Integrated Fabrication of Polysilicon Mechanisms

MEHRAN MEHREGANY, KAIGHAM J. GABRIEL, MEMBER, IEEE,
AND WILLIAM S. N. TRIMMER, MEMBER, IEEE

Abstract—**Successful implementation of simple mechanisms on silicon is a prerequisite for the design of monolithic microrobotic systems. This paper describes the integrated fabrication of planar polysilicon mechanisms incorporating lower and higher *kinematic pairs*, where the term *kinematic pair* signifies a joint. The two lower kinematic pairs (revolute and prismatic) commonly used in macrorobotic systems are precisely those two joints that are compatible with silicon microfabrication technology. The mechanisms are fabricated by surface micromachining techniques using polysilicon as the structural material and oxide as the sacrificial material. Turbines with gear and blade rotors as small as 125 μm in diameter and 4.5 μm in thickness were fabricated on 20-μm-diameter shafts. A clearance as tight as 1.2 μm was achieved between the gear and the shaft. Gear trains with two or three sequentially aligned gears were successfully meshed. A submillimeter pair of tongs with 400-μm range of motion at the jaws was fabricated. This structure incorporates a single prismatic joint and two revolute joints, demonstrating linear-to-rotary motion conversion.**

I. INTRODUCTION

BULK and surface micromachining of silicon have been used extensively to fabricate a variety of micromechanical structures such as thin silicon diaphragms [1]–[3], beams [4]–[6], and other suspended structures [7]–[9] in single-crystal silicon or in films deposited on a silicon substrate. These micromechanical structures are generally limited in motion to small deformations and are physically attached to the substrate. Such elastic components may be used occasionally as flexible joints, but their overall usefulness in the design of *mechanisms* is limited. "Mechanism" as used here is a means for transmitting, controlling, or constraining relative movement and is considered as a collection of rigid bodies connected together by joints.

Mechanisms, actuators, sensors, and drive electronics are the four building blocks of any robotic system. For a robot arm to trace a specified trajectory, the actuators provide the input to move the arm mechanism. The sensors in conjunction with the control and drive electronics provide the necessary local or global feedback for correcting the in-route and final position of the end-effector. Therefore, a prerequisite to the design of any monolithic microrobotic system is the successful implementation of mechanisms on silicon. Although it is difficult to envision the variety of future applications for such microrobotic systems, the more immediate impact of these systems may be in the area of photonic component alignment.

This paper discusses the design and fabrication of conventional mechanisms scaled down to submillimeter dimensions. Initially, a brief discussion of the necessary kinematic pairs for monolithic microrobotics systems is presented. Related work is reviewed, and the integrated fabrication process for polysilicon mechanisms is discussed. Finally, fabricated mechanisms including turbines, gear-trains, and a submillimeter pair of tongs are described.

II. KINEMATIC PAIRS

A joint, also referred to as a kinematic pair, signifies a connection between two bodies. This connection may be in the form of a point, line, or curve contact such as the straight line contact between the teeth of two meshed gears. Joints of this type are classified as higher kinematic pairs. On the other hand, the two bodies may be in contact over a large area of a surface such as a ball joint (spherical pair). These joints are classified as lower kinematic pairs and may be found in six configurations (in three dimensions) including spherical, planar, cylindrical, turning, prismatic, and screw pairs. Hunt [10] has discussed this topic in detail, which has been summarized here to establish a common terminology among researchers working in the area of microsensors, microactuators, and robotics.

Due to the planar nature of the silicon microfabrication technology, any mechanism design at this time would essentially have a planar geometry. Of the six lower kinematic pairs in space, two have appropriate planar counterparts for mechanism design on silicon. The turning and prismatic pairs in space simplify to revolute (rotary) and prismatic (linear) joints in the plane. Conventional robotics mostly relies on these two single-degree-of-freedom joints due to their single input nature. Therefore, limiting to these two forms of joints is not constraining in the design of monolithic micromechanisms. However, lower kinematic pairs do not provide all of the necessary movements as demanded by robotic systems. Gear trains (joining via higher kinematic pairs) are indispensable in many mechanism designs.

