

Silicon Micromachined SCALED* Technology

Denny K. Miu and Yu-Chong Tai

Abstract— Silicon micromachining technology will play an important role in the fabrication of high-bandwidth servo controlled microelectromechanical (mechatronic) components for super-compact disk drives. At the University of California, Los Angeles, and the California Institute of Technology, for the last three years, we have initiated a number of industry-supported joint research projects to develop the necessary technology building blocks for an integrated drive design of the future. These efforts include a silicon read/write head microgimbal with integrated electrical and mechanical interconnects, which targets the next-generation 30% form factor pico-sliders, and an electromagnetic piggyback microactuator in super-high-track-density applications, both of which utilize state-of-the-art silicon micromachining fabrication techniques.

I. INTRODUCTION

ADVANCES in VLSI and software technology have been the primary engines for the ongoing *Information Revolution*. But the steady stream of technical innovations in magnetic disk recording technology are also important factors contributing to the economic strengths of the computer and information industry. One important technology trend for the disk drive industry has been that of miniaturization. The storage capacity of the recently announced wristwatch-size 1.3-in diameter disk drives is about eight times that of the shoebox-size $5\frac{1}{4}$ inch drives of the early 1980s which themselves are more than twice the capacity of the refrigerator-size 24-in disk drives of the mid-1950s. In terms of storage density, this corresponds to approximately one order of magnitude increase for every decade. As this trend continues (in fact, accelerates), future disk drives will have the same form factor as VLSI's, storing gigabytes of data.

Fig. 1 shows the major mechatronic components of the conventional single-actuator/pivot-bearing rigid disk drive design. In computer disk drives digital information is recorded in concentric tracks on rotating disks using miniaturized read/write (R/W) electromagnetic transducers that are mounted on self-

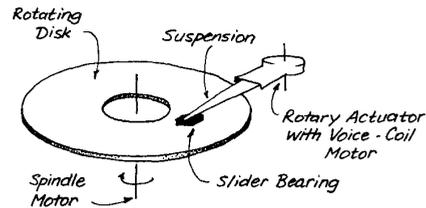


Fig. 1. Major mechatronic components of a conventional high-performance rigid disk drive.

lubricated submicron flying slider bearings. These R/W heads are connected to stainless steel suspension arms which are in turn connected to voice-coil actuators allowing cross-track seek and track-following

Whereas bit density (along the track) is much higher than that of optical recording, track density of magnetic recording is typically much lower (although the access speed and data rate are much faster). Unlike optical recording, in magnetic recording, in order to maintain high bit density, the R/W heads must be placed very close to the recording media. On the other hand, in order to minimize latency and maximize data transfer rate, the relative speed between the transducers and the media must be very high. Therefore, tribomechanical and tribochemical wear are important problems inherent in any form of magnetic recording and in order to maintain proper head/media interface, the actuator arm/suspension which serves as the interconnect between the actuator and the sensor must be very compliant in the vertical, pitch, and roll directions. Unfortunately, such mechanical flexibilities tend to limit the bandwidth of the servo systems and therefore the track density. Furthermore, access time is severely limited by residual vibrations caused by the flexibility of the actuator-arm/suspension system, imposing another constraint on track density.

Table I shows the approximate maximum areal density (MAD) of some typical commercial products of recent years as well as a projection of the required performance for products in the next decade. Note that areal data density is a combination of track density in the radial direction measured in tracks-per-inch (TPI) and bit density in the tangential direction measured in bits-per-inch (BPI). This performance is extremely impressive considering that the areal density of the first commercial product which was introduced to the market place in the mid-1950s was only 2 kb per square inch.

II. MECHATRONIC CHALLENGES

Historically, bit density of magnetic rigid disk drives is at least an order of magnitude higher than track density, resulting

Manuscript received February 1, 1994; revised September 2, 1994. This work was conducted at the Caltech Micromachining Laboratory with support from the University of California MICRO program and matching funds from the Applied Magnetics, Hewlett-Packard, IBM, Magnacomp, Maxtor, Quantum, Read-Rite and Seagate Technology Corporations, and the National Storage Industry Consortium (NSIC). An earlier version of this paper was presented at the JSME International Conference on Advanced Mechatronics, Tokyo, Japan, Aug. 2-4, 1994.

