Microelectromechanical Systems (MEMS) Research

BYU Department of Mechanical Engineering

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Microelectromechanical systems (MEMS) integrate mechanical and electrical components and have feature sizes ranging from micrometers to millimeters. They may be fabricated using methods similar to those used to construct integrated circuits. Their size makes it possible to integrate them into a wide range of systems. Microsensors (e.g., accelerometers for automobile crash detection and pressure sensors for biomedical applications) and microactuators (e.g., for moving arrays of micromirrors in projection systems) are examples of commercial applications of MEMS.

BYU MEMS research has a strong history of developing revolutionary devices, including fully-compliant bistable mechanisms, thermal actuators and piezoresistive sensors. Current research focuses on biological applications of MEMS, creating actuators capable of large displacement with integrated position sensing, and using MEMS to store and transform energy. Many of the resulting devices are being fabricated in an innovative high-aspect ratio technique using thick arrays of carbon nanotubes. Several of the projects are in collaboration with faculty in other departments and with other institutions.

A few highlights are listed below, followed by a list of recent outcomes.

Nanoinjection

Nanoinjection research is in collaboration with Dr. Sandra H. Burnett in BYU's Department of Microbiology and Molecular Biology.

We are creating a new approach, called "nanoinjection" as a means for conveying macromolecules, such as DNA, across cell membranes. Nanoinjection has the potential of expediting the development of transgenic animals and cellular biology studies, both of which are essential to biological and medical research. Nanoinjection offers possible new mechanisms for drug delivery, and application to therapies for treatment of genetic diseases. Example research areas that would be affected include immunology, cancer, genetic disorders, genomics, reproduction, infectious diseases, development and aging, and metabolic disorders.

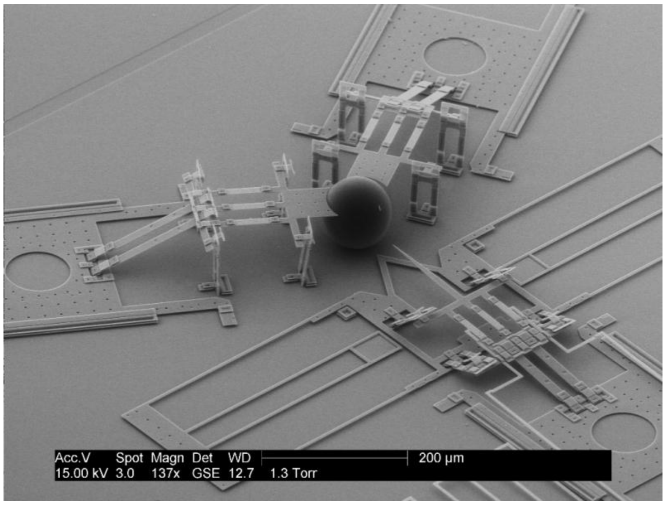


Figure 1. A scanning electron micrograph (SEM) of a nanoinjector prototype designed at BYU. A latex sphere is shown to present the target cell and is approximately the size of a mouse zygote.

The intent of nanoinjection is to transport DNA through cell membranes while causing minimal cell trauma and resulting in a dramatic improvement in cell survivability and expression. A scanning electron micrograph of a nanoinjector prototype is shown in Figure 1.

The process is illustrated in Figure 2 and the different components of the nanoinjector are shown in Figure 3. The process can be summarized as follows:

1. The cell is positioned and held in place by two MEMS constraining mechanisms.
2. Nano-scale phenomena are exploited by applying a voltage, small enough to avoid electrolysis and to preclude any danger of cell damage, to a "lance" that is in a solution containing the DNA.
3. DNA is electrostatically attracted to the charged lance and concentrates on its surface.
4. A novel MEMS device translates the lance in a path normal to the cell membrane, and the lance penetrates the cell membrane. The lance's nano-scale features cause negligible damage to the membrane.
5. Polarity on the lance is reversed and the DNA is electrostatically repulsed, distributing it inside the cell.
6. The lance is retracted and the cell is released.

The project's preliminary studies have demonstrated the feasibility of nanoinjection using a prototype to inject DNA into mouse egg cells. Testing showed that fertilized mouse eggs nanoinjected with a gene encoding red fluorescent protein have both an exceptional rate of viability and transgenic expression. Figure 4 includes an image of a blastocyst with

