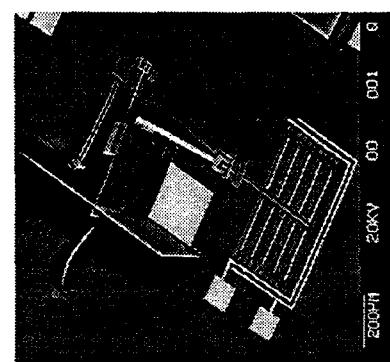
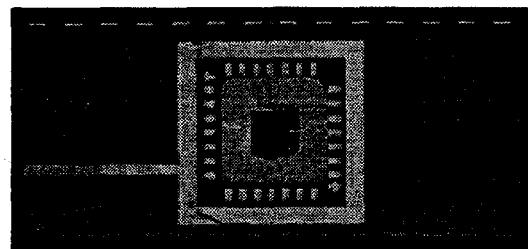


ETO MEMS

# MicroElectroMechanical Systems (MEMS)



Dr. Kaigham J. Gabriel  
Director  
Electronics Technology Office  
Defense Advanced Research Projects Agency

703/696-2252

kgabriel@darpa.mil

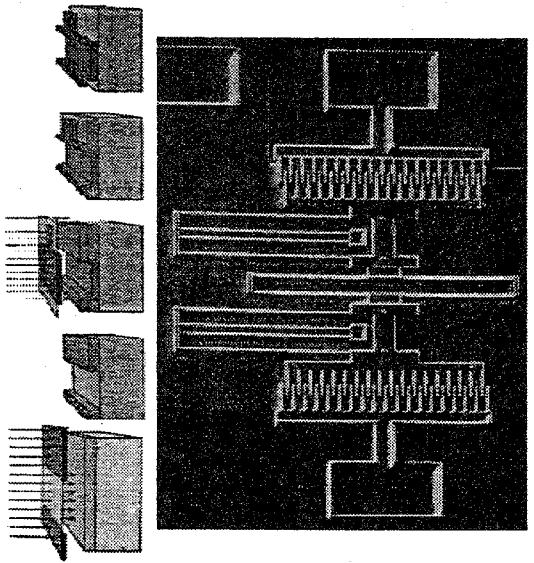
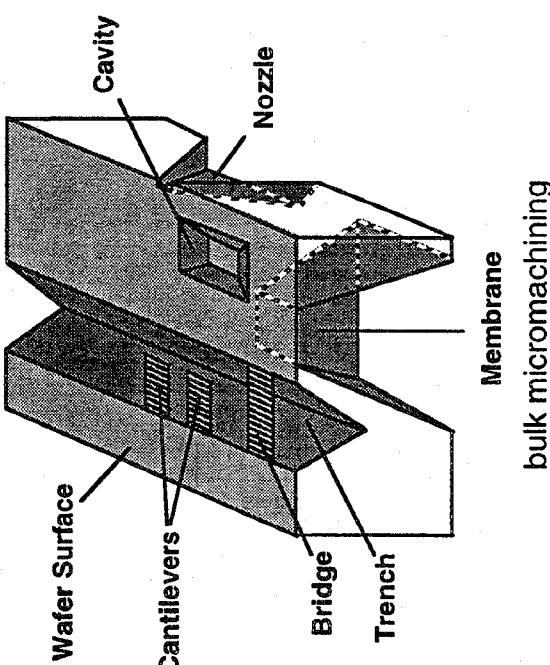
<http://eto.sysplan.com/ETO/MEMS/>

# MEMS



ETO      MEMS

## Common MEMS Fabrication Processes



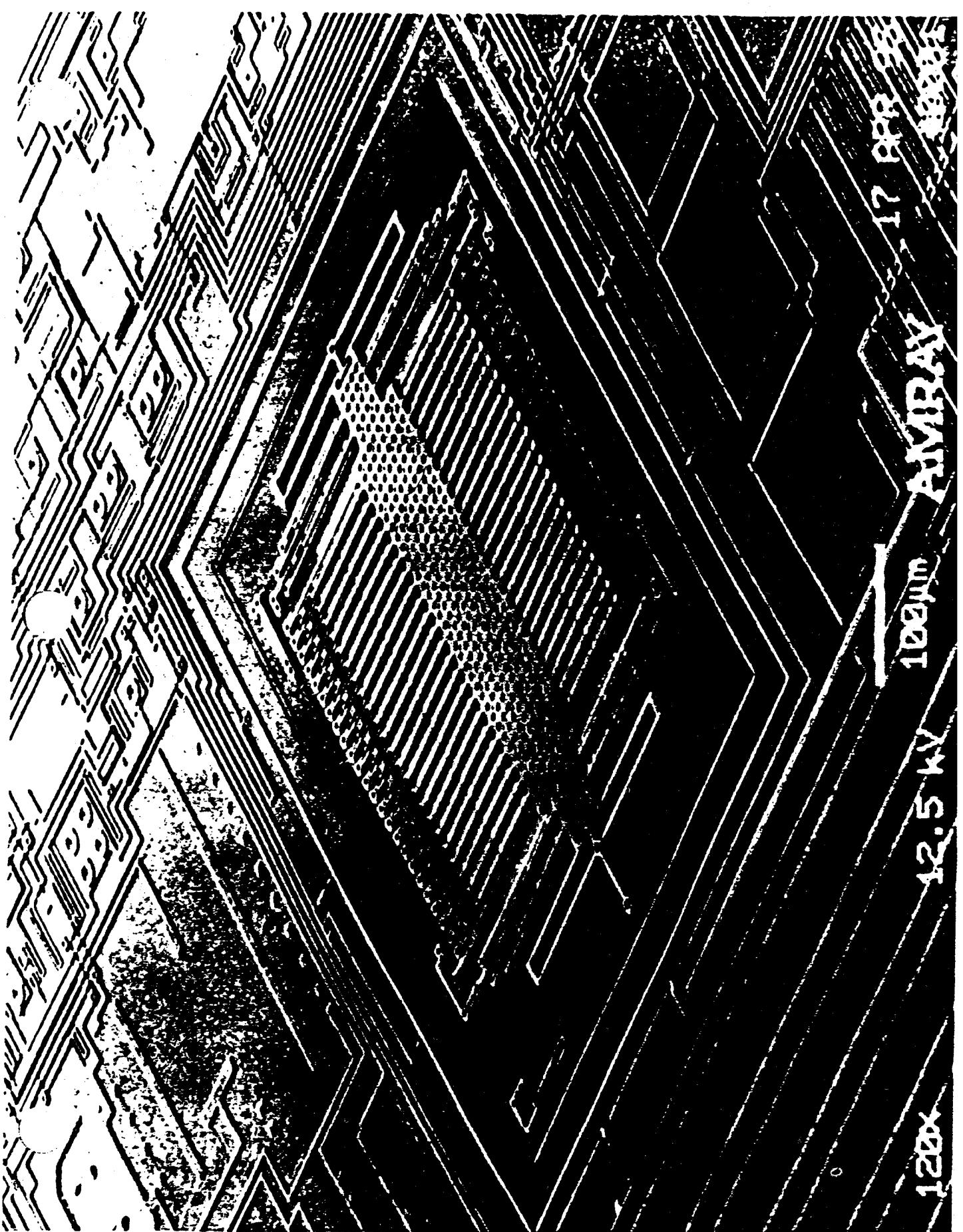
- MEMS merges computation with sensing and actuation to change the way we perceive and control the physical world,
- Is a new way to make both mechanical and electrical components,
- and conveys the advantages of *miniaturization, multiple components, and microelectronics.*
- MEMS mechanical components have dimensions measured in microns and numbers measured from a few to millions
- MEMS makes possible integrated electromechanical systems, and puts these systems on the same cost-performance trajectory of microelectronic systems

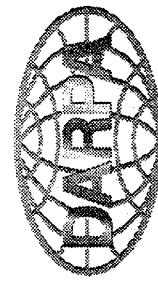
102nm

42.5 K

120x

AMD RA

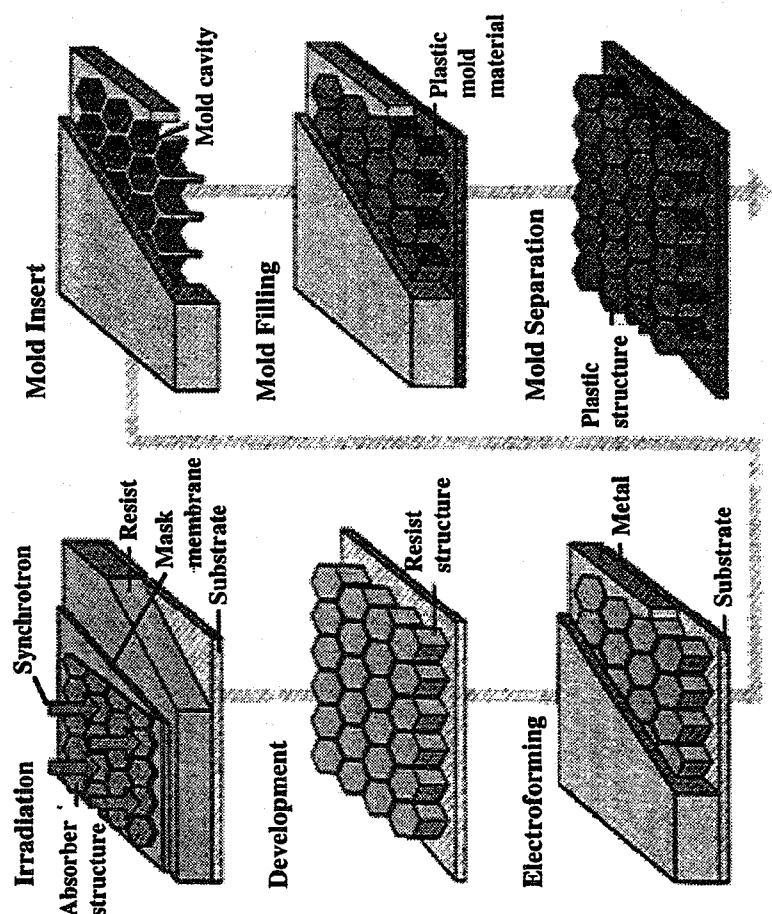




# MEMS Fabrication Technologies

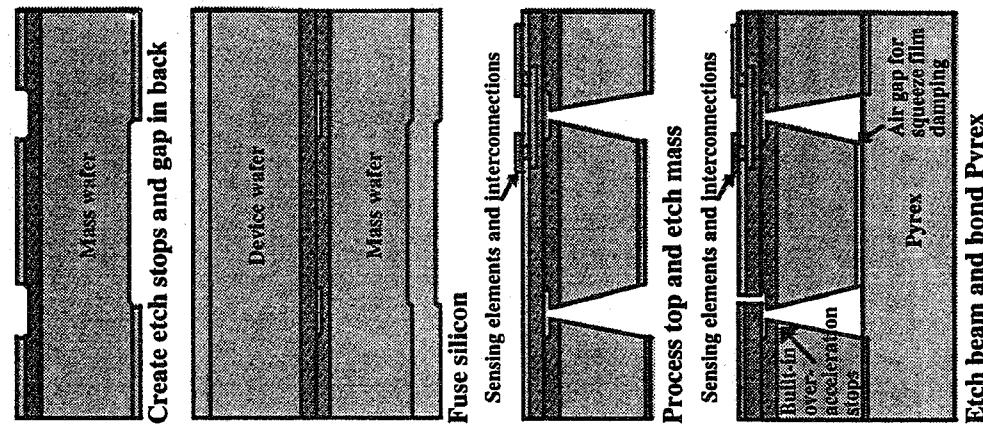
ETO      MEMS

## LIGA\*, Deep UV



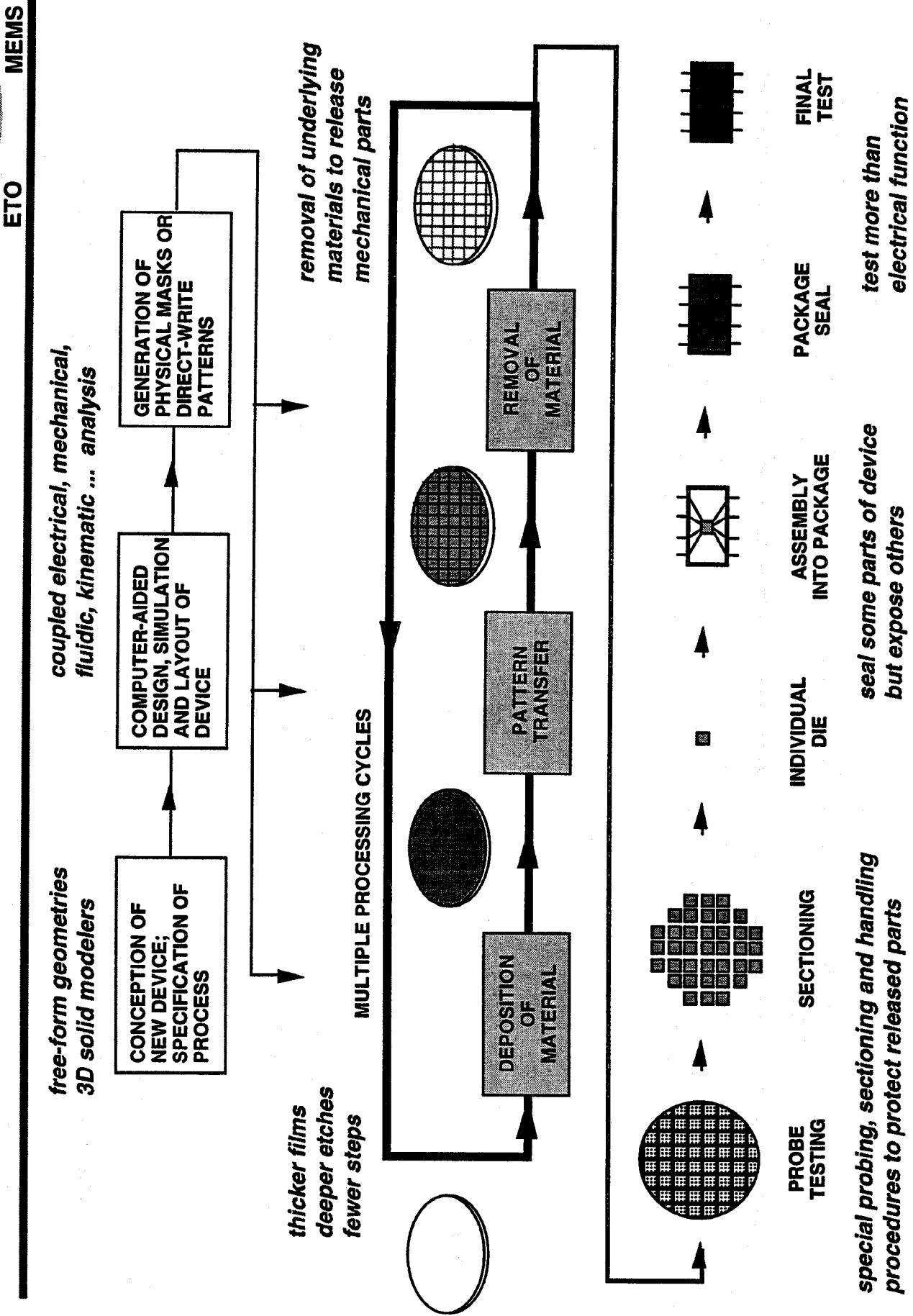
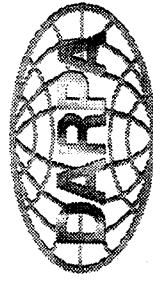
Source: IMM (Mainz Institute for Microtechnology)