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IEEE Log Number 9410549.

*Super Compact Array of Low-cost Enormous-capacity Disk-drives.

TABLE I
APPROXIMATE MAXIMUM AREAL DENSITY (MEASURED IN
MEGABITS PER SQUARE INCH) OF SOME RECENT COMMERCIAL
PRODUCTS AND PROJECTIONS FOR THE NEXT DECADE

| | MAD | TPI | BPI |
|-------|---------|---------|-----------|
| 1971: | 1 | 200 | 5,000 |
| 1981: | 10 | 800 | 12,500 |
| 1991: | 100 | 2,000 | 50,000 |
| 1995: | 600 | 5,000 | 120,000 |
| 2001: | 10,000 | 25,000 | 400,000 |
| 2005: | 100,000 | 100,000 | 1,000,000 |

in a more than 10 to 1 aspect ratio in the lateral dimensions of the unit recording bit cell. It is also interesting to note that for the last two and a half decades, the industry has progressed on a steady $10\times/\text{decade}$ (+26% annual compound growth) improvement curve but since the early 1990s, in order to stay competitive, it has accelerated onto a +60% annual growth curve. As a result, by the beginning of the next century, it is projected that the track density will have to be at least 25 000 TPI which corresponds to a track pitch of 1 μm and a tracking accuracy of less than 100 nm. Furthermore, in another five years, it is projected that the magnetic recording industry must deliver at least 100 000 TPI which corresponds to a track pitch of 250 nm and an astonishing servo resolution of 25 nm. The technological challenges to mechatronic engineers working in the disk drive industry are obvious.

Besides contributing factors such as mechanical resonances, spindle runouts, temperature drifts, humidity variations, external shocks/vibrations, bearing hysteresis, cable bias, etc., there are a number of significant sources of off-track positioning errors that are unique to computer disk drives. As opposed to other applications where cost is not a primary concern (aerospace, for example), in disk drives sensors are used only when they are absolutely necessary, otherwise the industry cannot remain competitive. Instead of using position sensors and servo patterns physically encoded on the disk surface, typically in computer disk drives off-track errors are derived using the so-called embedded servo technique where the necessary off-track information is sandwiched within the magnetic data.

As the disk rotates, the magnetic R/W head will cross specially-coded magnetic servo patterns at regular intervals. After amplification, on-board demodulation electronics will convert the encoded servo data into an off-track position error signal. This signal is then fed into a digital servo controller which will compensate the error signal by driving the voice-coil actuator. Therefore, any nonlinearity and inaccuracy in the servo patterns caused by defects in and inadequacy of the media, head and electronics will show up as measurable off-track error which cannot be avoided. As bit density and track density increase, this becomes more and more problematic.

In addition, besides track following, the servo system must also move the entire head/suspension assembly across the disk

surface as fast as possible. This must be done in such a way to minimize residual vibration. Typically the servo controller will drive the actuator to follow an idealized velocity profile calculated based on a rigid body model. The actuator velocity is not measured since not only is there not a position sensor, there is also not a velocity sensor. Instead, the velocity is estimated from the embedded off-track error using a reduced-order Kalman-type estimator. Therefore, seek settling of the actuator/suspension system is one of the biggest source of off-track error (both residual vibration of the inherently flexible mechanical structures and the unavoidable velocity estimation error).

Obviously, the higher the servo bandwidth, the easier it is to correct these errors, and the higher the track density, the more important it is to have a high-bandwidth servo system. Currently, track density is less than 5 000 and servo bandwidth is approximately 500 Hz, limited mainly by inherent in-the-loop mechanical resonances. For 25 000 TPI, it is projected that the servo bandwidth must be higher than 2 kHz. Furthermore, with spindle speed increased to 7 200 r/min, the required bandwidth will increase to 3 or 4 kHz. It is well recognized throughout the industry that this level of performance simply cannot be done by using or improving upon the existing mechatronic hardware. The only solution is to add a dual-stage piggyback actuator system similar to that of the optical disk drives. By moving only the R/W head, it is possible to design a high-bandwidth system without requiring unreasonable amount of power.