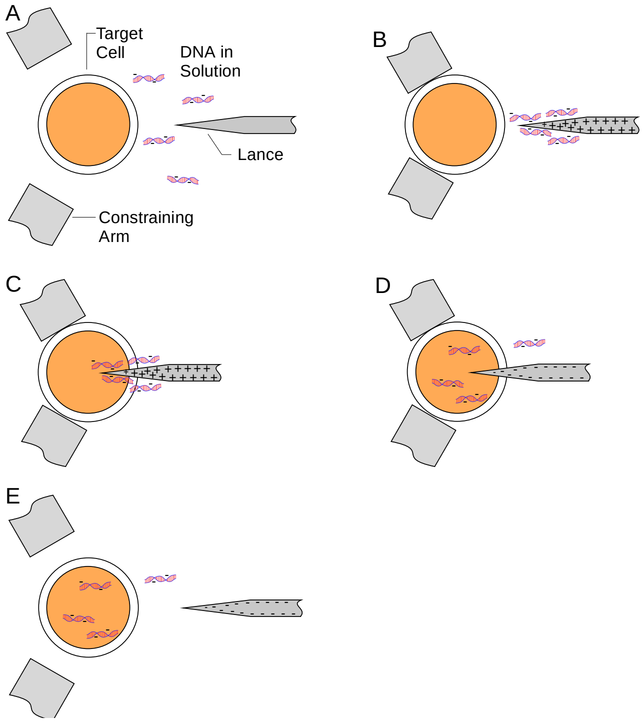


Figure 2. The nanoinjection process. (**A**) DNA is put in ambient media with target cell, lance, and constraining arms. (**B**) A positive voltage is applied to the lance to attract negatively charged DNA. (**C**) The lance enters the target cell. (**D**) A negative voltage is applied to the lance to repell DNA into the cell. (**E**) The lance and constraining arms are retracted to release the cell.

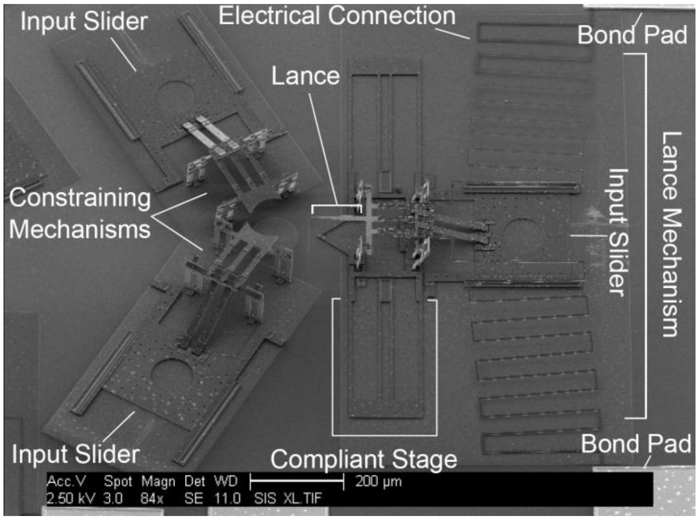


Figure 3. A scanning electron micrograph (SEM) of the MEMS nanoinjector.

full expression (early transgene incorporation) and with chimeric expression.

The DsRed-Monomer data indicates that nanoinjection can result in early DNA integration and that nanoinjection does not interfere with blastocyst development.

The survival and expression rates of nanoinjected cells are being studied and nanoinjection capabilities are being expanded to achieve multiple gene injection, and to deliver proteins, chemicals, or siRNA into cells.

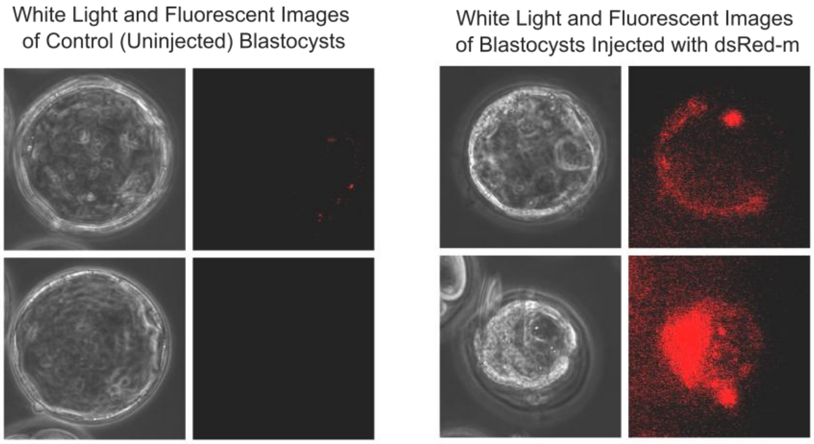


Figure 4. Nanoinjected blastocysts express red fluorescent protein either fully (lower right) or chimerically (upper right); compare to the lack of expression in control blastocysts (left).

Nanoinjection has the potential of replacing current fluid-injection-based microinjection methods with a dramatically more efficient process (at least five times more efficient according to preliminary data), thus affecting the numerous areas where microinjection is currently used. Moreover, nanoinjection will enable critical research beyond what is currently possible. Potential applications include simultaneous injection of multiple genes, injection of macromolecules such as siRNA and proteins, possible new mechanisms for drug delivery, and application to therapies for treatment of genetic diseases. Such a tool can be used to improve and accelerate transgenic animal development and influence research in all areas of cellular and molecular biology and medicine.