## Wafer/Wafer Bonding

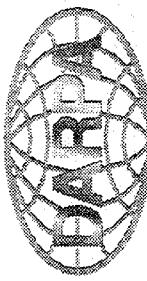


\*Lithographie, Galvanoformung, Abformung

# MEMS Builds on Microelectronics Manufacturing

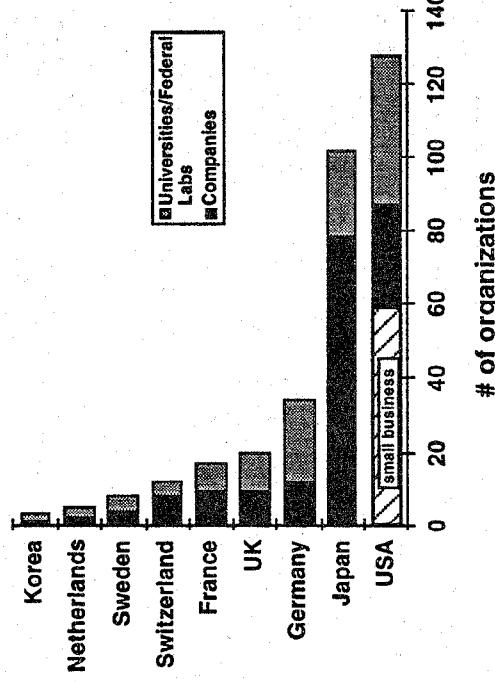
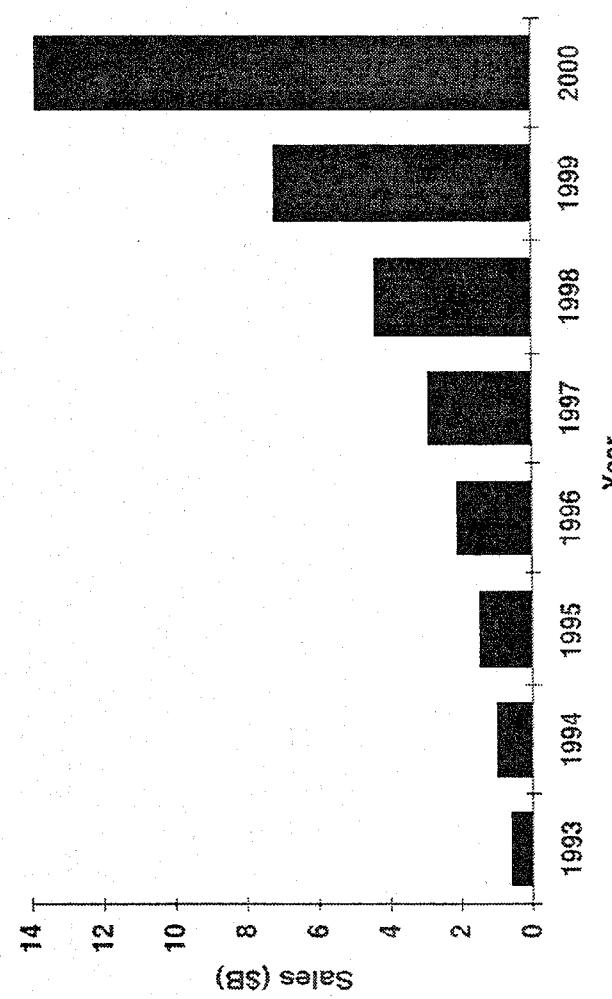


# MEMS Market and Industry Structure



ETO      MEMS

**Projected Growth of Worldwide MEMS Market**



Battelle Institute Study

Industry structure in US, Japan &  
Europe very similar:

manufacturers of

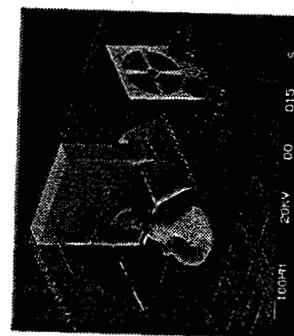
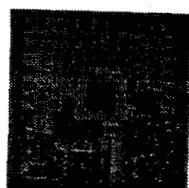
- sensors
  - industrial & residential controls
  - electronic components
  - computer peripherals
  - automotive & aerospace electronics
  - analytical instruments
  - office equipment
- **populated by diverse industries**
  - **not dominated by defense manufacturers**
  - **leverages microelectronics fabrication resources and economies of scale**

# Defense Applications of MEMS

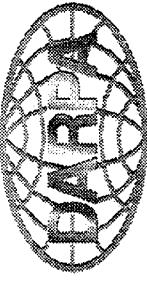


ETO      MEMS

- inertial navigation units on a chip for munitions guidance and personal navigation
- distributed unattended sensors for asset tracking, border control, environmental monitoring, security surveillance, and process control
- integrated fluidic systems for miniature analytical instruments, hydraulic and pneumatic systems, propellant and combustion control
- weapons safing, arming and fuzing 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
- mass data storage devices for storage densities of terabytes per square centimeter
- integrated micro-optomechanical components for identify-friend-or-foe systems, displays and fiber-optic switches/modulators
- active, conformable surfaces for distributed aerodynamic control of aircraft, adaptive optics, and precision parts and material handling



# MEMS Investment Assessment



ETO      MEMS

## MICROELECTROMECHANICAL SYSTEMS

### A DOD DUAL USE TECHNOLOGY INDUSTRIAL ASSESSMENT

Final Report



#### Table of Contents

Introduction

Defense Applications of MEMS

MEMS Market and Industry Structure

Global Investments in MEMS

The DoD Investment Strategy for MEMS

Appendix: MEMS Technology

Reference List

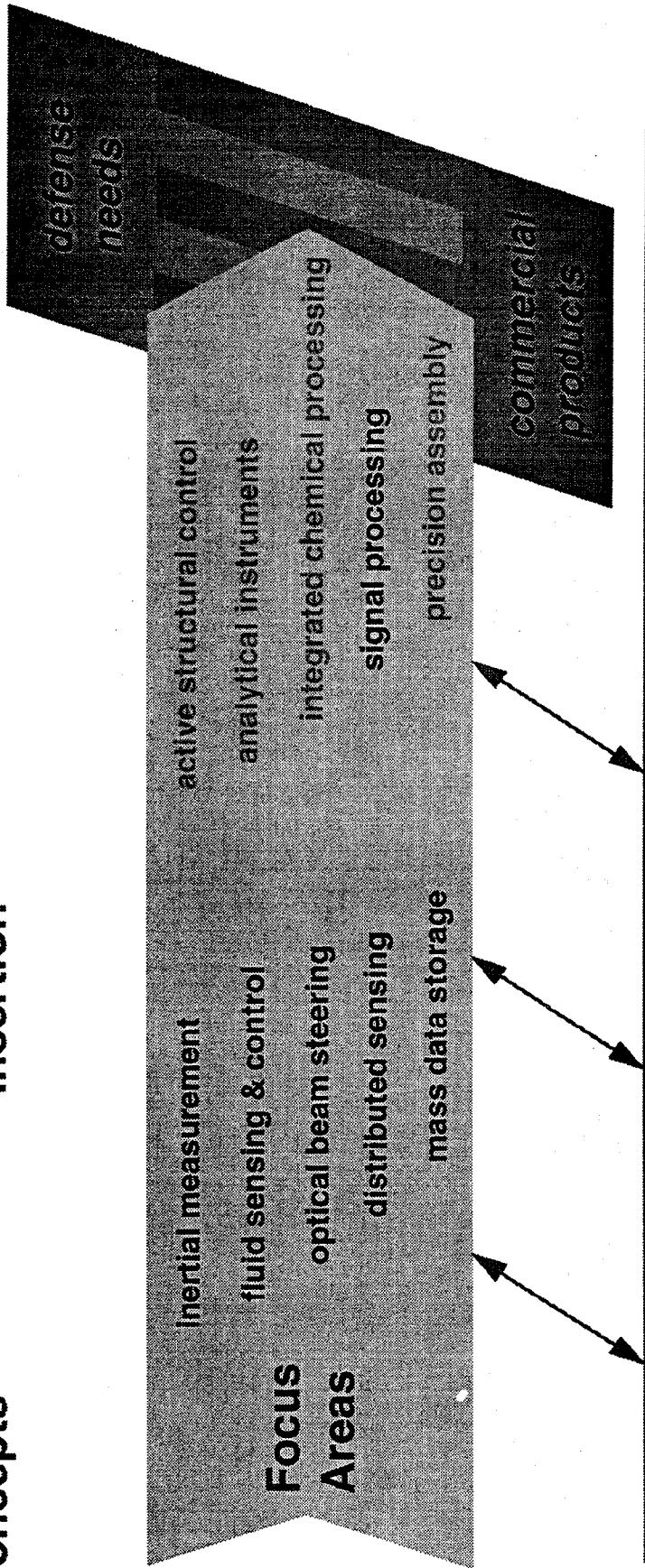
Available from  
<http://www.acq.osd.mil/es/dut/>

DoD-wide MEMS Working Group formed  
First meeting 3/96  
Second meeting scheduled for 9/96

# MEMS Program Objectives and Plan

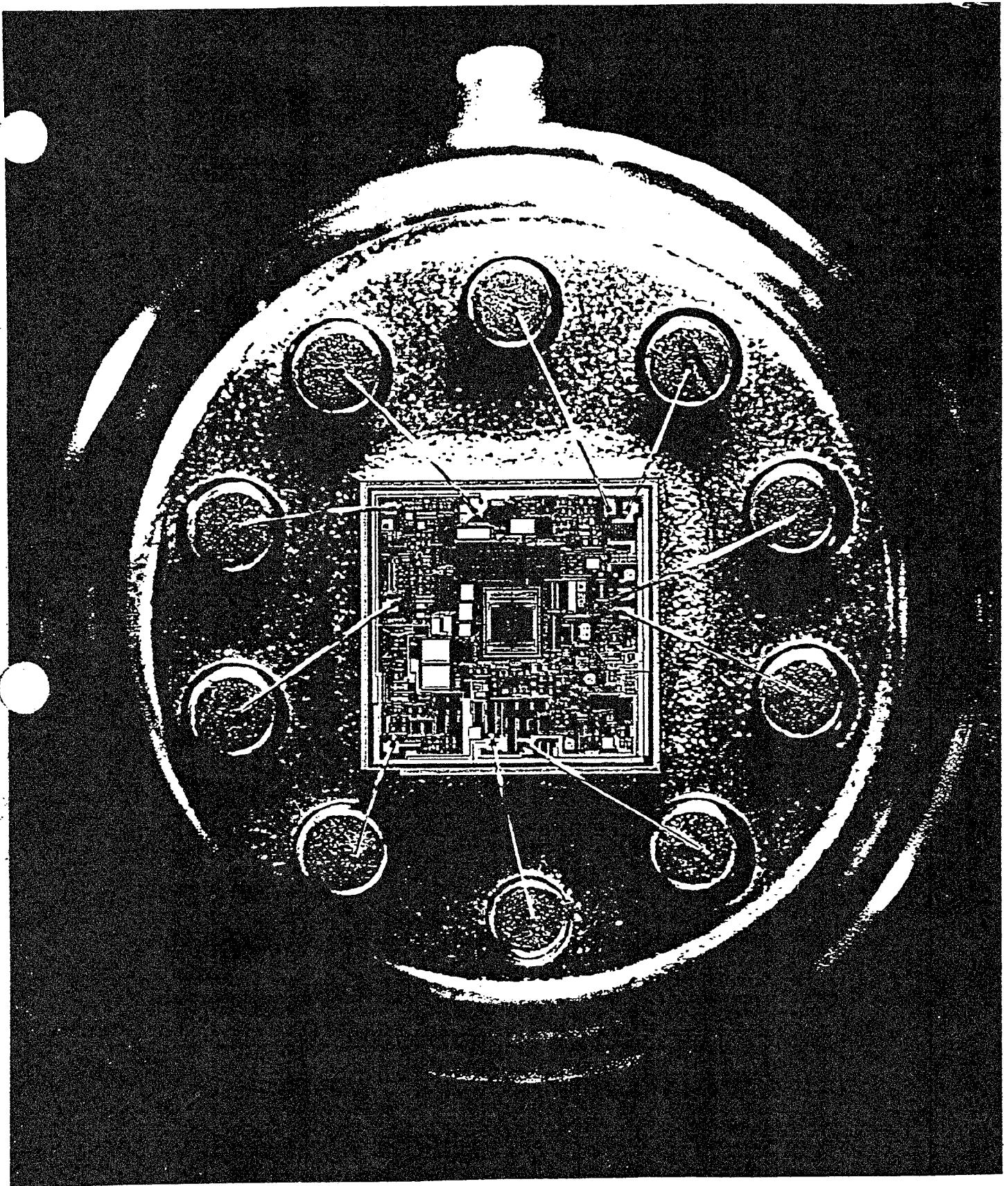
ETO      MEMS

- realize advanced device and process concepts
- accelerate system development and insertion
- catalyze a technology infrastructure



