LBL-34767
UC-411

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

Edited By Steven Hunter

Technology Transfer Department
Administration Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

October 1993

MASTER

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Table of Contents

Proceedings of
HAR-MEMMS Workshop at LBL
August 3, 1993

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

6

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 Acuators Center" Richard Muller, and Dick White
- "The Institute for Micromachining" Robert Warrington La Tech

National Laboratories

- "Space Microsensors and Microinstruments" Tom Kenny JPL
- "MEMMS activities at LLNL" Dino Ciarlo LLNL

Industrial Contributions

- "IBM MEMS Interests" Longshen Fan IBM
- "Commercial Sensor Applications" Hal Jerman IC Sensors

Benifits Obtainable with Microsystems

- Reduction of energy comsumption 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 x 2.6 x 2.6 = 17.6 in^2

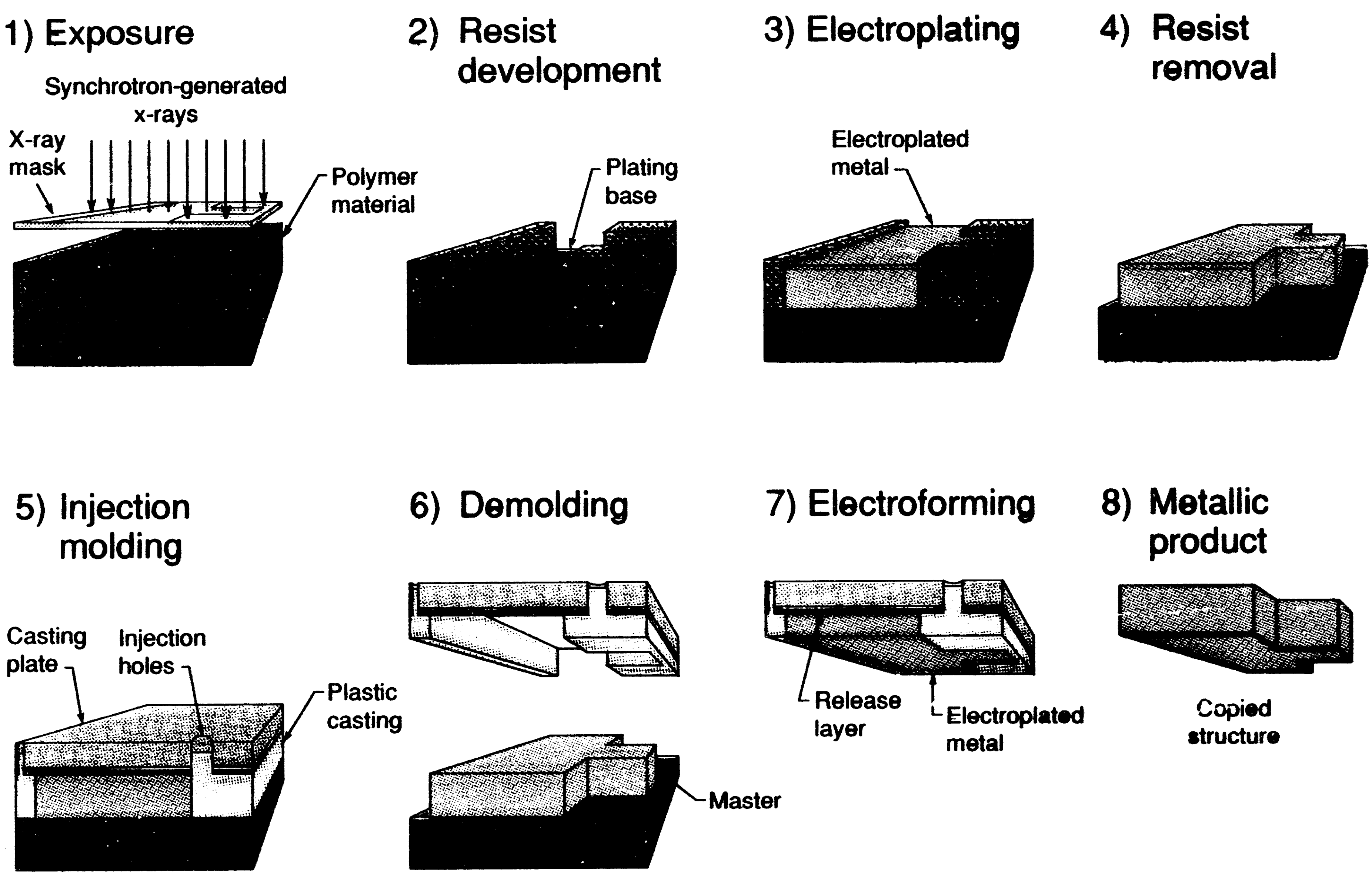
"Small is really what matters"

"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

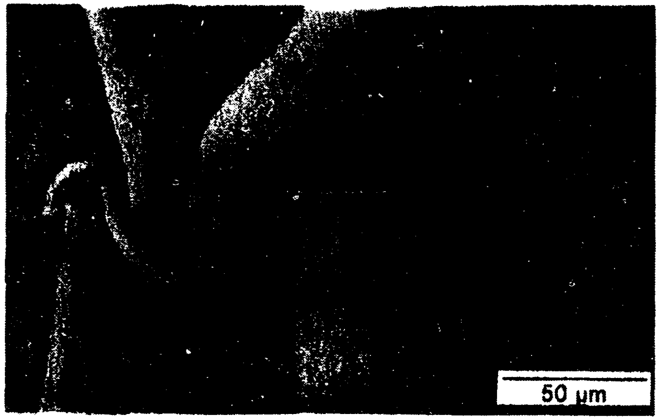


Prototypes of microproducts produced using deep etch x-ray lithography

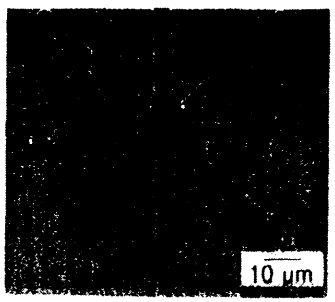
- Sensors for the measurement of physical, chemical, and physiological processes.
- Actuators and micromotors
- Microvalves and nozzles
- Micromechanical elements
- Components for integrated optics
- Electrical and Optical microconnectors
- Microfiltration systems

12

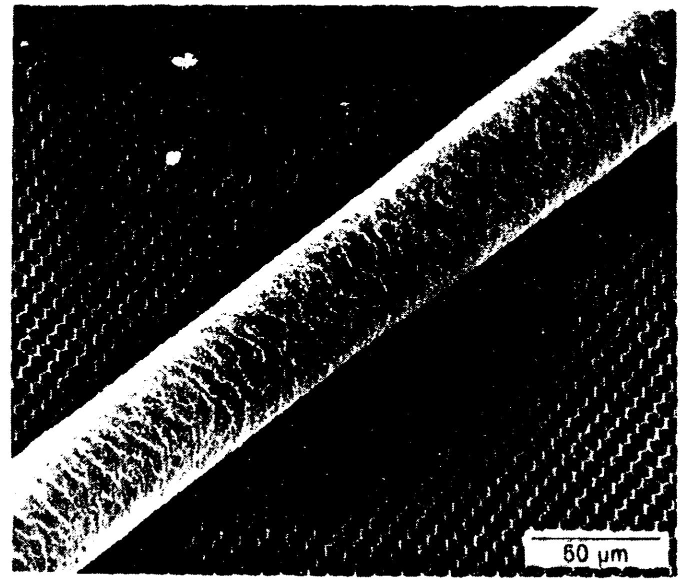
Filters and Nozzles Fabricated with LIGA



Separation nozzle



Spinneret nozzle



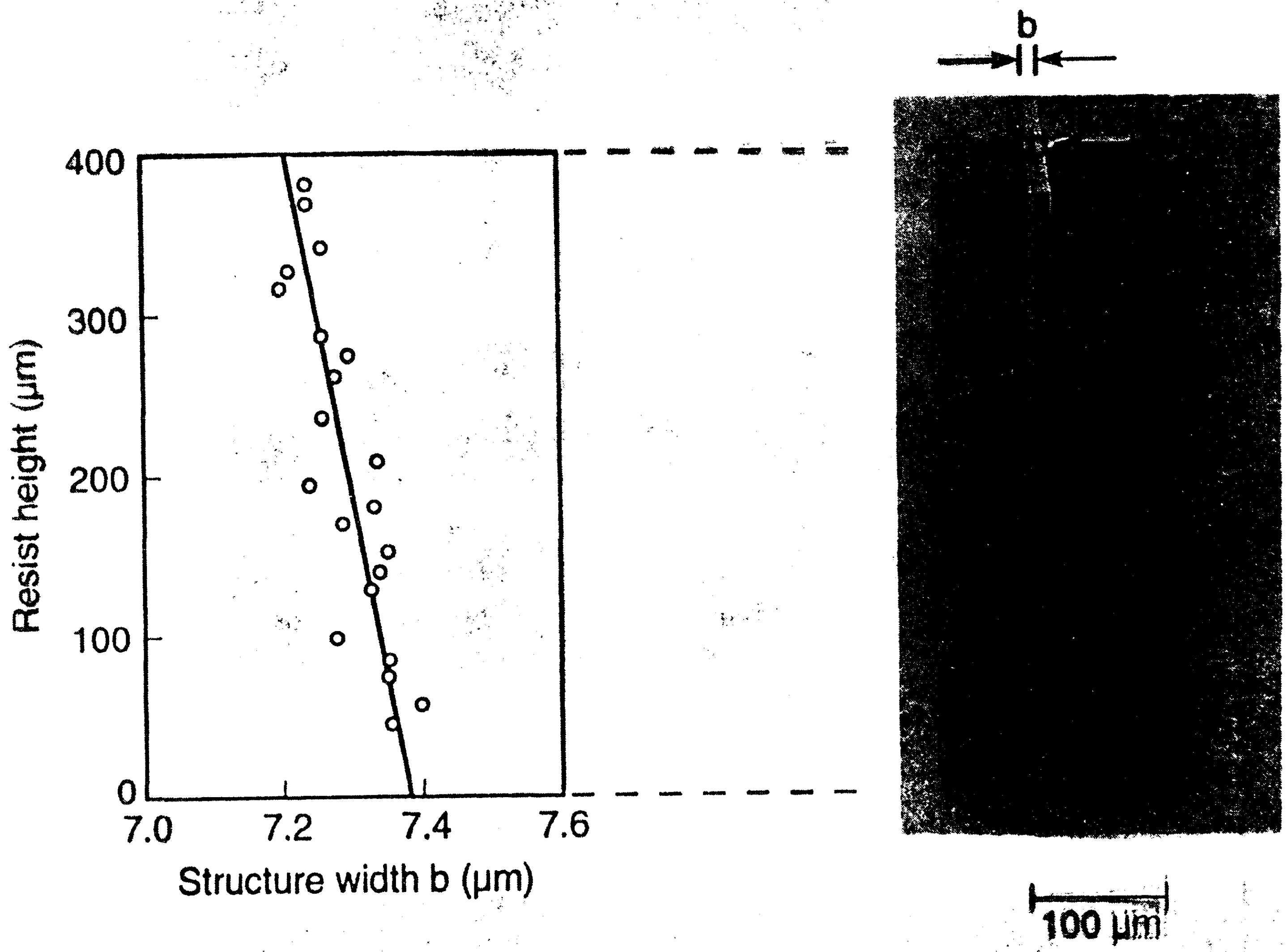
LIGA microfilter compared to a human hair

Source: KfK, Karlsruhe, Germany

Fiber Optic Flow Sensor

Source: KfK, Karlsruhe, Germany

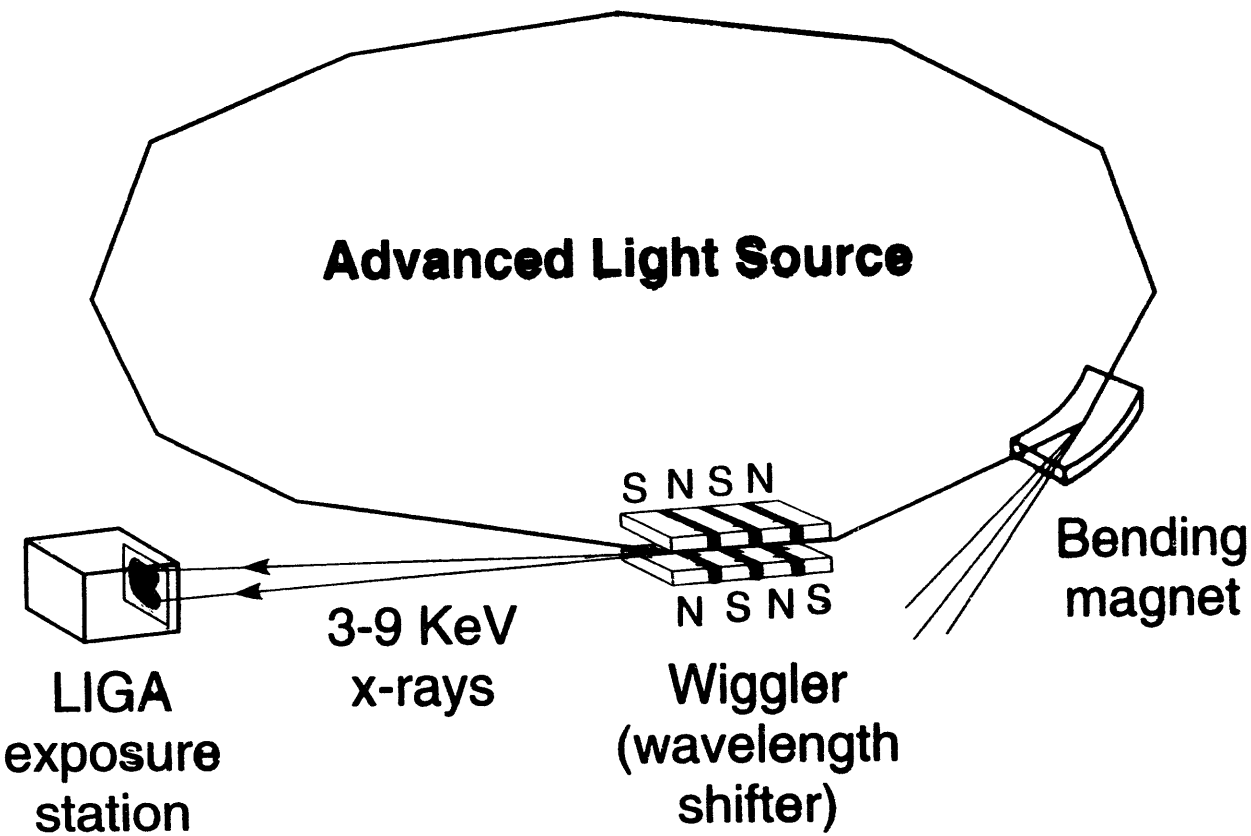
Structural Accuracy of Deep X-ray Lithography



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

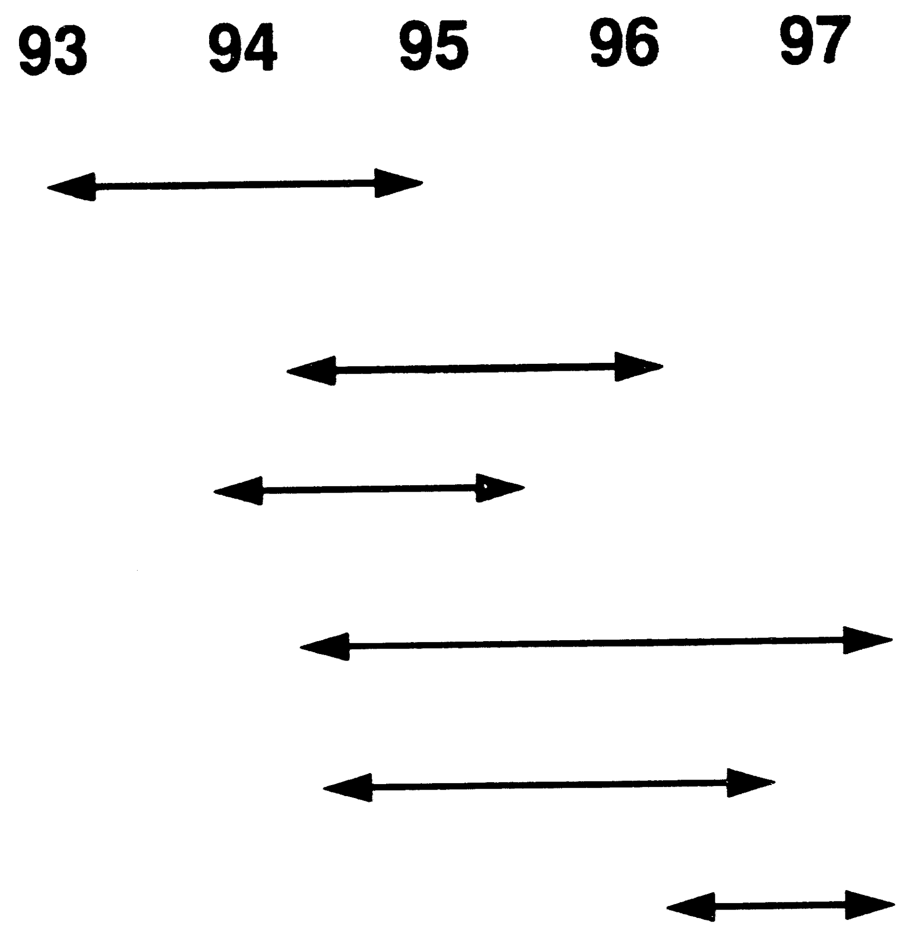


XBL 937-4832

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

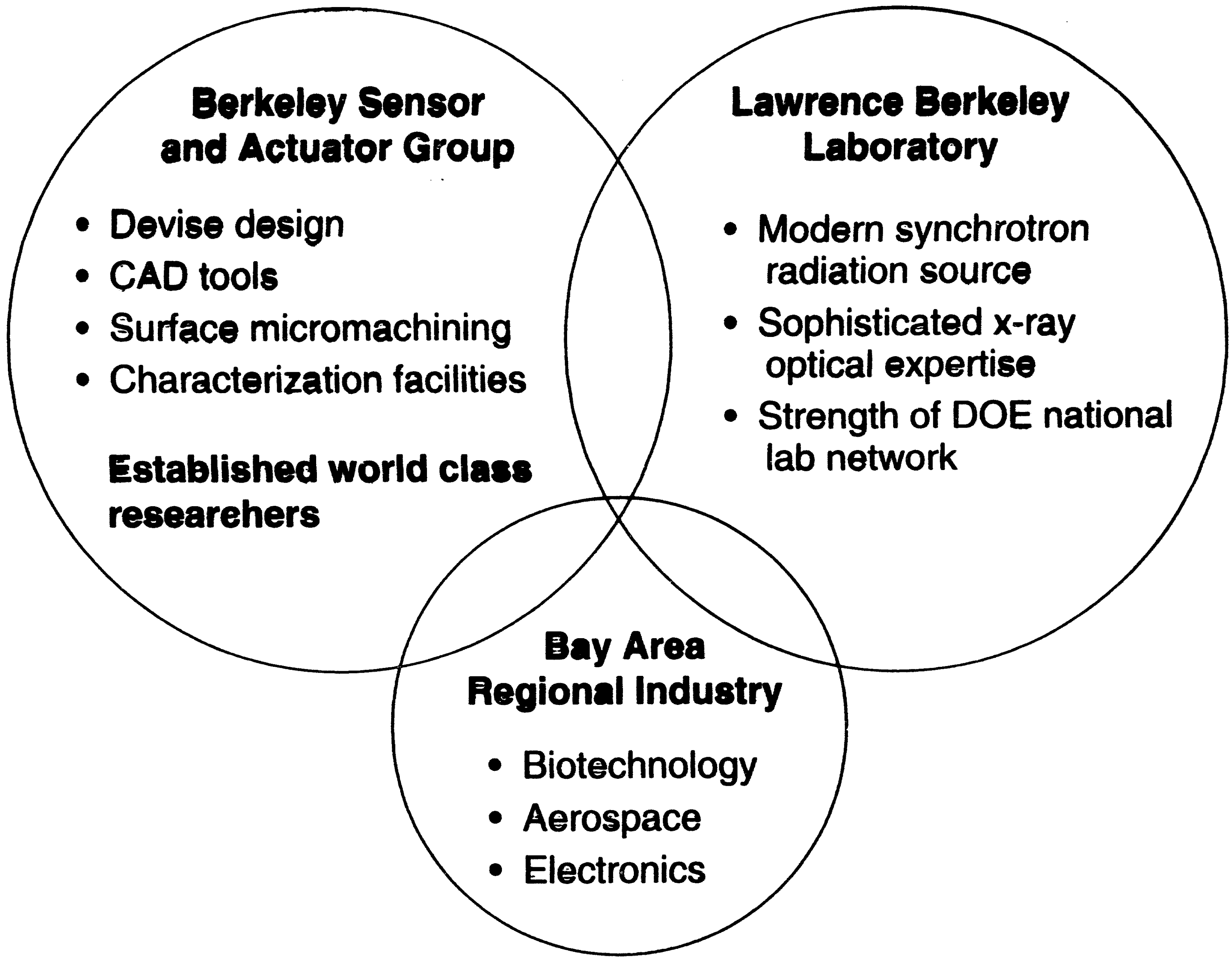
Phase 2

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



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 a excellent source of 3-10 keV x-rays.
- UCB has a vigorous microelectromechanical research program.
- LBL has a ongoing research programs 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

22

tech transfer

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

tech transfer

DEMONSTATE EXISTING PROCESS IN RESEARCH MODE-EDUCATE USERS

DEFINE PROCESS CONTROL PARAMETERS

PROVIDE DUPLICATIVE INFRASTRUCTURE

NEW PROCESSES, LIMITS, MODELS

REALISTIC COST MODELING

EXISTING PROCESS

tech transfer

KfK LIGA transfered 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

tech transfer

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

tech transfer

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

tech transfer

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

tech transfer

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

tech transfer

$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

#wafers	1	30	100	1000
#dies	1.5e2	4.6e3	1.5e4	1.5e5
#widgets	1.4e5	4.1e6	1.4e7	1.4e8
$/wafer	5.4e3	5.3e2	4.1e2	3.7e2
$/die	3.5e1	3.5e0	2.7e0	2.4e0
$/widget	3.9e-2	1.3e-4	3.0e-5	2.7e-6

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

32

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)

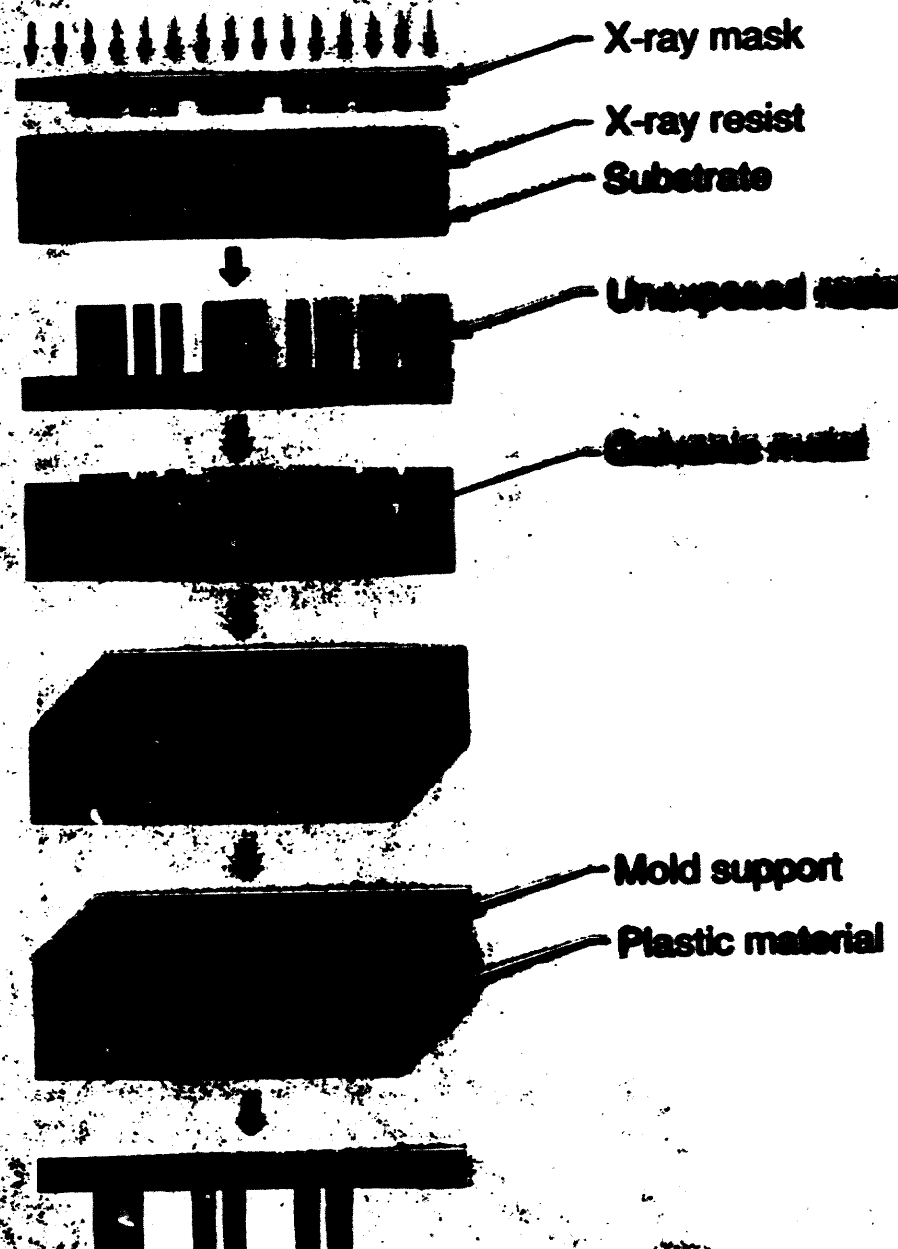
Resist development

Electroforming

Resist removal

Plastic molding

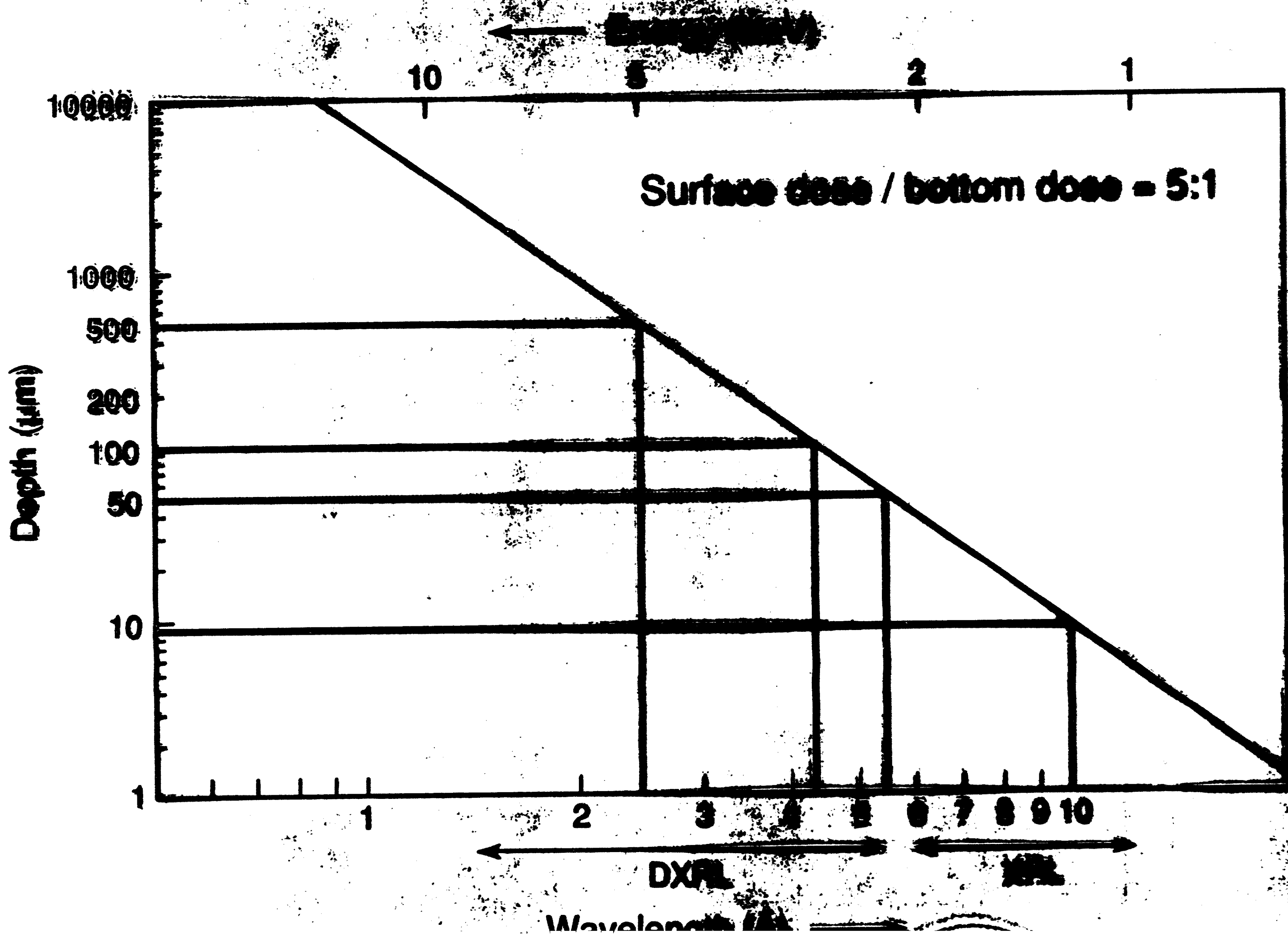
Final part



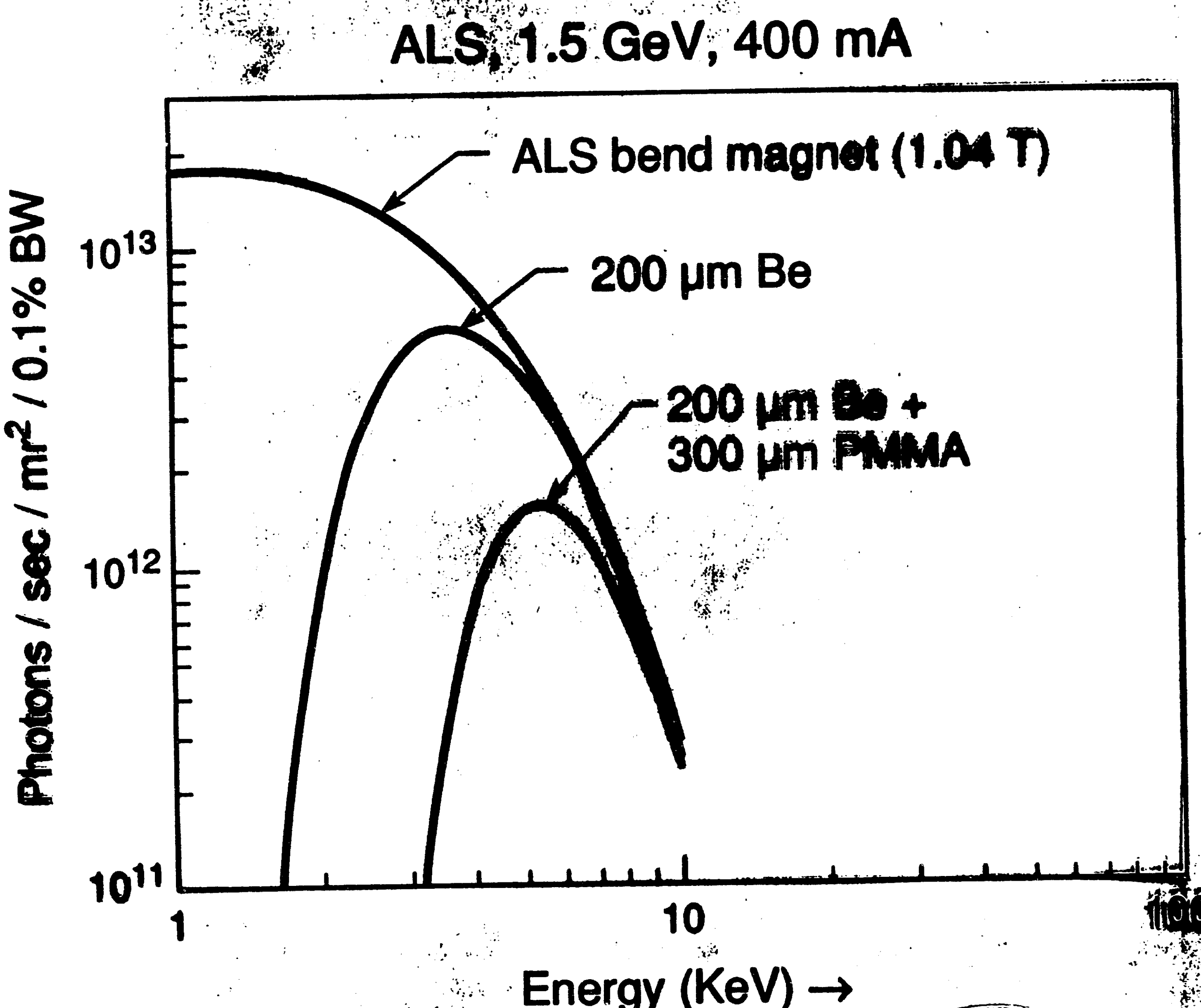
SOURCE REQUIREMENTS FOR DEEP ETCH LITHOGRAPHY

