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An Analysis of Microsystems Development at Sandia National Laboratories

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ABSTRACT

While Sandia initially was motivated to investigate emergent microsystem technology to miniaturize existing macroscale structures, present designs embody innovative approaches that directly exploit the fundamentally different material properties of a new technology at the micro- and nano-scale. Direct, hands-on experience with the emerging technology gave Sandia engineers insights that not only guided the evolution of the technology but also enabled them to address new applications that enlarged the customer base for the new technology. Sandia's early commitment to develop complex microsystems demonstrated the advantages that early adopters gain by developing an extensive design and process tool kit and a shared awareness of multiple approaches to achieve the multiple goals.

As with any emergent technology, Sandia's program benefited from interactions with the larger technical community. However, custom development followed a spiral path of direct trial-and-error experience, analysis, quantification of materials properties at the micro- and nano-scale, evolution of design tools and process recipes, and an understanding of reliability factors and failure mechanisms even in extreme environments. The microsystems capability at Sandia relied on three key elements. The first was people: a mix of mechanical and semiconductor engineers, chemists, physical scientists, designers, and numerical analysts. The second was a unique facility that enabled the development of custom technologies without contaminating mainline product deliveries. The third was the arrival of specialized equipment as part of a Cooperative Research And Development Agreement (CRADA) enabled by the National Competitiveness Technology Transfer Act of 1989. Underpinning all these, the program was guided and sustained through the research and development phases by accomplishing intermediate milestones addressing direct mission needs.

Keywords: microsystems, MEMS, technology evolution

1. INTRODUCTION

The first applications of disruptive technologies often are driven by analogies to established technologies. This was true of the use of iron for bridges; it is true for the use of composite materials in modern aircraft; and it is true for the development of microsystem technology at Sandia National Laboratories. Sandia National Laboratories has long experience not only with microelectronics but also with precision mechanical components. It should be noted that laminar-flow clean room technology was invented at Sandia National Laboratories to assemble intricate and delicate mechanisms. Those mechanical devices of the 1950s required such extremely rigid specifications that contamination by dust particles or other contaminants rendered the mechanisms inoperable [1]—thus motivating the development of the laminar-flow clean room. Four decades later, the goal of miniaturizing the same types of mechanical components motivated Sandia's development of integrated microsystems technology.

As research activity in semiconductor microsystem technology began to blossom in the 1980s, Sandia became interested in the possibilities of the emergent microsystem technology. Initially Sandia was motivated by the possibility of miniaturizing macroscopic mechanical components to reduce volume and weight while ideally improving reliability—where reliability improvement would be addressed through high-level integration that would reduce the number of interconnections among a larger number of discrete subcomponents. This ambitious initial goal required fabricating multiple structural levels of patterned polysilicon separated by sacrificial layers of silicon dioxide at levels of process complexity far beyond the initial state of the art. Adding additional structural layers required overcoming numerous technical challenges, such as residual stresses from differential thermal expansion between layers during fabrication.

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Later, as Sandia designers and engineers became more familiar with the possibilities of multi-level sacrificial silicon surface micromachining, they began to combine the micromachine technology with other technologies such as optics and photonics to achieve the high-level integration that initially motivated the early investigations of microsystem technology several decades previously.

A historical analogy provides a useful context. In 1709, a new disruptive technology emerged: the coke-fueled blast furnace which helped create the British Industrial Revolution. This new technology dramatically lowered the cost of cast iron, which had previously been too expensive for use in larger structures. The first foundry was located near the river Severn. By coincidence, in the early eighteenth century, the only way to cross the river Severn was by ferry. The local industries needed a more reliable crossing. As a result, when cast iron became affordable, local entrepreneurs proposed in 1773 to build a durable iron bridge to connect those local industries. The bridge was the first of its kind and thus the construction had no precedent. Lacking an understanding of the material properties of cast iron, the bridge was severely over engineered. Lacking any other insights, known carpentry techniques were used to create the structure. As a result, it required 379 tons of iron by the time it was completed six years later in 1779. [2]

As bridge builders developed greater expertise with iron as a construction material, a similar bridge was built over the river Severn in 1818 roughly a mile downstream from the first iron bridge. The new Coalport bridge required half the amount of cast iron as the original Iron Bridge. This dramatic reduction in material costs was the result of design insights gained from previous structures that exploited the unique properties of coke pig iron.

As we look back at the development of microsystem technology at Sandia National Laboratories, we encounter the same human limitations in creating a disruptive technology. Similar to the first iron bridge, the development of microsystems technology required patient capital for its development; it required new design tools based on an understanding of the properties of the new materials; its first applications were driven by direct analogy to existing macroscopic components, and it required a new way of thinking to surface the unique advantages of the new technology. Familiarity with the emergent technology in turn drove technological evolution and led to its application to resolve problems far beyond those that drove the initial investigations.

2. The Birth and Rebirth of MEMS Technology

In 1964 Dr. Harvey Nathanson of Westinghouse Research Labs in Pittsburg produced the first batch-fabricated Micro-Electro-Mechanical System (MEMS). [3]. This work generated the first MEMS patent [4] awarded in 1968 for a "resonating gate transistor" which structurally consisted of a conducting cantilever above a silicon substrate. Even in its earliest form, the early MEMS technology offered batch fabrication that required no additional pick-and-place assembly (the components came out of the batch-fabrication process completely assembled at the micro level), included energy conversion (electrical to mechanical and vice versa), and attempted to generate system solutions to problems of commercial interest. For a variety of technical and performance reasons, the initial Westinghouse devices did not create a commercial market. [5] Instead, the nascent semiconductor industry pursued transistors and integrated circuits—which already had achieved a sustaining market and showed great opportunity for future market growth. As a result, the potential advantages of MEMS technology went unrealized for almost two decades.

