REPORT OF
DEPARTMENT OF DEFENSE
ADVISORY GROUP ON ELECTRON DEVICES
WORKING GROUP C (ELECTRO-OPTICS)

SPECIAL TECHNOLOGY AREA REVIEW

ON

MICRO–OPTO–ELECTRO–MECHANICAL–SYSTEMS

(MOEMS)

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Prepared by the AGED Secretariat
Palisades Institute for Research Services, Inc.
1745 Jefferson Davis Highway, Suite 500, Arlington, VA 22202

FOREWORD

Periodically, the Advisory Group on Electron Devices (AGED) conducts Special Technology Area Reviews (STARs) to better evaluate the status of an electron device technology or defense application. STARs strive to elicit the applicable military requirements for a particular technology while relating the present technology status to those requirements. The STAR culminates in a report that provides a set of findings and recommendations which the Office of the Secretary of Defense can utilize for strategic planning. Since each electron device technology that falls under AGED's purview resides at a different level of maturity, and thus, varying requirements, the content of each STAR is tailored to extract the appropriate data through preparation of "Terms of Reference."

This STAR report documents the findings from the review and assessment of micro-opto-electro-mechanical-systems (MOEMS) that was held on 28 May 1997, by AGED Working Group C (Electro-Optics) at the Naval Command, Control and Ocean Surveillance Center, San Diego, CA. The goal of the STAR was to assess the overall status of MOEMS technology and to provide recommendations concerning technical direction and resulting Tri-Service cooperative efforts that will be needed to meet the MOEMS needs of future electron device based systems. Presentations were made by a distinguished panel of experts selected from both industry and government. Working Group C members are subject matter experts in electro-optical technology. The group includes representatives from the Army, Navy, Air Force and the Defense Advanced Research Projects Agency as well as consultants from industry and academia.

On behalf of Working Group C, I would like to take this opportunity to express my sincere appreciation to all of the people who took part in this study – listed on the next page – for their valuable contributions. This applies particularly to Dr. Susan Turnbach, ODDR&E/S&E, whose support and encouragement were essential for the successful completion of this effort. I would also like to extend my thanks to Dr. Jane Zucker of Lucent Technologies for conceiving this STAR topic and recommending expert speakers. Dr. Robert Leheny of the Defense Advanced Research Projects Agency, and Dr. Paul Kelley of Tufts University are also thanked and commended for significant contributions to this study. Their expertise and excellent background material helped immensely in the preparation of this report.

Dr. Thomas S. Hartwick
Chairman, Working Group C

CONTRIBUTORS

Dr. Susan Turnbach
Executive Director, Advisory Group on Electron Devices
ODDR&E/S&E, The Pentagon
Washington, DC

Dr. Thomas Hartwick
Chairman, Working Group C (Electro-Optics)
Advisory Group on Electron Devices
Washington, DC

Major John Comtois
Air Force Phillips Laboratory

Dr. James Harris, Jr.
Stanford University

Ms. Lorna Harrison
Army Research Laboratory

Dr. Anis Husain
DARPA

Dr. Paul Kelley *
Tufts University

Mr. John King
Air Force Wright Laboratory

Dr. William Krupke *
Lawrence Livermore National Laboratory

Dr. Robert Leheny *
DARPA

Dr. Richard Payne *
Air Force Rome Laboratory

Dr. John Pollard *
Army Night Vision Laboratory

Dr. Doran Smith
Army Research Laboratory

Dr. Olav Solgaard
Silicon Light Machines

Mr. Charles Stevens *
Air Force Wright Laboratory

Dr. William Tang
NASA Jet Propulsion Laboratory

Dr. Elias Towe
DARPA

Mr. Steven Walker
Naval Research Laboratory

Dr. Ming Wu
University of California at Los Angeles

Dr. Andrew Yang *
Optoelectronics Industries Development Association

Mr. John Zavada *
Army Research Office

Dr. Jane Zucker *
Lucent Technologies

* Advisory Group on Electron Devices

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EXECUTIVE SUMMARY

Few new defense technologies have excited the professional community as much as MEMS. Utilization of the chip making manufacturing infrastructure to create a new class of devices ranging over a wide number of military applications makes a compelling statement. DARPA initiated this activity and has provided the major sponsorship. Now, an outgrowth of this technology into the optical region, micro-opto-electro-mechanical (MOEMS) devices, offers new potential for defense exploitation. This STAR report has assessed the current status of this technology and provides findings and recommendations for use in future defense technology planning. In particular, the STAR revealed that we are at the beginning of an era of technological advancement that could offer revolutionary new optical system concepts. Evaluation of the individual STAR presentations found that:

- MOEMS affords the capability to fabricate a variety of devices.
- MOEMS has significant potential for use in military systems.
- Commercial opportunities exist for MOEMS, particularly in the display arena.
- Existing fabrication lines can be easily adapted for MOEMS production.

Already, one manufacturer has produced a MOEMS product capable of scanning more than 10^6 laser beams and R&D into integration of this technology into lasers and optical switches is proceeding. Integration of a number of optical functions onto a single chip of silicon has been demonstrated. The Services and NASA are closely following these developments and developing projects to extend the application of the basic technology into a number of system applications. For example, fast optical switches for communication channels, laser beam steering and control, spatial light modulators, image aberration correction, and ultra-fine optical element adjustments all seem to be important applications. The definition of systems requirements to utilize MOEMS is a process which is just starting and will accelerate as the specific devices mature.

Based on these findings, the committee believes that this technology presents an opportunity for revolutionary new optical designs which can offer a competitive military advantage. As devices emerge, the committee recommends that export controls must be carefully planned in recognition of both the significant foreign investment in this technology and the necessity to maintain a large industry production base to lower device costs. The constitution of military service representatives to champion this technology and develop system requirements is deemed an essential recommendation of this committee to properly exploit the technological advantage. From this Service team, with the participation and leadership of DARPA, the committee recommends that a coordinated technology roadmap and plan for system insertion be prepared. The committee has agreed to monitor the progression of MOEMS technology, and, at the appropriate time, report this progression in a follow-up STAR.

REPORT OF SPECIAL TECHNOLOGY AREA REVIEW (STAR) ON MICRO–OPTO–ELECTRO–MECHANICAL–SYSTEMS (MOEMS)

INTRODUCTION

Micro-opto-electro-mechanical-systems (MOEMS) are very new, but, have the potential to be broadly utilized in many military systems. During this STAR the major MOEMS sponsor DARPA, the Services, NASA, industry and university representatives convened to discuss and describe their roles in developing this technology. An effort was made to consider all relevant aspects from military requirements and system utilization, through device development and ultimate production by industry. The Working Group then assessed the collected data in accord with the Terms of Reference, detailed in Appendix E of this report, to develop the Findings and Recommendations, the major product of this review.

The inclusion of micro-mechanical components that have the ability to alter the path of a light beam or to modify a light beam has expanded the range of functionality of MEMS. The MEMS-based optical elements or components are usually versions of bulk or physical optics devices. The most common micro-optical elements are those that reflect, diffract or refract light. Micromachines or systems that include optical components are often referred to as optical MEMS (O-MEMS), micro-opto-mechanical systems (MOMS), or micro-opto-electro-mechanical systems (MOEMS). Perhaps MOEMS is the most appropriate and general descriptor of these systems; it conveys the essential ideas about the size and nature of the elements that are integrated to form a system.

There are three primary characteristics that make MOEMS an important technology development: the first is the batch process by which the systems are fabricated; the second is the size of the elements in the systems; and the third, and perhaps most distinctive, is the possibility of endowing the optical elements in the system with precise and controllable motion. Movement of a micro-optical element permits dynamic manipulation of a light beam. This manipulation can involve (amplitude or wavelength) modulation, diffraction, reflection, refraction or simple spatial deflection. Any two or three of these operations can be combined to perform a complex operation on the light beam. The ability to carry out these operations, using miniaturized optical elements, is one of the key attributes that distinguishes MOEMS from classical physical optics.

TECHNOLOGY BACKGROUND

The field of modern optics has been largely concerned with the generation, manipulation, guidance, or detection of light for information processing. The operation that is relevant to micro-opto-electro-mechanical-systems (MOEMS) is the manipulation of light in one, two or three dimensional space. Here, light is defined to be the electromagnetic radiation in the spectral band from about 200 nm to about 15 microns. This boundary definition is important because the wavelength of light that is manipulated or made to interact with micro-optical elements imposes a lower bound on the component size. This lower bound is a consequence of the laws of diffraction. In order to avoid unintentional diffraction effects, the feature sizes of micro-optical elements must be at least ten times larger than the wavelength of light that is intended to interact with the micro-optical element. If diffraction is the desired effect, then this restriction does not apply.

Conventional micromachines are comprised of micrometer-sized electrical and mechanical components integrated to form micro-electro-mechanical systems (MEMS). These systems are fabricated using the techniques and materials of microelectronics. The most common techniques are (1) bulk micromachining, (2) wafer-to-wafer bonding, (3) surface micromachining, and, (4) high-aspect ratio micromachining. In bulk micromachining, a wet chemical etchant whose etching characteristics depend on the crystallographic surface chemistry of the substrate is used to selectively remove material from unmasked areas to define the geometry of the desired features. Wet chemical etching of this kind is generally anisotropic and a limited set of geometric features can be constructed in this way. To overcome this limitation, wafer-to-wafer bonding is used in conjunction with bulk micromachining to fuse together separately micromachined bulk wafers and achieve the desired geometric features. For further versatility in feature construction, surface micromachining is used. In this method, one starts with a substrate material which serves as a working surface. Multiple structural and sacrificial layers are deposited on it and then portions are selectively removed using a sequence of masking and etching steps. The etching is generally done using reactive ion etching—an isotropic etching process which is independent of the crystallographic surface. To fabricate thick (hundreds of microns to centimeters), high-aspect ratio structures, one uses deep UV lithography, in conjunction with reactive ion etching. In some cases, X-ray radiation from a synchrotron generator may also be used as the source for the lithography. Figures 1(a) and 1(b) show illustrations of two of the most commonly used methods for constructing micromachine features.

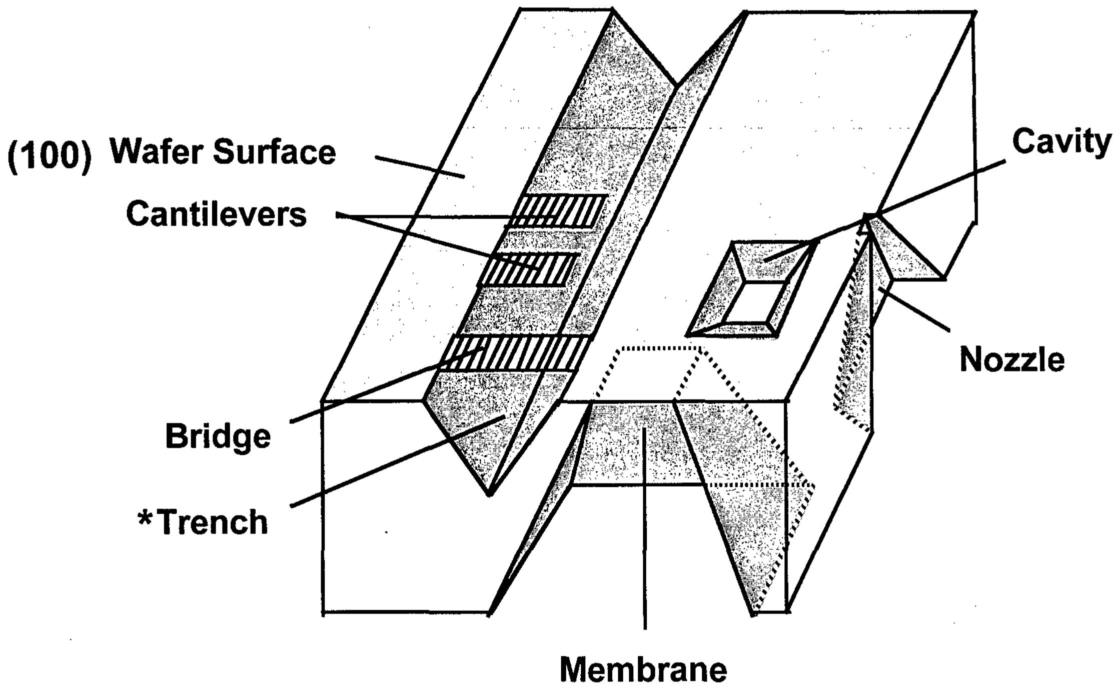


Figure 1(a): An arbitrary component with a composite of all common features and mechanical structures that can be etched in a piece of single-crystal silicon using bulk micromachining. Note that all etched walls are at the same angle as defined by the crystal orientation of the silicon.