- **Short wavelength**
  - Uniform energy deposition with depth into resist
    - 1.4 - 5 Å (3 to 9 keV)
- **High flux**
  - ALS
    - Bend magnet: [illegible] W/cm^2 at [illegible] m for 3 - 9 keV
- **Collimation**
  - Good replication quality
    - 1 mrad => 0.1 µm shift / 100 µm height

Maximum Structure Height in PMMA as a Function of Wavelength



Photon Flux at the ALS Bend Magnet for Deep Etch Lithography



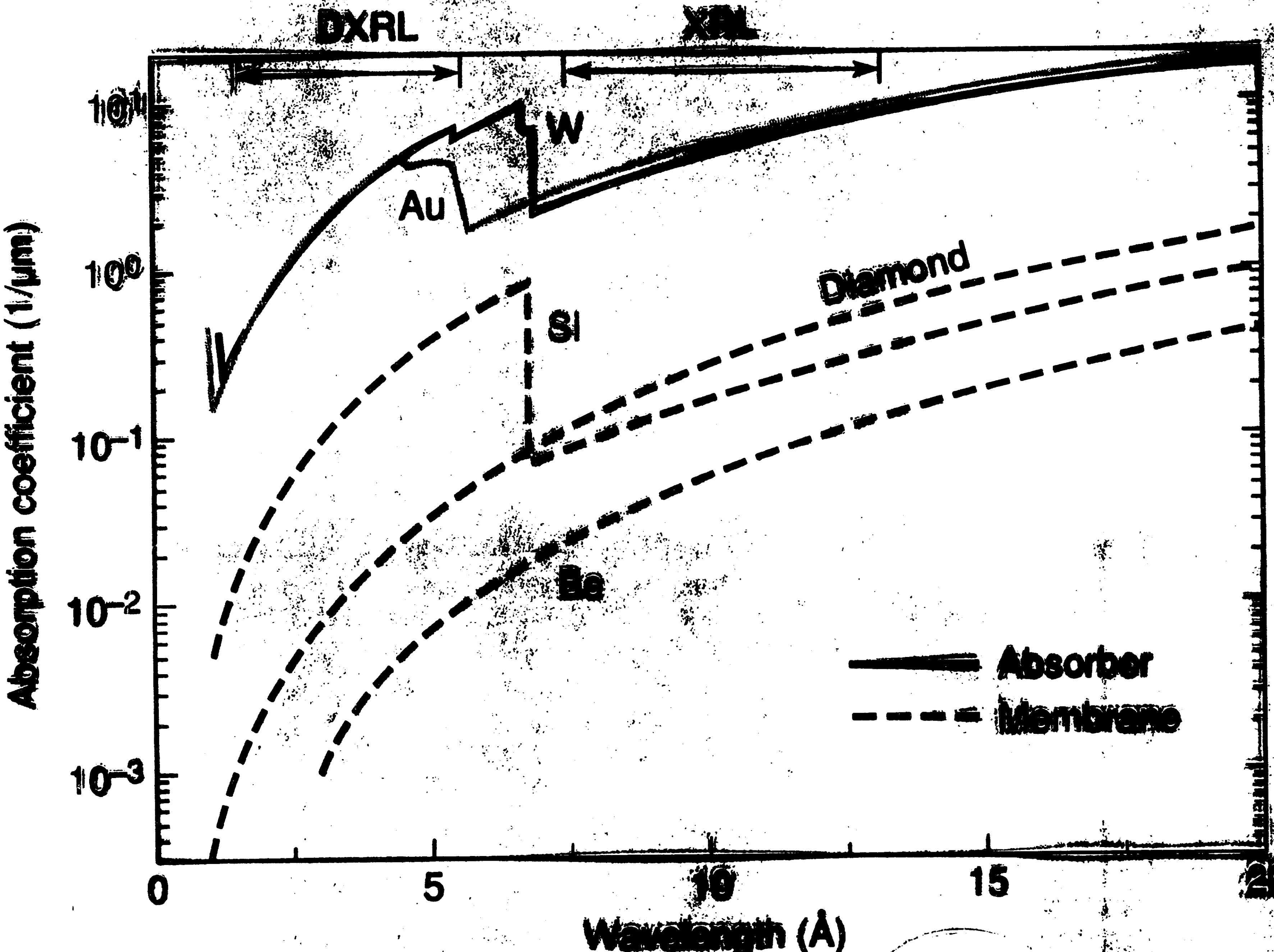
MASK FOR DEEP ETCH LITHOGRAPHY

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

Mask substrate	Absorber pattern

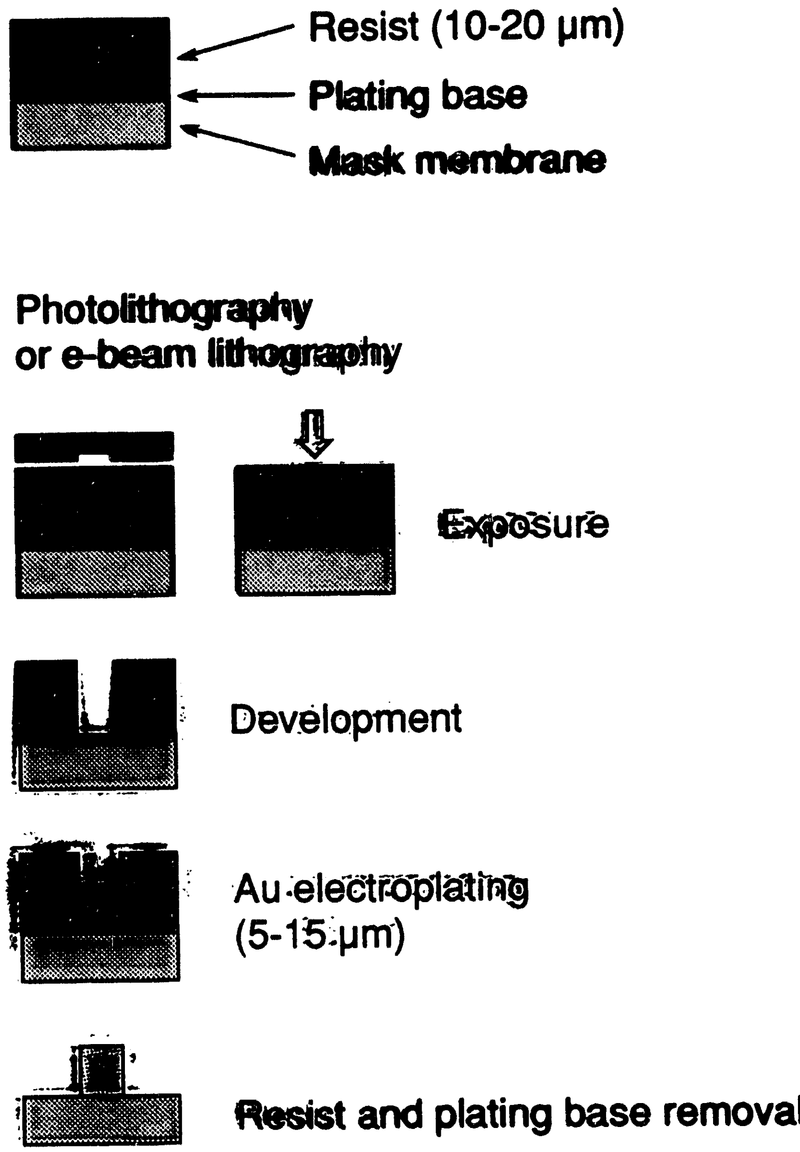
• X-ray transparent
  - light material
  - thin membrane
• Good mechanical properties
  - high Young's modulus
• Radiation resistant
• Optically transparent
	• X-ray absorbing structures
	  - heavy material
	  - absorber thickness: 5-15 μm
	  - minimum lateral width: 1 μm
	  - vertical walls
	• Low stress

Mask Materials for Deep X-ray Lithography



Mask Fabrication for Deep Etch Lithography

1 Step Fabrication Process



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/cm^3 at bottom, up to 20 kJ/cm^3 at top
- **Development**
  - Specially tailored developer "G-G" (Ghia-Glashauser)
    - » highly selective
    - » minimization of stress corrosion

EXPOSURE STRATEGY FOR DEEP ETCH LITHOGRAPHY

–Scanner

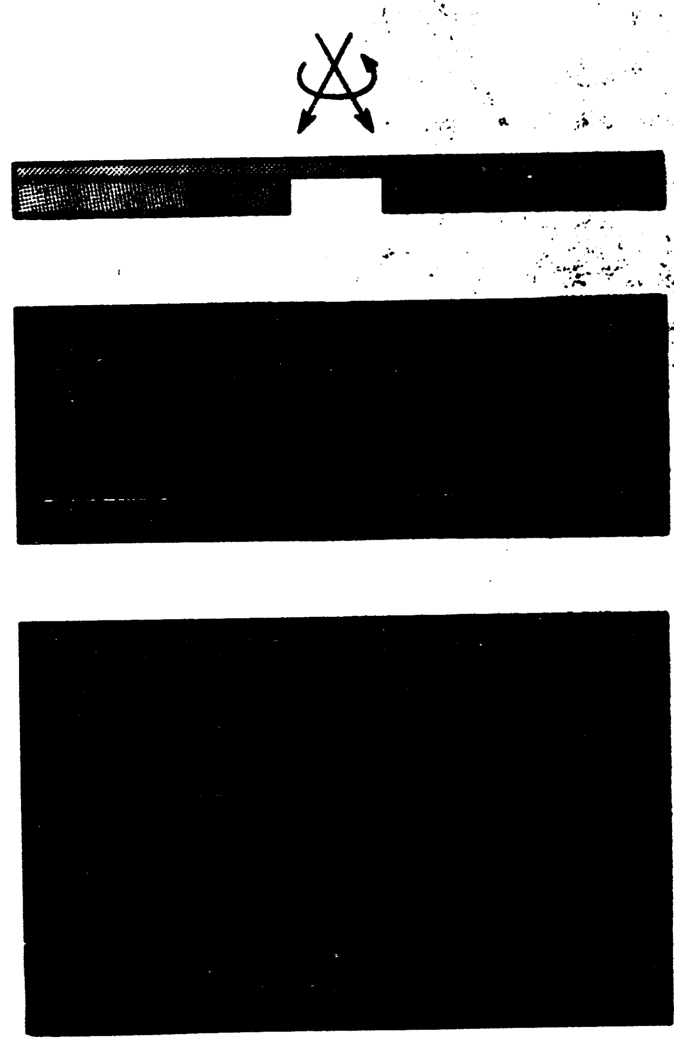
- » Proximity printing
  - • 50 μm mask / substrate gap
- » Vertical movement of mask/substrate ensemble
  - • parallelism tolerance below 0. 1 mrad
  - • Heat removal
    - – Speed 50 - 100 mm/s
    - – He atmosphere
    - – Cooled substrate
- » Multiple exposures
  - • Alignment

–Tilted exposures / Rotation

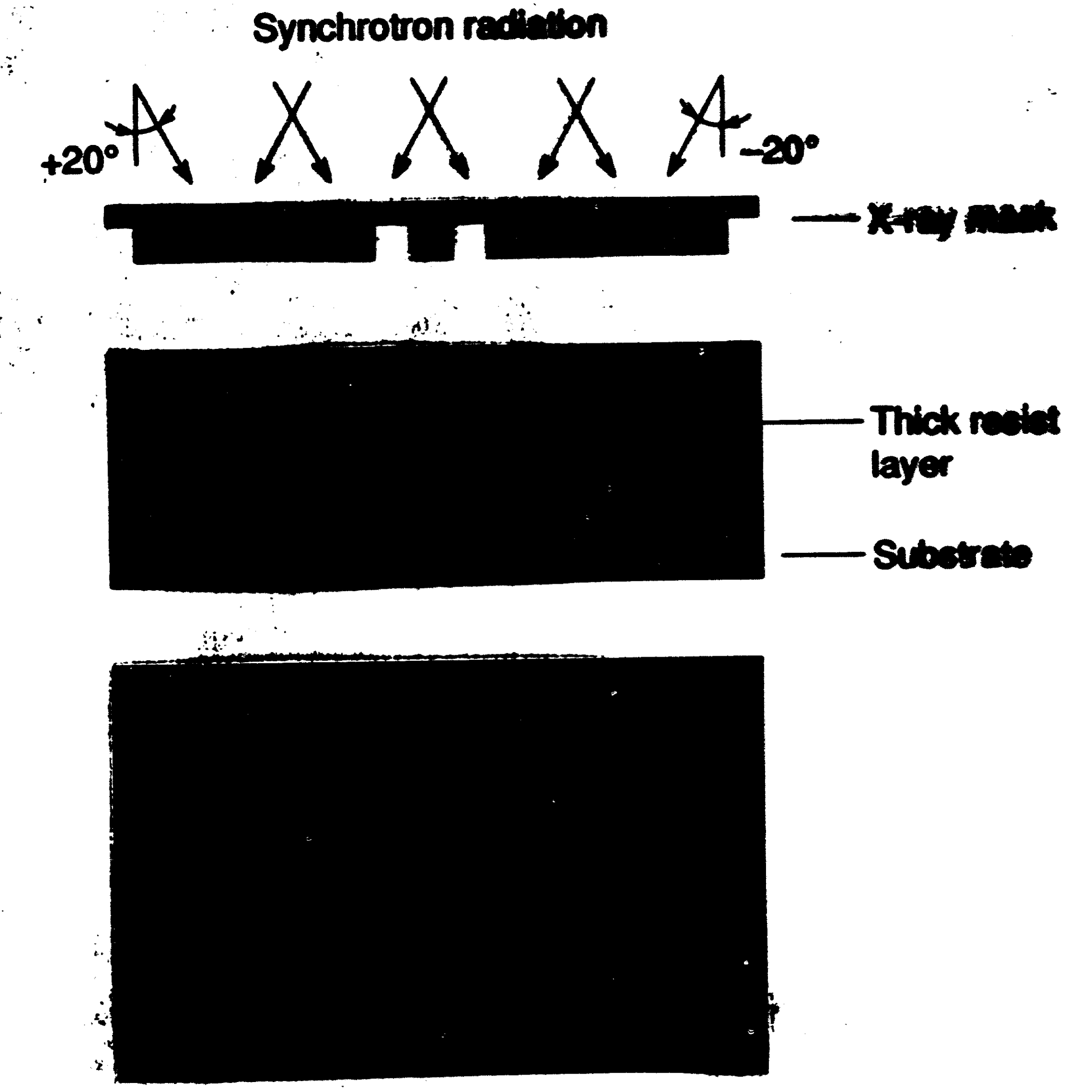
- » Inclined walls
- » Conical structures

Microstructures with Inclined Side Walls

Oblique irradiation with rotation



Oblique irradiation



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

EVALUATION OF LIGA PROCESS SEQUENCES

Level of difficulty (scale 1 to 5)	Processing step
2	Resist preparation
2	Mask making
1	X-ray exposure
1	Development
3	Electroforming
4	Replication

CRITICAL ISSUES IN ELECTROPLATING

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

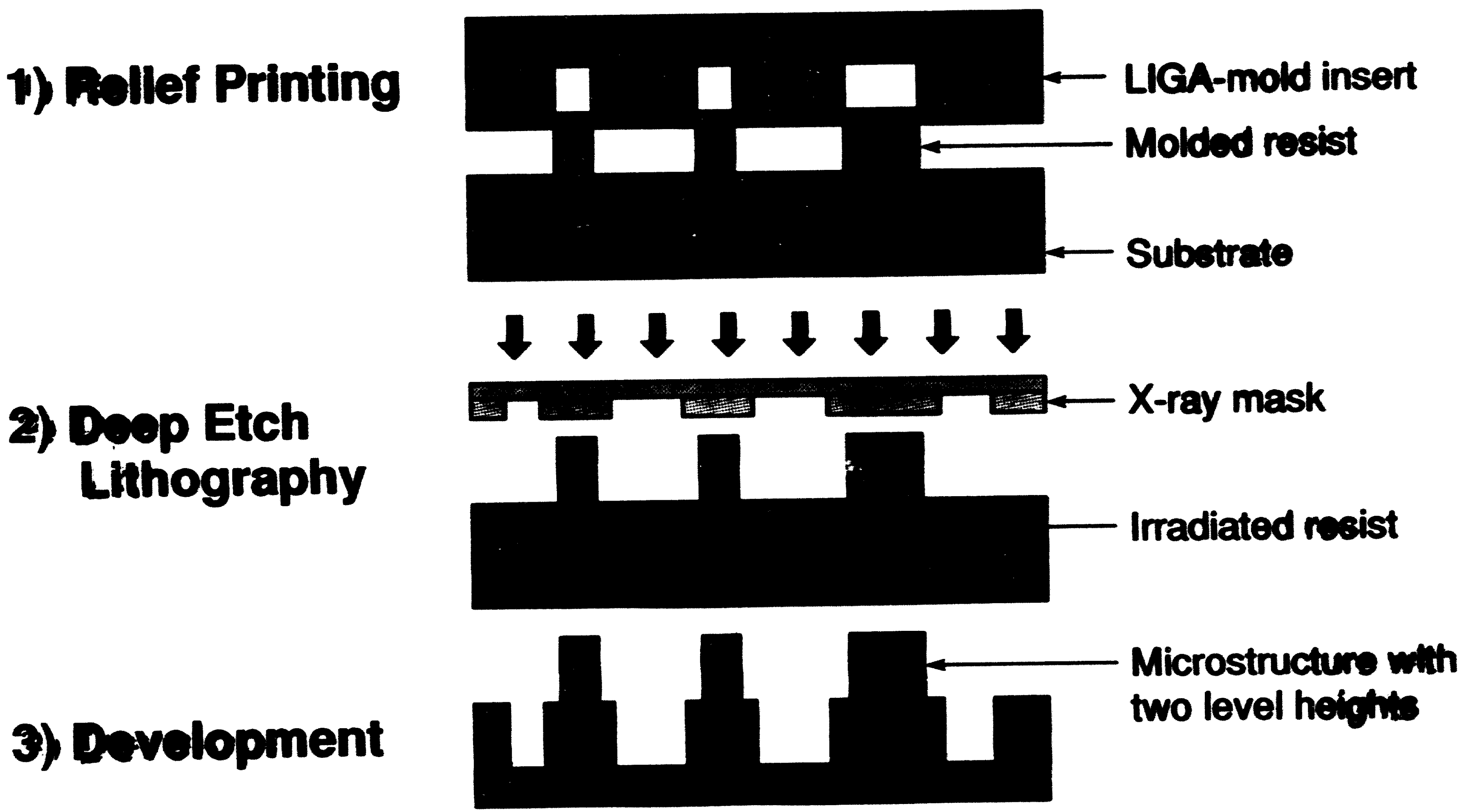
EXTENSIONS OF THE LIGA TECHNIQUE

- COMBINATION WITH OTHER TECHNIQUES
  - Plastic molding and LIGA

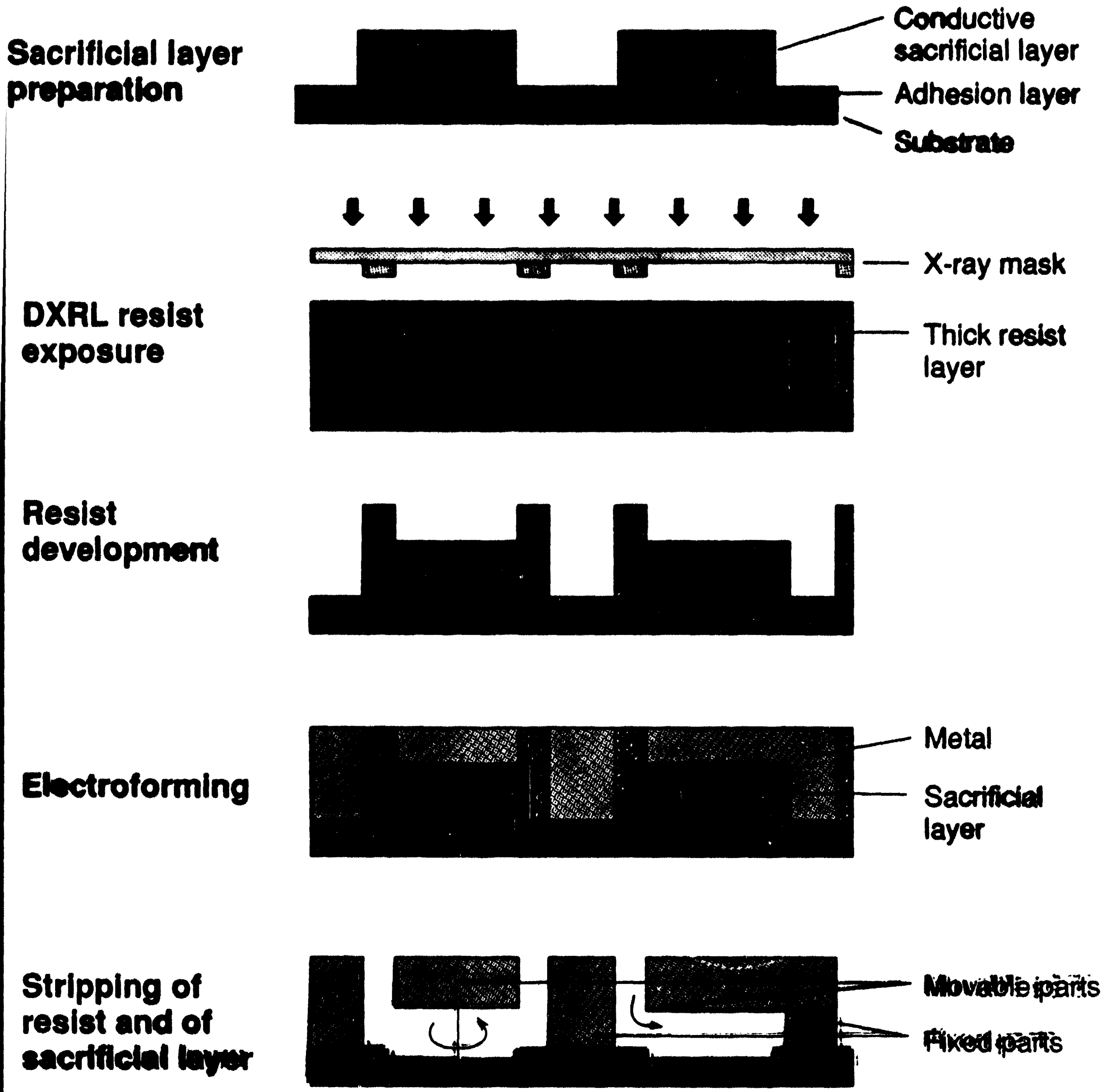
    stepped structures
  - Sacrificial layer technique and LIGA

    Free / flexible structures
  - ...
- COMPATIBILITY OF LIGA WITH SILICON PROCESSING

50


1) Relief Printing
LIGA-mold insert
Molded resist
Substrate
2) Deep Etch Lithography
X-ray mask
Irradiated resist
3) Development
Microstructure with two level heights

Movable, Flexible and Free Microstructures: SLIGA



52

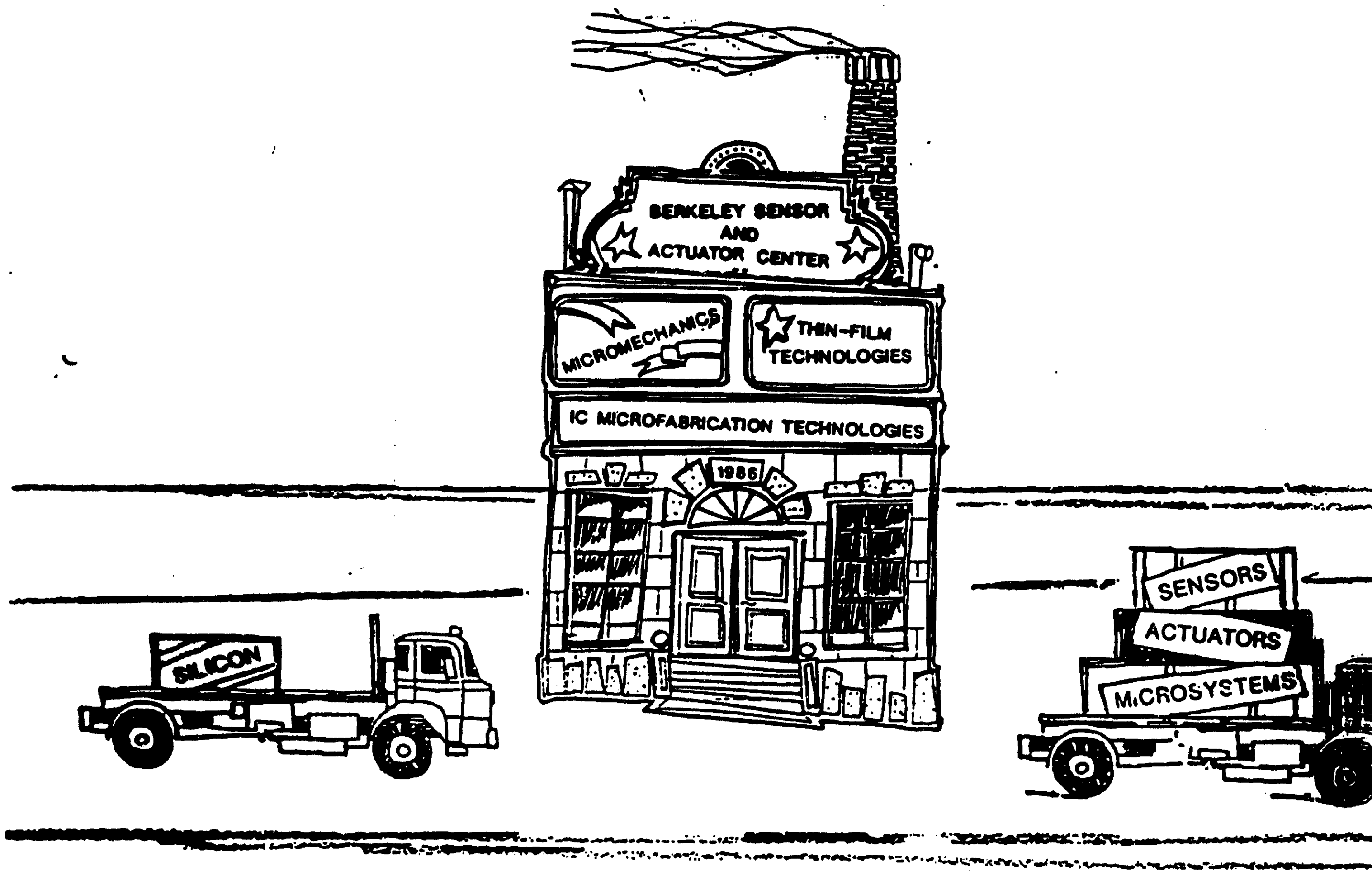
SUMMARY

- 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:

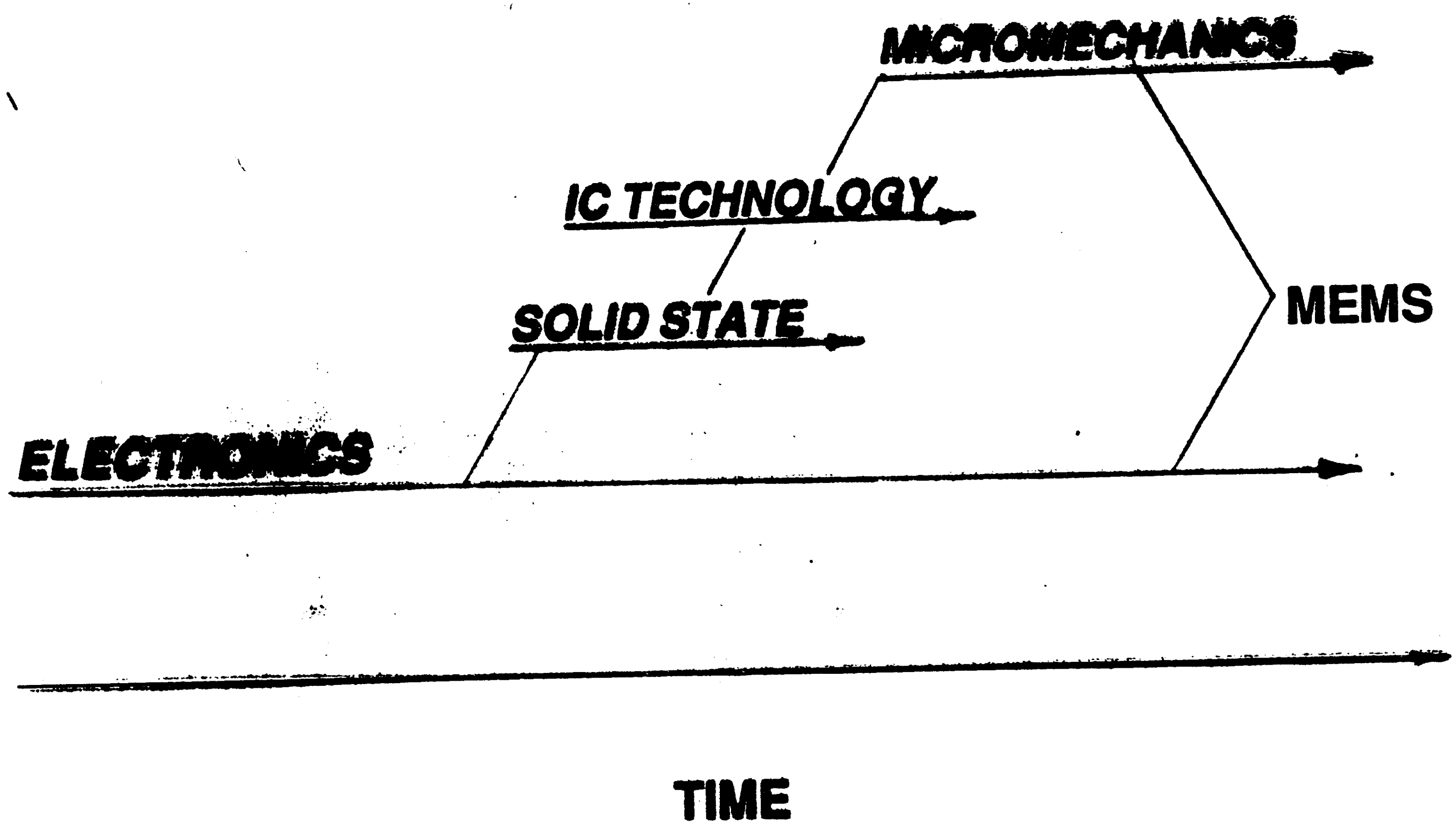
TO DEVELOP A SCIENCE AND ENGINEERING BASE FOR MICROSENSORS, MICROACTUATORS AND MICROELECTROMECHANICAL SYSTEMS.