In the early 1980s, workers at the University of California at Berkeley and the University of Wisconsin revived interest in MEMS technologies by demonstrating the advantages of polysilicon structural layers with sacrificial oxide layers. In this technology, the components are built up on a semiconductor substrate using standard techniques before a mask-less post-processing release step etches away sacrificial layers, allowing the structural layers to move and later to rotate.

By 1984, a group at the University of California-Berkeley had demonstrated the integration of polysilicon microstructures with NMOS electronics, which won the Best Student Paper Award for the International Electron Devices Meeting of the Institute of Electrical and Electronics Engineers. [6] Achieving a Best Paper Award at the signature conference of the Electron Devices Society of the Institute for Electrical and Electronics Engineers sparked renewed interest in MEMS technology and brought MEMS technology back to life.

An essential development in the evolution of MEMS technology was the awareness that a fundamental understanding of material properties at the microscopic level was needed to advance the technology. In that regard, the best student paper of the 1987 IEDM was awarded to the Berkeley group for measuring thermal properties of the polycrystalline silicon used for the early micromachines [7].

The ambitious Berkeley group began to develop other microscopic analogs to macroscopic devices. In 1988 they developed the first rotary electrostatic side drives motor [8] based on movable pin joints, gears, springs, cranks, and slider structures. The motor is not assembled from individual components. Instead these complex components were built up by the same processing steps, allowing the structural layers to move and rotate. These demonstration devices were not able to drive a mechanical load. Such advances would require greater technology than available to the Berkeley group.

3. Silicon Micromachining Development at Sandia

3.1 The Origins of Micromachining at Sandia National Laboratories

As interest renewed in silicon micromachining in the 1980s, Sandia's mechanical engineers began considering microsystems technology as an option for miniaturizing critical mechanical functions. Because Sandia had a functioning microelectronics fabrication facility with full-flow CMOS technology that delivered qualified product, Sandia's mechanical engineers began to discuss with their microelectronics colleagues whether Sandia's silicon processing technology could be exploited to fabricate advanced micromachines to replace macroscopic mechanical components. Sandia's cleanroom at the time was configured in a ballroom-style layout and thus could not accept new processes or new process chemicals without contaminating their existing CMOS production process. Also at the same time Sandia was totally committed to production deliveries for a major defense system. Lacking internal support, Sandia's mechanical engineers began to collaborate with workers at the University of New Mexico to investigate silicon micromachining for accelerometers and switches.

Three major events led to the emergence of a major Micromachining activity at Sandia.

1. Sandia received Congressional Approval to create the Microelectronics Development Laboratory, which began operations in 1989. This new facility was configured in a finger-and-chase layout with the unique property that each clean room bay (the finger) could be separated from the rest of the clean room by sliding glass doors on each end to prevent cross contamination between distinct process areas. This design permitted the introduction of materials and processes into the fab that would be a contamination risk in a ballroom-style clean room. This design resulted in a facility where high-yield standard flow manufacturing could exist with research and development of novel microsystems technologies.
2. The second was the the end of the cold war. The resultant drop in Sandia's integrated-circuit production for national security applications freed capacity previously devoted to product and thus expanded the availability of Sandia's semiconductor facilities for research and development.
3. The final element was the passage by Congress of the National Competitiveness Technology Transfer Act of 1989. This legislation assigned to DOE National Laboratories the mission of supporting US industrial competitiveness and funded joint research between US companies and National Laboratories under Cooperative Research and Development Agreements (CRADAs). This led to over $100M of cooperative R&D in semiconductor research with US industry and an influx of specialized equipment from industry, valued at over $40M, in support of the joint R&D. Among the approximateAs we describe below, this influx of equipment and supplies enabled additional partnerships with university and industrial researchers to further advance Sandia's ability to develop custom micromachining technology.

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3.2 Early Development at Sandia

Following a seminar at Sandia by Professor Mueller of the Berkeley group, Sandia's semiconductor fab management identified internal funding to support Sandia's initial attempts at micromachining. While excited by the possibilities of this emergent technology, Sandia microelectronics engineers realized they could not sustain the needed long-term development by technology push alone. Thus, their first efforts were devoted to identifying internal customers who might benefit from the new technology (customer pull). The microelectronics engineers found such an internal customer in Sandia's precision mechanical components group—the same group which they were not able to support in the earlier facility. To be relevant to Sandia's mission, the internal customers demanded one technical advance: they explicitly required the technology be capable of performing useful work. In other words, Sandia had to develop linkages between electrostatic motors and gears—each of which had been demonstrated by other groups independently but which had never been integrated into a single system that could perform useful work. This experience only reinforces the importance of carefully choosing intermediate goals in the development of an emergent technology. [9]

The Sandia engineers confronted the same obstacles as those that confronted the other pioneers in silicon micromachining. In those days, silicon technology relied on the deposition and patterning of multiple fabrication layers that conformed to the topology of the patterned layers that preceded it. In Figure 1 we demonstrate an electron micrograph of the polysilicon technology common to the CMOS fabrication of the mid-1980s. The CMOS technology at the time was limited to only a few layers of interconnections because the nonplanarity of the top surface increased with the number of layers. In the technology shown in Figure 1, the top level of metallization had to cross steps with heights of 0.8μm—which could lead to long-term reliability problems from stress voiding and electromigration [10]. The non-planarity of additional layers was a major issue that limited the complexity of all integrated circuits at the time.

