Overview of MEMS/NEMS Technology Development for Space Applications at NASA/JPL

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ABSTRACT

This paper highlights the current technology development activities of the MEMS Technology Group at JPL. A diverse range of MEMS/NEMS technologies are under development, that are primarily applicable to NASA's needs in the area of robotic planetary exploration. MEMS/NEMS technologies have obvious advantages for space applications, since they offer the promise of highly capable devices with ultra low mass, size and power consumption. However, the key challenge appears to be in finding efficient means to transition these technologies into "customer" applications. A brief description of this problem is presented along with the Group's innovative approach to rapidly advance the maturity of technologies via insertion into space missions. Also described are some of the major capabilities of the MEMS Technology Group. A few important examples from among the broad classes of technologies being developed are discussed, these include the "Spider Web Bolometer", High-Performance Miniature Gyroscopes, an Electron Luminescence X-ray Spectrometer, a MEMS-based "Knudsen" Thermal Transpiration pump, MEMS Inchworm Actuators, and Nanowire-based Biological/Chemical Sensors.

Keywords: MEMS, NEMS, space, sensor, NASA, JPL, inertial guidance, micro-propulsion, micro-electroplating, micro-instruments, TRL, PICOSAT,

INTRODUCTION

The explosion in Micro Electro Mechanical Systems (MEMS)[1] and most recently in Nano Electro Mechanical Systems (NEMS)[2] has occurred primarily within academic and research institutions. These institutions have concentrated for the most part on demonstrating the proof-of-principle for novel MEMS/NEMS devices. Although silicon integrated circuit technology was the initial enabler for these new technological thrusts, MEMS/NEMS have very quickly become truly multi-disciplinary, exploiting novel physical, chemical and biological phenomena, using a diverse range of materials systems. Also, the initial "top down" lithographic fabrication approach has been augmented with a "bottom up" self-assembly approach. The "bottom up" approach has been especially effective in NEMS, in order to bridge the gap between atomic dimensions and the limits of high-resolution lithography techniques such as electron beam lithography. However, despite the excitement and optimism generated over the last fifteen years, a key dilemma that confronts both researchers and investors alike is that relatively few of these technologies have made the successful transition to the marketplace. Among the most successful examples are cases such as the thermal ink-jet print-head[3], airbag accelerometers[4], and digital micromirror displays[5]. In many of these instances, the successful transition occurred either as a result of the initial development being undertaken by the in-house research department within a company, and subsequently followed by transfer to the manufacturing department, or as a result of a successful partnership between a company and an external research institution.

The development of advanced MEMS/NEMS technologies for space applications faces a similar dilemma in successfully "maturing" new concepts. NASA pioneered a means of evaluating the maturity of technologies, known as the Technology Readiness Level (TRL) scale[6], that has now found widespread use in government and industry. The TRL scale ranges from levels 1through 9, with levels 1-3 being at the so-called "Low TRL", basic research into demonstrating the proof-of-concept, while levels 4-6 correspond to "Mid TRL" development, which is the reliable demonstration of subsystems based on the new technologies, and finally, levels 7-9 (High TRL) correspond to successful utilization of these subsystems in NASA's space missions. The MEMS Technology Group at JPL pursues the development of advanced MEMS/NEMS technologies for space applications[7]. Thus, a significant fraction of our technology development activities are low TRL efforts analogous to the ones being pursued by academic and other research institutions. The challenge that confronts us is to bridge the "TRL Gap"[8], in order to successfully transition our technologies to space applications. Although our "customer" (NASA) only needs parts in relatively minuscule volumes compared to the consumer market, the requirements to be met are no less stringent, and in most cases much more so than for consumer products. Our primary barrier-to-entry is of course in generating sufficient test data in order to conclusively demonstrate the reliability of the new MEMS/NEMS technologies. Additionally, there is also a more subtle perception barrier to be overcome. This involves the generation of sufficient "space heritage" for the new technology. Although NASA's New Millennium Program[8] does provide flight demonstration opportunities for new technologies, these flights are few and far between and hence generally restricted to technologies that are already at a high level of maturity (TRL 4 and above).

The MEMS Technology Group at JPL has thus taken the revolutionary approach of attempting to develop within the group, and through partnerships with external organizations, the end-to-end expertise required for taking new technologies from concept to system level demonstrations. A novel solution developed to overcome the "TRL Gap" problem has been to fly MEMS/NEMS devices at the low TRL stage of development. It is hoped that such flight demonstrations will generate the necessary space heritage required for NASA's missions. More importantly, by having flights at low TRL one can either "screen" the technology for space-worthiness or alternatively, build in the requisite robustness, far more cheaply and cost-effectively, than at higher TRLs. Screening space-suitable devices at an early stage in the development cycle avoids wastage of effort and investment over several years into technological "dead-ends". On the other hand, design changes necessary to incorporate robustness into MEMS/NEMS are far easier and cheaper at low TRL.

An important innovation that makes testing new technologies in space competitive with terrestrial, laboratory testing is the development of the low cost, rapid launch, PICOSAT spacecraft. The PICOSAT is an invention of the Aerospace Corporation[9] and was developed for the express purpose of testing MEMS technologies in low earth orbit. The MEMS Group is partnering with the Aerospace Corporation under sponsorship from the Defence Advanced Research Projects Agency (DARPA) and the Air Force Research Laboratory (AFRL) to develop 1kg class (10cm x 10cm x 12.5 cm) PICOSAT spacecraft. The PICOSAT is fully autonomous, and can communicate directly with ground stations on earth. Its low mass and size allow us to take advantage of numerous opportunities to fly secondary payloads on earth-orbiting missions, in some cases by replacing "ballast" that would otherwise be flown. The PICOSAT spacecraft is amenable to testing a wide range of MEMS/NEMS technologies including those developed for inertial guidance, micro-propulsion, RF communication and micro-instrumentation. The most recent flight of the PICOSAT was on the Space Shuttle (STS-113) in December 2002. Figure 1 shows a pair of PICOSATs being released into low earth orbit from the cargo bay of the Space Shuttle.