Aside from the aforementioned tracking control problems which mainly have to do with microactuation, there are other major mechatronic issues pertinent to future-generation supercompact disk drives, for example, mechanical packaging, manufacturing, and electromechanical interconnect. To be relevant to disk drive applications, any proposed mechatronic component design must be consistent with these concerns. In today's disk drive design, much of these problems are solved by compromising and synergizing the design and performance of various mechatronic devices including R/W head, the stainless steel suspension and voice-coil actuator.

Therefore, from the perspective of a disk drive *system*, one cannot design the microactuator without worrying about how it will affect the rest of the interconnecting components. Moreover, one cannot design it without thinking about how it will preserve the traditional volumetric cost advantage (dollar-per-megabyte) of magnetic over optical disk drives (i.e., low disk-to-disk spacing, low media cost and low unit cost of mechatronic components). Finally, one must also project how the proposed design will coincide with the miniaturization trend of the magnetic disk drive industry such that it can lend itself to manufacturing automation and high-shock environments.

At the University of California, Los Angeles, and the California Institute of Technology, we have initiated two closely related research programs to develop two silicon micromachined mechatronic components for future supercompact, high-track-density computer disk drives, microgimbals and microactuators.

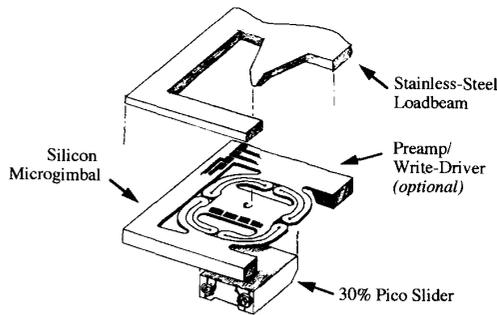


Fig. 2. The proposed design concept of a hybrid silicon microgimbal/stainless steel loadbeam suspension system.

III. SILICON MICROGIMBALS

Conventional suspensions are made of stainless steel of uniform thickness with the various features manufactured by a combination of chemical etching, precision stamping, and metal forming operations. As the drive form factor reduces to less than 2 in in diameter and the slider bearing shrinks to about 1×1 mm in size, the suspension will be less than 1 cm long and the size of its gimbal (which is the structural component that connects the slider to the load-beam of the suspension) will be less than 1.5 mm square. Therefore, it becomes increasingly difficult if not altogether impossible to fabricate the suspension/gimbal system using existing material and manufacturing techniques.

Typically, one thinks of silicon as a brittle material and would not normally use it to construct flexible structures. However, brittle material is also elastic and the only difference is that unlike ductile material, it will not yield; it will simply fracture when the stress reaches the ultimate strength. It is well known that the ultimate strength of silicon microstructures is orders of magnitude higher than that in bulk form. Therefore, silicon microstructures can be made to be flexible but with a very high load-carrying capacity.

Fig. 2 shows our proposed hybrid silicon micromachined microgimbal and stainless steel loadbeam suspension system which has a number of operational and cost advantages. First of all, since silicon is a brittle material, silicon microgimbals cannot be plastically deformed during manufacturing and handling; quality assurance therefore consists of only visual inspection. In comparison, plastic deformation of stainless steel suspensions (i.e., degramming) is the major contributing factor of reduced production yield and in-drive performance problems, representing a significant cause of revenue loss.

In addition, due to the difference in process technology, much smaller features can be realized in silicon than in stainless steel (using various anisotropic wet and dry etching techniques), providing much needed additional degrees of design freedom. For example, in our design, we fabricate very intricate serpentine planar microsprings at the four corners of the microgimbal in order to satisfy the conflicting out-of-plane compliance, lateral stiffness and shock resistance design requirements.

Furthermore, with silicon, it is relatively easy to incorporate electrodes (or even preamps) in the suspension arm



Fig. 3. SEM micrograph of a five-turn silicon microgimbal.

as well as an electrical coupler in the gimbal area, thereby allowing the possibility of automating not only the mechanical but also the electrical interconnect manufacturing procedures. Currently, in many state-of-the-art products, assembly of the head/gimbal/suspension subsystem represents nearly half of the total manual labor cost.

The design requirements of the silicon microgimbals are quite challenging. In addition to being soft enough for head/media compliance and stiff enough for tracking (in order to increase servo bandwidth), they must also be strong enough to survive shocks on the order of hundreds of g 's. In a way, designing gimballs for the read/write heads is not much different from designing suspensions for our cars; automobile suspensions must be soft enough to give a smooth ride but yet stiff enough to handle fast turns. But most importantly, they must survive shocks with amplitudes well above normal operating conditions.