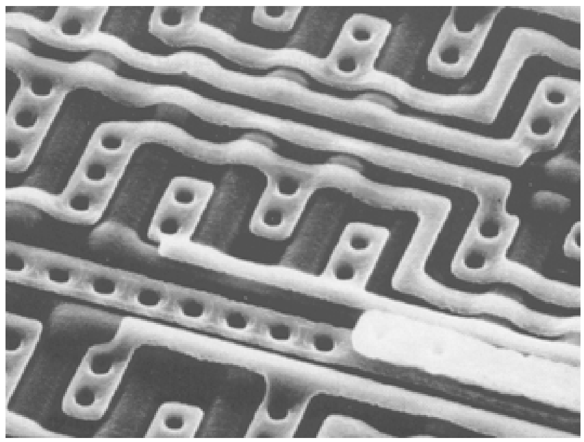


Figure 1. Electron micrograph of 1980s-vintage Polysilicon-Gate CMOS Integrated Circuit. The micrograph illustrates cumulative topology variations of 0.8micrometers at the uppermost level of a two-level interconnection circuit.

Knowing that the future of Sandia's emerging microsystems technology depended on developing a working microengine, Sandia's semiconductor engineers entered into a partnership with Sandia's precision mechanical engineers. The partnership between mechanical and semiconductor engineers was essential to moving the technology forward to meet the mandated internal technology relevance criterion.

While Sandia already employed subject-matter experts in silicon-integrated-circuit fabrication and precision mechanical engineering, the program made a major advance when it brought in a new staff member from the University of Wisconsin whose Ph.D. thesis on micromachining gave him direct experience with low-stress polycrystalline structural layers. These insights became critical to Sandia's ability to create significantly more complex mechanical structures than the two-level structures that characterized the state of the art in mechanical complexity at the time.

To go beyond layout options available from semiconductor circuit layout programs, Sandia applied the software program Vellum on a Macintosh platform to design involute gears for the photolithographic masks needed to realize the gear and linkages. [Later, the design package migrated to AutoCAD.] Involute gears are the most commonly used system for gearing today. In an involute gear the two-dimensional profiles of the teeth are involutes of a circle so that contact occurs at a single instantaneous point and the angular velocity ratio between two gears of a gearset remains constant throughout the mesh. The inability to planarize the steps meant that the gear teeth had to be trimmed to prevent interfering with the non-planar linkages (Figure 2). As the goal of this initial project was to demonstrate proof of principle, the lack of optimized gear teeth was not seen as a limitation. No sooner was the first microengine printed using a linear actuating motor than Sandia researchers stumbled across a major limitation of working at the microscale: namely, stiction or sticky friction. Unlike steam locomotives, in which the drive actuator could rely on the inertia of the driving wheels, the drive gear for the microengine had to be driven by two orthogonal linear actuators operating in quadrature because the microgear did not have sufficient momentum to continue beyond the dead spot that occurred when the actuator was aligned with the radius of the gear and thus provided no torque. This first successful demonstration is illustrated in Figure 2 below. [11] Note the non-planarity of the step coverage for the gear linkage and the need for quadrature drive (two drive linkages at 90 degrees to each other) from each of two electrostatic engines.

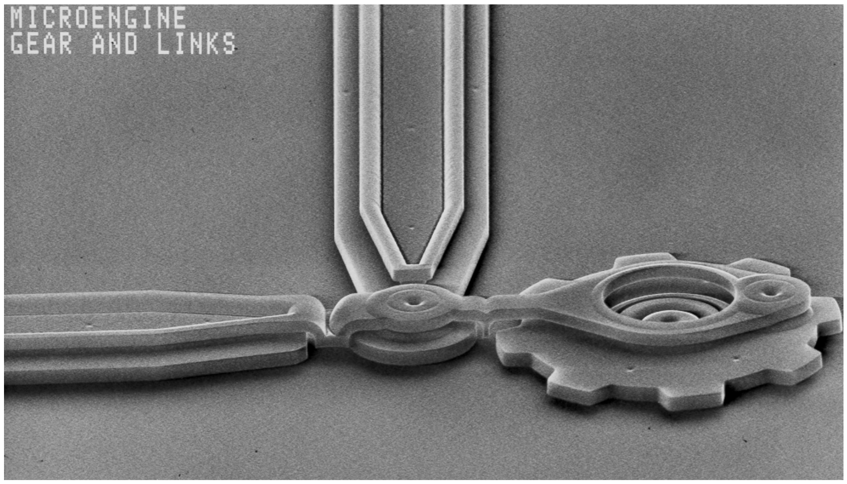


Figure 2. Electron Micrograph of the Functioning Gears and Linkages Fabricated with Non-Planarized Micromachine Technology using Non-Planarized Polycrystalline Silicon as a Structural Material. Note the non-planarity of the step coverage for the gear linkage and the need for quadrature drive from the electrostatic engines.