III. RELATED WORK

We have previously reported on the fabrication of discrete silicon components in an attempt to investigate the

---

Manuscript received September 30, 1987; revised January 15, 1988.

M. Mehregany is with the Robotic Systems Research Department, AT&T Bell Laboratories, Holmdel, NJ 07733, and with the Massachusetts Institute of Technology, Cambridge, MA 02139.

K. J. Gabriel is with the Machine Perception Research Department, AT&T Bell Laboratories, Holmdel, NJ 07733.

W. S. N. Trimmer is with the Robotic Systems Research Department, AT&T Bell Laboratories, Holmdel, NJ 07733.

IEEE Log Number 8820665.

potential of small hybrid silicon mechanisms [11], [12]. Gears and turbine blades 40 to 50 μm in thickness and 300 to 2400 μm in diameter were fabricated. Reactive-ion etching was used to form the structures on the surface of a silicon substrate that was later dissolved to free the components. A silicon air turbine was assembled out of discrete components and operated at 400 rps. However, the final assembled systems have large tolerances due to discrete assembly requirements. In addition, handling of small discrete parts is difficult, limits component-size reduction, and reduces final yield. Finally, gears and turbine blades fabricated from single-crystal silicon are prone to cleaving along crystallographic planes.

The integrated fabrication of pin joints and bearings using surface micromachining techniques have been previously reported [12]–[17]. The following sections describe in detail the integrated fabrication of polysilicon mechanisms including: turbines incorporating appropriate flow channels and using gear or blade rotors, gear trains incorporating appropriate flow channels and having two or three meshed gears, and a pair of tongs with both revolute and prismatic joints. The integrated fabrication technique eliminates the need for discrete component assembly, and further dimensional control (component size and intercomponent clearance) is only limited by the standard integrated circuit fabrication capabilities.

IV. FABRICATION

Fig. 1 illustrates the process steps for the microfabrication of a typical structure (e.g., a turbine with gear rotor):

First oxide step: Using high-pressure oxidation, a 4.0-μm-thick layer of thermal oxide is grown at 850°C. A photolithography step is used to remove the oxide where the flow channel walls are to be fabricated. A second photolithography step is performed to create circular and annular steps (2.0 to 2.5 μm deep) in the oxide (Fig. 1(a)). This provides the depressions necessary for annular bearings to be incorporated into the movable parts. The oxide etches here and in the next two steps are all performed in a reactive-ion etcher using a CHF_3 plasma.

First polysilicon step: A 4.5-μm-thick LPCVD polysilicon layer is deposited at 630°C using a silane-hydrogen mixture. The polysilicon is patterned in a reactive-ion etcher using a $Cl_2/CFCl_3/Ar$ plasma, forming the movable part and the flow channels (if needed) of the eventual structure (Fig. 1(b)). For the polysilicon etch step, a 2.0-μm-thick CVD oxide layer deposited at 700°C from tetraethylorthosilane (TEOS) and patterned in a CHF_3 plasma is used as an etch mask. Upon completion of the polysilicon etch, the remaining masking oxide is removed in a CHF_3 plasma.

Second oxide step: Additional CVD oxide (1.2 μm thick) is deposited at 700°C from TEOS, covering the entire structure. The oxide is patterned in a CHF_3 plasma opening a hole, exposing the substrate below and allowing for the attachment of the constraining member. In addition, this etch defines the flow channels in the oxide (Fig. 1(c)).