Safing and Arming

The safing and arming work described in this section was done in collaboration with researchers at Sandia National Laboratories.

A safety and arming (S&A) device is an electromechanical system designed to ensure protection of personnel and equipment against premature weapon detonation through the “stockpile-to-target sequence”. Many S&A devices are designed to ratchet a mechanical wheel into the “arm” position when the predesignated electrical sequence of inputs is completed correctly. If the input sequence is incorrect, the mechanism should “lock” and render the weapon useless until it is reset. In the locked or unarmed position the S&A device should be able to withstand extreme environments without allowing the weapon to “arm”.

As S&A devices have become smaller and approached micro proportions, previously insignificant issues have become more influential. In the micro regime, friction is considered to be a major cause of failure. Experience has also shown that the conventional spring elements, which are helical extension springs, are a major source of reliability concern.

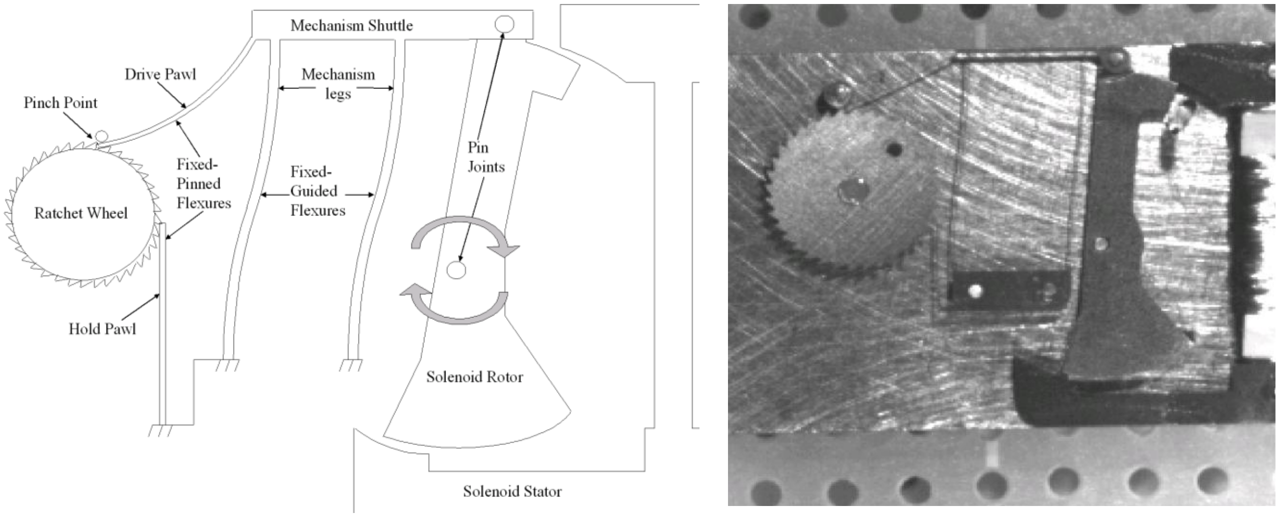


Figure 5. A schematic of the Compliant High-precision E-Quintet Ratcheting (CHEQR) mechanism with a rotary solenoid actuator (left), and a micrograph of a prototype micro-wire EDM CHEQR mechanism.

Our work developed the Compliant High-precision E-Quintet Ratcheting (CHEQR) mechanism as a means of exploiting the advantages of compliant mechanisms to create safety devices that eliminate the need for bearings and springs. The CHEQR mechanism is shown in Figure 5. Mathematical models were used to design a mechanism with the desired force-deflection characteristics, and the result is a radical departure from traditional ratchet and pawl mechanisms. Large-scale proof-of-concept prototypes were followed by micro wire EDM fabrication of precipitation hardened stainless steel devices with flexible segment widths of 50 μm. The device was integrated with a 6 mm ratchet wheel and rotary solenoid actuator.

Bistable MEMS

A bistable mechanism has two stable equilibrium states within its range of motion. At these states, the mechanism requires no input power to remain in position, and the mechanism will return to its stable position after small disturbances. Because of their ability to stay in position without input power and regardless of external disturbances, bistable mechanisms can allow MEMS to be designed with increased energy efficiency and improved accuracy and precision in positioning. The efficiency may be critical in autonomous applications which must produce or store their own energy. Bistable micro-mechanisms could be used as switches and relays, optical switches, non-volatile memory, micro-valves, discrete sensors, or micro-positioners with two repeatable positions.

Bistable micromechanism designs operate on the principle of creating stable equilibrium positions that are local minimums of potential energy. Several novel bistable mechanism designs have been developed at BYU and SEM's of three of these are shown in Figure 6.