While silicon surface micromaching was a major area for investigation, Sandia's semiconductor engineers were also examining other micromaching technologies. Sandia's first bulk micromachining technology used KOH solutions to anisotropically etch silicon to create through-wafer vias. The ability to perform KOH etching in the same facility that produces CMOS integrated circuits was a testament to the design flexibility of Sandia's Microelectronics Development Lab (presently Sandia's MESA silicon fab) because potassium is a contaminant in integrated-circuit fabrication that produces mobile ions in the silicon-dioxide gates of CMOS transistors. Mobile ions produce uncontrolled variations in the turn-on and turn-off voltages of CMOS transistors as they switch states. Use of KOH etches allowed Sandia to create thin suspended silicon nitride membranes which served as a platform for quartz resonators and pressure sensors. [12] Later, KOH etching was replaced by the Bosch process for Reactive Ion Etching to achieve the same kinds of through-wafer vias for other applications. Still, these early experiences with KOH introduced thought patterns that would prove useful as Sandia evolved to integrated microsystems rather from discrete micromachined components.

3.3 Maturing the Technology: Infrastructure Development

The timing of Sandia's entry into sacrificial surface micromachining benefited from the rapid introduction of new materials and process technology by leading edge semiconductor manufacturers. The semiconductor industry was devoting substantial effort into planarizing the topology of multiple interconnect layers in high-density integrated circuits at a time when integrated-circuit technology was beginning to migrate from standard aluminum interconnects toward copper metallization. A Cooperative Research and Development Agreement (CRADA) with the International Business Machines Corporation (IBM) brought Sandia tens of millions of dollars of prototype semiconductor processing equipment, including chemical-mechanical polishing machines. While IBM did not share their proprietary recipe for CMP for integrated circuits, Sandia was able to apply the scientific resources of a National Laboratory to develop a similar technology using IBM's donated equipment. While Sandia did not discover CMP, it was the first to apply CMP to sacrificial surface micromachining. [13]

The development of in-house chemical-mechanical polishing had three significant benefits.

First, in-house CMP enabled Sandia to advance its CMOS to multiple levels of on-chip interconnections (Fig. 3).

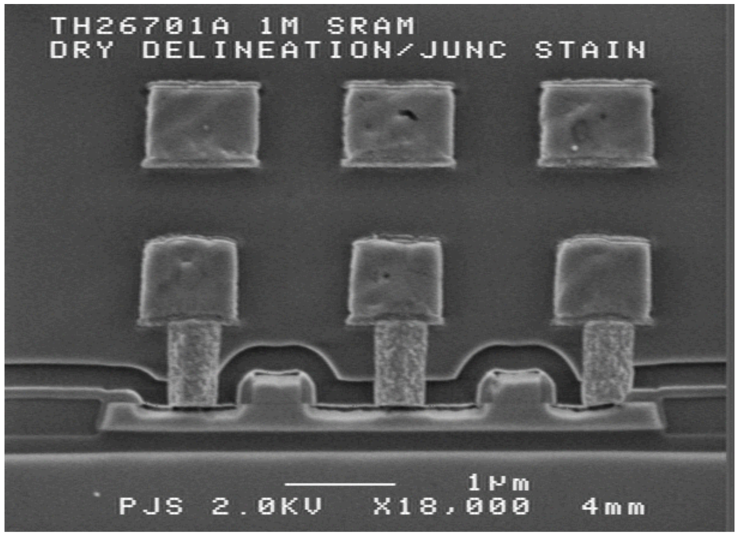


Figure 3: Cross-Sectional Micrograph of Multiple Levels of Interconnection in Sandia's Integrated-Circuit Technology Enabled by Chemical-Mechanical Polishing. Contrast the planarity of the interconnect levels (the rectangles) with the topology of the non-CMP technology illustrated in Figure 1.

Second, this planarization technology was now available to eliminate the topological variations and enable printing of true involute gears. As multilevel silicon surface micromachining evolved, Sandia had to develop techniques to planarize not just the 1-micrometer steps for integrated circuits but more demanding two- to three-micrometer step heights for micromachined gears and linkages.

Finally, because Sandia was a leader in publicizing the advantages of chemical-mechanical polishing and further was extending CMP beyond integrated-circuit applications, Sandia obtained CRADAS that provided the facility with alpha-test equipment, colloidal suspensions and polishes, polishing pads, and partnerships with universities such as MIT and Clarkson University that set new standards for pads and polishing slurries. Among the outputs of these partnerships was a density-characterization die to enable design for manufacturability of chemical-mechanical polishing.

With the advent of chemical-mechanical polishing and as a result of significant effort by Sandia scientists and engineers in adjusting the material properties and process recipes for depositing doped silicon dioxide and low-stress polycrystalline silicon to minimize residual stress from differential thermal expansion, Sandia was able to develop multiple mechanical layers in sacrificial silicon micromachining. Multiple layers were needed to create gear chains for actuators because of the low force generated by electrostatic comb drives. Designers were forced to create extensive gear chains (Figure 4) that traded speed for torque. With these gear chains, electrostatic microengines had to be driven to speeds of up to 600,000 revolutions per minute to enable a 1mm travel of a rack and pinion assembly in 1 millisecond.

