately 40 μm. The maximum aspect ratios that have been achieved using this process approach 8:1 (thickness:width); however, at this high aspect ratio, substantial dependence on layout geometry is observed, indicating that the process is developer-limited.

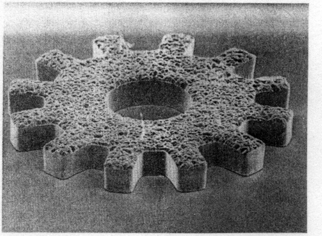

Fig. 3. SEM image of a copper gear fabricated using a photosensitive polyimide electroplating mold. The gear is approximately 45 μm high and 300 μm in diameter. The width of a single tooth is approximately 40 μm.

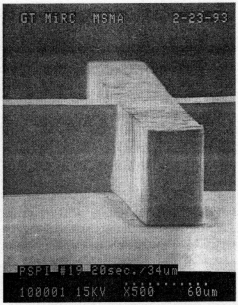

Fig. 2. SEM image of a cross test pattern fabricated from electroplated nickel–iron using a photosensitive polyimide electroplating mold. The cross linewidth is approximately 35 μm wide and the cross thickness is approximately 50 μm.

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 sacrificial layer [7,10,11], as well as special forms of polyimide [8,20,21]. Released structures can also be achieved using the polyimide-based processes, using a wide variety of materials as the underlying sacrificial layer. For example, fabrication of lifted-off micromachined gears can be achieved by applying the basic process to a substrate that contains a chromium or other release layer underlying the seed layer. Fig. 4 shows a nickel/iron micromotor structure where the rotor has been fabricated separately, lifted off, and microassembled onto the stator and pin assembly. Lateral underetch rates in excess of 25–35 μm h^{-1} have been observed using chromium as the sacrificial layer, with negligible attack on copper electroplated structures. It has been possible to achieve selective release (as opposed to blanket release) of electroplated structures fabricated using polyimide electroplated forms. For example, micromotor structures involving electroplated copper or nickel can be achieved by arranging the seed and sacrificial layers such that rotor structures can be released selectively without simultaneously releasing stator structures. Full details of this process have been discussed in Ref. [22].

Consider an application in which it is desirable to have several projected structures vertically integrated ('stacked') and attached by means of electroplating to form one continuous structure. An example of such an

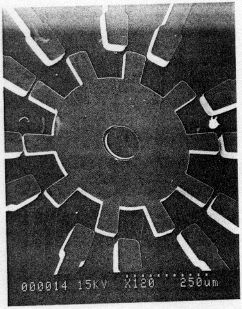

Fig. 4. SEM image of a separately fabricated and released nickel–iron rotor that has been microassembled onto a nickel–iron pin/stator assembly, illustrating the ability to perform microassembly with these structures.

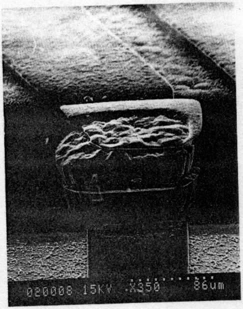

Fig. 5. SEM image of a thick wrapped microinductor coil formed through a multilayer polyimide electroplating process. A lower conductor is formed using a polyimide electroplating mold, a via connection is formed using a second polyimide electroplating mold, and an upper conductor is formed using a third polyimide electroplating mold. The total thickness from substrate to top conductor in this structure is 120 μm.

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. 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 degree of coplanarity between the resist and electroplated metal is a strong function of the electroplating conditions and variations in the uniformity of the current density across the substrate from pattern variations. The use of 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. It should be noted that, at all times, lithography is done on surfaces that are nearly planar. In theory, if the second pattern is identical to the first and well-aligned, a continuous projection of the original structure to high aspect ratios can be achieved. This scheme has been used to realize high current vias for micromachined magnetic inductors [23], as shown in Fig. 5, as well as magnetic micromotors (described below).

4. Plasma-based processes

As mentioned above, polyimides have been used for several years as interlayer dielectrics for integrated circuits and multichip modules. Much research has gone into dry etching of these materials for multilayer metallization schemes to form interconnect vias from one layer of metal to another through the polyimide layer. In particular, attention has been paid to the sidewall slope of the via. Sidewall slopes have been generated ranging from purely isotropic to 45° angles to straight sidewalls. If these etched vias in the polyimide are considered to be electroplating molds instead of simply electrical vias, the fabrication of electroplated microstructures with controllable sidewall geometry can be realized.