* Trench formed by the intersection of the (111) and (yyy) crystalline surfaces.

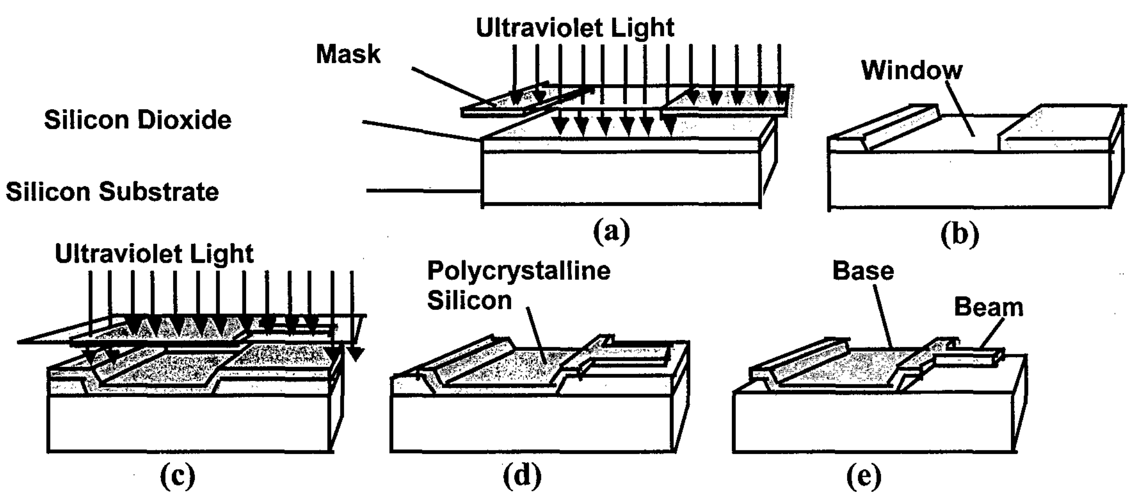


Figure 1(b): A single cycle in a common surface micromachining process. The process to build a single cantilever beam begins with the sacrificial material layer (silicon dioxide) being patterned and etched (a, b). Next, the structural material (polysilicon) is deposited over the entire surface. The polysilicon is then patterned and etched in the shape of the cantilever beam and base (c, d). Finally, the polysilicon is released by removing the remaining and underlying silicon dioxide (e).

The processes described above have been extended to the construction of optical and fluidic components in both silicon and other substrate materials. The generality of the fabrication processes allows one to construct MEMS machines with a diversity of functionality. This functionality can be a result of a distinct class of features or a combination of classes. The major classes of features are:

- Micro-mechanics
  - ◊ replacement of passive lumped electrical elements with surface micromachined equivalents
  - ◊ micro-actuatable membranes
  - ◊ elements with micro-mechanical linear or rotary motion
- Micro-optics
  - ◊ diffractive, refractive and reflective micro-optical elements (fixed or movable) e.g., lenses, gratings, mirrors
  - ◊ micro-optical elements that exploit the free-space properties of light
  - ◊ self-aligned micro-optical elements
- Micro-fluidics
  - ◊ microchannels for fluid transport, storage, separation and reaction
  - ◊ micro-actuated valves for fluid control
  - ◊ micro-pumps for fluid movement

Each class of features can, and often does, include electronic devices that give the microsystem intelligence for control.

In any micromachine, the components of the integrated system, numbering from a few to millions, have dimensions that are measured in micrometers. The fabrication processes described above bring the advantages of miniaturization, multiplicity and diversity of components to the design and construction of mixed technology integrated systems.

GOVERNMENT/SERVICE PRESENTATION SUMMARIES

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY'S (DARPA) MICRO-OPTO-ELECTRO-MECHANICAL MACHINE

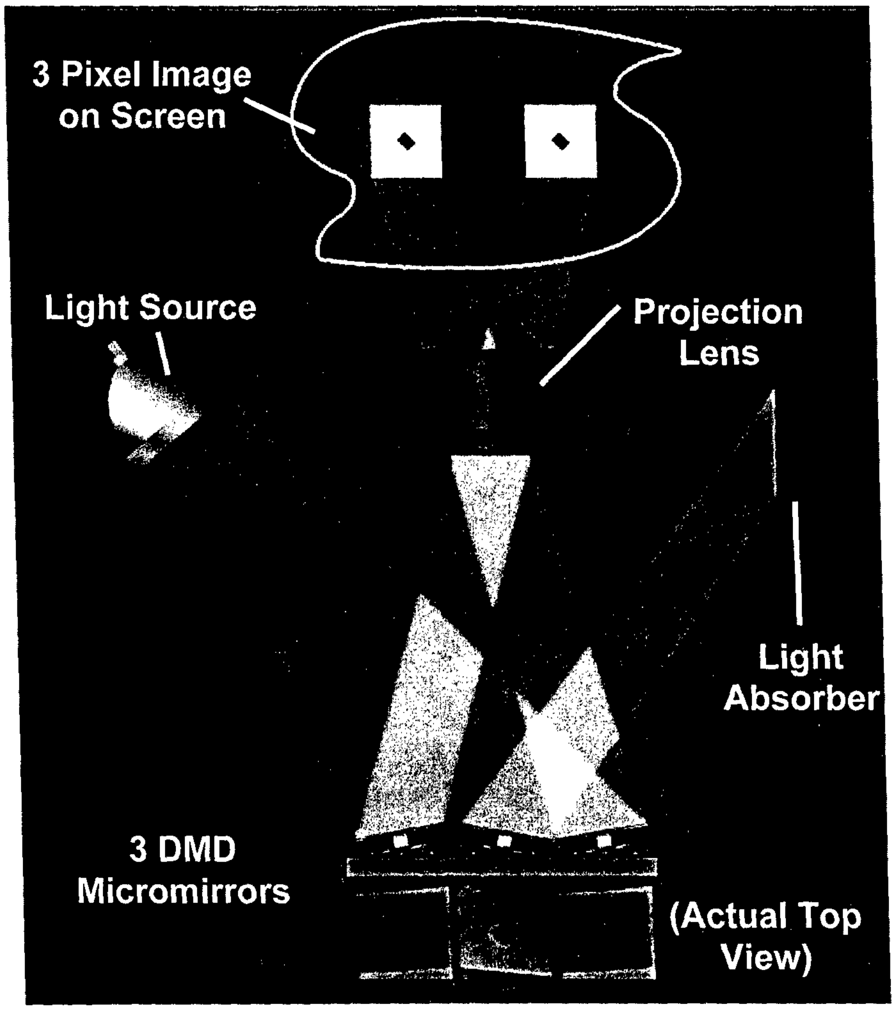
The Electronics Technology Office of DARPA has been involved in supporting research efforts in most areas of MEMS. Recently, the management of the research efforts has been restructured into three distinct areas. These are (1) the traditional MEMS program, (2) the microfluidic molecular systems program and, (3) the micro-opto-electro-mechanical systems area. This last area is currently not a separate program with its own budget; it is part of the traditional MEMS program, differentiated from it by the major role played by micro-optical components in the systems being developed. The emphasis of the microfluidic molecular systems program is on providing the capability to perform tailored, molecular-level chemical and biological reaction/analysis sequences in microsystems. The overall goal of all three areas is to integrate transducers that merge mechanical, optical, acoustic and fluidic elements with electronics to create microsystems that can sense, commute, act and communicate.

One particularly successful early DARPA MOEMS project has been the development and commercialization by Texas Instruments, Inc. of a MEMS based Digital-Micromirror-Display (DMD) Engine incorporating more than a million micro-mechanical components to realize a compact, high resolution, high brightness, projection display module. The DMD Engine represents the largest scale MEMS device undertaken to date as shown on the MEMS roadmap in Figure 5 (see page 11). Figure 2 illustrates the operation of the DMD. The basic structures of the DMD are illustrated in Figures 3(a) and 3(b). Figure 3(a) illustrates the complex micromechanical assembly of a single DMD light switch, while Figure 3(b) is an SEM photomicrograph of DMD chips with one mirror surface removed to exposed the underlying electromechnical structure.

The DMD is an exciting and promising development in the area of truly digital displays using MicroElectroMechanicalSystems (MEMS) technology. The DMD engine holds promise for use in many other applications. It is currently used in high-brightness projection displays. DARPA recognizes the broader applicability of the Digital Light Processing concept and the potential the DMD engine has for both future product innovation beyond the plans of TI and as a stimulating educational tool. To encourage broader application of the DMD engine, DARPA has sponsored a program to explore additional uses of the DMD by making these devices available to the research community. The following DARPA Awards were made for the development of innovative applications that use the Digital-Micromirror-Display (DMD) Engine.

- A New Technique for Adaptive Optics Compensation Using Digital Mirror Devices (DMDs) .... Boston University
- Integrated Modular Holographic Memory............................California Institute of Technology
- Holographic Search Engine for Multimedia Databases.....................Colorado State University
- The DMD-ICCD: Use of DMD Technology to Control Optical Interference in Night Vision Systems .... InterScience, Inc.
- DMD Assisted Intelligent Manufacturing of Mesoscopic Devices ....SRI International
- Dynamically Configurable Confocal Microspcopy Using the DMD Engine .... University of California San Diego

