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Title
Opportunity for High Aspect Ratio Micro-Electro-Magnetic-Mechanical Systems (HAR-MEMMS) at Lawrence Berkeley Laboratory (LBL)

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Opportunities for High Aspect Ratio Micro-Electro-Magnetic-Mechanical Systems (HAR-MEMMS) at Lawrence Berkeley Laboratory

Edited By Steven Hunter

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HAR-MEMMS Workshop at LBL
August 3, 1993

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Workshop Summary

On August 3, 1993 Lawrence Berkeley Laboratory (LBL) hosted a workshop for a national audience on local and national opportunities to develop high-aspect-ratio 3D microstructures in the U.S. The best example of an application for this technology is micro-electro-magnetic-mechanical systems (MEMMS). Locally, this opportunity is based on a unique combination of resources: the newly commissioned Advanced Light Source (ALS) and the Center for X-ray Optics (CXRO) at LBL; the contiguous UC Berkeley campus and its Berkeley Sensor and Actuator Center (BSAC); and the broad industrial base in microfabrication in nearby Silicon Valley. It is generally believed that in the near future applications for micro-electromagnetic mechanical systems sensors and actuators will be ubiquitous and incorporated into all major industries, including aerospace, transportation, data storage, and biomedicine.

This workshop was divided in two parts. In the first half, a variety of speakers from industry, academia and national laboratories expressed their views on the applications and technological challenges of MEMMS devices. Participants also outlined the resources their organization could provide for this national initiative. Copies of each speaker's viewgraphs are reproduced here. In the second half of the day, interested participants met to develop a consensus on the next steps required to implement the vision for a robust HAR-MEMMS capability in the U.S. In order to accomplish this locally, the participants agreed to a four point plan (outlined below). A Participating Research Team (PRT) was formed by BSAC, LBL, Lawrence Livermore National Laboratory (LLNL), Jet Propulsion Laboratory (JPL) and Sandia National Laboratories (SNLL) one week after the conference to initiate activities at the ALS.

Keith Jackson of LBL’s CXRO opened the meeting with a report on the plans for the ALS facility, which is in three phases. First a temporary white light beamline will be built as an extension of the existing "microprobe" beamline and hutch on bending magnet 10.3. This will be available in the first quarter of 1994 for exposures. The PRT will implement this station. In the second phase, two dedicated bending magnet beamlines will be built with planar and aspheric optics to permit research and normal incidence 4" wafer exposures respectively. In the third phase an exposure station based on a "wiggler" will be built, which will have shorter wavelengths to simultaneously expose thick resists in minutes.

Chantal Khan-Malek, also of CXRO, gave a talk introducing the basics of deep-etch x-ray lithography. She showed how the 3-9 KeV x-rays from the ALS or other light source can penetrate deeply in a resist medium and allow the construction of 3D microstructures that can be mass produced. She also outlined the mask requirements and resist processing issues that will be addressed at LBL.

Glen Dahlbacka of LBL’s Industrial Program Development outlined the goals of the industrial program which were to develop stable and reliable processes based on the philosophy that drove the CMOS revolution. He presented cost estimates showing the substantial economies that can be achieved using this massively parallel manufacturing technology. One ALS beamline can potentially manufacture a billion 300µm x 300µm "widgets" per year at an estimated cost of microdollars each.

JPL and LLNL, founding members of the PRT, presented the goals and capabilities of their microfabrication programs. They both have immediate applications in x-ray optics where deep-etch x-ray lithography is uniquely suited. LLNL has committed to make its extensive electroplating and diamond turning facilities available to the program. These
along with the LBL electrochemical capability for research (see Phil Ross's talk) and plating Au, Cu and Ni will provide substantial capability for materials selection. SNLL & JPL also have electroplating capability available. JPL also will make available its e-beam writer for precision mask writing.

Richard Muller of BSAC outlined the fundamentals of micromachines and pointed to the HAR-MEMMS capability to provide higher forces, greater accuracy and increase materials choice in microfabrication. Richard White, also of BSAC, presented a novel and important application for microfabrication with his work in polymerase chain reaction (PCR) chambers. Using microfabricated reaction chambers the PCR reaction can be driven 3-4 times as fast and 100 times more efficiently (wrt energy) than conventional equipment.

Bob Warrington of Louisiana Tech outlined a sister program that is starting at the Louisiana State University Center for Advanced Microstructures and Devices. Close collaboration between the ALS and LTU programs and others in the US will provide rapid development and duplicative infrastructure that will be important in commercialization, since industry will require backup sources for exposure during manufacturing runs.

IBM outlined their interest in this technology for precise head positioning for hard disk drives. IBM also has applications in shock and acceleration detectors to eliminate spurious writing and in track following. The hard disk market is a large potential market for this manufacturing technology.

Cheryl Fragiadakis, Head of the Technology Transfer Department at LBL outlined several mechanisms that industrial users can use to work with LBL. During this discussion, the issue of proprietary work on the ALS was raised. Industry proprietary data will be protected, both physically and intellectually. The ALS is a controlled access facility that will require badges. The mezzanine of the facility has space for locked offices with locked cabinets for secure storage. Proprietary data exchange agreements can be executed between key LBL staff that might assist in proprietary effort and an industrial user. A cost recovery fee is charged for proprietary users that will be $100/hour for the ALS use (light) and appropriate charges for other services as rendered.

The workshop participants met after the presentations and developed a consensus on four key issues. First, that the HAR-MEMMS community needs a bending magnet facility and a wavelength shifting wiggler at the ALS. This equipment will provide a high throughput deep x-ray lithography exposure facility suitable for industrial prototype development, a branchline for the further development of exposure systems, and a white radiation beamline for resist exposure modeling. Later in the program, the wiggler "wavelength shifter" will provide tunable higher energy radiation so that two wavelengths of exposure can be used simultaneously and optimally for the thickness of resist used. Second, that initiating MEMMS activities at LBL now will further establish the U.S. as a serious competitor in this emerging technology. Third, that in addition to the beamlines and exposure systems, there must be a baseline processing capability onsite in mask fabrication, resist processing, and electroplating. This will allow conceptual designs to be fabricated while more advanced processes are being developed. Fourth, that support of research in the areas of electro-plating, x-ray resists, mold release agents, and process modeling must be recognized as a critical part of any MEMMS program.
Opportunities for HAR-MEMMS at LBL

Keith Jackson
Center for X-Ray Optics
LBL

August 3, 1993
Opportunities for High Aspect Ratio Micro Electro Magnetic Mechanical Systems at LBL

Keith H. Jackson
Center for X-ray Optics (CXRO)
Lawrence Berkeley Laboratory

Glen Dahlbacka
Industrial Program Development
Lawrence Berkeley Laboratory
HAR-MEMMS Workshop

LBL Expertise
• "Industrial Needs and Opportunities", Glen Dahlbacka, LBL/Industrial Program Development
• "Deep Etch X-ray Lithography" Chantel Khan-Maleck LBL/CXRO
• "Electrochemistry Research at LBL" Phillip Ross LBL/MSD
• "The Advanced Light Source" Brian Kincaid LBL/AFRD

University Contributions
• "MEMMS activities at the Berkeley Sensors and Actuators Center" Richard Muller, and Diek White
• "The Institute for Micromachining" Robert Warrington La Tech

National Laboratories
• "Space Microsensors and Microinstruments" Tom Kenny JPL
• "MEMMS activities at LLNL" Dine Ciarlo LLNL

Industrial Contributions
• "IBM MEMS Interests" Lengshen Fan IBM
• "Commercial Sensor Applications" Hal Jerman IC Sensors
Benifits Obtainable with Microsystems

- Reduction of energy consumption due to miniaturization.
- Utilization of batch processes to obtain ultrahigh precision.
- Potential for construction of integrated Microsystems
Think Small

Example: Magnetic thin film head industry
Unit: NiFe thin film head (horseshoe magnet)
Size: Approximately 124 μm x 125 μm x 25 μm

| Total Production Worldwide 1992 | 100 million units |
| Total Revenue                  | 1.3 Billion Dollars |
| Total weight of worldwide 1992 production | 3.7lbs |
| Total volume occupied by 1992 production | $2.6 \times 2.6 \times 2.6 = 17.6 \text{ in}^2$ |

"Small is really what matters"
"Machine Shops" of the Future

Future applications of microelectromechanical systems, sensors and actuators will be ubiquitous (seeming to be everywhere at once)

- biomedical
- aerospace
- automotive
- chemical processing
- robotics
- electronics instrumentation and packaging
The LIGA Process

1) Exposure
   - Synchrotron-generated x-rays
   - X-ray mask
   - Polymer material

2) Resist development
   - Plating base

3) Electroplating
   - Electroplated metal

4) Resist removal

5) Injection molding
   - Casting plate
   - Injection holes
   - Plastic casting

6) Demolding
   - Release layer
   - Electroplated metal
   - Master

7) Electroforming

8) Metallic product
   - Copied structure
Prototypes of microproducts produced using deep etch x-ray lithography

- Sensors for the measurement of physical, chemical, and physiological processes.
- Actuators and micromotors
- Microvalves and nozzles
- Micromechanical elements
- Components for integrated optics
- Electrical and Optical microconnectors
- Microfiltration systems
Filters and Nozzles Fabricated with LIGA

Separation nozzle

LIGA microfilter compared to a human hair

Source: KfK, Karlsruhe, Germany
Fiber Optic Flow Sensor

Source: KfK, Karlsruhe, Germany
Structural Accuracy of Deep X-ray Lithography

Source: KfK, Karlsruhe, Germany
A Full LIGA / MEMS Capability in Berkeley

- Optimized x-rays
- Mask writing
- Exposure station and clean room
- Polymer chemistry
- Electroplating
- Industrial access to a national facility

Advanced Light Source

LIGA exposure station

3-9 KeV x-rays

Wiggler (wavelength shifter)

Bending magnet
Elements of LBL Program in HAR-MEMMS

• Phase 0
  - Fast track construction of a DXRL exposure station
    » Enough DXRL processing capabilities to fabricate demonstration structures

• Phase 1
  - Construction of a bending magnet beamline with 3 branchlines
  - Scientific Research programs to support key microstructure technologies
    » Process simulation
    » Electrodeposition
    » Resists for DXRL
    » Injection molding technology
  - DXRL mask fabrication roadmap
  - On site Electro-plating facilities

• Phase 2
  - Construction of a Wiggler beamline
HAR-MEMMS roadmap

Phase 0
   DXRL Demonstration at ALS

Phase 1
   Branchline with high throughput exposure station
   Baseline DXRL process established
   Scientific Research program on HAR-MEMMS begins
   Two additional branchlines installed on bending magnet

Phase 2
   Construction of Wiggler beamline
Program Goals

- Develop a regionally oriented national network with other US light source centers, industry and universities to advance the scientific and technological base in HAR-MEMMS
- Promulgate standardized processes for the community
- Build a research and industrial prototype capability on the ALS
- Help fabricate new microproduct prototypes with our partners
- Define the nature of industrial interactions in production mode
- Prepare a new generation of scientists and engineers to carry this technology to the market
- Advance the state of the art using LBL and Partner capabilities
Bay Area Strengths in MEMS

Berkeley Sensor and Actuator Group
- Devise design
- CAD tools
- Surface micromachining
- Characterization facilities

Established world class researchers

Lawrence Berkeley Laboratory
- Modern synchrotron radiation source
- Sophisticated x-ray optical expertise
- Strength of DOE national lab network

Bay Area Regional Industry
- Biotechnology
- Aerospace
- Electronics
Opportunities for HAR-MEMMS at LBL

Deep X-ray Lithography (DXRL) makes precise microstructures 30-500μm high and is expected to be a high payoff manufacturing technology.

• The Advanced Light Source is an excellent source of 3-10 keV x-rays.
• UCB has a vigorous microelectromechanical research program.
• LBL has an ongoing research program in electroplating polymer science and x-ray optical systems.
• The bay area is a center for commercial microdevice fabrication.

