Polyimide-Based Processes for the Fabrication of Thick Electroplated Microstructures

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Abstract

Recently a number of processes have been developed for the fabrication of thick electroplated microstructures, such as LIGA - based technologies and other processes. In this paper, the use of polyimide as an electroplating mold for thick electroplated microstructures is discussed. Polyimide-based processes have several. advantages: conventional lithography can be used in fabrication, deposition of the polyimide material can be performed in a conventional manner, and since the polyimide when cured is thermally and chemically resistant, it can in some applications form an integral, structural part of the final micromachined device. After a review of the available basic processes, selected applications utilizing this technology which are currently being pursued by our group are discussed.

Introduction

There is application in the field of micromachining for metallic microstructures of relatively large (i.e., 10-1000 J,lm) 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.

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 defmition and fabrication. Stationary structures including arrays of pillars and honeycombs have been produced using this method [1,2has 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 structures which 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 polyimide-based processes to realize thick electroplated microstructures.

Polyimide Materials

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. 12-14] and multichip packaging [e.g. 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 completely vertical to 45° slopes to completely isotropic have been achieved. Additional polyimide 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). electroplating in both acidic and some alkaline solutions. and the ability to electroplated three dimensionally varying structures using multicoat procedures. allow the realization of a wide variety of straight and sloped-sidewall electroplated microstructures in an inexpensive and manufacturable fashion. Use of polyimides in the fabrication of released and non-released micro machined structures made from a variety of metals is discussed below.

Photosensitive.Polyimide.Based Processes

UV-exposable, negative-working, photosensitive polyimides which can have spun-on thicknesses ranging from 3 - 150 ~ 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 is very similar to ordinary photolithography, with the exception of the large resist thicknesses used. 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 (optionally) polyimide stripping are then performed. Electroplated structures of copper, nickel, nickel-iron alloys, gold, silver as well as other metals can been realized using this technology.

The Basic Process

A typical fabrication process [18,19] is described in some detail below. Oxidized silicon wafers are used as the initial substrate (oxide thickness 0.3-1.3).tm), and a suitable electroplating seed layer of metal is deposited on the substrate. Photosensitive po1yimide (e.g., Ciba-Geigy Probimide 348, a photoimageab1e, thermally-imidiziab1e material), is then spun on the wafer. The spinning is accomplished in two stages, with a spread stage of 600 rpm for 15 seconds, and a high-speed stage of 1100 rpm for 10 seconds, leading to a film thickness of approximately 40).tm. 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 minutes at 80 °C, then 110 °C for 20 minutes to drive off solvent, followed by imaging using a standard G-1ine (436 nm) mask aligner. For a 40).!In thick film, a typical exposure energy of350 mJ/cm2 is used. The patterns in the po1yimide are then developed using Ciba-Geigy QZ 3301 developer and rinsed in QZ 3312 rinse. Either spray or ultrasonic development and rinse have been found to be sufficient for film thicknesses less than 25).tm. Ultrasonic development is needed for films with thicknesses greater than approximately 25).!In. Although no exact measurements of the sidewall profile have been performed, SEM observations indicate nearly vertical sidewalls. Antireflection coatings and G-line filters can be optionally used 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 the 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 !it 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 which 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 be optionally achieved by etching the underlying seed layer.

Results

Figure 1 shows a test cross pattern of electroplated nickel which has been fabricated using the above process. The structure is approximately 35 microns wide and 50 microns thick, with nearly vertical sidewalls. In Figure 2 an electroplated copper gear structure is shown. The gear is approximately 45 11m tall and 300 11m in diameter with a tooth width of approximately 40 11m. The maximum aspect ratios which 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 deve1oper limited.