Thus, while demonstrating proof of principle for micromechanical actuators, the initial attempts at drive motors led to immediate concerns for reliability. Simple calculations indicate that constant use for a 1 billion-cycle lifetime operating at 600,000 revolutions per minute would provide an operating lifetime of just under 28 hours—sufficient for some one-time or even low-duty cycle applications but not for others.

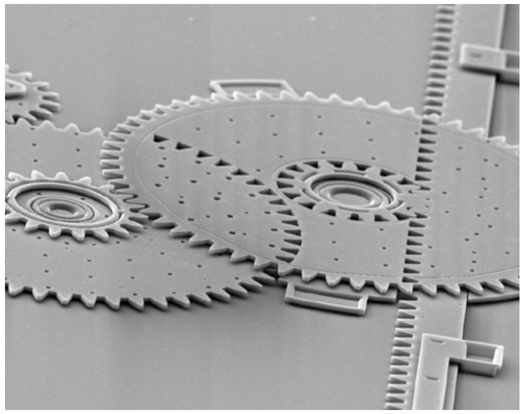


Figure 4. Example of planarized gear chains (note two levels of involute gear teeth) needed to amplify force from electrostatic comb drives sufficient to drive a rack and pinion assembly through a 1-mm travel.

Many of Sandia National Laboratories missions require high reliability for high-consequence applications. Thus, Sandia began an extensive program to understand the reliability limits of the early technology [14] supported by internal research and development funding (the Laboratory-Directed Research and Development program). Based on previous experience with reliability of electronics for high-consequence, long-lifetime applications, Sandia scientists and engineers realized that there existed a high degree of complexity in the tradeoffs between performance and reliability—all of which was compounded by the novelty of dealing with effects (such as stiction) that only became important at the microscale. As with other technologies, the performance/reliability trade space was determined by the interaction of three key elements: (1) device design, (2) materials choices and manufacturing process options, and (3) the application and the operating environment. It was found that properly designed micromachines were incredibly resistant to mechanical shock because the inherent lack of inertia of these miniature components—which had been an initial obstacle in developing the first microengine. Under best conditions, devices fabricated in sacrificial surface micromachining allowed survival beyond 20,000 times the acceleration of gravity and some devices remained working to 40,000 G.

Extensive testing revealed that generation of wear debris was a limiting factor even when all other factors (including humidity, drive waveforms, temperature cycling, storage conditions, etc.) were optimized (Figure 5). Clearly, Sandia had to pursue other mechanisms for mechanical actuation. The first was to tweak the fabrication process.

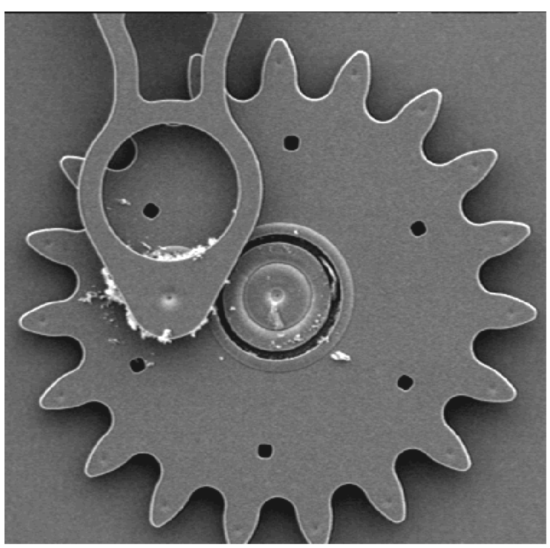


Figure 5. Early stages of failure of a polysilicon microgear after only one million operating cycles. Note debris inside the gear hub leading to operational failure.

Some Sandia applications must operate in the radiation environment of space. Thus Sandia investigated the radiation survivability of silicon surface micromachines. It was found that coating the moving surfaces with selective tungsten surface layers prevented charging of dielectrics. [Induced charges impede the operation of an electrostatic actuator.] With selective tungsten coatings as a ground plane, the electrostatic actuators survived megarads of radiation. [15]

An unexpected benefit of selective tungsten coatings was the increase in operating lifetimes. In Figure 5 we illustrated the early stages of failure for a purely polysilicon MEMS drive gear due to debris formation. Debris build up from friction and wear at the microscale interfered with device operation and led to failure after only one million cycles.

It was found that the selective tungsten coating that prevented dielectric charging in radiation environments proved beneficial in reducing wear from similar contacting surfaces. In Figure 6 we illustrate a similar gear assembly with selective tungsten coating after one billion cycles showing no signs of debris formation.

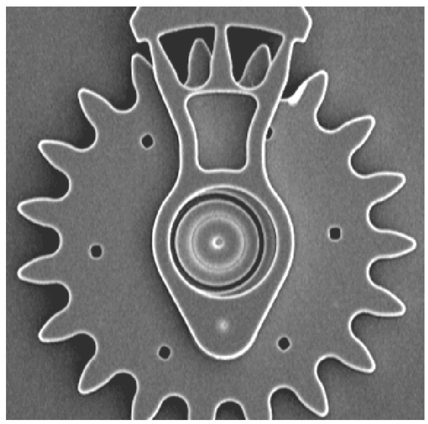


Figure 6. Gear assembly similar to that of Figure 4 except that a tungsten coating (white edges) was selectively applied to key contacting surfaces. Note the lack of debris formation even after one billion cycles of operation.