We welcome you to participate in a program to serve the needs of research and industry in this critical new manufacturing technology.
Industrial Needs and Opportunities for HAR-MEMMS at the ALS

Glen Dahlbacka
Technology Transfer Department
LBL

August 3, 1993
INDUSTRIAL NEEDS AND OPPORTUNITIES
FOR
HAR-MEMMS ON THE ALS

BY
GLEN DAHLBACKA
INDUSTRIAL PROGRAM DEVELOPMENT
TECHNOLOGY TRANSFER
LAWRENCE BERKELEY LABORATORY
510-486-5358
AUGUST 3, 1993
STABLE MANUFACTURING

DEMONSTATE EXISTING PROCESS IN RESEARCH MODE-EDUCATE USERS

DEFINE PROCESS CONTROL PARAMETERS

PROVIDE DUPLICATIVE INFRASTRUCTURE

NEW PROCESSES, LIMITS, MODELS

REALISTIC COST MODELING
EXISTING PROCESS

KfK LIGA transferred to Microparts

1st Commercial Product - fiber optics
Several Existing Application Patents

University of Wisconsin - Guckel / SRC

Only US effort to fab devices
Multi-level Processes, Resists, Masks
Patents Pending - WARF non-exclusive
Define Process Parameters

Use CMOS analogy to establish wide use

PMMA resist on plating base on Si wafer

Standard Mask/Pattern - start with 4” format

Compatible exposure hardware - Jenoptiks?

Publish Electrochemical processes/conditions
Provide Standard Infrastructure

3-4 Regional Centers to Start

Common beamlines, filters, optics

Common Resist Process and Electrochemistry

Common Exposure Hardware

Common "Rules of Engagement"
New Process Development

Forming technology - Polymers/Sprays/Molds

Expanded Electrochemistry options

Cost effective mask fabrication/12” wafers

CAD/CAM design rules & software

MOSIS like prototype foundries

BAA/SBIR STIMULATION OF MARKET
Cost Estimate for Ind. Beamline

4" wafer, full normal incidence exposure

Mask - Diamond film, 4-10 µm Au

Exposure time - 11 min - 100 µm resist @ 2:1
40 min - 500 µm resist @ 2:1

Use LBL costs for Electrochem = Resist

Plate 1-2 µm/min in Ni Bath
100μm process costs @ 4 wf/hr

$5000 for 4” mask
$85/hour resist application - $200/wafer
$250/hour ALS/beamline - $62.50/wafer
$85/hour Electroplating - $25.00/wafer
Budget for Diamond Turning - $50.00/wafer

$100/hr Process Monitor - $25.00/wafer
  $5000 fixed, $362.50 operating

70% wafer coverage - 17 cm²
9 dies/cm² - 153 dies/wafer
9 widgets/mm² - 137,700 widgets/wafer
## Astrophysical $ estimate

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<td>3.0e-5</td>
<td>2.7e-6</td>
</tr>
</tbody>
</table>

1 ALS beamline = 6000 wafers/year

ASSEMBLY & BATTERIES NOT INCLUDED
Deep Etch X-Ray Lithography
Chantal Kahn Malek
Center for X-Ray Optics
LBL

August 3, 1993
INTRODUCTION TO DEEP ETCH LITHOGRAPHY FOR 3-D MICROFABRICATION

Chantal KHAN MALEK

CENTER FOR X-RAY OPTICS

LAWRENCE BERKELEY LABORATORY
AN EXAMPLE OF A MICROFABRICATION PROCESS IN 3-D: LIGA

LIGA: Lithographie
     Galvanoplastie
     Abformung: Molding

initially developed (early 80s)
in the Nuclear Research Center (KfK), Karlsruhe, Germany

• depth and versatility of conventional machining techniques
• resolution and accuracy of semiconductor processes
LIGA PRODUCTS

- Manufacture of high aspect ratio microstructures
  - Structural height: 100s μm
  - Minimum feature size in the micron range
  - Submicron tolerance
  - Large variety of shapes
  - Large variety of materials
    » Metals
    » Plastics
    » Ceramics
    » Glass

- Mass production
LIGA = SERIES OF STEPS

- DEEP ETCH LITHOGRAPHY
  » Resist template formation

- BASIC REPLICATION STEPS
  - Electroplating
  - Plastic molding / Injection molding
    » Copies of primary template
The LIGA Fabrication Process

- Synchrotron radiation
  ALS (3–9 keV)
- Resist development
- Electroforming
- Resist removal
- Plastic molding
- Final part

Labels:
- X-ray mask
- X-ray resist
- Substrate
- Unexposed resist
- Galvanoic metal
- Mold support
- Plastic material
SOURCE REQUIREMENTS FOR DEEP ETCH LITHOGRAPHY

- **Short wavelength**
  - Uniform energy deposition with depth into resist 1.4 - 5 Å (3 to 9 keV)

- **High flux**
  - ALS
    - Bend magnet: 0.4 W/cm² at 50 m for 3 - 9 keV

- **Collimation**
  - Good replication quality
    - 1 mrad => 0.1 μm mm⁻¹/10 keV
Maximum Structure Height in FMFBA as a Function of Wavelength

Surface dose / bottom dose = 5:1
Photon Flux at the ALS Bend Magnet for Deep Etch Lithography

ALS, 1.5 GeV, 400 mA

- ALS bend magnet (1.04 T)
- 200 µm Be
- 200 µm Be + 300 µm PMMA

Photons / sec / m² / 0.1% BW

Energy (KeV) →
**Mask for Deep Etch Lithography**

- High contrast at short wavelength ~ 100
- Dimensionally stable
- Flat

<table>
<thead>
<tr>
<th>Mask substrate</th>
<th>Absorber pattern</th>
</tr>
</thead>
</table>
| • X-ray transparent  
  - light material  
  - thin membrane  
• Good mechanical properties  
  - high Young's modulus  
• Radiation resistant  
• Optically transparent | • X-ray absorbing structures  
• heavy material  
• absorber thickness: 5-15 μm  
• minimum lateral width: 1 μm  
• vertical walls  
• Low stress |
Mask Materials for Deep X-ray Lithography

Diagram showing absorption coefficient (1/μm) vs. wavelength (Å). Materials include Au, W, Si, and Diamond. Absorber and Membrane curves are distinguished.
Mask Fabrication for Deep Etch Lithography

1 Step Fabrication Process

Resist (10-20 µm)
Plating base
Mask membrane

Photolithography or e-beam lithography

Exposure

Development

Au-electroplating (5-15 µm)

Resist and plating base removal
STATE OF THE ART IN RESIST PROCESSING

• Positive PMMA resist
  – Cross-linked PMMA (100,000 mw) in MMA solution

• Coating
  – Several 100 µm cast on substrate
  – In-situ polymerization on substrate at RT
  – Thermal treatment
    » stress minimization

• Resist exposure dose
  – 2-4 kJ/cm³ at bottom, up to 20 kJ/cm³ at top

• Development
  – Specially tailored developer "G-Q" (Ghia-Glashauser)
    » highly selective
    » minimization of stress corrosion
EXPOSURE STRATEGY FOR DEEP ETCH LITHOGRAPHY

- Scanner
  - Proximity printing
    - 50 \( \mu m \) mask / substrate gap
  - Vertical movement of mask/substrate ensemble
    - Parallelism tolerance below 0.1 mrad
    - Heat removal
      - Speed 50 - 100 mm/s
      - He atmosphere
      - Cooled substrate
  - Multiple exposures
    - Alignment

- Tilted exposures / Rotation
  - Inclined walls
  - Conical structures
Oblique irradiation with rotation

Oblique irradiation

Synchrotron radiation

+20°

-20°

--- X-ray mask

--- Thick resist layer

--- Substrate
DEEP ETCH LITHOGRAPHY CHARACTERISTICS

- Structural height: several 100s μm
- Minimum feature size in the micron range
- Straight and planar walls
  Very vertical walls
- Highly parallel walls
  Run-out: 0.1 μm / 100 μm
- Low surface roughness
  30 - 50 nm
- Submicron accuracy over structure height
  0.05 μm / 100 μm
<table>
<thead>
<tr>
<th>Level of difficulty (scale 1 to 5)</th>
<th>Processing step</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Resist preparation</td>
</tr>
<tr>
<td></td>
<td>Mask making</td>
</tr>
<tr>
<td>2</td>
<td>X-ray exposure</td>
</tr>
<tr>
<td>1</td>
<td>Development</td>
</tr>
<tr>
<td>3</td>
<td>Electroforming</td>
</tr>
<tr>
<td>4</td>
<td>Replication</td>
</tr>
</tbody>
</table>
CRITICAL ISSUES IN ELECTROPLATING

- Plating base
- Stress minimization
- Thickness uniformity
- Grain size control
- Control of material properties
- Control of composition (alloys)
- Tight process control
EXTENSIONS OF THE LIGA TECHNIQUE

- COMBINATION WITH OTHER TECHNIQUES
  - Plastic molding and LIGA stepped structures
  - Sacrificial layer technique and LIGA Free / flexible structures
  - ...

- COMPATIBILITY OF LIGA WITH SILICON PROCESSING
SUMMARY

- Deep etch lithography is a powerful technique for the fabrication of HAR-MEMMs

- Existing mask and resist processing is available for deep etch lithography

- Extensions of LIGA-based processes provide a flexible technology for a variety of diverse applications
MEMS Activities at Berkeley
Sensor and Actuator Center
Richard Muller
UC Berkeley

August 3, 1993
MISSION:
TO DEVELOP A SCIENCE AND ENGINEERING BASE FOR MICROSENSORS, MICROACTUATORS AND MICROELECTROMECHANICAL SYSTEMS.
**BERKELEY**

**SENSOR & ACTUATOR CENTER**

An NSF/University/Industry Cooperative Research Center

- **INTERDISCIPLINARY**
  - Electrical Engineering
  - Mechanical Engineering
  - Chemical Engineering
  - Bioengineering
  - Materials Science

- **RESEARCH CONCENTRATION AREAS**
  - Integrated microsensors
  - Microactuators
  - Microdevice technologies
  - Microflow Systems
  - Microelectromagnetic Systems (MEMS)
SURFACE MICROMACHINING TECHNOLOGY:
BASIC PROCESS SEQUENCE

1. SPACER LAYER DEPOSITION

2. BASE PATTERNING (MASK 1)
SURFACE MICROMACHINING TECHNOLOGY (Cont.)

3. MICROSTRUCTURE LAYER DEPOSITION

MICROSTRUCTURE LAYER

SILICON SUBSTRATE

4. PATTERN MICROSTRUCTURE LAYER (MASK 2)

5. SELECTIVE ETCHING OF SPACER LAYER

FREESTANDING MICROSTRUCTURE

SILICON SUBSTRATE
EXAMPLES OF MICROMECHANICAL STRUCTURES

POLYSILICON ELECTROSTATIC MICROMOTOR

LATERAL POLYSILICON RESONATOR
Comb-Comb Multimode Resonator with mite

male Tetranychus sp. (urticae)
supplied by Prof. Manorie Hoy and Mr. Jim Prosnail, UC Berkeley
Vertical vs. Lateral Oscillation

VERTICAL OSCILLATION:
- Squeeze film damping
  [Low Q]
- Restricted design freedom

Δz vs. applied voltage nonlinear
Driven by parallel plate capacitor
[Millivolt drives in vacuum]

LATERAL OSCILLATION
- Reduced Drag
  [High Q]
- Sophisticated 2D geometry
  [Stress-relief design, comb drive,
  torsional resonant structures, etc]

Δx vs. applied voltage can be linear
Driven by fringing fields
[Larger drive voltage in vacuum]

Linear Resonant Structure Layout
Displacement vs. Applied Voltage

$F_p = \vec{F} = (V/\eta)^2$

where

$\vec{F} = F_0 + \text{Aperture}(\omega t)$

and

$V' = V_p + v_0 \sin(\omega t)$

Conclusion: $\Delta g$ must be limited to a small fraction of $g_0$ to maintain linearity.