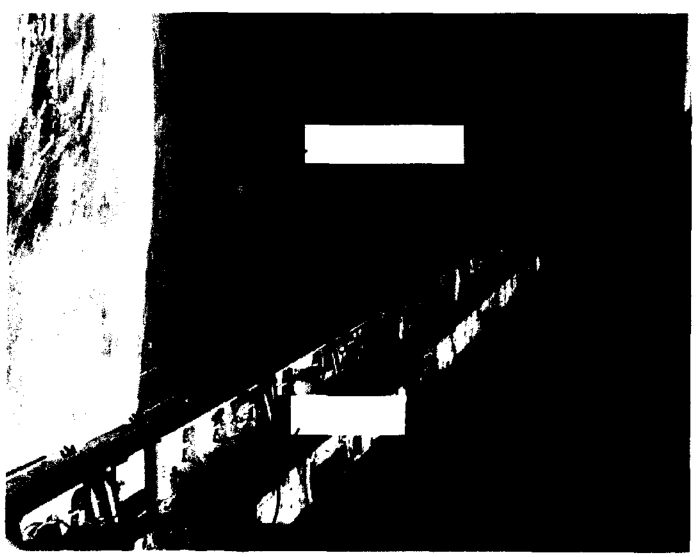

Figure 1. A pair of PICOSATS launched from the cargo bay of the Space Shuttle. The PICOSATs each carried a 3-axis inertial measurement assembly consisting of MEMS gyroscopes and accelerometers.

The technology development portfolio of the JPL MEMS Group spans the range from high TRL, sub-system level developments to low TRL, proof-of-principle demonstrations. The group develops micro-devices for spacecraft applications as well as micro-instrument technologies for astronomy and planetary exploration. Specific examples that are described below include the "Spider Web Bolometer", High-performance Miniature Gyroscopes, an Electron Luminescence X-ray Spectrometer, a MEMS-based "Knudsen" Thermal Transpiration Pump, MEMS Inchworm Actuators, and a Nanowire-based Biological/Chemical Sensor. End-to-end development, from concept design to fabrication, assembly and testing is carried out within the Microdevices Laboratory (MDL) at JPL. The MEMS Technology Group has recently added a new capability in Micro Nano Electroplating/Electromachining. JPL also possesses excellent reliability and failure analysis facilities, developed originally for the testing of micro-electronic parts, and some of which are being adapted for MEMS testing.

MEMS FACILITIES AT JPL

Microdevices Laboratory Facilities

The MDL is designed for the rapid prototyping of new device concepts and contains approximately 550m^2 each of clean room processing and device characterization laboratory space. The clean rooms are equipped with a wide range of facilities for lithography, material deposition and etching (both dry and wet) and post process packaging. The MDL also possesses equipment for surface and bulk micro-structural characterization (SEM, AFM, TEM, XRD), and for electrical and optical characterization of device performance. A detailed description of MDL facilities has been provided in a previous publication[7].

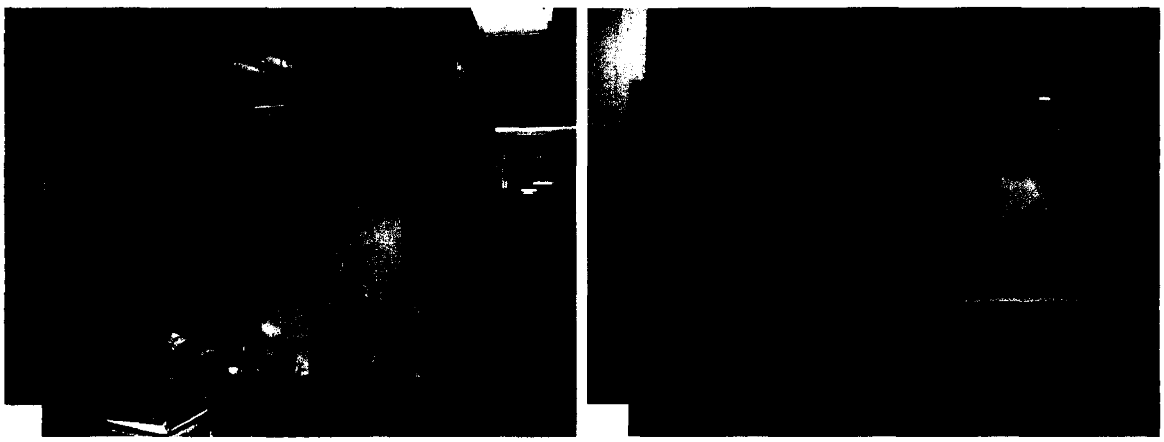

Figure 2. **(a)** The Micro Nano Electroplating Electromachining Laboratory (MNEEL). **(b)** A state-of-the-art bench for MEMS/NEMS electrochemical fabrication operations.

Micro-Nano-Electroplating-Electromachining-Laboratory (MNEEL)

The MNEEL is a recent addition to the JPL MEMS/NEMS fabrication toolset (Fig. 2). Electrochemical processes are very versatile and well suited for MEMS/NEMS fabrication[10]. These processes can either be used in the subtractive "machining" mode or in the additive "deposition" mode. Electrochemical processes have many advantages, including minimum wastage of material (as compared to physical deposition techniques such as evaporation), precisely controlled room temperature operation, low energy requirements, rapid deposition rates, capability to handle complex geometries, low cost, and simple scale-up with easily maintained equipment. In addition, the properties of materials can be "tailored" at the nano-scale by appropriately controlling solution compositions and deposition parameters.

We have developed the following capabilities within MNEEL:

1. ***Electroless Plating:*** Ni, Co, Au, Immersion Au, Zincate.
2. ***Electroplating:***
    a. ***Pure Elements:*** Gold, Silver, Copper, Nickel, Cobalt, Iron, Iridium, Indium, Palladium, Platinum, Ruthenium[11], Bismuth, Tin, Lead, Antimony, Zinc, Tellurium among others.

b. *Alloys:* NiFe, CoNi, CoFe, CoNiFe, CoPt, CoFeB, CoW, CoMo, PbSn, PtRu among others
c. *Metal Oxides:* LiCoOx, LiNiCoOx, MnOx, IrO_2, Cu_2O, ZnO.
d. *Semiconductors:* BiTe, $CoSb_3$, BiSbTe.