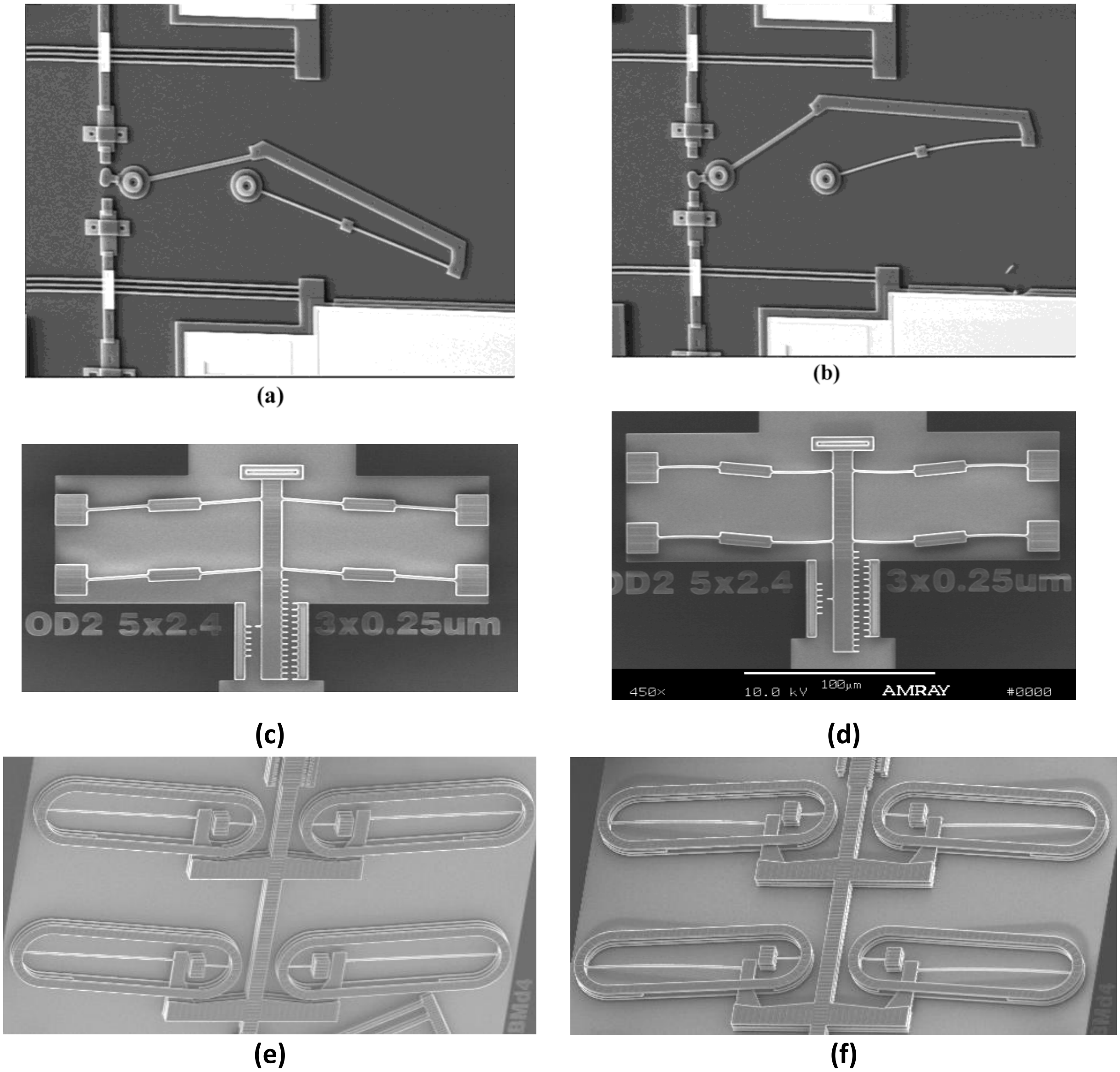


Figure 6. Examples of bistable MEMS designed at BYU. The first (as-fabricated) stable equilibrium position is on the left, and the second stable equilibrium position on the right for three different mechanisms, including (a), (b) a Young mechanism, (c), (d) a fully compliant bistable micromechanism (FCBM), and (e), (f) a double tensural bistable micromechanism (DTBM).

Thermal Actuators

Thermal actuation research was in collaboration with Prof. John N. Harb in BYU's Department of Chemical Engineering.

The magnitude of the thermal expansion is usually small and is not practical for use in macro devices. However, combined with approaches for amplifying thermal expansion, thermal microactuators can produce relatively large displacements.

