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Silicon-Processed Overhanging Microgripper

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Abstract—**A silicon-processed microgripper, suitable for mounting on a micropositioner, has been designed and fabricated by combining surface and bulk micromachining. The microgripper consists of a silicon die (7 mm × 5 mm), a 1.5 mm long support cantilever, made from boron-doped silicon substrate material (protruding from the die), and a 400 μm long polysilicon overhanging gripper extending from the end of the support cantilever. The microgripper is electrostatically driven by flexible, interdigitated comb pairs and has significantly smaller feature sizes than have been reported previously for overhanging microstructures. Problems addressed successfully in the microgripper fabrication include the protection of surface-micromachined fine structures during bulk-silicon etching and rinsing. The microgripper has successfully seized several microscopic objects in laboratory experiments.**

INTRODUCTION

MICROGRIPPERS that are capable of handling micron-sized objects have applications in biomedical as well as in microtelerobotics. Recently, progress has been made in microelectromechanical systems (MEMS) on the construction of microgrippers [1]–[3] having a dramatic reduction in size relative to existing small grippers.

We have previously described surface-micromachined polysilicon microgripper that was electrostatically driven by flexible, interdigitated comb electrodes. The electrostatic actuation has been adopted for its fabrication simplicity [4]. This microgripper showed a smooth, controllable gripper actuation [3], [4]. With this earlier gripper, however, positioning objects for actual gripping was difficult because of the small gap between the suspended gripper and the substrate. Based upon results with this "on-wafer" microgripper, we have developed an overhanging microgripper that is free of the substrate and mounted monolithically on a maneuverable silicon die. The gripper end has enough space for object movement, and the microgripper can be mounted on a positioning micromanipulator. Experimental manipulations with microscopic objects have been carried out.

The fabrication of the gripper makes use of combined surface-and-bulk micromachining. The microgripper has, however, significantly smaller feature sizes than the surface-and-bulk micromachined structures previously reported [5], [6].

DESIGN

Several microgrippers have been described recently [1]–[3] that are built on silicon wafers, but not made in a manner allowing them to be attached directly to a micropositioner—a positioning flexibility that is needed for many real-world applications. A simple way to remove the substrate in these grippers from underneath the gripper arms to form a mounting die is to break the wafer along silicon crystal axes. After a few trials, however, we found that the success rate for this approach is almost nil. The procedure is also incompatible with batch production. Furthermore, the significant size difference between the microgripper and the rectangular mounting die causes a "specimen-access problem" in object manipulation, as illustrated in Fig. 1. The corner of the rectangular die can strike the work surface before the much-smaller microgripper is in contact with the specimen.

These difficulties can be avoided by using bulk micromachining in combination with surface micromachining to make the gripper. The behavior of anisotropic etchants in silicon at convex corners is favorable in helping to round the corners of an otherwise rectangular die, thus alleviating positioning difficulties. The unit with a slender shape at the right side of Fig. 1 includes a 1.5 mm long support cantilever to improve the accessibility further.

Fig. 2 is a schematic of the microgripper unit before it is freed from the wafer. The top view includes a cutout figure of the miniature overhanging microgripper (a surface-micromachined polysilicon gripper, similar to the one described in [3]), which is 2.5 μm thick and 400 μm long. This element consists of a closure driver and two drive arms which connect to extension arms that extend to the gripper jaws. The beam widths for the drive arms and comb teeth are 2 μm, but that for the closure driver is 10 μm to provide relative rigidity. When voltage is applied between the closure driver and the drive arms, the drive arms, being flexible, bend to close the gripper jaws. The two drive arms are always at the same potential, which avoids currents flowing between the gripper jaws when they are fully closed or when they grasp a microscopic specimen.