Digital Light Processing (DLP) Concept



Texas Instruments

Figure 2

DMD Light Switches

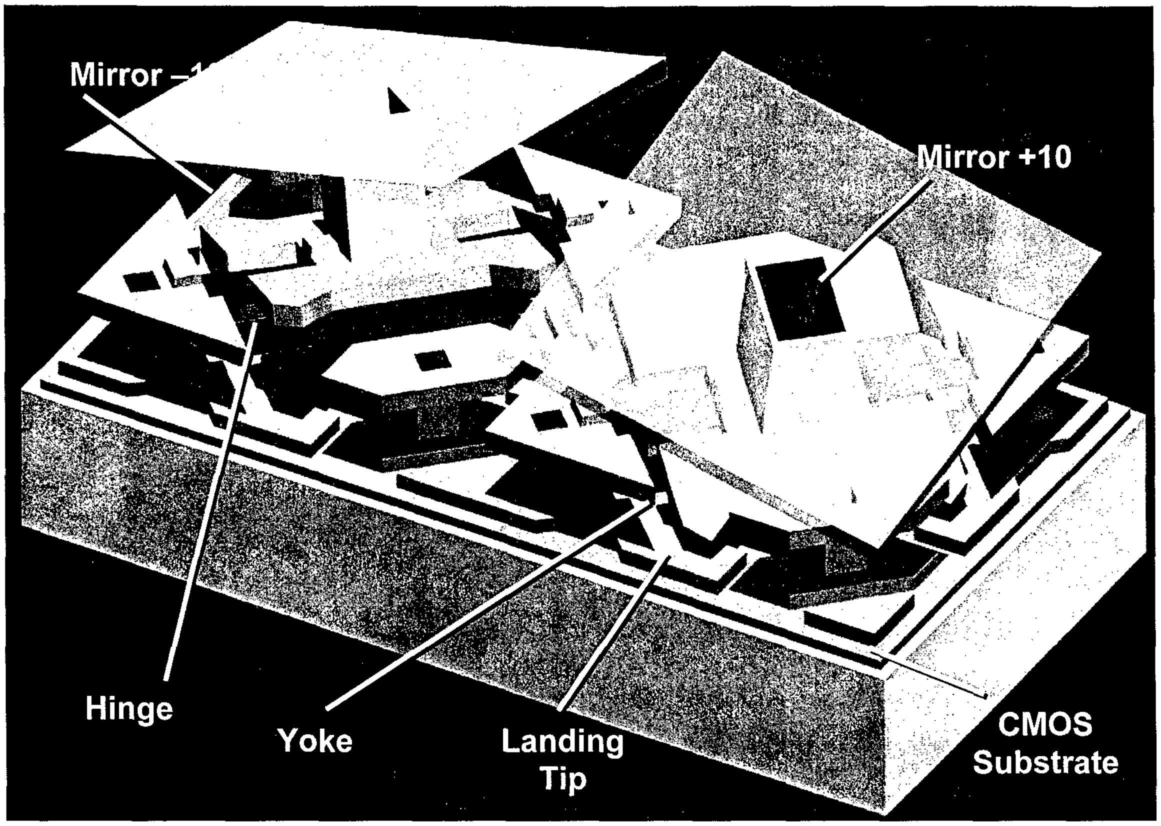
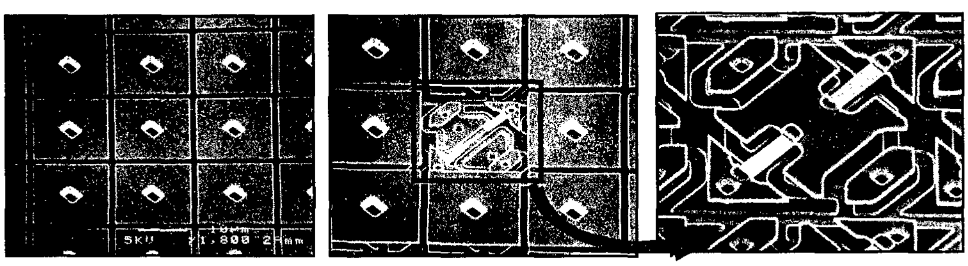


Figure 3(a)



SEM Photomicrographs of DMD Chips

Texas Instruments

Figure 3(b)

One of the goals of the MEMS program at DARPA has been to support and catalyze the development of a technology infrastructure in the United States. To foster this, the Electronics Technology Office helped create and support the Multi-User MEMS Projects (MUMPs) program at the Microelectronics Center of North Carolina (Figure 4). This program has enabled users who do not have access to microelectronics processing facilities to participate in the development of MEMS technology. Since its inception in 1992, over 550 projects from 1000 users have been completed through this program. In addition Sandia National Laboratories has developed a MEMS process based on CMOS processing which they refer to as their SUMMIT process. Air Force researchers (see the Air Force section of this report beginning on page 13) have made extensive use of this process for MOEMS devices. Based on this experience with both processing approaches, the Air Force researchers have found the Sandia multi-layer process has features not found in other approaches such as; a polished upper surface, one-micron design rules, multi layer capability which permits masking any wiring or flexures completely under the polished final optical surface layer. The multiple layers allow shielding wiring so that the optical surface can be metalized after the release etch. Also, an optical surface of choice can be deposited after etching without the necessity of concern about surface integrity after this harsh processing step.

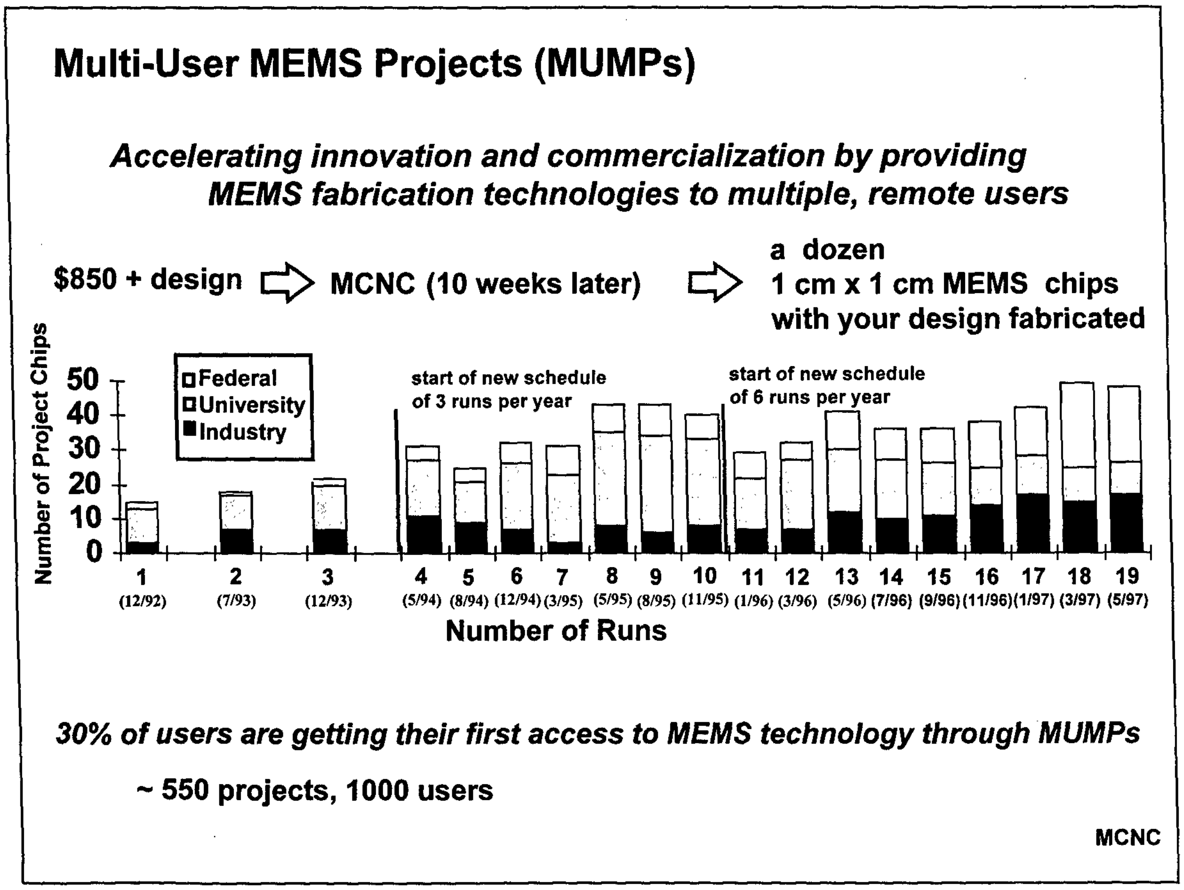


Figure 4

The trend in MEMS technology has been toward systems that can both perceive and control the environment they are in. This trend can be graphically depicted by plotting the number of mechanical components that comprise the system, along one axis, and in terms of the number of transistors that give the system the intelligence to control their environment, in another. The log-log graphic (Figure 5) below illustrates this concept of measuring the abilities to sense and act on the one hand, and the ability to compute, on the other. It can be noted that the mature Digital Mirror Device indicated on the chart offers the capability to scan more than 10^6 laser beams and demonstrates a very high level of integration product.

MEMS Technology Trend and Roadmap

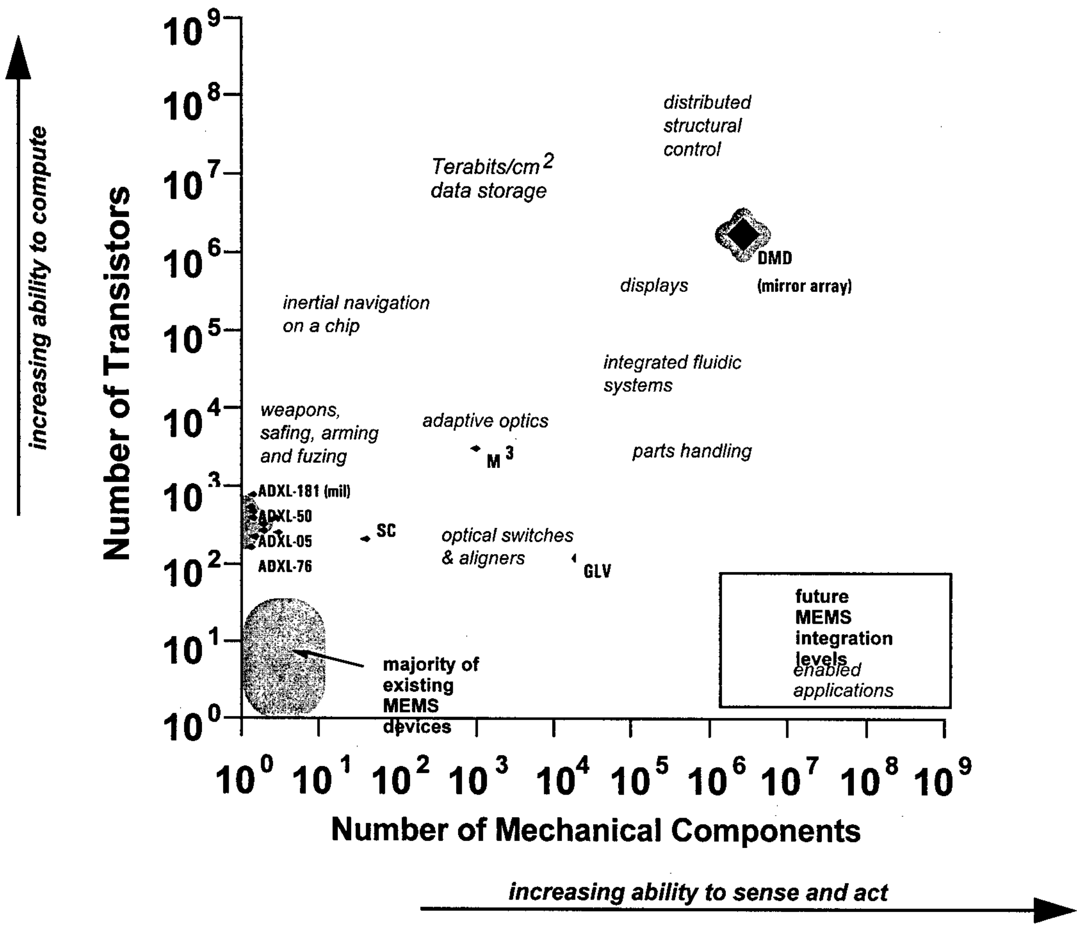


Figure 5

MEMS in general, and MOEMS in particular, have many potential insertion points in both commercial and military sectors. In the military sector, defense applications include (see: *Microelectromechanical Systems A DoD Dual Use Technology Industrial Assessment,* Final Report, December 1995):

- Active, conformable surfaces for adaptive optics.
- Integrated micro-optomechanical components for identify-friend-or-foe systems, displays and fiber-optic switches/modulators
- Mass data storage devices and systems for storage densities of terabytes per square centimeter
- Inertial navigation units on a chip for munitions guidance and personal navigation
- Distributed unattended sensors for asset tracking, border patrol, environmental monitoring, surveillance, and process control
- Integrated fluidic systems for miniature analytical instruments, hydraulic and pneumatic systems, propellant and combustion control
- Weapons safing, arming and fusing to replace current warhead systems and improve safety and reliability
- Embedded sensors and actuators for condition-based maintenance of machines and vehicles, on-demand amplified structural strength in lower-weight weapons systems/platforms and disaster-resistant buildings
- Active conformable surfaces for distributed aerodynamic control of aircraft and precision parts and material handling

Recognizing the potential for insertion of these devices in military systems, DARPA plans to maintain an on-going vigorous activity as can be noted by the sponsorship of projects reported in this STAR.