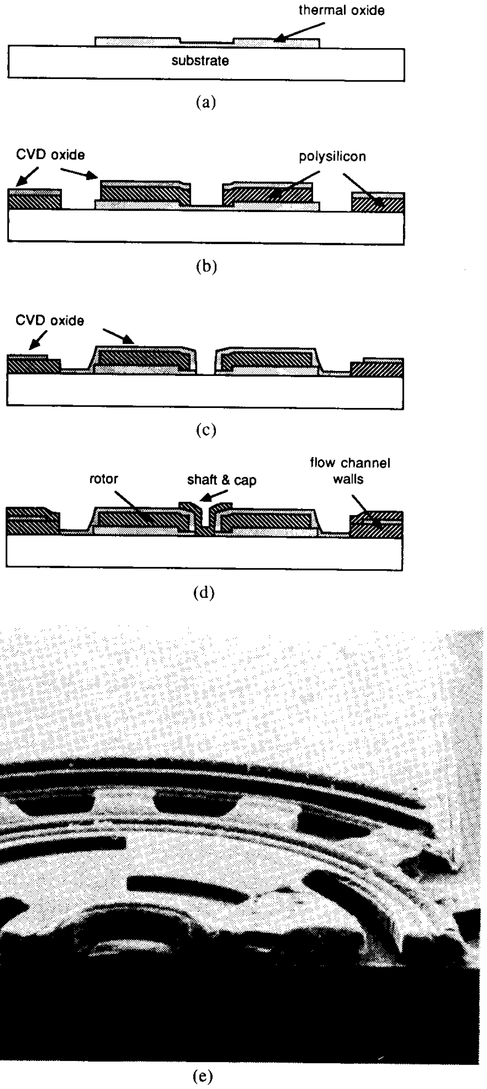


Fig. 1. Cross-sectional views of a typical structure during the fabrication process: (a) First oxide step; (b) first polysilicon step; (c) second oxide step; (d) second polysilicon step; and (e) a resulting 120-μm-radius gear which is sawed in half and partially released.

Second polysilicon step: A 3.0-μm-thick polysilicon layer is deposited under the same conditions as the first polysilicon step. This layer is patterned (using a reactive-ion etcher in a $Cl_2/CFCl_3/Ar$ plasma) to create the shaft and cap contacting the silicon substrate, and to build up the walls of the flow channels (Fig. 1(d)).

Finally, the movable part of the structure can be released by dissolving the oxide in a buffered or diluted HF solution (Fig. 1(e) shows a partially released gear sawed in half to display the cross section of the structure). When releasing the structures, the oxide about the shaft area is the last to dissolve. With the exception of the tongs, the length of time required in 10:1 buffered HF for the release of the structures presented in the next section is 6 to 8 h at room temperature. Shorter release times can be achieved by using straight HF-water mixtures. The release time is close to 40 min for a 1 : 1 HF-water solution at room temperature. The tongs require approximately 48 h in 7:1 buffered HF before they are entirely released. When the sacrificial oxide layers were fully dissolved, the structures were entirely free to move and did not require any additional manipulation to release them.

Even though stress nonuniformities through the polysilicon thickness can result in out-of-plane deformations of the structures, such deformations were not observed. This may have been due to the large thickness-to-length ratios of the structures (each polysilicon layer is at least 3 μm thick), the magnitude of stress variations in the polysilicon, or both. Therefore, it was not necessary to incorporate a step in the above fabrication process for annealing the stress in polysilicon.

Note that the clearance between the shaft and the moving part is determined by the smaller of the clearances allowed by the lithographic mask or the second oxide layer thickness. In our case, the oxide thickness was the controlling parameter giving a clearance of 1.2 μm on each side. The lithographic clearance was selected at 3.0 μm on each side of the shaft. Note that by using dry anisotropic etches throughout the patterning and definition steps the potential for undesirable lateral etching is eliminated.

V. Fabricated Mechansims

Turbines with gear or blade rotors, 125 to 240 μm in diameter, were fabricated using the above process steps. Each turbine incorporated two input ports and an output port. Fig. 2 is a SEM photograph of an entirely released turbine with a blade rotor, 125 μm in diameter. The SEM picture was taken after the turbine was spun by air. We have used a high-speed camera to measure the top speed of our turbines. However, even at 2000 frames per second (which is currently our limit), the motion of the turbine rotor cannot be resolved to allow accurate predictions of turbine speed. A lower limit of 15 000 rpm can be calculated assuming that the rotor advances by at least one eighth of a revolution (one blade) per frame. Furthermore, our current air flow control method does not allow for meaningful analytical estimation of rotor speeds based on simple fluid dynamic models.