Because the original motivation for Sandia's microsystem program was the actuation of precision mechanisms, Sandia's engineers and scientists investigated other actuation mechanisms. An early attempt at thermal actuation was Sandia's attempt to create a miniature steam engine (Figure 7). While the micro steam engine produced substantially more force than the electrostatic drive, the approach was impractical for a variety of reasons. This design does accentuate the diversity of approaches explored to address the force limitations of MEMS technology.

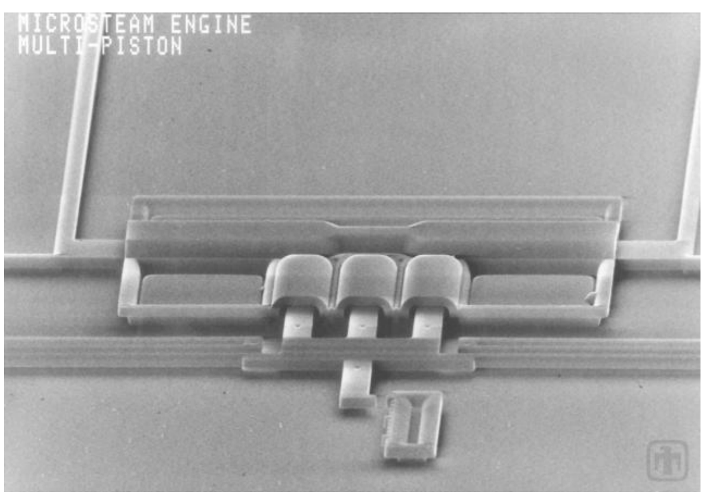


Figure 7. Micromachined Steam Engine. While the design generated substantially more force than the electrostatic comb drive, the approach was impractical.

Sandia's next attempt leveraged the expertise of Sandia's mechanical engineering community. They devised a ratchet and pawl mechanism (as one would find in mechanical watches) to create a tortional ratcheting actuator (Figure 8). The approach greatly minimized the amount of contacting surfaces and thus greatly extended the operating lifetimes for mechanical actuators. This approach also eliminated the need to convert linear to rotational forces, as required by earlier electrostatic comb drives, thereby eliminating the need for cams and greatly reducing the footprint required for micro-scale engines. The tortional ratcheting actuator is still being used in applications where drive force is not the major requirement.

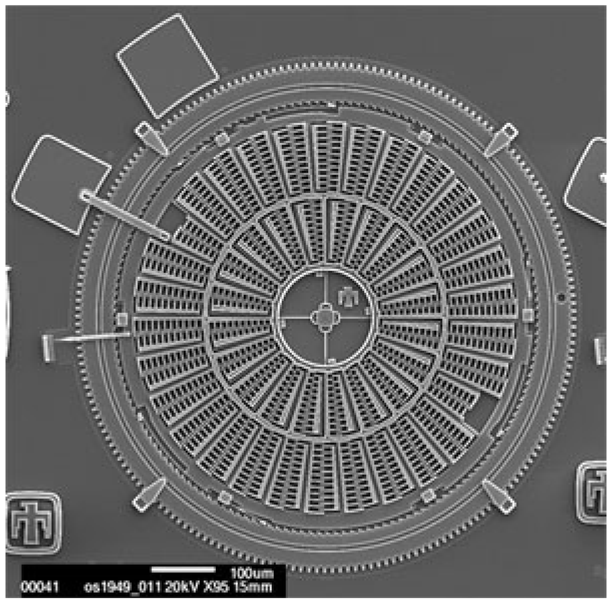


Figure 8. Tortional Ratcheting Actuator

Thermal expansion is a powerful force of nature. While the thermal expansion of water into steam did not prove useful at the microscale, Sandia engineers returned to the concept. Realizing that even the electrostatic actuator consisted of thin polysilicon lines suspended above the silicon substrate—and thus the only heat sinking came from radiation, Sandia engineers designed actuators that relied on joule heating from an applied current to cause thermal expansion of the suspended polysilicon. Appropriately designed, this expansion could produce significant force. Further, by working at the microscale, the thermal capacity of the suspended lines was minimized, allowing recover in an acceptable amount of time.

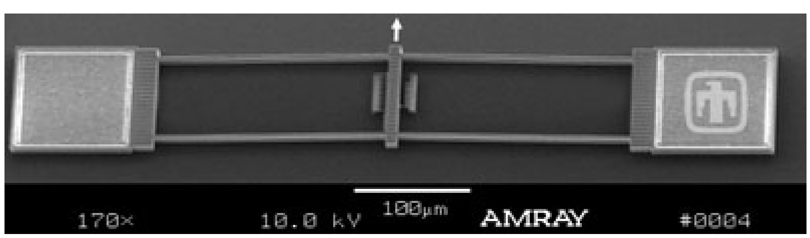


Figure 9. V-shaped thermal actuator.

As with the other microsystem elements, the thermal actuator provided an additional tool in the toolkit as evidenced by its integration with the ratchet and pawl mechanism illustrated in Figure 10. This discussion only addressed the challenging evolution of mechanical actuators. Integration into complete microsystems was a larger challenge.