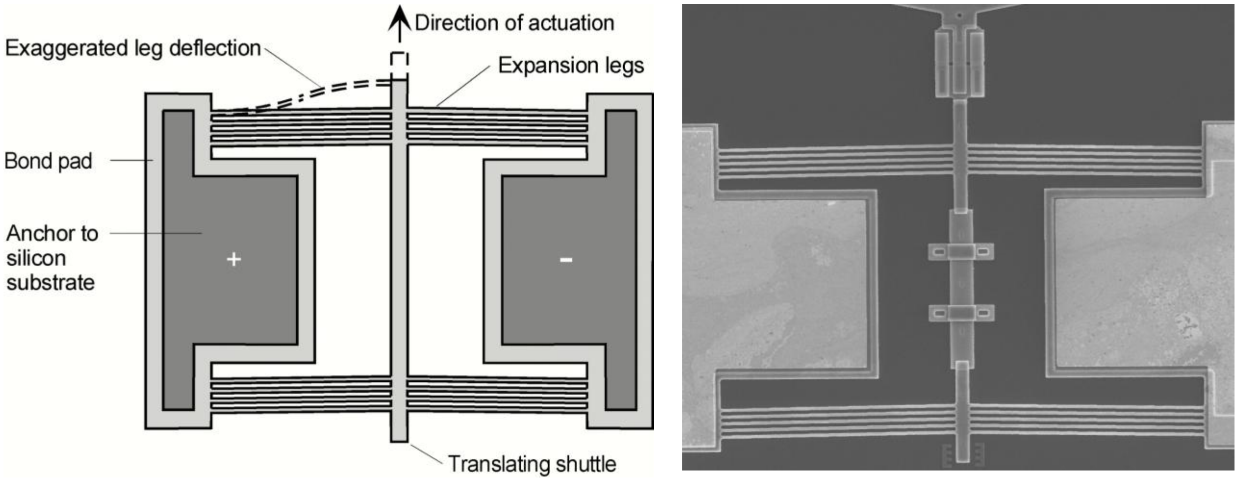


Figure 7. A schematic of a thermomechanical in-plane microactuator (TIM) and a scanning electron micrograph of a TIM.

The Thermomechanical In-plane Microactuator (TIM), illustrated in Figure 7, was developed at BYU. The TIM is made of a center shuttle connected to thin legs on both sides. The other ends of the legs are anchored to bond pads on the substrate. The legs are fabricated at a slight angle to bias them to move in the desired direction. As voltage is applied across the bond pads, electric current flows through the thin legs. The legs have a small cross sectional area and thus have a high electrical resistance. This high resistance causes the legs to heat up as the current passes through them. The legs expand but are constrained in their expansion. To accommodate the expansion, the shuttle moves forward. The displacement of the shuttle is influenced by a number of factors including the material properties, leg length, cross section area, initial biasing angle, and input power. The output force of the actuator is influenced by these same parameters plus the number of legs used. Advantages of this device include its ability to obtain high deflections and large forces, as well as its ability to provide a wide range of output forces by changing the number of legs in the design. A scanning electron micrograph of a TIM is shown in Figure 7.

The TIM has been used to actuate many other devices developed at BYU and has been employed by many other labs around the world.

Piezoresistance

Piezoresistivity in MEMS research was in collaboration with Prof. Timothy W. McLain in BYU's Department of Mechanical Engineering.

Piezoresistivity is a material property that couples mechanical strain to bulk electrical resistivity. In other words, if a piezoresistive member is bent, stretched, or compressed, its electrical resistance changes. The change in resistance can then be measured or converted into a change in voltage, and the corresponding stress (or strain) can be determined. Thus, stresses and strains can be related to physical phenomenon such as displacement or applied force through piezoresistivity. The piezoresistive effect has most widely been used in various types of sensors, including microphones, pressure sensors, force sensors, flow sensors, and displacement sensors.

Research at BYU has focused on integrated piezoresistive self-sensing. Integrated piezoresistive self-sensing is a sensing method that utilizes the deflection of intrinsic microflexures to sense the state of a microdevice. These microflexures deform under a force or displacement caused by a physical phenomenon. Due to their piezoresistive material property, the electrical resistance of a flexure changes in correlation with its deformation. This change in resistance can be used to calculate the value of the original force or displacement. Piezoresistive elements have often been implemented in microsystems in ways that place the piezoresistive elements in pure tension or compression (such as on the surface of a beam or a membrane). For integrated piezoresistive self-sensing devices, however, rather than the piezoresistive element being part of the flexure, it *is* the flexure. The loading conditions for such sensors are more complex than pure tension or compression.

BYU research has shown that analytical resistance data from the current model of piezoresistivity does not match experimental data for microflexures in bending, and new models have been introduced to accurately analyze piezoresistance behavior under these complex loading conditions. New applications have also been introduced, including sensing for threshold sensors and position sensing.