BERKELEY
SENSOR & ACTUATOR CENTER

An NSF/University/Industry Cooperative Research Center

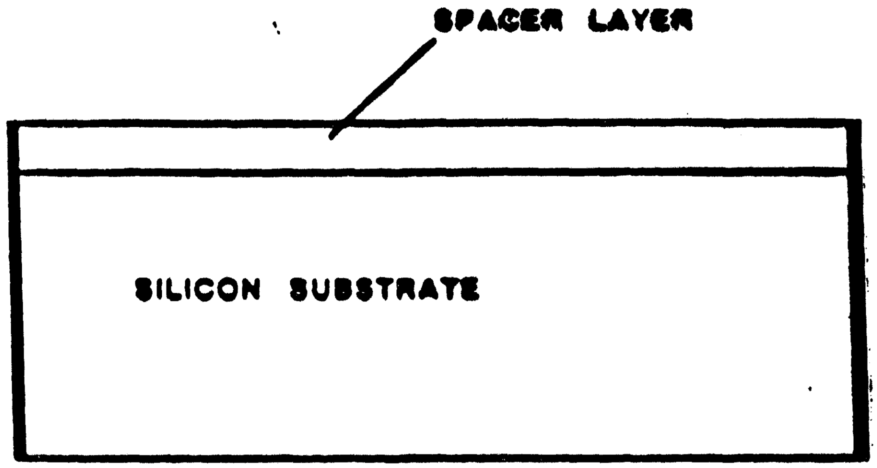
- **INTERDISCIPLINARY**
  - Electrical Engineering
  - Mechanical Engineering
  - Chemical Engineering
  - Bioengineering
  - Materials Science

- **RESEARCH CONCENTRATION AREAS**
  - Integrated microsensors
  - Microactuators
  - Microdevice technologies
  - Microflow Systems
  - Microelectromagnetic Systems (MEMS)

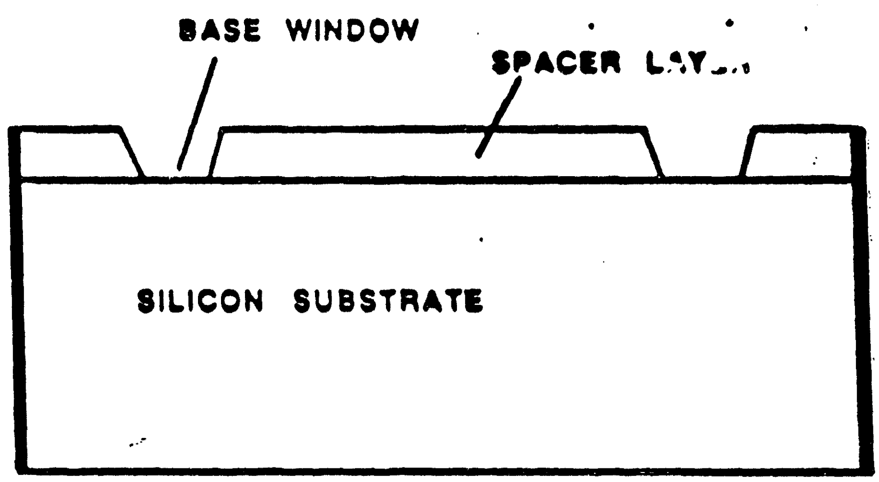

MICROMECHANICS
IC TECHNOLOGY
SOLID STATE
MEMS
ELECTRONICS
TIME

SURFACE MICROMACHINING TECHNOLOGY:
BASIC PROCESS SEQUENCE

1. SPACER LAYER DEPOSITION

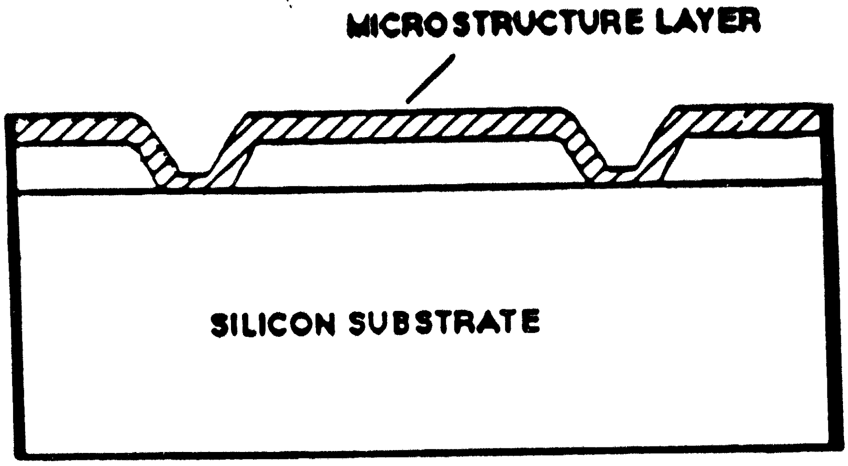


2. BASE PATTERNING (MASK 1)

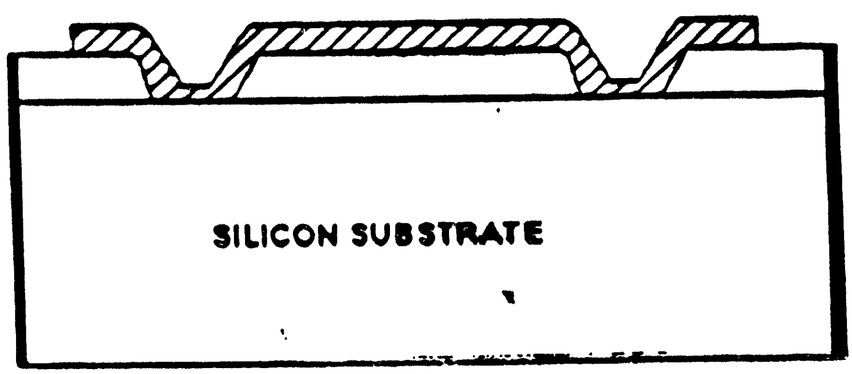


SURFACE MICROMACHINING TECHNOLOGY (Cont.)

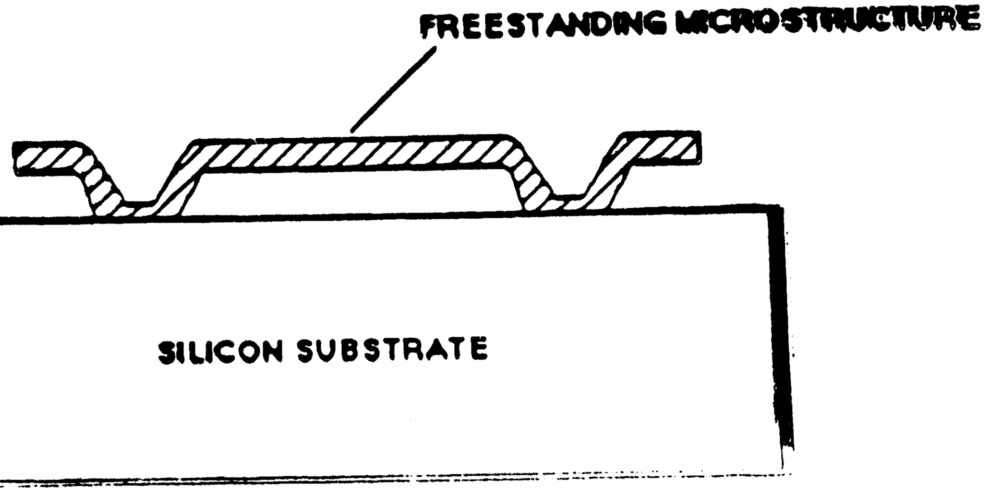
3. MICROSTRUCTURE LAYER DEPOSITION

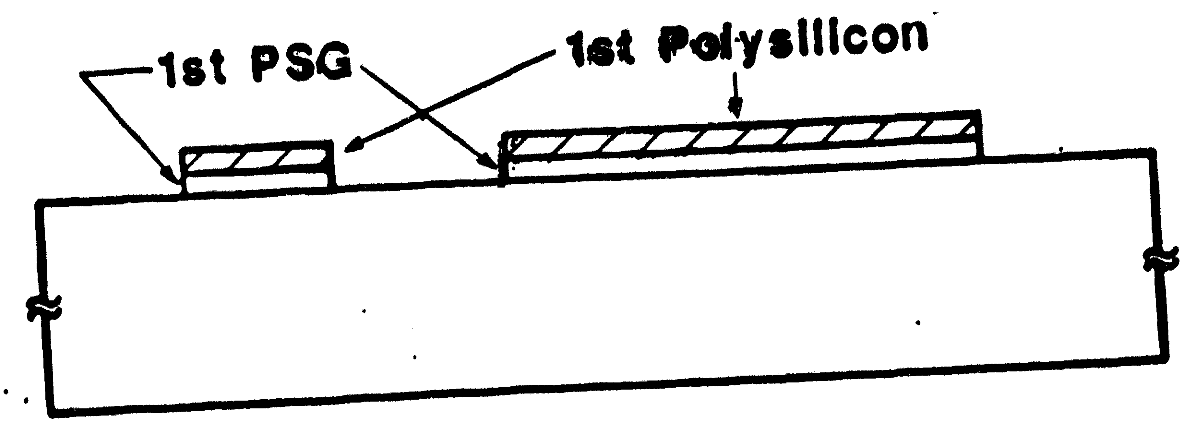


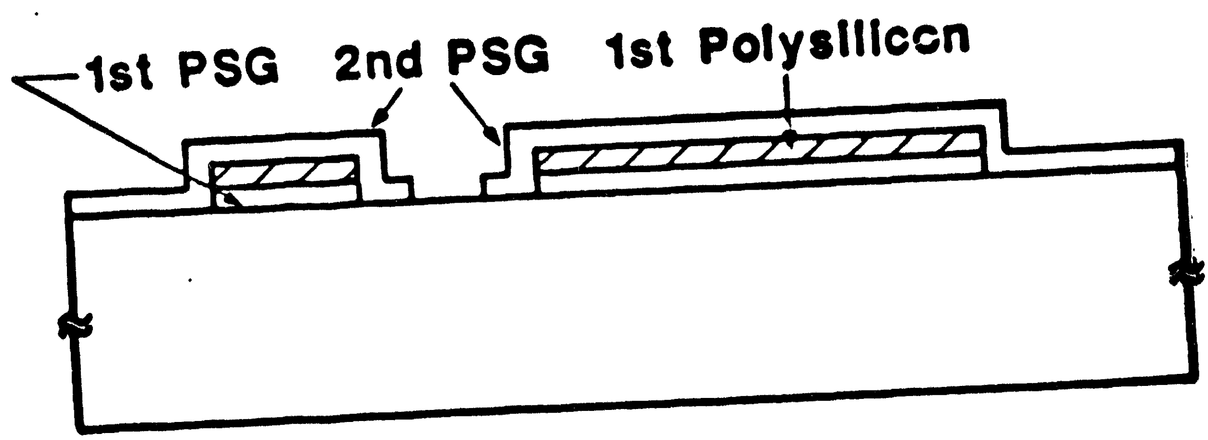
4. PATTERN MICROSTRUCTURE LAYER (MASK 2)

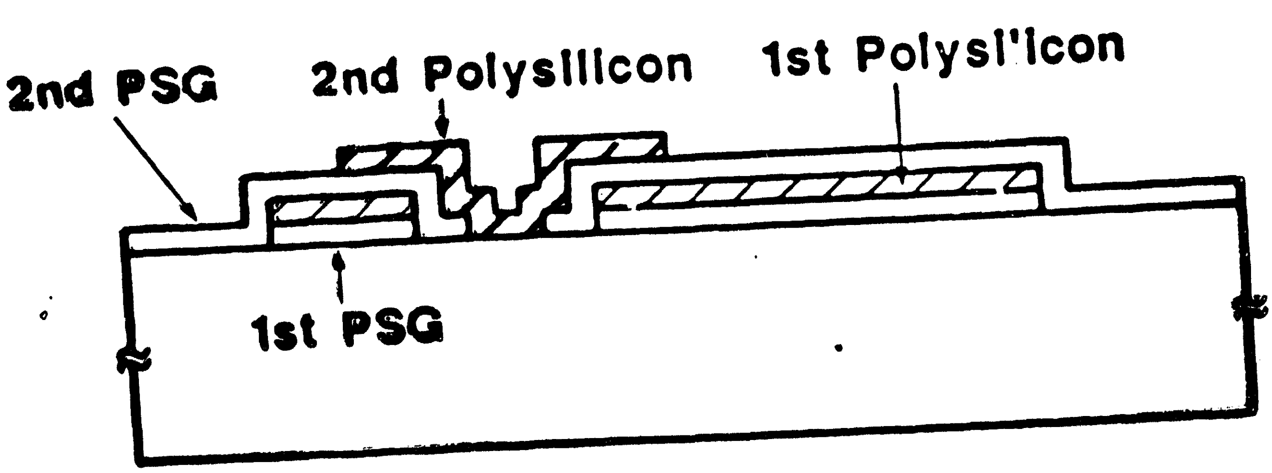


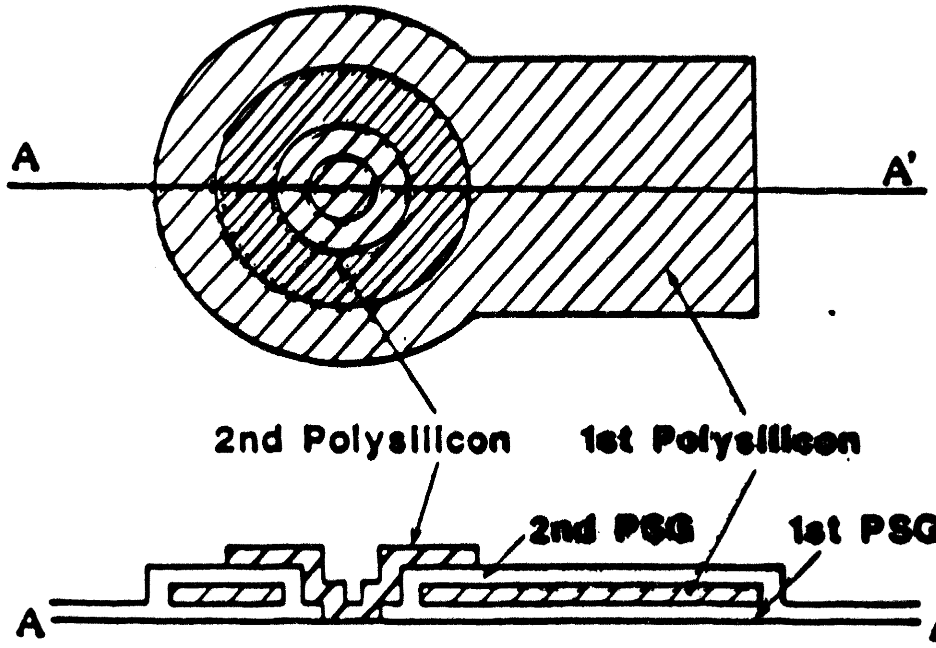
5. SELECTIVE ETCHING OF SPACER LAYER



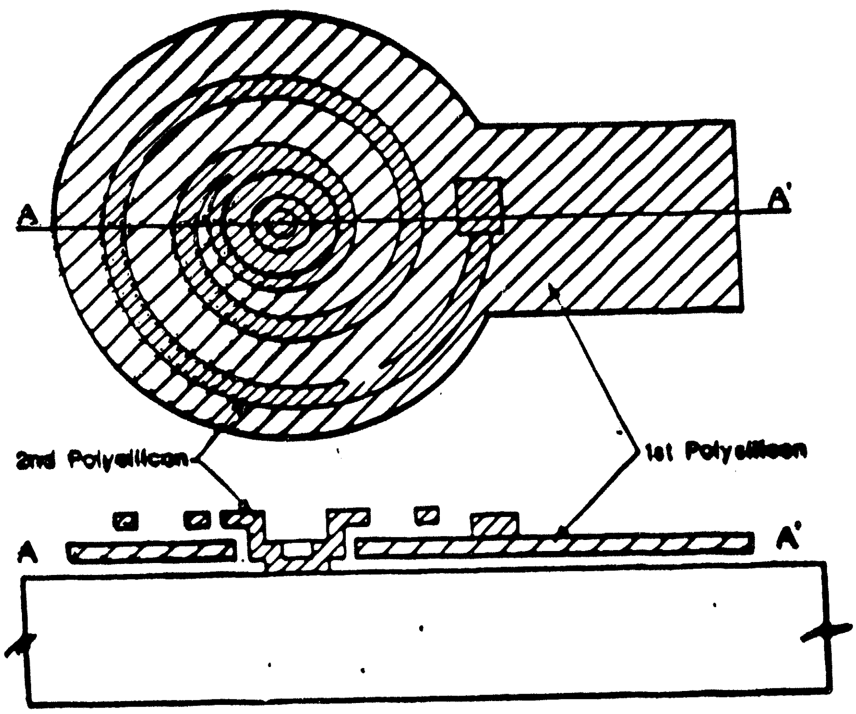

1st PSG
1st Polysilicon


1st PSG
2nd PSG
1st Polysilicon

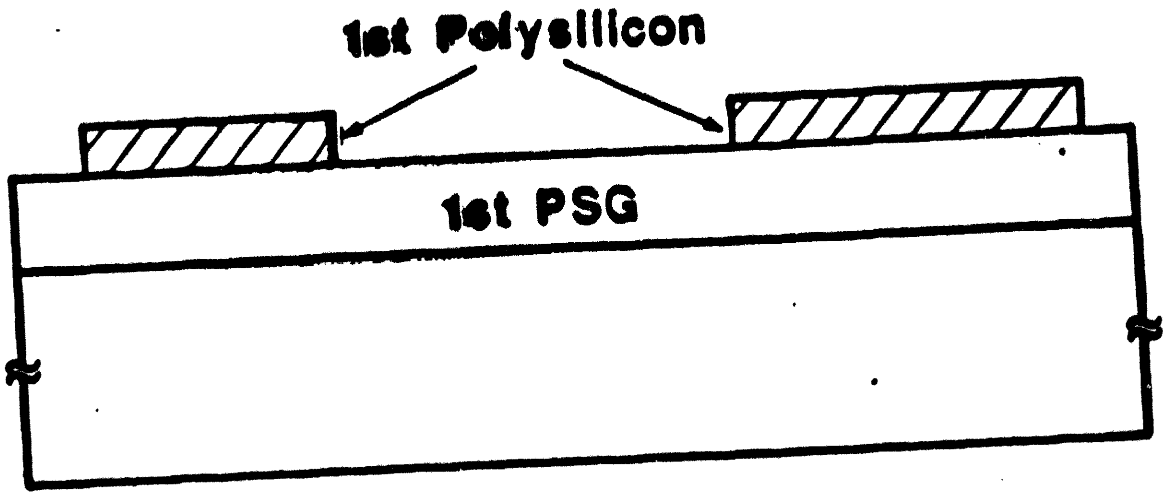

2nd PSG
2nd Polysilicon
1st Polysil'icon
1st PSG

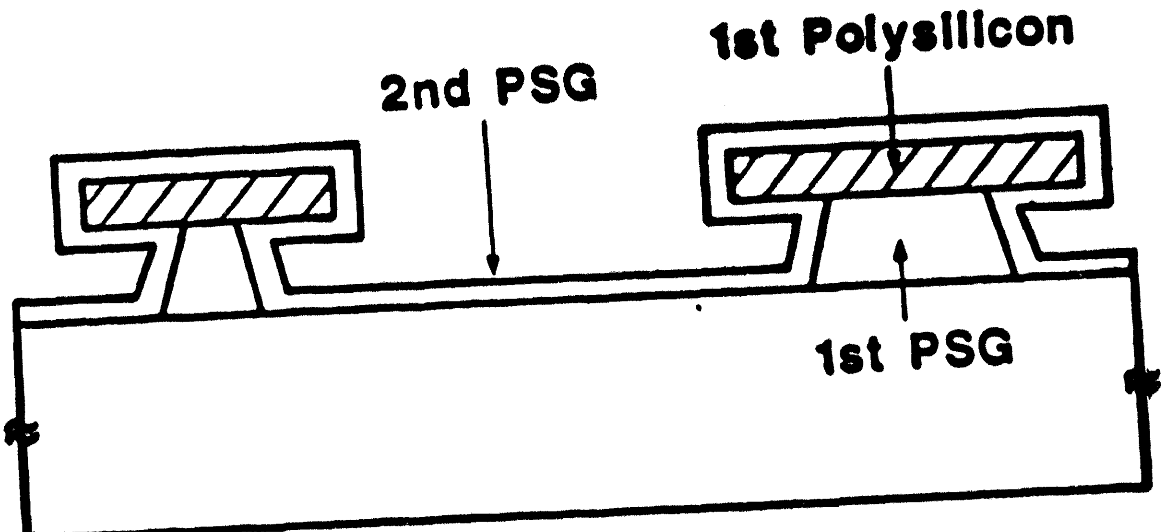


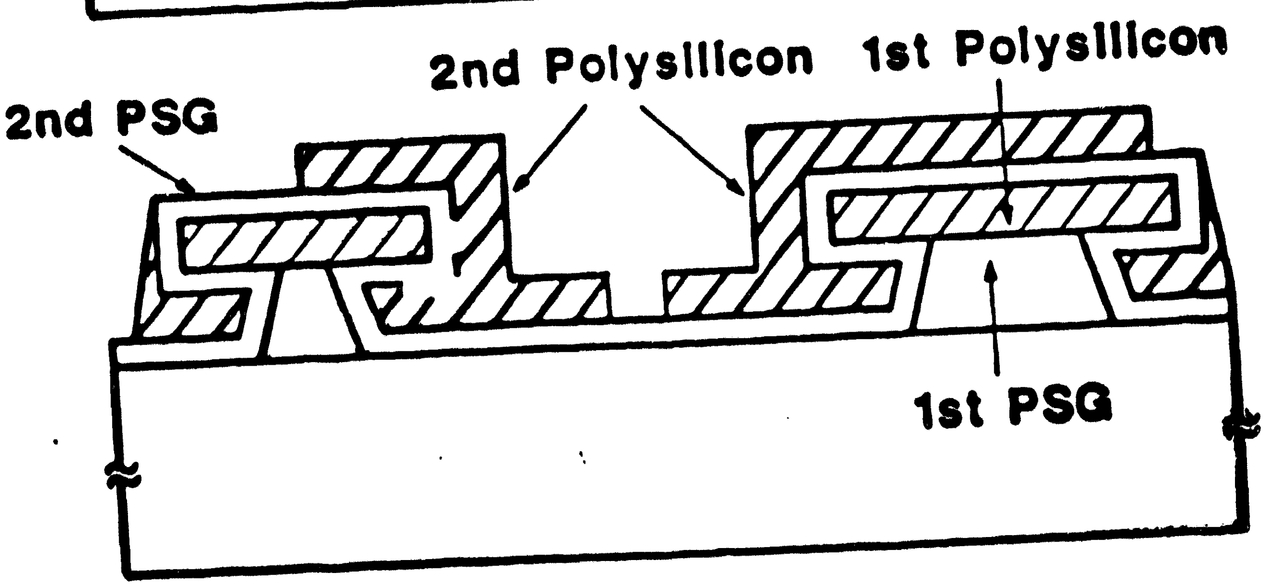
TOP VIEW



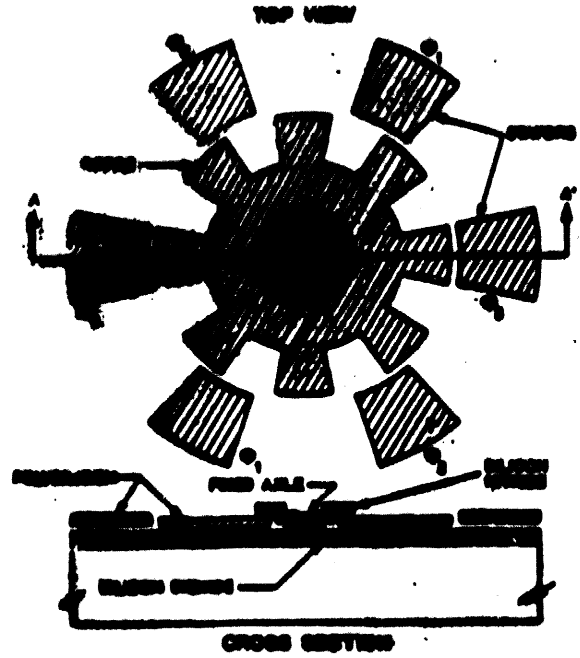
CROSS SECTION


1st Polysilicon
1st PSG

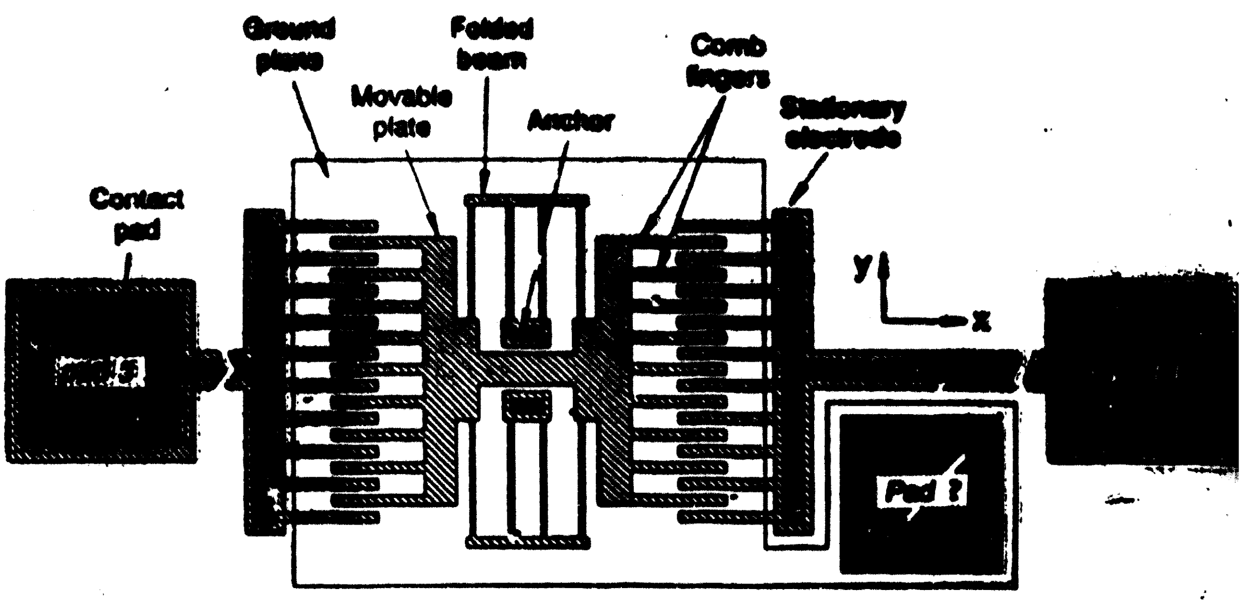

1st Polysilicon
2nd PSG
1st PSG


2nd Polysilicon
1st Polysilicon
2nd PSG
1st PSG

EXAMPLES OF MICROMECHANICAL STRUCTURES

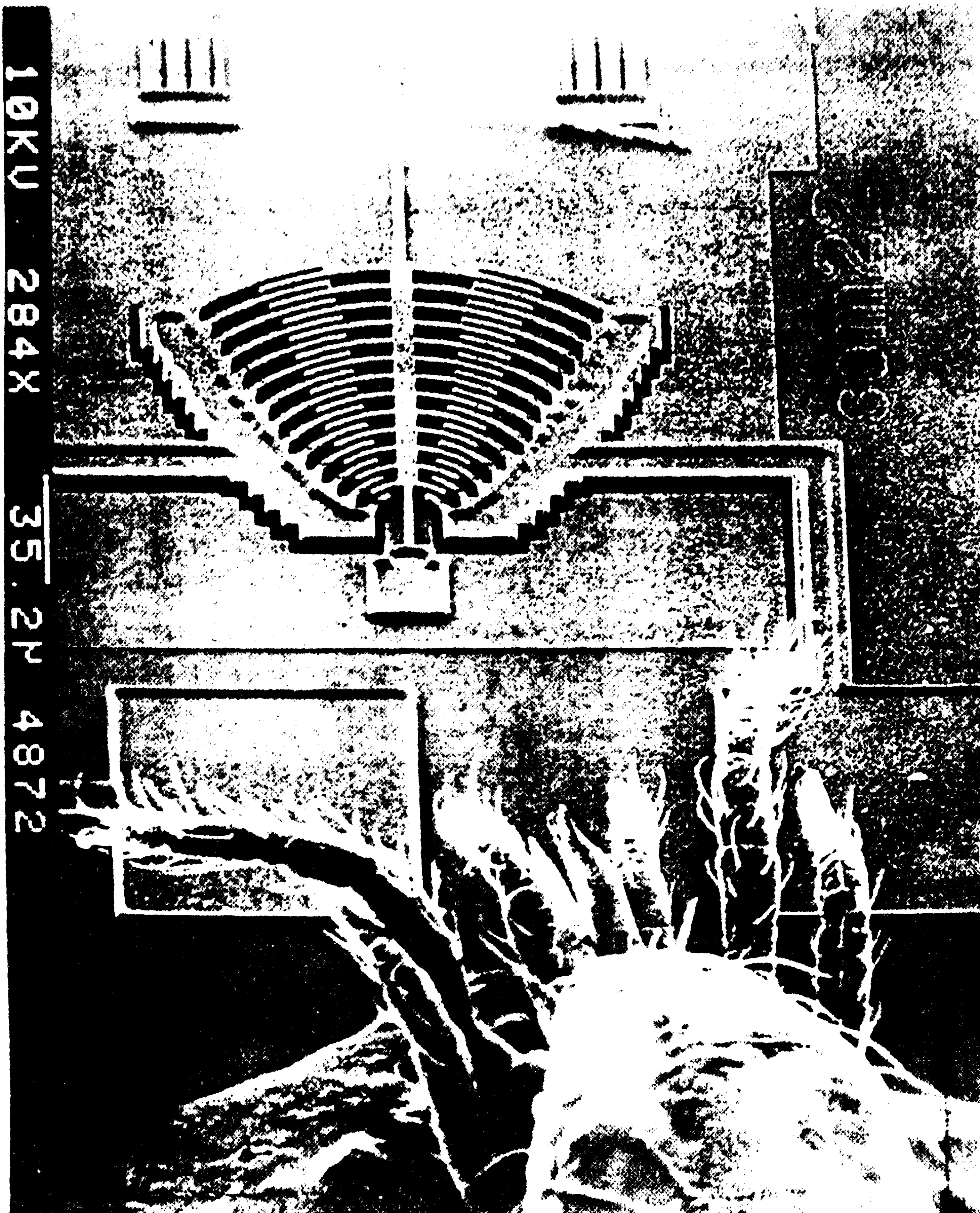


POLYSILICON ELECTROSTATIC MICROMOTOR



LATERAL POLYSILICON RESONATOR

62



Curved-Comb Multimode Resonator with mite

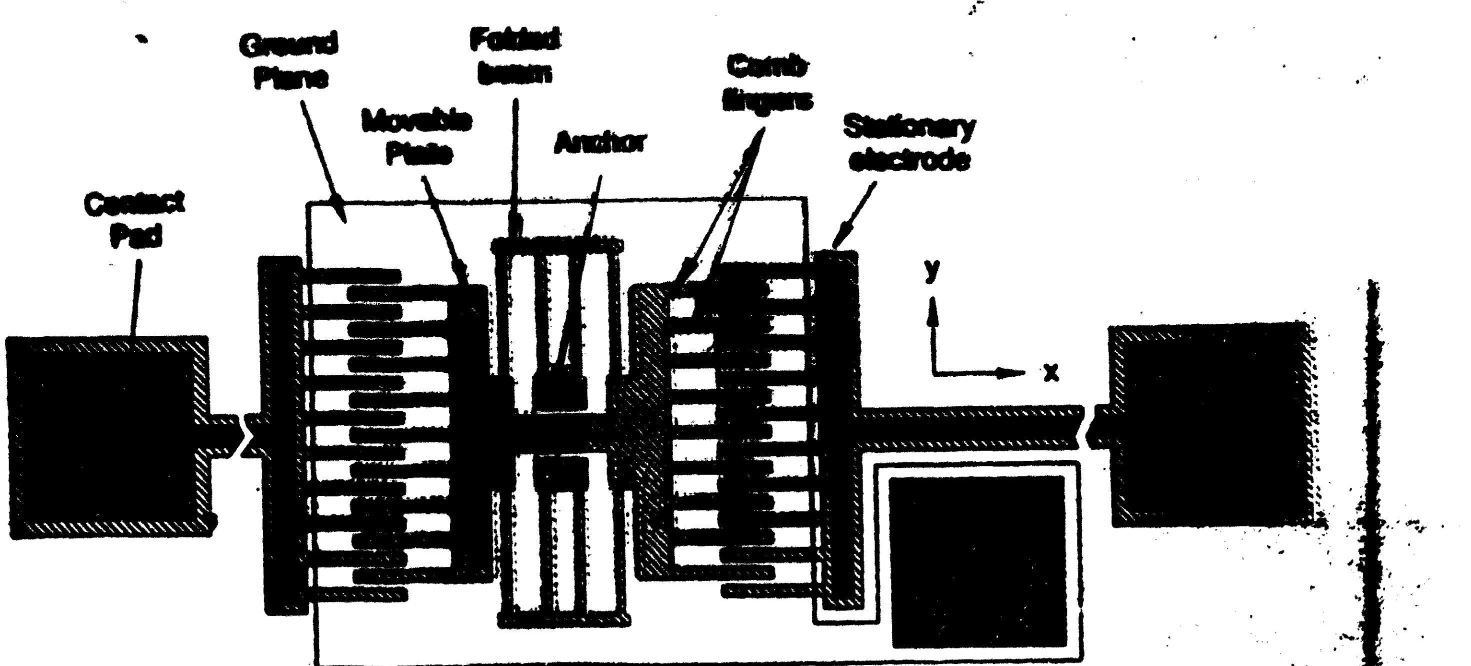
(male Tetranychus sp. (urticae)

supplied by Prof. Marjorie Hoy and Mr. Jim Presnail, UC Berkeley)

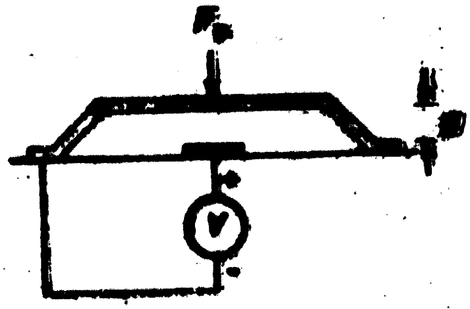
Vertical vs. Lateral Oscillation

VERTICAL OSCILLATION	LATERAL OSCILLATION
Squeeze film damping *[Low Q]*	Reduced Drag *[High Q]*
Restricted design freedom	Sophisticated 2D geometry *[Stress-relief design, comb drive, torsional resonant structures, etc]*
Δz vs. applied voltage nonlinear	Δx vs. applied voltage can be linear
Driven by parallel plate capacitor *[Millivolt drives in vacuum]*	Driven by fringing fields *[Larger drive voltage in vacuum]*

Linear Resonant Structure Layout



Displacement vs. Applied Voltage



$F_e \propto E^2 = (V/g)^2$

where

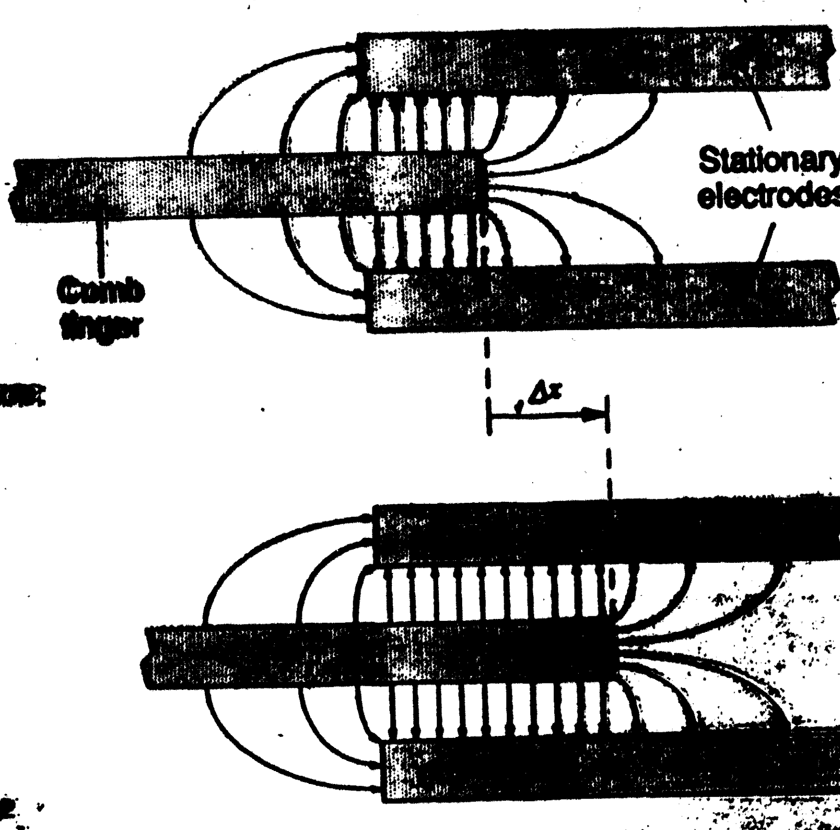
$g = g_0 + \Delta g\cos(\omega t)$

and

$V = V_p + v_d\sin(\omega t)$

Conclusion: Δg must be limited to a small fraction of g_0 to maintain linearity.