LINEAR COMB DRIVE

$C_f = \text{Displacement constant:}$

$\propto \text{Displacement of } \Delta x.$

$C_p = \text{Displacement constant:}$

$\propto \Delta x.$

$\vec{F} = C_f + C_p.$

Key Features:

$(\eta \Delta x) = \text{constant};$

$\Rightarrow F_p = \eta V^2 (\eta \Delta x) = V^2.$
Surface-Micromachined Force-Balance Accelerometer


Capacitive detection (100nF Static capacitance) integrated BiCMOS buffer circuit

Electrostatic force-balance, self-test capability

100 g range (airbag deployment)
1. LARGE ACCELERATIONS of up to ±50 g can be measured by this IC together with its signal-conditioning circuits, all on one chip. Designed for automotive air-bag deployment, the ADXL50's p. 47 IC is part of a differential accelerometer whose common plate moves in the plane of the chip.
This microgripper, made by C.-J. Kim, A.P. Pisano and R.S. Mu of Berkeley Sensor & Actuator Center, holds an Euglena (a sir cell protozoa, 7x40 μm), preserved by K.D. Lee. The SEM pict has been taken with the help of V. Gutnik.
B. Description

- Si die > Support beam > Gripper
- Si die as micro-macro interface
- $p^+$ support cantilever (extender)
Estimated Gripping Force of 0.4mm-Long Gripper

\[ 10^{-9} \text{N} \]

Initial jaw disp = 0E-6 m
Initial jaw disp = 2E-6 m
Initial jaw disp = 4E-6 m
Initial jaw disp = 6E-6 m

Fig. 5.3 Estimated gripping force of the 400μm-long (300μm-long driver arm and 100μm-long extension arm) microgripper as a function of driving voltage and with the initial jaw displacement (depending on object size) as a parameter.
Fig. 3.7 Comparison of three elastic models of gripper arm.
POLYSILICON LINEAR MICROVIBROMOTORS

Abraham P. Lee*, D.J. Nikkel, Jr.†, and Albert P. Pisano

Department of Mechanical Engineering
University of California at Berkeley
Berkeley Sensor & Actuator Center
An NSF/Industry/University Research Cooperative

†Lawrence Livermore National Laboratory

Fig. 1 Design layout of the linear microvibromotor with oblique pointer extended from converter.
Another type of microvibromotor is an inverted design with the oblique flexures extended from the microslider. A horizontal portion of the flexures provides an impact target for the converters. Figure 3 is an SEM micrograph of this type of microvibromotor.

**ACTUATION PRINCIPLE**

Figure 4 illustrates the actuation principle of linear microvibromotors. When the two converters are driven in phase toward the microslider, the oblique pointers begin to deflect as contact impact force is induced between the oblique pointer and the microslider. This deflection kinematically results in a forward displacement of the pointer tip, dragging the microslider along by means of friction force. The impact force is balanced with the inertial momentum of the converters, the bending forces of the oblique pointer and folded beam flexure, and the electrostatic driving force. Combined with the frictions and impact sustained between the flange and the microslider, the system becomes very nonlinear in nature. An attempt to explain some design aspects as well as a simplified forward motion analysis will be made.

For a static analysis, Fig. 5 illustrates a simplified model to represent the actuation principle of the microvibromotor. The net vertical force exerted on the converter is represented by $F_v$ and the net horizontal force exerted on the slider is $F_h$. One end of the oblique pointer is assumed to be clamped to the converter mass while the other end is hinged on the microslider. Assume the width of the beam negligible compared to the length of the beam and $F_v$ equal to zero. That is, assume the resisting friction force of the microslider nonexistent. The displacements can then be derived from the flexure of the oblique pointer as:
resolution. Batch erection of the plate structures has recently been shown to be possible by agitation during rinsing. An SEM showing several of these hinged structures with slotted-lock retainers are shown in Fig. III.C.5. A concept for these structures in a two-axis gyro is shown in Fig. III.C.6. The combined results of the research we propose will eventually make such a system possible.

![Vertical structures produced at BSAC by Kris Plass.](image1)

The hinged-up structures are of the order 1 mm in height.

![Concept for a hinged structure to form a two-axis gyroscope.](image2)

Microcutting and Joining. By avoiding bonding of polysilicon wafer layers, mechanical separation can be achieved by etching and mechanical joining is possible by microwelding [Fedder, MEMS 1991]. Flexible polysilicon supports can be used to

**MICROMACHINING METHODS**

Sapphire sapphire ribbon cable has been fabricated and freed from the wafer. In Fig. III.D.2, the plate is rotated upward on its hinges and the ribbon cable is pulled retained as a connecting link. The rotated plate is locked in place by retaining screws.

![Cable retained and rotated upward.](image3)

![Cable retained and rotated upward.](image4)

**Microcutting and Joining.** Research on thermal cutting and milling can lead to very useful microfabrication procedures. Further developments...
Possible Applications

- Micro fine tuning head of magnetic disk head.
- Micro positioner/manipulator/robot.
- Optical shutter.
Figure 2.3: Cross section of a surface hinge. The pin and staple are on the right side, and a poly-2 plate is attached to the hinged poly-1 plate on the left.

Figure 2.4: Polysilicon stringers are formed in areas where the poly-2 film passes over an edge of poly-1. In the worst-case shown here, the poly-1 sidewalls are vertical, and the oxide is conformal, resulting in an additional vertical film thickness equal to the poly-1 and the ox-2 thicknesses.

Figure 2.5: After release the structures are free to rotate out of the plane of fabrication.
MICROACTUATION

- Electrostatic
- Piezoelectric
- Pneumatic
- Thermal Bimorph
- Fluidic Phase Change
- Ultrasonic
- Magnetic
- Shape Memory Alloy
BATCH FABRICATION AND ASSEMBLY OF MICROMOTOR-DRIVEN MECHANISMS WITH MULTI-LEVEL LINKAGES

Yogesh Gianchandani and Khalil Najafi

Center for Integrated Sensors and Circuits
University of Michigan
Ann Arbor, Michigan 48109-2122

TWO SILICON-, ONE GLASS- WAFER
FOR ASSEMBLED MECHANISMS
UNIV. of MICHIGAN - MEMS'92
Figure 1: Process sequence for batch fabrication and assembly of micromotor-driven mechanisms.

a) Etch bonding posts (anchors) and bushings using RIE or XON on the first silicon wafer.

b) Perform deep boron diffusion and define microstructures (rotor, stator, and hub) using RIE.

c) Perform a deep anisotropic RIE etch on the second silicon wafer to define pins.

d) Perform deep boron diffusion. Etch in RIE to define the bar linkage.

e) Electrostatically bond the first silicon wafer to a glass wafer patterned with the interconnect metal and dissolve undoped silicon in EDP to free the motor and gear. Restraints prevent devices from floating away at this stage in the process.

f) Electrostatically bond the second silicon wafer to the glass wafer, dissolve the undoped silicon in EDP to free the entire structure. The mechanism is batch-assembled and fabricated at this point. The bar linkage allows the motor power to be coupled out to the outside world. The restraints are blown out either electrically or by laser.
What can HARMEMS Bring to Actuated Microstructures?

• Increased Force
• Increased Strength
• Power Train Possibilities
• New Degrees of Freedom

NEEDED RESEARCH

• Materials Studies
• Electronics Compatibility Studies
DNA Amplification with a Microfabricated Reaction Chamber
Dick White
Berkeley Sensors and Actuators Center
UC Berkeley

August 3, 1993
DNA AMPLIFICATION WITH A MICROFABRICATED REACTION CHAMBER

M. Allen Northrup 1, Michael T. Ching 2, Richard M. White 2, and Robert T. Watson 3

1 Engineering Research Division, L-222, Lawrence Livermore National Laboratory, POB 808, Livermore, California 94551
2 Berkeley Sensor and Actuator Center, Electrical Engineering and Computer Science Department, University of California, Berkeley, California 94720
3 Roche Molecular Systems, Alameda, California 94501

The 7th International Conference on Solid-State Sensors and Actuators
Motivation

- To develop a microflow system for synthesis and analysis of complex organic and inorganic reactions.

![Diagram showing a microflow system with icons for centrifuge, filter, mixing, oven, and testing, leading to Specimen and Product and Test results.]

- Advantages
  - Portability - size, power, driving circuitry
  - Fast, stable temperature control
  - In-situ monitoring of reactions with integrated sensor
  - Sonochemistry

Berkeley Sensor and Actuator Center
PCR / What is it?

- Organic reaction we chose to evaluate the bio-compatibility of our system.

- Polymerase Chain Reaction was invented by Mullis et al at Cetus Corporation in Emeryville, CA in 1985.

- PCR is a patented biochemical technique to synthesize target sequences of DNA. By combining an enzyme, target DNA template, DNA primers (monomer blocks), and enzyme cofactors. A synthetic polymerization reaction occurs under thermal cycling conditions.

- Thermal cycles (typically between 55 and 96°C) will cause the repeated melting (denaturing) and recombination (annealing) of DNA while TAr (enzyme) can build copy of the DNA target template. Each cycle (n) causes an exponential increase in the synthetic DNA making what was originally undetectable, very detectable (i.e. billions of copies).

- Biotechnology (Vol 10 Aug 92) predicts amplified DNA-based diagnostic market will be 1B$ by 1997 (with products such as medical (disease, HIV, etc.), environmental, forensic, and genetic testing.)
of a specific DNA and provide sufficient material for accurately sequencing the fragment or cloning it by standard techniques. Undoubtedly PCR will be used extensively for genetic mapping in the human genome project. PCR-based diagnostic tests for AIDS, Lyme disease, chlamydia, the human papilloma virus, and other infectious agents and diseases are being developed. PCR is particularly valuable in the detection of genetic diseases such as sickle cell anemia, phenylketonuria and muscular dystrophy. The technique is already having a profound impact on forensic science where it is being used in criminal cases. It is possible to exclude or incriminate suspects using extremely small samples of biological material discovered at the crime scene.

Preparation of Recombinant DNA

There are three ways to obtain adequate quantities of a DNA fragment. One can extract all the DNA from an organism, fragment it, isolate the fragment of interest, and finally clone it. Alternatively, all of the fragments can be cloned by means of a suitable vector, and each clone (the population of identical molecules with a single ancestral molecule) can be tested for the desired gene. One also can directly synthesize the desired DNA fragment as described earlier, and then clone it.
Basic Device

Prototype to evaluate system.
Temperature Cycling

- Temperature characteristics:
  - rise/fall times of $> 20 \text{ C/sec}$ for 50 ul device
  - rise/fall times of $> 40 \text{ C/sec}$ for 25 ul device
PCR Results

Side Standard

- Reaction Time for 20 cycles
  - Micro-Device: 13.3min
  - Commercial Cycler: 40mins

- Power Requirements
  - Micro-Device: > 1W
  - Commercial: 50-200W

Commercial Cycler  Micro-Device
COLLABORATORS

Jeff Kortright
Center for X-ray Optics
Lawrence Berkeley Laboratory

and

Mike Toney and Owen Melroy
IBM Almaden Research Center
San Jose CA

LBL Investigators supported by Office of Energy Research, Office of Basic Energy Sciences, Division of Materials Sciences, U.S. Department of Energy. IBM investigators supported by a grant from the Office of Naval Research. Experiments were conducted at the Stanford Synchrotron Research Laboratory, which is operated as a national user facility by Stanford University for the U.S. Department of Energy, Office of Energy Research, Office of Basic Energy Sciences, Chemical Sciences Division.
• ELASTIC WAVE AND DEVICE FUNDAMENTALS
• OPTIONS – OPEN OR CLOSED, GELS, CHANNELS, ...
• SENSING:
  VISCOSITY – FLUIDS; MOLECULAR WEIGHT EFFECT
  GRAVIMETRIC – LIQUID DENSITY; MOLECULES; CELLS
• KINETIC EFFECTS:
  MICROTRANSPORT – GRANULES IN GAS; LIQUIDS
  STIRRING AND MIXING
  SONOCHEMISTRY?
• CONCLUSIONS
  MICROFABRICATED DNA-PCR REACTOR
Top view of chip:

Cross section A-A':

- Metal ground plane (0.2-0.5 µm)
- IDTs (Al, 0.2-0.5 µm)
- ZnO (0.3-1.5 µm)

Silicon nitride (0.8-4 µm)

Membrane perimeter (2mm x 2mm)

Si substrate
Why Plate Waves?