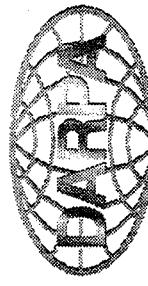
**Support & Access Technologies**

- shared design, fabrication and assembly services
- distributed data and knowledge networks
- manufacturing and packaging equipment
- test, visualization and characterization tools



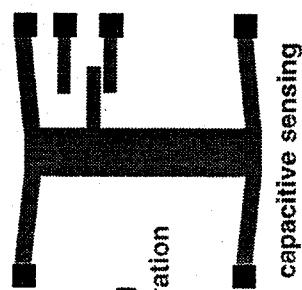
**ADXL05**

# Inertial Measurement Devices on a Chip



ETO MEMS

- single mechanical component with ~ 200 transistors (3  $\mu\text{m}$  design rules)



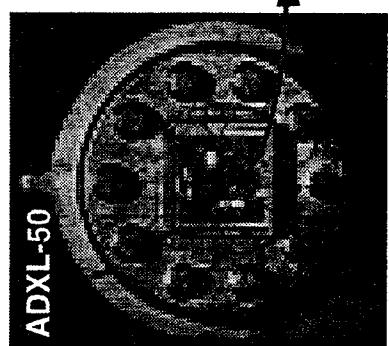
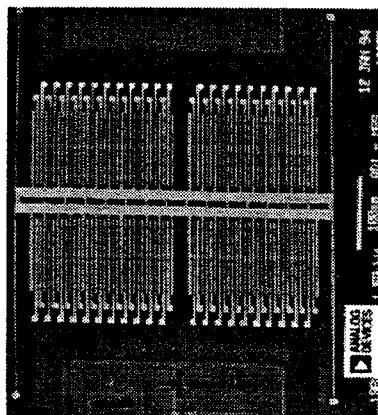
applied  
acceleration

+/- 50 g full scale

DC to 1 kHz

5 volt supply

\$10 in volume



ADXL-181



ADXL-05

## Funding Strategy

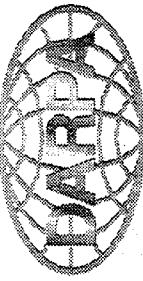
- inertial guidance for munitions
- platform stabilization
- personal and vehicle navigation

## Defense Needs

- intrusion, tamper and motion detection
- condition-based maintenance
- anti-lock braking systems
- side-impact sensors
- air-bag sensors
- suspension control shock sensors

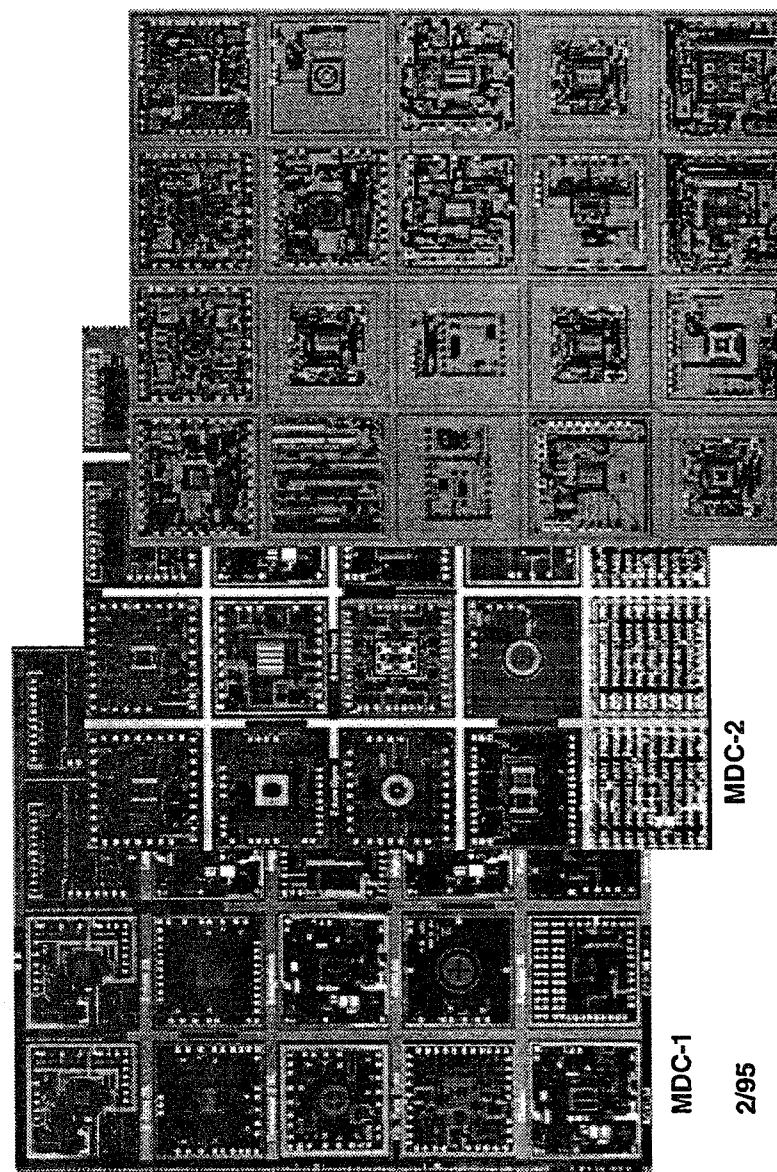
- automobile navigation
- camcorder stabilization

## Commercial Drivers



## Multiple Device Chips (MDCs)

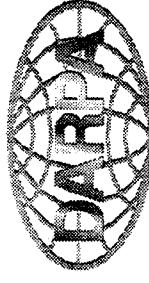
ETO      MEMS



- z-axis accelerometers
- lateral accelerometers
- angular accelerometers
- integrator structures
- vibrational rate gyros
- high-Q EM filters
- lateral oscillators
- flow sensors
- resonant accelerometers
- EEPROMS
  - ADXL05
  - ADXL50
  - ADXL75
- signal processing elements

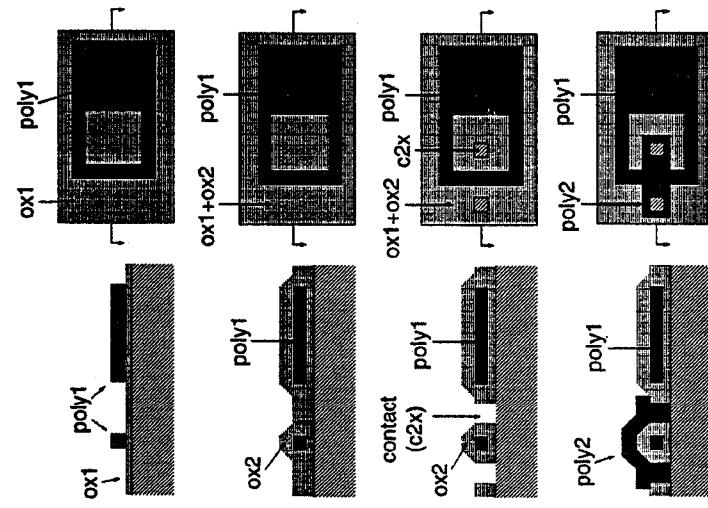
applications in fuzing, safing and arming, guidance/control and navigation,  
smart munitions simulators, machine health shock recorders,  
single- and multi-axis airbags, virtual reality joysticks, and shock protection

# Optical MEMS Components

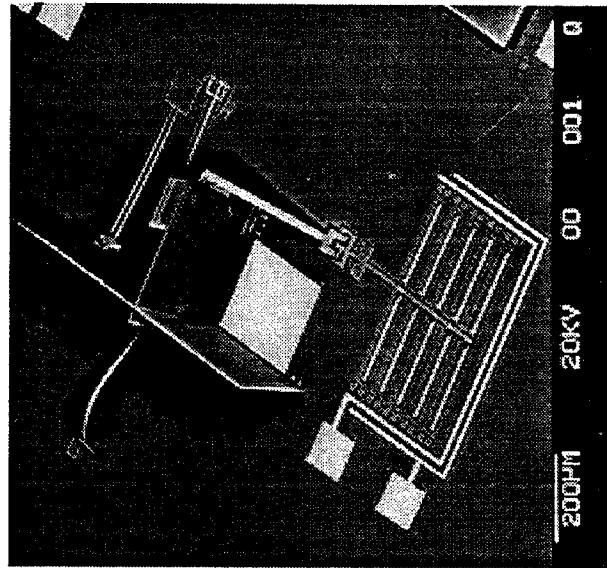


ETO      MEMS

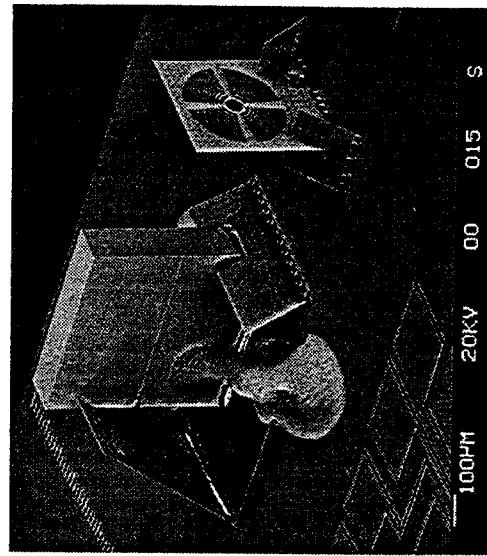
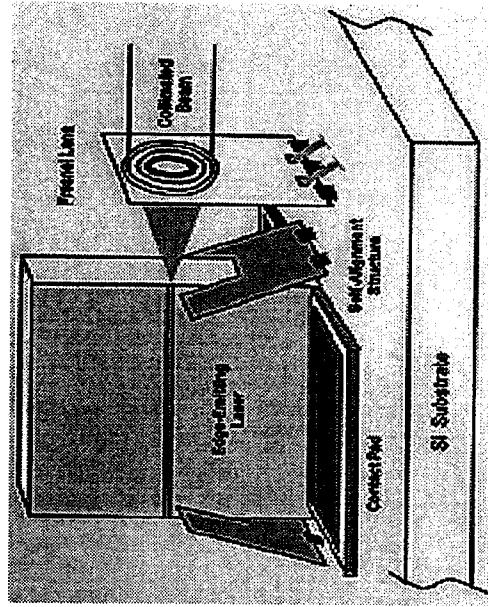
## fabrication sequence