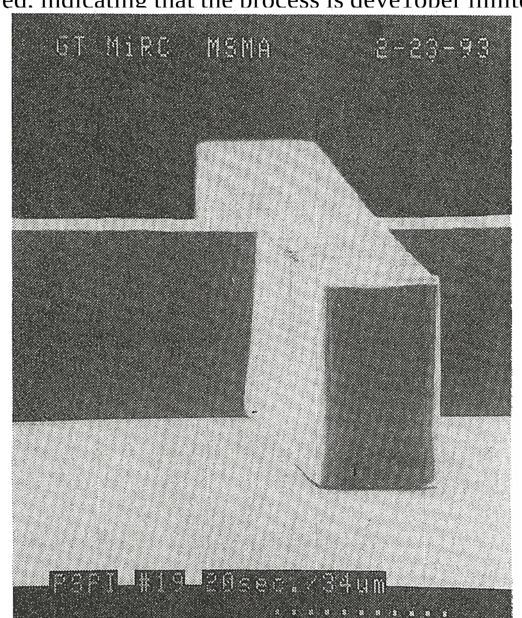

Figure 1. Scanning electron micrograph (SEM) of a cross text pattern fabricated from electroplated nickel-iron using a photosensitive polyimide electroplating mold. The cross linewidth is approximately 35 µm wide and the cross thickness is approximately 50 µm.

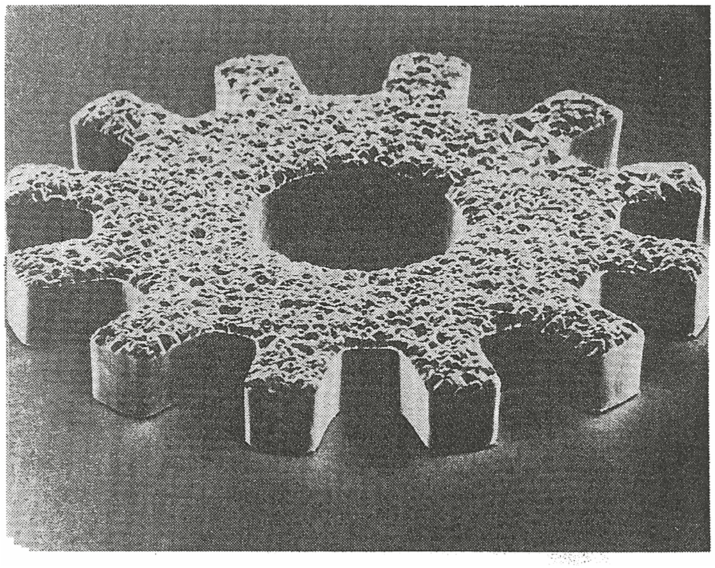

Figure 2. SEM of It copper gear fabricated using a photosensitive polyimide electroplating mold; The gear is approximately45 I.LIn in height and 300 µm in 9iameter. The width of a single tooth is approximately 40 µm. '

In order to achieve electroplated microactuators, provision must be made for release of the electroplated structures or parts pf 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 which contains a chromium or other release layer underlying the seed layer, Figure 3 shows a nickel/iron micromotor structure where the rotor has been fabricated seperately, lifted off, and microassembled onto the stator and pin assembly. Lateral underetch rates in excess'qf 25 - 35 l.Lm/hr have been observed, with negligible attack on the electroplated structures. It has also been possible to achieve selective release (as opposed to blanket release) of electroplated structures fabricated using polyimide electrpplated 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 relea~ed without simultaneously releasing stator structures. Full details of this process have been discussed in [22].

Consider an application where it is desirable to have several projected structures vertically integrated ('stacked') and attached by means of electroplasting to.form. one continuous structure. .An example of such an appl1cation rmight be the attachment of a vertical rotor shaft to an electroplated motor to .verticaly couple mechanical power out of the motor. One way to achieve this vertical integration is to cast a first..layer of resist, pattern, electroplate, yielding a metal structure1mbedded m 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 different pattern exposed, and a second metal structure plated' to ,yield a single continuous metal structure with three dimensional variation. 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 which are nearly planar. In theory, if the second pattern is identical to the rest 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 Figure 4, as well as magnetic micromotors (described below).