One example of a piezoresistive sensor designed at BYU is the piezoresistive microdisplacement transducer (PMT). Figure 8 illustrates how the PMT uses integrated piezoresistive sensing to monitor the output displacement of a thermomechanical inplane microactuator (TIM). Using the PMT as a feedback sensor for closed-loop control of the TIM reduced the system's response time from 500 μs to 190 μs, while maintaining a positioning accuracy of ±29 nm. Feedback control of the TIM also increased its robustness and reliability by allowing the system to maintain its performance after it had been significantly damaged.

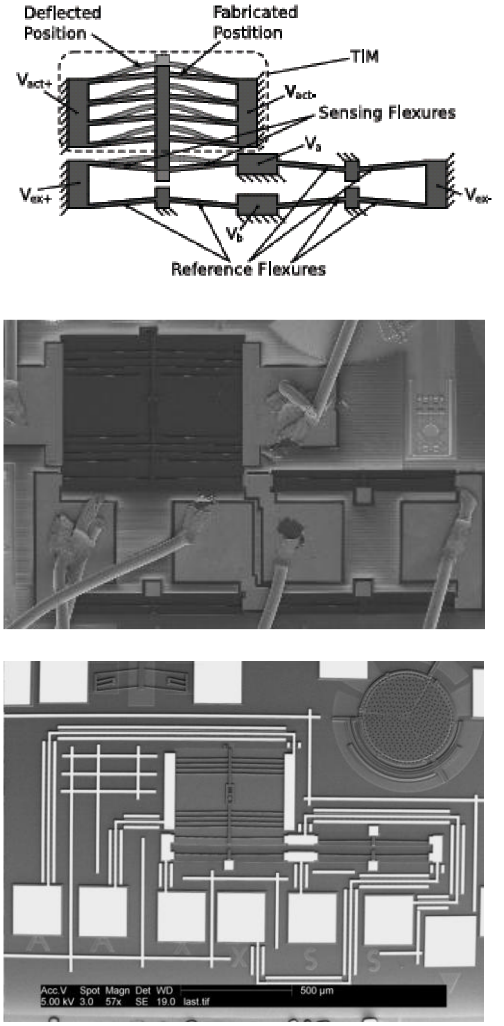


Figure 8. The piezoresistive microdisplacement transducer (PMT) as an example of an integrated piezoresistance device. A schematic (top) of the PMT with a TIM, a SEM (middle), and an SEM of a PMT-TIM device with shielding.

Carbon-nanotube-based Fabrication of High Aspect Ratio MEMS

The work in carbon nanotube fabrication of MEMS has been in collaboration with Professors Robert C. Davis and Richard R. Vanfleet in the Department of Physics and Astronomy.

A class of three dimensionally patterned carbon nanotube composite materials was developed for microelectromechanical systems. The method takes advantage of the precise high aspect ratio shape of patterned, vertically-grown nanotube "forests" and makes these structures mechanically robust by filling the inter-tube spaces nearly completely with silicon or silicon nitride by low-pressure chemical vapour deposition. We've shown that this novel surface micromachining technique can result in high aspect ratio MEMS. Figure 9 shows example MEMS devices.

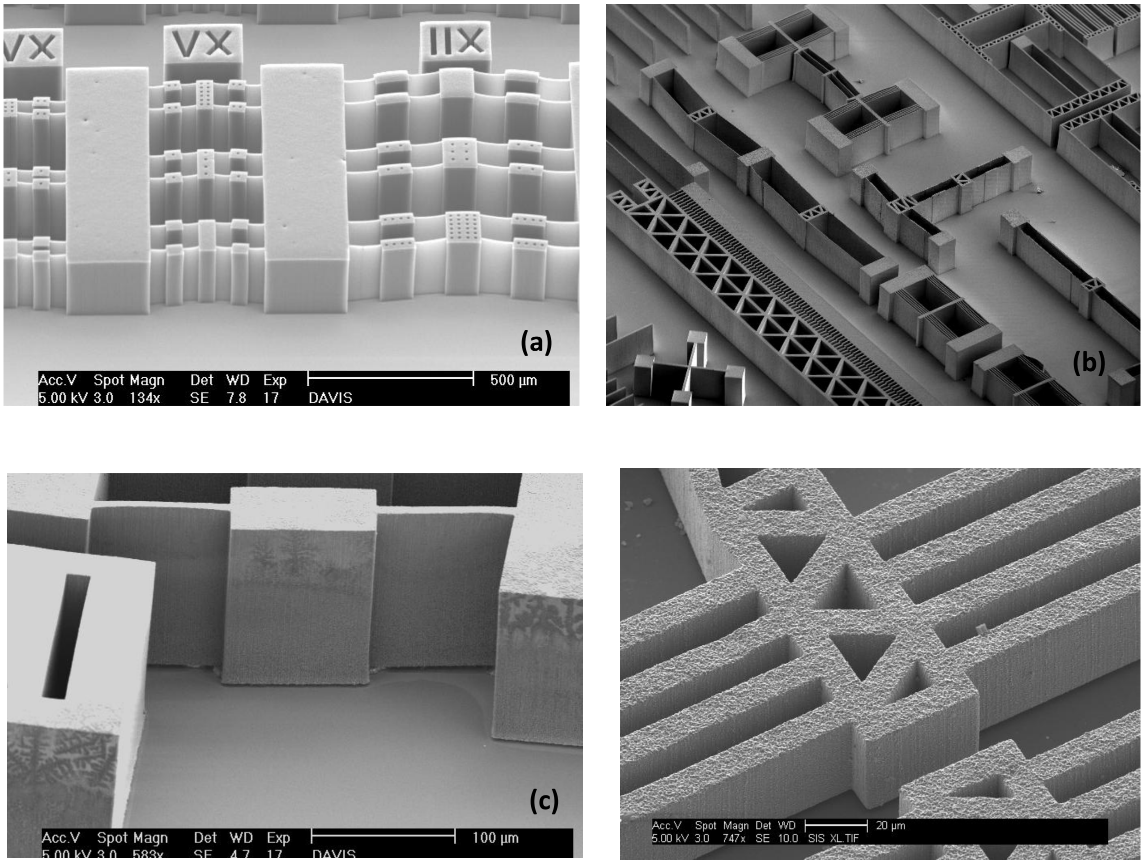
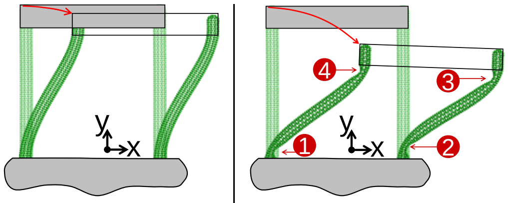