- Low velocity
  - low frequency
  - no radiation in liquids \(\rightarrow\) low-loss operation
- High sensitivity
- Large amplitude \(\rightarrow\) Pump solids and liquids
- Micromachinable
DIFFUSION

gel-coated sensor

salt solution

un-coated sensor

frequency (MHz)

time (min)

frequency (MHz)

time (min)
Kinetic effects

inverted cross section through A-B

cap

membrane

fluid

wavelength: 100 μm
frequency: 4 MHz
area: 3 x 8 mm

zinc oxide 1 μm

aluminum 0.4 μm
Integrated Systems

- Fluid Reservoir
- Fluid Pump
- Mixer and Sensor
- Reaction Activation
- Pump to Outside World
- Solids Reservoir
- Solids Pump
Kinetic effects

polystyrene spheres

liquid dye

polysilicon microblocks

live bacteria
VIDEO: ULTRASONIC MICROTRANSPORT
LOOKING DOWN ONTO MEMBRANE WITH TRANS-DUCERS
TO LEFT AND RIGHT:

LINEAR DRIVE

ROTATIONAL DRIVE

[Diagram of linear and rotational drives]
VIDEO: ULTRASONIC MICROTRANSPORT

LOOKING DOWN AT MEMBRANE – TRANSDUCERS L & R:

• IN AIR, DRIVING BOTH TRANSDUCERS CAUSES ROTATION OF POLYCRYSTALLINE SILICON FLAKE (MEASURES 1 MICRON x 300 MICRONS x 300 MICRONS). DRIVING ONE TRANSDUCER MOVES FLAKE IN ONE DIRECTION AT UP TO 3 cm/s

• WATER WITH 2.5-MICRON POLYSTYRENE SPHERES IS PUMPED AT UP TO 300 micron/s

• WITH STANDING WAVES, BACTERIA IN WATER ARE TRAPPED (AND SPUN!)
Electrochemistry Research at LBL

Phil Ross
Materials Sciences Division
LBL

August 3, 1993
BERKELEY ELECTROCHEMICAL RESEARCH CENTER

Elton Cairns, Head

INVESTIGATORS:

Elton Cairns (electrode optimization)
Lutgard De Jonghe (solid electrolytes, Li polymer batteries)
Kim Kinoshita (carbon electrodes)
Rolf Muller (ellipsometry, interfacial layers)
John Newman (modelling)
Phil Ross (x-ray methods, interfacial layers)
Charles Tobias (electrochemical engineering)

FUNDING:

DOE/CRE (Transportation) $2 M
USABC CRADA $1.3 M
DOE/BES $0.6 M

STAFFING:

GSRA 10
Postdoc 7
Staff Scientists 4
Technical 3
JOB AFFILIATIONS OF FORMER GRADUATE STUDENT ASSOCIATES OF CHARLES W. TOBIAS

<table>
<thead>
<tr>
<th>Category</th>
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<td>Battery Industry, Including Research Laboratories:</td>
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<tr>
<td>National Laboratories, Battery Related Research:</td>
<td>5</td>
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<tr>
<td>- Other Functions:</td>
<td>5</td>
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<tr>
<td>University Faculty, Involved with Battery Research:</td>
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</tr>
<tr>
<td>- Concerned with Design, Metal Deposition, Corrosion, Modeling:</td>
<td>10</td>
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<td>IBM, Bell Labs:</td>
<td>9</td>
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<tr>
<td>Other High Tech Industries:</td>
<td>6</td>
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<tr>
<td>Chemical Industry:</td>
<td>14</td>
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<tr>
<td>Own Business Undertaking:</td>
<td>3</td>
</tr>
</tbody>
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**Total:** 68*

*Further two graduate students haven't as yet complete their degree requirements.

May 21, 1991
Chemical Engineering Departments with
Recognized Research Programs in Electrochemical Engineering

- University of California (Berkeley)
- University of California (Los Angeles)
- Clarkson University
- Brigham Young University
- Carnegie-Mellon University
- Case-Western Reserve University
- Columbia University
- University of Houston
- University of Illinois (Urbana)
- Illinois Institute of Technology
- Johns Hopkins University
- University of Michigan
- University of Minnesota
- North Carolina State University
- South Carolina State University
- University of Rochester
- Texas A & M
- Texas Tech
- University of Virginia
- University of Wisconsin (Madison)
- University of Texas (Austin)
- Rutgers University

In Universities marked by (o) the faculty in charge is a former student of Tobias's
" " " " (+) " " is a former student of a student " " 
Fig. 6. CVD-tungsten film profile in trenches of the same depth but with various widths (a) and the simulation of these conditions (b). Note that the width of the void (here measured at 6 μm depth because the trench profile is distorted near the bottom) does not depend on the width of the trench. Trench dimensions: 4.73 × 10.85 μm (left), 3.77 × 16.85 μm (middle), and 3.15 × 10.85 μm (right). The dimension of the void is in micrometers. See text for more details.

<table>
<thead>
<tr>
<th></th>
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<th>micrometers</th>
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<tr>
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<td>0.59</td>
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<tr>
<td>void experiment</td>
<td>0.59</td>
<td>0.55</td>
<td>0.54</td>
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</tbody>
</table>
Step coverage = \((x/y) \times 100\%\)

Fig. 2. Definition of step coverage (a) and of void size (b). This definition is arbitrary, other definitions in use in the literature might work as well.

\[ h_T = \sqrt{\left[ k^* L_i^2 / (C_{W_{\text{Wii}}} D_{W_{\text{Wii}}} R_i) \right]} \]
\[ n = 1 - \delta - \beta \]

\[ n' = 1 - \delta' - \beta' \]
Figure 1. Electrochemical Cell: A) Silver or Gold (111) electrode, B) Ag/AgCl reference electrode, C) Platinum counter electrode, D) Polypropylene window, E) O-ring holding polypropylene to cell, F) External electrical connection to the working electrode, G) Solution inlet, and H) Solution outlet.

Insert: Grazing incidence scattering geometry showing the incident angle \( \alpha \), the output angle \( \delta \), the scattering angle \( \theta \), and the azimuthal angle \( \phi \). In all experiments reported here, \( \alpha = \delta \). \( I_0 \) is the incident beam, \( I_s \) the scattered beam which goes to the Soller slits and detector, and \( I_s \) is the specular reflection.
Electrodeposition of Pb Monolayer on Ag(111)

\[ \text{Pb}^{2+} + 2e^- \rightarrow \text{Pb} \]  
\( \text{two distinct equilibrium states} \)

\[ q = \int i \, dt \]

\[ q_{\text{form}} \]

\[ q_{\text{eq with Pb}} \]

\[ q_{\text{Pb monolayer}} \]

Why Pb on Ag(111)?

1. High Z metal on low Z substrate
2. Vapor deposited structure well-known
3. Incommensurate structure
MEMS Activities at LLNL
Dino Ciarlo
Micro Technology Center
LLNL

August 3, 1993
August 3, 1993

Lawrence Berkeley Laboratory

HARP-MEMS Workshop

Lawrence Livermore National Laboratory

Jack Dini
Chris Steffani - Metal Finishing Facility
Abe Lee
Dino Cirilo - Micro Technology Center

Near Term - Long Term Research & Technology
Targets for coded imaging are now made with conventional IC resist and 405 nm UV exposures.

- Spin multiple coats of resist, planarize, remove solvent without cracking.
- Plating seed layer.
- Contact mask.
- Expose resist with 405 nm UV.
- Develop resist.
- Diffraction effects and long development causes sidewall taper (65°).
- Electroplated gold follows mold pattern.

<table>
<thead>
<tr>
<th>Height/width ratio</th>
<th>Fan Engelmann</th>
<th>Allen NTT</th>
<th>LIGA</th>
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<td>20:1</td>
<td>6.7:1</td>
<td>7:1</td>
<td>6.7:1</td>
</tr>
<tr>
<td>Resist</td>
<td>Polyimide RIE</td>
<td>PMMA</td>
<td></td>
</tr>
</tbody>
</table>
Individual modules are assembled together.

Figure 5. (a) A two-dimensional microchannel-cooled laser diode array being assembled. (b) This 42-module stack was fabricated for pumping a Nd:YAG high-average-power crystalline slab laser.
Other long term needs for LIGA includes the desire to fabricate "stronger" actuators

- Adaptive Optics
  20,000 segments
each segment is 4 gms, 3 kHz, ± 50 μ

- Arming and firing mechanisms

- Surgical Instruments
  Grippers and cutters
  Catheter based tools

- Biomedical Applications
  Pumps and valves
  Miniature mixers
  Miniature reaction chambers
LLNL can assist in two specific areas of the LIGA process

- Planarization using our diamond turning technology

PMMA
Electroplated metal
Copper - OK  20 Å rms smoothness
Gold - some problem with tool wear
Nickel - needs 10 - 12 % phosphorus content

- Electroplating (Chris Steffani)
**Metal Finishing Facility**  
Chris Steffani, Supervisor  
(510) 423-1780

**Electrolytic processes**

- Anodizing - Type II and III, many colors available, thicknesses to .004”. For decoration, color coding, wear and corrosion resistance.
- Black Nickel - thin, decorative nickel zinc alloy. Used as light absorbing coating, good corrosion resistance.
- Copper - Bright or Dull, dead soft to 80 KSI tensile strength, thicknesses to > .500” for brazing, electrical/thermal conductivity, single point diamond machinable.
- Gold - high purity, 99.99+, soft, thicknesses to > .300” for corrosion resistance, electrical conductivity, reflectivity.
- Indium - malleable, matte white, thicknesses to .050” excellent as a sealing gasket low temperature solder.
- Iron - pure, magnetic, thicknesses to .250” good for building up worn surfaces, magnets.
- Nickel - Bright or Dull, Hard or Soft, to 175 KSI tensile strength, thicknesses to > .500” magnetic, corrosion resistant, strong.
- Platinum - Bright, silvery, hard, thin coatings only excellent electrical conductivity, best corrosion resistance.
- Rhodium - Bright, silvery, hard, thin coatings only excellent electrical conductivity, very wear and corrosion resistant.
- Silver - Bright or Dull, thicknesses to > .050” for anti galling, electrical conductivity, reflectivity.
- Tin - pure or 60/40 SnPb, matte, thicknesses to .050” excellent solderability, can be reflowed.
- Zinc - pure, matte, thicknesses to .050” excellent corrosion resistance

**Chemical Processes**

- Black oxide - on copper, steel, SST, brass, aluminum. Produces black, corrosion resistant coating with a minimal dimensional change.
- Cleaning - UHV processing.
- Chemical Milling - Parts can be fabricated from your artwork. Allows zero stress fabrication of thin (.0001” to .100”) metallic parts.
- Electroforming - any metal can be used to form your component. Fabricate your parts to size on a mandrel of your design.
- Electropolishing - SST, Copper, Aluminum, many refractories and alloys. Provides smooth, clean, passivated surfaces.
- Electroless nickel - High or low phosphorus, dull or bright, thicknesses to .003” very uniform thickness, hardenable via heat treatment, diamond turnable.
- Passivation - for SST alloys provides maximum corrosion resistance.