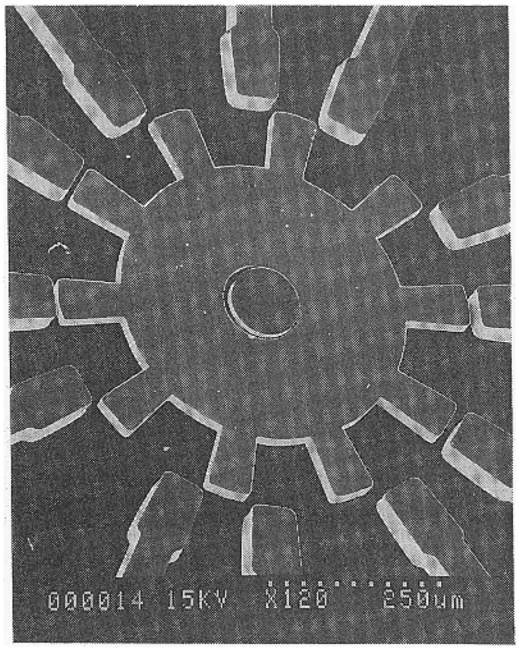

Figure 3. SEM of a separately fabricated and released nickel-iron rotor which has been microassembled onto a nickel-iron pin/stator assembly, illustrating the ability to perform microassembly with these structures.

Figure 4. SEM ora thick wrapped microinductor coil formed through a ~ultilayer polyimide electroplating process. A lower conductor is formed using a fIrst polyimide electroplating mold, a via connection is formed using a second polyimide electroplating mold, ~d an upper conductor is formed using a third polyimide el~ctroplating mold. The total thickness from substrate to top conductor in this structure is 120 J.1m.

Plasma-Based Processes

As mentioned abOve, polyimides have been used for several years as interlayer dielectrics for chips and multichip modules. Much research has gone into dry etching of these ma~erials for forming 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 vias. Sidewall slopes have been generated ranging from purely isotropic to 45 ° angles to st,raight 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.

A simple illustration of this effect is shown in Figure 5. In the fabrication of this 'bowl-shaped' structure, dry etching in a CF4iO2 plasma was used to etch a via into a thick polyimide layer. which was ultimately used to form the 'bowl'. The isotropy of the ,dry etch was controlled by varying the ratio of oxygen to fluorine in the etching ambient.

Recently, there has been much work by a variety of researchers in dry etching of polyimides to form extremely high aspect ratio structures. 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 [24] and fluorinated polyimides [25] has been used for deep etching of polyimides with high aspect ratio, excellent mask selectivity, and smooth sidewalls. Circular cylinders 15 ~m in diameter and 100 ~m in height have been achieved using these methods. Another method which has been used is cryogenic reactive ion etching [26], 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 which can be achieved by reducing any latecral etching of the structures to a very small amount.

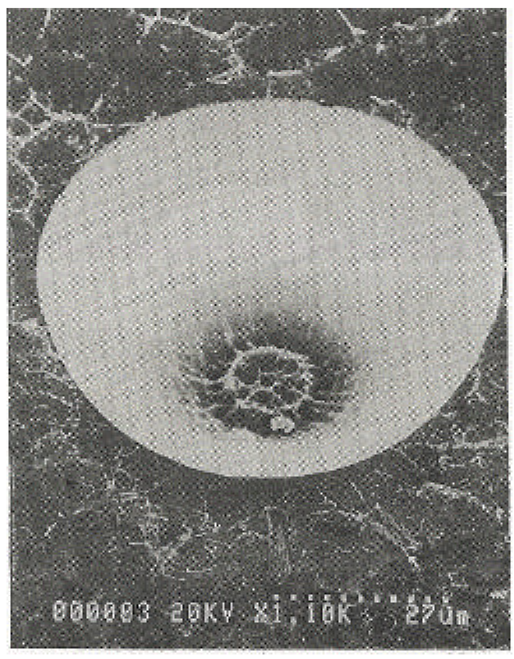

Figure 5. SEM of a bowl-shaped structure formed using an isotropic, dry-etched polyimide electroplating mold.