DARPA's total FY97 funding for MOEMS related research is in excess of $32.5M, including more than $783K in investments in multiple contracts related to DMD Engine applications. More details on the DARPA MEMS program can be found on the DARPA-ETO Web page at the following URL: http://www.darpa.mil.

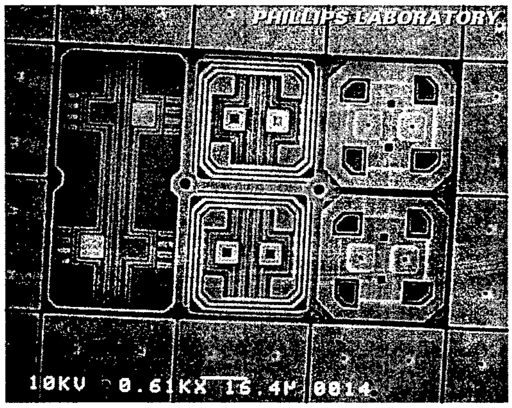
AIR FORCE PROGRAM

Among the services, the Air Force appears to have the most extensive experience with optical applications of MEMS technology. This is the result of the involvement of a small group of individuals at the Air Force Academy and Air Force Institute of Technology (AFIT) almost from the beginning of the emergence of MEMS. In particular, these researchers have had extensive experience working with both the DARPA MUMPs Foundry program and Sandia National Laboratories' CMOS based SUMMIT process for fabricating MEMS devices. Figure 6 illustrates a test mirror array developed at Phillips Laboratory, using the Sandia process. This 64 element array functions as a deformable mirror. It is used for the correction of atmospheric optical aberrations in imaging systems. Figure 7 illustrates the improved image obtained using such a 64 element MOEMS mirror array.

Flexure-Beam Micromirror Device

The FBMD is a phase-only device which deflects its reflective surface along an axis orthogonal to the array. Its characteristic behavior is easily derived from beam theory and electrostatics.

- Poly-0 address wiring runs beneath the arrayed devices
- Poly-1 flexures and shielding which protects wiring from shorting during post-process metallization
- Poly-2 address electrode
- Poly-3 planarized mirror surface

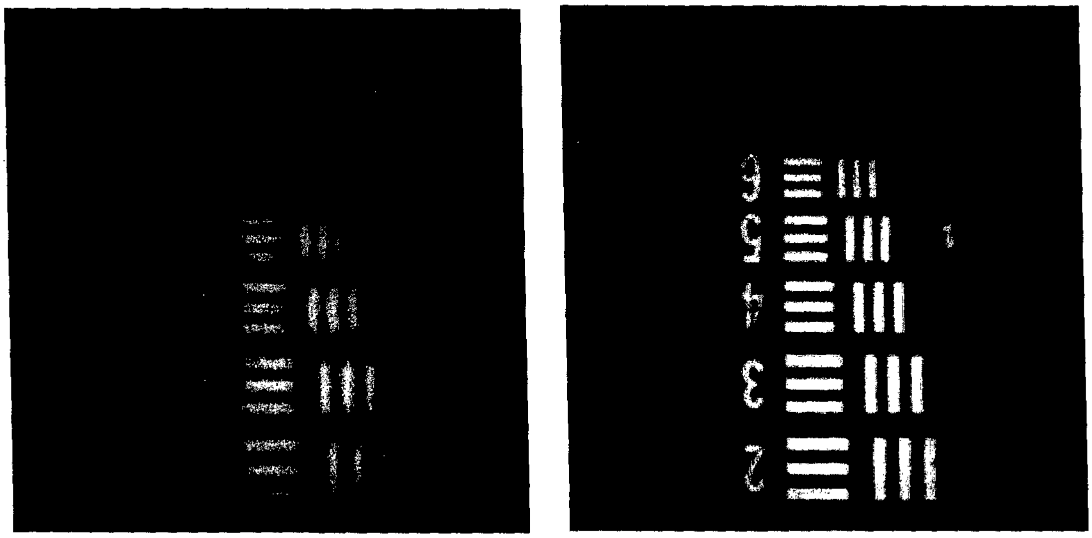


This device is 50μm square and deflects to 320nm at a potential of approximately 7 volts.

Figure 6

Phillips Laboratory researchers are currently pursuing development of micromirror arrays for aberration correction. The objective is to produce a "Silicon Eye" combining state-of-the-art micromirror arrays fabricated at Sandia with a Phillips-patented optics processor which solves partial differential equations encountered in optical processing. This analog processor promises high throughput and direct analog control of the micromirror positions. The goal is a system which can be digitally controlled to adapt to changing missions, and which also can adapt to changes in itself, caused by radiation degradation, optics degradation, or shock damage. This adaptability to internal or external aberrations will hopefully allow the use of more cost effective optics. In addition, the system should be tolerant of misalignment, reducing the precision needed in the manufacturing and final adjustment of the optics.

64 actuator spatial light modulator,
0.4 wave coma aberration, 0.375 waves corrected
(diffraction limited)



Uncorrected **Corrected**

Figure 7

In other work, Phillips' researchers have designed various 2-D tilt/piston-driven mirrors for more sophisticated beam steering and phase control. They also continue to develop thermal actuation and microstepper motors for the assembly and positioning of microoptical components, on, for example, a micro-optical bench. The Phillips approach yields motors with a low-voltage (5-10V) requirement compared to alternative MEMS electrostatic and "scratch" motors which use voltages well in excess of what common CMOS circuitry can provide (upwards of 50V). For this work they will also be exploring use of Sandia's combined micromechanical/electronics fabrication process. DARPA is currently funding a transfer of this process to Analog Devices, Inc., providing a direct manufacturing path for systems developed in this technology.

Preliminary studies on the radiation hardness of micromirror components have begun. Specifically, testing is in progress of the effects of exposure to radiation on micromirror flexures, the most sensitive part of a micromirror, and one for which accurate models exist. This ground based characterization will be followed by space experimentation, to compare device performance in an actual space environment against predicted modeling and ground test results.

Phillips' also sponsors many of the current AFIT research efforts, including work on spatial light modulators, mirror/array characterization, tilting mirrors/variable blaze gratings, beam steering, tracking mirrors, modeling and control of thermal actuators, and MCM packaging of MEMS with control electronics. Past AFIT efforts include: phase control for edge-emitting diode laser beam combining, optical switches including scanning mirrors, and self-assembly of microoptical structures.

At Wright Laboratory, researchers have pursued micro-optics for avionics applications for a number of years. Initial work investigated the use of piston micro-mirror arrays for beam shaping in laser communications systems. As part of this investigation AFIT was sponsored to perform a variety of mirror characterization experiments leading to the understanding of how the arrays functioned as phase and amplitude modulators. More recently, Wright Laboratory researchers have begun investigations aimed at laser beam steering and shaping for laser radar (LADAR) applications. One effort is concentrating on aircraft-based LADAR, and another effort on LADAR for munitions seekers. Models for micro-mirror arrays have been developed and used to estimate expected steering efficiencies. Results of these analyses have been relayed to AFIT, which is being sponsored to design, fabricate, and test mirror array concepts.

The Air Force Office of Scientific Research (AFOSR) is also sponsoring AFIT and other 6.1 research on continuous mirrors for aberration correction.

The present Air Force funding profile for MOEMS is as follows:

• Wright-Patterson AFB	50K/year	97, 98, 99	In-house funds
• AFOSR	115K/year	97, 98, 99	In-house funds
• Kirtland AFB	120K/year	97, 98	In-house funds
and Phase II SBIR	750K/2 years	97, 98	DARPA funds

Some of the issues which must be considered when creating working micro-optical systems identified by the Air Force researchers include: mirror quality, fill factor (optical efficiency), flatness, uniformity of response, mirror coating process compatibility, diffraction from multiple mirror edges, and power handling of micromirror arrays. Also potential bottlenecks in packaging, particularly for large arrays which require many connections, may stimulate research on integration of the mirrors' mechanical devices with their drive and control electronics. Eventually an integrated process that allows integration of all components constituting the entire system on one die—sensors, processing, drive and the mirror themselves may emerge.

Note: For additional information see Appendices A and B.

ARMY PROGRAM

The Army's interest in MOEMS technology arises as part of an overall strategy for success in the information age through improved battlefield situational awareness. ARL researchers have identified (Figure 8) how MEMS based microsensors can help in meeting the Army's advanced technology objectives for individual soldier condition monitoring, distributed sensing for small unit operations, micro-robots, and meso-scale integration. MOEMS are one component of an array of "micro-capabilities" that include micro-actuators, micro-sensors (including optical sensing of micro-cantilever based mechanical and RF probes), and micro photonic devices. The integration of these capabilities is expected to provide enhanced detection of acoustic, mm-wave, microwave, photonics and bio/chemical signals, imaging and unique types of signal processing, on-chip optical processing, information processing and displays and provide affordable, near perfect detection, and rapid, precise discrimination and targeting of all threats in all environments.

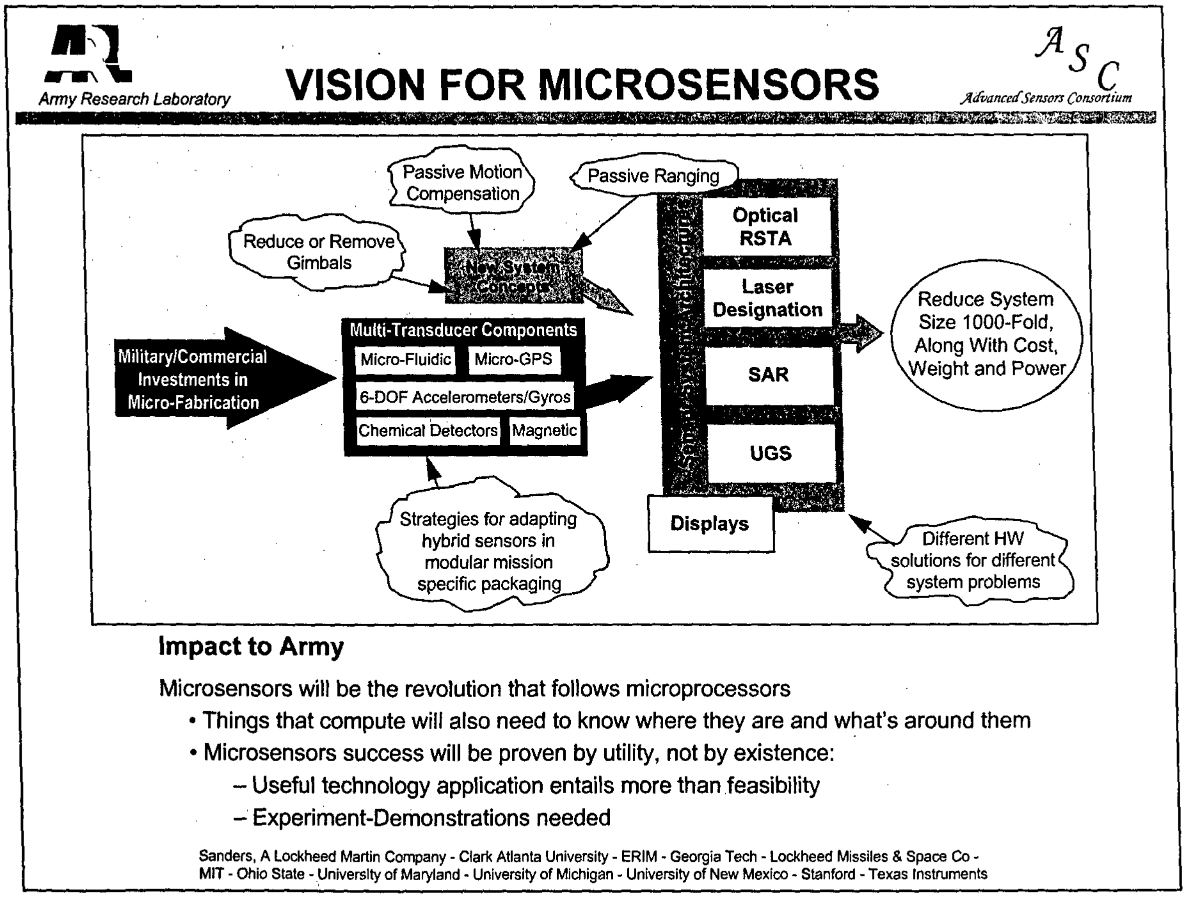


Figure 8

The Army MOEMS development is part of a micro-sensors program for realizing miniature optical, mechanical and electrical components to reduce the size, cost, and power of sensor system architectures. Army philosophy is to augment commercial investments in micro-fabrication with military specific research efforts to provide solutions to various system problems. These solutions will be developed by integrating hybrid sensors into modular, mission specific packages. This type of mixed technology integration will enable new systems capabilities through higher connectivity and higher performance. The long term goal is to provide the Army with affordable micro-sensors that can be widely distributed and interconnected from the soldier to larger scale platforms.