**Other processes**

Mechanical Finishing - Buffing, graining, sand and bead blasting.
Broken tap and drill removal - saves expensive assemblies.
Full Machine shop services.
Materials Fabrication Division

Engineering

Fabrication

Machining

CAE
CAD
CAM
Electroplating
Vacuum coating
Plastics
Optics
Laser processing
Conventional
Diamond turning
EDM
Water jet
Ceramics
Spin/press
Electroplating

85 processing tanks (400 to 1500 liters)

7 technicians with experience totaling 95 years

Environmentally conscience processing
MICROSENSORS AND MICROINSTRUMENTS

W.J. Kaiser, T.W. Kenny, J.K. Reynolds, H.K. Rockstad,
T.R. Van Zandt, J.A. Podosek, E.C. Vote, L. Miller,
R. Stieke, M. H. Hecht, P. Maker, R. Muller, M. Hoenk,
P.J. Grunthaner, F.J. Grunthaner, M.A. Agronin, R.K. Bartman,
and R.L. Norton

Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
JPL MICRODEVICES CAPABILITIES

- End to end device fabrication and characterization
- Material deposition
  - Evaporation
  - Magnetron sputtering
  - Molecular beam epitaxy (MBE) (SI & III-V)
  - Liquid phase epitaxy (LPE)
- Metallorganic chemical vapor deposition (MOCVD)
- Laser assisted chemical vapor deposition (LACVD)
- Plasma enhanced chemical vapor deposition (PECVD)
- Lithography
  - Nanometer electron beam lithography
  - Optical lithography
- Device fabrication
  - Diffusion and oxidation furnaces
  - Wet and dry etching
  - Reactive ion etching
Nanotechnology & Science Group
Michael Hecht, Supervisor

- New Technologies (Michael Hecht)
  - Soil Chemistry Probes
  - Electron & Ion Optics (Energy & Mass Analyzers)
  - X-ray Optics (Modulation Collimators, Lobster eyes, HARMM)
- Microinstruments (Bill Kaiser)
  - Seismometer
  - Weather Station (humidity, pressure, temperature, wind, aerosols)
  - Adaptive Optics (deformable mirrors, edge sensors)
  - Scanned Probes (BEEM, TTM, STM, AFM)
- Tunnel Sensors (Tom Kenny)
  - Magnetometers
  - Accelerometers
  - Infrared Sensors
- Nanofabrication (Paul Markert)
  - Electron Beam Lithography
  - Metrology
  - Binary Optics
Themes

• **Mix of R&D**
  - ~25% Basic Research (BEEM, HARM)
  - ~25% Advanced Development (MESUR)
  - ~50% Novel Instruments

• **Customer Mix (~$3.7M Total)**
  - ~50% NASA
    • ~40% Code C
    • ~40% Code S
    • ~20% DDF, etc.
  - ~50% DoD (SDIO, Navy)
  - Technology Affiliates (Boeing, Eaton, etc.)

• **New principles**
  - BEEM
  - Tunnel Sensors
  - UHFC

• **New Techniques**
  - Micromachining
  - Direct-Write Binary Optics
  - LIGA
EXAMPLE : MESUR

An example of an application that constrains the instrument parameters is the Mars Environmental Survey (MESUR).

MESUR requires:

- Total landed vehicle mass less than 100 kg
- Entire science payload less than 10 kg
- Some individual conventional instruments exceed entire payload
- The science requirements for these instruments have not been reduced

A variety of important mission opportunities require a reduction in instrument mass by a factor of ten or more without loss of performance.
JPL MICROSEISMMETER:
TESTING - EARTHQUAKE MEASUREMENT

M = 4.0 Earthquake, Big Bear, California, 12/4/91
Photograph of JPL Prototype Mars Seismometer. In this device a 3 gm copper proof mass is suspended by a silicon crystal cantilever in the vertical orientation. A sensitive capacitive displacement transducer measures the deflection of the proof mass in the event of a vertical acceleration. This device features sensitivity better than $10^{-9}\ g/\sqrt{\text{Hz}}$ and bandwidth of 40 Hz.
This photograph shows the JPL seismometer being attached to drill string and prepared for insertion into well
This photograph shows the hygrometer mounted on a thermo-electric cooler, which is cooled onto an electronic board. The quartz is shown for scale.
MICROHUMIDITY SPECTRUM

DEWPOINT MEASUREMENT

Micro Weather Stations for In-Situ Meteorological Measurements
This photograph shows a prototype pressure sensor which is based on a measurement of the thermal conductivity of the ambient medium. In this device, current is passed through the nitride supported platinum wires around the perimeter, and the changes in the central nitride-supported platinum wire is recorded.
TUNNELING INFRARED SENSOR DESIGN

- Feedback circuit deflects membrane into tunneling contact with tip
- Absorbed radiation increases pressure in cell
- Feedback circuit responds by reducing deflection voltage
output voltage noise spectra are recorded at the output of the error amplifier (upper curve) and at the deflection electrode (lower curve). the noise at the deflection electrode is reduced by stray capacitance.
SENSOR IN CIRCUIT BOARD WITH FEEDBACK CIRCUIT
PROOF-OF-CONCEPT ENERGY FILTER

selected energy (101.4 eV)
FULL MEMBRANE MIRROR

Optical window with transparent electrode coating

UV sensitive epoxy

Silicon nitride optical layer ~0.5 μm thick

Cr/Au ground electrode

UV sensitive epoxy

Actuation electrodes

Cr/Au reflective surface

Silicon, ~400 μm thick

Silicon or glass with ~30 μm deep electrode well

V_l, V_m, V_n

V_{bias}
MICRO-OPTICAL DEVICES

- Computer generated phase holograms (CGPHs) are conventionally produced by a set of binary masks
- JPL's JEOL JBX-5DII E-Beam system provides continuously variable dose control and exquisite patterning, under computer control
- Technology for partial exposure and removal of photoresist (PMMA) has been developed at JPL. The PMMA becomes the optical phase delay medium
- Control of development depth to ±100Å has been demonstrated
- CGPH patterns generated at Carnegie Mellon Center of Excellence for Optical Data Processing have been fabricated
- This represents a single-step process for very precise fabrication of complex CGPHs
- Used in:
  - Optical data processing
  - Laser beam shape control
  - High N.A. lenslet arrays for CCD's with image plane electronics
  - Optical computing
Development vs Exposure

PMMA Dose Sensitivity

Development:
6.0 sec in Acetone

3rd Order Fit
Std Error 17nm
Knife Edge Test of Diffractive Lens

Focal Length 1.49"  Diameter 0.10"

Relative Intensity

Distance from Axis, microns

Observed

Calculated
Microfabricated Grids for HESP

JPL/Caltech Technical Staff:

Michael Hoch (Task Manager)
Frank Grunthamer (Electrochemistry)
Tom Kenny, Judy Podosek (Chemical Micromachining)
Peter Siegel (Mechanical Micromachining)
Paul Maker (E-Beam Masks)
Gordon Hurford, Jim Ling (Space Science)
Thanks to... Metal Surfaces, Inc.

OBJECTIVE: Produce half-scale prototype grids for HESP using silicon micromachining & electroforming.
Figure 4.9: Schematic representation of the Fourier-transform technique used to obtain images of active sites with multiple-rotating modulation collimators (RMG's).
Figure 4.1. Schematic cross-sections of the High Energy Imaging Spectrometer (HEIS). The upper and lower tungsten grids separated by 5 cm, form the rotating modulation collimator (RMC's). The two-segment germanium detectors provide high spectral resolution measurements from $\sim$10 keV to 20 keV. The combination of the Ge detector and the bismuth germanate (BGO) shield extends the gamma-ray range to >800 keV and provides excellent coverage from $\sim$20 MeV to $\sim$1 GeV. The silicon detectors cover the energy range from $\sim$2 keV to 20 keV. The BGO shield and collimator form an anti-coincidence shield to reduce the background.
<table>
<thead>
<tr>
<th>Collimator Length (mm)</th>
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<tbody>
<tr>
<td>Inner Collimator Diameter (mm)</td>
<td>71.0</td>
</tr>
<tr>
<td>Inner Collimator Diameter (mm)</td>
<td>28.8</td>
</tr>
<tr>
<td>Angle of Inner Collimator</td>
<td>0.009</td>
</tr>
<tr>
<td>Angle in Pitch</td>
<td>0.800</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Field of View (deg.)</th>
<th>1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid rim thickness (mm)</td>
<td>10.00</td>
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<tr>
<td>Grid density (g/cm³)</td>
<td>19.30</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Top grid weight (kg)</th>
<th>0.09 0.13 0.19 0.27 0.40 0.58 0.77 0.77 0.77 0.77 0.77 0.77</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (kg)</td>
<td>6.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bottom grid weight (kg)</th>
<th>0.06 0.09 0.13 0.19 0.28 0.40 0.54 0.54 0.54 0.54 0.54 0.54</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (kg)</td>
<td>4.37</td>
</tr>
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<table>
<thead>
<tr>
<th>Energy for 50% transmission</th>
<th>308. 379. 481. 648. 947. 1864. 0. 0. 0. 0. 0. 0. 0.</th>
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</thead>
<tbody>
<tr>
<td>Energy (keV)</td>
<td>308. 379. 481. 648. 947. 1864. 0. 0. 0. 0. 0. 0. 0.</td>
</tr>
</tbody>
</table>

| Diffraction Energy limit (keV) with 10%, 50%, and 100% reduction in modulation amplitude (0.0 = < .1 keV) |
|--------------------------------------------------|------------------|
| 10% red, 0 fundamental | 13.1 6.2 3.0 1.4 0.7 0.3 0.2 0.0 0.0 0.0 0.0 0.0 |
| 10% red, 0 2nd harmonic | 52.5 24.9 11.8 5.6 2.7 1.3 0.6 0.3 0.1 0.0 0.0 0.0 |
| 10% red, 0 3rd harmonic | 118.1 56.1 28.6 12.7 6.0 2.9 1.4 0.6 0.3 0.1 0.0 0.0 |
| 50% red, 0 fundamental | 5.7 2.7 1.3 0.6 0.3 0.1 0.0 0.0 0.0 0.0 0.0 0.0 |
| 50% red, 0 2nd harmonic | 22.6 10.7 5.1 2.4 1.2 0.5 0.3 0.1 0.0 0.0 0.0 0.0 |
| 50% red, 0 3rd harmonic | 50.9 24.2 11.5 5.5 2.6 1.2 0.5 0.3 0.1 0.0 0.0 0.0 |
| 100% red, 0 fundamental | 3.8 1.8 0.9 0.4 0.2 0.0 0.0 0.0 0.0 0.0 0.0 0.0 |
| 100% red, 0 2nd harmonic | 15.1 7.2 3.4 1.6 0.8 0.4 0.2 0.0 0.0 0.0 0.0 0.0 |
| 100% red, 0 3rd harmonic | 33.9 16.1 7.7 3.6 1.7 0.8 0.4 0.2 0.0 0.0 0.0 0.0 |

| First Diffraction Peak in Modulation Amplitude (keV) |
|-----------------------------------------------------|------------------|
| 1st pk, fundamental | 1.9 0.9 0.4 0.2 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 |
| 1st pk, 2nd harmonic | 7.5 3.6 1.7 0.8 0.4 0.2 0.0 0.0 0.0 0.0 0.0 0.0 |
| 1st pk, 3rd harmonic | 17.0 8.1 3.8 1.8 0.9 0.4 0.3 0.0 0.0 0.0 0.0 0.0 |
A. COARSE GRID MANUFACTURED
BY ELOX PROCESS.

B. SECTION OF ACTUAL SINGLE BLADE
AND SPACERS FOR FINE GRID.

C. DESIGN CONCEPT FOR PACKET OF BLADES
AND SPACERS FOR FINE GRID.

Figure 14: Illustration of two different grid fabrication techniques.
HESP GRID FABRICATION STAGES

Silicon mold is diced with high speed diamond saw

Metal is electroplated into slots left in mold

Silicon/metal surface is polished flat

Silicon is etched away leaving all metal grid
Silicon Micromachining

- Status
  - 2" diameter 30:1 ratio 100 μ pitch structure looks very good

- Undercutting Limitations:
  - For tolerable etch rates in deep trenches, preferential etch ratios seem to be <100:1 on each side, hence 1 mm deep trench is broadened by >20 microns
  - Part of the problem is alignment, i.e. a trench of length L will broaden by up to Lsinφ where φ is misalignment angle. << 1 mrad may be required for .050 mm pitch.