All suspension springs basically are composed of cantilever or torsional beams. The design trick of course, is to utilize beams of enough length such that for a given tip displacement, the operating strains are well below the yield or fracture point of the material. For applications where space is a concern, the obvious solution is to use helical springs which pack the most material into the smallest area. In the case of the microgimbal, the ideal solution would be to put individual springs at the four corners of the slider. Obviously, these soft springs must be designed so that they have sufficient stiffness in the lateral directions which requires careful optimization of the geometry.

Given the form factor that we are designing for, it is nearly impossible to design helical springs out of stainless steel sheet. On the other hand, the advantage of using silicon is that very small features can be achieved. The difficulty however, is not so much in fabricating a planar helical spring but in fabricating the interconnect between the center of the spring and the slider. Fig. 3 shows the individual planar microsprings at the four corners of the microgimbals. These springs are a variation of the conventional helical springs. Instead of spiral beams (which will require interconnects), they are composed of alternating curved beams. Much work has been performed in optimizing the various beam widths and the stress relief holes around the turns.

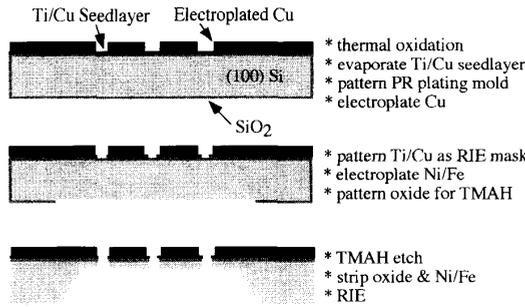


Fig. 4. Processing steps for the silicon serpentine microgimbal.

The fabrication process for the silicon microgimbals is rather simple and consists of only two major steps: reactive-ion etching (RIE) using SF_6 plasma to define the microspring on the front surface of the wafer and anisotropic chemical etching on the back to create a trapezoidal cavity which would allow the attachment of the R/W slider directly under the center coupon. For etch stop, we use epi-wafers which consist of a 20- to 30- μm -thick lightly doped epitaxial layer on top of a 4- μm heavily boron-doped buried layer.

Fig. 4 shows a summary of the complete processing steps which require only three masks. The silicon wafer is first thermally oxidized at 1050°C to form a 3000-Å-thick silicon oxide layer on the top and bottom surfaces, which serves as the protection coating for subsequent chemical etching as well as insulation for the electrical interconnect. The 200-Å-thick titanium and the 1000-Å copper are then electron-beam evaporated on the top surface. Photoresist is then spun and patterned using the first mask to form the electroplating mold for the electrodes. After electroplating, the seed layer is then patterned using the second mask to define the microsprints. The 2000-Å thick permalloy is then electroplated to protect the copper. The third mask is finally used to pattern the silicon oxide on the back surface for the cavities.

After the final photolithographic step, the wafer is ready for anisotropic etching using TMAH (tetramethyl ammonium hydroxide). Since the copper seed layer is protected by permalloy, it will not be attacked by TMAH. After TMAH back-etch and removal of silicon oxide, we perform RIE until the microgimbals are completely free-standing. This is then followed by chemical removal of the permalloy, once again revealing the copper electrodes. The very last step is to dice and individualize the microgimbals.

IV. SILICON MICROACTUATORS

Our next mechatronic component is an electromagnetically driven piggyback microactuator which can be packaged to move the slider relative to the suspension arm such as to completely eliminate any in-the-loop structural resonances. This device must be very low-profile so that it is consistent with the disk-to-disk spacing requirement of future products. In addition, it must be mass-manufacturable and be able to operate in low-voltage, low-power environment. Furthermore, electromagnetic interference must be at an absolute minimum in order not to degrade the read/write operations.

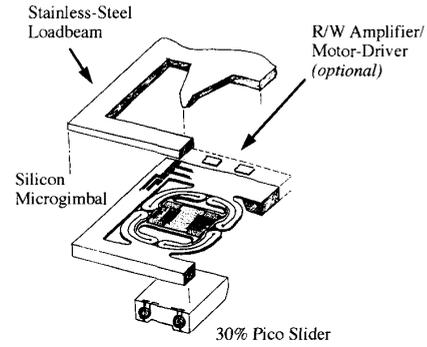


Fig. 5. Design concept for a silicon micromachined electromagnetic piggy-back planar microactuator for high TPI applications.