One specific area where MOEMS can have significant impact is in surveillance and reconnaissance requiring the acquisition and processing of visible, IR and near IR images. For this application, the Army is conducting research on an opto-electronic early vision pre-processor coupled to an adaptive detector array. This combination will enable more robust ATR and reduced need for imager data transmission. For example, the human eye is currently better at acquisition and recognition of hidden targets than automated systems are. An adaptive imager patterned after the human process would be capable of performing variable contrast and variable resolution over a single scene. The adaptive nature of this imager is realized from its construction, which consists of layers of opto-electronic devices interconnected optically. The technological challenge for adaptive imaging is the necessity for massive interconnectivity in a small volume. MOEMS could potentially enhance the performance of these arrays.

The Multi-domain Smart Sensor program at ARL is aimed at developing new ways to combine sensors and sensor processing on the focal plane to achieve performance improvements over second generation FLIRs. The concept is to combine passive imaging in the mid-to-far-IR band through a common aperture surveillance system. The architecture is envisioned to include an active Diffractive Optical Element (DOE) imaging system, vertical cavity surface emitting lasers (VCSELs), and DOE coupling to an off-chip processing unit that incorporates advanced signal processing such as scene based uniformity corrections and local gain and offset control. Figure 9 illustrates a conceptional schematic for this integrated vision-based photonic processor. The micro-mechanical part of this system might include micro-dithering of the image by a lenslet array at the focal plane to achieve sub-pixel resolution.

Full awareness of the battlefield is not complete without the addition of chemical and biological sensing. Chemical and biological weapons can be extremely potent. Perhaps the most frightening aspects of chem/bio agents is their low cost, easily concealed production and ease of delivery. Current research is aimed at developing sensor mechanisms that possess the characteristics of detection sensitivity, specificity, compactness, ruggedness, and low cost.

Magnetic Resonance Force Microscopy (MRFM) has been proposed as a means of obtaining 3-D images of individual biological molecules. MRFM is a technique that uses the magnetic resonance imaging concept of selectively exciting magnetic resonances within a slice of a sample. Magnetic resonance is detected by measuring the oscillating magnetic force acting between spins in a sample and in a nearby magnetic particle. High spatial resolution is achieved as a result of the narrowness of the magnetic resonance spectral response and the large magnetic

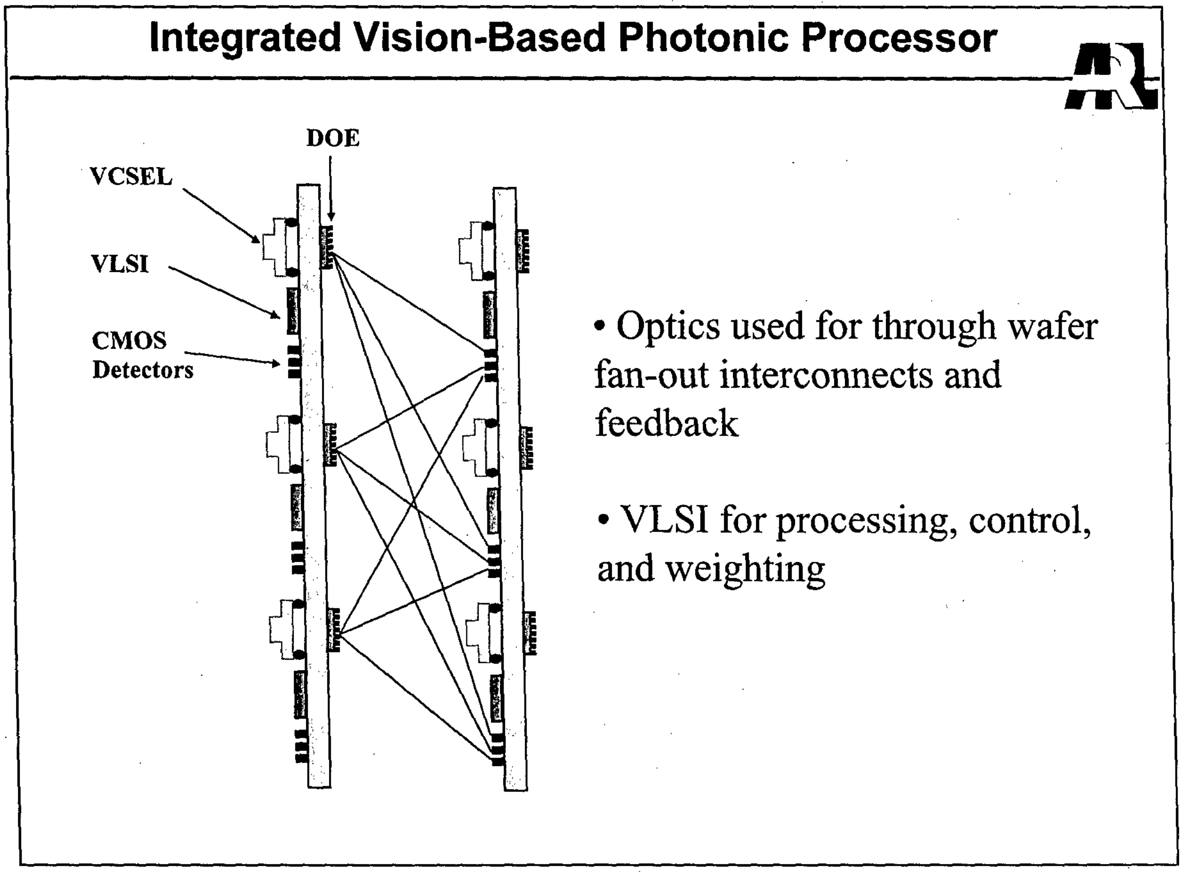


Figure 9

field gradient produced by the ferromagnetic particle. ARL is interested in MRFM for a number of applications that are detailed in the Army Tech Base Master Plan. For example, it is hoped that MRFM can be directly applied to the imaging of sub-surface defects and mapping of dopant distributions in semiconductors. If force detection of nuclear magnetic resonance can be made sufficiently sensitive to detect singular nuclear magnetic moments it would allow molecules to be imaged in a chemically specific way with 3-D, sub-Angstrom resolution. Optics may be beneficial as a means of detecting the MRFM signal.

The Army is developing novel ways to combine sensors, computation, and communication components into lightweight, low power, modular packages. Various types of microstructures are being investigated for their application to solution of problems with detection, imaging and image processing, optical interconnects and on-chip optical processing, information processing, and displays. Micro-sensor, micro-optic, micro-actuator, and micro-photonic structures can be integrated into hybrid devices to solve these problems for specific Army needs. However, establishment of low cost, monolithic manufacturing capabilities is essential for achieving the payoff from the R&D investment. Government and industrial partnerships are recognized as the key to the success of MOEMS for use in Army applications.

NAVY PROGRAMS

No active MOEMS-specific Navy programs were identified. Presently, NRL is conducting a study for DARPA of the application of optics to MEMS manufacture and the potential uses for MOEMS. Of particular interest is application of deformable mirrors, such as the Texas Instruments optical beam steering engine, to such applications such as eye and sensor protection. NRL is also interested in the effects of radiation on these devices to assess their appropriateness for use in space. In a separate effort, NRL has investigated the use of micro-machined mirrors for tuning solid state lasers using an approach similar to that discussed by Professor Harris of Stanford University at this STAR. This effort provided a small business supplier of micro-cavity, laser-diode-pumped, solid-state lasers with the financial support to develop the technology allowing deflective mirror control of the solid state laser output wavelength. However, the program was terminated before a successful prototype was demonstrated. The approach, particularly for use with diode lasers as discussed by Professor Harris, continues to be of interest to NRL researchers.

Note: See Appendix C for Naval Research Laboratory abstract.

NASA (JPL) PROGRAMS

No present JPL activities are focused specifically on MOEMS. However, MOEMS are anticipated to have significant potential for cost effective implementation in a range of missions, particularly for exploration of the planets. For this class of application, incorporation of MOEMS into robotic techniques can offer effective solutions for a variety of problems. Specifically, opto-mechanical system applications important to NASA parallel those discussed by the Air Force. These include beam focusing, reflection, diffraction, interferometry, modulation and switching functions, all of which can be miniaturized by use of MOEMS technology.

Among the applications for which MOEMS are anticipated to enhance functionality are: optical imaging of distant and near objects, including higher resolution interferometric measurements; spectrometry across the UV, visible, and IR spectral ranges; beam steering for optical communications; and, optical navigation.

INDUSTRY/ACADEMIA PRESENTATION SUMMARIES

Non-governmental researchers and technologists were in general agreement on a number of characteristics of MOEMS. These opto-mechanical devices/systems are smaller, faster, more rugged and insensitive to shock, capable of precise alignment and displacement, and consume less power than macro-scale devices. Compatibility with VLSI technology enables mass production at low cost. While many of the current device concepts and demonstrations are impressive, the marriage of the base technologies [optics, semiconductor active devices (both opto-electronic and CMOS-electronics) and actuation/agility through semiconductor based micromachining] through large scale integration should achieve significant gains in functionality and entirely new systems capabilities. MOEMS also have advantages when compared to conventional opto-electronic integrated circuits (OEICs); for example, they are the non-planar 3-D devices that are mechanically adjustable and reconfigurable. Since most current MOEMS are Si based, they need to be hybridized with other material systems, such as GaAs and InP, when fabricating active optical devices. It is reasonable to expect that the two microelectronic approaches to optical systems, OEICs that use waveguiding optical circuits, and MOEMS, will merge.

The most successful MOEMS device from a market perspective has been the Texas Instruments Digital Micromirror Display (DMD). VGA and super-VGA displays have been made which are capable of projecting large area images of high luminance. The DMD consists of a 2-D addressable array of electrically deflectable micromirrors, each about 15 micrometers on a side. They are fabricated in a multilayer stack; the process includes removal of a sacrificial layer so that the mirrors can be deflected by an electric field. Currently, there are 13 companies either manufacturing or developing projection systems using DMD technology.[1] Texas Instruments representatives were unable to attend this STAR to make a presentation on this technology.

SILICON LIGHT MACHINES

Dr. Olav Solgaard presented the Silicon Light Machines' approach to commercial display technology. The grating light valve (GLV) that they have invented and are developing is shown in Figure 10. As with most other MOEMS, this device is implemented in Si. In the array of Si ribbons shown, every other element can be electrically displaced vertically, forming a grating and deflecting the light into the projection system of a display (bright state). When there is no voltage applied to deflect the ribbons, diffraction is absent and the system is in the dark state. The width of the ribbons is 2 μm and the length is in the 40 – 120 μm range. The device is fabricated using seven masking steps. In Figure 11, the switching speed and hysteresis behavior are shown. The fast switching speed indicates that a 1-D array can be used together with a galvanometer system for the other dimension. The hysteresis behavior allows clamp-down operation at low voltages. The GLV technology is a potential competitor with another MOEMS based display, the Texas Instruments DMD device. The DMD device is a 2-D array (640x480 and higher) of individually addressable, electrically deflectable micromirrors.