3. *Electromachining:* Anodized Alumina nano-templates[10]

MEMS Reliability Testing Laboratory Facilities
Reliability assurance is an integral part of the space qualification process. Over the last few decades, JPL has built a very impressive infrastructure for the reliability testing of spacecraft and instrument payloads. Some of these facilities are being adapted for the testing of MEMS/NEMS devices and instruments being developed for space applications. Reliability testing of MEMS/NEMS devices is currently in its infancy and is complicated by the fact that there are relatively few devices available for the generation of a statistically significant database. The testing protocols are also very device dependent. The major capabilities of the Reliability Testing Laboratory include equipment for vibration and shock testing, radiation testing[12], thermal cycling, electrical stress testing, surface morphology, chemical profiling, cross-section imaging of unreleased structures, and life testing. In addition, facilities for RF MEMS device testing have recently been developed. Subsequent to the testing, failure analysis is performed on the non-functioning devices by combining decades of experience in microelectronics failure analysis with JPL's resident expertise in a wide variety of fields, including MEMS technology, surface physics, electrical engineering, and device physics.

MEMS/NEMS TECHNOLOGY DEVELOPMENT ACTIVITIES

A few key examples of MEMS/NEMS technology developments being pursued by the group are described in brief below. The examples are presented in order of high to low TRL. These technologies are being developed by the group in collaboration with other groups at JPL and outside institutions.

"Spider Web" Bolometer Detector Development
NASA and ESA are jointly developing the PLANCK Surveyor Mission and the Herschel Space Observatory, both scheduled for launch in 2007. The PLANCK Surveyor will carry on board a High Frequency Instrument (HFI)[13], which will map the entire sky in 6 frequency bands ranging from 100 GHz to 857 GHz to probe the Cosmic Microwave Background anisotropy and polarization. SPIRE[14], the Spectral and Photometric Imaging Receiver, will be an imaging photometer and spectrometer for ESA's Herschel Space Observatory. SPIRE will be used to conduct deep extragalactic and galactic imaging surveys as well as spectroscopy of star-forming regions. It contains a threeband imaging photometer with bands in the range of 570 – 1200 GHz, and an imaging Fourier Transform Spectrometer (FTS) covering

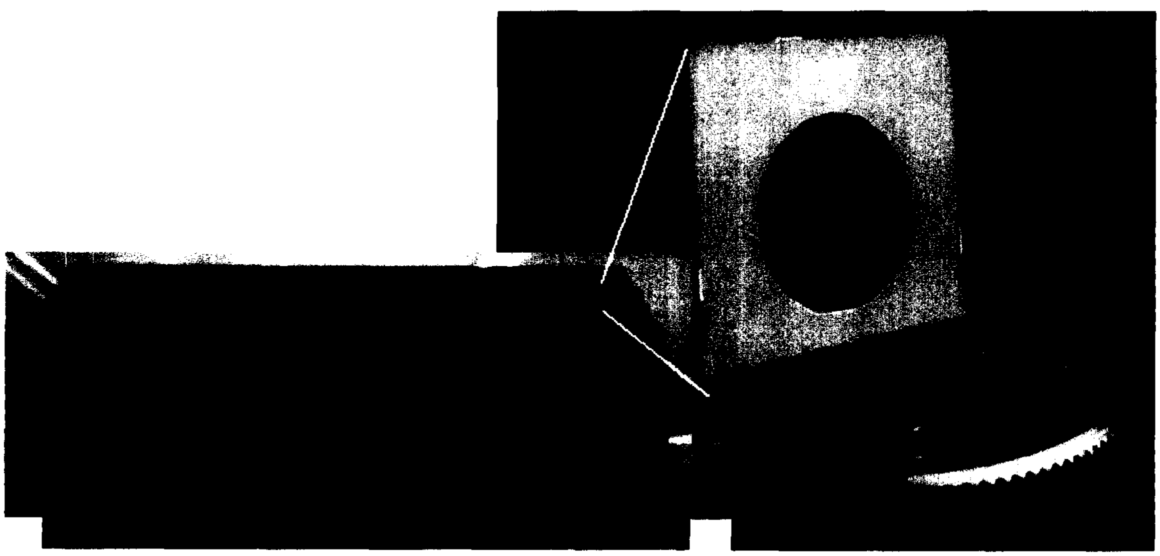

Figure 3. (a) An array of Spider Web Bolometer detectors **(b)** Close-up view of a typical detector showing the Ge NTD thermistor mounted on the SiN "spider web".

the 450 – 1500 GHz range. Both HFI and SPIRE depend on "Spider Web" Bolometer detectors operating at temperatures between 0.1 and 0.3K.

The Spider Web Bolometer detector[15,16] was developed at JPL (Fig. 3) and rapidly made the transition from a low TRL "push" technology, to a mission-enabling "pull" technology. Thus, this highly sensitive detector (Noise Equivalent Power ~10^{-18} W/rt-Hz at 100mK) is the first "success story" for JPL-developed MEMS technologies. The device consists of a high-purity, neutron transmutation doped (NTD), single crystal Ge thermistor chip mounted on a "spider web" comprising metallized, suspended SiN filaments. The SiN spider web is fabricated by bulk micromachining a silicon wafer coated with Low Pressure Chemical Vapor Deposition (LPCVD) grown SiN. The spider web structure has several advantages: a) It provides a large area for microwave absorption; b) It has low heat capacity; c) It provides excellent thermal isolation for the NTD chip from the surrounding environment; and d) It has a low cross-section for cosmic rays. The detectors work by using the NTD chips to measure the local temperature rise due to absorbed microwave radiation. NTD Ge thermistors offer high reproducibility and excellent noise characteristics with a negligible noise background at frequencies as low as 0.01 Hz. The primary benefit for space missions from the low-frequency noise stability is that observations can be conducted in a slow-scanned or a rastered mode rather than requiring lock-in techniques to improve the detectivity.

The extreme cryogenic operation requirement for the detectors brings with it a major challenge of interfacing the bolometers with silicon-based amplifier electronics, which offer best performance at considerably warmer temperatures (120K). Once again, a novel, MEMS-based thermal isolation scheme (Fig. 4) was developed[17] for maintaining the JFET