The polysilicon microgripper is overhanging from a support cantilever that protrudes from the silicon die to serve as the base for the gripper structure. The support cantilever, heavily doped with boron, is defined geometrically by etch-stopping in ethylenediamine and pyrocatechol (EDP). It is about 12 μm thick, 1500 μm long, and tapered from a 400 μm width at the base to 100 μm

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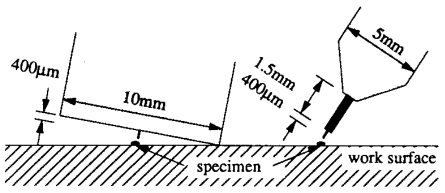

Fig. 1. A microgripper (400 μm long) accessing a specimen on a work surface. The slender unit (right) has more freedom of access than does the unit in which a microgripper extends directly from a rectangular die (left).

TABLE I
ESTIMATED GRIPPING FORCES AS A FUNCTION OF APPLIED VOLTAGES WITH THE INITIAL JAW DISPLACEMENT AS A PARAMETER

	Force in 10^{-9} N					
	0 V	10 V	20 V	30 V	40 V	50 V
0 μm	0	4.1	16.4	37.0	65.7	102.7
2 μm				15.3	44.1	81.1
4 μm					22.4	59.4
6 μm						37.7

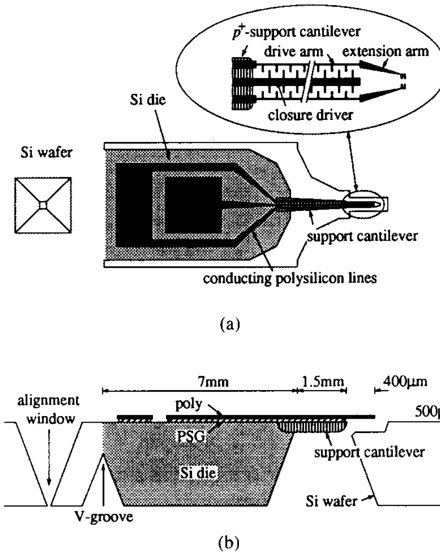

Fig. 2. Schematics of the microgripper unit (not to scale). (a) Top view. (b) Cross-sectional view.

width at the end. This support cantilever accurately locates the overhanging polysilicon microgripper and provides a thin extender for the unit.

The silicon die, formed by anisotropic etching in EDP, is 5 mm × 7 mm in area and 0.5 mm thick. When fabrication is completed, one edge of the die is still connected to the silicon wafer as shown in Fig. 2. The anisotropic etching step must be controlled so that the two convex corners of the die do not become rounded enough to meet under the p^+-region. If these edges were to meet, there would be a rapid etch propagation that would undermine the silicon near the base of the p^+-cantilever. The silicon die is snapped free along a backside V-groove with a portable vacuum pen. At this point, the microgripper and its foundation die are ready to be mounted on a positioner and electrically contacted using two large contact pads that are provided for wire bonding.

The mathematical modeling and the characteristics of the 500 μm long, on-wafer microgripper has been reported previously [3]. The microgripper that we describe here, however, is 100 μm shorter in order to achieve higher yield during fabrication with an overhanging structure. The estimated gripping forces for this 400 μm long microgripper are shown in Table I. These gripping forces are obtained from a lumped-beam model for beam deformation [3] and an assumption that the specimen is rigid. The size of the force depends upon the initial jaw displacement and on the voltage applied to close it against the specimen. For example, if each gripper jaw needs to close 2 μm to be in contact with the specimen, then 23 V applied between the driver (stator) and the drive-arms initially brings the jaws in contact with the object. Voltages higher than 23 V will generate a gripping force, and a total of 40 V will lead to a 44 nN force on the specimen.