[1]J. Ouellette, *Industrial Physicist*, pp. 9-12, June 1997.

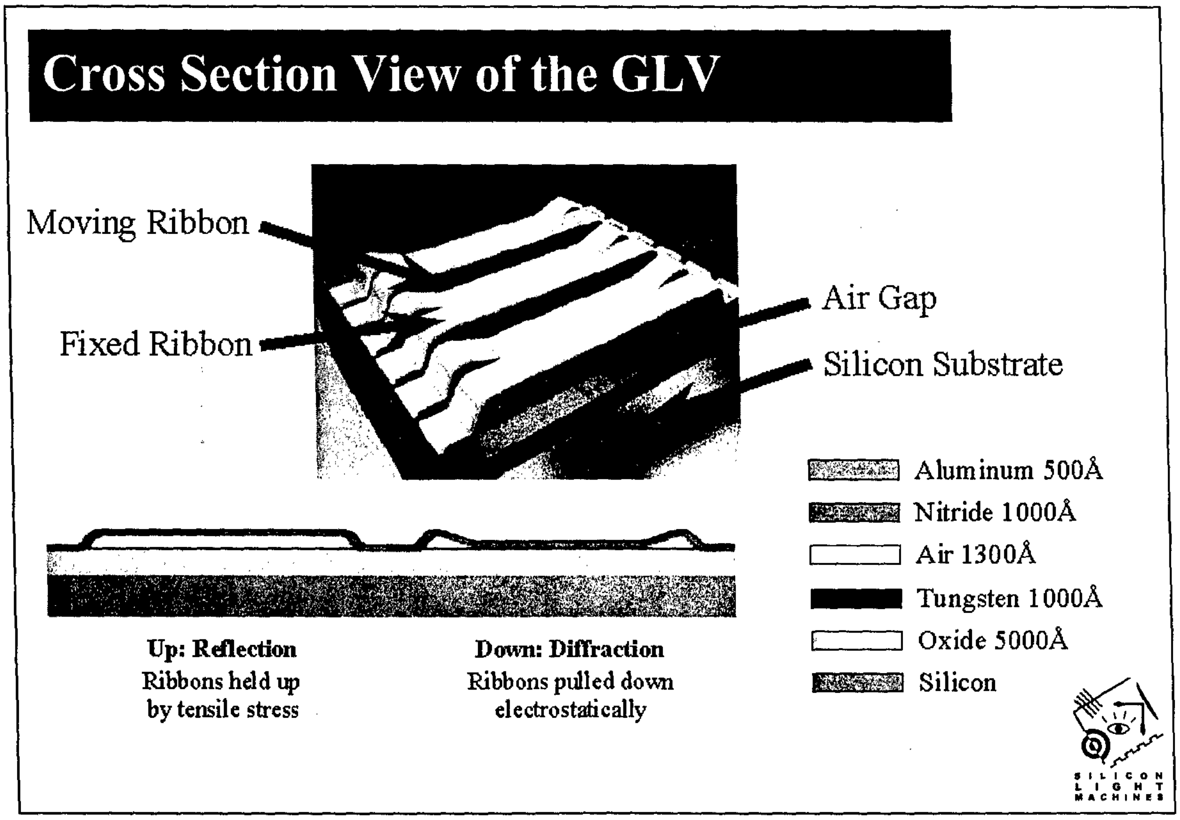


Figure 10

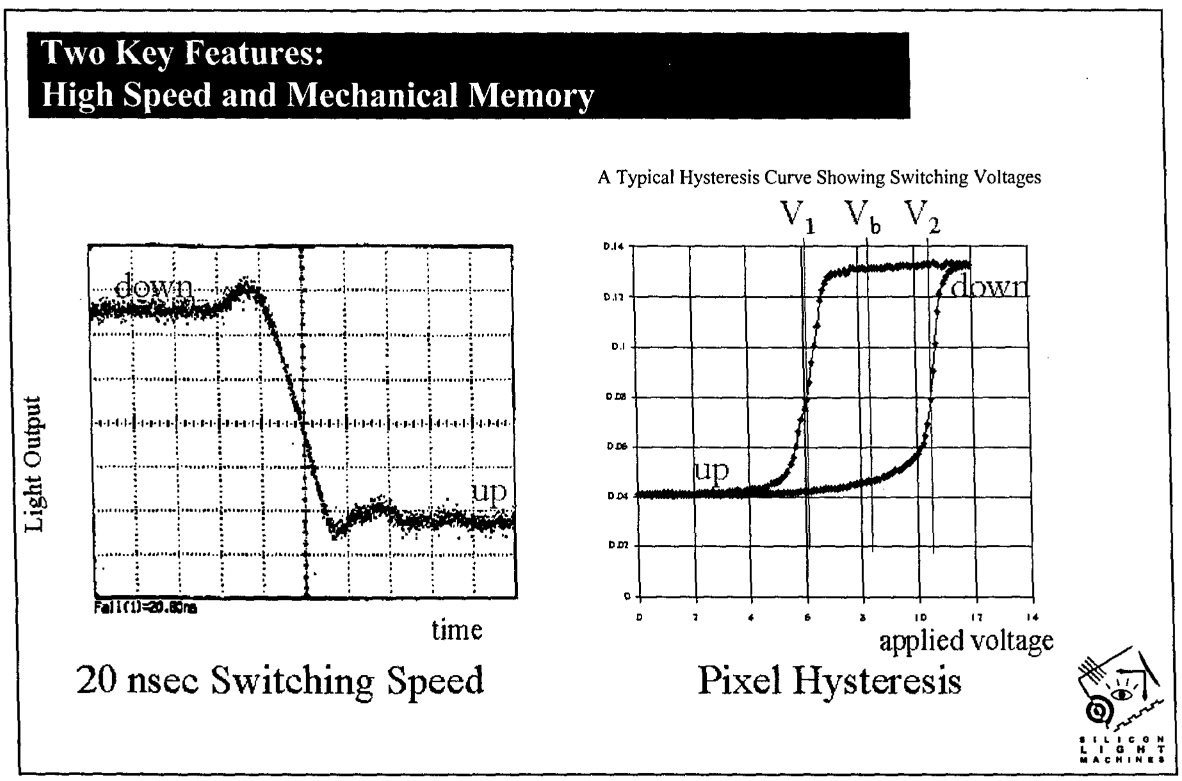
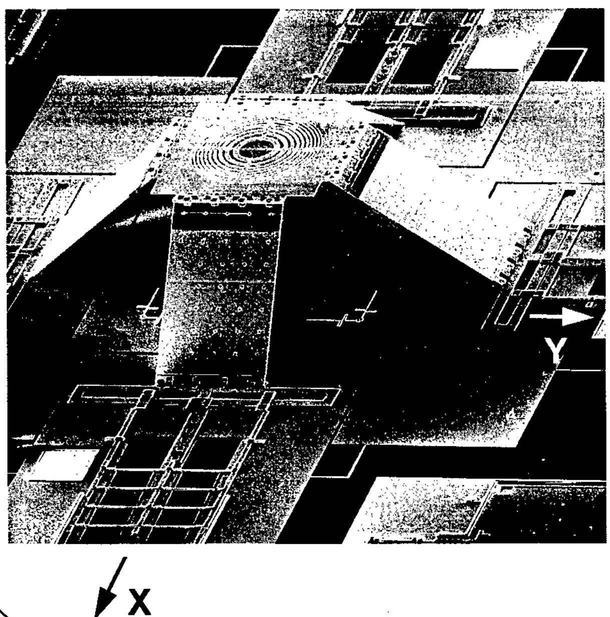


Figure 11

Professor Ming Wu of UCLA discussed a number of examples of MOEMS devices such as optical switches, micro-XYZ stages, optical pickup heads, and femtosecond optical autocorrelators. A photograph of the optical pickup head is shown as an electron micrograph in Figure 13. The device uses electrostatic comb drive actuators for adjustment of the pickup. The MOEMS optical disk pickup head can be 1000x lighter than conventional pickup heads which enables faster access time (~ 30x). The micromachined devices are very stable against vibration because of the small inertial masses; individual elements in these devices have high ratios of contact area to volume. Professor Wu gave data on bit error rates for an optical switch, which showed little degradation in performance with a 50g vibration at 150Hz. A self-assembling XYZ stage with integrated microlens, as shown in Figure 12, demonstrates the 3-D character and mechanical adjustment capability of the micromachined devices. The lens shown can be precisely adjusted for XYZ position and pointing accuracy.

NOTE: FIGURES 12 AND 13 PLACEMENT REVERSED DUE TO FORMAT LIMITATIONS

Self-Assembled Micro-XYZ Stage with Integrated Microlens



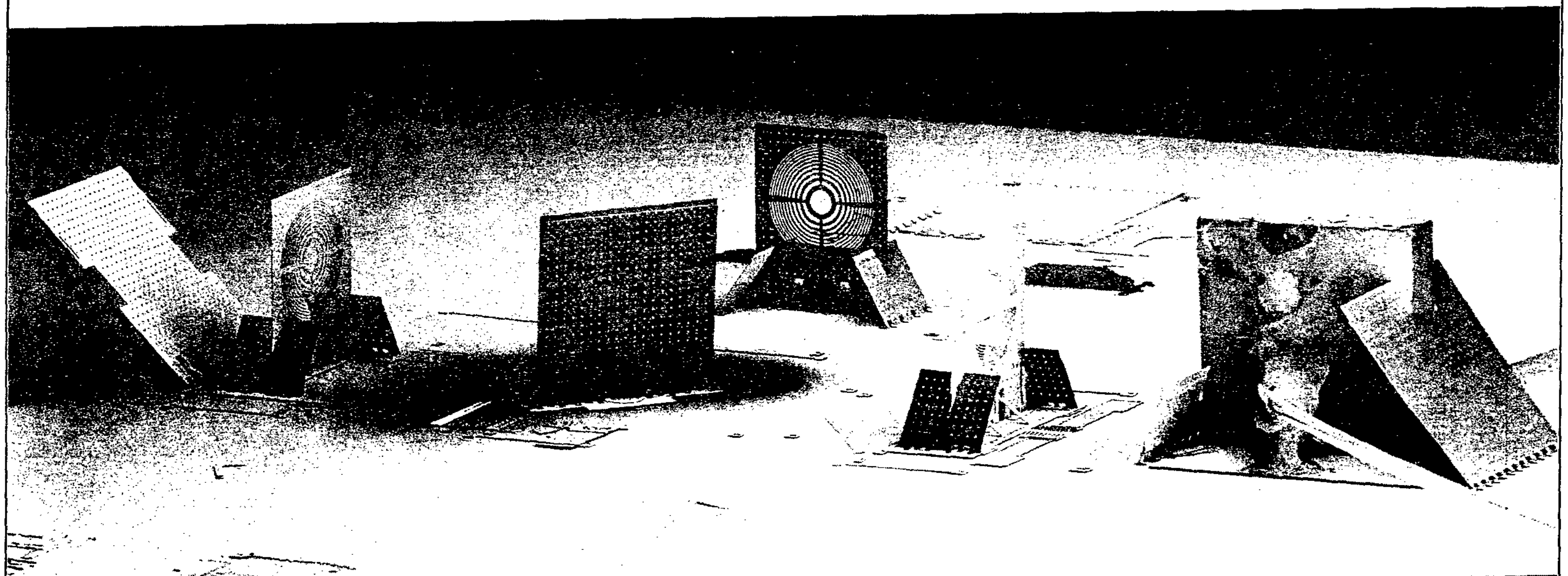
- **Vertical actuation**
  - **by pushing all 4 actuators inward**
- **Translation in XY plane**
  - **Move both actuators along X (or Y) axis in the same direction**
  - **Sliding ring allow simultaneous XY motion**
- **Microlens can be integrated or hybrid mounted**

M. C. Wu

Integrated Photonics Laboratory UCLA

Figure 12

Monolithic Optical Disk Pickup Head



Micro Optics (laser, 3 fresnel lenses, beam splitter, & 45 deg. mirror) Nano-fabrication Micromachining (Fabricated by Ming Wu, L. Y Lin, J. L. Shen, S. S. Lee, and C. R. King @ U.C.L.A., E.E. Dept.)
50X @ 4"x5" size. (9605-009a)

Free-Space Micro-Optical Bench (FSMOB)

- **Miniaturization**
- **Monolithic integration**
- **Batch fabrication**
- **Optical "pre-alignment"**
- **Integrated microactuators**

- Lin, Shen, Lee, and Wu, Optics Letters, p.155, 1996.
- Picture taken by David Scharf for Scientific American

M. C. Wu

Integrated Photonics Laboratory UCLA

Figure 13

STANFORD UNIVERSITY

Professor James Harris described the research of his group at Stanford on semiconductor diode lasers tuned using a MOEMS structure as one of the cavity mirrors. The mirror membrane structure, which is fabricated over a GaAs/AlGaAs vertical cavity laser, consists of a stress-matched $SiO_2/Si_3N_4/SiO_2$ trilayer and a gold top-layer, the latter serving as one of the cavity mirrors. Electron micrographs of the device are shown in Figure 14, while Figure 15 is a schematic of the structure. Tuning by electrically displacing the cavity mirror gave a response time of 2 μm. In Harris' view MOEMS based tunable lasers, filters, and detectors will be the building blocks for ultra-high capacity fiber and free space WDM optical interconnects, agile reconfigurable interconnects, optical switching, and spectroscopy systems for environmental and battlefield monitoring. Spectra of water vapor taken with the tunable laser are shown in Figure 16.