LINEAR COMB DRIVE



C_f = fringing-field capacitance; independent of Δx.

C_o = overlap capacitance; proportional to Δx.

$C = C_f + C_o$

Key Feature:

$(\partial C/\partial x)$ = constant;

$\Rightarrow F_e = \frac{1}{2}V^2(\partial C/\partial x) \propto V^2$.

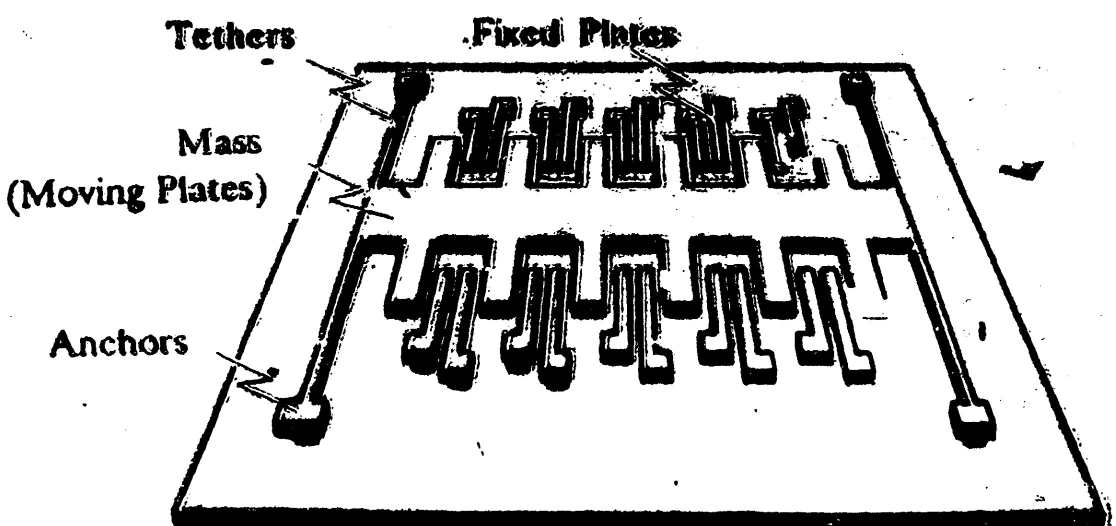
Surface-Micromachined Force-Balance Accelerometer

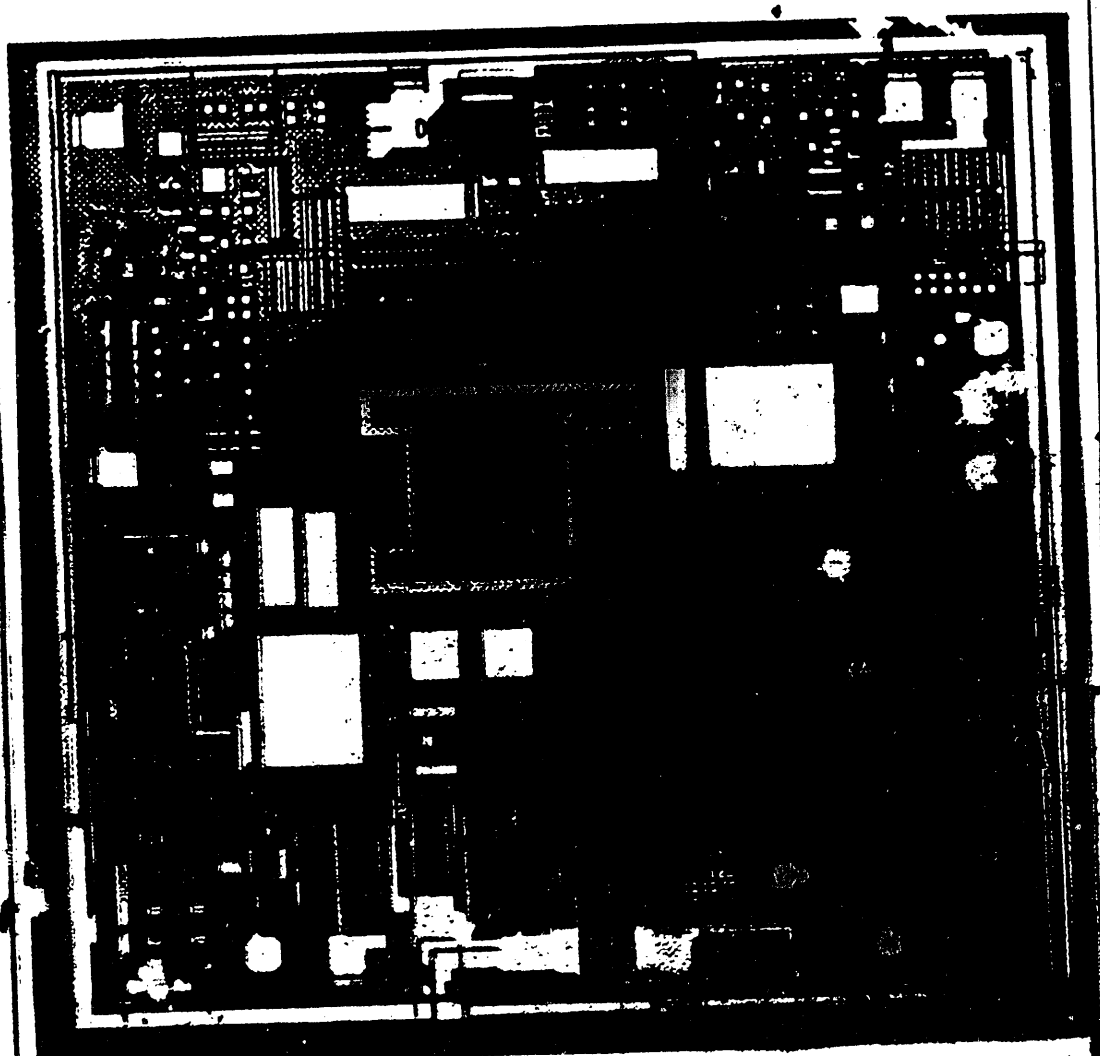
R. S. Payne and K. A. Dinsmore, Sensors and Actuators 1991,
Society of Automotive Engineers, Detroit, Mich. February 1991.

Capacitive detection ([illegible] fF Static capacitance)
integrated BiCMOS buffer circuit

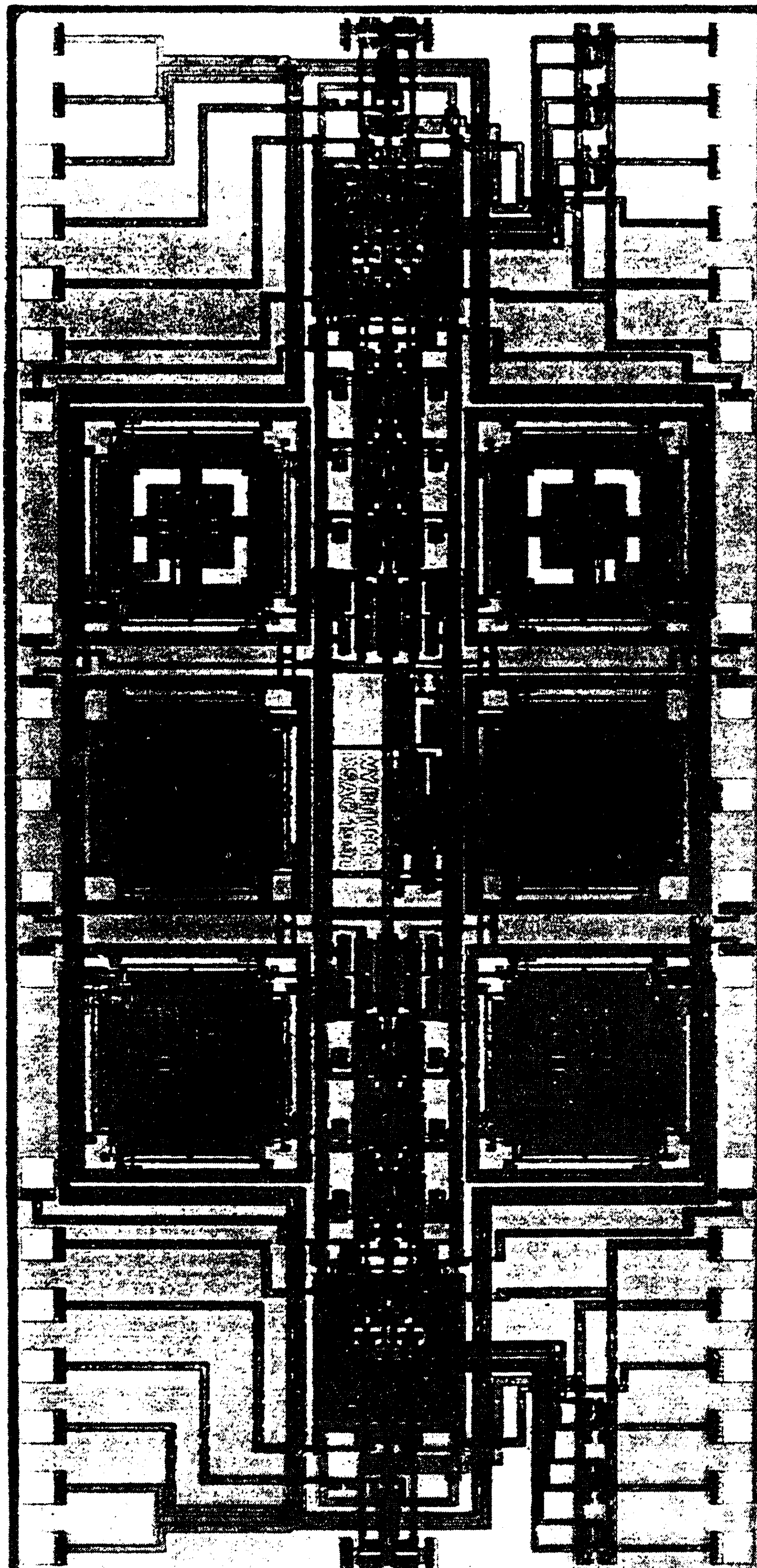
Electrostatic force-balance, self-test capability

100 g range (airbag deployment)





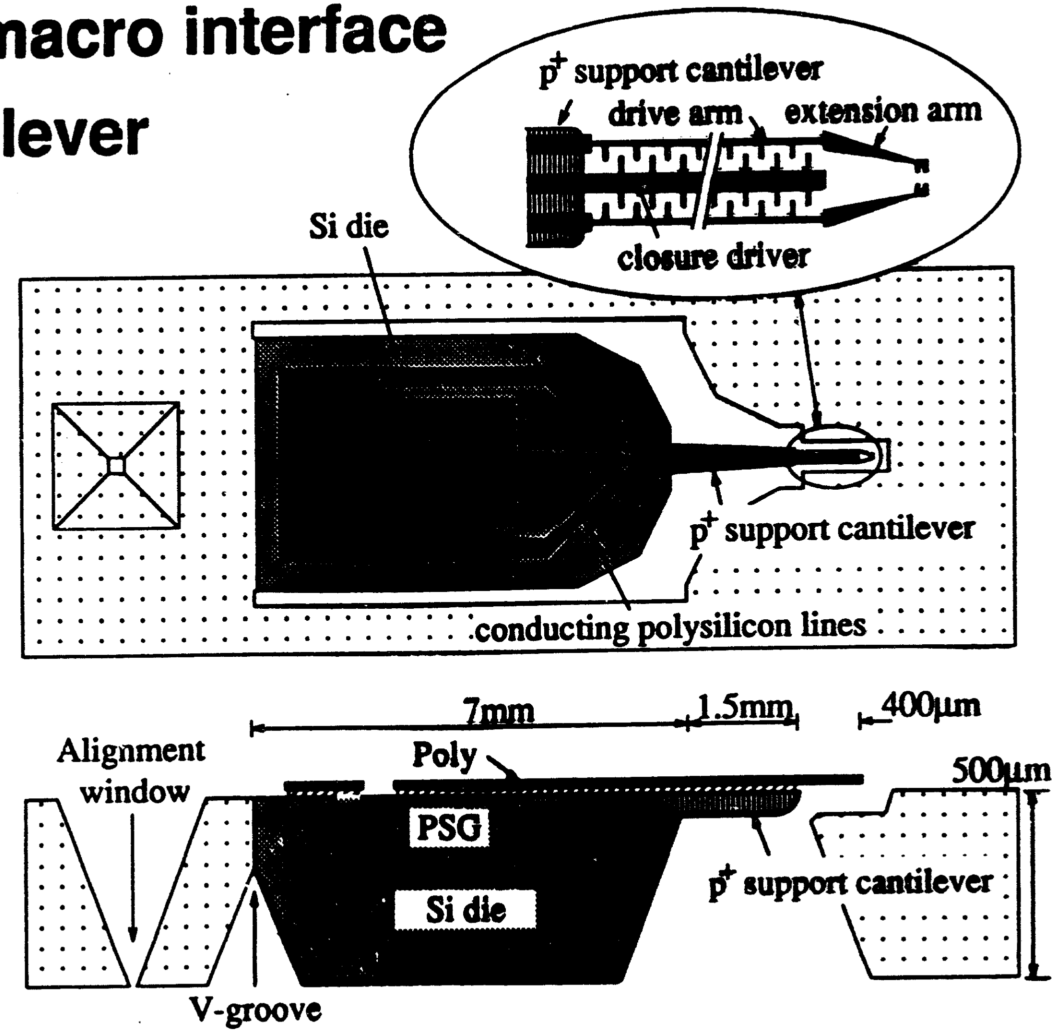
1. LARGE ACCELERATIONS of up to ±50 g can be measured by this [illegible] sensor that's surrounded by signal-conditioning circuits, all on one chip. Designed for automotive air-bag deployment, the ADXL50's proof mass is part of a differential and [illegible] capacitor whose common plate moves in the 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)



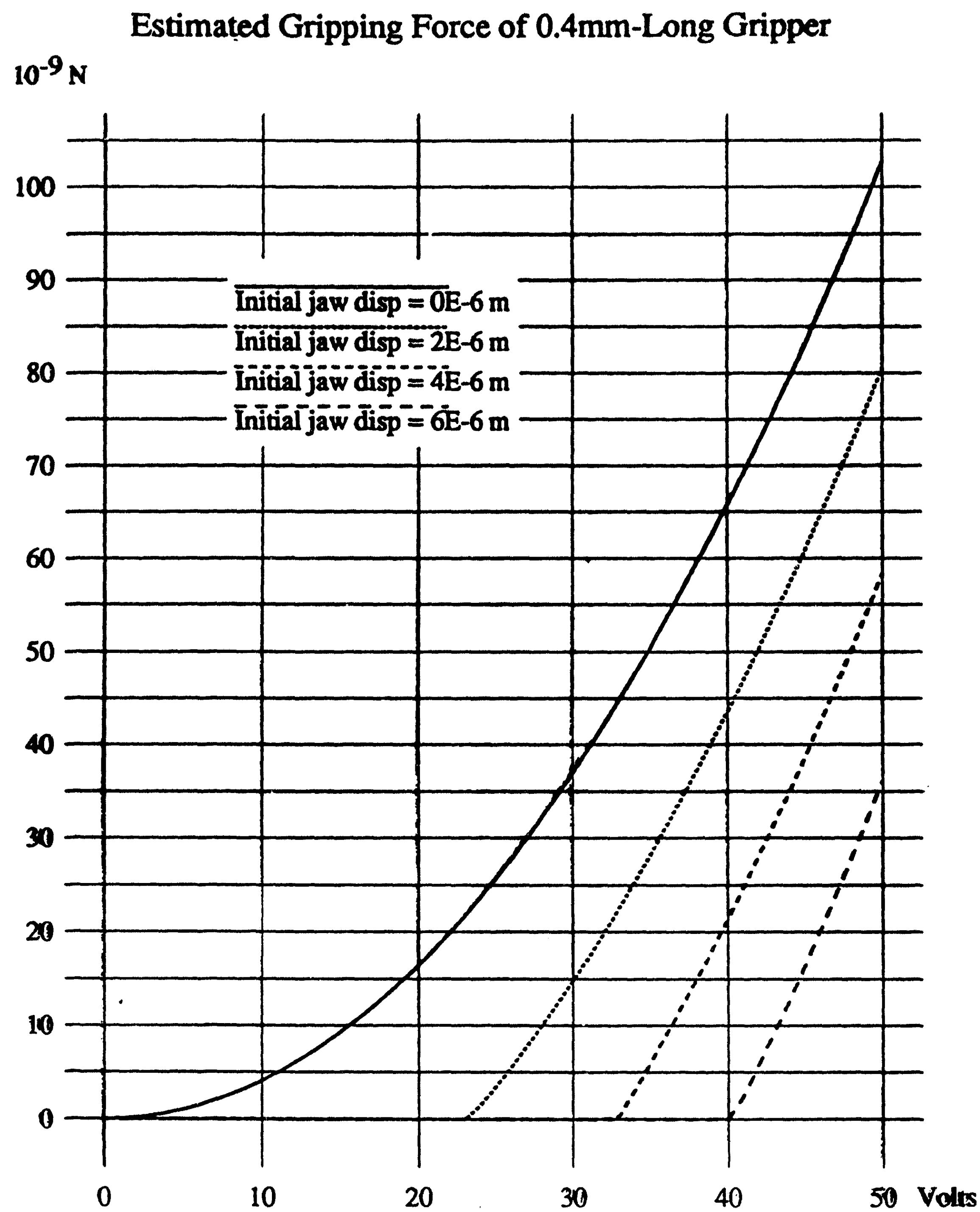


Fig. 5.3 Estimated gripping force of the 400μm-long (300μm-long driver arm and 100μm-long extension arm) microgripper as a function of driving voltage and with the initial jaw displacement (depending on object size) as a parameter.

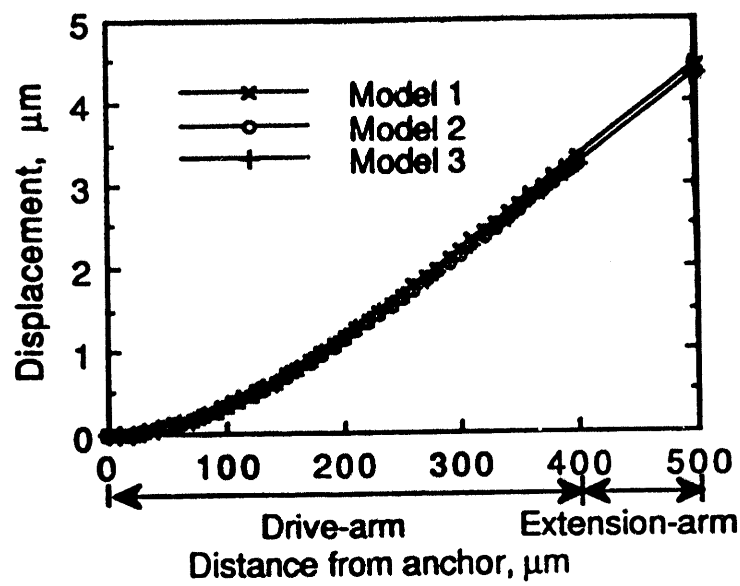


Fig. 3.7 Comparison of three elastic models of gripper arm.

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

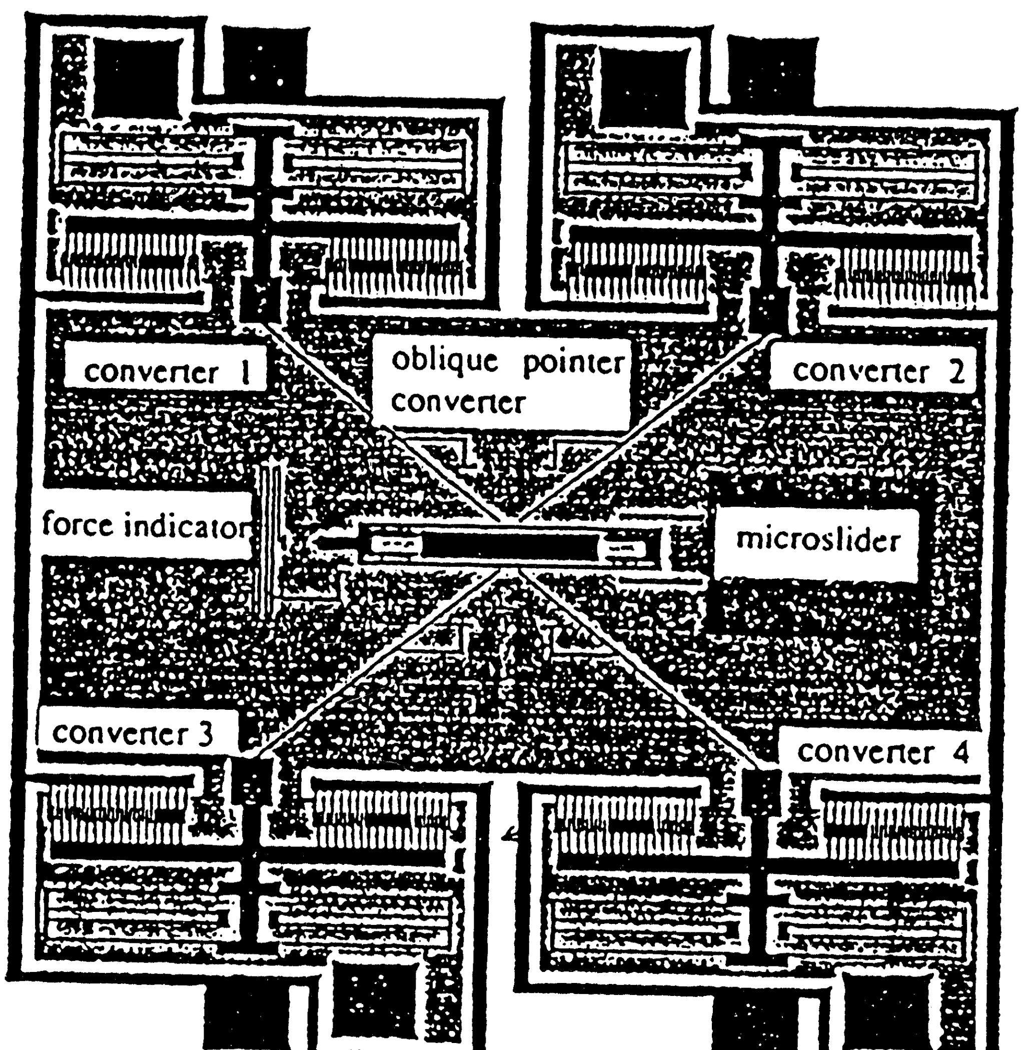
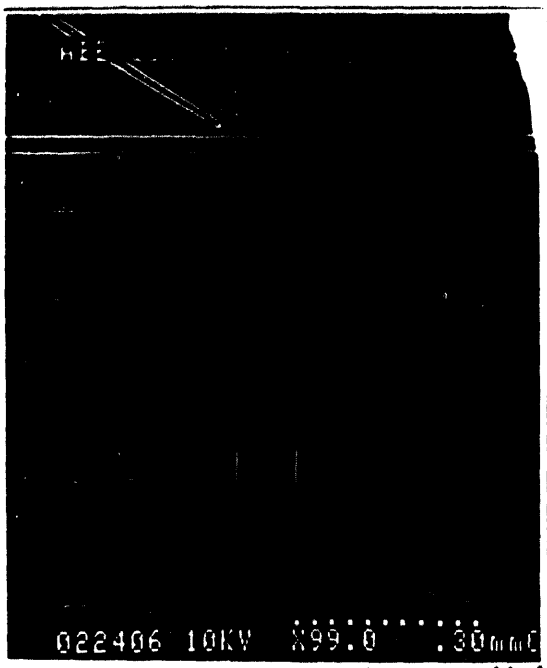
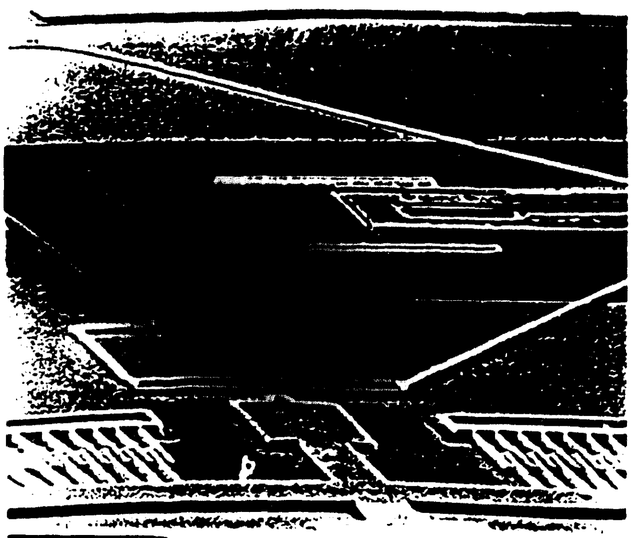


Fig. 1 Design layout of the linear microvibromotor with oblique pointer extended from converter.



ig. 2 SEM micrograph of linear microvibromotor with close-up of the converter oblique pointer tips. Notice the double layer rim on the side of the slider.



g. 3 SEM micrograph of linear microvibromotor with oblique pointer extended from microslider.

e comb finger drives of the converters are designed such that the ectrostatic force will push the pointers toward the slider instead earlier designs [7] that pull away from the rotor. The folded am flexures are 1.6 μm wide and 200 μm long. The microslider a hollow rectangular block constrained to move in the horizontal rection by a flange in the middle. The block is 360 μm x 58 μm d the hollow portion is 320 μm x 18 μm. The flange is 211 μm ng which leaves a 109 μm total drive range of the microslider. ouble layer side rims are on both drive sides of the slider to ovide a larger impact target. These rims are 4.3 μm high. The ertical clearance between the microslider and the flange is 0.9 μm hile the lateral clearance is 2 μm. Dimples are evenly distributed ong the converters and the slider, and the height of the dimples is .5 μm. Figure 2 is an SEM micrograph of this type of linear microvibromotor with a close-up of the oblique pointers by the side of the microslider.

Another type of microvibromotor is an inverted designed with the oblique flexures extended from the microslider. A horizontal portion of the flexures provide an impact target for the converters. Figure 3 is an SEM micrograph of this type of microvibromotor.

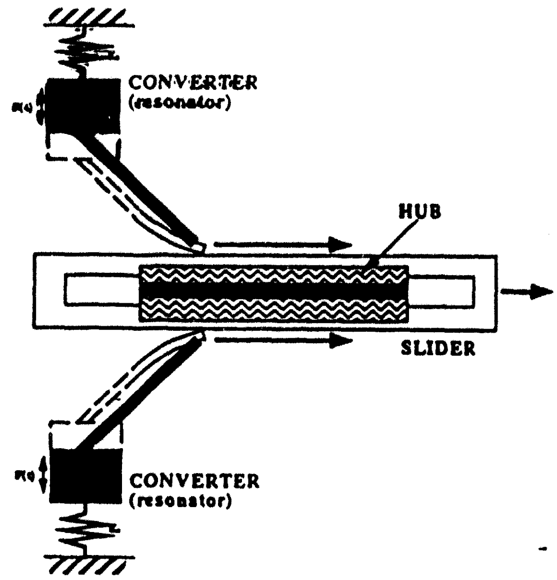


Fig. 4 Actuation principle of linear microvibromotor.

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 friction 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_c and the net horizontal force exerted on the slider is F_s. 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_s 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 use 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.

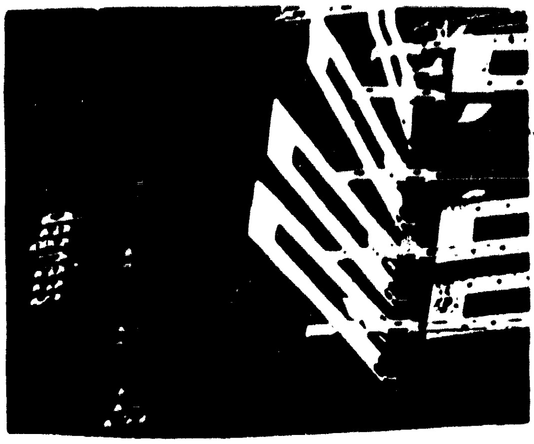


Figure III.C.5. Vertically elevated structures produced at BSAC by Kris Pister. The hinged-up structures are of the order ... mm in height.