- Other Problems
  - Flaws in nitride passivation give 2-3% broken bars
Mask Fabrication (JPL, E-Beam)

DEXL (JPL, SSRL/ALS/NSLS)

MetalForming (Metal Surfaces)

W CVD (Ultramet)

Metrology (JPL, GSFC)
W CVD Process

- Deposit on sides for Rapid filling
- Low cost Process
- Surface Prep Critical
- W/Re Possible
Fine Grid Status

- Demonstration Structure
  - 3" Cu grid, ~10:1 (0.1 mm)
- Au Electroforming (Metal Surfaces, Inc.)
- CVD Tungsten (Ultramet)
  - Test blanks fabricated
  - Uniform deposition demonstrated
  - Diffusion barrier required to eliminate undercutting
- Mold Fabrication
  - Probe limits of sawed molds
    » 0.1 mm, 20:1 obtainable
  - Fabricate chemically micromachined molds
    » Problem 1: Support Structures
    » Problem 2: Flaws in material
  - Fabricate Acrylic molds (Deep Etch X-Ray Lithography)
    » E-Beam Mask Fabricated
    » Multiple Exposure Test
    » Plexiglass sheet test
    » ALS facility under construction
    » Solid vs. Free-Standing
The Advanced Light Source
Brian Kincaid
Advanced Light Source
LBL

August 3, 1993
Advanced Light Source Update

Brian Kincaid
• On time

• On budget

• It works!
• National User facility funded by DOE

• Provides UV and soft x-ray beams of unprecedented brightness

• Utilized by researchers from industry, academic, and national laboratory communities

• Construction project started in late 1986, begin operations — spring 1993

• Project complete — spring 1993

• Overall cost — $146M
Evolution of Synchrotron Radiation

Todays Synchrotrons:
- Continuous e⁻ trajectory "bending"
- Circular electron motion
- "Bending magnet radiation"
- "X-ray light bulb"

Today's Synchrotron Systems:
- Photons

Tomorrows Synchrotrons:
- Many straight sections (periodic magnets)
- Tightly controlled electron beam
- "Undulator" and "wiggler" radiation
- Partially coherent
- Tunable
The ALS Has Both Undulators and Bending Magnets

Bending magnet radiation (spawning searchlights)

Undulator radiation

$N$ periods

$E_0 = \gamma m_e c^2$

$\theta_y = \frac{1}{4}$

Beamline optics acceptance angle
**The U.S. Scene**

- **ALS**
- **APS**
- **Existing Facilities** (NSLS, SSRL, CHESS, Aladdin)

**Spectral Brightness**

- $10^{10}$
- $10^{14}$
- $10^{18}$

**Photon Energy**

- $1$ eV
- $1$ keV
- $100$ keV

---

**Competition Overseas**

- Italy
- Germany
- Taiwan
- Korea
- France
- England
- Russia
- Europe
- Japan

**Existing Facilities** (Japan, Germany, England...)

**Spectral Brightness**

- $10^7$
- $10^4$
- $10^2$

**Photon Energy**

- $1$ eV
- $1$ keV
- $100$ keV

---

*Photons/mrad$^2$/mm$^2$/0.1% BW*
## Ten Microscopes are Planned for the ALS

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Photon Source</th>
<th>Type of Microscope</th>
<th>Application</th>
<th>P.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td>U3.9 Undulator</td>
<td>Scanning (2)</td>
<td>Biological &amp; Materials Sciences</td>
<td>ALS (Attwood)</td>
</tr>
<tr>
<td>6.1</td>
<td>Bend Magnet</td>
<td>Zone Plate Imaging</td>
<td>Biological &amp; Materials Sciences</td>
<td>Meyer-Ilse</td>
</tr>
<tr>
<td>7.0</td>
<td>U5 Undulator</td>
<td>Photoemission Imaging</td>
<td>Surface &amp; Materials Sciences</td>
<td>Tonner/Ade</td>
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<tr>
<td></td>
<td></td>
<td>Zone plate Scanning (fluorescence)</td>
<td>Surfaces, Materials Sciences &amp; Polymers</td>
<td>Tonner/Ade</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zone plate Scanning (photoemission)</td>
<td>Surface &amp; Materials Sciences</td>
<td>Tonner/Ade</td>
</tr>
<tr>
<td>8.0</td>
<td>U5 Undulator</td>
<td>Zone plate Scanning</td>
<td>Surface &amp; Materials Sciences</td>
<td>Stöhr</td>
</tr>
<tr>
<td>10.3</td>
<td>Bend Magnet</td>
<td>Microprobe (2)</td>
<td>Materials Sciences</td>
<td>Thompson</td>
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<tr>
<td>11.0</td>
<td>Elliptical Wiggler</td>
<td>Spin-polarized Photoemission</td>
<td>Magnetic Materials</td>
<td>Stöhr</td>
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### Advanced Light Source Schedule

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>FY87</th>
<th>FY88</th>
<th>FY89</th>
<th>FY90</th>
<th>FY91</th>
<th>FY92</th>
<th>FY93</th>
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<tbody>
<tr>
<td>1.1 Project Mgmt. &amp; Administration</td>
<td></td>
<td></td>
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<td>1.2 Special Facilities</td>
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<td>1.2.2 Injector System</td>
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<td>1.2.3 Control System</td>
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<td></td>
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<td>1.2.4 Insertion Devices</td>
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<td>1.2.5 Beam Lines</td>
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<td>1.3 Conventional Facilities</td>
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<td>1.3.2 Thermal Stabilization/AC</td>
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</tbody>
</table>

**Milestones**

- Project Start
- Beneficial Occupancy, start injector installation
- Complete Injector system installation
- Finish Building 6 addition, start storage ring installation
- Complete storage ring installation
- Project Completion

- Design
- Proc/Fab
- Test/Install

---

* DOE RWV*
A week ahead of schedule, the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory (LBL) exceeded the baseline performance requirement for project completion while remaining within budget. The ALS achieved 65 milliamperes (mA) of electron-beam current in its storage ring, well above the 50-mA goal called for in the project plan. On March 31, 1993, the actual deadline, the beam current far surpassed all expectations, reaching 290 mA. By April 9, the current exceeded the 400-mA design goal, reaching 407 mA. This performance is a testimony to the team of engineers, physicists, and technicians working on the project, whose near-perfect work in design, assembly, alignment, and electronic control enabled the ALS to operate as soon as it was turned on. This is a rare occurrence in high-tech projects as complex as this one.

Built with $100 million in DOE construction funds, the ALS is a national user facility providing high-brightness beams of ultraviolet and soft x-ray light. It has been eagerly awaited by researchers in the physical, chemical, materials, and life sciences. Its principal component is a storage ring 200 meters in circumference.

A stored electron beam circulates in the ring at nearly the speed of light. The beam is guided and focused by hundreds of precision electromagnets situated around the ring. Special undulator magnets cause the electron beam to produce synchrotron radiation, making the ALS the world’s brightest ultraviolet and soft x-ray light source.

The most remarkable aspect of commissioning the ALS storage ring is the speed with which it progressed (see table). For a project as large and complex as the ALS, this timetable would have been impossible if not for the high quality of the engineering that turned the ideas of physicist planners into reality. The fact that electron beam was stored on the same day the rf system was turned on clearly attests to this quality.

Once the conceptual design was established, perhaps the greatest engineering challenge was the requirement for extremely tight tolerances in building and aligning components. For instance, the typical tolerance for aligning the magnets around the storage ring was 150 µm (barely the thickness of two human hairs), and the tolerance for machining the 10-meter aluminum sectors that make up the storage-ring vacuum chamber was about the same.

At a time when some say U.S. expertise in science and technology is slipping, the ALS proves we have the knowledge, skill, and dedication to build a world-class scientific facility on time, within budget, and to a level of perfection rarely achieved on a comparable scale.
April 30, 1993
from 3:40 am

456.6 mA
MAJOR SPECIFICATIONS FOR ACCELERATOR SYSTEMS

- **Injector:**
  - Linac: 50 MeV
  - Booster: 1.5 GeV, 1 Hz

- **Storage Ring Optimum Energy:** 1.5 GeV

- **Max. Current (multibunch):** 400 mA (460 mA achieved)

- **Max. Current (single bunch):** 7.6 mA (27 mA achieved)

- **Horizontal Emittance:** < 10^{-8} m-rad

- **Time Structure (2 sigma):** 20-50 psec

- **Variety of Operating Modes:** multibunch, few-bunch, single bunch

- **Lifetime:** > 6 hours (now 1.5 h, will improve)

- **High Position and Angular Stability:** (coming soon)
Dr. Charles Shank  
Director  
Lawrence Berkeley Laboratory  
University of California  
Berkeley, California 94720

Dear Dr. Shank:

Congratulations on the successful completion of the new Advanced Light Source. Please convey my appreciation to the Lawrence Berkeley Laboratory staff members who contributed to this effort, especially Drs. Brian Kincaid and Jay Marx who guided the project. Achieving the first stored beam in the storage ring with all systems operating was a crucial milestone.

We are proud that this project will soon contribute to the Nation’s technology base.

Sincerely,

[Signature]

[Signature]
Department of Energy
Washington, DC 20585

MEMORANDUM FOR ACQUISITION EXECUTIVE

FROM: JAMES F. DECKER
ACTING DIRECTOR, OFFICE OF ENERGY RESEARCH

SUBJECT: ACTION: Approval of Key Decision 4 - Approval to Commence Operation of the Advanced Light Source

ISSUE: The 1-2 GeV Synchrotron Radiation Source Project (also known as the Advanced Light Source) is complete, tested, and ready to begin operation. The Project Management System (DOE Order 4980.1) requires approval by the Acquisition Executive to begin operation for experiments.

- The Advanced Light Source at Lawrence Berkeley Laboratory was reviewed (attachment 1) by a Department of Energy Review Committee on May 25, 1993, and was found to have met its technical commissioning goals.

- The close-out review of the construction project was followed by a safety review (attachment 2) to determine whether this facility had the necessary safeguards and procedures in place to be operated safely and to be a safe place for scientists to carry out experiments. The result of the safety review was that the necessary safeguards are in place and that the staff have environment, health, and safety uppermost in their concern in operating the facility.

- Many user scientists from Lawrence Berkeley Laboratory, industry, universities, and other Federal laboratories are anxious to begin experiments using the unique qualities of synchrotron light in the vacuum ultraviolet and X-ray spectral regions. They have committed substantial efforts and resources toward the design and fabrication of sophisticated instrumentation which will exploit the synchrotron light generated by the Advanced Light Source.

RECOMMENDATION: I recommend that the Acquisition Executive approve Key Decision 4 to begin operation of the Advanced Light Source.