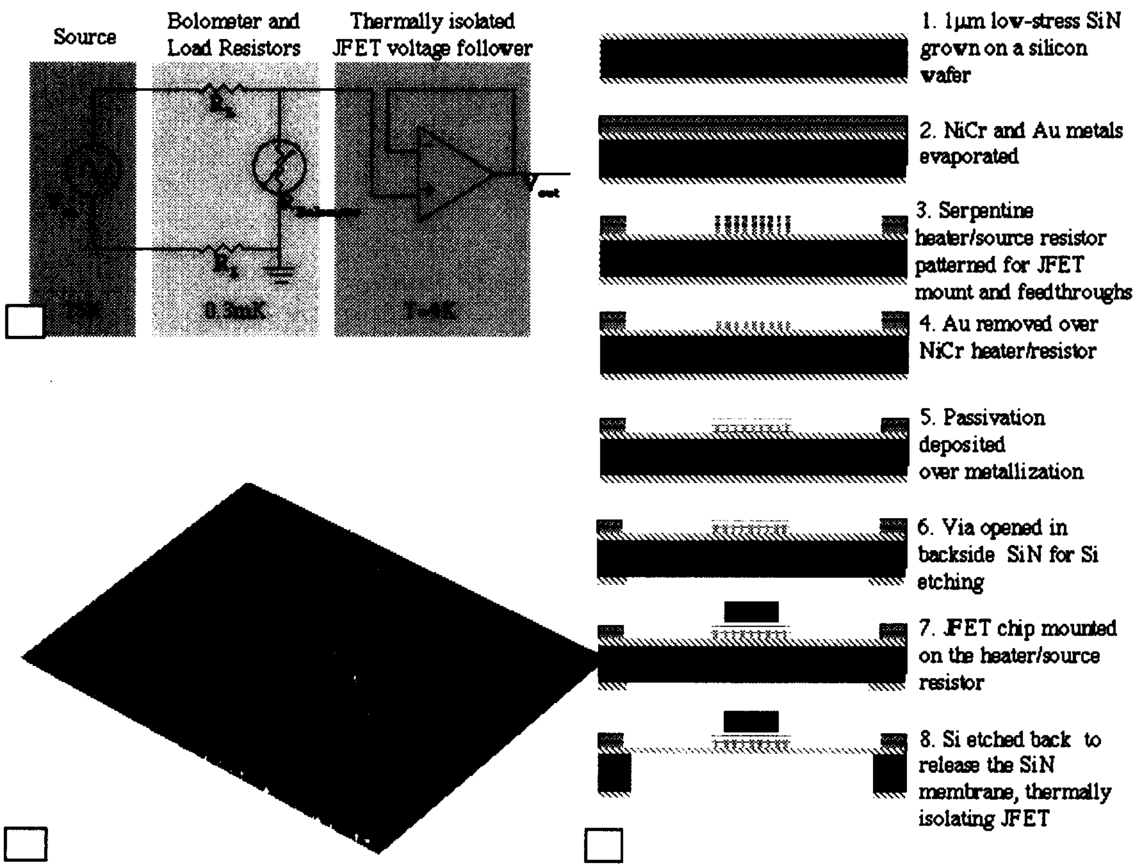

Figure 4. **(a)** Simplified circuit diagram for the Spider Web Bolometer showing the thermal environments of the detector and the JFET amplifier. **(b)** Partially assembled stage showing 12 JFET chips mounted on the SiN membrane. **(c)** Microfabrication and assembly sequence for the JFET amplifier stage.

amplifiers operating at 120K in close proximity to the detectors operating at 0.3 mK. The thermal isolation was achieved by mounting the JFETs on microfabricated silicon nitride membranes optimized for this purpose. In this instance however, as opposed to the Bolometer case, the membranes are continuous since they not only have to provide excellent thermal isolation, but should also be mechanically robust and capable of withstanding stresses generated during thermal cycling, vibration and shock. The device configuration for the JFET readout stage consists of 24 dual Siliconix U401 JFETs mounted on a metallized (heaters/bias resistors) SiN thermal isolation membrane. The entire stage is mounted on a 4K-cryostat for thermal dissipation (5.5 mW maximum) purposes. Extensive testing showed that this configuration meets both the maximum thermal dissipation and noise floor (below 10nV/rtHz) specifications for 120K-amplifier operation at a frequency of 150Hz.

Inertial Guidance: Miniature Vibratory Gyroscopes

The MEMS Technology Group has a very active research effort aimed at the development of miniature gyroscopes with inertial grade performance. The main parameter used for classifying gyroscope performance is the angular bias stability or the minimum uncertainty in rotation rate as a function of the time over which the measurements are averaged or integrated. For inertial grade performance, i.e. for spacecraft navigation applications, the requirements are for angular bias stabilities to be in the range of 0.001 – 0.01 degrees/hour.

The JPL Miniature Gyroscope falls in the class of vibratory, Coriolis force gyroscopes. In brief, a two degree-of-freedom, planar resonator arrangement is "rocked" about an in-plane axis using capacitive actuation electrodes. The gyroscope senses rotation, also capacitively, by measuring the Coriolis coupled vibration about the orthogonal in-plane axis. Thus, for optimum performance it is very important for the frequencies of the orthogonal, in-plane resonance modes to be "degenerate" i.e. be closely matched (for maintaining linearity with feedback control). Mismatched resonance frequencies can be somewhat compensated by the use of additional "tuning" electrodes. However, stability of the measurements in a fluctuating temperature environment could become an issue. The quality factor for each resonance mode needs to be as high as possible, in order not only to reduce the drive voltage for actuation, but also to have a high sensitivity (signal-to-noise ratio).

The JPL Miniature Gyroscope technology can be classified as a relatively mature (TRL 4) effort. Initial devices were fabricated from Silicon-on-Insulator (SOI) substrates, with the in-plane resonators being microfabricated in 26-micron-thick Si layers[18,19]. Subsequently, rotation sensing posts were attached by manual assembly. It was soon realized that manufacturing tolerances in the fabrication/assembly process were perhaps too coarse to achieve the necessary precise match (less than 1Hz at resonance frequencies of a few kHz) between the frequencies of the orthogonal resonance modes. From this experience, a "Meso" Gyroscope development effort was launched. In the Meso design, the entire silicon wafer is used to fabricate the resonators[20]. This approach has yielded our first repeatable, successes in breaking through the "1 degree/hr" angular bias stability barrier for MEMS-based gyroscopes.