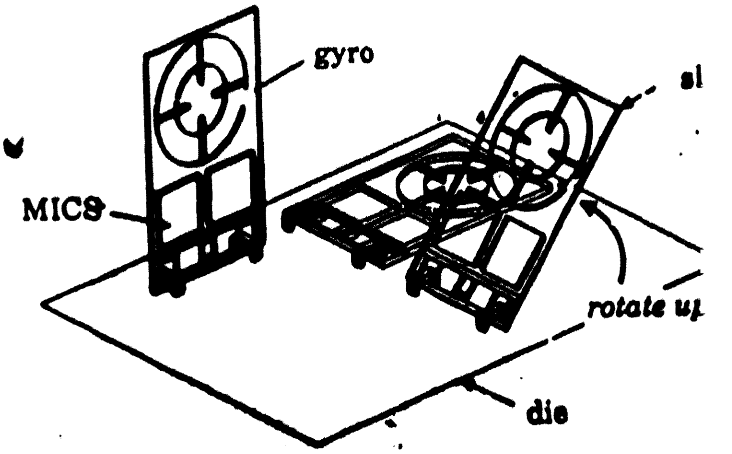


Figure III.C.6. Concept for a hinged structure to form a two-axis gyroscope.

Microcutting and Joining. By resistive heating of polysilicon ... mechanical separation can be achieved by fusing and mechanical joining is possible by microwelding [Fedder, MEMS 1991]. Fusible polysilicon supports can be used to

MICROMACHINING METHODS

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

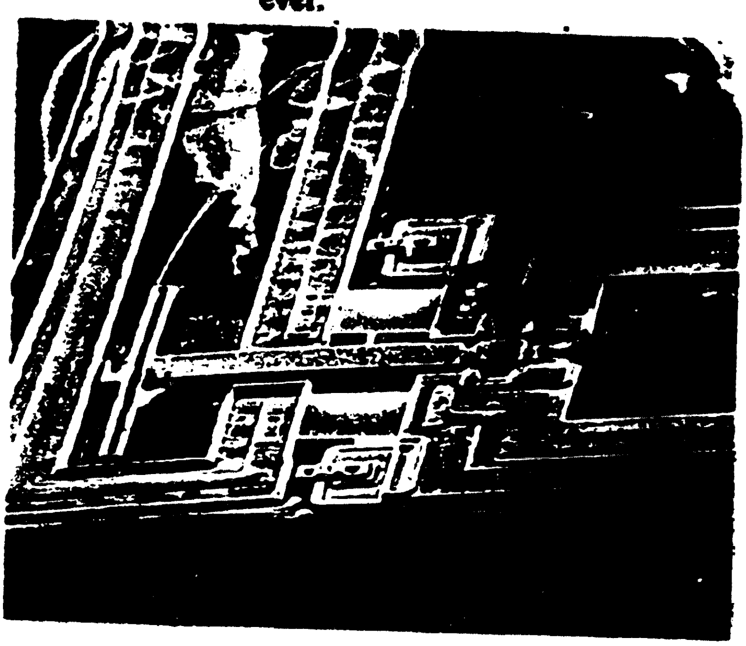


Figure III.D.1.

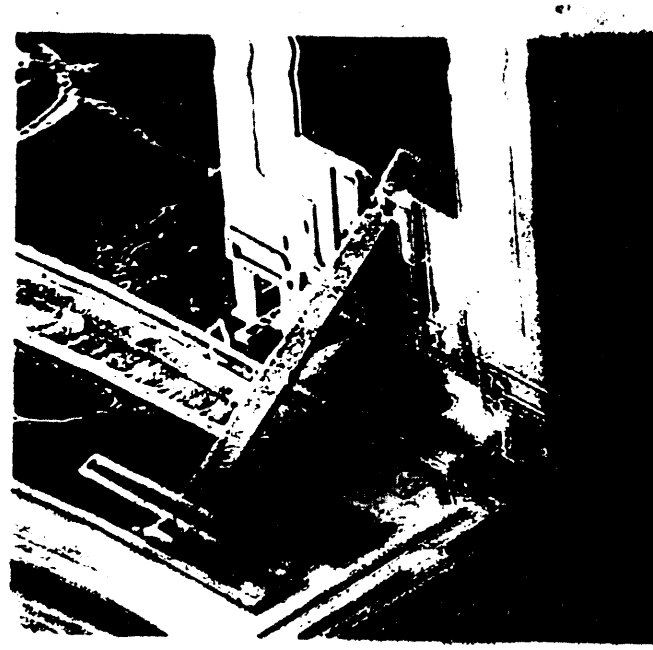


Figure III.D.2.

Microcutting and Joining. Research on thermal cutting and joining of polysilicon will lead to very useful microfabrication procedures. ...

Possible Applications

- Micro fine tuning head of magnetic disk head.
- Micro positioner/manipulator/robot.
- Optical shutter.

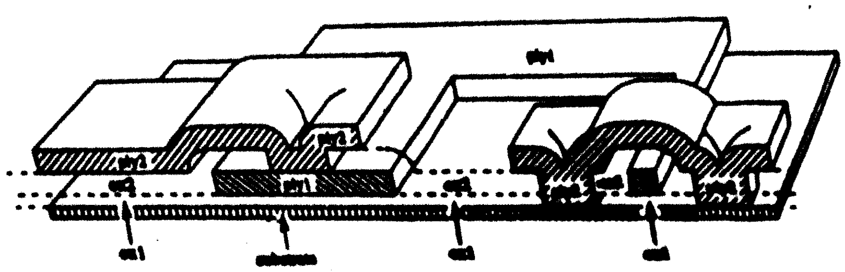


Figure 2.3: Cross section of a surface hinge. The pin and staple are on the right side, and a poly-2 plate is attached to the hinged poly-1 plate on the left.

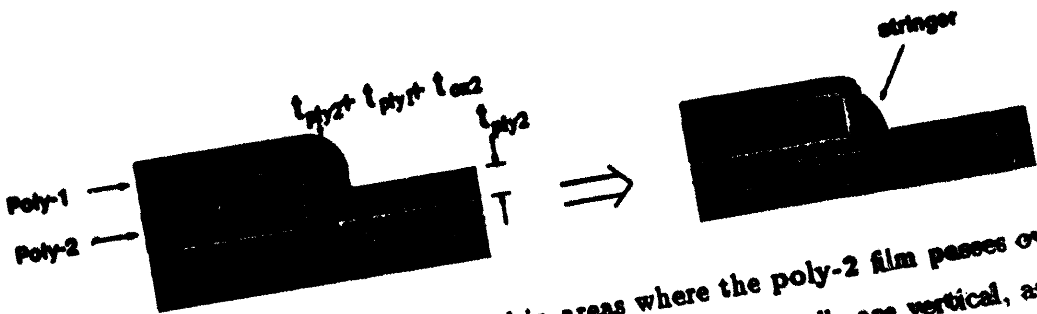


Figure 2.4: Polysilicon stringers are formed in areas where the poly-2 film passes over an edge of poly-1. In the worst-case shown here, the poly-1 sidewalls are vertical, and the oxide is conformal, resulting in an additional vertical film thickness equal to the poly-1 and the ox-2 thicknesses.

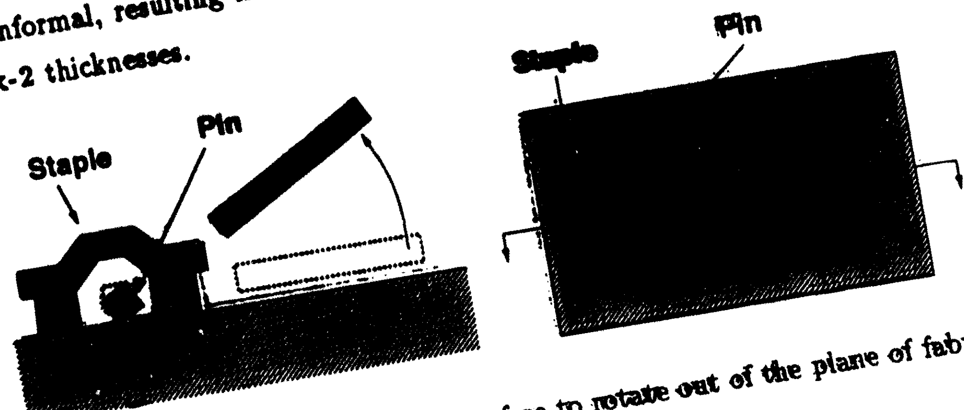


Figure 2.5: After release the structures are free to rotate out of the plane of fabrication.

78

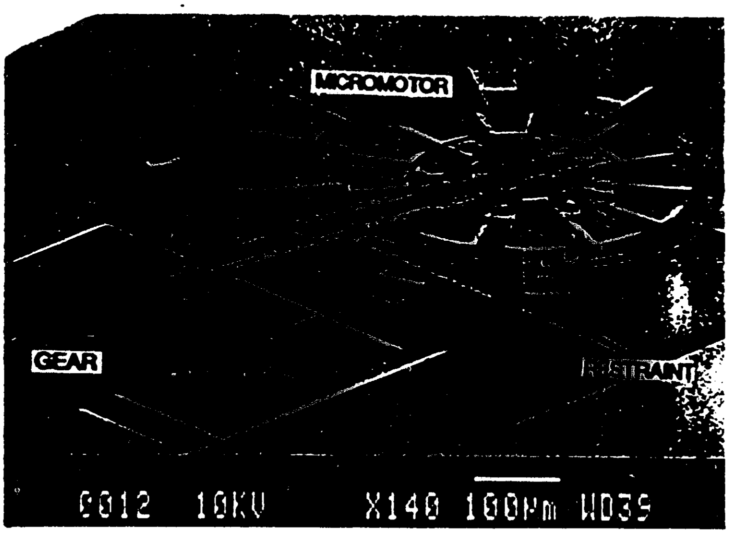
MICROACTUATION

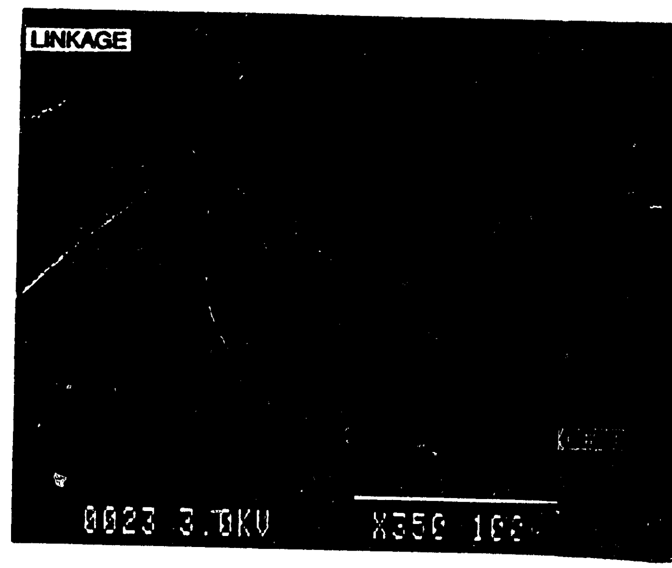
- *Electrostatic*
- *Piezoelectric*
- *Pneumatic*
- *Thermal Bimorph*
- *Fluidic Phase Change*
- *Ultrasonic*
- *Magnetic*
- *Shape Memory Alloy*

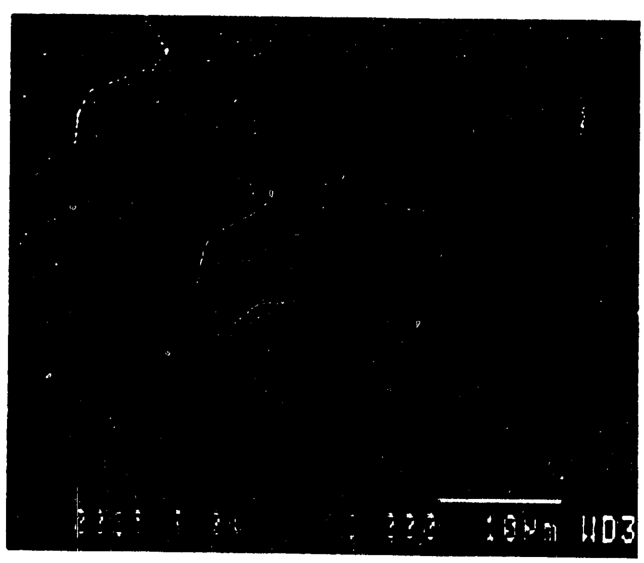
BATCH FABRICATION AND ASSEMBLY OF MICROMOTOR-DRIVEN MECHANISMS WITH MULTI-LEVEL LINKAGES

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

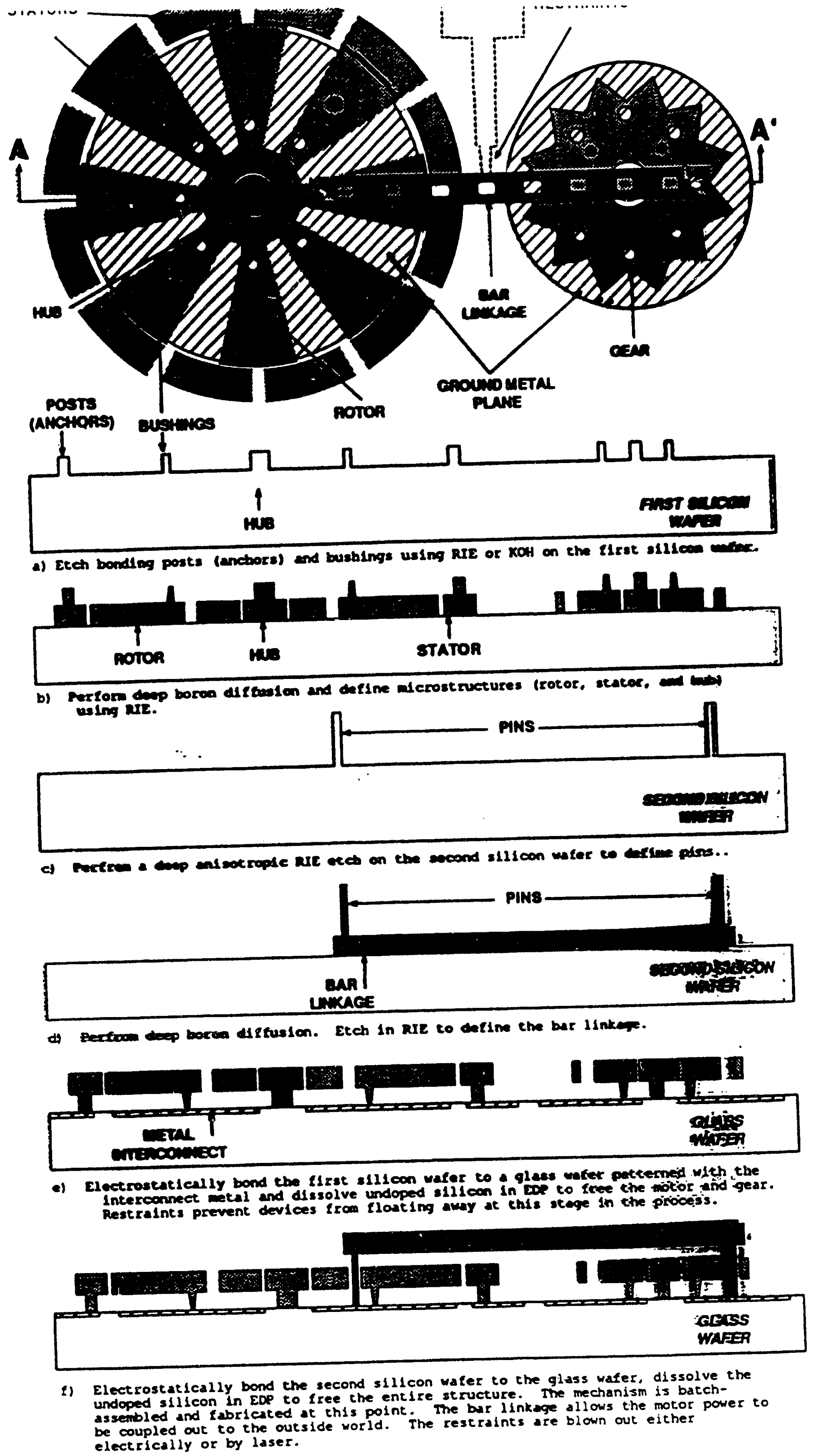


Figure 1: Process sequence for batch fabrication and assembly of micromotor-driven mechanisms.

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

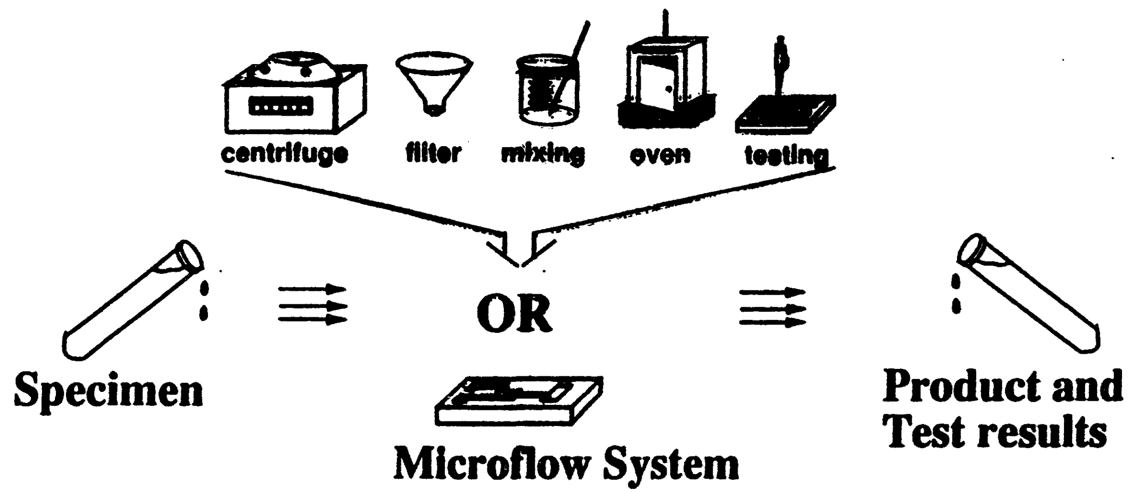
M. Allen Northrup [1], Michael T. Ching [2], Richard M. White [2], and Robert T. Watson [3]

[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.



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

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 96C) will cause the repeated melting (denaturing) and recombination (annealing) of DNA while TAq (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.

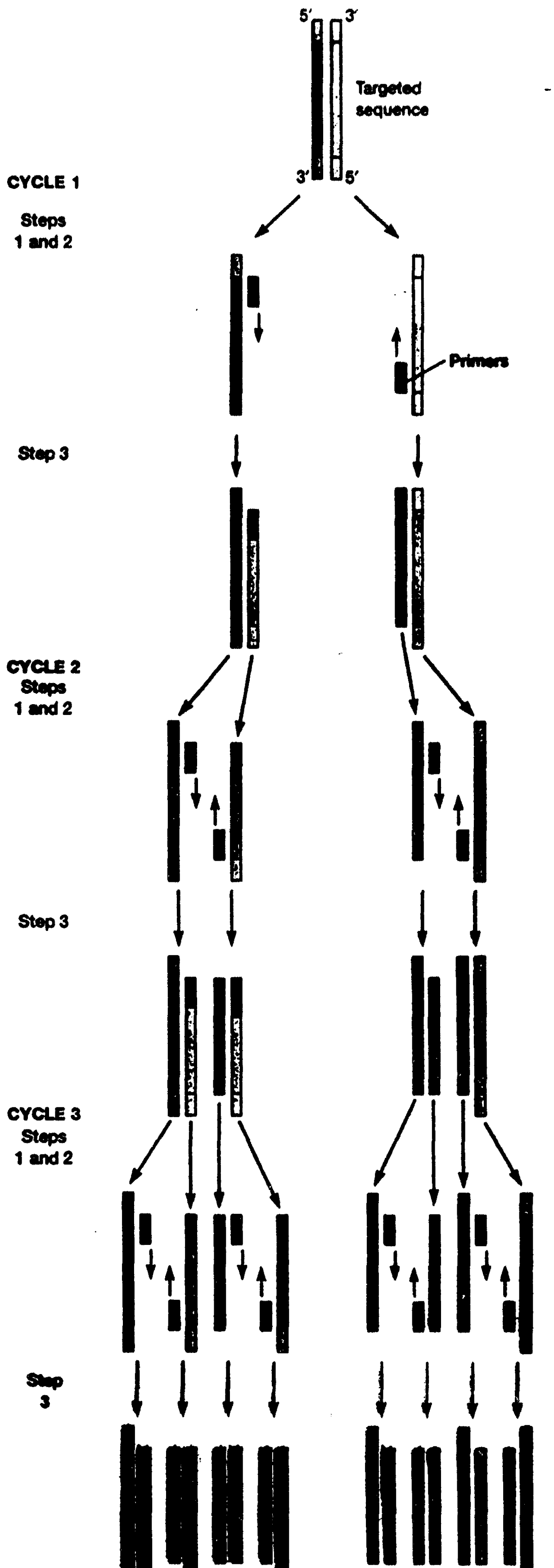


Figure 14.8 **The Polymerase Chain Reaction.** In three cycles, the targeted sequence has been amplified to produce eight copies. See text for details.

Figure 14.9 **A Modern PCR Machine.** PCR machines are now fully automated and microprocessor controlled. They can process up to 96 samples at a time.

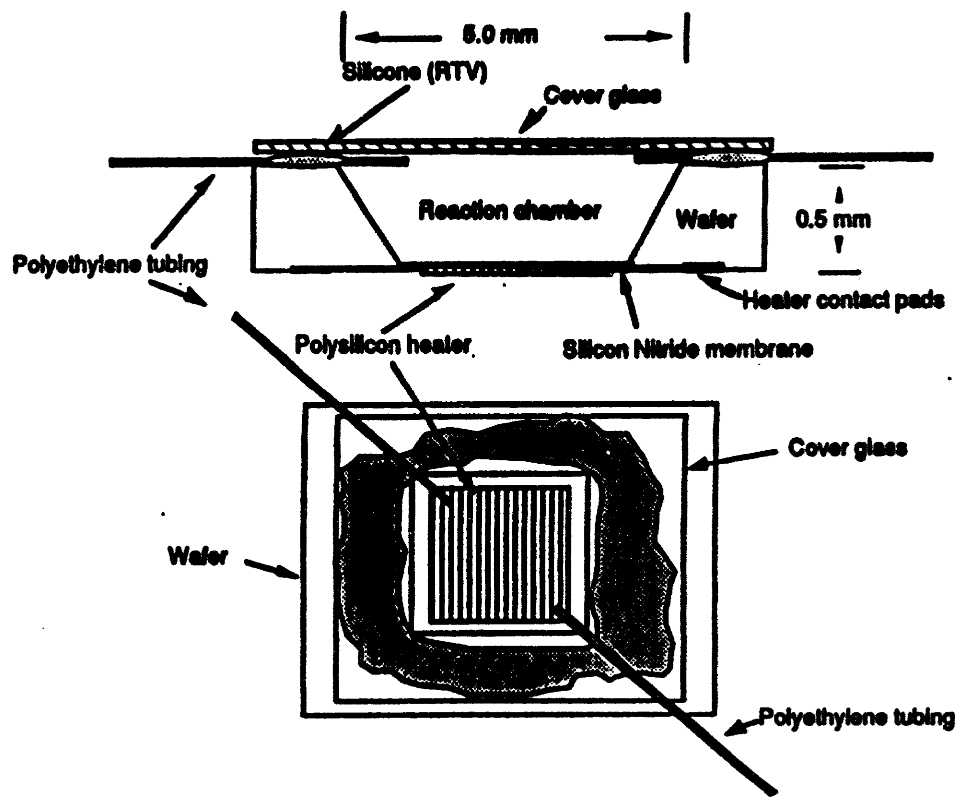
of a specific DNA and provide sufficient material for accurately sequencing the fragment or cloning it by standard techniques. Undoubtedly PCR will be used extensively to aid genetic mapping in the human genome project. PCR-based diagnostic tests for AIDS, Lyme disease, chlamydia, the human papilloma 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 an 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.

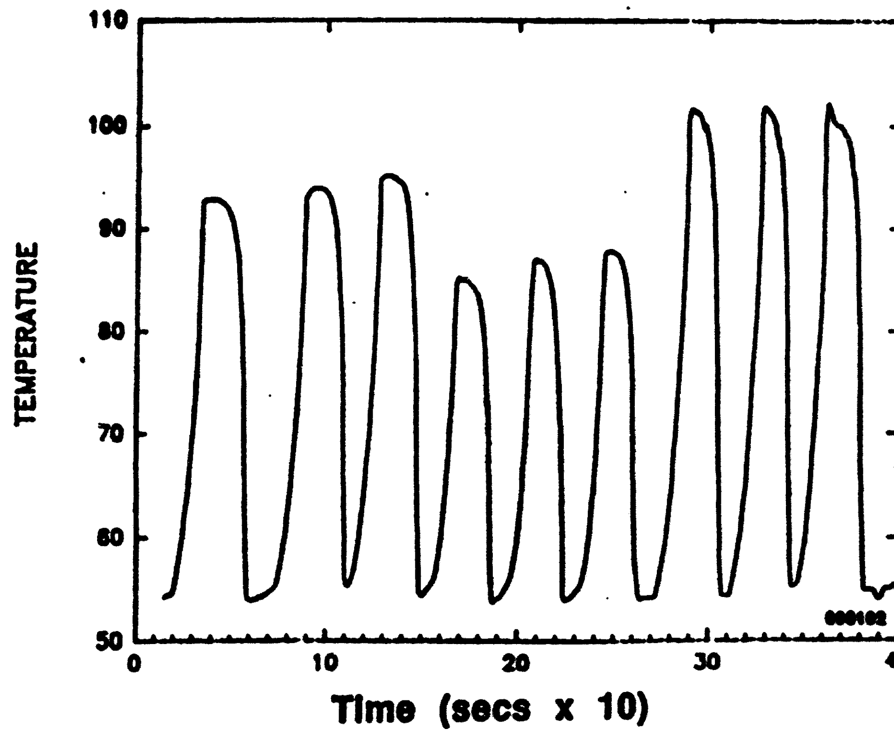
Basic Device

- Proto-type to evaluate system.



Temperature Cycling

- Temperature characteristics:
  rise/fall times of > 20 C/sec for 50 ul device
  rise/fall times of > 40 C/sec for 25 ul device



PCR Results

Side Standard

Commercial Cycler Micro-Device

- Reaction Time for 20 cycles
  - Micro-Device: 13.3min
  - Commerical Cycler: 40mins
- Power Requirements
  - Micro-Device: > 1W
  - Commerical: 50-200W

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.

MICROFLU[illegible]

ROADMAP

- ELASTIC WAVE AND DEVICE FUNDAMENTALS
- OPTIONS – OPEN OR CLOSED, GELS, CHANNELS, ...
- SENSING:

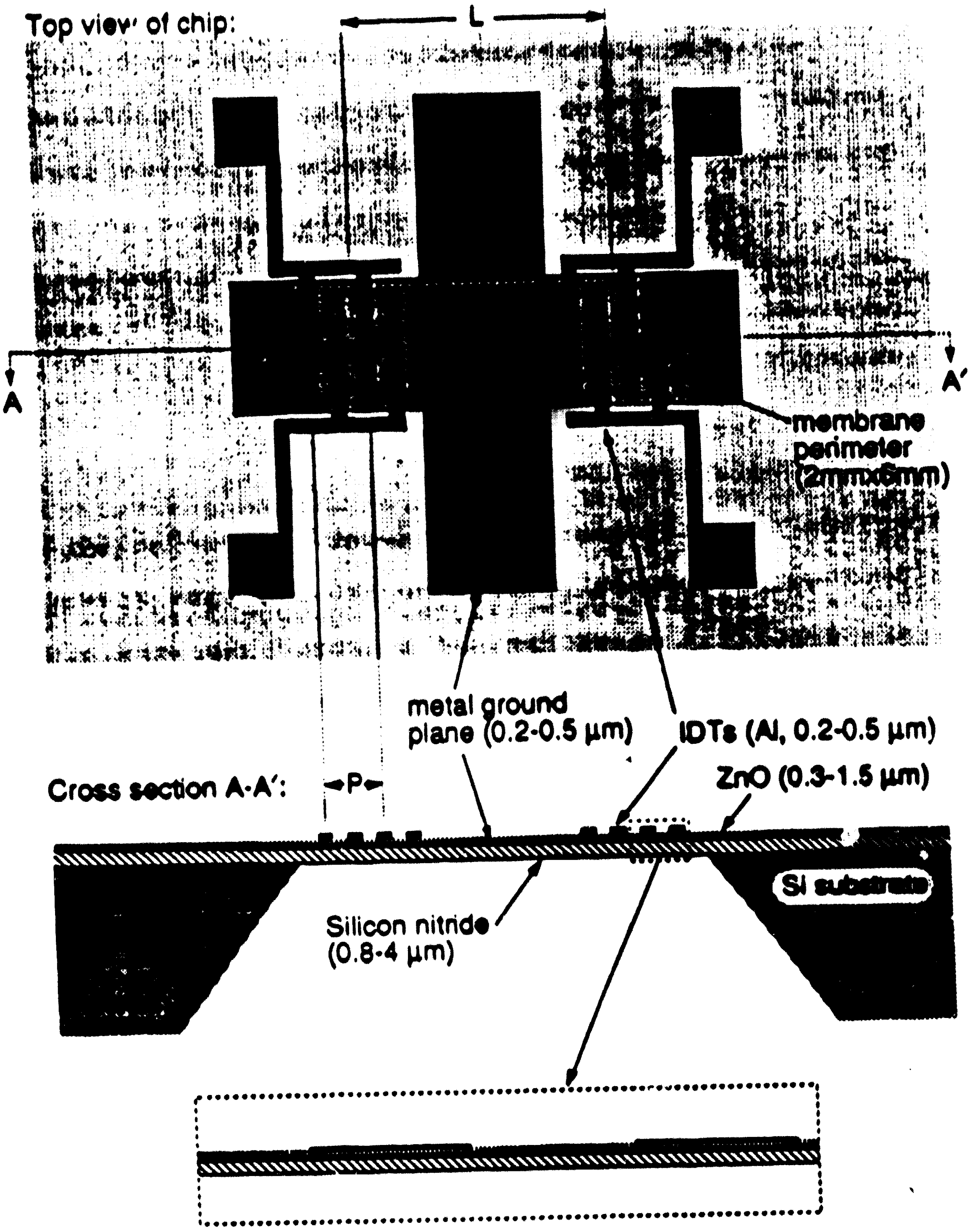
  VISCOSITY – FLUIDS; MOLECULAR WEIGHT EFFECT

  GRAVIMETRIC – LIQUID DENSITY; MOLECULES; CELLS
- KINETIC EFFECTS:

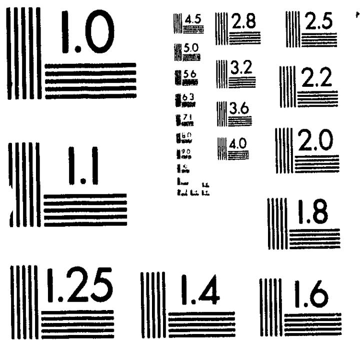
  MICROTRANSPORT – GRANULES IN GAS; LIQUIDS

  STIRRING AND MIXING

  SONOCHEMISTRY? ← MICROFABRICATED DNA-PCR REACTOR
- CONCLUSIONS

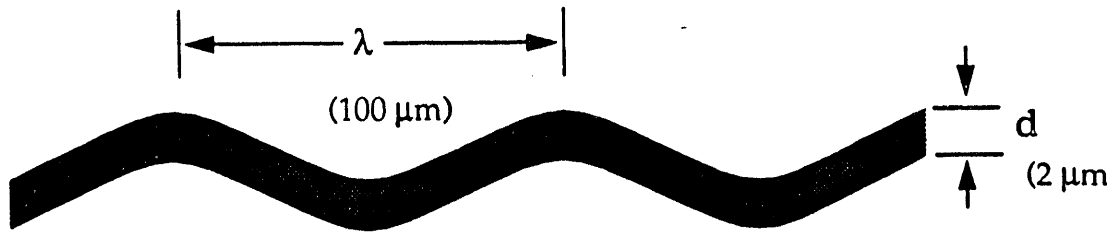


Top view of chip:
L
A
A′
membrane perimeter (2mmx8mm)
metal ground plane (0.2-0.5 µm)
IDTs (Al, 0.2-0.5 µm)
ZnO (0.3-1.5 µm)
Cross section A-A′:
P
Si substrate
Silicon nitride (0.8-4 µm)