FABRICATION

Fabrication Process

Fig. 3 illustrates steps in the process needed to produce the microgripper. With thermally grown SiO_2 as the masking layer, boron is diffused at 1125°C for 15 h from solid-dopant sources. The masking SiO_2 layer, as well as the borosilicate glass (BSG) grown during the boron diffusion, are subsequently removed (Fig. 3(a)). Following low-pressure-chemical-vapor deposition (LPCVD) of a 2 μm thick phosphosilicate glass (PSG) layer, a 2.5 μm thick undoped polysilicon layer is deposited (at 605°C) by LPCVD. The polysilicon is then patterned anisotropically by reactive-ion-etching (RIE) in a CCl_4 plasma. This step defines the patterns of the gripper and conducting lines. The polysilicon film on the wafer backside is subsequently removed (Fig. 3(b)).

Three sequential PSG-film depositions were performed to produce a 6 μm thick film. The resulting thick PSG film, along with the bottom PSG, is a source for the symmetric diffusion of phosphorus into the sandwiched-polysilicon layer [7] and also protects the polysilicon during the subsequent bulk micromachining. Each coating is followed by a 1 h anneal at 1000°C. Annealing drives the phosphorus into the polysilicon, reflows the PSG over the polysilicon, and densifies the PSG film to protect the polysilicon in subsequent EDP etching steps. To make a front-to-back alignment reference, an alignment window is formed [8] by patterning the PSG on the wafer frontside and then by anisotropically etching in EDP (Fig. 3(c)). Only two dice on the wafer have the alignment window.

Break lines are patterned on PSG around the polysilicon gripper area as shown in Fig. 4. These predetermined break lines effectively prevent the crack in the PSG membrane from propagating to the gripper arms. By aligning to the window, the PSG film on the wafer backside can be positioned and patterned in the last masking step. Etch-

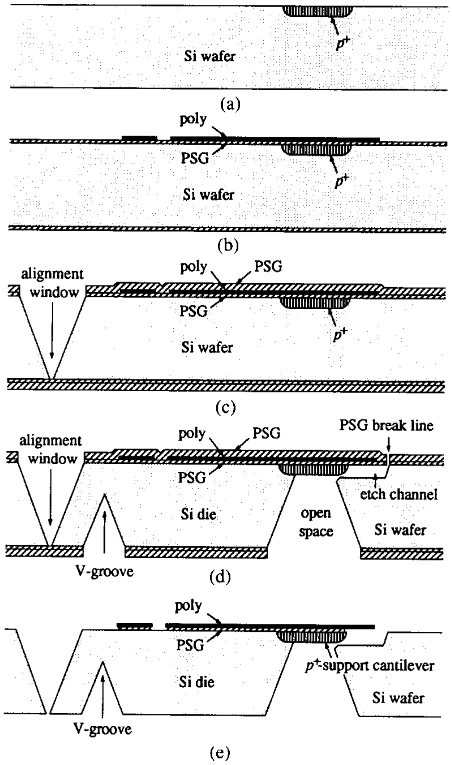

Fig. 3. Processing sequence to build the microgripper. (a) Boron diffusion. (b) Deposition of PSG, deposition and definition of polysilicon film, removal of polysilicon on wafer backside. (c) Deposition of thick PSG, annealing, front-to-back alignment-window etching. (d) Definition of PSG break lines on frontside, definition of Si die and V-groove on backside, etching in EDP. (e) Final (timed) PSG etching.

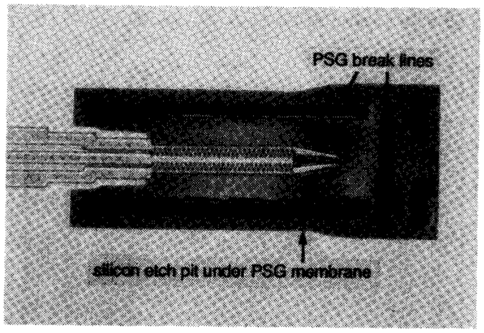

Fig. 4. Break lines on PSG membrane and etch channel formed under the PSG membrane, in which the microgripper is embedded. Silicon removal from the wafer backside is not yet completed at this point in the process.

ing in EDP removes unwanted silicon from the wafer backside. Convex corners are attacked and rounded during the etching as shown in Fig. 2. The V-groove along one side of the die extends about two thirds through the wafer.