ATTACHMENTS

APPROVED: 

DISAPPROVED: 

DATE: July 19, 1993

CONCURRENCES: 

180
# Comparison of Approximate Heat Flux Levels in Various Physical Processes

<table>
<thead>
<tr>
<th>Process Or Component</th>
<th>Approximate Heat Flux (w/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteor re-entry</td>
<td>100 to 500 — APS</td>
</tr>
<tr>
<td>Fusion reactor components</td>
<td>0.05 to 80</td>
</tr>
<tr>
<td>Sun's surface</td>
<td>60</td>
</tr>
<tr>
<td>Commercial plasma jet</td>
<td>20</td>
</tr>
<tr>
<td>Interior of rocket nozzle</td>
<td>10 — ALS</td>
</tr>
<tr>
<td>Fission reactor cores</td>
<td>1 to 2</td>
</tr>
</tbody>
</table>
* Will change to U10 in 1995
Operating Plans for FY93 and FY94

Beamlines

7.0 U5 Undulator --- materials
8.0 U5 Undulator --- surfaces & materials
9.0 U8 Undulator --- atomic physics & chemistry
9.3.1 Bend Magnet --- soft x-ray beamline
9.3.2 Bend Magnet --- surfaces and materials
10.3 Bend Magnet --- microprobe

Additional Bend-magnet Beamlines

3.1 .......... Diagnostic
6.1 .......... Microscopy
6.3 .......... Metrology
# ALS User Space Requirements

## Beamlines

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>IDT's</td>
<td>82</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
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<tr>
<td>BMT's</td>
<td>82</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
<td>8</td>
<td>10</td>
<td>14</td>
<td>21</td>
<td>24</td>
<td>27</td>
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## Users

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<tr>
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<tbody>
<tr>
<td>Users Total</td>
<td>450</td>
<td>100</td>
<td>200</td>
<td>250</td>
<td>350</td>
<td>475</td>
<td>600</td>
<td>725</td>
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<tr>
<td>Users/Year</td>
<td>.75</td>
<td>50</td>
<td>100</td>
<td>125</td>
<td>175</td>
<td>240</td>
<td>300</td>
<td>360</td>
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<tr>
<td>Users on site</td>
<td>24</td>
<td>16</td>
<td>32</td>
<td>40</td>
<td>56</td>
<td>76</td>
<td>96</td>
<td>118</td>
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## Cars

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<tr>
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<tbody>
<tr>
<td>Cars on site</td>
<td>45</td>
<td>10</td>
<td>20</td>
<td>25</td>
<td>35</td>
<td>48</td>
<td>60</td>
<td>72</td>
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## Lab and Office Space

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<tr>
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</thead>
<tbody>
<tr>
<td>Offices</td>
<td>428</td>
<td>18</td>
<td>20</td>
<td>28</td>
<td>38</td>
<td>48</td>
<td>58</td>
<td>68</td>
</tr>
<tr>
<td>Office Space (sq. ft)</td>
<td>1,800</td>
<td>2,400</td>
<td>3,000</td>
<td>4,200</td>
<td>5,700</td>
<td>7,200</td>
<td>8,700</td>
<td>10,200</td>
</tr>
<tr>
<td>Lab Space (sq. ft)</td>
<td>2,700</td>
<td>3,000</td>
<td>4,500</td>
<td>8,000</td>
<td>7,800</td>
<td>9,000</td>
<td>10,400</td>
<td>13,200</td>
</tr>
<tr>
<td>Labs and offices (sq. ft)</td>
<td>4,500</td>
<td>5,400</td>
<td>7,500</td>
<td>10,200</td>
<td>13,500</td>
<td>16,200</td>
<td>19,100</td>
<td>23,400</td>
</tr>
</tbody>
</table>

FS: June 5, 1992
(Update) FS: May 5, 1993
• Operations begin now
  — Construction project completed: April 1993
  — Installation of undulators and beamlines: May–July 1993 (shutdown)
  — Research program begins: August 1993

• Six user beamlines for FY93 and FY94

**Beamlines**

7.0 —— U5 Undulator —— materials
8.0 —— U5 Undulator —— surfaces & materials
9.0 —— U8 Undulator —— atomic physics & chemistry
9.3.1 —— Bend Magnet —— soft x-ray beamline
9.3.2 —— Bend Magnet —— surfaces and materials
10.3 —— Bend Magnet —— microprobe
...the end of the beginning.
Institute for Micromachining
Robert Warrington
Louisiana Tech University

August 3, 1993
MICROMANUFACTURING INITIATIVES IN LOUISIANA

1985  AT&T Foundation Planning Grant for Manufacturing

1986-89  AT&T Foundation Grant for Manufacturing Systems Engineering

1986  Focus on micromanufacturing; micro fluids and heat transfer, miniaturized cryogenic probes

1988  Award from the DOE for the Establishment of the Center for Advanced Microstructures and Devices (CAMD)

1989-92  AT&T Foundation Grant; Manufacturing Systems Engineering, Phase II, Focus Micromanufacturing

1990  Start Construction of CAMD Facility

1991  DOE Development Grant for Micromanufacturing First Injection for CAMD Storage Ring

1992  DOE Infrastructure Grant for IfM CAMD Synchrotron Operational

1992-93  State Appropriation for Equipment for the IfM State Line Item Funding for the IfM

1992-95  AT&T Foundation Grant, Phase III Award from DOE for the Establishment of the IfM

1993  X-ray Transport Lines and Exposure Station Ordered

1993  Groundbreaking IfM Facility
MICROMANUFACTURING

A set of processes for the creation of structures, devices or systems with feature sizes typically on the order of micrometers.
THE INSTITUTE FOR MICROMANUFACTURING

- A resource for the development of fabrication processes for the Industrial Utilization of Micro-Structures, Devices, or Systems.

- Diversity in process research activities with the ability to match the best miniaturization technologies for the economic manufacture of small products.

- Interdisciplinary and flexible organization capable of adapting to meet the needs of industry.

- Committed to partnerships with industry.

- Curricula development and education in the micromanufacturing technologies.
* A 40,000 ft$^2$ building dedicated to MEMS with 20,000 ft$^2$ of environmentally controlled and vibrationally isolated laboratory space. Initially, 2,500 ft$^2$ of cleanroom will be installed with future expansion capacity to 5,000 ft$^2$.

* State supported positions for the Institute.

* Conventional photolithography and chemical etch for surface and bulk micromachining of silicon.

* Teaching laboratories for MEMS processing will be included.

* X-ray micromachining using the CAMD synchrotron (critical wavelengths of 4.8 angstroms have been achieved at 1.5 Gev; 125 ma and 200 ma at 1.5 Gev appears possible). The beamline and exposure station have been ordered and the IfM effort should be operational in early 1994.

* Post Processing for LIGA (lithography, electroplating and injection molding) for the production of high aspect ratio parts in plastics, metals, etc.) will be available at the IfM in late 1993.

* Alternative micromachining capabilities will include diamond turning, microdrilling, micro edm, focused ion beam, laser, and precision sawing.

* Metrology and testing for MEMS processes including SEM, AFM, STM, interferometric microscopes, etc.
OPTICAL AND X-RAY LITHOGRAPHY PROCESSES
Institute for Micromanufacturing - Louisiana Tech University

** OPTICAL MASK FABRICATION (F):** The Institute will have the ability to generate optical masks. A pattern generator capable of 1μm resolution will be used to create the desired features on reticle emulsions. Then these will be developed to produce the desired reticules and masks. Applications: contact, proximity and projection printing, and step-and-repeat printing.

** X-RAY MASK FABRICATION (F):** The Institute will have the ability to fabricate X-ray masks for micromachining applications (not necessarily sub-micron feature sizes). These masks will be a multilayer metal Ta/Au/Ta absorber on polyimide structure. Applications: Exposure of high-aspect ratio microstructures in polymethylmethacrylate at the CAMD synchrotron in Baton Rouge, LA.

** BULK PROCESSING (F):** The Institute will have the necessary equipment to perform both isotropic and anisotropic etching of silicon wafers using wet and dry processes. The Institute will also have the capability to perform anodic wafer bonding. Applications: Create single-crystal structures in Si and to release microstructures from the wafer substrate.

** SURFACE PROCESSING (F):** The infrastructure to deposit surface and sacrificial layers will be available in the Institute. Film deposition will be done by both CVD and sputtering while film removal will be accomplished with both dry etching with RIE and wet etching facilities. Application: the fabrication of MEMS devices and actuators using polycrystalline material.

** X-RAY LITHOGRAPHY (C/F):** A Linac linear accelerator and a synchrotron storage ring have been commissioned at CAMD, in Baton Rouge, Louisiana. The Institute has purchased a beamline and exposure station for this synchrotron. The Institute’s beamline and exposure station are dedicated to the fabrication of high-aspect ratio microstructures (not VLSI). Applications: creation of deep trenches with aspect ratios better than 10.1 and several hundred microns in depth.

(C) Process capability currently in routine use.
(C/F) Process capability currently being acquired/under development.
(D) Process capability to be acquired/developed during 199X.
ELECTROPLATING (C/F): The trench-like features created in the resist exposed to x-rays in the synchrotron can be "filled" with metal by electroplating. Removal of the resist yields metallic microstructures. These metallic structures can be the final structure or they can in turn be used to create other microstructures by extrusion. Applications: researchers have already used this technique to make micromotors, microvalves, micronozzles, etc.

INJECTION MOLDING (F): The microstructures made by electroplating can be used as positive molds to generate polymeric female microstructures by injection molding of the polymeric bulk material. Applications: mass production of microstructures using the x-ray-made master parts.

COMPLEMENTARY MICROMANUFACTURING PROCESS CAPABILITIES

MICRODIAMOND MACHINING (C): Machining a variety of materials with diamond cutting edge dimensions are typically 100 micrometers or less. Very small precision features are possible with excellent surface finish. Applications: Ultra-high flux microcompact heat exchangers, Actively cooled metal optics, Post-processing of photoresist and LIGA molds, Direct machining of micromechanical parts.

FOCUSED ION BEAM MACHINING (C): Machining any material with a focused beam of high energy ions. Couples a relatively high material removal rate with micrometer-sized features with nanometer tolerances. Applications: Special tips for scanning probe microscopy, Fabrication of micromechanical and diamond tooling, Post-processing of parts produced by LIGA, Direct writing of surface features.

MICRODRILLING/MICROMILLING (C): Mechanical drilling and milling with micro tools below 100 micrometers in diameter. Cobalt steel or tungsten carbide tools provide very clean holes in metals and plastics. Applications: Nozzles, injectors, etchings to 2.5 micrometers diameter, Optical fiber connectors, Convection enhancement and drag reduction in micro heat transfer.

MICRO ELECTROPLATING (C): The mass fabrication of metallic micro parts is possible by electroplating material into dies/molds made with lithographic or complementary processes. The molds are of any suitable material which may be etched away to release the parts. Applications: Microelectrical mechanical systems (MEMS) components, Micro gears, motors, sensors, actuators, flow controls.

MICRO ELECTRICAL DISCHARGE MACHINING (C/F): Micro-EDM allows production of micro features (holes, slots, etc.) in any electrically conductive material. Can be adapted for micro turning operations. Applications: Especially suitable for difficult materials such as titanium, carbides, etc., Production of round parts of non-diamond machinable metals.

(C) Process capability currently in routine use.

(C/F) Process capability currently being acquired/under development.

(F) Process capability to be acquired/developed during 1994.
**LASER ABLATIVE/CURING MICROMACHINING (C/F):** The use of ultraviolet (excimer) laser light to vaporize material at high energy density or to cure photoresist at low energy density. Spot size can be sub-micrometer in diameter. Applications: Direct writing on ceramics, diamond, or other "easy" materials, Direct-write curing of UV resists (polyimide, etc.) for LIGA mold making, Rapid prototyping of micromechanical parts...

**MICRO INJECTION MOLDING (F):** Injection molding of plastics or low melting point metals around lithography-fabricated "cores" to form die/molds for subsequent electroplating of micro parts. Allows mass-fabrication of micromanufactured parts from a single x-ray lithography exposure. Applications: Mold fabrication for mass production of micromanufactured parts and components, Mass production of plastic micro parts for valves, insulators, etc.

**MICROMETROLOGY CAPABILITIES**

**SCANNING ELECTRON MICROSCOPY**

**C**

AMRAY 1830/T4 with LaB6 source configured for electron beam writing with RAITH/ELPHY II, Multi-level Alignment, and Proximity Correction. TV-rate scanning for real-time dynamic imaging of microdevices.

**C**

CAMBRIDGE 250 with LAB6 source configured for x-ray microanalysis with KEVEX SESAME system.

**F**

FIELD EMISSION scanning electron microscope configured for low-voltage imaging of photoresists and other insulators and electronsensitive materials. Computer enhancement and critical dimension measurement package.

**SCANNING PROBE MICROSCOPY**

**C**

WYKO MicroProbe 3-D scanning probe microscope with atomic force, scanning tunneling, nanolithography and atomic resolution capability. Specially configured input and output module for maximum user flexibility and dedicated research. Research test-bed for custom tip fabrication using complementary micromanufacturing processes.

**LARGE RANGE VERTICAL METROLOGY**

**C**

WYKO Roughness/Step Tester (RST) non-contact microscopy for vertical features ranging from 3 Angstroms to 100 micrometers peak-to-valley. Field of view from 100 micrometers square to 2 millimeters square with 2-D linescan and 3-D image analysis.
Stylus Profilometer for contact metrology of thin, transparent films and large vertical features. Measurement range from Angstroms to approximately 300 micrometers. Extra-low contact force head for sensitive materials such as resists.