Gear trains incorporating two or three meshed gears were fabricated with gear reduction ratios ranging from 1.4 : 1 to 1 : 1. Fig. 3 shows a partially released gear train with a 1.4 : 1.0 : 1.0 gear reduction ratios. The two flow channels on the top are connected to the two independent input ports; the two flow channels at the bottom are connected to the output port. Fig. 4 is a SEM photograph of the gear-train after the gears have been entirely released and then moved manually using a micro-probe to turn the larger gear. Fig. 5 shows a close-up of the engaged teeth of the two smaller gears. Note that the annular bearing steps that are incorporated in the gears keep them approximately 2 μm above the substrate surface, reducing the surface contact area. Also note the partially etched surface near the teeth that resulted from partial failure of the first polysilicon layer etch mask. Fig. 6 is a side-view

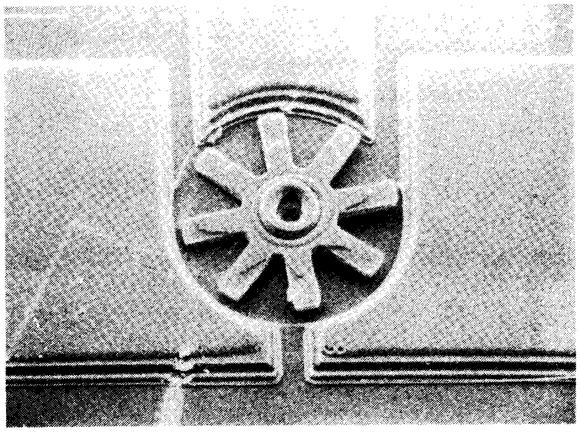


Fig. 2. A released polysilicon turbine with a blade rotor (10 μm per white dash).

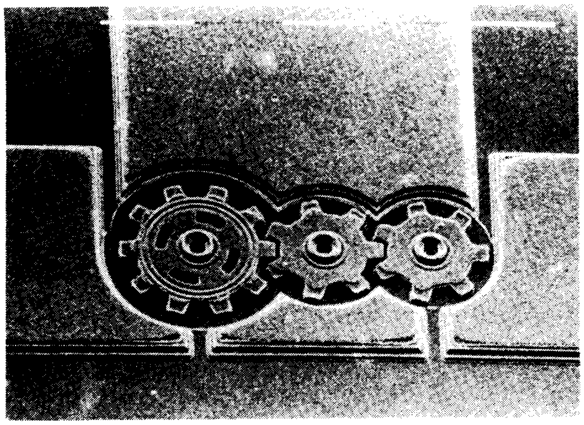


Fig. 3. A partially released polysilicon gear-train (100 μm per white dash).

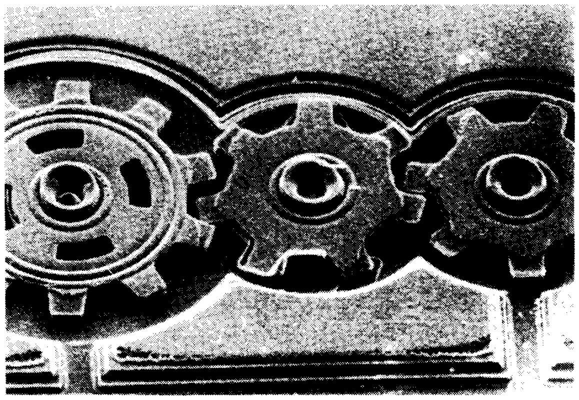


Fig. 4. The gear-train after being released and moved.

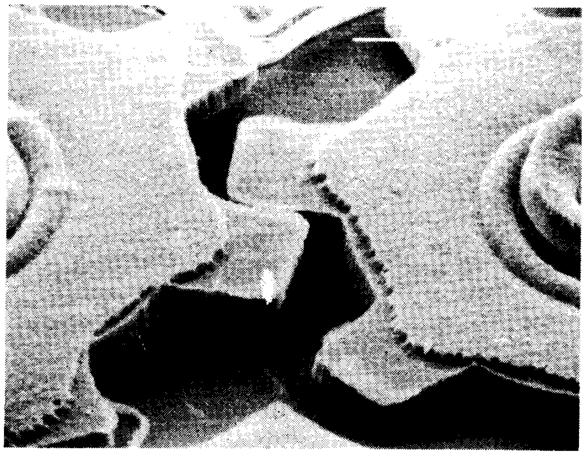


Fig. 5. The meshed teeth of the two small gears in Fig. 4 (tooth depth is 20 μm).