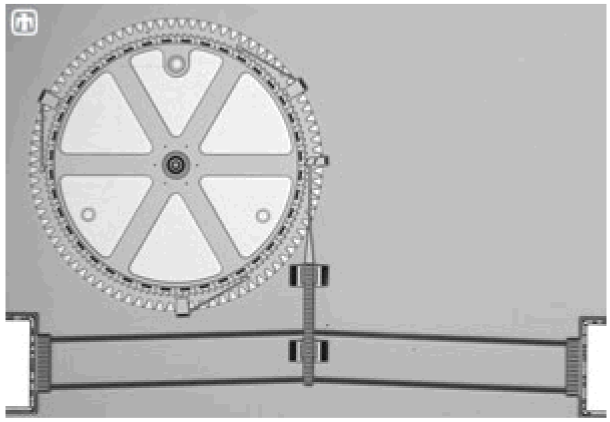


Figure 10. Integration of thermal actuator with ratchet and pawl mechanism to realize a ratcheting thermal actuator.

As part of its mission as a National Laboratory, Sandia worked to make its microsystem technology available to the larger community. The first step was to train users in Sandia's microsystem technology through the SAMPLES program. [16] This program made the possibilities of the technology known to potential users within Sandia, in the university community, and among potential partners in government and industry. Partly as a result, Sandia licensed its silicon surface micromachining technology to Fairchild Semiconductor Corporation in Portland Maine in 2001.

3.3 Attempts at Integration

Having developed mechanisms to perform useful work, Sandia ambitiously tried to integrate control and data-processing circuitry on the same chip as the micromachines. Sandia had previously developed a wide-range sensor that detected the presence of hydrogen gas over six orders of magnitude in concentration. The integrated hydrogen sensor featured extensive on-chip electronics to perform temperature compensation and to interface to the external world through an RS 232 interface. [17] Sandia was then challenged to develop on-chip integration for the micromachines with full-flow CMOS processes. An initial brute-force approach is illustrated in Figure 9.

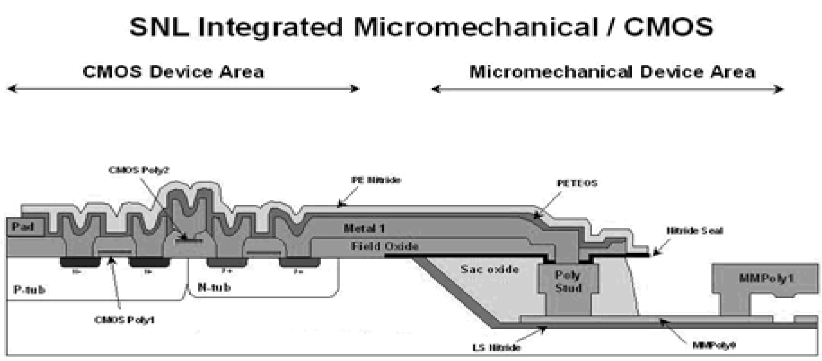


Figure 9. Cross section of Sandia's initial attempts at an Integrated-MEMS (I-MEMS) technology. The approach relied on fabricating the micromachines in a deep trench. On the same die, CMOS circuitry was then fabricated on the original wafer surface. Process complexity and limited yield proved this approach impractical.

In this technology, deep trenches were cut into the silicon wafer. The desired micromachines were then fabricated in inside the deep trench. This step alone introduced significant process delays because the photolithographic tool had to be refocused to pattern the devices inside the trench. Worse, with the focus lithographic tool set deeper than the surface of a standard silicon wafer, the photolithographic tool was unsuitable for standard CMOS until re-focused back to the wafer surface. Further, because there was no synergy between fabricating the MEMS and the accompanying CMOS circuitry, the process required processing all the photolithographic mask levels for the MEMS, then serially processing all the photolithographic masks for the desired CMOS circuitry. With so many mask levels processed serially, the number of functioning die (the chip yield) was disappointing.

After the initial attempt, it was clear that the brute-force approach to I-MEMS would not succeed. In contrast, the integrated hydrogen sensor described above relied on only two variations to the existing CMOS process: fabricating selected transistors with gates of a special palladium alloy and fabricating resistors also of a special palladium alloy.

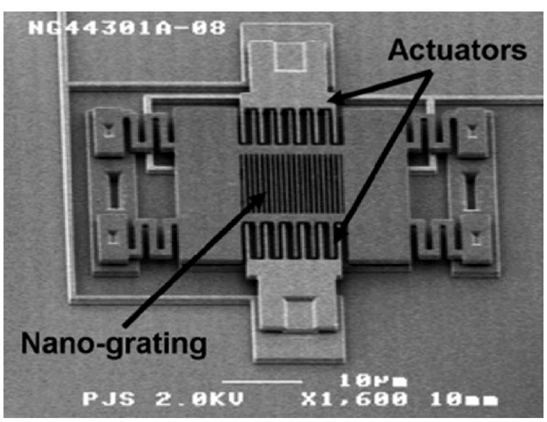
Sandia's microsystems technology thus evolved in two related directions. In the first, drawing on the lessons of the integrated hydrogen sensor, Sandia developed NMOS transistors that could be built on the same chip as the sacrificial silicon surface micromachining using the basic MEMS process flow. These simple on-chip devices enabled basic switch/driver electronics with limited functionality—sufficient to get signals to and from the MEMS structure without degradation from parasitic and impedance mismatches.

Second, and more important, Sandia's micromachine technology evolved to add *functionality* rather than *digital processing power* to their microsystems. Over the years, Sandia developed a wide-range of microsystem capabilities that can be integrated as the application demands. [18] These include radio-frequency MEMS, microoptics, switches and actuators, and microfluidics.