1.0
4.5
2.8
2.5
5.0
3.2
2.2
5.6
3.6
6.3
2.0
4.0
1.1
1.8
1.25
1.4
1.6

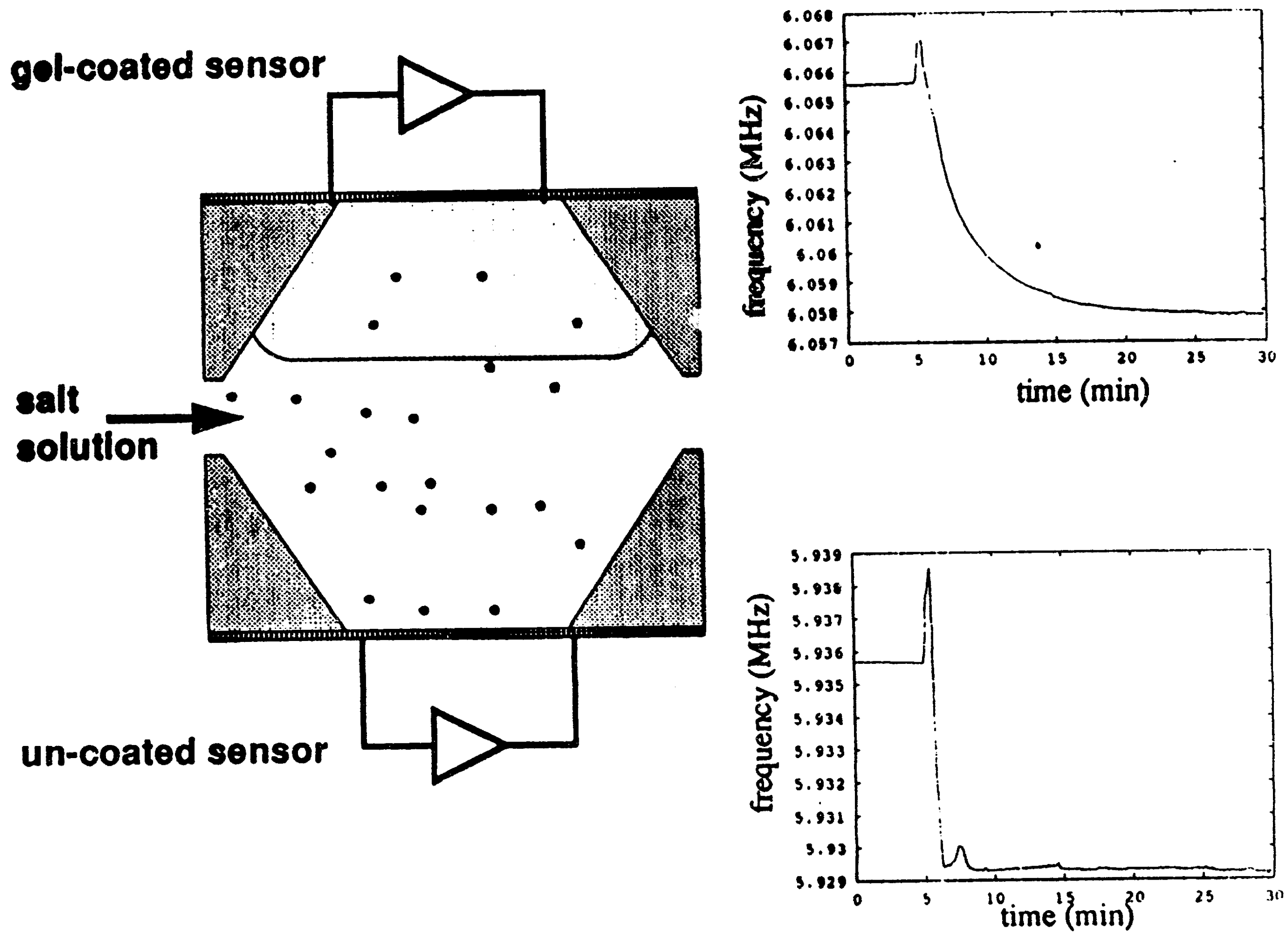
2 of 3

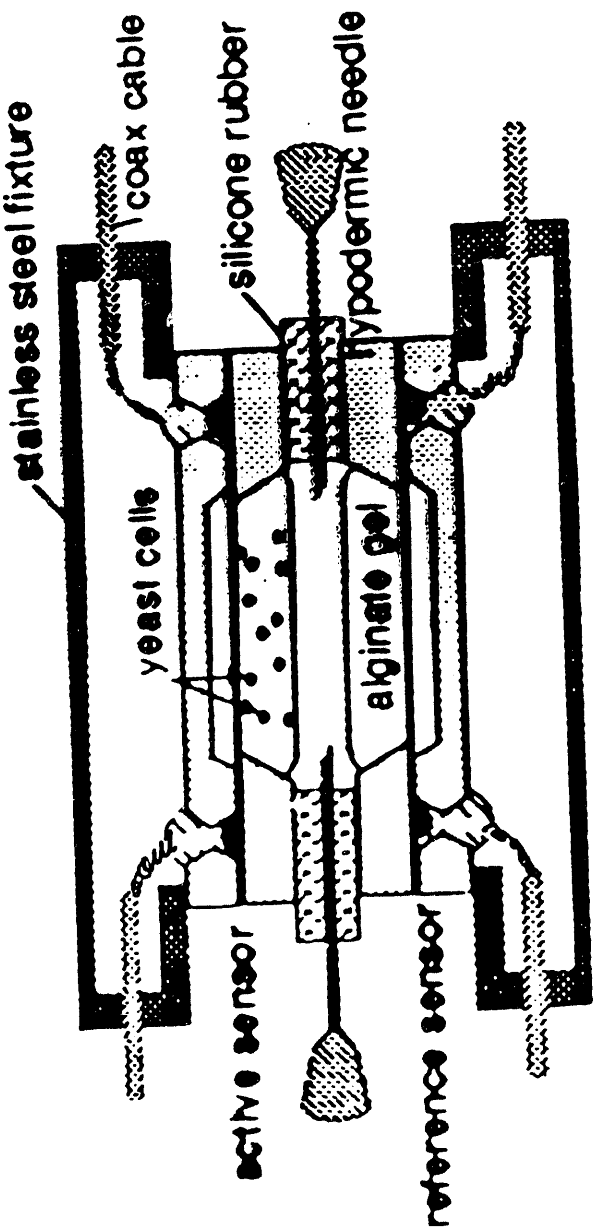
Why Plate Waves?

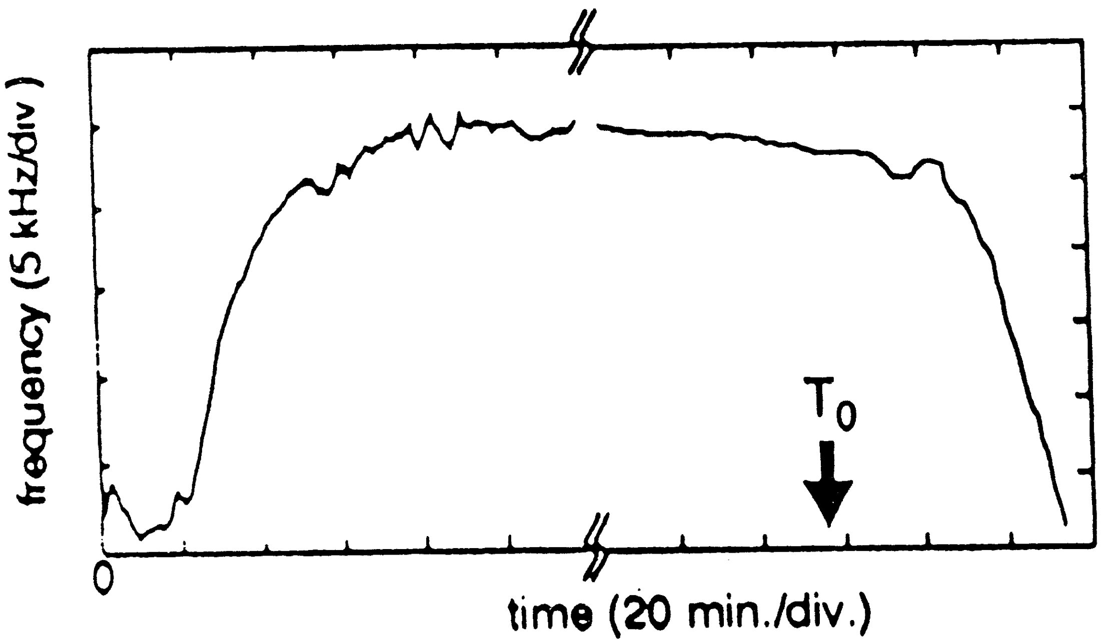


- Low velocity
  - low frequency
  - no radiation in liquids → low-loss operation
- High sensitivity
- Large amplitude → Pump solids and liquids
- Micromachinable

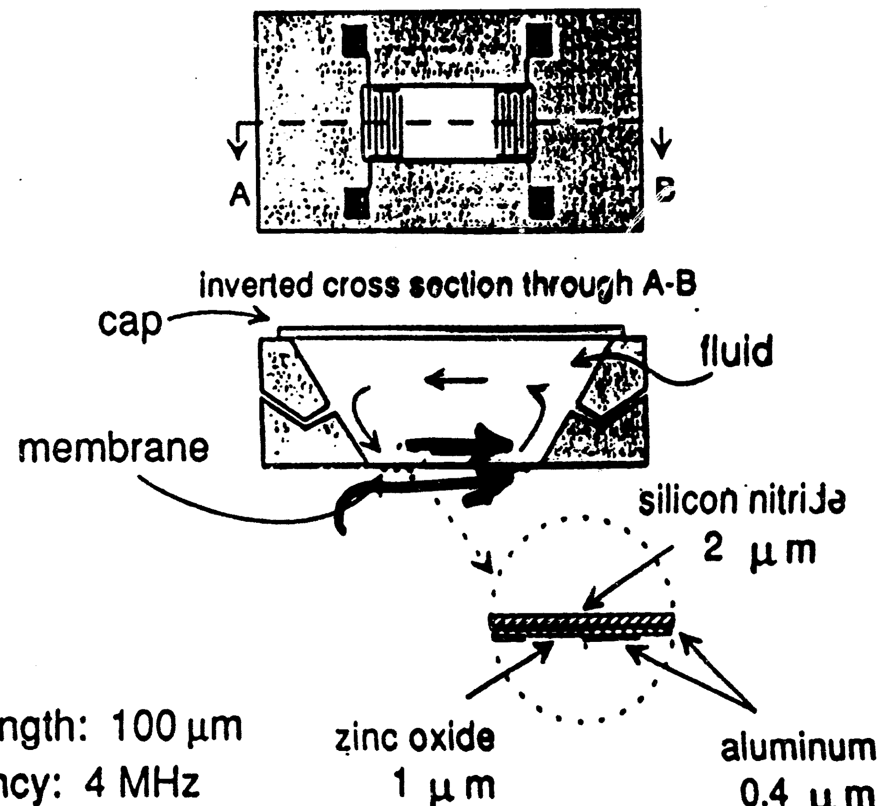
DIFFUSION


gel-coated sensor
salt solution
un-coated sensor
frequency (MHz)
6.068
6.067
6.066
6.065
6.064
6.063
6.062
6.061
6.06
6.059
6.058
6.057
0 5 10 15 20 25 30
time (min)
frequency (MHz)
5.939
5.938
5.937
5.936
5.935
5.934
5.933
5.932
5.931
5.93
5.929
0 5 10 15 20 25 30
time (min)


stainless steel fixture
coax cable
silicone rubber
hypodermic needle
yeast cells
alginate gel
active sensor
reference sensor

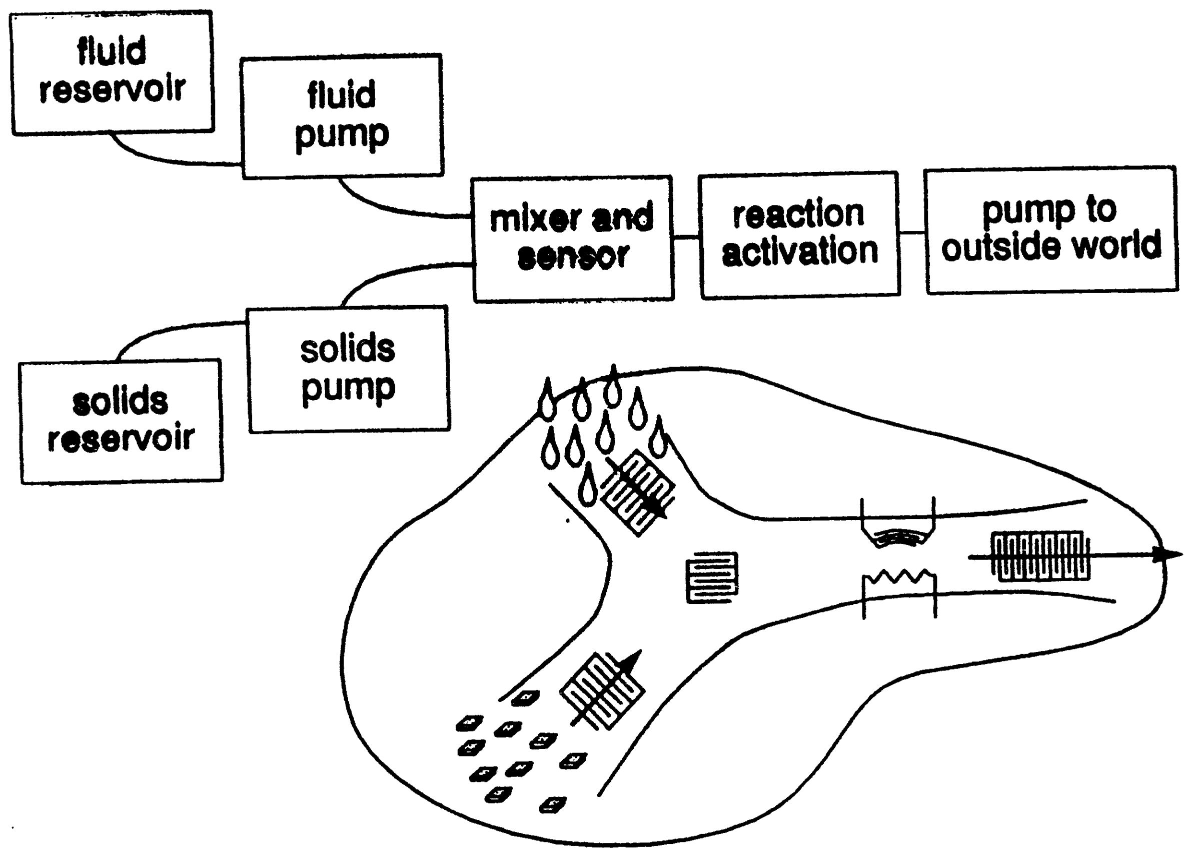

frequency (5 kHz/div)
0
time (20 min./div.)
T_0

Kinetic effects

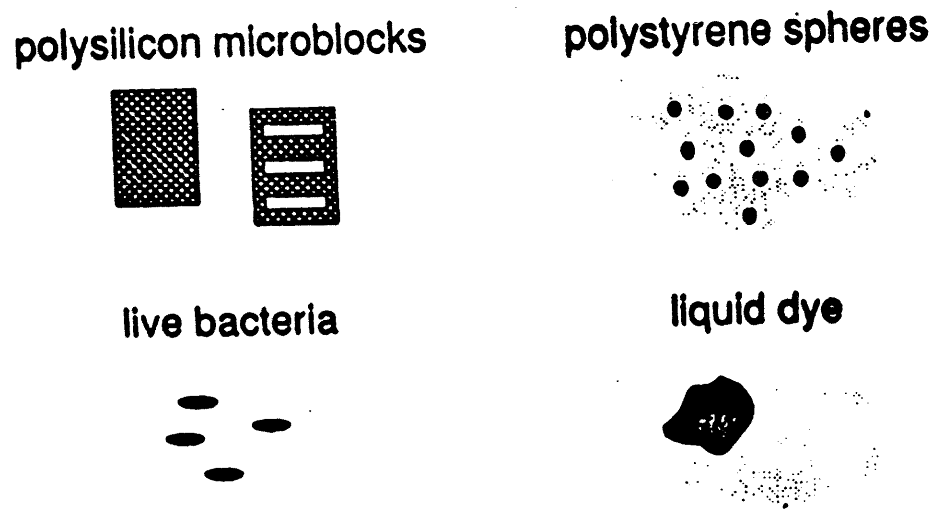


wavelength: 100 µm
frequency: 4 MHz
area: 3 x 8 mm

Integrated Systems

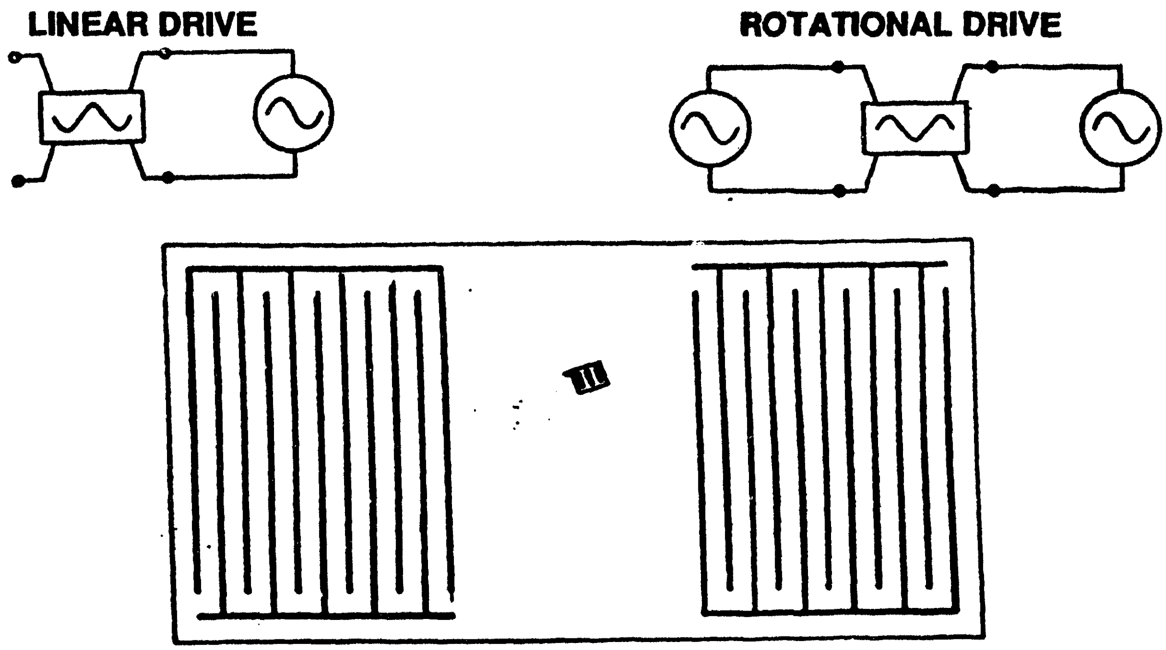


Kinetic effects



VIDEO: ULTRASONIC MICROTRANSPORT

LOOKING DOWN ONTO MEMBRANE WITH TRANS-DUCERS TO LEFT AND RIGHT:



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

BATTERY INDUSTRY, INCLUDING RESEARCH LABORATORIES:	8
NATIONAL LABORATORIES, BATTERY RELATED RESEARCH:	5
" " " OTHER FUNCTIONS:	5
UNIVERSITY FACULTY, INVOLVED WITH BATTERY RESEARCH:	8
" CONCERNED WITH DESIGN, METAL DESPOSITION, CORROSION, MODELING:	10
IBM, BELL LABS:	9
OTHER HIGH TECH INDUSTRIES:	6
CHEMICAL INDUSTRY:	14
OWN BUSINESS UNDERTAKING:	3
TOTAL:	68*

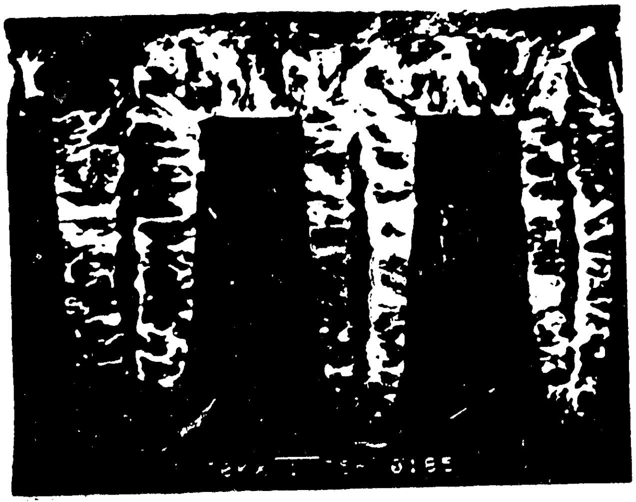
*Further two graduate students haven't as yet complete their degree requirements.

May 21, 1991

Chemical Engineering Departments with
Recognized Research Programs in Electrochemical Engineering

oo University of California (Berkeley
o University of California (Los Angeles)
Clarkson University
o Brigham Young University
o Carnegie-Mellon University
o Case-Western Reserve University
o Columbia University
+ University of Houston
o University of Illinois (Urbana)
o Illinois Institute of Technology
o Johns Hopkins University
University of Michigan
o University of Minnesota
+ North Carolina State University
+ South Carolina State University
o University of Rochester
+ Texas A & M
o 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 " "



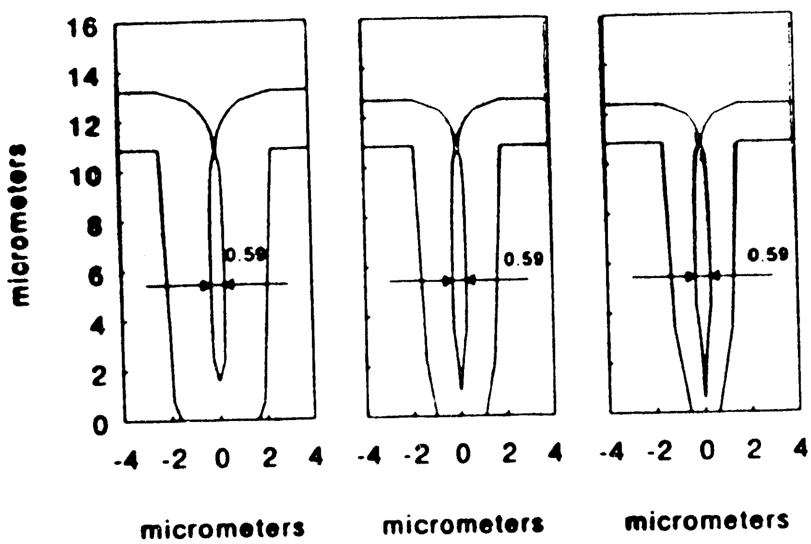


Fig. 6. CVD-tungsten film profiles in trenches of the same depth but with various widths (a) and the simulation of these conditions (b). Note that the width of the void (here measured at 6 μm depth becouse the trench profile is distorted near the bottom) does not depend on the width of the trench. Trench dimensions: 4.73 × 10.85 μm (left), 3.77 × 10.85 μm (middle), and 3.15 × 10.85 μm (right). The dimension of the voids is in micrometers. See text for more details.

void simulation	0.59	0.59	0.59
void experiment	0.59	0.55	0.54

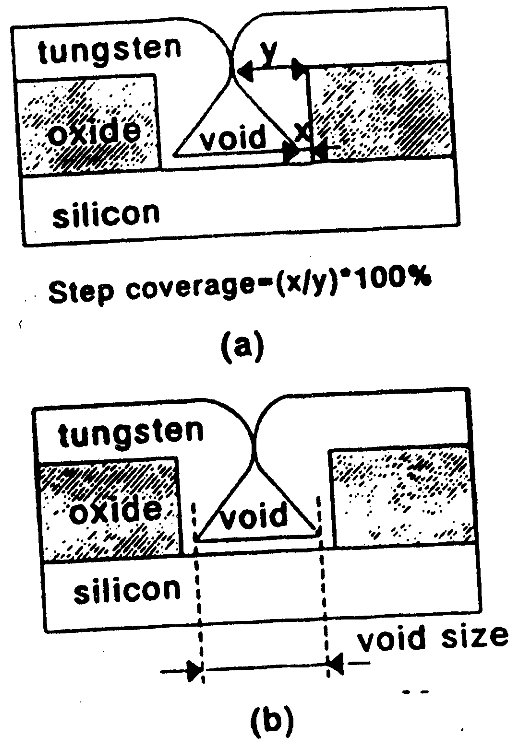
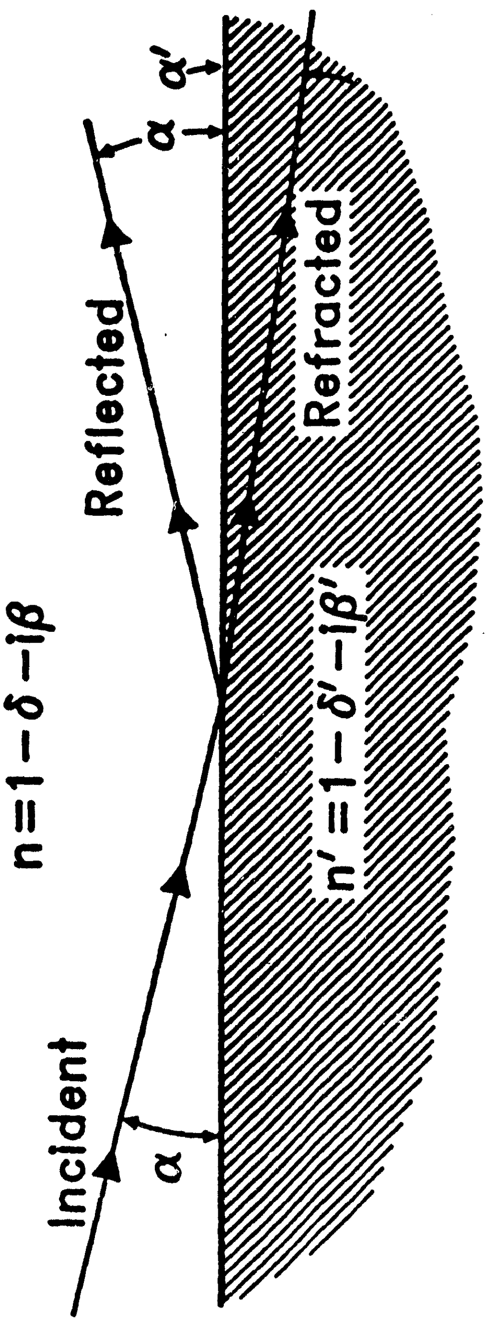


Fig. 2. Definition of step coverage (a) and of void size (b). This definition is arbitrary, other definitions in use in the literature might work as well.

$$h_T = \sqrt{[k'' L_t^2/(C_{WF_6} D_{WF_6} R_t)]}$$



Incident
α
n=1−δ−iβ
Reflected
α
α'
Refracted
n'=1−δ'−iβ'

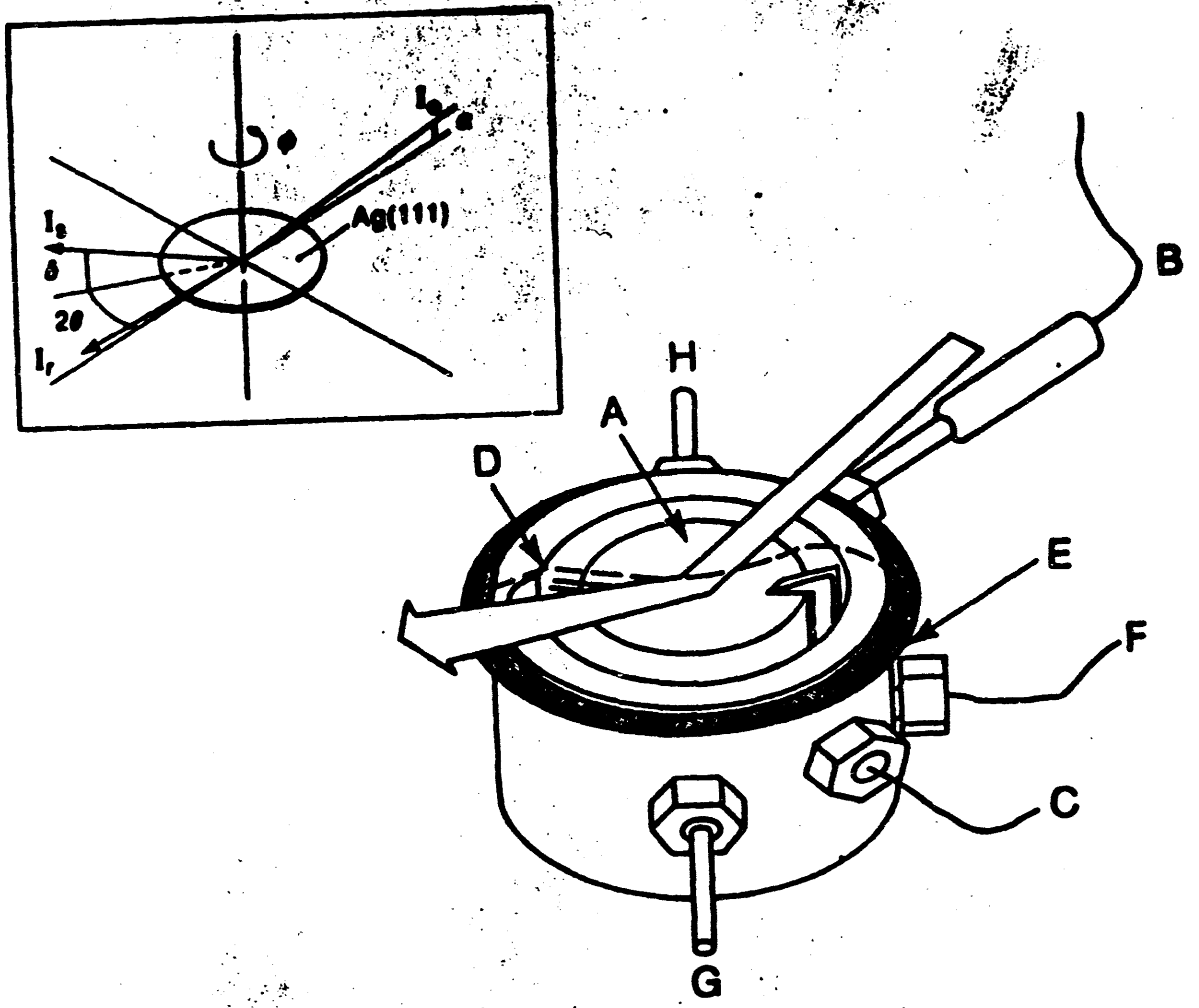
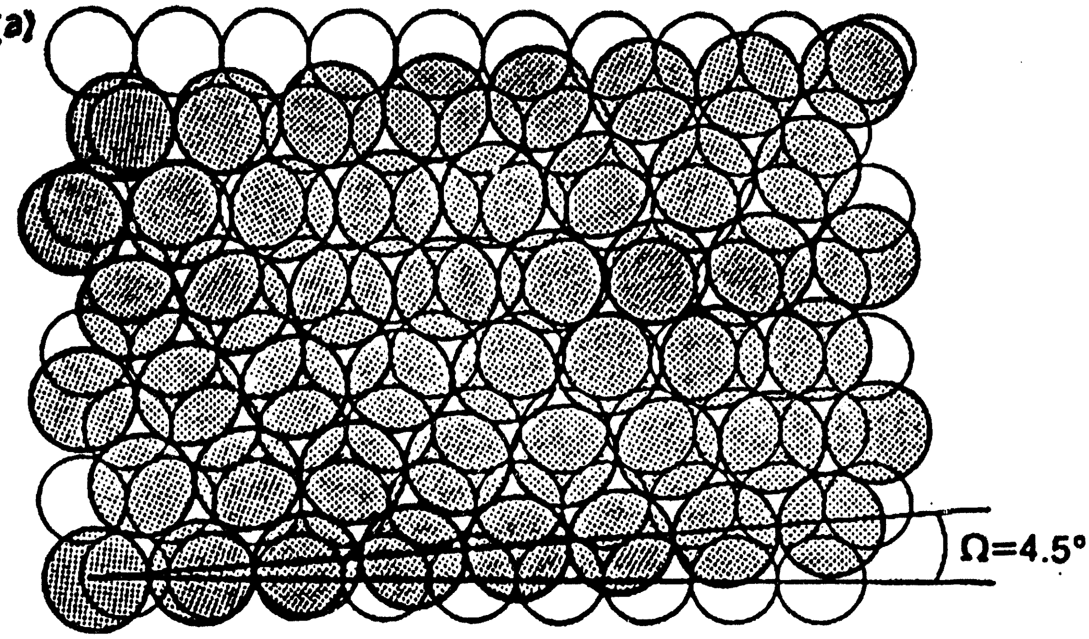


Figure 1. Electrochemical Cell: A) Silver or Gold (111) electrode, B) Ag/AgCl reference electrode, C) Platinum counter electrode, D) Polypropylene window, E) O-ring holding polypropylene to cell, F) External electrical connection to the working electrode, G) Solution inlet, and H) Solution outlet.