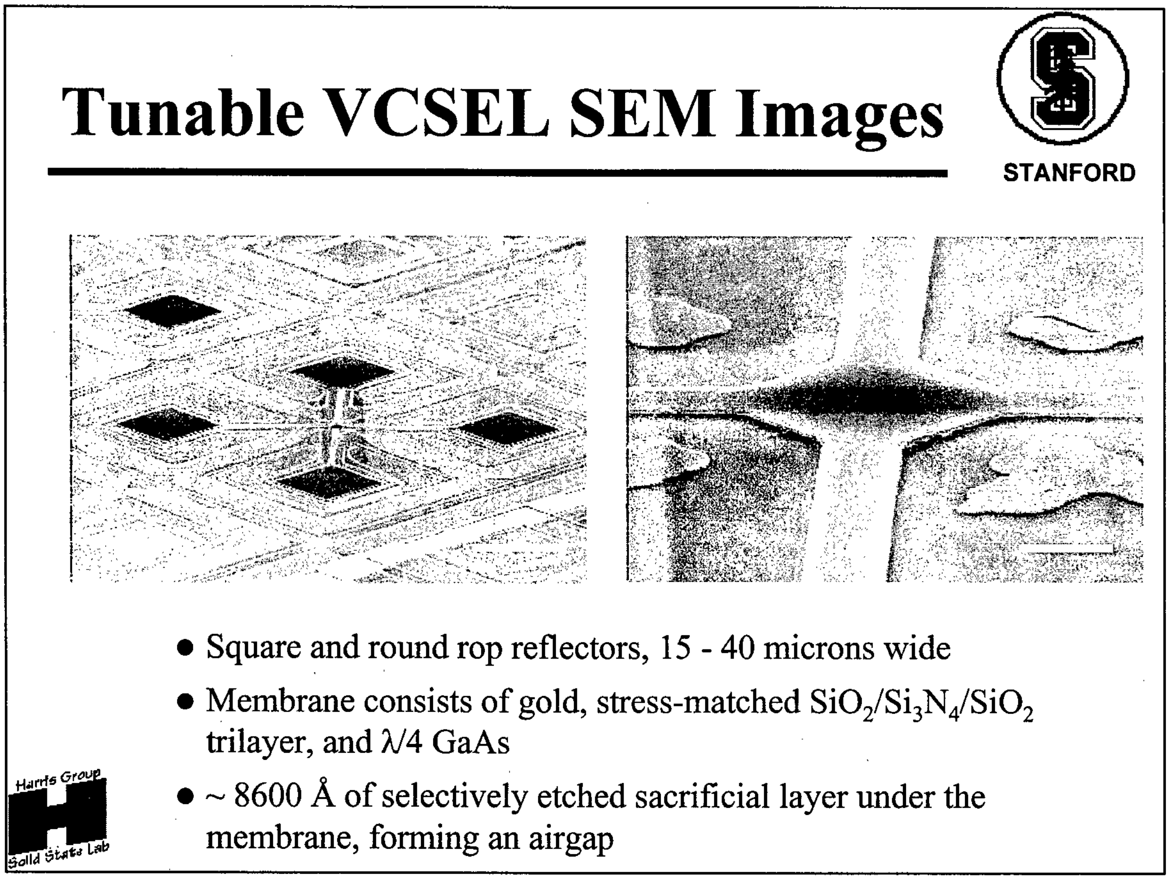
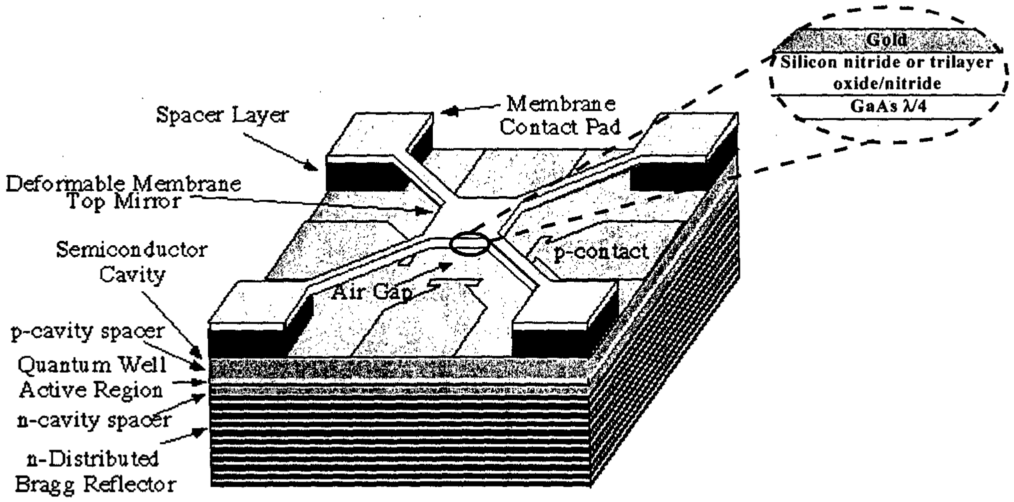


Figure 14

Tunable VCSEL Structure

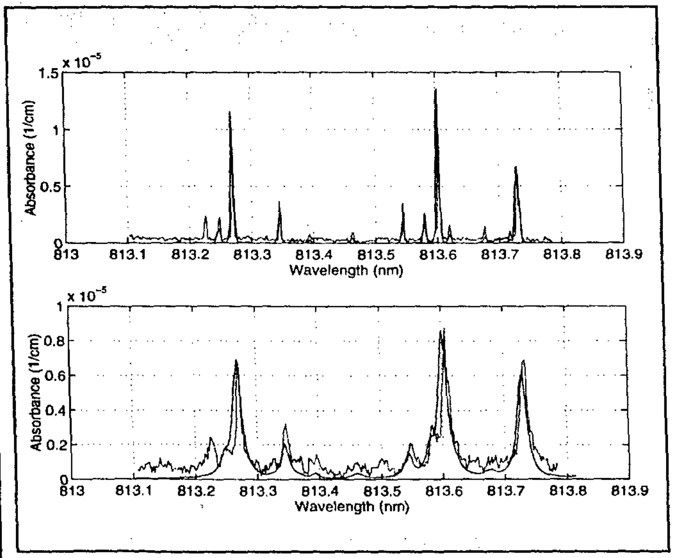
STANFORD



Harris Group Solid State Lab

Figure 15

Water Vapor Spectra



- 5 Torr Water Vapor
- Total Pressure: 5 Torr
- Resolution: 180 - 240 MHz
- Scan Step Size: 0.001 nm
- Baseline Noise: 2 x 10^{-8} cm^{-1}
- Sensitivity: 20 ppm

- 60 Torr Water Vapor
- Total Pressure: 1 atm
- Resolution: 240 - 500 MHz
- Scan Step Size: 0.002 nm
- Baseline Noise: 8 x 10^{-8} cm^{-1}
- Sensitivity: 200 ppm

—— **Experimental** —— **HITRAN96**

Figure 16

COMMITTEE FINDINGS AND RECOMMENDATIONS

FINDINGS

1. *The innovative aspect of this new MOEMS technology is the capability to combine several mechanical, electrical, and optical functions in a manufacturable "chip" context.*

   Using chip making lithography to define the structures, a variety of devices can be fabricated. A rough categorization of system complexity can be made as a function of degrees and facility of dimensional movement. 1st generation devices feature x, y surface definition with Δ out-of-plane motion over a few optical wavelengths providing, for example, an optical switch via interference. 2nd generation devices feature x, y, z definition with larger mechanical motion possible such as the tunable VCSEL device of Stanford University. 3rd generation x, y, z devices provide definition over extremely large distances, for example, the silicon, erectable optical bench work of UCLA.

2. *At this stage of development of the MOEMS technology, the desirable features and effectiveness for use in military systems, especially laser and sensor systems, can be perceived in generic fashion, but a detailed evaluation has yet to be made.*

   By combining several functions in a technology which seems inherently suited to mass production, MOEMS could offer great cost and performance advantages. This promise must be assessed for individual cases. MOEMS value for performing specific DoD system functions should be compared with that of other emerging technologies.

3. *Current MOEMS device fabrication techniques build on existing chip manufacturing methods. A producible technology capability must evolve, which provides optimization of the key optical parameters.*

   Electrical and mechanical properties have been the focus of MEMS fabrication efforts to date. Key optical parameters like the flatness and low loss in reflection or transmission must be addressed to avoid the performance limitations. Fabrication constraints on, for example, planarization and coatings are important producibility considerations.

4. *There is a large competitive commercial display market which MOEMS can address.*

   The first US company to enter this competitive market is Texas Instruments. It reports success in establishing markets with several licensees for its Digital Mirror Display devices. These are now being produced in a commercial facility.

5. *Generic features of MOEMS have been described which establish this technology as a broadly applicable one with breakthrough potential.*

These demonstrated features include:

high mechanical speed..demonstrated t < 20ns
high stiction to inertia ratio.................................implies stability
integrated opto-mechanical devices....................adaptive
small mass...implies low power and high accuracy

Other inherent advantages could be enumerated.

6. *Many technical issues remain to be addressed; this technology is still in an infancy stage.*

With the experience of the integrated circuit industry as a model, several important technical areas and disciplines can be identified as being among those which require additional research and development. These include: packaging, coatings, integrated opto-mechanical CAD design tools, and device models. These technical issues will be addressed in the creation of a MOEMS roadmap.

7. *MOEMS production can exploit the existing integrated circuit manufacturing infrastructure, through suitable adaptation and modification.*

This could be a real capital investment plus. MOEMS fabrication and production physical plant infrastructure is very similar to that employed by chip manufacturers. As chip making facilities upgrade to accommodate smaller and smaller design features, it seems likely that MOEMS device production could proceed with the addition of special processing equipment on these old excess production lines.

8. *There is vigorous foreign MEMS technology activity as indicated by conference participation and personal contacts. The US appears* to *have a strong MEMS position. MEMS technology is readily translatable to MOEMS technology.*

9. *The export control status of MOEMS is not completely clear.*

MOEMS are emerging technologies and are not explicitly covered by existing regulations. However, it is clear that:

- MOEMS "specially developed" for military applications <u>are</u> covered by the United States Munitions List.
- Devices developed for civilian or dual use applications are only covered if the capability they enable is controlled. For example, an adaptive optics controller that allows

wavefront correction at closed loop bandwidths above 100Hz is controlled by Section 6.4 of the Commerce Commodities List (CCL), irrespective of how it functions.