4.1. The plasma-based process

The process used to achieve metallic microstructures with continuous out-of-plane dimensional variation is shown in Fig. 6. The process can be implemented using silicon, gallium arsenide, ceramic, or any planar substrate. After choosing the appropriate substrate for the application, the electroplating seed layer(s) are deposited. Typically, the seed layer system is a tri-level metal system. First, an adhesion layer is deposited between the substrate and actual electroplating seed layer. The adhesion layer can also be used as a release layer for structures or portions of structures for sacrificial layer technology. After deposition of the adhesion layer, the appropriate seed layer is deposited for electroplating. A third metal is deposited after the seed layer

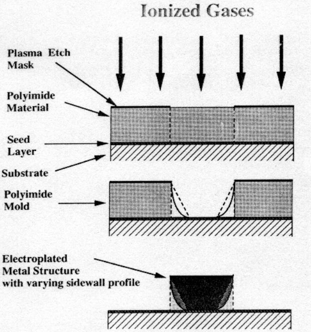

Fig. 6. Schematic representation of the process sequence for fabricating electroplated microstructures using nonphotosensitive polyimide. The process utilizes standard plasma techniques.

to serve as an adhesion and protective layer for processing leading up to electroplating. This layer protects the seed layer from contamination during polyimide processing and oxidation during plasma etching of the mold pattern. After deposition of the tri-level metal system, the polyimide adhesion promoter and the polyimide material can be deposited. Deposition of the polyimide can be achieved by several methods. For relatively thin films (less than approximately 20 μm), the most conventional approach is to use multicoat spinning with partial curing of the film in between the spin states. A typical spin and cure cycle for the multicoat process is 3000 rpm for 30 s, followed by a 150 °C soft bake for 15 min. Obviously, this procedure must be modified for the polyimide material under consideration. Typical final cures for polyimide films are 350–400 °C. If thicker films of polyimide are desired, other deposition techniques such as screen printing or spray can be used. After deposition of the polyimide, a suitable masking material for the plasma etching is deposited and patterned. Aluminum is a standard masking material. Plasma etching of the polyimide material can be achieved using a wide variety of techniques. Typical gases for the polyimide etching processes are O_2, CF_4, CHF_3 and SF_6. The slope of the sidewall can be controlled by varying the relative concentrations of the gases, the plasma power and the ambient pressure in the etching chamber [24–31]. After the plasma etching is complete, the masking material and the protective layer are removed. The structure is electroplated through the polyimide mold and the polyimide is removed (if desired). Electroplated copper, nickel, nickel alloy and gold microstructures have been achieved using the above basic process.

4.2. Results

A simple illustration of the plasma-based process is shown in Fig. 7. In the fabrication of this 'bowl-shaped' structure, a 300 W, 50 mtorr plasma of 10% CF_4/90% O_2 was used to dry etch a sloped via into a 40-μm-thick polyimide layer. The dry-etched polyimide mold was used to form the gold 'micro-bowl'. The isotropy of the dry etch was controlled by varying the ratio of oxygen to fluorine in the etching ambient plasma at a pressure of 50 mtorr and a plasma power of 300 W.

Recently, there has been much work by a variety of researchers on dry etching of polyimides to form extremely high aspect ratio structures for micromachining applications. Most of these methods involve some modification of a traditional etching apparatus in order to achieve these large aspect ratios. For example, magnetically controlled dry etching of polyimides [32] and fluorinated polyimides [33] has been used for deep etching of polyimides with high aspect ratios, excellent mask selectivity, and smooth sidewalls. Circular cylinders 15 μm in diameter and 100 μm in height have been achieved using these methods. Another method that has been used is cryogenic reactive ion etching [34], where the substrate to be etched is cooled to temperatures on the order of -100 °C. Deep trenches in both silicon and polyimide have been etched using this technique. This cooling greatly increases the aspect ratio that can be achieved, by reducing any lateral etching of the structures to a very small amount.

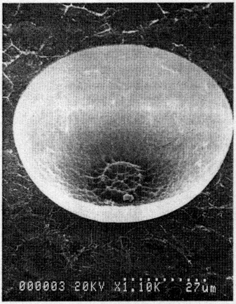

Fig. 7. SEM image of a bowl-shaped structure formed using an isotropic, dry-etched polyimide electroplating mold.