The break lines of the PSG also serve as etching holes on the wafer frontside in EDP. The undercut etching in EDP forms a channel underneath the overhanging microgripper area, as shown in Fig. 4, and polysilicon structures are embedded in the PSG membrane at this point. The etched channel is eventually connected to the open space that is etched from the backside (Fig. 3(d)). A final timed etch of PSG fully exposes the overhanging polysilicon microgripper by removing PSG from the top and bottom. All polysilicon conducting lines on the die (and on the p^+-support cantilever) have a PSG layer left underneath them which anchors them to the substrate (Fig. 3(e)).

Discussion of Fabrication

After considerable bulk micromachining, it is found that on occasion wafers become difficult to handle because of their increased fragility. In addition, the wide etch areas made by bulk micromachining cause a special problem in passing them through vacuum-assisted transport systems due to the difficulty of establishing a vacuum seal. Furthermore, spin-on films become difficult to apply uniformly on the bulk-micromachined surfaces. It is advisable, therefore, to carry out the bulk-micromachining steps as late in the fabrication process as possible. Scheduling the substrate-removing step last is especially important in the microgripper fabrication process because of the large area affected by the bulk micromachining to form the silicon die. Silicon removal for alignment windows is not as critical for subsequent process steps (including lithographic steps) since these windows exist in only two boundary dice on the wafer.

A major challenge in the microgripper fabrication is the protection of polysilicon features during the bulk micromachining steps. In an early test, we found that a single layer of 2 μm thick densified PSG over the patterned polysilicon did not sufficiently protect the polysilicon in EDP. We used "F" etch as described by Reisman *et al.* [9] (a mixture of ethylenediamine (1000 ml), pyrocatechol (320 g), water (320 ml), and pyrazine (6 g)) at 100°C. Further tests showed that two additional PSG coatings, laid down sequentially, provide enough etch resistance to obtain essentially 100% yield for the step. Covering of pinholes in one layer by the overlying additional layers may account for the observed success. By using only PSG in several layers instead of overlays of different materials, we achieve simplification in etching requirements and in compatibility of materials.

After bulk micromachining is carried out in EDP, a PSG membrane that will later be removed is formed as a protective layer. The polysilicon gripper is embedded in the membrane at this stage. As the membrane thins during final PSG etching, we have observed that tensile residual stress in the p^+-support cantilever usually causes the PSG membrane to crack. The cracks do not propagate across the introduced break lines, however, and the polysilicon microgripper is not damaged by the cracks. Without the break lines, the PSG membrane and the gripper structure embedded in it were always riddled by cracks.

Final rinsing in de-ionized (DI) water is even more critical in this process than it is for other surface-micromachined structures of similar feature sizes because of the large cavity formed by silicon removal from under the fine-featured gripper. For rinsing in a typical micromachining process, water movement is slowed (especially in the vertical direction) very close to the wafer surface, where surface-micromachined structures are typically located. An overhanging structure such as the gripper, however, lacks the substrate underneath it, and can be buffeted directly by a rinsing stream. We have found that the yield through a rinse step has been increased significantly[1] by the introduction of an etch channel (Fig. 3(e)) instead of leaving widely open space (etched from wafer backside) directly below the overhanging-gripper structure. The etch channel restricts water flow around it.

Fabrication Results

An optical micrograph of a completed microgripper unit is shown in Fig. 5. The die is still connected to the wafer at this point. The boron-doped support cantilever is bent downward because of stress mismatch between the bottom p^+-layer and the top polysilicon/PSG layer (seen in Fig. 2) and therefore appears darkened in this picture.