- The equipment and technology used to make MOEMS may be controlled by Section 3.B.1 of the CCL, which covers lithography equipment. (The latter section only controls equipment with a source in the EUV below 400nm or where a feature size of less than 0.7 microns can be produced.)

10. *Most MOEMS devices to date have utilized silicon, but other material systems (glass, III-V and II-VI compounds) offer potential important advantages for optical systems.*

RECOMMENDATIONS

1. *The value of MOEMS for use in military system applications should be demonstrated through the following actions:*

    - Each service should identify a technical champion/management team focal point.
    - A service team/DARPA working group should be established to carry out applications definition and other pertinent studies, including identification of R&D transition paths and service budgetary needs.

    The high potential system leverage afforded by MOEMS, even at this early stage of development is the impetus for this recommendation.

2. *As MOEMS R&D projects are conducted a strategy and roadmap should be evolved to implement the required manufacturing infrastructure. This will allow military production to be attained in timely fashion.*

3. *MOEMS may well follow the MEMS course as a global technical activity. The DoD leadership team should be responsive to the need to formulate criteria—protecting military specific developments without hampering commercial activities—for submission to the proper authority establishing export policy.*

CONCLUSION

It should be clear from the foregoing text of this STAR that considerable unfinished business remains in this technical area. To take a positive view, this assessment affords a great opportunity to shape military requirements and technical projects at the outset of a promising new technology. On the negative side, the factual data base regarding the technology potential, applications and ultimate system insertion costs is sparse. The paucity of data and coordinated DoD planning underscores an ongoing need to revisit this STAR and update the findings and recommendations at periodic intervals.

APPENDIX A

AIR FORCE '96 TECHNOLOGY NEEDS FOR MOEMS

Potential Application Areas for MOEMS within the *USAF SPACE & MISSILE COMMAND FY 96 TECHNOLOGY NEED LIST* include:

1. GLOBAL PROMPT STRIKE
    - Autonomous surveillance, tracking, imaging
    - Real time tracking/targeting
    - SBL-multiple - target acquisition, tracking and pointing (ATP) laser development/demonstration (SFA: Full Power Beam Quality)
    - Increased signal collection efficiency of electro-optical (EO) sensors (SFA: High Rate Optical Data)
    - Decreased optical wavefront error for space-based sensors (SFA: Outgoing wavefront Sensing & Measurement)
    - Increased detectivity and/or reduced noise of electro-optical (EO) detection (SFA: Precision Optical Structures)
    - Low cost star sensor

2. SURVEILLANCE AND THREAT WARNING
    - Large, ultra light weight, deployable optics
    - Optical wavefront sensors and correctors

3. ENVIRONMENTAL MONITORING
    - Micromachined earth and sun sensors

4. COUNTERSPACE
    - Adaptive optics for large mirrors
    - Advanced EO weapons threat protection
    - Survivable optics

5. NATIONAL MISSILE DEFENSE
    - Acquisition, tracking, and pointing (ATP)

6. SPACE SURVEILLANCE
    - Autonomous searching, detecting, and tracking by space-based sensors
    - Decreased optical wavefront error for space-based electro-optical (EO) sensors

APPENDIX B

SERVICE POINTS OF CONTACT FOR MOEMS

ARMY

- Ms. Lorna Harrison, Army Research Laboratory, Adelphi, MD (301) 394-3802

NAVY

- Mr. Steven Walker, Naval Research Laboratory, Washington, DC (202) 767-6978

AIR FORCE

- Major John Comtois, PL/VT Kirtland AFB, NM (505) 846-5813
  Spatial light modulators, thermal actuators, steering optics, space systems
- Dr. Lenore McMackin, PL/LI Kirtland AFB, NM (505) 846-2047
  Digital aberration correction, mirror characterization
- Dr. Edward Watson, WL/AA Wright-Patterson AFB, OH (937) 255-9614 ext240
  Beam steering for aircraft laser radar
- Major Jeffrey Grantham, WL/MN Eglin AFB, FL (904) 882-1726
  Beam steering for munitions laser radar
- Major William Arrasmith, AFOSR Washington, DC (202) 767-4907
  Micromirrors for aberration correction
- Dr. Victor Bright, AFIT Wright-Patterson AFB, OH (937) 255-3636 x4598
  MEMS research, micro-optics, design and modeling, thermal mirrors

DARPA

- Dr. Elias Towe (703) 696-0045

APPENDIX C

OPTICS and MEMS

S. J. Walker and D. J. Nagel
Naval Research Laboratory
Washington DC 20375

Optical science and technology have undergone a rebirth during the last three decades, because of lasers and fiber optics. Large new industries resulted. During this same period, integrated circuits have produced the information revolution. In the last decade, the techniques developed for the production of electronic chips have been employed, along with new processes, to produce chips with moving parts. These are called microelectromechanical systems (MEMS). Now, there is an exciting and important confluence of these trends. Optics enable MEMS and optical MEMS to manipulate light and exploit the vast capability of photonic devices.

Optics and MEMS have a natural synergism. On one hand, optical techniques are basic to the manufacturing of MEMS. This is most true of photolithographic patterning methods. However, it increasingly applies to laser direct-write methods for etching or depositing materials during production of MEMS, as well as to the metrology of MEMS during and after manufacturing. On the other hand, a wide variety of MEMS have already been demonstrated to produce, modify or detect optical radiation.

Optical MEMS can be loosely defined as any MEMS device which manipulates light. There is no such thing as a completely optical MEMS, since the second "M" represents "mechanical." Thus we are defining optical MEMS as devices that couple photons and mechanical motion in a meaningful way. Some MEMS devices, which primarily use lasers, waveguides, and photodetectors, test the limits of this definition. Ultimately, these borderline systems will probably include some form of active lens or mirror, and thus will meet the criteria of a true optical MEMS.

Entire optical MEMS with volumes on the order of 1 cm^3 have been demonstrated. Both the small ratio of optical wavelengths to the lateral dimensions of MEMS, and the low energy needed in a MEMS to manipulate light, contribute to the increasing interest and capabilities. The rapid motion of micro-mirrors and other optical elements, which are possible due to the lightweight component parts of MEMS, is also a major beneficial factor. So, too, are the similar physical scales of integrated circuits, fiber-optic diameters, laser diodes, and MEMS.

This review of optics and MEMS begins with a survey of optical techniques used to produce and characterize MEMS. The following section is a detailed treatment of all types of optical MEMS, with emphasis on the few MEMS which are already in commercial production and those devices which show the most promise of being commercial successes. The next section reviews current and projected applications of optical MEMS in a wide variety of research and commercial systems. It is likely that MEMS will be very important in the flat panel display and optical-fiber communications markets, among others. The concluding section contains remarks on possibilities for the further development and application of optical MEMS, with particular attention to incorporating advanced optical materials in MEMS. An extensive bibliography of the ordinary and patent literature appended.

Selected References:

1. M. E. Motamedi, "Micro-opto-electro-mechanical systems," *Optical Engineering* **33** (11), pp. 3505-3517, (1994).
2. H. Fujita, "Application of micromachining technology to optical devices and systems," *Microelectronic Structures and MEMS for Optical Processing II, Proc. SPIE* **2881**, pp. 2-11, (Oct. 1996).

This abstract is excerpted from NRL Memorandum Report #7975. Copies of this report may be obtained from the authors or the Naval Research Laboratory Technical Information Division at (202) 767-2187

APPENDIX D

REPORT OF SPECIAL TECHNOLOGY AREA REVIEW (STAR) ON MICRO–OPTO–ELECTRO–MECHANICAL–SYSTEMS (MOEMS)

AGENDA
28 May 1997

SPEAKER	AFFILIATION	TOPIC	TIME
Tom Lapuzza	NCCOSC/NRaD	NCCOSC/NRaD Overview	0900-0945
Tom Hartwick	AGED Working Group C	STAR Introduction	0945-1000
Elias Towe	DARPA	DARPA MEMS Program Overview	1000-1030
		BREAK	1030-1045
Olav Solgaard	Silicon Light Machines	Grating Light Valve Displays	1045-1115
Lorna Harrison	Army	ARL Present and Future Needs in Optical MEMS Technology	1115-1130
John Comtois	Air Force	Phillips Laboratory Micromirror Developments	1130-1215
Bob Leheny	DARPA	Review of Morning Presentations	1215-1230
		LUNCH	1230-1330
Bill Tang	NASA JPL	Future Directions in Optical MEMS Technology for Space Applications	1330-1345
Ming Wu	University of California at Los Angeles	UCLA Optical MEMS Program	1345-1415
Jim Harris	Stanford University	Optical MEMS in Tunable Lasers and Detectors	1415-1445
		BREAK	1445-1500
Group Discussion	Speakers & AGED Working Group C		1500-1630
Writing Assignments	AGED Working Group C		

APPENDIX E

REPORT OF SPECIAL TECHNOLOGY AREA REVIEW (STAR)
ON
MICRO–OPTO–ELECTRO–MECHANICAL–SYSTEMS (MOEMS)

TERMS OF REFERENCE

1. Which technical areas offer the highest leverage for DoD to improve systems and capability? Are there any critical technical issues that should be addressed by DoD?

2. What are the current and future commercial markets for MEMS?

3. Are there specific near-term MEMS applications for DoD systems? If so, when will they be fielded and what is their impact?

4. What DoD funding level is devoted to Optical MEMS? What projects are supported and why? Is the funding adequate and distributed properly? Which areas might be driven by commercial interests? Is the government support for basic research appropriate, given the fact that many other fields are competing for the same funds?

5. Is there competitive pressure from foreign interests? Is there any infrastructure weakness, such as manufacturing processes or a paucity of joint ventures, which would result in an impediment to exploitation of this technology by DoD?

APPENDIX F

REPORT OF SPECIAL TECHNOLOGY AREA REVIEW (STAR) ON MICRO–OPTO–ELECTRO–MECHANICAL–SYSTEMS (MOEMS)

ABBREVIATIONS, ACRONYMS AND DEFINITIONS

AFIT............................Air Force Institute of Technology
AFOSR.........................Air Force Office of Scientific Research
AGED ....Advisory Group on Electron Devices
ARL.............................Army Research Laboratory
ATR.............................Automatic Target Recognition
CCL.............................Commerce Commodities List
CMOS ....Complementary Metal Oxide Semiconductor
DARPA ....Defense Advanced Research Projects Agency
DMD ....Digital Micromirror Display
DoD.............................Department of Defense
DOE ....Diffractive Optical Element
EO ....Electro-Optic(al)
FLIR............................Forward Looking Infrared
GaAs ....Gallium Arsenide
GaAs/AlGaAs ....Gallium Arsenide/Aluminum Gallium Arsenide
GLV ....Grating Light Valve
InP ....Indium Phosphide
IR.................................Infrared
JPL ....(NASA) Jet Propulsion Laboratory
LADAR.......................Laser Radar
MCM...........................Multi-chip Module
MEMS.........................Micro-electro-mechanical-systems
MOEMS......................Micro-opto-electro-mechanical-systems
MOMS ....Micro-opto-mechanical-systems

MRFM........................Magnetic Resonance Force Microscopy

MUMPs......................Multi-User MEMS Projects

NASA.........................National Aeronautics and Space Administration

NRL............................Naval Research Laboratory

ODDR&E/S&E..........Office of the Director of Defense Research and Engineering/Sensors and Electronics

OEIC..........................Opto-Electronic Integrated Circuit

RF..............................Radio Frequency

SBL............................Space Based Laser

Si...............................Silicon

$SiO_2/Si_3N_4/SiO_2$.........Silicon Dioxide/Silicon Nitride/Silicon Dioxide

STARs........................Special Technology Area Review(s)

USAF.........................United States Air Force

VCSEL.......................Vertical Cavity Surface Emitting Laser

VLSI...........................Very Large Scale Integration

WDM.........................Wavelength Division Multiplexing