Applications

In this section, several applications of metallic microstructures fabricated using polyimides as either electroplating molds, integral device components, or both, which are being
pursued at Georgia Tech, are briefly discussed. c

High Current Solar Cell Metallization

In the fabrication of solar cells, there is a tradeoff in the design of the metallic traces which are used to make contact to the cell. The larger these traces are, the lower the series resistance of the cell; however, if the area of the traces is increased, more light is blocked from the cell, decreasing the total power output of the cell. This effect is especially severe in concentrator solar cells, where the incident light is concentrated on the cell by an external optical system, and the resultant cell currents are much higher. One possibility for overcoming this problem is to fabricate relatively thick, straight,.sidewall metallization 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.

Figure6a shows an SEM photograph of a solar cell structure with electroplated straight-sidewall metallization. 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 Ii1 Figure 6b, a closeup view of one of the fingers is shown. This particular finger is 17 microns in height and 10 microns in width.

Probes for Neural Monitoring and Stimulation

The use of micromachining to create miniature probes for the stimulation and recording of neural activity is well-documented [e.g., 27]. Previous micromachining-based efforts have focused almost exclusively on silicon-based probes. Electroplated metallic probes fabricated using polyimide-based processes have also been recently demonstrated [28]. These metallic probes have several advantages: long (several millimeter) prismatic probes which minimize insertion tissue damage can easily be fabricated; electr... able; a variet... nd the probe... undry integr... be.

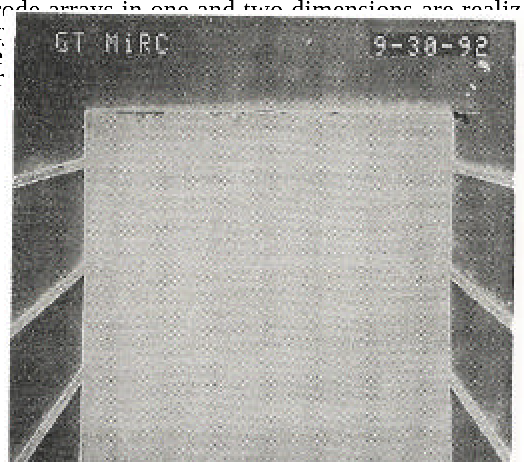

Figure 6a. SEM of a thick, straight-sidewall, low resistance interconnection formed on a concentrator solar cell. View of cell; the cell is lcm x lcm in area.

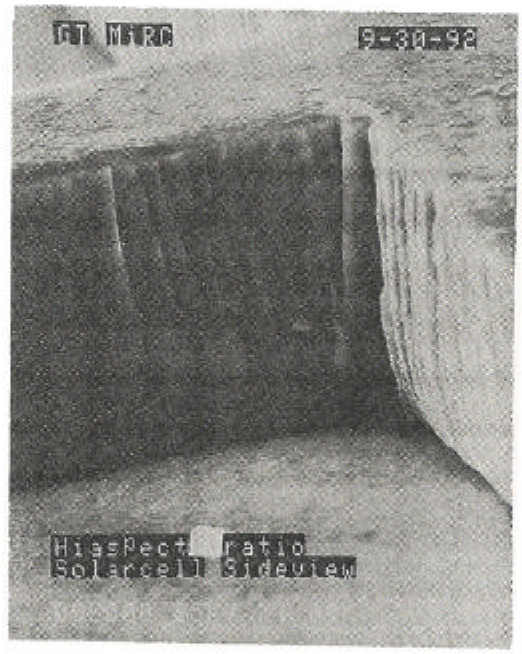

Figure 6b. SEM of a thick, straight-sidewall, low resistance interconnection formed on a concentrator solar cell. Close view of a single metallization 'fmger' the finger is 17 microns in height and . 10 microns in thickness.