Figure 9. (a) CNT fabricated bistable mechanisms, (b) several high aspect ratio MEMS, (c) and (d), close ups of mechanism features.

Carbon Nanotube as Element of Compliant Mechanisms

The work in carbon nanotubes as elements of compliant mechanisms has been in collaboration with Prof. Martin Culpepper at the Massachusetts Institute of Technology (MIT).

It is hypothesized that carbon nanotubes (CNTs) can be used to create nanoscale compliant mechanisms that possess large ranges of motion relative to their device size. Figure 10 shows a possible parallel-guiding mechanism, with CNT flexible members, in two regions of motion. However, the motions are very complex and the analysis computationally expensive. Our work in this area has focused on developing simplified mathematical models that accurately predict the motion of carbon nanotubes undergoing large elastic deflections. This work has shown that a pseudo-rigid-body model may predict a CNT's fixed-clamped behavior with less than 7.3% error from molecular simulations. This removes the need for iterative, time-intensive molecular simulations during the initial design phases.



A: Region 1

B: Region 2

Figure 10. A CNT–based compliant mechanism in 2 regions of motion.

Other

We have done work in many other areas of MEMS, including micro force gauges, reliability, positioning, and compliant mechanisms. Scanning electron micrographs of some of these devices are shown in Figures 11-14.

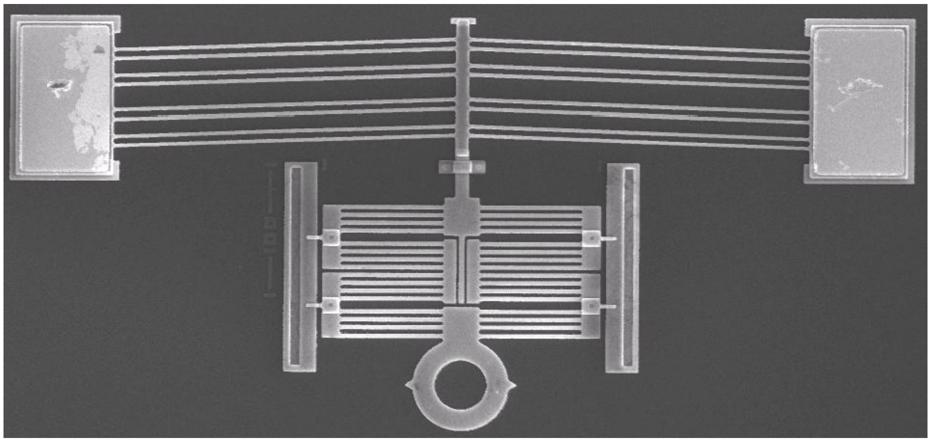


Figure 11. A TIM connected to a micro force gauge.