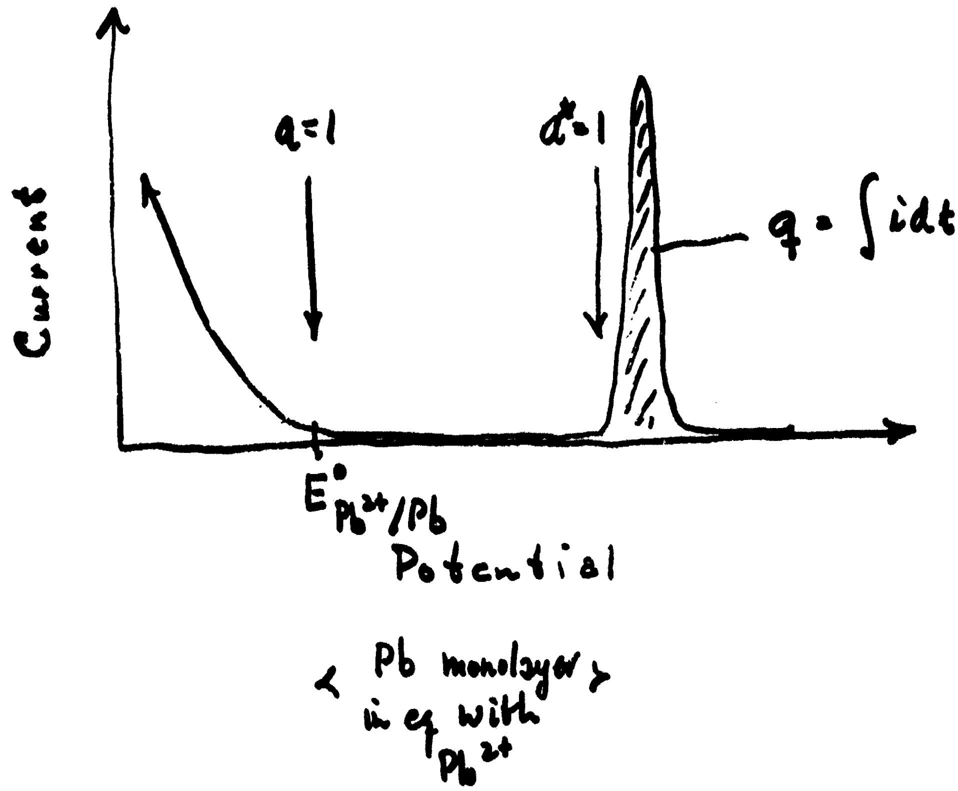
Insert: Grazing incidence scattering geometry showing the incident angle α, the output angle δ, the scattering angle θ, and the azimuthal angle ϕ. In all experiments reported here, $\alpha = \delta$. I_0 is the incident beam, I_s the scattered beam which goes to the Soller slits and detector, and I_r is the specular reflection.

(a)



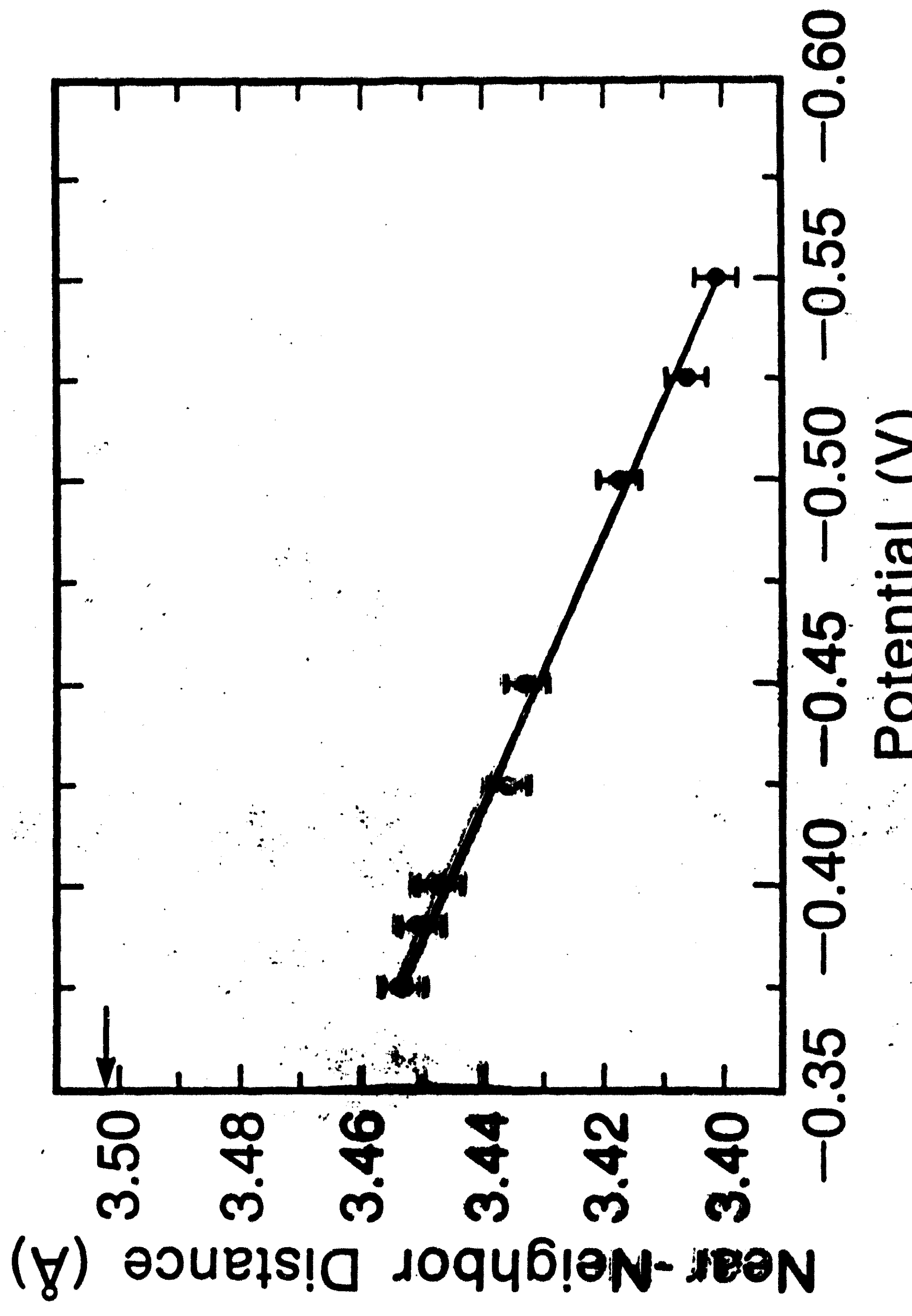
Electrodeposition of Pb Monolayer on Ag(111)

$Pb^{2+} + 2e^- \rightarrow Pb$ { two distinct <u>equilibrium</u> states

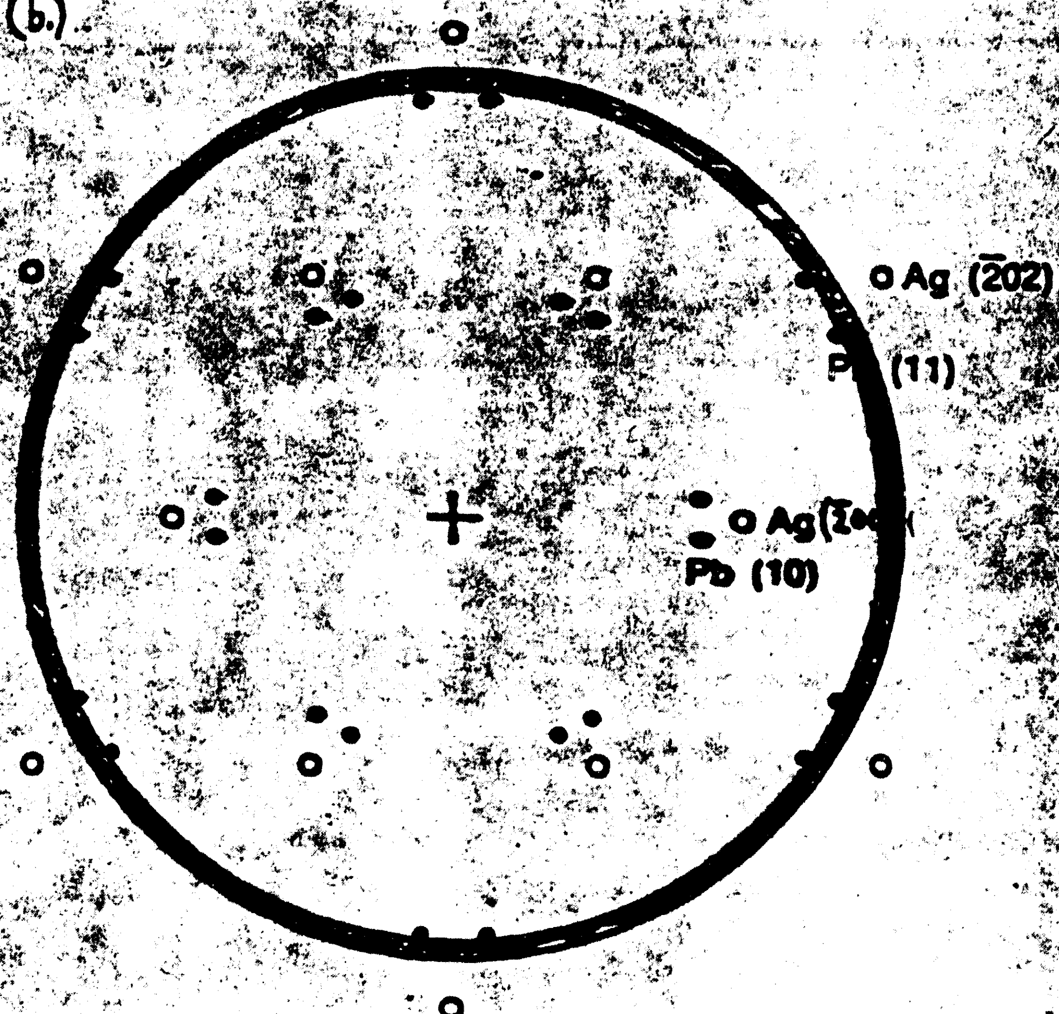


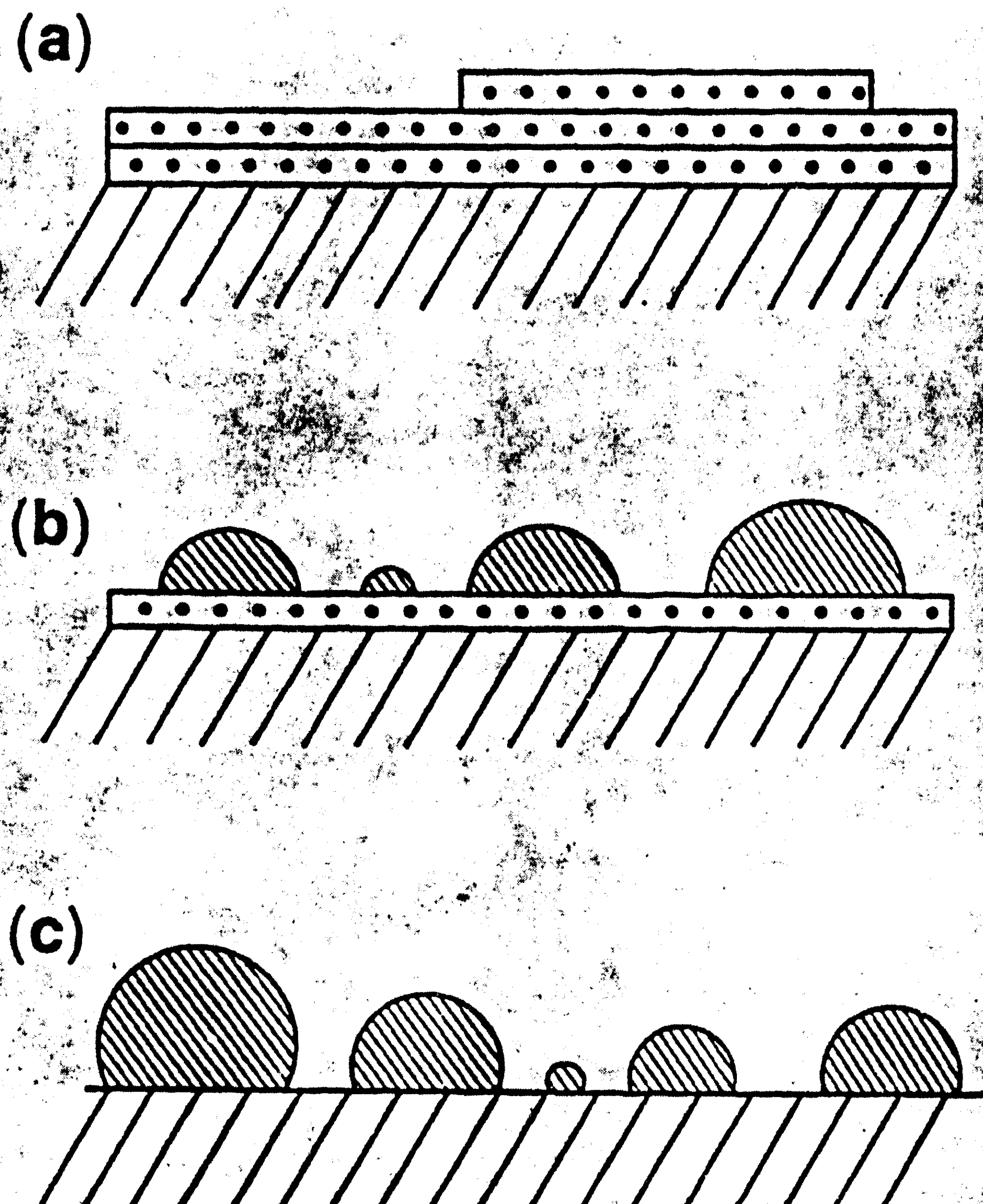
Why Pb on Ag(111)?

1. High Z metal on low Z substrate
2. Vapor deposited structure well-known
3. Incommensurate structure


Near-Neighbor Distance (Å)
3.50
3.48
3.46
3.44
3.42
3.40
−0.35
−0.40
−0.45
−0.50
−0.55
−0.60
Potential (V)

(b.)




(a)
(b)
(c)

MEMS Activities at LLNL

Dino Ciarlo
Micro Technology Center
LLNL

August 3, 1993

Near term - long term needs for LIGA at LLNL

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

Lawrence Livermore National Laboratory

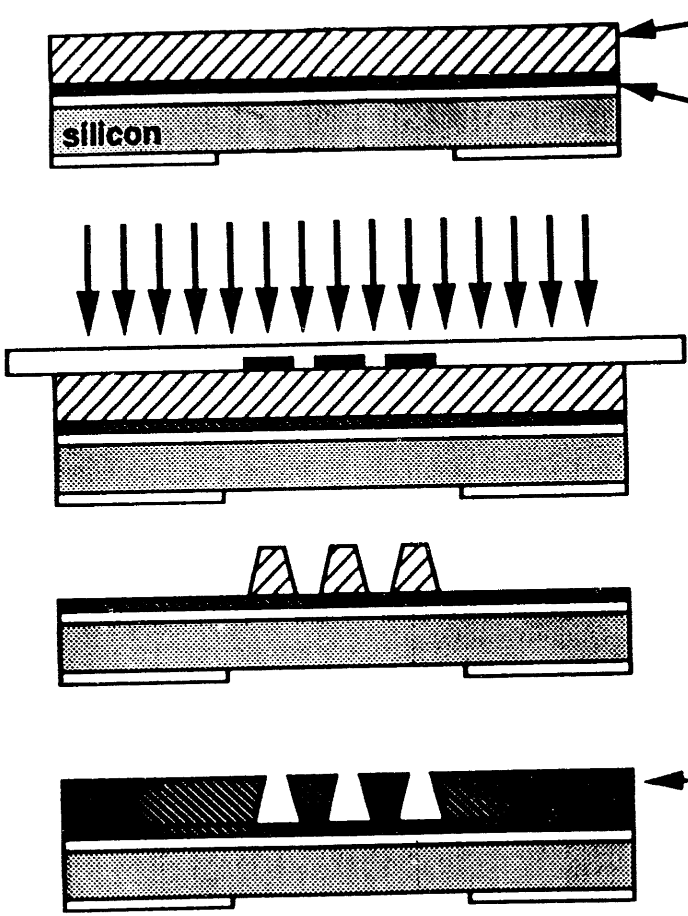
HAR-MEMMS Workshop

Lawrence Berkeley Laboratory

August 3, 1993

120

Targets for coded imaging [redacted]
conventional IC resist and [redacted]



[redacted]

plating [redacted]

contact mask

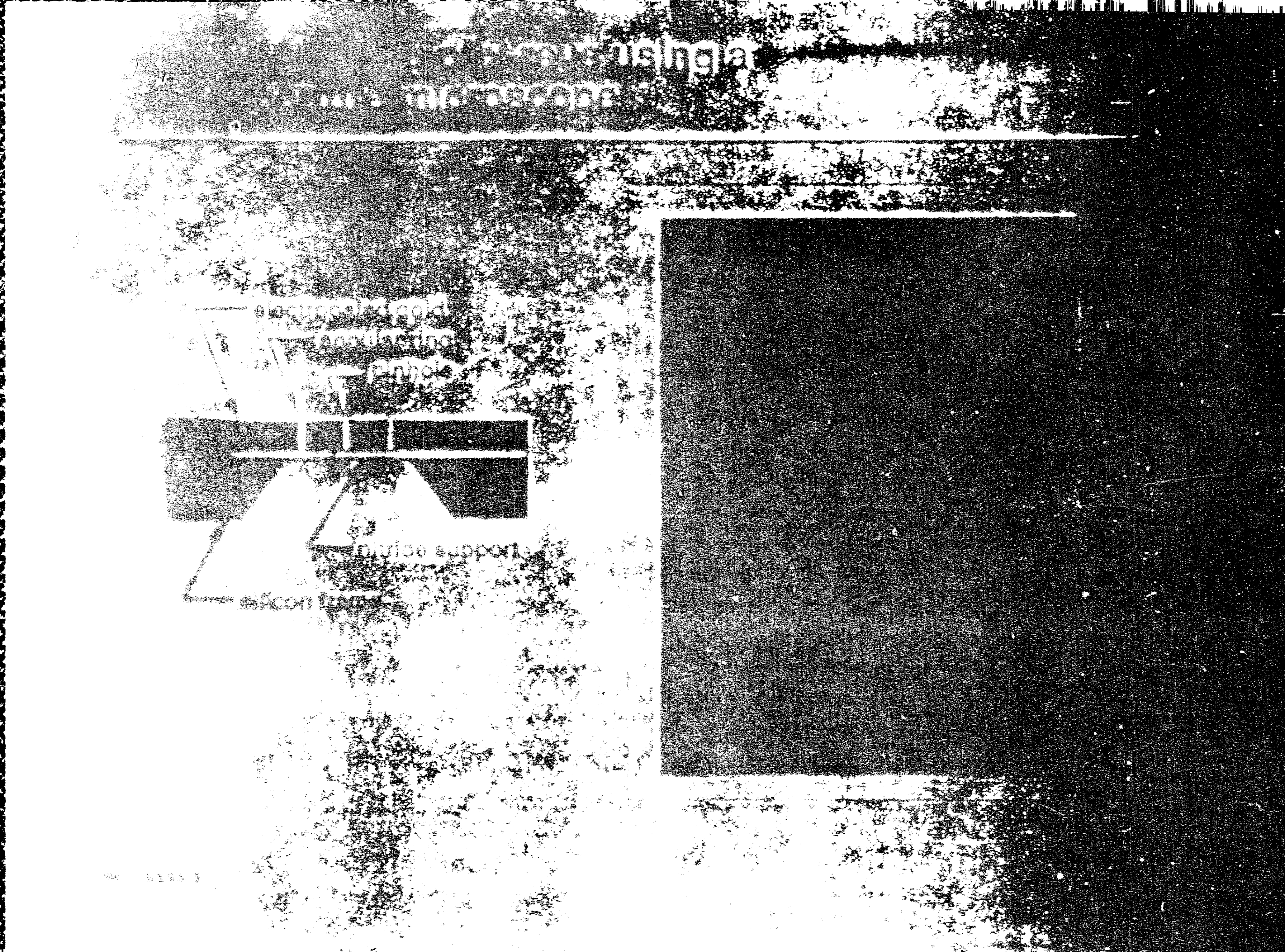
expose resist with 405 nm UV

develop [redacted]
diffraction [redacted] long development
causes side[redacted] (85°)

electroplated gold follows mold pattern

height/width ratio

Fan	Engelmann	Allen	NTT	LIGA
20:1	6.7:1	7:1	6.7:1	54:1
Resist		Polyimide RIE		PMMA


electroplated gold
conducting
pinhole
nitride support
silicon frame

124

Individual modules are assembled together

(a) (b)

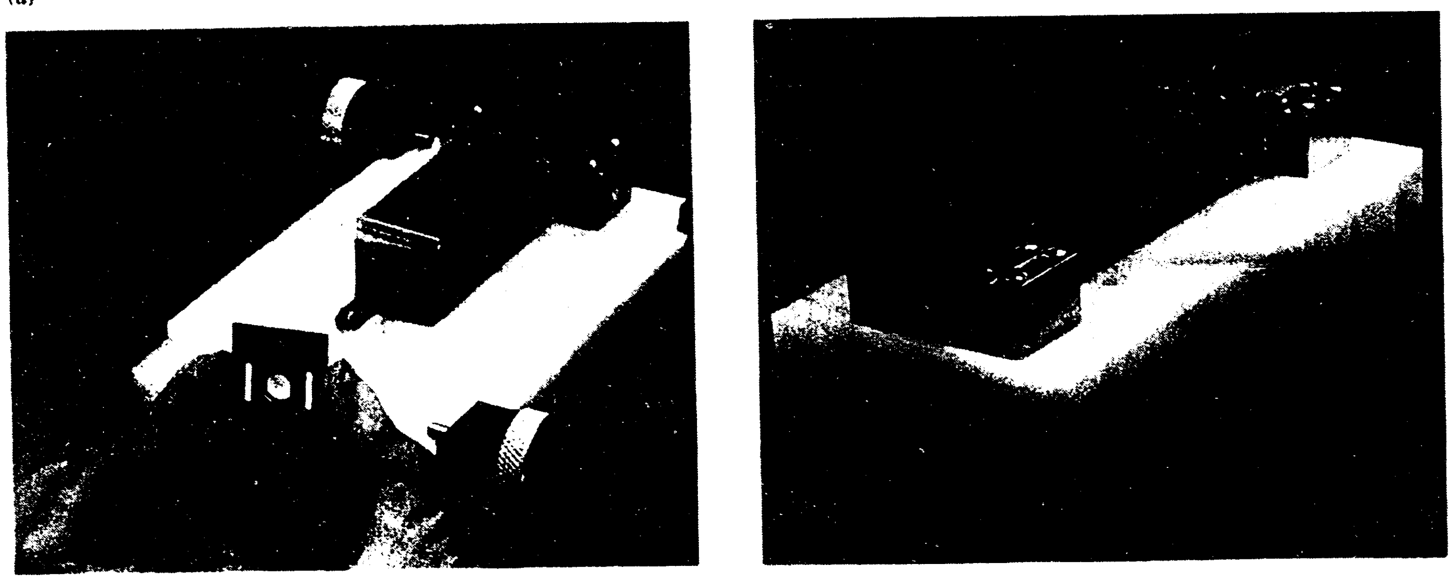


Figure 5. (a) A two-dimensional microchannel-cooled laser diode array being assembled. (b) This 42-module stack was fabricated for pumping a Nd^{3+}:YAG high-average-power crystalline slab laser.

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, $\pm 50\ \mu$

- 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.
reduce outgassing contamination and pumping time.
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

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

Electroplating

85 processing tanks (400 to 1500 liters)

7 technicians with experience totaling 95 years

Environmentally conscience processing

Space Microsensors and Microinstruments

Michael Hecht
Jet Propulsion Laboratory

August 3, 1993

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. Stalder, 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 Maker)
  - Electron Beam Lithography
  - Metrology
  - Binary Optics

Themes

- **Mix of R&D**
  - ~25% Basic Research (BEEM, HARMM)
  - ~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 <u>requires</u>:

- 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

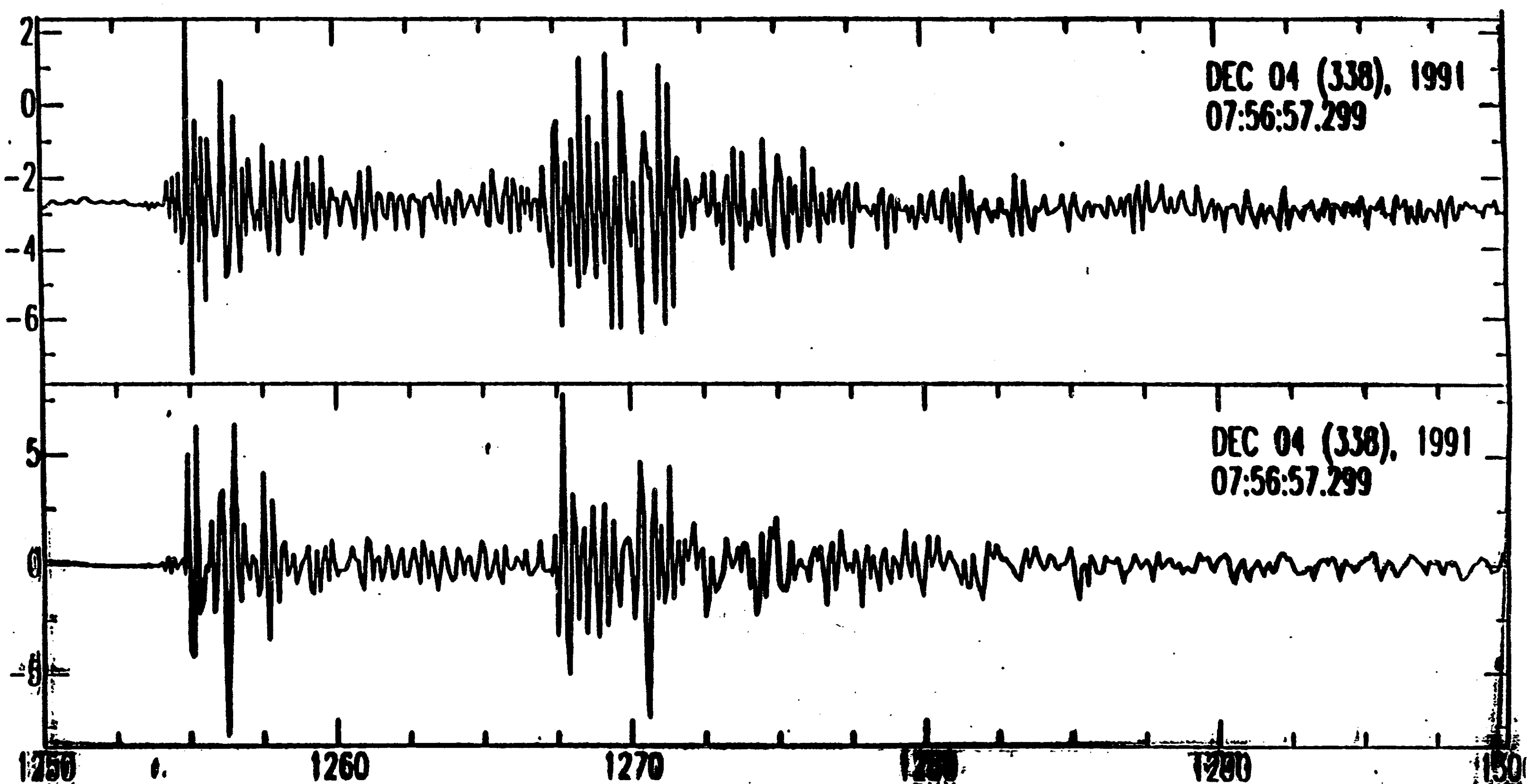
A variety of important mission opportunities require a reduction in instrument mass by a factor of ten or more without loss of performance

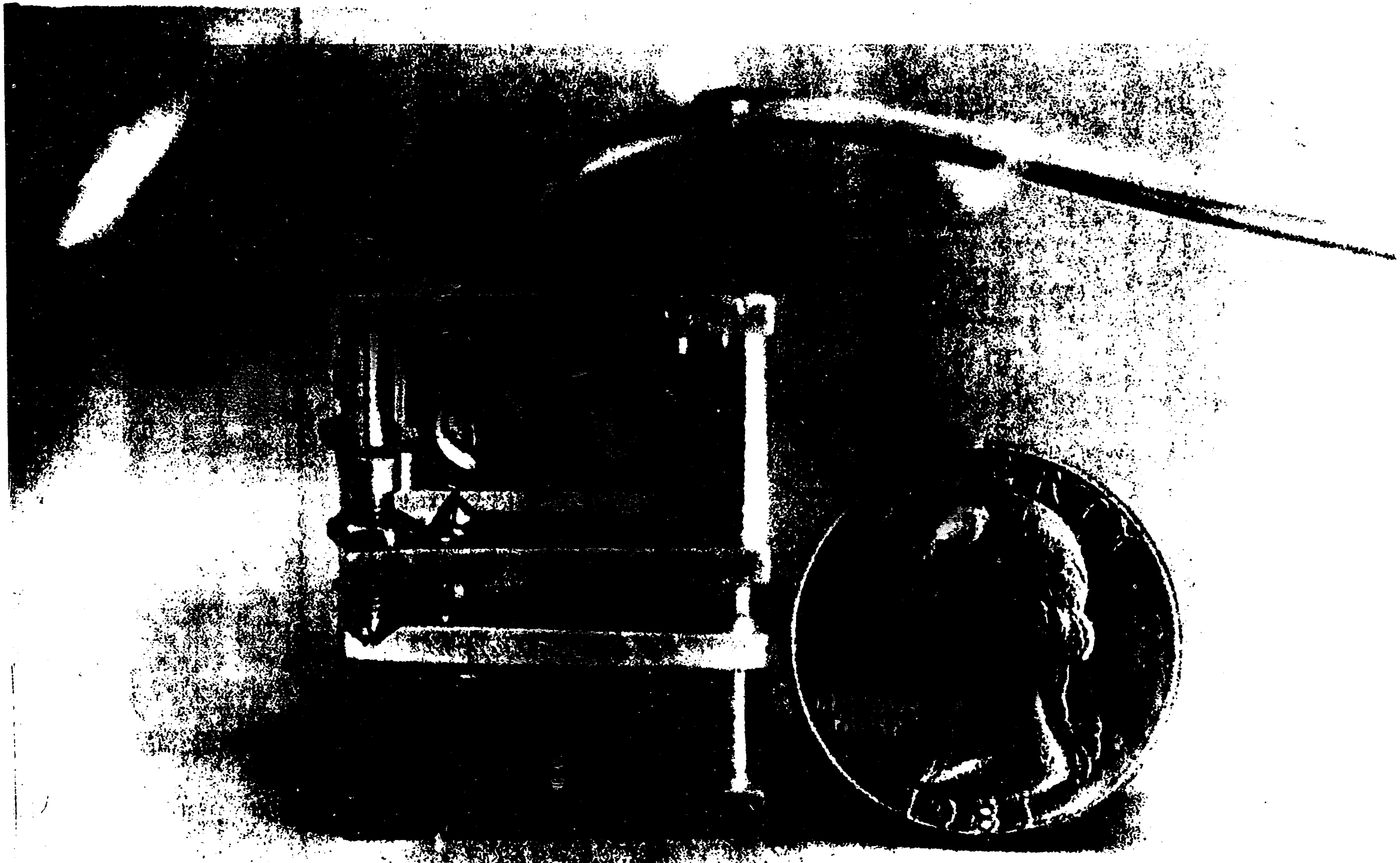
JPL MICROSEISMOMETER:
TESTING - EARTHQUAKE MEASUREMENT

M = 4.0 Earthquake, Big Bear, California, 12/4/91

JPL Microseismometer (Mass = 100 grams)

Conventional Instrument (Mass = 5.5 kg)