Figs. 6–8 are SEM micrographs of the completed microgripper. Fig. 6 shows three 2.5 μm-thick polysilicon conducting lines (each 20 μm-wide) on the 12 μm thick boron-doped support cantilever. The remaining PSG insulating layer between the conducting lines and the support cantilever is shown in the figure. Fig. 7 shows a part of the closure driver and drive arms, the 100 μm long extension arms, and the gripper jaws. Fig. 8 shows a close-up of the completely free gripper jaws which have a span of 10 μm.

Demonstration Applications and Packaging

The microgripper has been used in several experiments to seize various microscopic objects including 2.7 μm dimeter polystyrene spheres, dried red-blood cells, and various protozoa. All cells were fixed (the proteins in the cells were chemically cross linked) and preserved in alcohol before being dried and held by the gripper jaws. The SEM picture of Fig. 9 shows the microgripper holding a one-celled protozoa that is common in garden ponds, a euglena.

We found that if a gripper looked (in an optical microscope) to be formed properly, it invariably was found to work properly. Levitation [10] of the drive-arms was not a problem in gripper operation. In repeatable tests, the jaws for all grippers closed completely with ~45 V of drive. The fundamental frequency of the gripper arms was measured to be ~5 kHz.

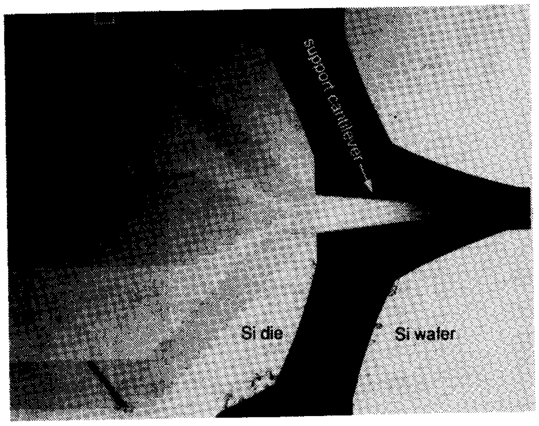

Fig. 5. Microgripper unit when fabrication is completed. The die is yet to be broken free from the wafer. The end of the support cantilever is bent downward and therefore appears darkened. The polysilicon microgripper is barely visible.

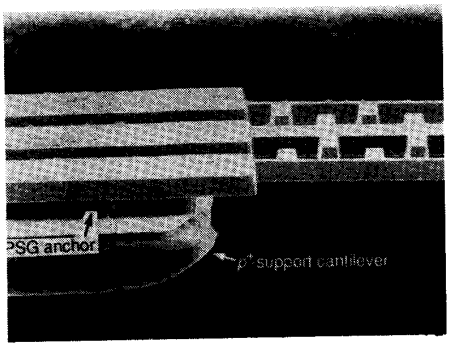

Fig. 6. SEM micrograph showing three conducting lines crossing the end of the support cantilever to the gripper arms. The remaining PSG insulating layer between the conducting lines and the support cantilever is marked.

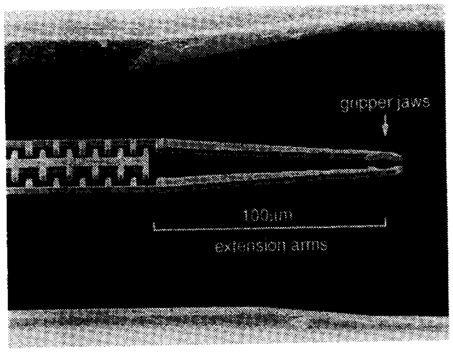

Fig. 7. SEM micrograph showing the flexible comb-drive structures, extension arms, and the gripper jaws.

Sticking between the gripper jaws and the test specimens is a problem that needs to be addressed. The gripper in Fig. 9, for example, was distorted by an external force from a probe tip applied during efforts to position the cell between the jaws. Sticking force between the jaws and the dried cell results in the structure maintaining the distorted shape. No effect of the object weight was observed (as expected from a dimensional analysis in microscale [11]). The degree of sticking was not observed to be consistent

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[1] From only two successfully finished grippers out of 27 attempted on a wafer in a first run to 20/27 in a subsequent run.