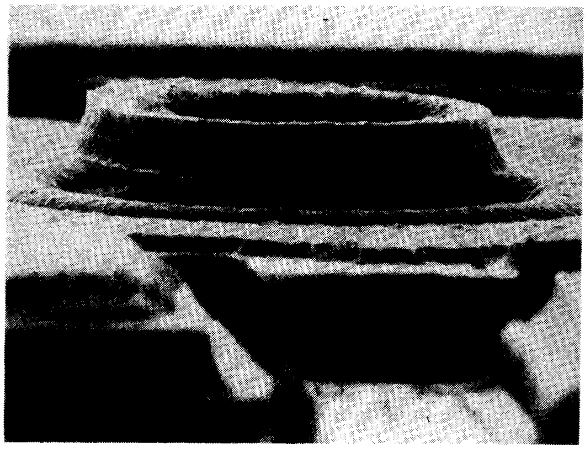


Fig. 6. Side view of the cap, shaft, and the annular bearing depression of the gear on the right in Fig. 5.

SEM photograph showing the cap, the shaft, and the annular bearing depression for the small gear on the right in Fig. 5.

Fig. 7 is a SEM photograph of a partially released pair of tongs. The jaws open when the linearly sliding handle is pushed forward, demonstrating the linear slide and the linear-to-rotary motion conversion. Fig. 8 shows an entirely relased pair of tongs with the jaws open. For this pair of tongs, the jaws open up to 400 μm wide.

The above structures are rugged and are not easily damaged by external manipulation. We have regularly used microprobes to pull and push on these structures without damaging them. However, when air is used to spin the turbines or the gear trains at high speeds, the cap portion of the shaft often breaks allowing the rotor to come loose (Fig. 9). Shaft cap fracture has been the only mode of failure observed for these structures thus far. This is most likely due to vertical motion of the rotor introduced by uncontrolled air flow in the turbine. Fig. 10 shows a close

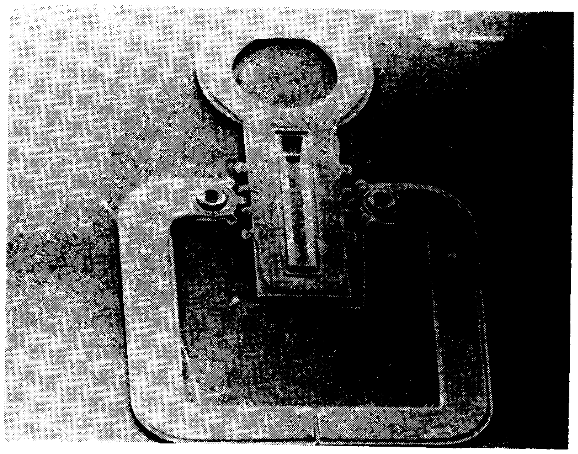


Fig. 7. A partially released pair of tongs (100 μm per white dash).

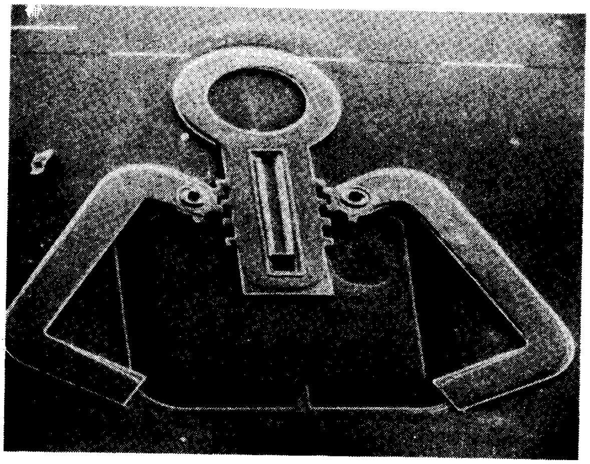


Fig. 8. A released pair of tongs opened by pushing the handle forward (100 μm per white dash).