## corner cubes



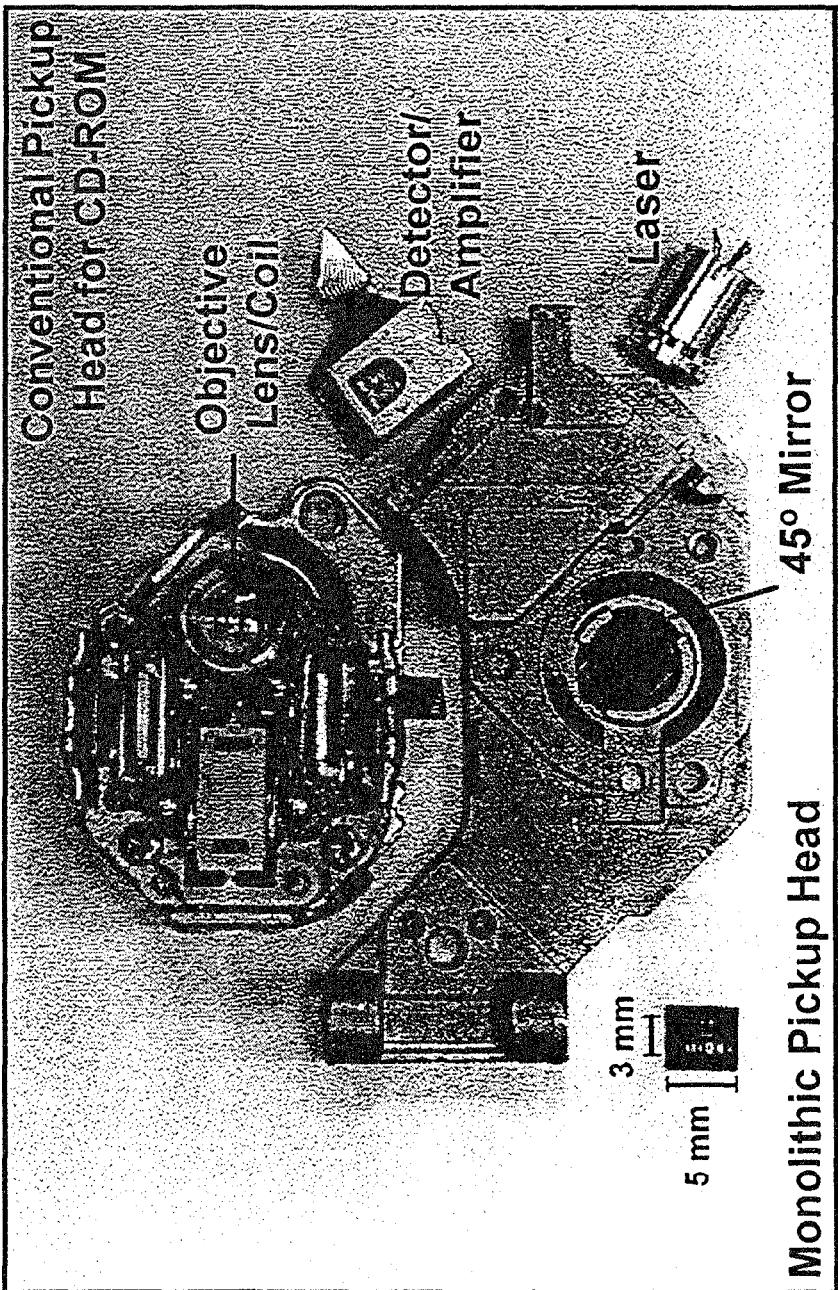
## integrated optical components



- out-of-plane hinged structures fabricated in-plane

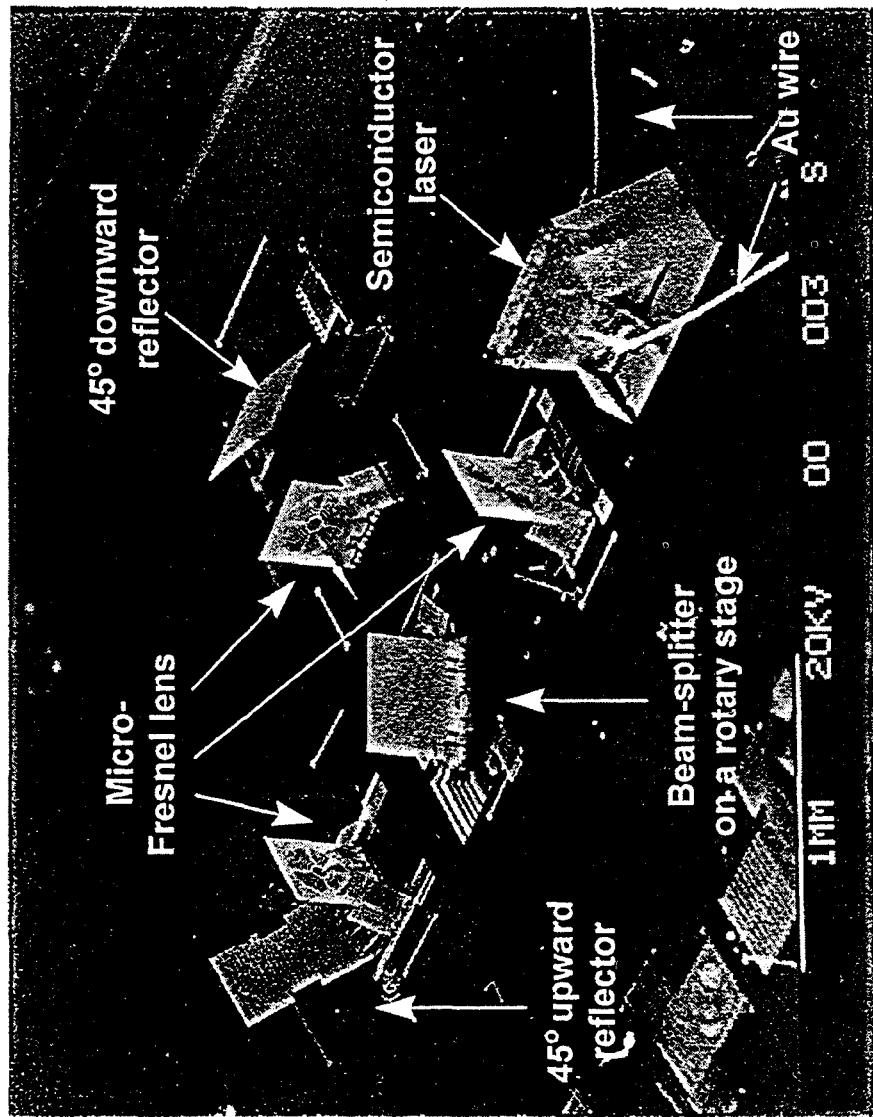
- integrated micro-optomechanical components & assembly structures
  - corner cube reflectors (low-power communications and identify-friend-or-foe)
  - optical interconnects and aligners

# Monolithic Optical Disk Pickup Head by Micromachined Free-Space Micro-Optical Bench



UCLA

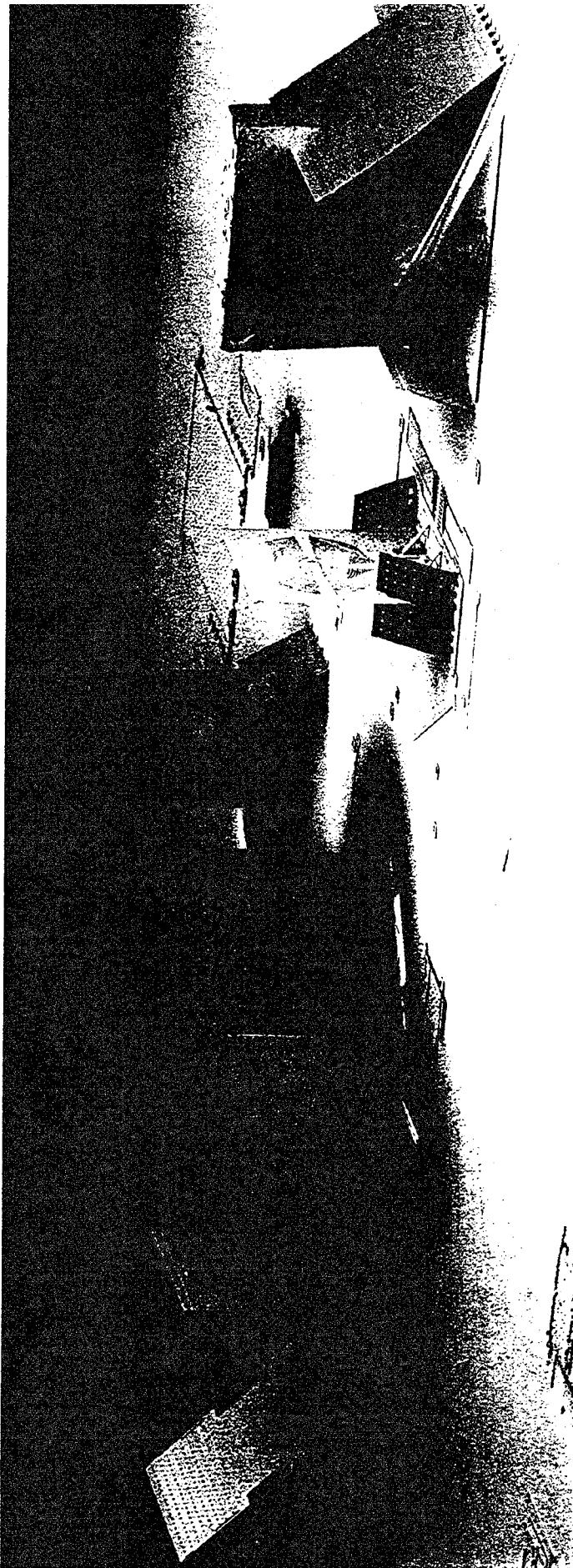
# Monolithically Integrated Free-Space Optical Disk Pickup Head



UCLA

M. Wu, April 1996

# SEM Micrograph of the Monolithic Free-Space Optical Disk Pickup Head



45° Mirror

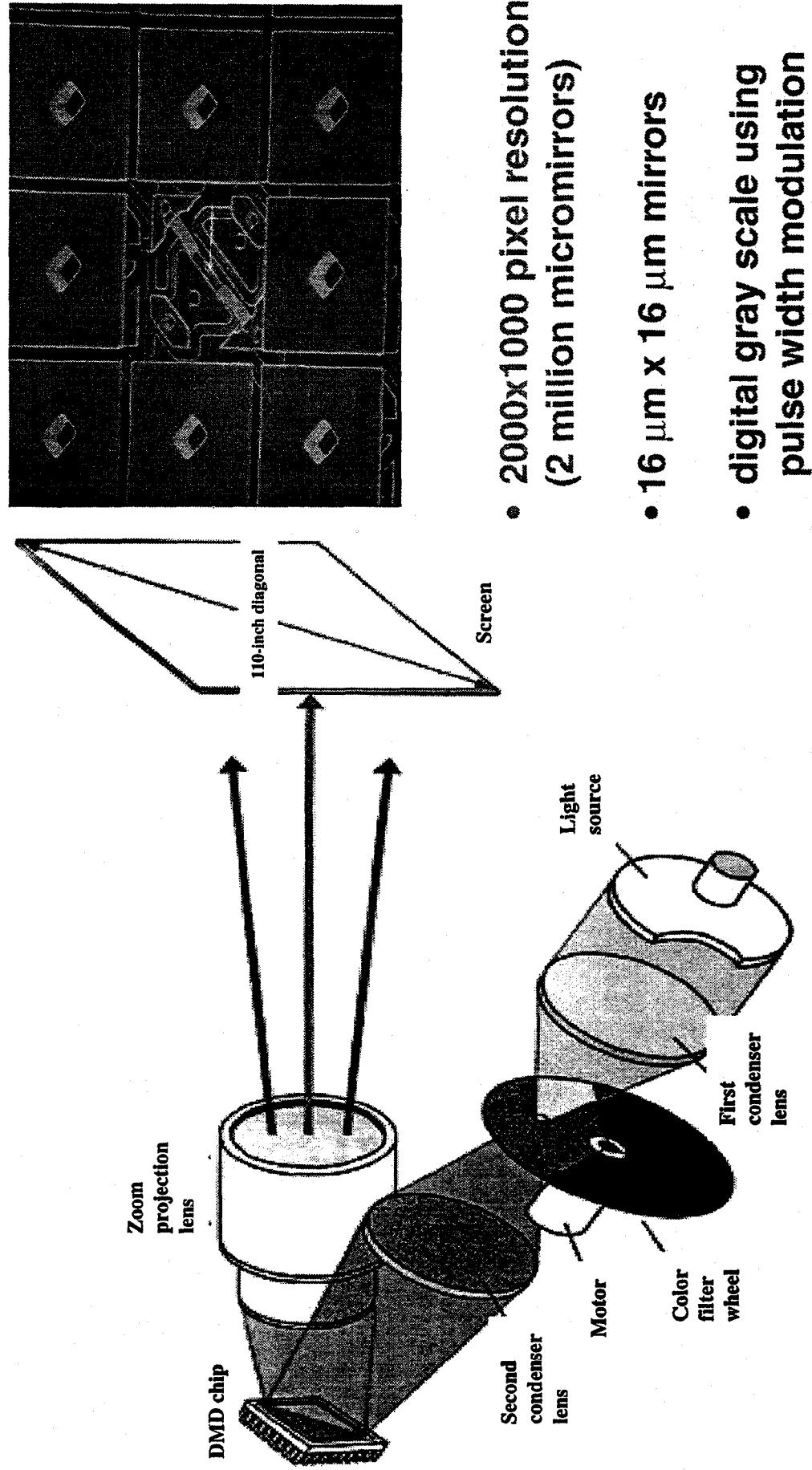
Micro-Fresnel Lenses Semiconductor Laser