Figure 6 shows the test data for a packaged Meso Gyroscope. In Fig. 6a, the measured uncertainty in angular rate is plotted as a function of the averaging time and shows a minimum at below 0.1 degrees/hour. We believe that this is the best performance to date, experimentally measured on MEMS-

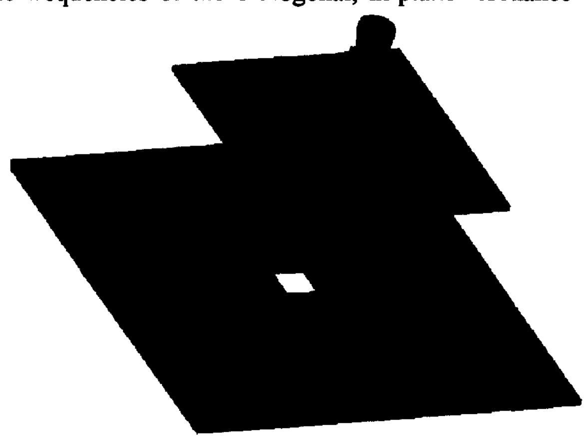

Figure 5. Schematic, exploded view of the JPL single-axis gyroscope. The inertial sensing element is the central post, about whose axis the rotation is sensed. The post is mounted on a layer containing in-plane orthogonal resonators. The post/resonator assembly is suspended over a substrate containing an arrangement of multiple electrodes for actuation, sensing and tuning the frequencies of the resonance modes. The gyroscope operates by "rocking" the post about an in-plane axis and consequently sensing the deflection about the orthogonal in-plane axis generated by the Coriolis force. The novel design is aimed both at closely matching the orthogonal resonance frequencies, and at maximizing the quality factor by minimizing mechanical coupling losses to the frame. The ultimate performance of the gyroscope has a strong dependence on both of these above factors.

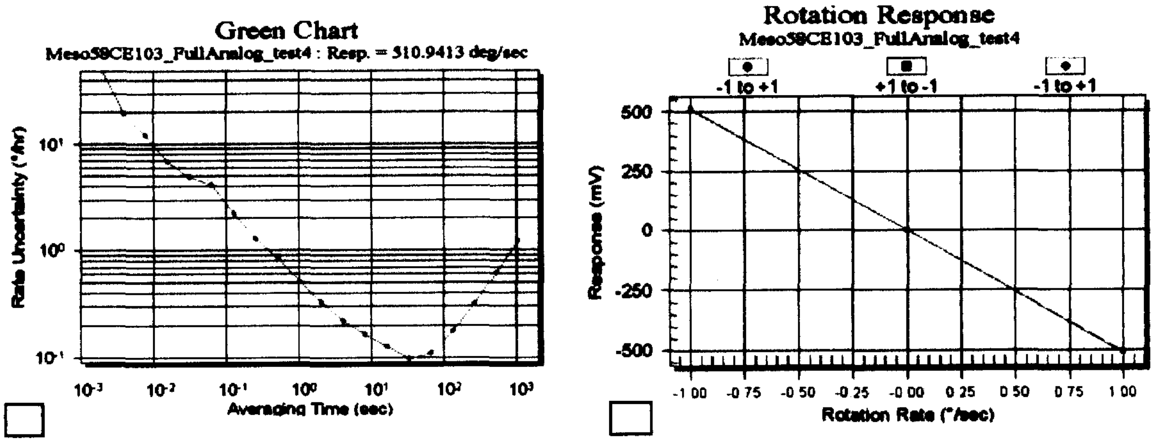

Figure 6. (a) "Green Chart" plotting the Meso Gyroscope's measured uncertainty in the rotation rate as a function of the time for averaging shows a minimum uncertainty of less than 0.1 degrees/hour **(b)** A linear response is observed over a range of 2 degree/second in rotation rate.

based gyroscopes. The device exhibits a linear response (Fig. 6b) and has an "Angular Random Walk" of 0.008 degrees/rt.hr. Future Miniature Gyroscope development is aimed at further improving the performance of the device and moving more into system issues such as packaging and compact drive-and-sense electronics. This phase of the development is being pursued in collaboration with several external partners.

MEMS-based Micro Instruments: ELXS

The Electron Luminescence X-ray Spectrometer (ELXS)[21] is being developed for future *in situ* planetary exploration missions. The ELXS works on the principle of electron-beam excitation of x-ray fluorescence and optical luminescence from samples in the ambient atmosphere. Thus, the ELXS is essentially a miniaturized and enhanced version of an Electron Probe Analyzer (an analysis mode found in most Scanning Electron Microscopes (SEMs)) without the need for sample preparation or examination within an evacuated chamber. The enabling technology for this revolutionary concept[22] is a microfabricated, 1.5mm x 1.5mm, 200-nm-thick SiN membrane suspended over a Si frame (Fig. 7a). The SiN membrane is used to vacuum encapsulate a miniature, high-voltage electron gun (Fig. 7b). The remarkable property of the SiN membrane is that it is strong enough to withstand a differential pressures of greater than one bar and yet thin

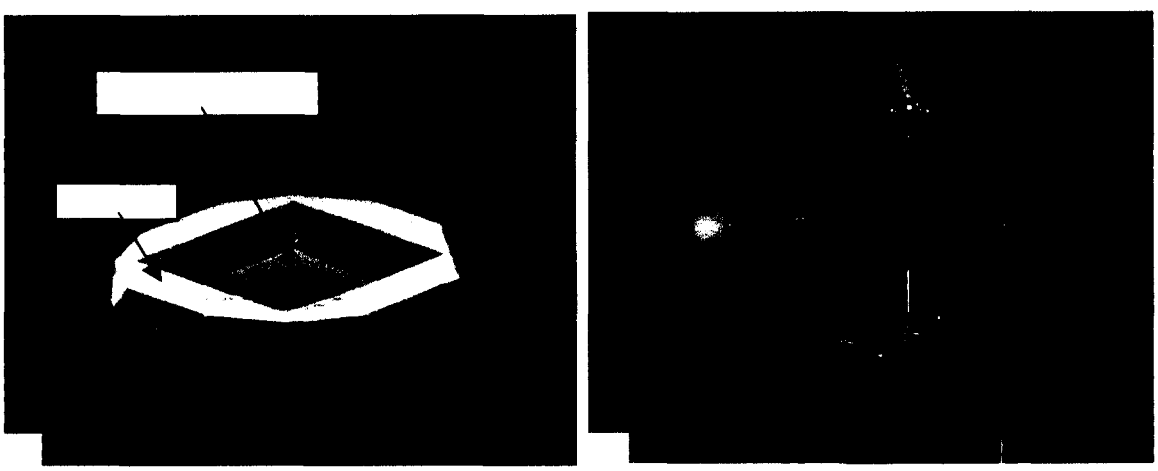

Figure 7. (a) A microfabricated, 1.5mm square, 200-nm-thick SiN membrane used to vacuum encapsulate a miniature, high-voltage electron gun. The membrane is the enabling feature of the ELXS instrument, capable of withstanding differential pressures of greater than one bar and yet thin enough to allow the transmission of electrons into the atmospheric ambient. **(b)** A laboratory test setup for the ELXS concept. Shown is the miniature electron gun encapsulated with a microfabricated SiN membrane.