5. Applications

In this section, several applications of metallic microstructures fabricated using photosensitive and dry-etched polyimides as electroplating molds, integral device components, or both, are discussed briefly.

5.1. High-current solar cell metallization

In the fabrication of solar cells, there is a trade-off in the design of the metallic collector traces which are used to make contact to the cell and collect the current. The larger these traces are, the lower the series resistance of the cell; however, if the surface area of the traces in increased, more light is blocked from the cell, decreasing the total power output and efficiency of the cell. This effect is especially severe in concentrator solar cells, where the incident light may be concentrated on the cell by an external optical system, resulting in much higher cell currents. One possibility for overcoming this problem is to fabricate high-aspect-ratio metallization traces for the cell. In this way, the cell resistance can be lowered without a corresponding increase in the shadowing of the cell surface by the metallization.

A commonly found collector design is composed of a central pad with raylike collector fingers extending from the pad. The central pad is the contact point for the cell, and the raylike fingers extend out over the cell area to collect the generated photocurrent. Fig. 8 shows an SEM image of a solar cell structure with electroplated straight-sidewall metallization. The collector fingers on this particular structure are 17 μm high and 10 μm wide. Collectors fabricated using gold, copper, nickel and aluminum have been realized. The cross-sectional area of the thick electroplated metallization is approximately an order of magnitude greater than that of the standard metallization procedures for similar collector geometries [35]. As a result, the current-carrying capacity of the collectors will increase and the series resistance of the metallization will decrease.

5.2. Probes for neural sensing and stimulation

The use of micromachining to create miniature probes for the stimulation and recording of neural activity is well documented (see, for example, Ref. [36]). Previous micromachining-based efforts have focused almost exclusively on silicon-based probes. Electroplated metallic probes fabricated using polyimide-based processes have also been demonstrated recently [37]. These metallic probes have several advantages: long (several millimeters) prismatic probes which minimize insertion tissue damage can easily be fabricated; electrode arrays in one and two dimensions are realizable; a variety of different metals can be used in fabrication; and the probes can be added in a post-processing fashion to foundry integrated circuits to inexpensively realize a 'smart' probe.

Fig. 9 shows electrically isolated microprobes fabricated using polyimide-based processes. The microprobes were fabricated using electroplated nickel and gold as structural materials. Typical device thicknesses were 15–20 μm, with an electrode width and stagger

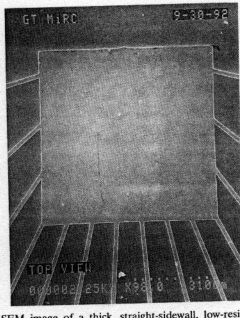

Fig. 8. SEM image of a thick, straight-sidewall, low-resistance interconnection formed on a concentrator solar cell. View of the cell; the cell is 1×1 cm in area. The metallized fingers are 17 microns high and 10 microns thick.

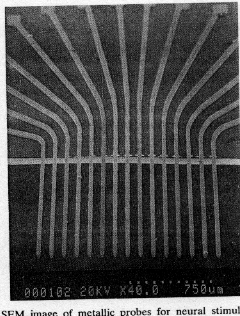

Fig. 9. SEM image of metallic probes for neural stimulation and recording. The probes are 1.1 mm long, 25 μm wide and 15 μm thick, and are overhanging the substrate onto which they are formed. Note that there is no observable out-of-plane warpage of these probes.

of 25 and 100 μm, respectively. The microelectrode array was fabricated in an overhanging fashion by forming the shaft section of the probes over a thin p^{++} silicon diaphragm and dry etching this diaphragm upon completion of the electroplating and top side isolation. A detailed description of the fabrication procedure has been given in Ref. [37]. These individual probes of the arrays have successfully been isolated; the arrays have been packaged; and the arrays have been tested in vitro to monitor neural activity in the rat olfactory bulb. The microprobes were used in more than ten testing cycles (insertion and withdrawal) without mechanical failure. Spontaneous neural signals of 10–15 μV were recorded.