Micro-Fresnel Lens Beamsplitter

• Photograph by David Scharf

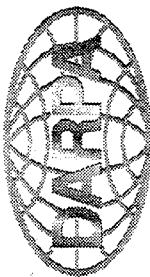
in ucu

# Digital Micromirror Display



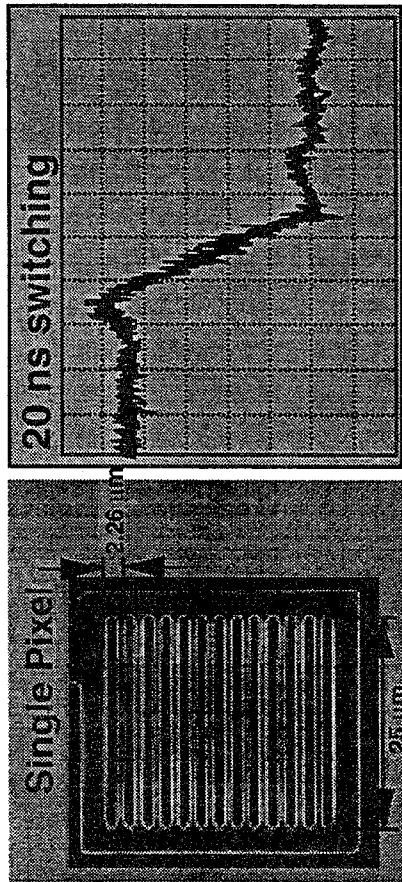
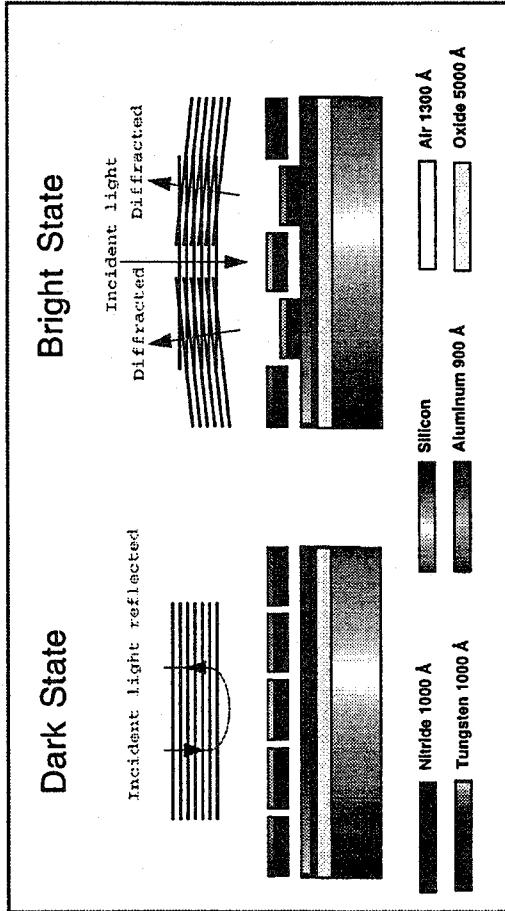
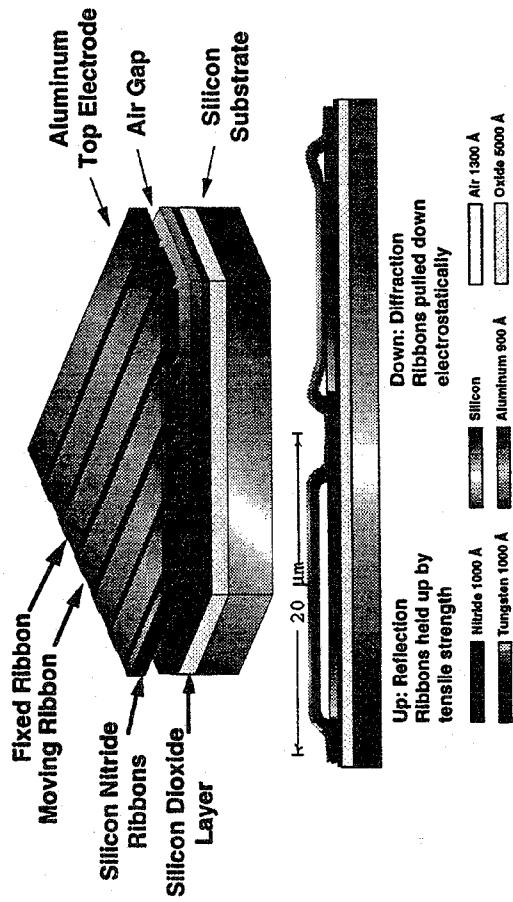
Texas Instruments, Inc.

# Optomechanical Displays



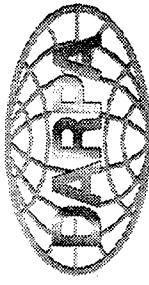
ETO      MEMS

## Grating Light Valves



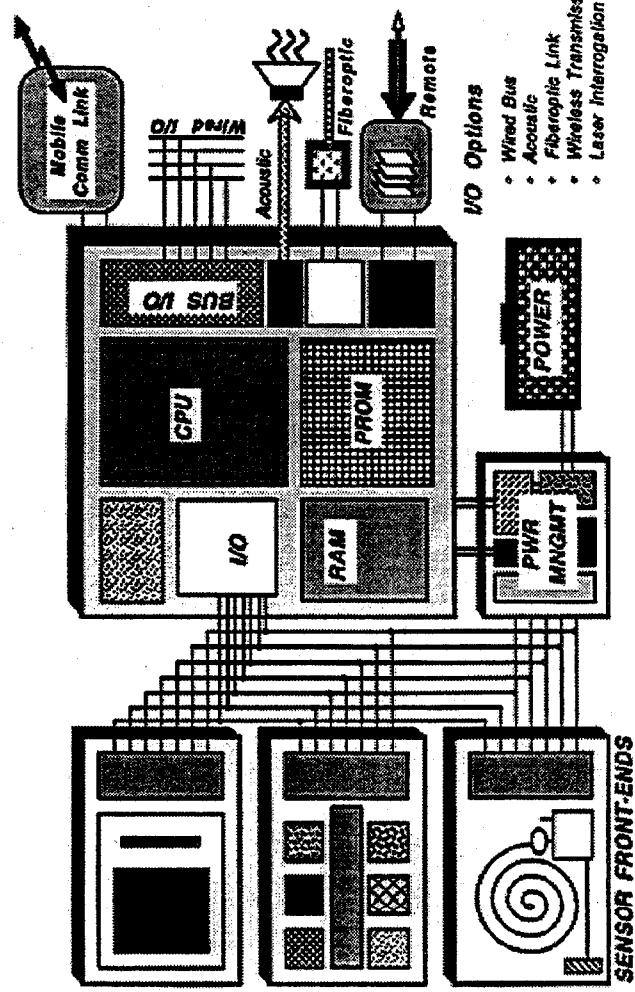
- silicon surface-micromachined,  
deformable grating modulator
- no phosphors or liquid crystals
- low-power, bistable switching
- RGB color capability
- 20 nanosecond switching time
- full motion video
- digital gray scale

# Environmental Monitoring Sensor Cluster



ETO MEMS

wristwatch-sized generic sensor cluster -  
measurement of temperature, barometric pressure, & vibration



## Specific Applications:

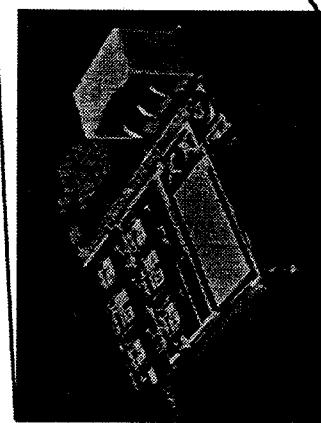
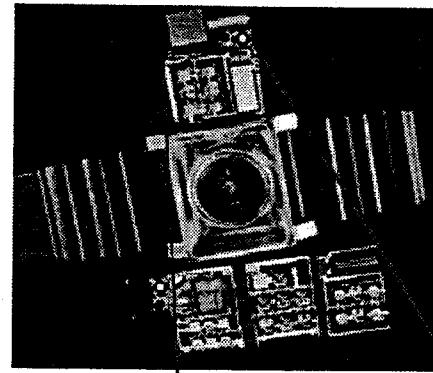
Air Force Phillips Laboratory  
Airport Weather Monitoring

Naval Research Laboratory  
Unmanned Air Vehicle Applications

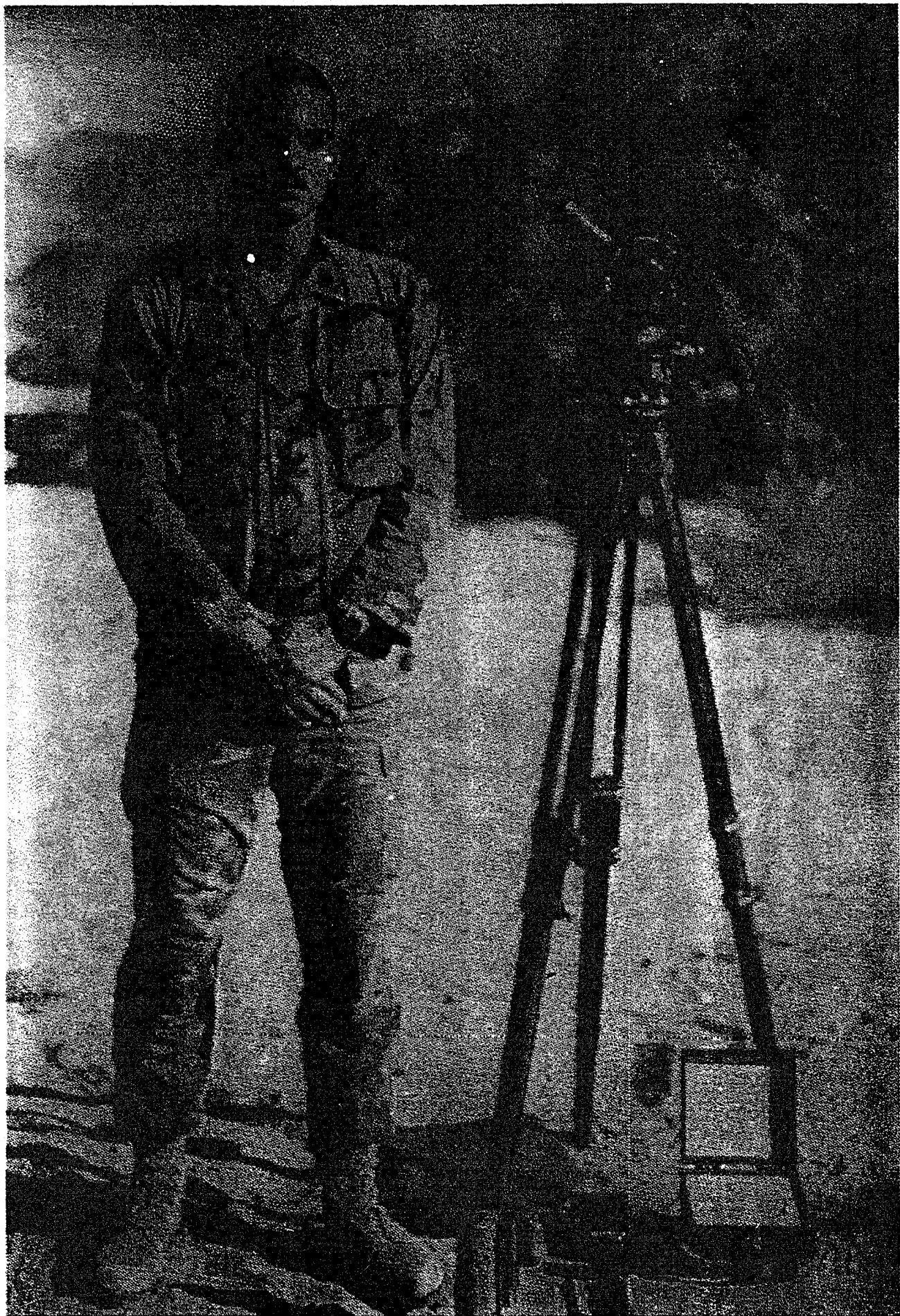
Naval Research Laboratory  
Ocean Buoy-Mounted  
Environmental Sensing

Marine Science Advisor  
Environment/Weather Sensors

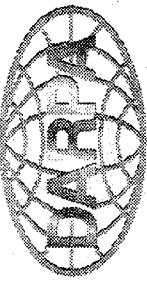
Department of Transportation  
Airport Weather Monitoring



Telemetry Range: 50 ft.  
Average Power Dissipation: <500  $\mu$ W  
Portable Operating Life: 120 days  
Barometric Pressure Range (Abs): 550–850 Torr  
Ambient Temperature Range: -20 to +60° C  
Humidity Measurement Range: 30–90% RH  
Acceleration Range: +/- 2g



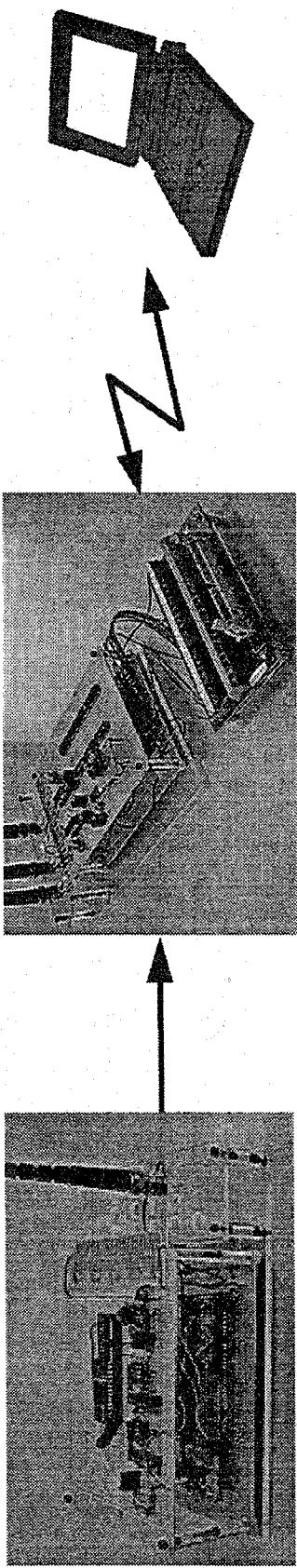




## Low Power Wireless Integrated Microsensors (LWIM)

ETO      MEMS

- micropower, distributed, autonomous, wireless microsensor network with signal processing decision capability
- single-chip RF transceiver integrated with sensors, including optimized, integrated RF components
- low power/low noise analog signal processing based on weak inversion CMOS
- CMOS Integrated Microsensor process for battlefield tactical remote sensors



### *Emerging Applications*

- battlefield awareness**
- situational awareness**
- munitions targeting**
- condition-based maintenance**
- environmental monitoring**
- biomedical monitoring**
- civil safety and security**
- commercial manufacturing**
- transportation**