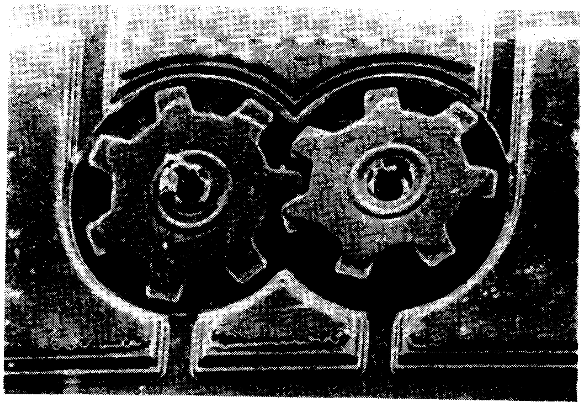


Fig. 9. A pair of gears with damaged caps resulting from a high-speed spin (10 μm per white dash).

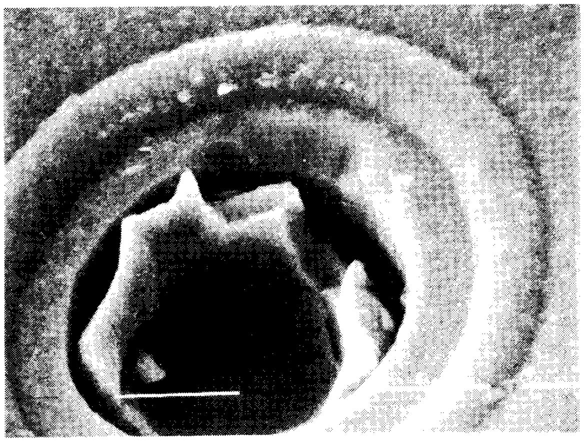


Fig. 10. A close-up view of the right shaft in Fig. 9 (10 μm per white dash).

up of the broken shaft of the right gear in Fig. 9. Note the tight clearance between the shaft and the gear (i.e., 1.2 μm on each side) and the top view of the annular bearing step near the shaft.

VI. CONCLUSION

Silicon microfabrication processes are used for integrated fabrication of polysilicon mechanisms capable of large rotary or linear motion in the plane of the substrate about the normal axis. The integrated fabrication process has two distinct advantages: first, it provides the potential for accurate control of the structural geometries and required clearances, avoiding undesirably large tolerances in the final structure. Second, it eliminates the need for handling individual parts, greatly reducing the processing cost and improving the final yield. Successful implementation of the lower and higher kinematic pairs incorporated in the planar mechanisms presented here is the preliminary step toward the design of monolithic microrobotic systems.

ACKNOWLEDGMENT

The authors wish to thank K. Orlowsky and N. Ciampa for fabrication resources and J. Walker for valuable technical assistance.

REFERENCES

[1] Y. S. Lee and K. D. Wise, "A batch-fabricated silicon capacitive pressure transducer with low temperature sensitivity," *IEEE Trans. Electron Devices*, vol. ED-29, no. 1, pp. 42-48, Jan. 1982.

[2] H. Guckel, S. Larsen, M. G. Lagally, J. B. Miller, and J. D. Wiley, "Electromechanical devices utilizing thin silicon diaphragms," *Appl. Phys. Lett.*, vol. 31, no. 9, pp. 618-619, Nov. 1977.

[3] M. Mehregany, M. G. Allen, and S. D. Senturia, "The use of micromachined structures for the measurement of mechanical properties of thin films," in *Tech. Dig. IEEE Solid-State Sensors Workshop* (Hilton Head, SC, June 1986).

[4] K. E. Peterson, "Micromechanical light modulator array fabricated on silicon," *Appl. Phys. Lett.*, vol. 31, no. 8, pp. 521-523, Oct. 1977.

[5] L. M. Roylance and J. B. Angell, "A batch fabricated silicon accelerometer," *IEEE Trans. Electron Devices*, vol. ED-26, no. 12, pp. 1911-1917, Dec. 1979.

[6] H. Guckel, T. Randazzo, and D. W. Burns, "A simple technique for the determination of mechanical strain in thin films with application to polysilicon," *J. Appl. Phys.*, vol. 57, no. 5, pp. 1671-1675, Mar. 1985.