Figure 7 shows electrically isolated microprobes fabricated using polyimide-based processes. These devices were fabricated in an overhanging fashion by forming the overhanging section of the probes over a thin silicon diaphragm and etching away this diaphragm upon completion of the fabrication. These probes have been successfully isolated, packaged, and used *in vivo* to monitor neural activity in the rat olfactory bulb.

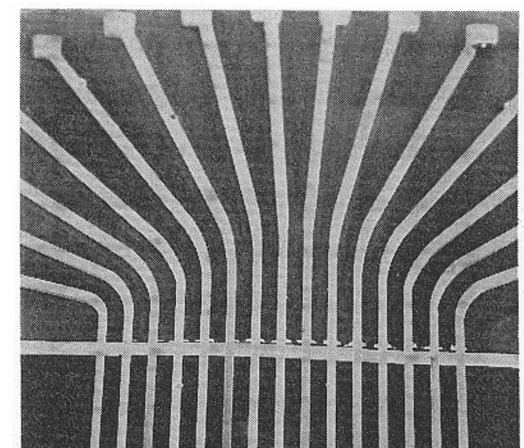

Figure 7. SEM of metallic probes for neural stimulation and recording. The probes are 1.1 rom long, 25 ~m wide, and 15 ~m thick, and are overhanging the substrate onto which they are formed. Note that there is no observable out-of-plane warpage of these probes~

Magnetic MIcroactuators

Although electrostatic microactuators have been successfully demonstrated In thick as well as thin versions (less than 10 microns), magnetic microactuators will probably require thicker structures, if for no other reason than the winding coils must be made thick m order to decrease the coil resistance and thereby increase the overall efficiency of the actuator. Thus, the use of polyimide-based processes for fabricatmg these devices is appropriate. In addition, m 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 mterlayer dielectric material in multilevel metal mterconnect schemes, it will be an excellent integral structural material in the fabrication of magnetic microactuators.

Using polyirnide-based processes, we have fabricated fully integrated micromagnetic actuators [29] as well as magnetic micromotors [30]. Figure 8 shows a functional magnetic micromotor which has been. achieved using polyimide-based processes. 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 [31]. The stator and pin of this motor have been fabricated using polyimide- based electroplating techniques.' In addition, polyimide is used as the mterlayer dielectric m which both the cores and the coils are imbedded. The rotor is 40 µm thick nickel-iron, 500 µm m diameter, and the fully integrated nickel-iron stator is 120 µm thickness. 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. Contmuous rotor rotation was observed at speeds up to the maximum speed of the motor drive controller, 500 rpm.

Conclusions

Polyimide-based processes offer an attractive method for the fabrication of thick electroplated microstructures. Electroplating forms can be produced either using a photosensitive material approach, or by using dry etching techniques. In addition, since polyimides are chemically and thermally stable, they are also useful as integral parts of micromachined devices.

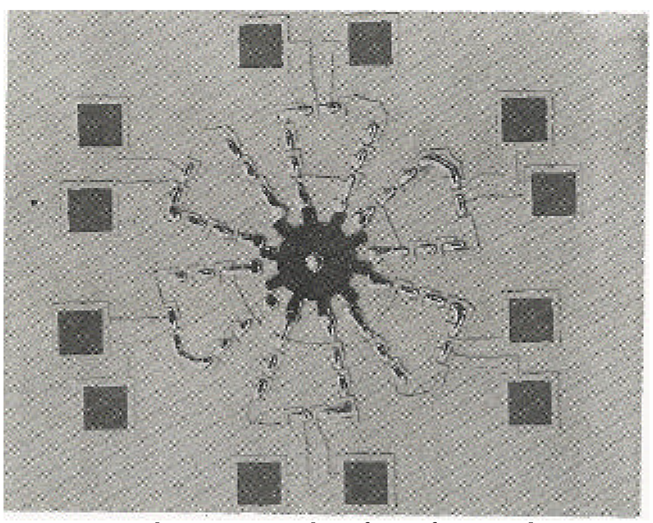

Figure 8a. .Photomicrograph of a functional magnet micromotor with fully integrated staator and coils and microassembled rotor. The structure dimensions are given in the text.