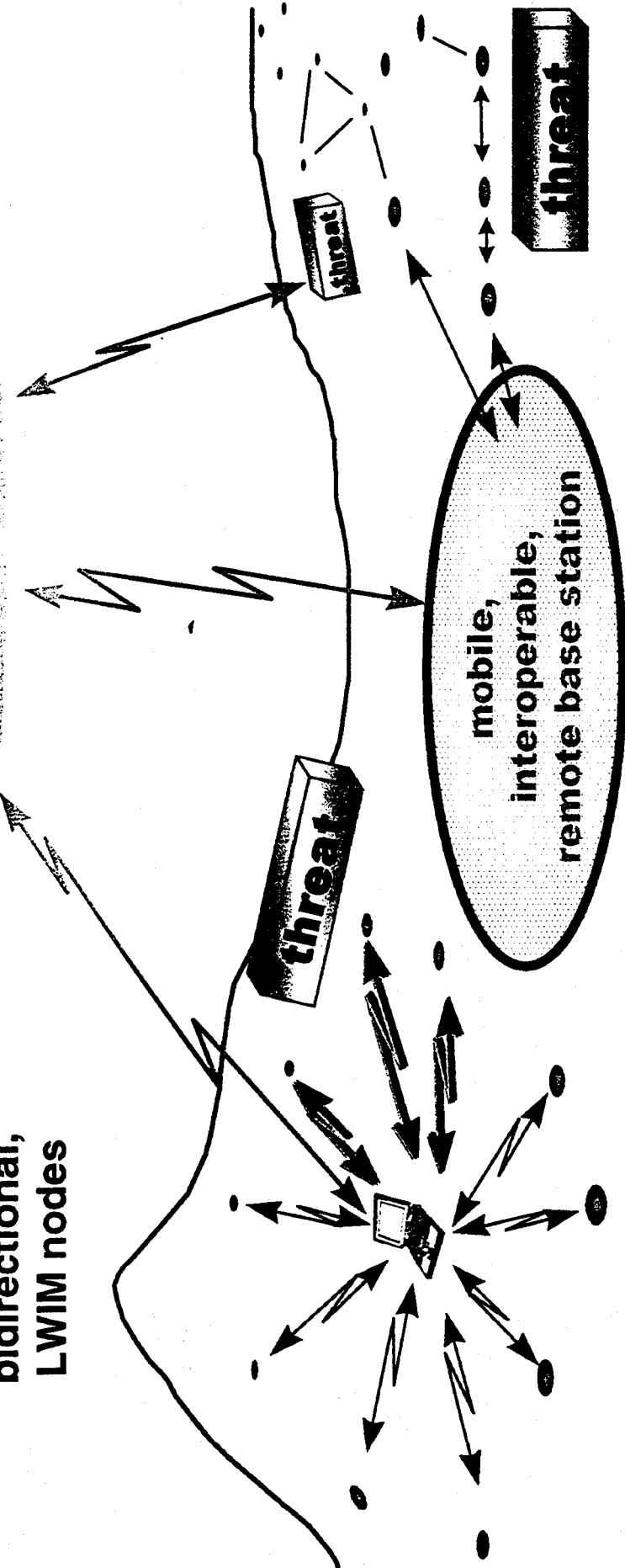
surveillance, perimeter and base security  
detection, identification, tracking  
munitions impact, target **location**  
vehicle, powerplant, transmission, propulsion  
external and internal local and global control  
personnel health status monitor  
residence, commercial, public structures, urban  
precision machining with low cost tools  
VHS, vehicle control

## LOW POWER WIRELESS INTEGRATED MICROSENSORS (LWIM)

DARPA    
**LWIM Intelligent Distributed Nodes:**  
Tactical Remote Sensor Systems

rapidly deployed,  
distributed,  
bidirectional,  
LWIM nodes

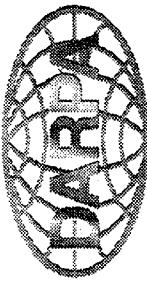
global mobile monitoring



LWIM surveillance  
perimeter

Multiuser LWIM  
reconnaissance network

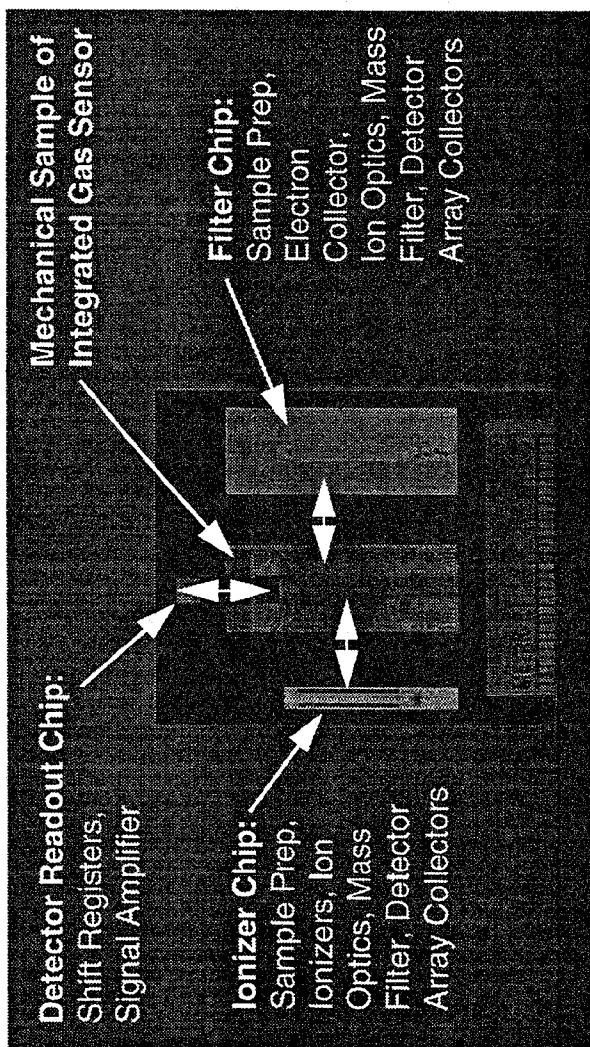
# Mass Spectrograph on a Chip



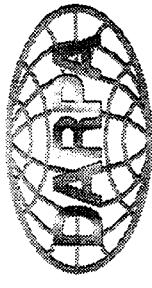
ETO      MEMS

- miniaturization of an ionic mass spectrometer using MEMS fabrication techniques
- combining microelectronics with MEMS geometry yields a gas sensor that is >100 times smaller, lighter & cheaper
- miniaturization takes advantage of detector arrays, high field magnets, mean free path advantage, & solid-state ionizer to build system

Mass Range:	1 to 200 amu
Mass Resolution:	1 amu at 200 amu
Sensitivity:	100 ppm in 10 sec. 1 ppm in 4 min. 0.1 ppm in 4 min. (limited mass range)
Power:	< 0.5 W
Warm-up Time:	< 15 min. 2 sec. from standby
Working Lifetime:	3 to 5 years
Shelf Life:	5 years
Size:	< 170 cm <sup>3</sup>
Weight:	< 300 g



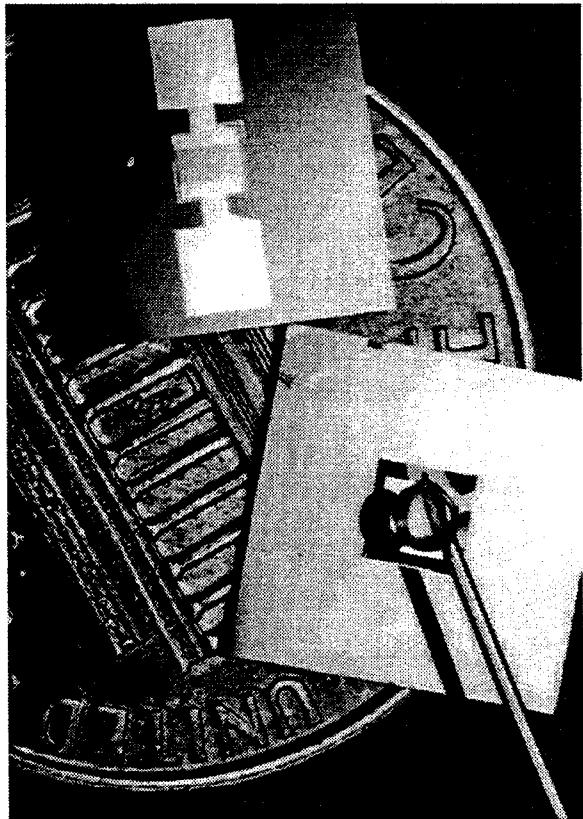
# Miniature DNA-based Analytical Instrumentation



ETO      MEMS

## Miniature Analytical Thermal Cycling Instrument (MATCI)

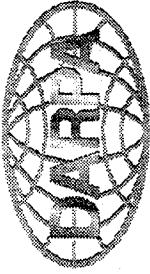
- detection of polymerase chain reaction (PCR)
- low-power operation (average 1.2W per reaction chamber)
- high cycling speed (10x commercial instruments)
- multiplex PCR (8 simultaneous amplicons)
- real-time, CCD-based detection of DNA production
- amplification of viral, human genomic, and pathogenic bacteria targets
- integrated microPCR and microelectrophoresis



- *low-cost, portable, DNA-based, biotechnological & clinical diagnostic instrumentation*

Lawrence Livermore National Laboratory

# Silicon Micro-Disk Arrays for Data Storage

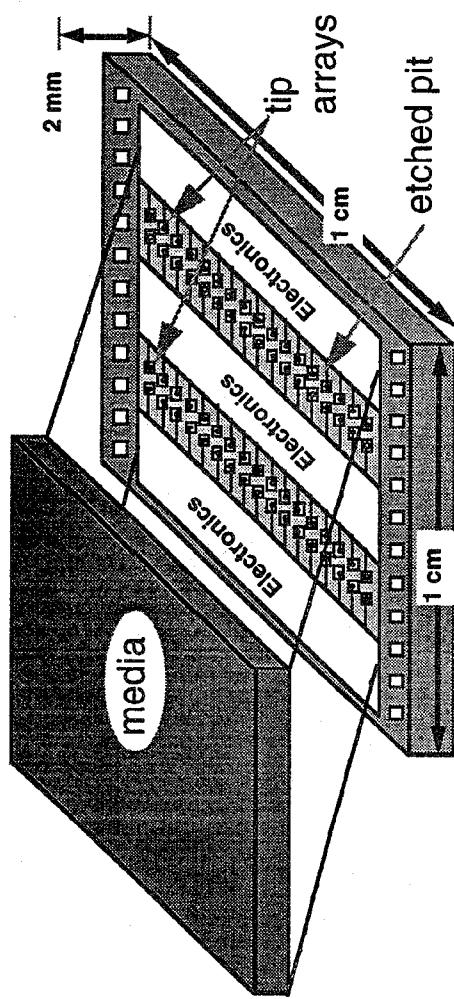


ETO      MEMS

- Store 10GB in 10mm x 10mm x 2mm
  - » lightweight, miniature information retrieval

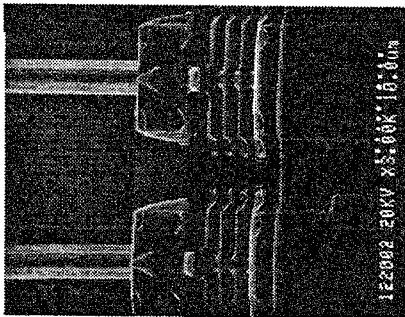
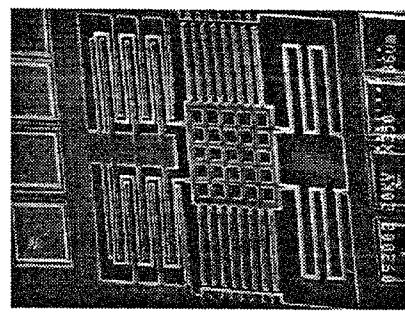
- Write-Once Storage  
using STM Tips

- LARGE Array of Tips
  - » reliability
  - » data rate
  - (parallelism)



- Need VLSI-Style Manufacturing

- » parallel creation
- » integration of electronics & sensors & actuators



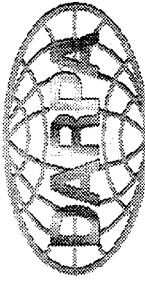
x-y-z microstages with  
standard MOYSIS CMOS

multiple Spindt tips

STM writing to carbon film

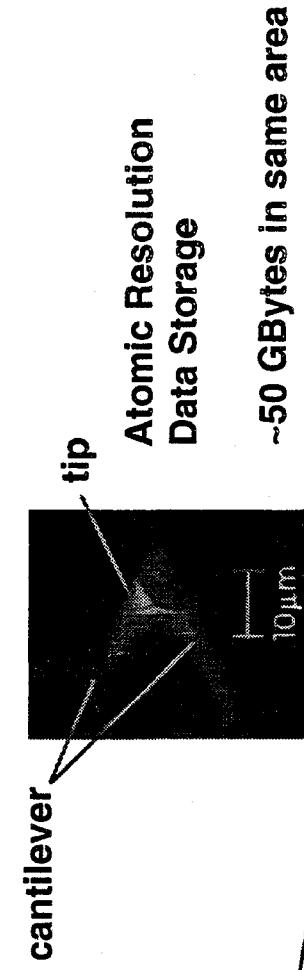
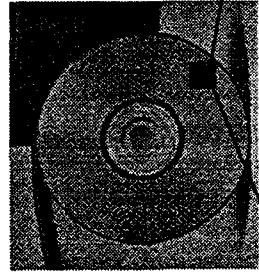
Carnegie Mellon University