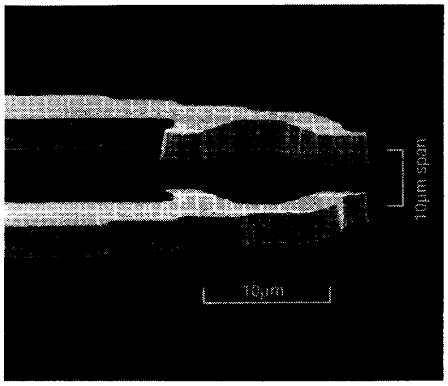


Fig. 8. Close-up SEM micrograph of microgripper jaws.

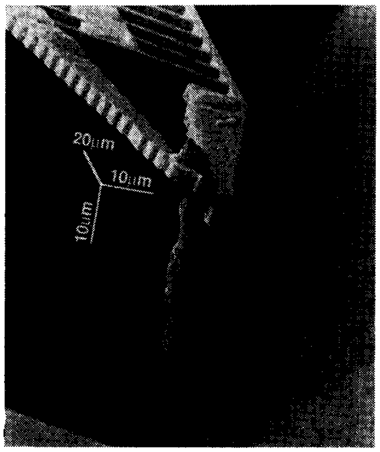
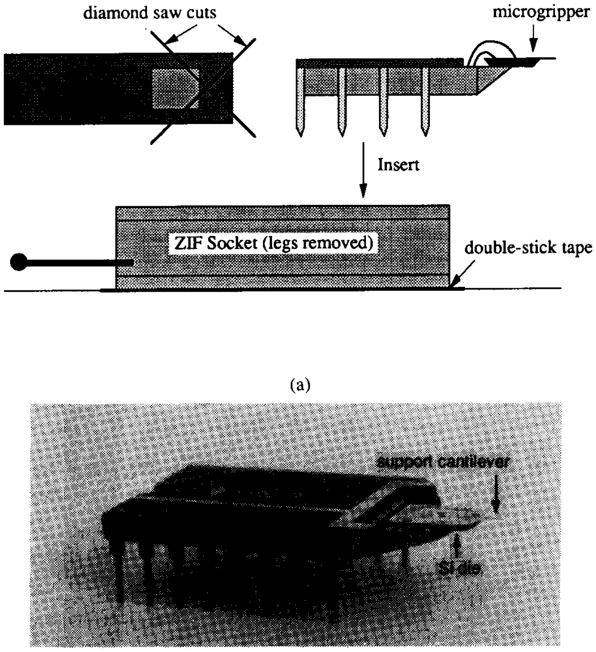


Fig. 9. SEM picture of a one-celled protozoa, a euglena, being held by the microgripper. The euglena is 40 μm long and 7 μm in diameter.



(a)

(b)

Fig. 10. (a) Schematic showing gripper packaging and electrical access. (b) Photograph of the packaged gripper.

in repeated experiments even with the same object; however, it was generally less problematic when the gripper being used was newly made or if the objects were larger. We suspect static electricity is the main source of the sticking observed, but a systematic study is needed to understand this phenomenon and to learn ways to avoid it.

The overhanging microgripper is prone to breakage if touched by macro-objects while handling after fabrication. Extreme care and immediate packaging is desirable as soon as the gripper unit is freed from the wafer. To package the gripper, a conventional dual-in-line IC package is cut with a diamond saw. The front end, where the gripper unit is to be attached using silver epoxy, is sawed and ground to a slender shape, as shown in Fig. 10(a). Wire bonding, not shown in Fig. 10(b), completes the electrical connections to the gripper. For storage, the package is inserted into a zero-insertion force (ZIF) socket (which has had its legs removed) and glued to a petri dish, which can be covered to block air movement. These procedures ensure safe storage and transportation. Stronger air movement than that of normal handling (wind velocity of ~ 1 ms^{-1}) often breaks the exposed microgripper.