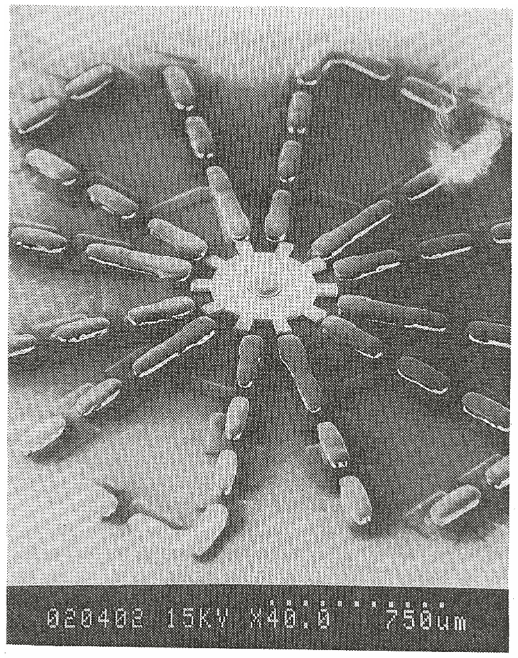

Figure 8b. SEM of a functional magnetic micromotor with fully integrated stator and coils and microassembled rotor. The structure dimensions are given in the text.

Acknowledgements

The work done at Georgia Tech which is described in 1his paper was performed by Mr. Chong-Hyuk Ahn, Mr. A. Bruno Frazier, and Mr. Jeong-Bong Lee. Portions of this work were 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. Donation of the polyimides used in this work by both DuPont and OCG Microelectronic Matecrials is also gratefully acknowledged.

References

1. E.W. Becker, W. Ehrfeld, P. Hagmann, A. Maner and D. Munchmeyer, 'Fabrication of Microstructures with High Aspect Ratios and Great Structural Heights by Synchrotron Radiation Lithography, Galvanoforming, and Plastic Moulding (LIGA Process), Microelectronic Engineerin~, vol. 4, 1986, pp. 35-56.

2. W. Ehrfeld, P. Bley, F. Gotz, P. Hagmann, A. Manar, J. Mohr, H.O. Moser, D. Munchmeyer, W. ScheIb, D. Schmidt and E.W. Becker, 'Fabrication of Microstructures using the LIGA Process', Proceedin&s of the 19R7 IEEE Micro Robots and Teleo~erators Worksho~, Hyannis, MA, Nov. 9-11,1987.

3. H. Guckel, T.R. Christenson, K.J. Skrobis, D.D.nenton, B. Choi,E.G. Lovell,J.W. Lee, S.S. Bajikar and T.W. Chapman, 'Deep X-Ray and UV Lithographies for Micromechanics', ProQeedin!!s of the IEEE Solid-State Sensor and Actuator Worksho~, Hilton Head, SC, June, 1990, pp. 118.122.

4. W. Menz, W. Bacher, M.Harmeningand A. Michel, 'The Liga Technique - A Novel Concept for Microstructures and the Combination with Si- Technologies by Injection Molding', Proceedin!!s of the 1991 IEEE~ Micro Electro Mechanical Svstems Conference, Nara, Japan, January, 1991, pp. 69-73.

5. W. Ehrfeld, F. Gotz, D. Munchmeyer, W. ScheIb and D. Schmidt, 'Liga Process: Sensors Construction Techniques Via X-ray Lithography', Proceedin&s of the illEE Solid-State Sensor andActuatorWorksho~. Hilton Head, SC, June, 1988, pp. 1-4.