# Mass Data Storage

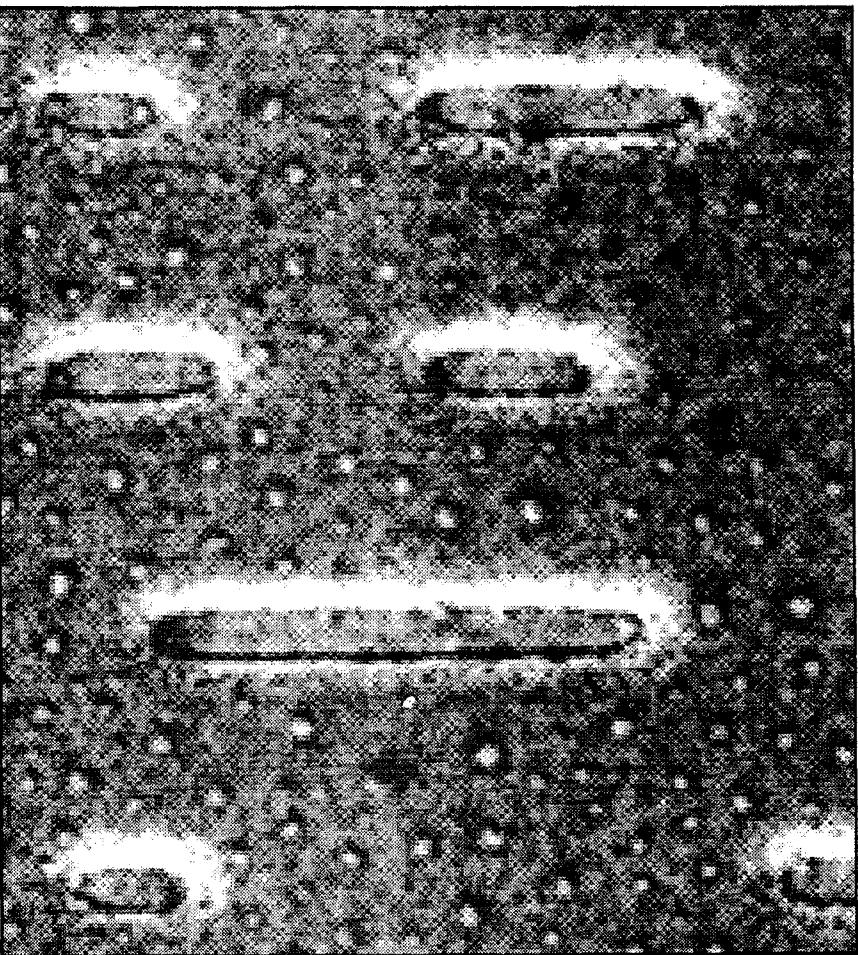


ETO      MEMS

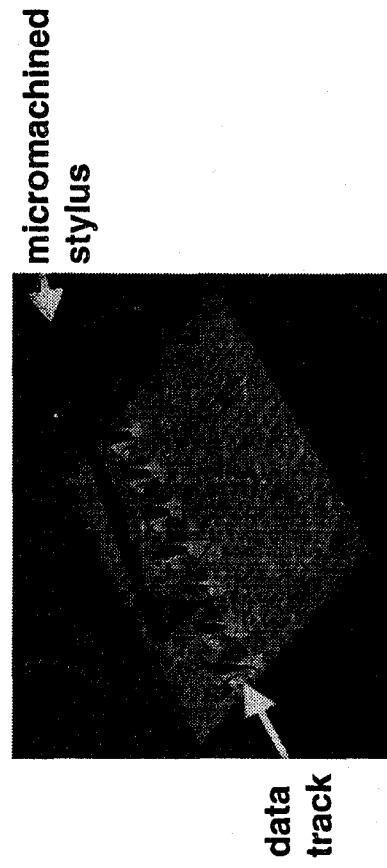
**Compact Disk**  
~620 MBytes in ~23 in<sup>2</sup>



~50 GBytes in same area



micromachined silicon read/write  
tip and cantilever



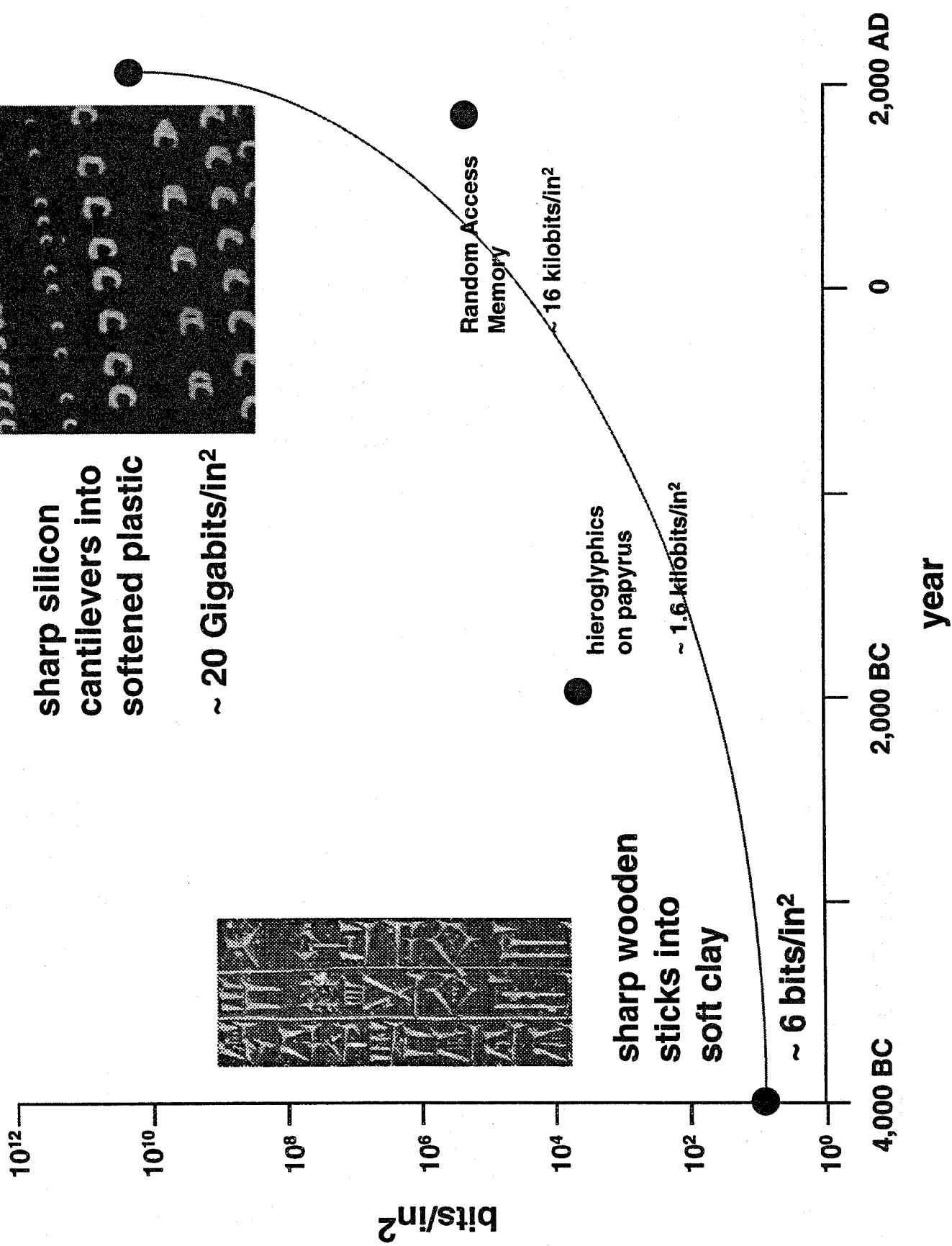
data pits read using AFM techniques



written data pits

IBM

## Back to the future ...

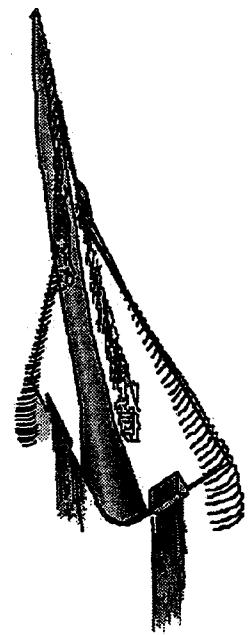


# Active Conformable Surfaces

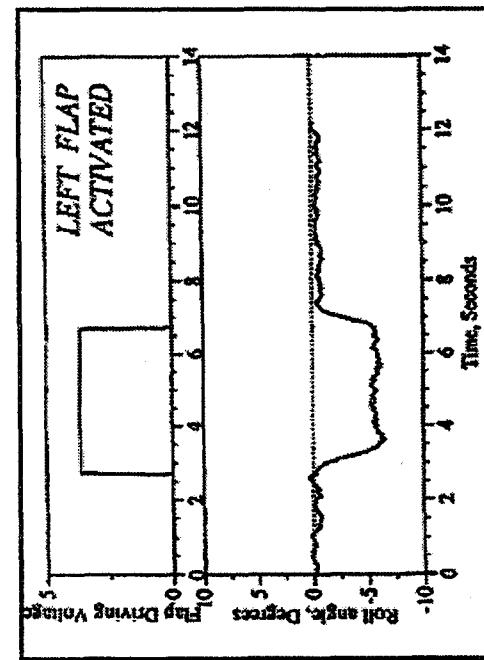
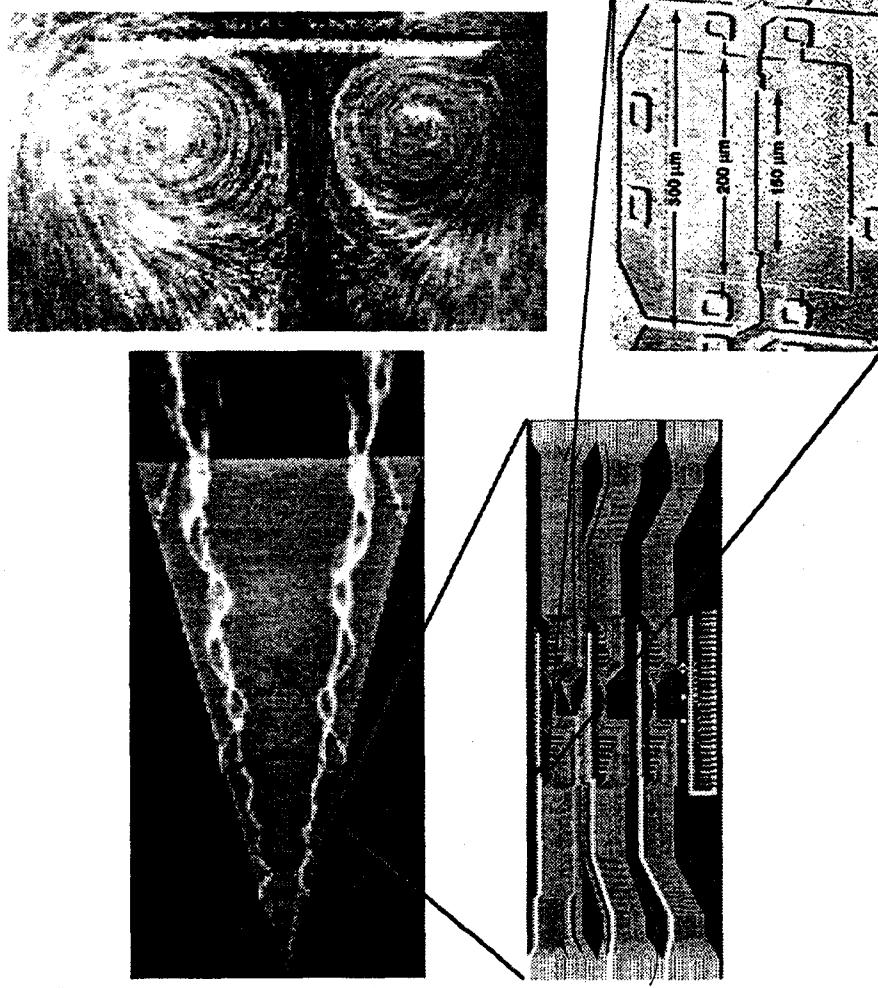


ETO      MEMS

## Advanced Aerodynamic Control



*distributed MEMS sensors  
& actuators control separation  
of leading-edge vortices*



wind tunnel roll measurements

- aircraft and projectiles with no large, discrete control systems
- higher maneuverability, reduced drag