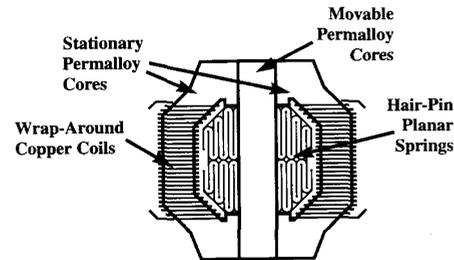


Fig. 6. Schematic drawing for silicon micromachined electromagnetic piggy-back planar microactuator with wraparound copper coils.

Fig. 5 shows a design concept which uses the aforementioned silicon microgimbal as the structural platform. Instead of a solid coupon in the center, the read/write slider is now attached to the microgimbal by a set of hairpin-like planar springs which are designed to have maximum in-plane compliance while maintaining adequate out-of-plane, pitch and roll stiffnesses.

As shown in Fig. 6, a pair of thin-film variable-reluctance microactuators are used to move the slider/recording head in the in-plane direction, each of which is consisted of two pieces. The stationary piece is mounted on the outside frame and is constructed of one layer of permalloy with a wrapped-around helical flat copper coil. The moving piece is attached to the slider and when a voltage is applied to the coil, magnetic force will be exerted on the moving core, pulling it toward the stator and resulting in in-plane/cross-track micron-level fine motion of the read/write slider. This design has the important advantage that the required fabrication technology is very similar to that of thin-film heads, leveraging the expertise of the magnetic recording industry. Fig. 7 summarizes the fabrication process for the electromagnetic components of the microactuator and Fig. 8 shows a fabricated device.

V. SCALED TECHNOLOGY

The paths of product development for magnetic disk drives are littered with thousands of technically great ideas whose only sins are being ahead of their time. With hindsight, it is clear that if one wishes the magnetic storage industry (or

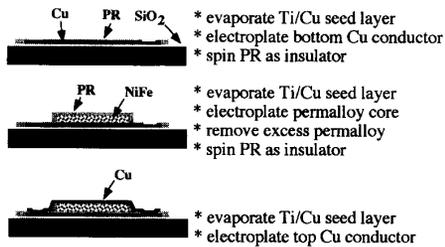


Fig. 7. Process steps for the silicon electromagnetic microactuator.

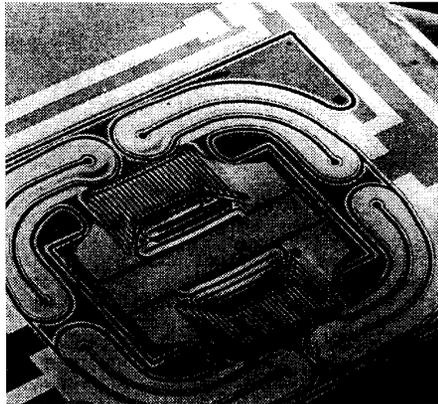


Fig. 8. Micrograph of a fabricated electromagnetic microactuator.

any industry, for that matter) to accept and embrace any proposed changes in design paradigm, one must not only solve the fundamental technical problems but must also provide a gradual and logical path such that the industry can proceed one technology step at a time. That is, as an industry, it will never allow itself to fly a new engine with an entirely new air-frame. For that reason, we focus our immediate effort on a number of strategically important near-term research projects to fabricate silicon microgimbals and microactuators using the proposed micromachining technology. Our self-imposed constraint is that these proposed silicon mechatronic devices must be a one-to-one replacement to its conventional equivalent, requiring no (or at least minimal) changes in the drive design.

At the same time, we envision and in fact position these silicon devices to be the enabling precursor technology necessary to achieve a truly integrated design of the future. Fig. 9 illustrates our futuristic product concept for the high-performance supercompact VLSI-level data storage array. At a recording density of 100 Gb per square inch, the recording capacity for each of the 2-cm diameter, 0.5-cm-high module is approximately 20 gigabytes of digital data. At that form factor, they are compatible with surface-mounting technology and as an array, will significantly increase the on-line storage capacity, access speed, data rate, redundancy, and reliability of future products.