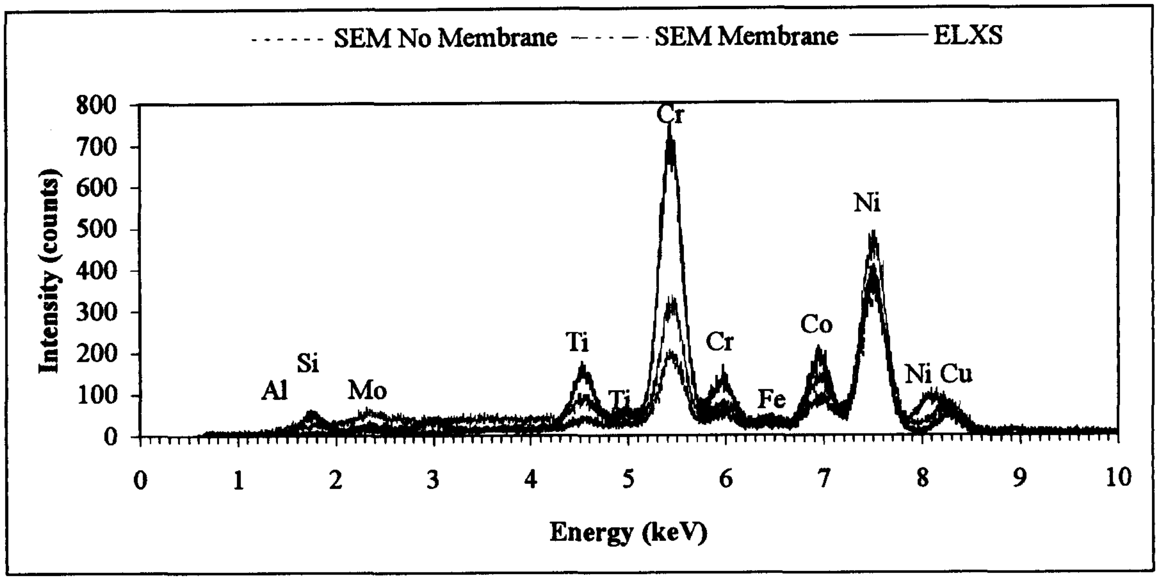

Figure 8. Energy dispersive X-ray (EDX) spectra acquired from a Waspalloy sample. The three spectra were acquired using a Peltier-cooled x-ray detector in a Scanning Electron Microscope (SEM No Membrane), with the SiN membrane placed above the sample (SEM Membrane) and by the ELXS. Qualitatively, there is an excellent match between all three spectra in terms of element identification. Work is in progress to determine the correction factors necessary to obtain good quantitative agreement with SEM Analysis.

enough to allow efficient transmission of high energy (10-20 keV) electrons into the atmospheric ambient[23,24].

The proof-of-principle for the ELXS concept has been successfully demonstrated. Both x-ray fluorescence (Fig. 8) and optical luminescence were excited in air using a nominally 10 keV beam of electrons. The ELXS x-ray fluorescence data was compared to that acquired from the same sample in an SEM, with and without a microfabricated membrane being placed above the sample (Fig. 8). Excellent qualitative agreement was obtained in terms of elemental identification. Near term efforts are focused on developing analytical tools for producing quantitative elemental compositions from the acquired ELXS x-ray fluorescence spectra. It is hoped that the development of the ELXS will provide NASA with a highly capable, low-power, portable instrument. The applications of the instrument for NASA's *in situ* planetary exploration missions include the determination of surface elemental composition and identification of signatures of extinct life through correlation of x-ray and optical luminescence data.

Table 8 contains a comparison of the ELXS performance against competing portable, elemental analysis instruments being developed or already flight-tested. It is seen the strengths of the ELXS technique lie in the extremely short spectrum acquisition times, resulting in very low energy consumption per acquired spectrum and also in the high degree of spatial resolution with which these measurements can be made.

Table 1: A comparison of ELXS parameters vs competing miniature x-ray fluorescence instruments

Parameter	**ELXS**	**XRF/XRD (proposed)**	**APXS (flight)[25]**
Excitation source	High energy electrons (20 keV)	X-ray photons	α-particles
Flux	6×10^{13}/s (10μA)	Primary current: 0.3mA; X-ray photons: 2×10^{12}/s	2×10^{9}/s (50mCi)
Power dissipation	5 W (peak)	13 W	0. 34 W
X-ray fluorescence count (/s)	> 2×10^{4}	10^{2} to 10^{3}	~ 1
Spectrum acquisition time	< 1 minute	5 minutes	10 hours
Energy per acquired spectrum	50 J	5,000 J	10,000 J
Spatial resolution	Variable: mm^2–cm^2, changed by focusing and varying the working distance	**~ 4 cm^2** (at 2 cm working distance)	**~ 20 cm^2**

MEMS-based "Knudsen" Thermal Transpiration Pump

Miniaturization of instruments for NASA's *in situ* exploration missions, in many cases, also requires the miniaturization of ancillary equipment in order to maintain a small, overall system size. For example, miniature vacuum-based instruments such as mass spectrometers require the development, in parallel, of miniaturized vacuum pumps. While miniaturized high-vacuum pumps are now commercially available, very little work has gone into the development of miniature low vacuum pumps. An additional constraint placed by NASA is the preference for a minimum number of moving parts. A novel, no moving parts approach to miniature low vacuum pumps is the "Knudsen" Thermal Transpiration pump currently in joint development between JPL and the University of Southern California[26-28].

Thermal transpiration is a phenomenon in which a pressure difference can be generated across a specially constructed porous membrane simply by maintaining a temperature difference across it. Gas flow occurs in the direction of the higher temperature if the diameters of the pores are in the same range as the mean free path of the gas molecules. Thus a Knudsen flow regime exists in which inter-molecular collisions are largely prevented and a vast majority of the gas molecular collisions are with the walls of the orifices in the porous material. The kinetic energy and hence the average velocity of the gas molecules increases in the direction of increasing temperature, causing a net flow and consequently a pressure difference between the hot and cold sides (Fig. 9). In addition to the small pore diameters, additional constraints on the porous material include having a low heat capacity and most importantly, a low thermal conductivity. Two materials systems that are being actively explored for making up the porous membrane are aerogel[26] and an assemblage of microspheres[27].