UCLA

# On-Demand Amplified Structural Strength

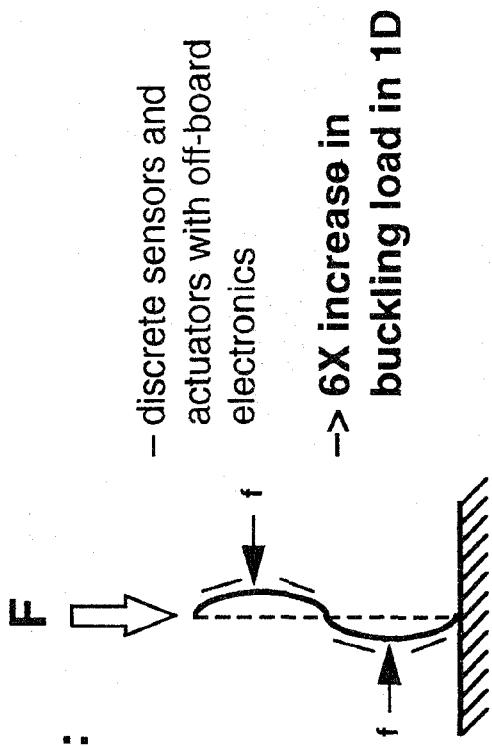
ETO

MEMS

## Active Stabilization of Buckling

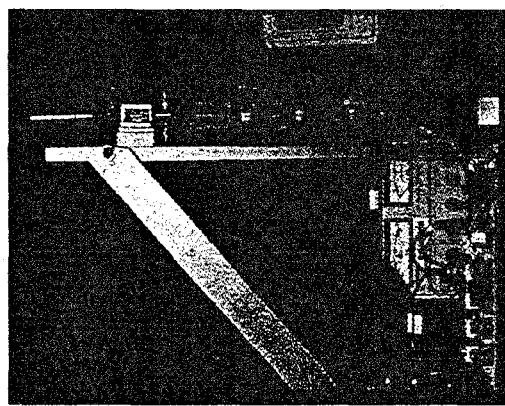
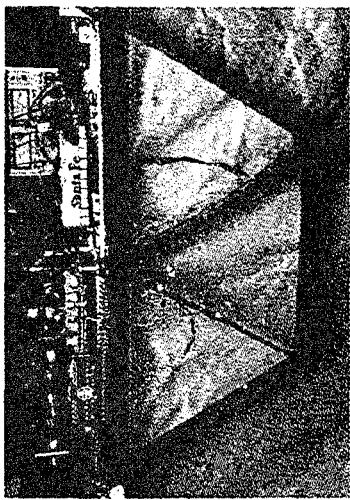
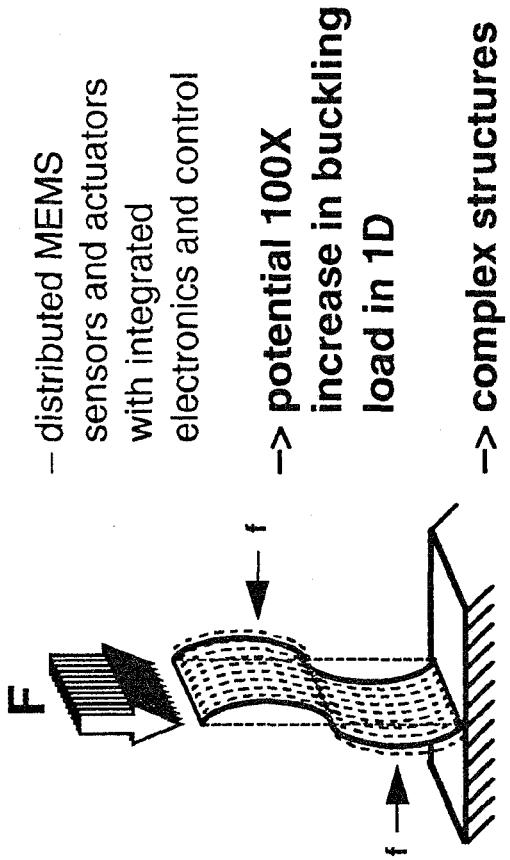
### small control forces yield:

- *large strength gains*
- *reduced metal fatigue*
- *reduced weight*
- *emergency strength*

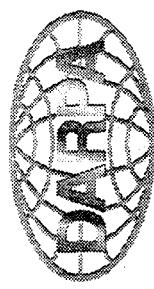


### applications in:

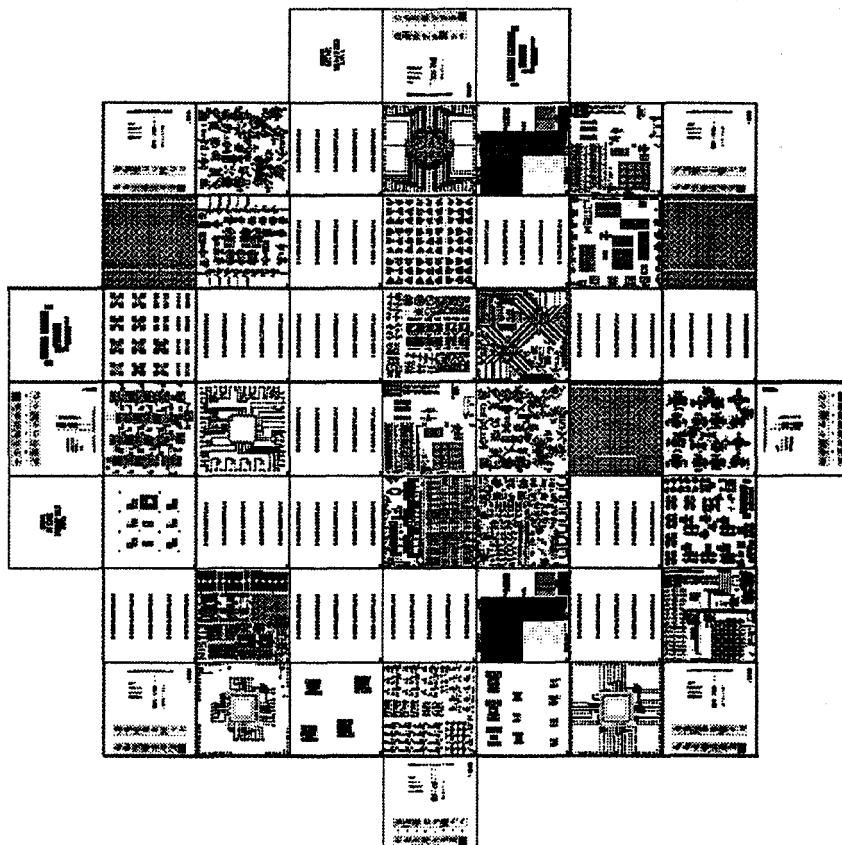
- *aircraft landing gear*
- *jet engine housings*
- *human-portable structures*
- *active armor*
- *ship keels*



# MCNC-DARPA MEMS Multiproject Run



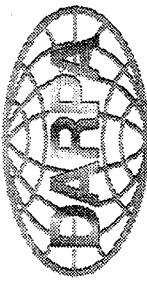
ETO  
MEMS



MUMPs 1.3

MCNC - DARPA MEMS Multiproject Run

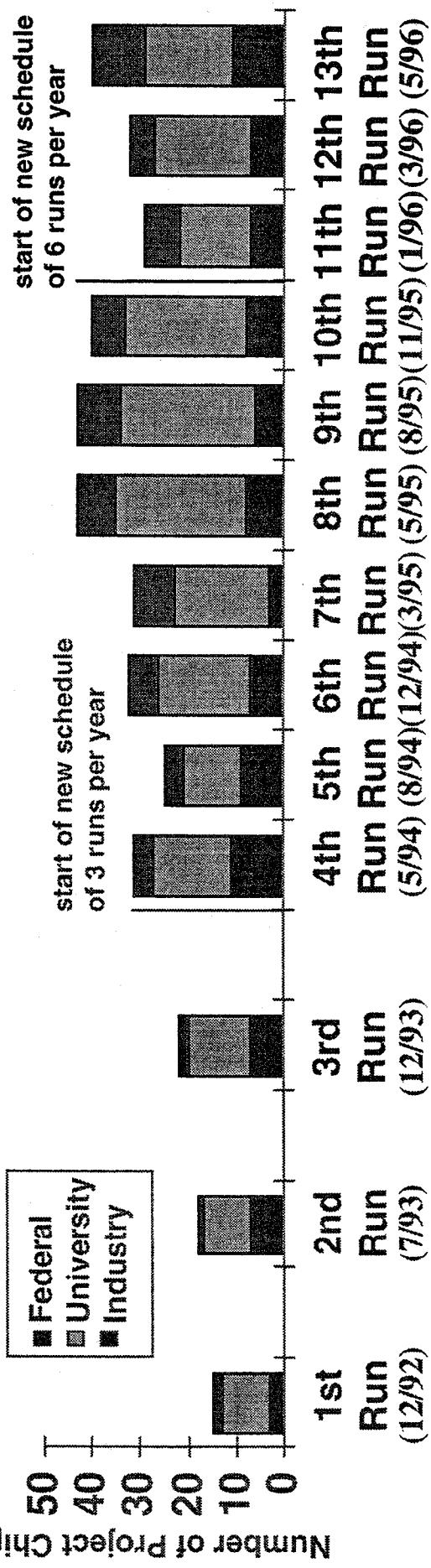
## Multi-User MEMS Projects (MUMPs)



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*Accelerating innovation and commercialization by providing  
MEMS fabrication technologies to multiple, remote users*

\$850 + design → MCNC (10 weeks later) → a dozen  
1 cm x 1 cm MEMS chips with your design fabricated



*30% of users are getting their first access to MEMS technology through MUMPs*

~ 400 projects, 500 users

MCNC

# Electronic Design Aids

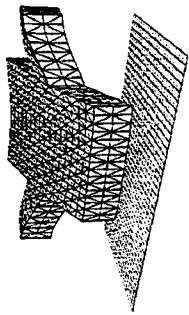


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MEMS

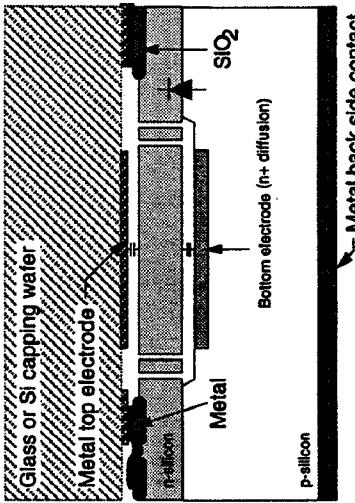
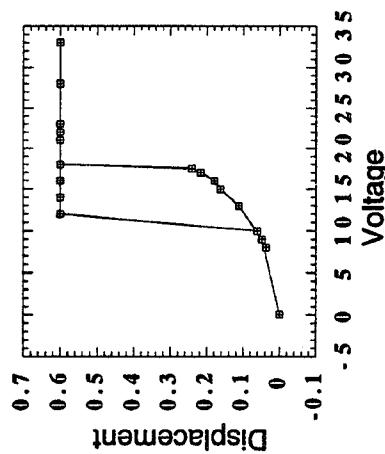
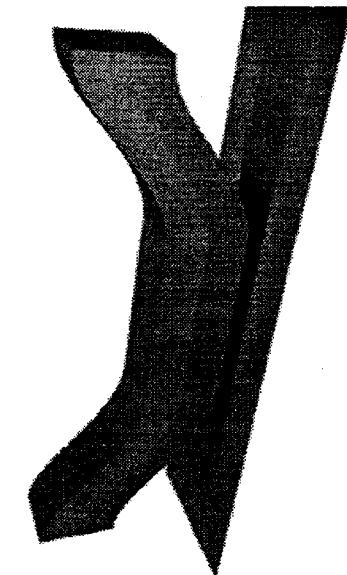
## Microelectromechanical CAD (MEMCAD)

**Goal:** To enable MEMS design in a workstation environment

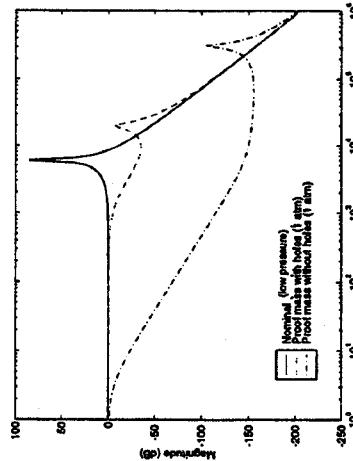
**Approach:** Develop simulators for coupled energy domain, computer-aided macro-models, and test structures for MEMS processes



Simulation of  
electrostatic  
hysteresis for  
relays, valves,  
and actuators



Simulation of  
squeeze-film  
damping of  
accelerometers  
and switches



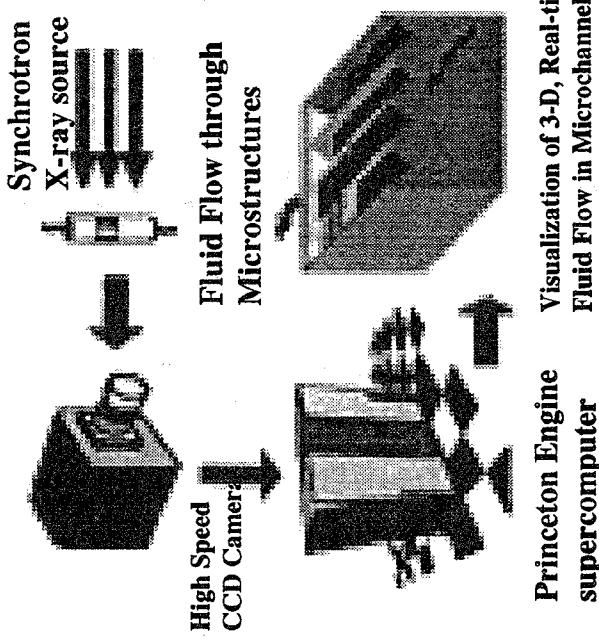
MIT

# MEMS Fluid Flow Analysis

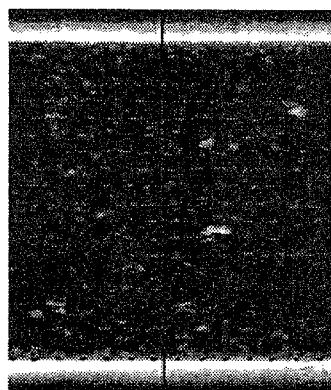
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- quantitative measurements of microscale fluid flows
- validate device operation/function
- enhance computational fluid dynamics (CFD) microscale fluidic modeling

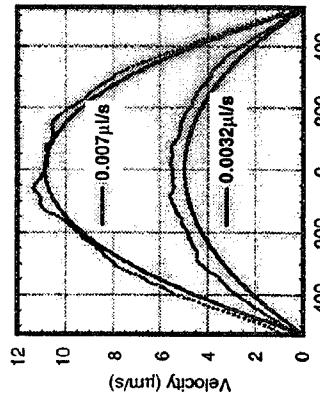
- Extract and analyze flow characteristics



- Extract and analyze flow characteristics



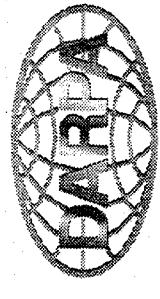
2-D image of emulsion fluid flow  
through cylindrical microstructure



extracted velocity profile  
across channel width

- Generate real-time, 3-D image sequences of fluidic microdevices during operation

# MEMS Technology Trend and Roadmap



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