CONCLUSION

The design and fabrication of a freely accessible microgripper using semiconductor batch processing has been described. The microgripper is electrostatically driven by flexible, interdigitated comb pairs and consists of a silicon die, a single-crystal-silicon support cantilever, and an overhanging polysilicon microgripper. Placing microscopic end-effectors on readily manipulatable blocks helps to accomplish micro–macro size interfacing, which is necessary for real-world applications of microelectromechanical systems. The gripper's utility has been demonstrated in several experiments.

The major challenge in fabricating this device is the protection of the surface-micromachined polysilicon structures during subsequent batch processing. Embedding the polysilicon structures in PSG film during etching in EDP, introducing break lines to the PSG membrane, and partially blocking liquid flow during etching and rinsing operations are keys to the successful fabrication sequence.

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REFERENCES

[1] M. Mehregany, K. J. Gabriel, and W. S. Trimmer, "Integrated fabrication of polysilicon mechanisms," *IEEE Trans. Electron Devices*, vol. 35, pp. 719–723, June 1988.

[2] L. Y. Chen, Z. L. Zhang, J. J. Yao, D. C. Thomas, and N. C. MacDonald, "Selective chemical vapor deposition of Tungsten for microdynamic structures," in *Proc. IEEE Micro Electro Mech. Syst. Workshop*, Salt Lake City, UT, Feb. 1989, pp. 82–87.

[3] C.-J. Kim, A. P. Pisano, R. S. Muller, and M. G. Lim, "Polysilicon microgripper," in *Tech. Dig. IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, June 1990, pp. 48–51.

[4] ——, "Design, fabrication, and testing of polysilicon microgripper," *Micro Structures, Sensors and Actuators* (DSC vol. 19), *ASME Winter Annu. Meet.*, Dallas, TX, Nov. 1990, pp. 99–109.

[5] S. Akamine, T. R. Albrecht, M. J. Zdeblick, and C. F. Quate, "A planar process for microfabrication of a scanning tunneling microscope," *Sensors and Actuators*, vol. A21-A23, pp. 964–970, 1990.

[6] L. C. Kong, B. G. Orr, and K. D. Wise, "A micromachined silicon scan tip for an atomic force microscope," in *Tech. Dig. IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, June 1990, pp. 28–31.

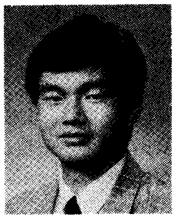
[7] W. C. Tang, T. H. Nguyen, R. T. Howe, "Laterally driven polysilicon resonant microstructures," *Sensors and Actuators*, vol. 29, pp. 25–32, 1989.

[8] E. S. Kim and R. S. Muller, "IC-processed piezoelectric microphone," *IEEE Electron Device Lett.*, vol. EDL-8, pp. 467–468, Oct. 1987.

[9] A. Reisman, M. Berkenblit, S. A. Chan, F. B. Kaufman, and D. C. Green, "The controlled etching of silicon in catalyzed ethylenediamine-pyrocatechol-water solutions," *J. Electrochem. Soc.*, vol. 126, no. 8, pp. 1406–1415, Aug. 1979.

[10] W. C. Tang, M. G. Lim, and R. T. Howe, "Electrostatically balanced comb drive for controlled levitation," in *Tech. Dig. IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, June 1990, pp. 23–27.

[11] C.-J. Kim, "Silicon electromechanical microgrippers: Design, fabrication, and testing," Ph.D. dissertation, Dept. Mech. Eng., Univ. California, Berkeley, CA, 1991.



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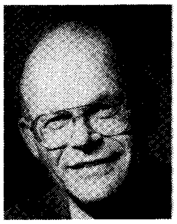

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