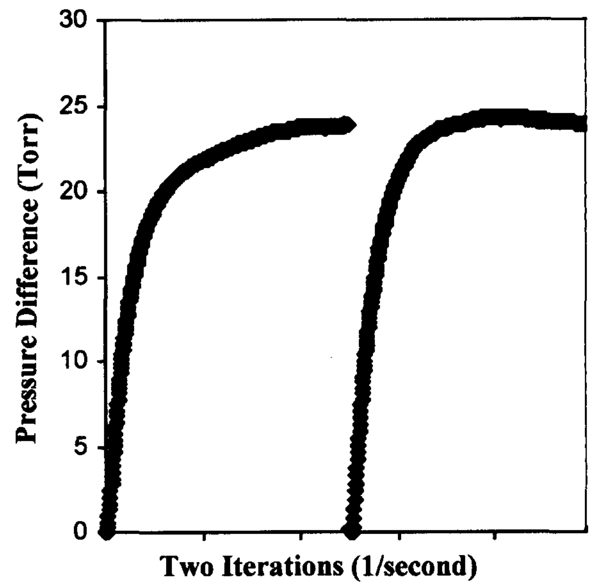

Figure 9. Pressure difference obtained during the operation of a single-stage, MEMS Thermal Transpiration pump. The 25 Torr pressure difference with an input optical heating power of 120 mW, creating a temperature difference of 60K across an aerogel slab. Shown are two pumping iterations (one per second).

To the best of our knowledge, this is the earliest known, successful use of aerogel[29] within a MEMS device[30]. Also, a novel anodic bonding process was developed to bond pyrex to Kovar substrates[31]. As shown in the exploded view in Fig. 10a,

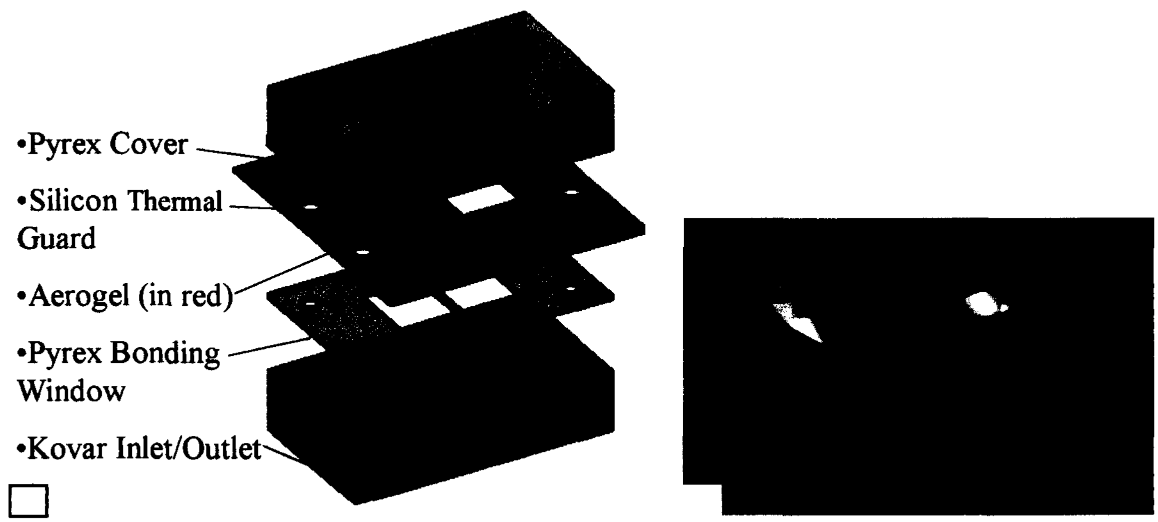

Figure 10. (a) Exploded view of the prototype, single-stage, thermal transpiration pump (42mm x 45mm x 20mm). The entire assembly is mounted on a Kovar base containing the inlet and outlet ports. The active pumping material is a slab of aerogel (placed on a Si support layer). A temperature gradient is created in the aerogel by heating it with optical illumination. **(b)** A fully assembled, single-stage, prototype pump.

the thermal transpiration pump consists of stack of pyrex and silicon layers bonded together. The active material is a slab of aerogel, which is supported on a micromachined silicon "thermal guard" layer (Fig.10). The aerogel, which is carbon doped for good absorption properties, is heated optically to create a temperature gradient within it. Figure 9 contains experimental data obtained from a prototype, single-stage thermal transpiration pump. A pressure difference of 25 Torr was obtained by the creation of a 60K temperature difference using an input optical power of 120 mW. The ultimate goal of the development effort is to construct a cascade of 15 thermal transpiration pumps to achieve milliTorr vacuum levels when pumping down from an atmospheric pressure ambient. The cascade configuration can essentially be fabricated within a single 100-mm-diameter silicon wafer, using multiple aerogel slabs. In reverse, the thermal transpiration pump can also be used as a compressor. Starting from an atmospheric pressure ambient, it is estimated that a similar cascade should produce compressed gas pressures as high as 10 atmospheres.

MEMS-based Inchworm Actuators

Instrument payloads for space missions are always constrained by size and mass limitations, yet astronomers desire orbiting space telescopes with as large an aperture as possible. A novel approach to resolving this dilemma is to assemble, in space, ultra-large telescopes from low-mass silicon mirror segments[32]. The proposed design, known as ASSiST, has a primary mirror composed of between ten to fifteen thousand, 300mm diameter, 400μm thick, hexagonal, silicon wafer segments. A hierarchical assembly technique is used in which the mirror is constructed from hexagonal rafts containing approximately 100 silicon segments, each mounted on a rigid frame, which provides stiffness locally at 3m length scales. However, inter-segment actuators are needed with a control range of a few tens of microns in order to accommodate misalignments that occur during segment assembly. The forces required to correct warps of order 10μm over a segment are in the 1mN range. These forces correspond to accelerations of the entire telescope of approximately 10^{-7} rad s^{-2} during pointing change rotations of order 1 rad hr^{-1}.