6. H. Guckel, T.R. Christenson,K.J. Skrobis, J.J. Sniegowski, J.W. Kang, B. Choi and E.G. Lovell, 'Microstructure Sensors', Proceedin~s of the 1990 IEEE International Electron Devices Meetin~, San Francisco, CA, December, 1990, pp. 613-616.

7. C. Burbaum, J. Mohr and P. Bley, 'Fabrication of Capacitive Acceleration Sensors by the Liga Technique', Sensors and Actuators, A25-27, 1991, pp. 559-563.

8. B. Choi, E.G. Lovell, H. Guckel, T.R. Christenson, K.J. Skrobis and J. W. Kang, 'Development of Pressure Transducers Utilizing Deep X-ray Lithography, Proceedings of the 6th International Conference on Solid-State Sensors and Actuators, San Fransisco, CA, June, 1991, pp. 393-396.

9. J. Mohr, B. Anderer and W. Ehrfeld, 'Fabrication of a Planar Grating Spectrograph by Deep-etch Lithography with Synchrotron Radiation', Sensors and Actuators, A25-27, 1991, pp.571-575.

10. J. Mohr, C. Burbaum, P. Bley, W. Menz and U. Wallrabe, 'Movable Microstructures Manufactured by the Liga Process as Basic Elements for Microsystems', Micro S~stem Technologies 2Q:, Berlin, Germany, September, 1990, pp. 529-537.

11. J. Mohr, P. Bley, C, Burbaum, W. Menz and U. Wallrabe, 'Fabrication of Microsensor and Microactuator Elements by the Liga-Process', Proceedings of the 6th International Conference on Solid-State Sensors and Actuators, San Fransisco, CA, June, 1991, pp. 607-609.

12. I. Milosevic, A. Perret, E. Losert and P. Schlenkrich, 'Polyimide Enables High Lead Count TAB', Semiconductor International, October, 1988, pp. 28-31.

13. K.K. Chakravorty, C.P. Chien, J.M. Cech, L.B. Branson, J.M. Atencio, T.M. White, L.S. Lathrop, B.W. Aker, M.H. Tanielian and P.L. Young, 'High Density Interconnection Using Photosensitive Polyimide and Electroplated Copper Conductor Lines', Proceedin~s of the Thirt~-ninth Electronic Com12onents Conference, Houston, Texas, May, 1989, pp.135-142.

14. K. Moriya, T. Ohsaki and K Katsura, 'Photosensitive Polyimide Dielectric and Electroplating Conductor', Proceedings of the The-fourth Electronic Com12onents Conference, New Orleans, LA, May, 1984,pp. 82-87.

15. P.G. Rickerl, J.G. Stephanie and P. Slota, 'Processing of Photosensitive Polyimides for Packaging Applications', IEEE. Transactions on Components. H~brids. and Manufacturing Technology, December, 1987, pp. 690-694.

16. G.J. Dishon, S.M. Bobbio, T.G. Tessier, Y. Ho andR.F. Jewett, 'High Rate Magnetron RIB of Thick Polyimide Films for Advanced Computer Packaging Applications', Iournal of Electronic Materials, vol. 18, 1989, pp. 293-299.

17. G.M. Adema, I. Turlik, P.L. Smith and M.J. Berry, 'Effects of Polymer/Metal Interaction in Thin-Film Multichip Module Applications', Pmceeding of the Fortieth Electronic Com12onents Conference, Las Vegas, Nevada, May, 1990, pp. 717-726.

18. A.B. Frazier and M.G. Allen, 'High Aspect Ratio Electroplated Microstructures Using A Photosensitive Polyimide Process', Proceedings of the lEER Microelectromechanical S);stems Conference, Travemlinde, Germany, February, 1992, pp. 87-92.