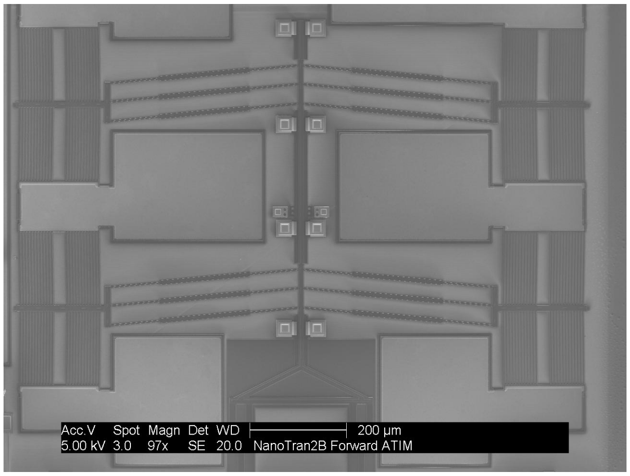


Figure 12. An amplified TIM, or ATIM, which further amplifies the displacement of thermal actuators.

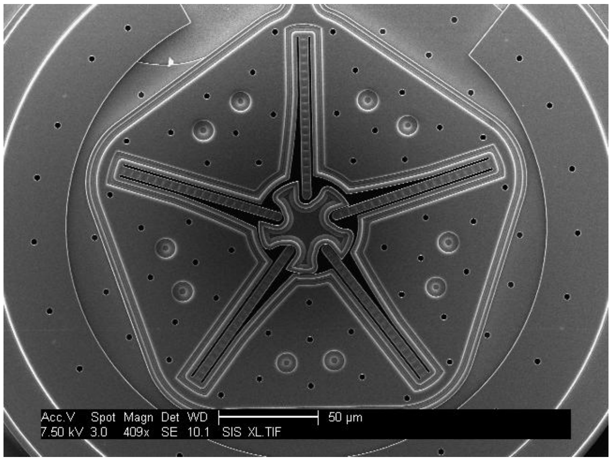


Figure 13. A bearing designed to withstand high transverse g-loads in safing and arming applications.

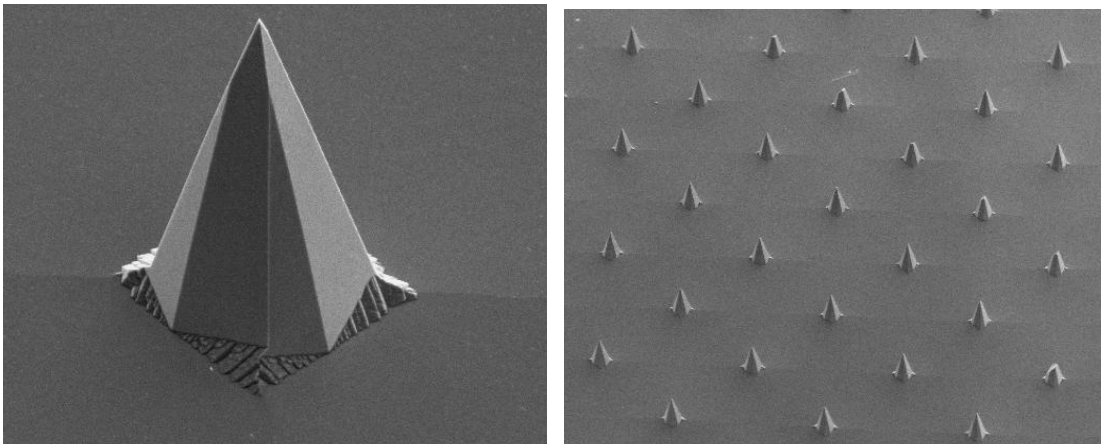


Figure 14. A silicon micro needle (left) and micro needles in an array (right).

Outcomes

This section summarizes some of the outcomes that are most easily quantified. Other outcomes, such as the impact of the work, is more difficult to summarize but hopefully can be inferred from this data.

Students

Education is a critical outcome of our work and graduate and undergraduate students are an integral part of our research. The level of participation in MEMS-related research is summarized below:

- 80 technical publications with student coauthors
- 51 different student coauthors on technical publications
- 16 student co-inventors on patent applications, provisional patents, and disclosures
- 16 patents applications, provisional patents, and disclosures with student co-inventors
- 30 graduate student theses and dissertations completed (7 currently in progress)
- Numerous undergraduate students involved in MEMS research, including the completion of two undergraduate Honors theses.

Graduate alumni have been employed in a diverse set of organizations, including the following:

- Sandia National Laboratories
- Lawrence Livermore National Laboratory
- Raytheon Missile Systems
- L-3 Communications
- Lockheed Martin
- Intel
- Motorola
- Micron
- Hewlett Packard
- ExxonMobile
- Ford Motor Company
- Xerox
- University of South Florida

Publications and Patents

- 87 MEMS-related technical publications
- 16 MEMS-related patent applications, provisional patents, and invention disclosures

Sponsors and Collaborators

In addition to the BYU research collaborators mentioned above, the BYU MEMS research group has been sponsored by or collaborated with the following institutions:

- National Science Foundation
- Sandia National Laboratories
- Army Research Office
- DARPA
- Block MEMS
- Massachusetts Institute of Technology