5.3. Electrostatic microactuators

One of the first applications for sensitive polyimide-based processing was the electrostatic micromotor [22]. The motivation for this application was threefold. First, the photosensitive polyimide process offered a method for achieving high-aspect-ratio rotor and stator components, thus providing a way to achieve higher torque production from electrostatic micromotors. Second, using multilevel processing, this technique allowed for future integration of torque coupling structures directly onto the micromotor. This created a method for distributing the power from the micromotor to other components of a microsystem or directly to an external environment. Third, using electroplating as the process for forming the metallic microstructures offers the advantage of a wide choice of metals/alloys and material characteristics that can be customized for a given application. In the case of the electrostatic micromotor as well as other dynamic systems, material issues such as the wear resistance and residual stress are important structural parameters. These material characteristics can be controlled by electroplating variables such as the current density and the constituents of the electrolytic solution. Fig. 10 shows an electrostatic micromotor with the conventional 18–12 stator–rotor configuration. These micromotors are approximately 50 μm in height, with a rotor–pin gap of 1 μm and a rotor–stator gap of 3 μm. These devices have been constructed of several materials, including copper, gold and nickel. The micromotor illustrated in Fig. 10 was realized using post-assembly techniques. The rotor and stator/pin combination were fabricated on separate substrates; the rotors were released using sacrificial layer technology and positioned onto the pin structure. Similar micromotors with larger gaps, in which the rotor and stator/pin were fabricated in situ, have been fabricated and tested [22]. The stepping action of the micromotors was demonstrated using 350 V.

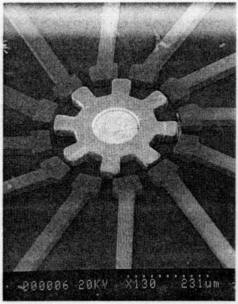

Fig. 10. Photomicrograph of an electrostatic micromotor with integrated stator/pin and a post-assembled rotor. This micromotor is 50 μm high, with a rotor–pin gap of 1 μm and a rotor–stator gap of 3 μm.

5.4. Magnetic microactuators

Although electrostatic microactuators have successfully been demonstrated in thick as well as thin versions (less than 10 μm), magnetic microactuators will probably require thicker structures, if for no other reason than that the winding coils must be made thick in order to decrease the coil resistance and thereby increase the overall efficiency of the actuator. Thus, the use of polyimide-based processes for fabricating these devices is appropriate. In addition, in the fabrication of the windings, provision must be made to 'wrap' either the coils or the cores in the third dimension using a multilevel metallization process. As polyimide has already been demonstrated to be an excellent interlayer dielectric material in multilevel metal interconnect schemes, it will be an excellent integral structural material in the fabrication of magnetic microactuators.

Using polyimide-based processes, fully integrated micromagnetic actuators [38] as well as magnetic micromotors [39] have been fabricated. Fig. 11 shows a functional magnetic micromotor achieved using polyimide-based processes [39]. The inductive component which generates flux is of the 'meander' type, meaning that a multilevel electroplated nickel–iron core is 'wrapped' around a planar meander conductor [40]. The stator and pin of this motor have been fabricated using photosensitive polyimide-based electroplating techniques. In addition, polyimide is used as the interlayer dielectric in which both the cores and the coils are imbedded and isolated from one another. The rotor is 40 μm thick nickel–iron, 500 μm in diameter, and

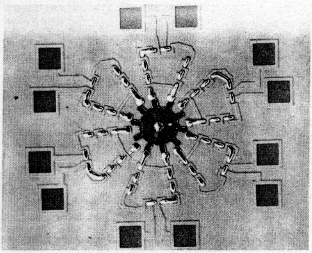

Fig. 11. SEM image of a magnetic micromotor with fully integrated stator/coils and microassembled rotor components. The rotor is 40 μm thick nickel–iron, 500 μm in diameter, and the fully integrated nickel–iron stator is 120 μm thick.

the fully integrated nickel–iron stator is 120 μm thick. By applying three phase 200 mA current pulses to the stators, rotation of the rotor was observed. The speed and direction of the rotation could be adjusted by changing the frequency and phase firing order of the power supply, respectively. Continuous rotor rotation was observed at speeds up to the maximum speed of the motor drive controller, 500 rpm.

6. Conclusions

Polyimide-based processes offer an attractive method for the fabrication of thick electroplated microstructures. Electroplating forms have been produced using both a photosensitive material approach and dry etching techniques. In this paper several applications have been demonstrated for this technology, including micromachined electrostatic and magnetic actuators, microsensor devices and high-aspect-ratio collectors for concentrator solar cells. Several applications (electrostatic micromotor, microelectrode array, and solar cell collectors) were demonstrated in which the polyimide materials were used exclusively as a tool for processing. Magnetic applications were also presented in which the polyimide material was useful as an integral part of the micromachined device.

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