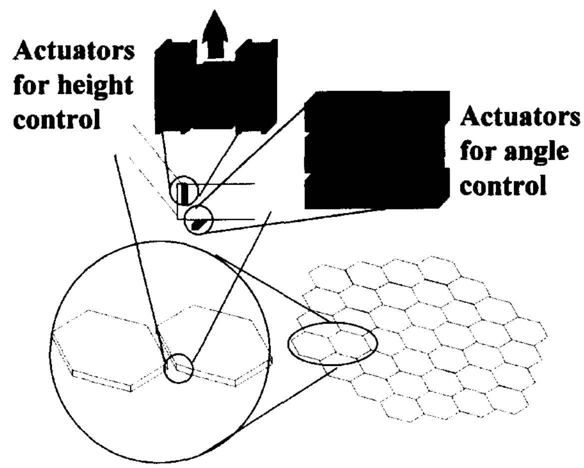

Figure 11. Schematic diagram showing the MEMS Inchworm Actuator configuration within a segmented mirror telescope. The actuators are used for adjusting both the height differences (piston mode) and angles (tip/tilt) between adjacent mirror segments.

JPL is currently developing a novel, piezoelectrically-driven, inchworm actuator[33] designed to meet the above requirements for the ultra-precise positioning of silicon mirror segments in space. The compact actuator has the following salient features:

- Operation up to 1 kHz
- Operation at temperatures at or below 77K with 15-20% room temperature efficiency
- 250 μm total travel with nanometer-level precision
- Electrostatic holding force between segments of approximately 1 N (@ 100V)
- Mean steady-state power consumption of 100 mW per actuator

Previously reported work on inchworm motor development include actuators designed to move horizontally on the surface of a silicon wafer, which of course, precludes their use for vertical, out-of-plane motion[34]. A mesoscale inchworm actuator has also been developed[35]. In this case, further miniaturization would be needed to adapt these actuators for the ASSiST application. A thermal inchworm actuation concept has also been presented in literature, with 50 μN actuation force and 0.2 μm travel resolution[36]. The application requirements however, demand significantly more precision, as well as rapid actuation with a larger force. Although the proof-of-concept for a MEMS-based out-of-plane inchworm actuator has been reported[37], this approach also falls short of the required large vertical actuation (~ hundreds of microns).

The JPL inchworm microactuator is designed to achieve large, ultra-precise, out-of-plane (vertical) travel by means of compliant beam structures fabricated within a silicon wafer. The inchworm consists of mostly DRIE-fabricated structures on a silicon wafer, including the moving parts, which are a driver and a slider, and the static parts, which are a

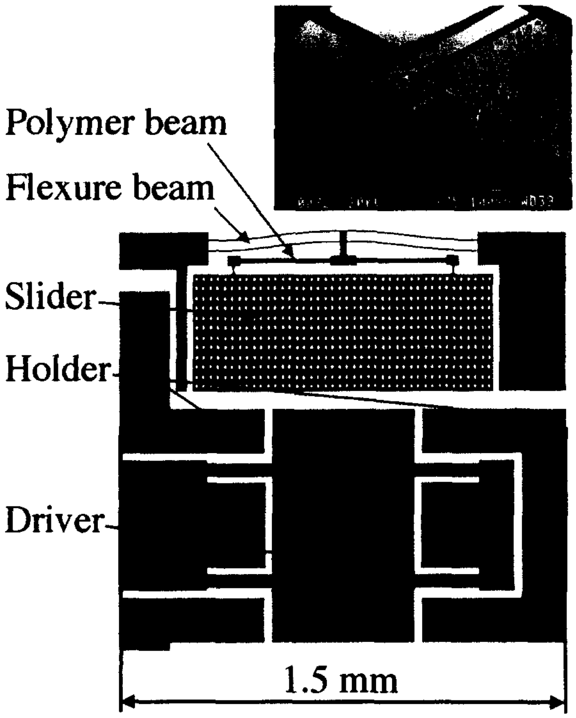

Figure 12. Plan view of the JPL MEMS inchworm actuator concept. The inchworm is microfabricated on a Si wafer using DRIE. The moving parts are the Driver and the Slider. Not shown is a piezoelectric stack actuator bonded to the Driver (within the dotted rectangle) that provides the out-of-plane (vertical) displacement stroke. The slider is alternately clamped electrostatically to the Driver and the Holder during each stroke. A polymer suspension beam accommodates the large (250 μm) travel. Shown above the schematic diagram is an SEM micrograph of the Slider and the beam assembly.

pair of holders and a pair of polymer beams connected to a centrally clamped flexure beam[38] (Fig. 12). A piezoelectric stack actuator is bonded to the driver and provides the nanometer-precision, vertical stroke. The slider is alternately clamped to the driver and the holder during each stroke.

Nanowire-based Biochemical Sensors

We have recently initiated a project aimed at exploiting the unique capabilities of nanowire-based sensors. Nanostructure-based sensors offer several advantages over macroscopic sensors. Among them are their ultra-small sizes, making possible the fabrication and assembly of compact, multi sensor arrays. Another significant advantage is their high surface-to-volume ratios, which allow increases of several orders-of-magnitude in the number of reaction sites and consequently the magnitude of the signal generated within a comparable volume for a macro-scale sensor.

Carbon nanotubes[39] and silicon nanowires[40] have been used previously for highly sensitive, real-time detection of biomolecular species. However, the construction of these types of nanowire sensors is fraught with difficulties. Carbon nanotubes for example are currently produced in mixtures of metallic and semiconducting structures, each type of which behaves differently for sensing applications. Also, "functionalization" methods for carbon nanotubes are not well established. These are where the surfaces are chemically modified[39] to become selective for binding, with a high degree of specificity, to analytes of interest. Methods for producing silicon nanowires include either a laser-assisted vapor-liquid-solid growth method[40] or deposition from a supercritical fluid solution phase method[41]. These methods operate at high temperature and low pressure and require sophisticated equipment. Ultimately, in both of these cases, there is the tedious process of aligning and then electrically connecting the nanowires.

We at JPL are pursuing a far simpler, electrochemical approach to producing "self-aligned" nanowires that can be functionalized easily and are automatically electrically addressable. The electrochemical approach, using the excellent MNEEL capabilities described above, offers numerous choices of materials systems appropriate to the sensing tasks. Coupled with the state-of-the-art, electron beam lithography-based, nanofabrication facilities available within the MDL, a great deal of flexibility is possible in the choice of sensor configuration, i.e. constructing either single nanowire-based sensors or alternatively, nanowire array (mat) type sensors. To date, nanowires from a number of materials, including metals, alloys and oxides, have been produced successfully.

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