19 A.B. Frazier and M.G. Allen, 'Metallic Microstructures Fabricated Using Photosensitive Polyimide Electroplating Molds', Journal of Microelectromechanical Systems. in review.

20. H. Guckel, K.J. Skrobis, T.R. Christenson, J. Klein, S. Han, B. Choi and E.G. Lovell, 'Fabrication of Assembled Micromechanical Components Via Deep X-ray Lithography', Proceedings of the 1991 IREE Micro Electro Mechanical Systems Conference, Nara, Japan, January, 1991, pp. 74-79.

21. H. Guckel, K.J. Skrobis, T.R. Christenson, J. Klein, S. Han, B. Choi, E.G. Lovell, T.W. Chapman, 'On the Application pf Deep X-ray Lithography with Sacrificial Layers to Sensor and Actuator Construction (the Magnetic Micromotor with Power Takeoffs)', Proceedings of the 6th International Conferenceg on Solid-State Sensors and Actuators, San Fransisco, CA, 1991.

22. A.B. Frazier, J. W. Babb, M.G. Allen and D.G. Taylor, 'Design and Fabrication of Electroplated Micromotor Structures', Proceedings of the ASME Winter Annual Meeting, Atlanta, GA, December 1991.

23. C.H. Ahn, Y.J. Kim, and M.G. Allen, 'A Fully Integrated Micromachined Toroidal Inductor With A Nickel-Iron Magnetic Core', Proceedings of the Seventh International Conference on Solid State Sensors and Actuators. Yokohama, Japan, June, 1993.

24. F. Shimokawa and S. Matsui, 'Fast and Extremely Selective Polyimide Etching with a Magnetically Controlled Reactive Ion Etching System, Proceedings of the IEEE MicroelectrQ- mechanical Systems Conference, Nara, Japan, February, 1991, pp.192-197.

25. A. Furuya, F. Shimokawa, T. Matsuura, ~d R. Sawada, 'Micro- grid Fabrication of Fluorinated Polyimide By Using Magnetically Controlled Reactive Ion Etching', Proceedings of the IEEE Microelectromechanica1 Systems Conference, Fort Lauderdale, Florida, February, 1993, pp. 59-64.

26. K. Murakami, Y. Wakabayashi, K. Minami, and M. Esashi, 'Cryogenic Dry Etching for High Aspect Ratio Microstructures', Pr()ceedin~i\ of the IEEE Microelectromechanical Systems Conference, Fort Lauderdale, Florida, February, 1993, pp. 65- 70.

27. S.L. BeMent, K.D. Wise, D.J. Anderson, K. Najafi, and K.L. Drake, 'Solid-State Electrodes for Multichannel Multiplexed Intracortical Neuronal Recording', IEEE Transactions on Biomedical Engineering, vol. BME-33, 1986, pp. 230-241.

28. A. B. Frazier, D..P. O'Brien, and M.G. Allen, 'Two Dimensional Metallic Microelectrode Arrays for Extracellular Stimulation and Recording of Neurons', Proceedin~sof the IEEE Microelectromechanical S~stems Conference, Fort Lauderdale, Florida, February, 1993, pp. 195-200.

29. C.H. Ahn and M.G. Allen, 'A Fully Integrated Magnetic Microactuator With A Multilevel Meander Magnetic Core', Proceedings of the IEEE Solid State Sensor and Actuator Workshop, Hilton Head, South Carolina, June, 1992.

30. C.H. Ahn, Y.J. Kim, and M.G. Allen, 'A Planar Variable Reluctance Magnetic Micromotor With Fully Integrated Stator and Wrapped Coils', Proceedings of the IEEE Microelectro, mechanical Systems Conference, Fort Lauderdale, Florida, February, 1993, pp. 1-6.

31. C.H. Ahn and M.G. Allen, 'A Toroidal-Meander Type Inte- grated Inductor With A Multilevel Meander Magnetic Core'; IEEE Transactions on Magnetics, in review.