3.4 Integrated Microsystems

Two examples illustrate the potential of the heterogeneous integration of these microsystems components.

In the first, we describe a micro-optical nano-g accelerometer (Figure 10) that at the time established the limits of optical sensing, acceleration sensing, and lithography by achieving noise floors corresponding to 17nG/rt-Hz (at 1Hz) using some of our most sensitive optical displacement sensors with sensitivities as low as 12 fm/√Hz (at 1kHz). [19]



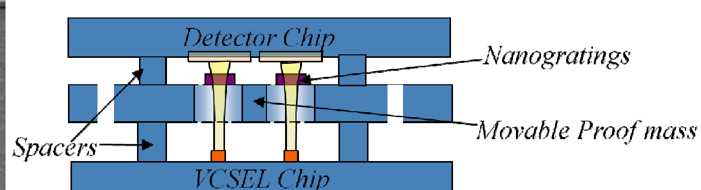


Figure 10. Left. MEMS optical near-field resonant displacement sensor based on vertically stacked sub-wavelength nano-gratings. The nano-gratings are attached to electrostatic actuators to control their motion and characterize their displacement sensitivity. Right: Device concept. In this optical sensing method, sub-wavelength grating structures are coupled in the near-field where very small changes in lateral displacement (femtometers) are detectable as changes in optical reflectance of the Vertical-Cavity, Surface-Emitting Lasers (VCSELs)

In the second, we illustrate a promising approach to engineered neural networks using microfabricated cell guidance cues. [20] The goal of this activity is to test hypotheses regarding the relationship between brain network architecture and function, researchers require the ability to engineer, measure, and modify living neural networks in controlled environmental conditions. Eventually, such technology could provide the capability to repair damaged nerve tissue and fully restore lost motor, sensory, and cognitive functions. At the time, many neural engineering efforts organize large populations of neurons into grossly-defined patterns with minimal success at organizing individual synaptic connections. Thus, Sandia developed microfabricated cell guidance cues which contain patterned chemical and topographical features that promote neuron attachment and outgrowth at pre-defined locations. This microsystem is illustrated in Figure 11. This represents a significant departure from mechanical actuators and yet was fabricated with the same technology.

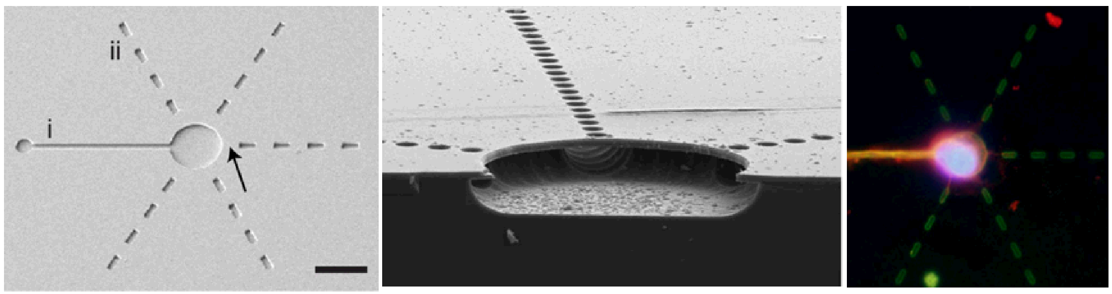


Figure 11. Microfabricated cell guidance cues for controlling neural attachment. Left: Top view of guidance cues for controlled neuron polarization illustrating continuous features (i) for directing axons and interrupted features (ii) for guiding dendrites. Middle: side view of buried guidance cues. Right: Fluorescence image of a properly polarized rat neuron.

The above illustrations provide only a brief glimpse of the possibilities that have emerged following two decades of work at Sandia on engineered microsystems. A more complete inventory can be obtained online [18].

SUMMARY

From its inception through to its present maturity, we note several factors that were essential to Sandia's future success in developing integrated microsystem technology:

- A mission need to miniaturize mechanical components and make them more robust. This mission need motivated patient funding for technology exploration and maturation sustained by realizing intermediate goals.
- Direct involvement of a wide variety of subject-matter experts from the very inception of the technology.
- Interaction with the larger community: academic, industrial, and government.
- An external regulatory environment that provided a mechanism (the National Competitiveness Technology Transfer Act of 1989) which enabled partnerships. These partnerships provided specialized equipment and supplies to initiate, renew, and advance the technology.
- The availability of the resulting in-house state-of-the-art equipment which provided the capability for future advances.
- Direct interactions across multiple scientific and technological disciplines. These interactions occurred both within Sandia as well as external to Sandia.
- Flexible fabrication facilities that supported both a mainline CMOS technology and yet could also support the development of non-CMOS technologies without interference combined with capacity that was available for exploratory technology development.
- Targeted hiring from leading-edge universities before the field became commercially relevant.
- Ability to leverage development costs by identifying multiple applications of similar technologies for multiple sponsors.

As Sandia's programmatic interest was initially driven by the need for electrostatic actuation, one sees how direct experience with the emerging technology surfaced issues and led to solutions that would not have been apparent to the novice (they initially weren't even obvious to the Sandians working on the program). Modern scientific and simulation tools can be applied to answer many of the issues that confront those working on emerging technologies. Often technological barriers arise not from an inability to answer questions, but rather from knowing the right questions to ask.

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