[7] M. Mehregany, R. T. Howe, and S. D. Senturia, "Novel microstructures for the *in-situ* measurement of mechanical properties of thin films," *J. Appl. Phys.* vol. 62, pp. 3579-3584, Nov. 1987.

[8] J. C. Greenwood, "Etched silicon vibrating sensor," *J. Phys. E: Sci. Instrum.*, vol. 17, pp. 650-652, 1984.

[9] M. A. Schmidt, R. T. Howe, S. D. Senturia, and J. H. Haritonidis, "A micromachined floating-element shear sensor," in *Tech. Dig. 4th Int. Conf. Solid-State Sensors and Actuators* (Tokyo, June 1987), pp. 277-282.

[10] K. H. Hunt, *Kinematic Geometry of Mechanisms*. London: Oxford, 1978, ch. 1.

[11] M. Mehregany, K. J. Gabriel, and W. S. N. Trimmer, "Micro gears and turbines etched from silicon," *Sensors and Actuators*, vol. 12, pp. 341-348, Nov./Dec. 1987.

[12] K. J. Gabriel, W. S. N. Trimmer, and M. Mehregany, "Micro gears and turbines etched from silicon," in *Tech. Dig. 4th Int. Conf. Solid-State Sensors and Actuators* (Tokyo, June 1987), pp. 853-856.

[13] K. J. Gabriel, M. Mehregany, and W. S. N. Trimmer, "Micro mechanical components," in *Proc. ASME Winter Ann. Meeting* (Boston, MA, Dec. 1987), DSC vol. 6, pp. 397-401.

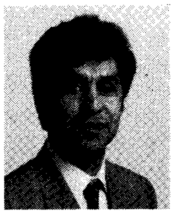
[14] L. S. Fan, Y. C. Tai, and R. S. Muller, "Pin joints, gears, springs, cranks, and other novel micromechanical structures," in *Tech. Dig. 4th Int. Conf. Solid-State Sensors and Actuators* (Tokyo, June 1987), pp. 849-852.

[15] R. S. Muller, "From ICs to microstructures: Materials and technologies," in *Tech. Dig. IEEE Micro Robots and Teleoperators Workshop* (Hyannis, MA, Nov. 1987).

[16] S. F. Bart, T. A. Lober, R. T. Howe, J. H. Lang, and M. F. Schlecht, "Microfabricated electric actuators," *Sensors and Actuators*, in press.

[17] J. H. Lang, M. F. Schlect, and R. T. Howe, "Electric micromotors: Electromechanical characteristics," in *Tech. Dig. IEEE Micro Robots and Teleoperators Workshop* (Hyannis, MA, Nov. 1987).

*



Mehran Mehregany received the B.S.E.E. degree from the University of Missouri in 1984 and the S.M. degree from the Massachusetts Institute of Technology in 1986. He is currently working toward a doctoral degree at M.I.T.

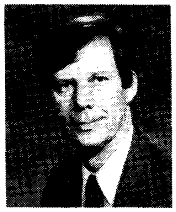
He is also a consultant in the Robotic Systems Research Department of AT&T Bell Laboratories, Holmdel, NJ. His research interests include sensors, actuators, micromanipulation, and *in-situ* measurement of the mechanical properties of thin films.

*

Kaigham J. Gabriel (S'74–M'86) received the B.S.E.E. degree from the University of Pittsburgh in 1977 and the S.M. and Sc.D. degrees in electrical engineering from the Massachusetts Institute of Technology in 1979 and 1983, respectively.

He is a Member of Technical Staff in the Machine Perception Research Department of AT&T Bell Laboratories, Holmdel, NJ. He is interested in micro-teleoperators with a current emphasis on the associated sensor, actuator, and component technologies.

*



William S. N. Trimmer (M'86) was born in Long Beach, CA, in 1943. He received the B.A. degree from Occidental College, Los Angeles, CA, and the Ph.D. degree from Wesleyan University, Middletown, CT.

He is a Member of Technical Staff of the Robotic Systems Research Department of AT&T Bell Laboratories, Holmdel, NJ. He is interested in microrobotics.