Fig. 10 shows the proposed silicon micromachined mechatronic microactuator array which would allow such integrated design paradigm to take place. Our vision is that disk drives

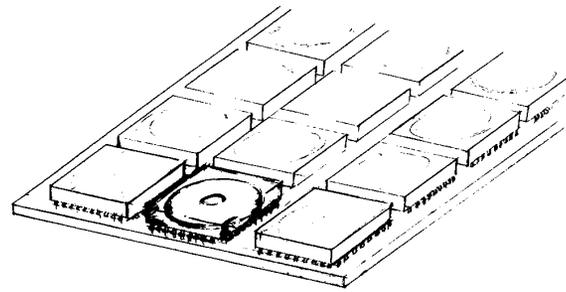


Fig. 9. SCALED technology.

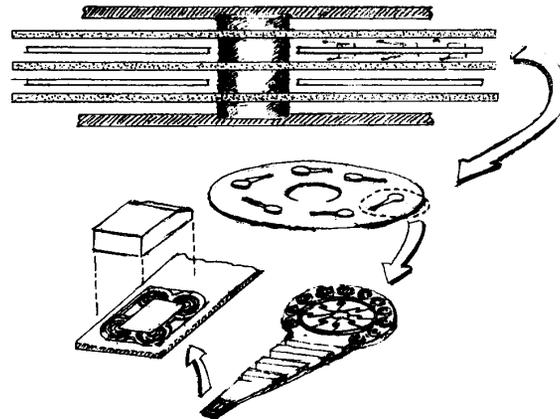


Fig. 10. Array of articulated torsional bearings with integrated electromagnetic microactuators.

of the future shall consist of only two major components—a stack of rotating disks which contain the recording media and a stack of stationary silicon disks sandwiched between the recording disks, which consist of arrays of high-resolution, high-bandwidth microactuator/suspension/read-write-head to accomplish the required positioning and recording operations. These integrated mechatronic microdevices will perform all of the sensing, actuation, signal processing, and control functions in a single low-cost, mass-manufacturable, silicon based package, thereby eliminating much of the costly and complicated external electrical and electromechanical interconnections that exist in the conventional disk drive design. Perhaps one day we shall think of such silicon micromachined integrated disk drives (ID's) the same way we think of integrated circuits (IC's) today, a logical and rather obvious technology evolution consistent with miniaturization and performance improvement.

VI. SUMMARY

Silicon micromachining techniques offer many exciting opportunities for fabricating both passive (microgimbals) and active (microactuators) mechatronic components for significant form factor reduction and increase in recording density of future magnetic recording rigid disk drives. In this overview paper, we have presented some recent results and novel

product concepts. In other related papers, we have documented detail results related to design optimization, process refinement and static/dynamic testing.

ACKNOWLEDGMENT

The authors would like to thank their many colleagues: Amish Desai, Wen Hsieh, Raanan Miller, Weilong Tang, Viktoria Temesvary, and Shuyun Wu for the results of their combined efforts.

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Denny K. Miu has been with the Mechanical Engineering Department, University of California, Los Angeles, since 1987, where he is an Assistant Professor. He has been working with the computer rigid disk drive industry since 1983. His previous work includes head/disk dynamics, suspension design, and residual vibrationless tracking accessing control. Since 1992, he has been working with Prof. Yu-Chong Tai on silicon micromachining and its application to computer disk drives. He has published over 25 journal papers on mechanics and control issues related to computer disk drives, as well as a graduate-level textbook, published by Springer-Verlag, on advanced mechatronics problems of controlled electromechanical systems.

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In 1989, he joined the faculty of electrical engineering at the California Institute of Technology, Pasadena, where he is currently an Assistant Professor. His research interests have included silicon micromachining and its applications, such as neural prosthetic devices, integrated millimeter-wave waveguides, microfluidic devices, miniature hard-disk drives, microphones, silicon hot-wire anemometers, magnetic milli- and microactuators, shock sensors, and microelectromechanical systems for active fluid control.

Prof. Tai received the Presidential Young Investigator Award and the David and Lucile Packard Fellowship in 1991. He is a member of the editorial boards for the *Journal of Micromechanics and Microengineering*.