** IN-PROCESS METROLOGY **

Long Working Distance Microscopes with photo, video, and computer imaging capabilities. Microscopes will be used to monitor microdiamond machining operations, electroplating and micro injection molding, and microdrilling/micromilling. Vision systems will also be used in the continued development of automated inspection and quality control of micromanufacturing processes and products.

(C) Process capability currently in routine use.
(C) Process capability currently being acquired under development.
(C) Process capability to be acquired/developed during 1994.
Diamond Machined Micro Shaft

30um diameter by 110um long

shown relative to 4mm stock

Initial attempt, poor quality tool, eyeball alignment
CURRENT PROJECTS

• SMART BEARING
• SURFACE DRIVER ELECTROSTATIC POSITIONER
• DIAMOND TURNED MICROHEAT EXCHANGER
• FOCUSED ION BEAM MICROMILLING
• MEMS SIMULATION/MODELING
• OPTICAL TWEEZERS FOR MICROASSEMBLY
• LIGA PROCESSING
• CHARACTERIZATION OF MEMS SURFACES USING FRACTALS
• STEREO LITHOGRAPHY AT THE MICROSCALE
• PROCESS IMPLEMENTATION
Anchor Tenant for Research Park

Services (Chemical Analysis and
Fabrication, Manufacturing)
Industrial Applications (R&D, Prototype
Research (Basic & Applied)
Education

CAMP MISSION
COLLABORATIONS/COORDINATION

- Louisiana Tech University, Ruston, LA
- TNT
  - Tulane University, New Orleans, LA
  - NIST, Washington, DC
  - University of Tennessee, Knoxville, TN
- LNLS Campinas, Brazil
- North Carolina State University, Raleigh, NC
- MCNC Research Triangle Park, NC
- Science and Engineering Alliance, Washington, DC
- Northeast Louisiana University, Monroe, LA
- Naval Research Laboratory, Washington, DC
- CXrL at University of Wisconsin, Madison, WI
- IBM East Fishkill, NY
- ANORAD, Hauppauge, NY
- ANVIK, Elmsford, NY
CAMD Status May, 1993

Building                                           completed, May 1991

Linac Injector                                     in Operation since 9/91

Storage Ring                                       
first Injection Oct. 27/91
Beam ramped to 1.2 GeV
June 3, 1992;
311 mA @ 1.3 GeV 10/22/92
157 mA @ 1.4 GeV 8/25/92
115 mA @ 1.5 GeV 8/25/92
200 mA @ 1.3 GeV Routine

Accept. of Acc. System                             August 29, 1992

XRL Beamline                                       Commissioning
Basic Sciences Beaml.  Commissioning
LNLS Beaml.                                          Operation
TNT Beaml.                                           Delivery June 1993
SURA Beaml.                                         Design Phase
Louis. Tech. Beamlines(2)                          Installation End of 1993
Harder X-Ray Beaml.                               August 1993 (?)

Clean Room                                         Installation compl. Mar. 93
Exposure Tool/Stepper                              Delivery June 1993
Ancillary Equipment                                Partly acquired or funded
LIGA Stepper (Loui.Tech)                           May 1994

SC-Wiggler                                         Proposal completed
Circ. Pol. Undulator                               Proposal completed
CAMD Facility Layout

X-Ray Lithography Sector

Micromachining & LIGA
Area (Class 1000)

Beam Lines

2A Louisiana Tech University Micromachining (LTUMM1)
2B Louisiana Tech University Micromachining (LTUMM2)
4A Plane Grating Monochromator (PGM)
5B Diagnostic Port (DP)
6A Variable-Line-Space Grating Monochromator (VLSGM)
6B Toroidal Grating Monochromator (TGM)
7A X-Ray Lithography 1 (XRL1)
ID1 Undulator
ID2 Wavelength Shifter (Wiggler)

Other beamlines are in design phase. Space allocation is not determined.

May 1993
EDUCATIONAL INITIATIVES IN MICROMANUFACTURING

1. Technical Enrichment Program

Micromanufacturing learning modules designed for undergraduates, typically sophomores and juniors

2. Senior level technical electives

Micromanufacturing I and II covering lithographic processes, complementary micromachining processes and micrometrology

3. Five new graduate courses will be developed over the next several years

Fundamentals of Microengineering
Metrology and Probe Microscopy
Complementary Micromachining Processes
Microsensors in Automated Manufacturing
Advanced Topics in Micromanufacturing Processes
ENGINEERING FOUNDATION CONFERENCE
ON
THE MANUFACTURE OF
MICROELECTROMECHANICAL SYSTEMS

Late Summer/Fall 1994
Banff, Alberta, Canada

A conference which will focus on the problems and opportunities for the manufacture of microelectromechanical systems, including the transfer/management of the technology. The roles of Industry, Government, and Universities will be examined and the development of support infrastructure will be discussed.
IBM MEMS Interests
Longshen Fan
IBM Almaden

August 3, 1993
MEMS for DATA STORAGE

• Overview
• Micromotors
• Shock, Acceleration Detectors
• Track-Registration Servo Devices
• Flying Height Adjustment Devices
• Suspensions
• Load/Unload Mechanisms
• Si-based Sliders
• Optical Storage Applications
• Advanced Data Storage Applications
Storage Hierarchy

- **Decreased Cost**
  - Cache
  - RAM
  - I/O Cache
  - Magnetic Disk
  - Library (Optical Disk, Mag. Tape)
  - Offline Storage

- **Increased Performance**
  - ns
  - 10 ns
  - 100 ns
  - 10 ms
  - 10 s

L.S.Fan (March 1993)
High-Performance Data Storage Systems

- 50% of the total system cost is in the storage system
- Bank of America, San Francisco, (4 large computers, IBM 3090)

- 1 GB of main storage
- 1 GB of extended storage
- 416 MB of solid-state disk
- 96 MB of disk cache (within controller)
- 750 GB of magnetic disk
- 2000 x 200 MB tape cartridges/day

- 24 hour operation: 12 hour on-line; 12 hour batch
- 20 - 30% growth in capacity
- cost/MB and MB/cu.ft. are key metrics

R. Katz
Components for Magnetic Data Storage

- Rotating Magnetic Disk
- Suspension
- Rotary Actuator + Voice-coil Motor
- Slider + Read/Write Head
- Spindle Motor
Trends in Magnetic Data Storage*

- Higher areal densities
- Higher data transfer rates
- Lower power consumption
- Smaller form factor; lower drive height
- Lower flying heights
- Decreased disk spacing
- Ruggedized products
Electrostatic Micromotors

• Several groups (UCBerkeley, Case, MIT, U. Neuchatel, U. Michigan, Karlsruhe, U. Tokyo, IBM, ...)

• Primarily low-torque devices, commonly a few μm Si

• Potential torque improvements:
  — Wobble motor (harmonic motor)
  — Increase height

• IBM-Research/U. Tokyo collaboration; Furuhata, et al., 1993
  — Initial structure: 7 μm thick Ni, 100 μm diameter, 10,000 rpm, \( \sim 10^6 \) s lifetime.
  — Recent structure: 20 μm thick Cu, 1-6 mm diameter, constructed at IBM-Almaden, under evaluation.
Microactuators for Storage

- Spindle motors for small disk
- Positioning actuator for small HSA
- Tracking fine actuator
ELECTROSTATIC WOBBLE MOTOR

A complete electrical excitation cycle causes only a fraction of a rotation, effectively amplifying torque.
Micro motor

Fabrication sequence of low frictional drive

(a) Resist
(b) Sputtered nickel
(c) Electro-plated nickel
(d) Silicon nitride
(e) Silicon substrate

Stator Rotor Shaft
Plated Electrostatic Wobble Motor


\[ T \propto r^3 V^2 h \Delta d^{-3} \]
Plated Electrostatic Wobble Motor

Shock, Acceleration Detectors

- Primarily to eliminate spurious writing

- Cost may limit sophistication of MEMS device

- Potential future application: accelerometer to assist in track following
Gigabit Demonstration

10 Gigabit?

Microactuator
Microactuator for Two-Stage Track Registration Servo

- Slider motion
- Thick plated copper (20 μm); millimechanics
Top view and cross section of an electric crab-leg flexure.
SEM micrograph of thick photoresist plating stencil for 2 µm gap electrodes.
SEM micrograph of a microactuator.
Micro-Actuator Frequency Response Functions

Mobility Magnitude (arb. units)

Frequency (kHz)
Flying Height Adjustment Techniques

- C. Yeack-Scranton, et al., IBM, 1986: "Taildragger" piezoelectric bender to reduce head-disk spacing

![Diagram of piezoelectric bender system]


![Diagram of dual slider system]
Thermo-mechanical Writing with an AFM Tip

- Tip is illuminated by focused laser beam
- Tip acts as nanometer-scale local heat source
- Plastic is heated above softening point
  - Local stress creates indentation

D. Rugar and H.J. Mamin
Figure 2. (a) AFM image of a pit written in PMMA. Pit is roughly 300 nm in diameter
(b) AFM image of the IBM logo written between the grooves of an optical disk. The individual pits are approximately 100 nm in diameter.

Figure 3. The AFM image of several tracks written on a rotating PMMA substrate. A blow-up of one section of track.
MEMS for DATA STORAGE

- Overview
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- Load/Unload Mechanisms
- Si-based Sliders
- Optical Storage Applications
- Advanced Data Storage Applications
HAR-MEMMS at LBL

Technology Transfer at Lawrence Berkeley Laboratory
Cheryl A. Fragiadakis
Technology Transfer Department
LBL

August 3, 1993
Defining Success

- Contribution to U.S. economy
- Contribution to industries and companies
  - Defined by partner
    - Responsive
    - Reliable
    - Results
  - Proxies for success
    - Repeat business
    - Milestone and budget control
- Contribution to Laboratory mission: leveraging the Lab investment
- Startup company, licensee of LBL technology
- Rechargeable lithium/polymer battery
  - Three to four times the storage capacity of conventional batteries
  - Non-toxic and environmentally benign
- Aiming at electric vehicle and consumer markets
USABC

- $260 Million CRADA with Consortium of US Automakers and Department of Energy
- Goal to develop advanced batteries for electric cars
  - LBL contributing lithium/polymer battery expertise
- By 1998, two percent of cars sold in California must be "zero-emission"

GM Prototype Electric Car
California Institute for Energy Efficiency (CIEE)

- $20M CRADA with Consortium of California Utility Companies

Mission:
- Improve energy efficiency in buildings, industry and transportation;
- Improve air quality; and
- Develop better end-use resource planning
CIEE designed to fill the "R&D" gap

- Industry R&D: Emphasis on Short-Term return
- Laboratory/University R&D: Long-Range return
- CIEE "bridges the gap"
Keys to Being a Good Business Partner

- **Reliability**
  - Companies need to be able to count on timely funding decision
  - Companies need to rely on predictable business terms

- **Value added**
  - Each partner must add value by bringing particular expertise, facilities or resources

- **Responsiveness**
  - LBL must be able to act quickly
  - Industry has a time frame commitment with a business cycle
Partnership Indicators on the Rise

CRADAs

- FY 91: 0
- FY 92: 6
- FY 93: 10
- FY 94: 20 (projected)

Licenses

- FY 89: 0
- FY 90: 1
- FY 91: 6
- FY 92: 5
- FY 93: 13

Inquiries

- FY 89: 149
- 1990: 171
- 1991: 329
- 1992: 587
- 1993: 1000

WFO $M

- FY 90: 38
- FY 91: 38
- FY 92: 42
- FY 93: 45

(1993 Projected)
Opportunities for High Aspect Ratio Micro-Electro-Magnetic-Mechanical Systems (HAR-MEMMS) at Lawrence Berkeley Laboratory (LBL)

August 3, 1993

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August 3, 1993

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August 3, 1993

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Opportunities for High Aspect Ratio Micro-Electro-Magnetic-Mechanical Systems (HAR-MEMMS) at Lawrence Berkeley Laboratory (LBL)

August 3, 1993

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