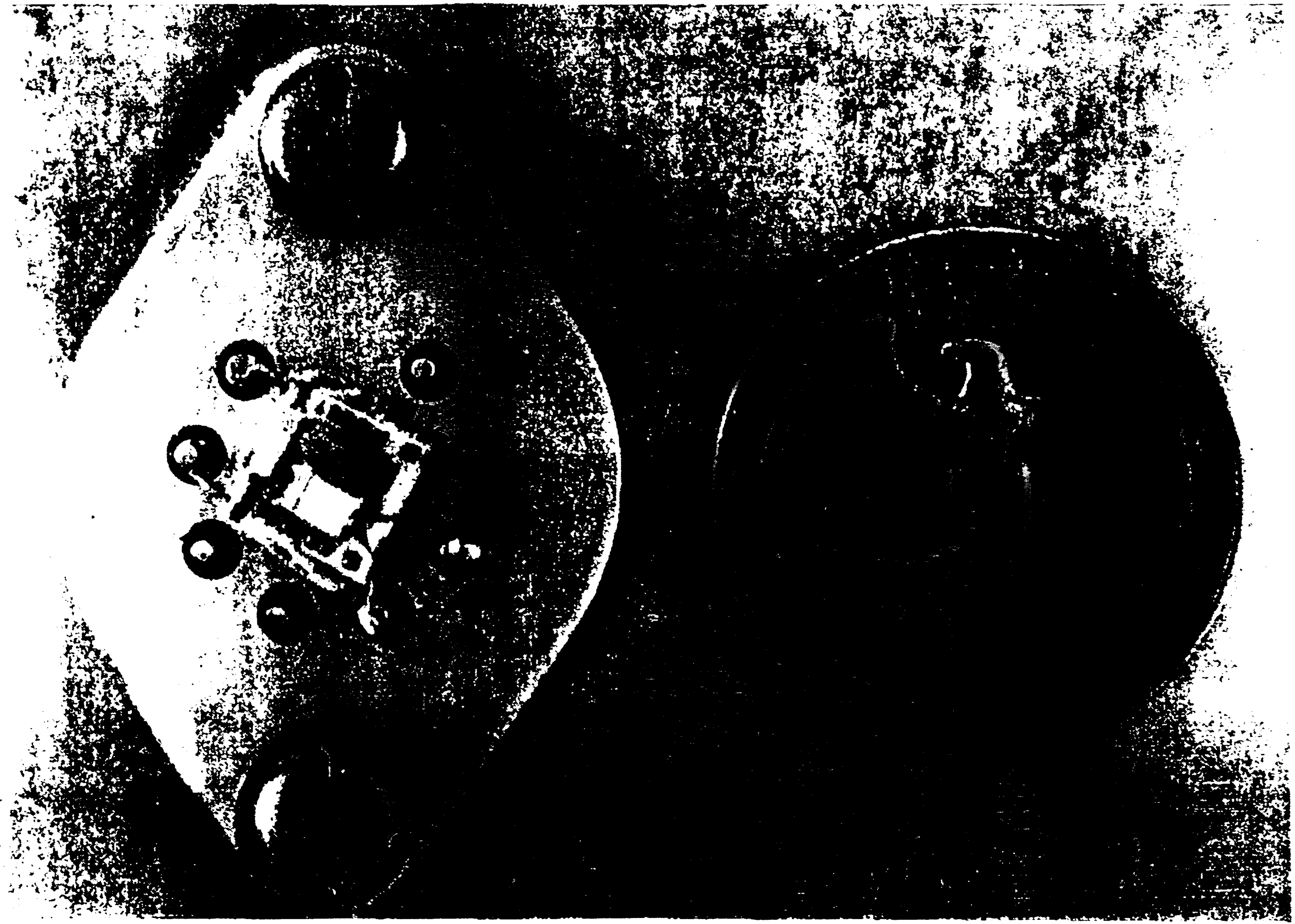


Photograph of JPL Prototype Mars Seismometer. In this device a 3 gm copper proof mass is suspended by a silicon crystal cantilever in the vertical orientation. A sensitive capacitive displacement transducer measures the deflection of the proof mass in the event of a vertical acceleration. This device features sensitivity better than 10^{-9} g/$\sqrt{\text{Hz}}$ and bandwidth of 40 Hz

SEISMOMETER PHOTO (CSMT 92091)

This photograph shows the JPL seismometer being attached to drill string and prepared for insertion into well

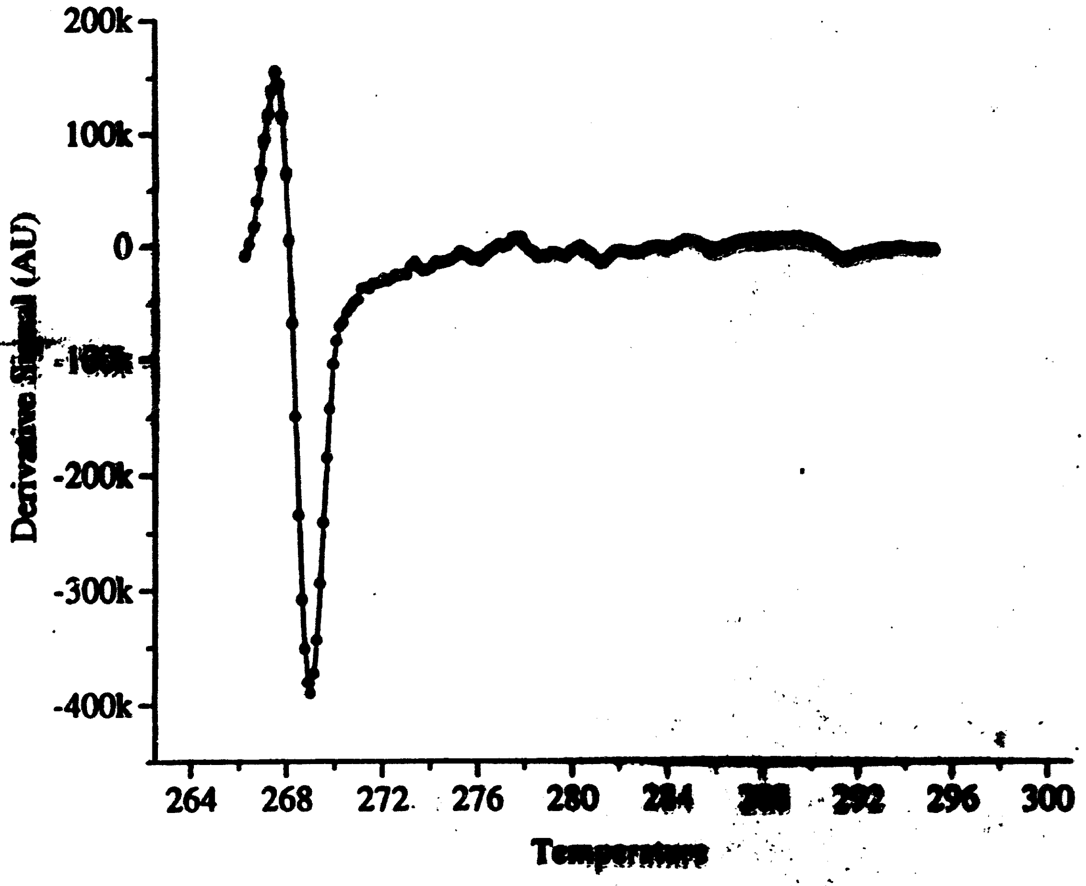
HYGROMETER PHOTO (CSMT 93032)



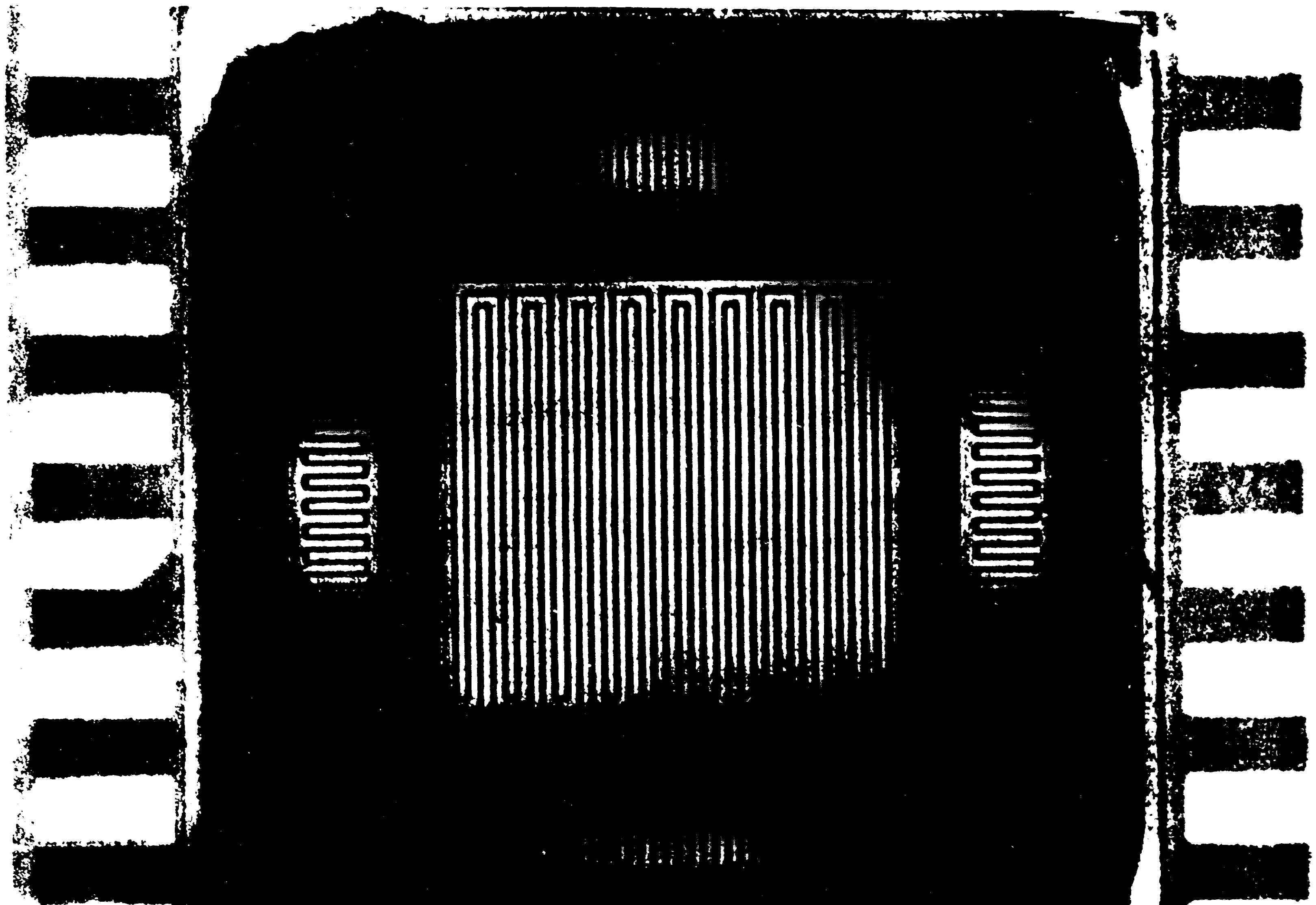
This photograph shows the hygrometer mounted on a thermo-electric cooler, which is

MICROHYGROMETER DERIVATIVE FREQUENCY SPECTRUM

DEWPOINT MEASUREMENT

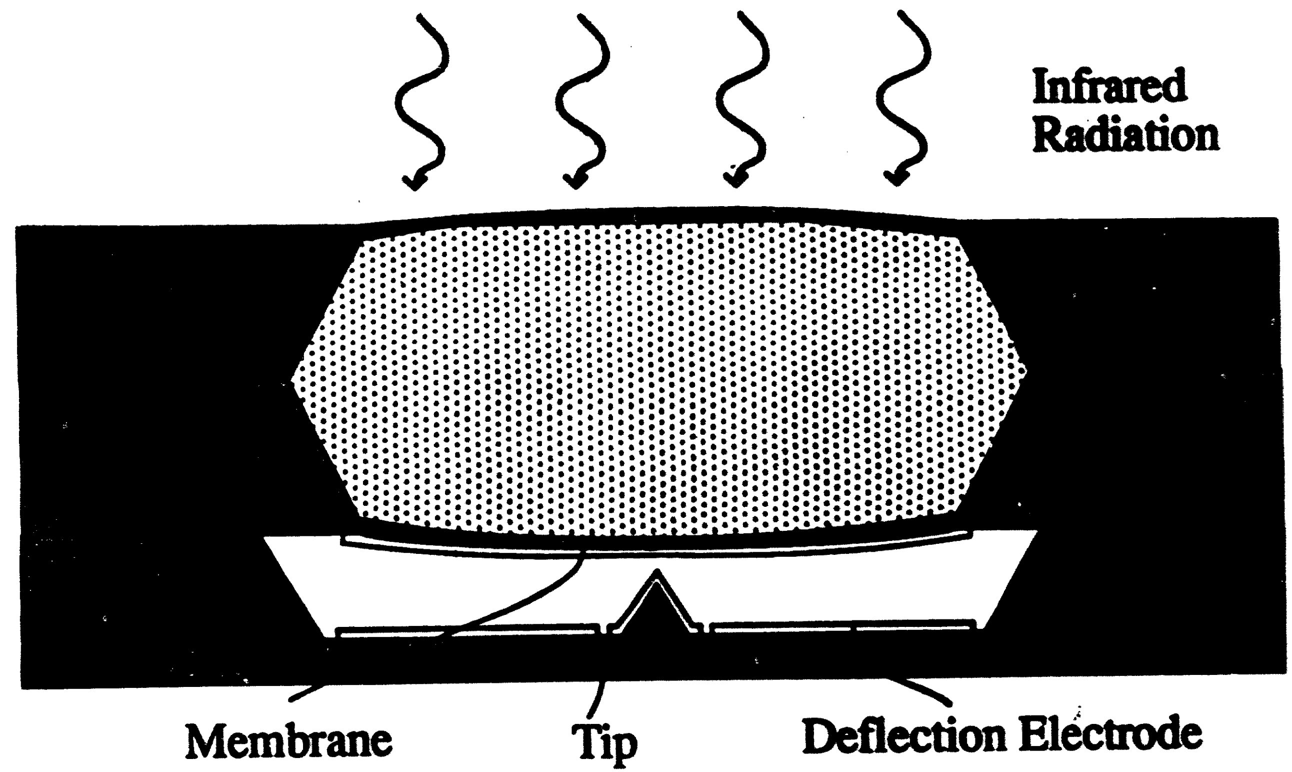


THERMAL-PRESSURE SENSOR PHOTO (P-41203BC)



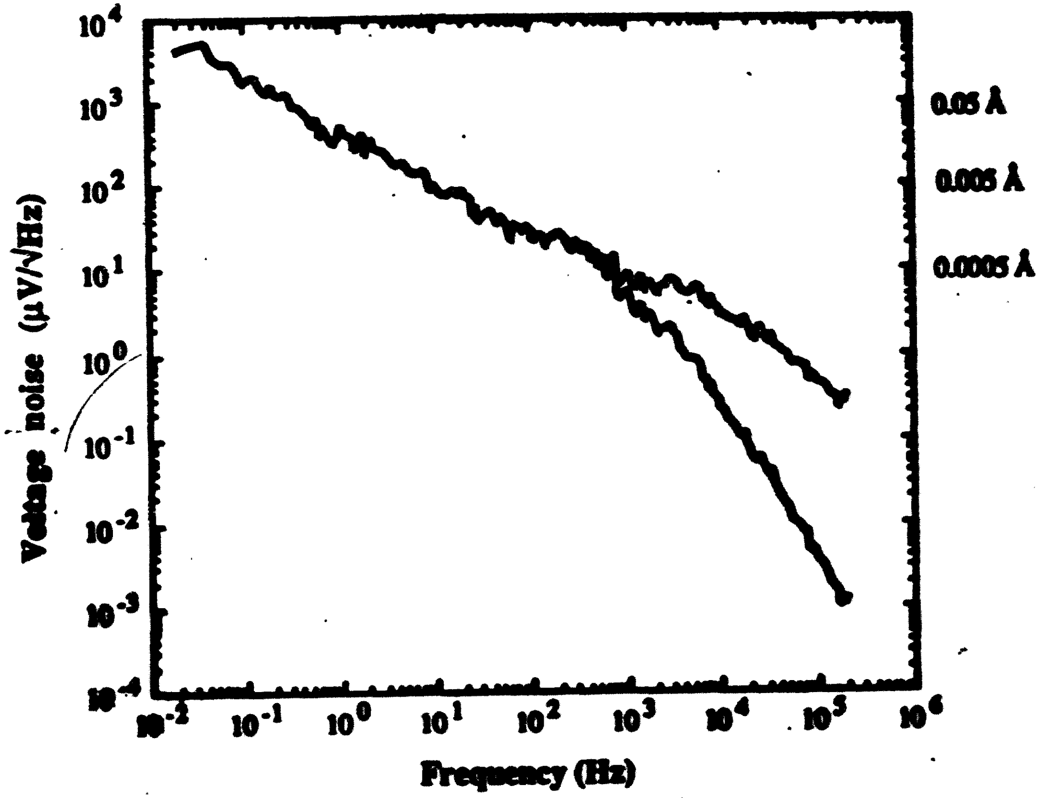
This photograph shows a prototype pressure sensor which is based on a measurement of the thermal conductivity of the ambient medium. In this device, current is passed through the nitride supported platinum wires around the perimeter, and the changes in resistance of the central nitride-supported platinum wire is recorded.

TUNNELING INFRARED SENSOR DESIGN



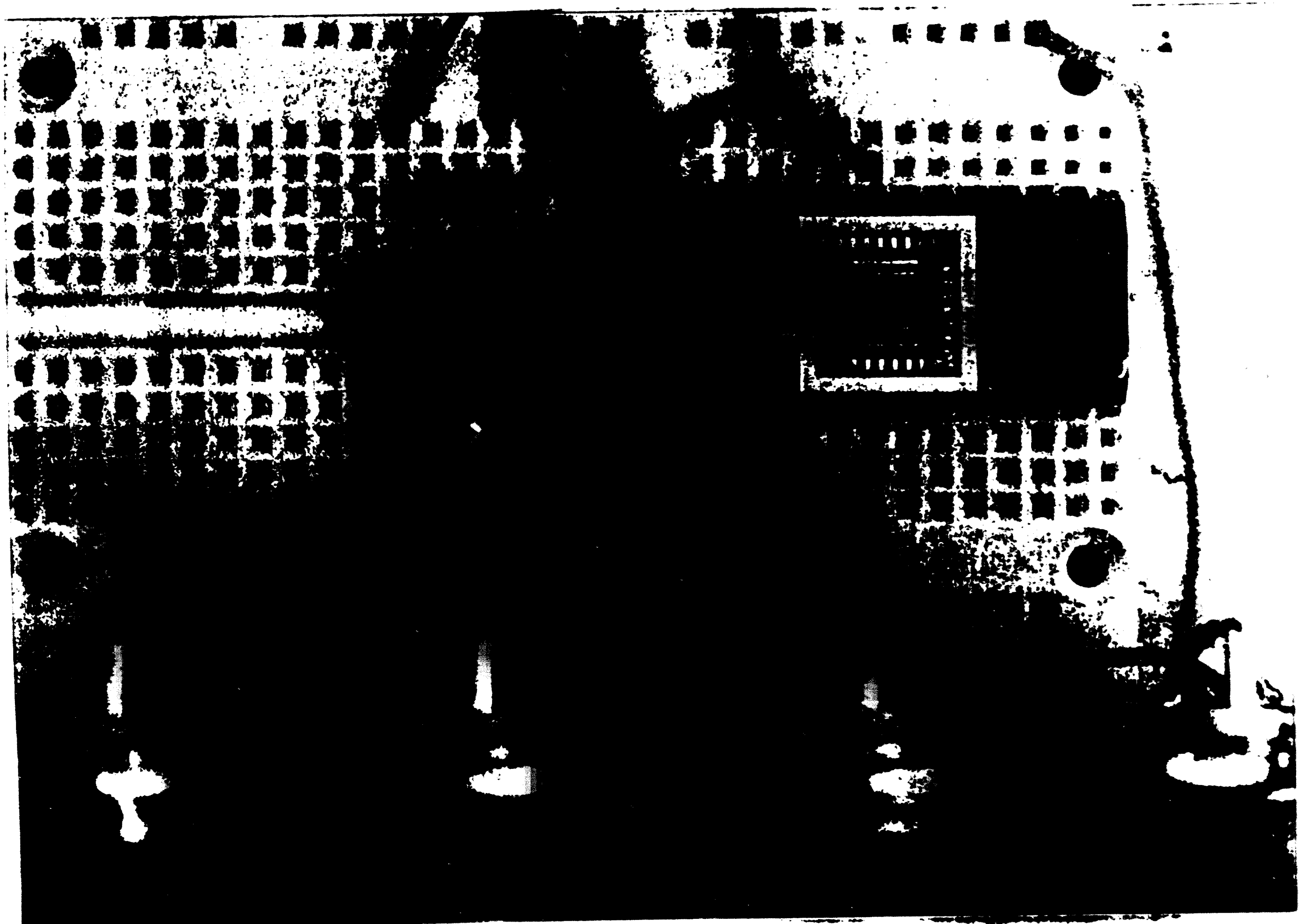
- Feedback circuit deflects membrane into tunneling contact with tip
- Absorbed radiation increases pressure in cell
- Feedback circuit responds by reducing deflection voltage

NOISE IN THE MEMBRANE TRANSDUCER

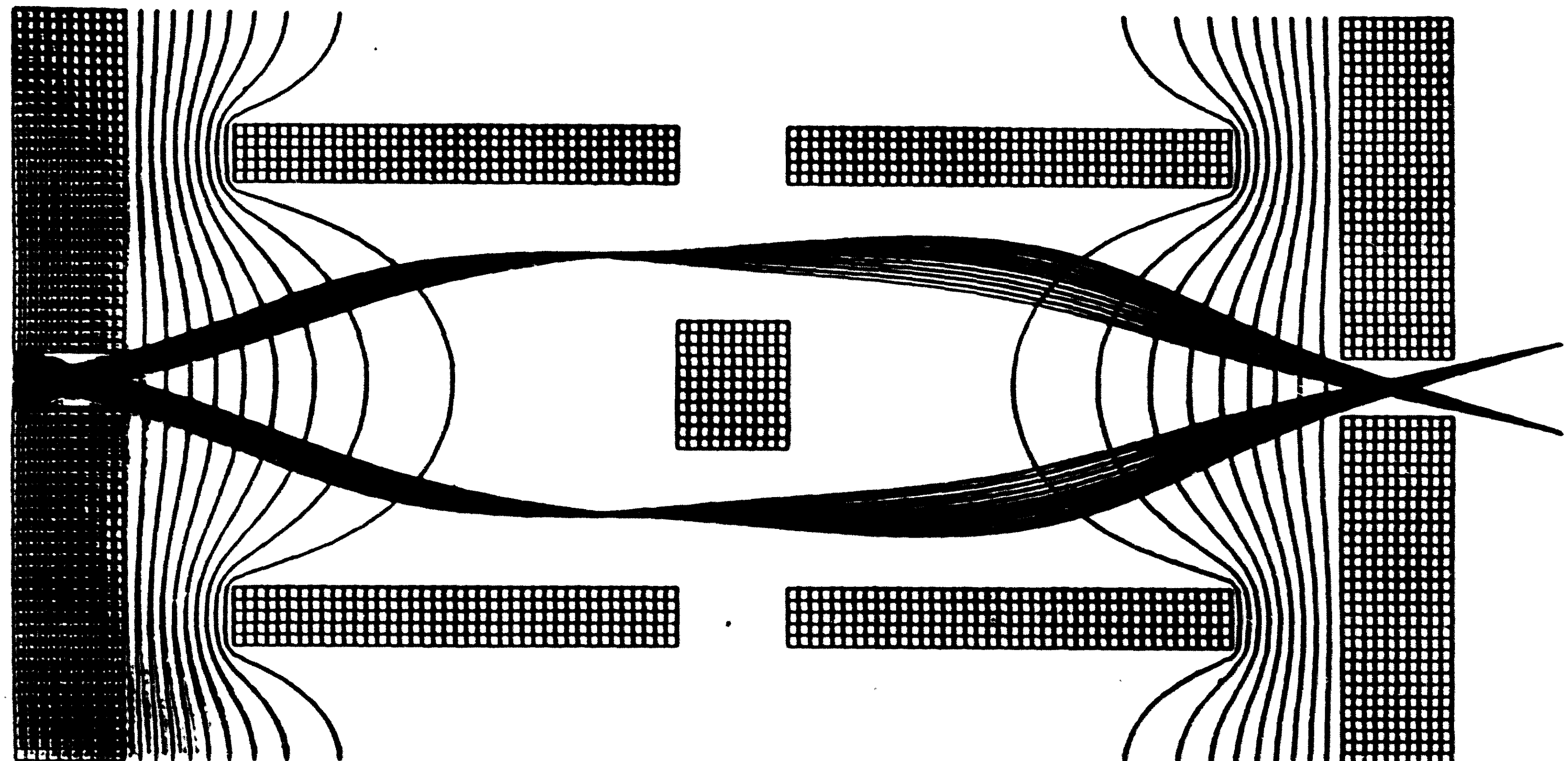


Output voltage noise spectra are recorded at the output of the error amplifier (upper curve) and at the deflection electrode (lower curve). The noise at the deflection electrode is reduced by stray capacitance.

SENSOR IN CIRCUIT BOARD WITH FEEDBACK CIRCUIT

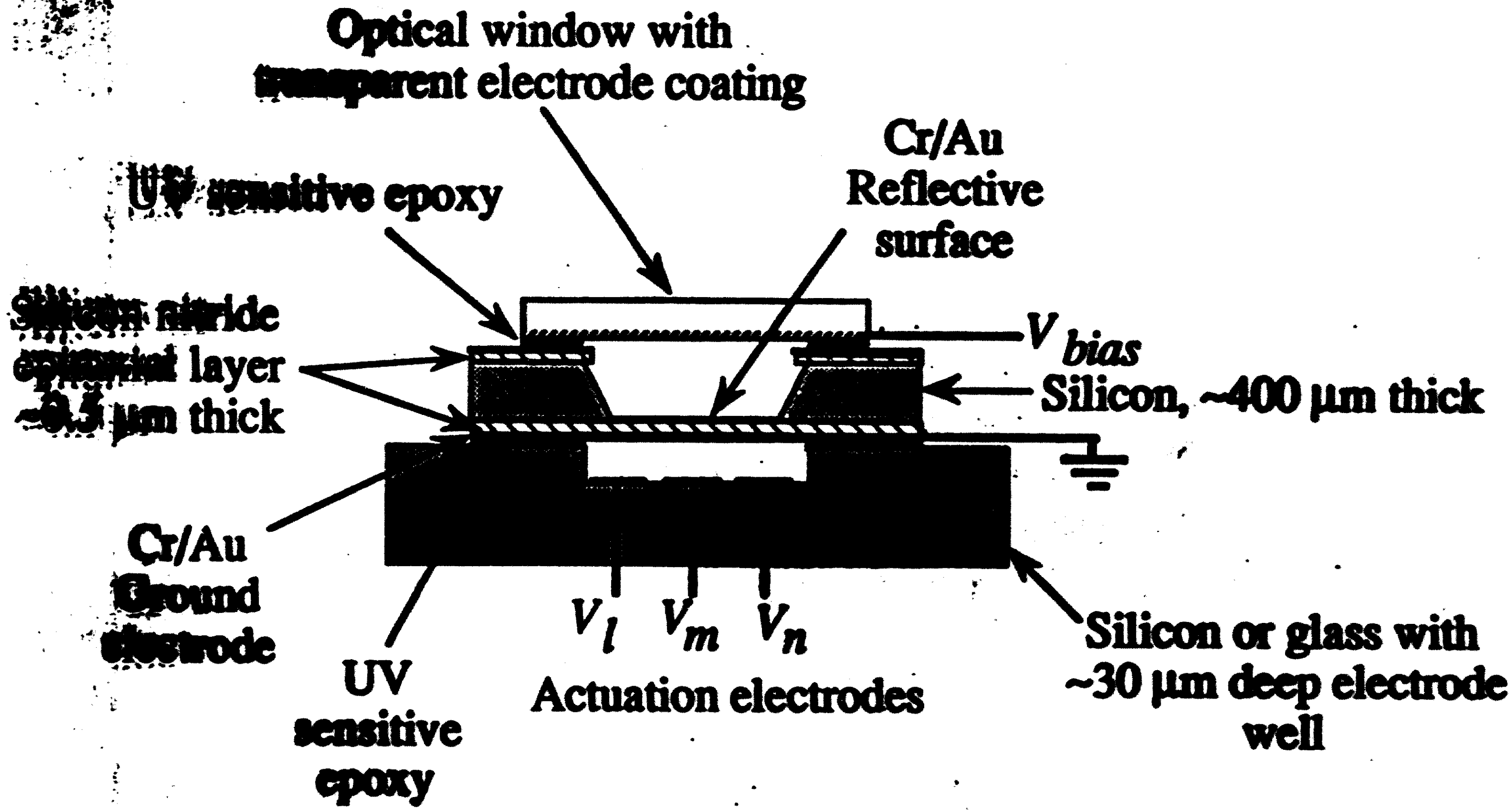


PROOF-OF-CONCEPT ENERGY FILTER



selected energy (101.4 eV)

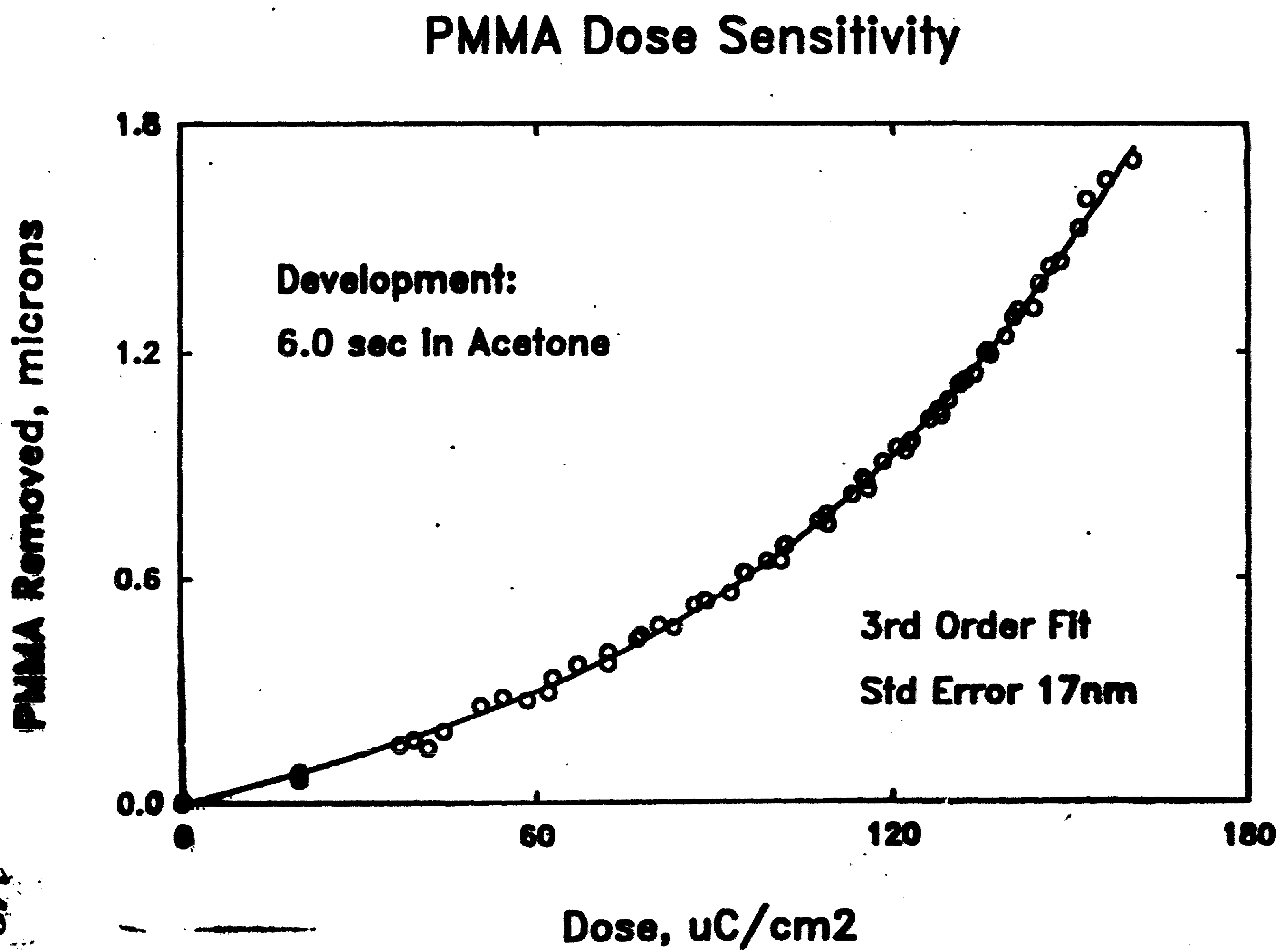
FULL MEMBRANE MIRROR



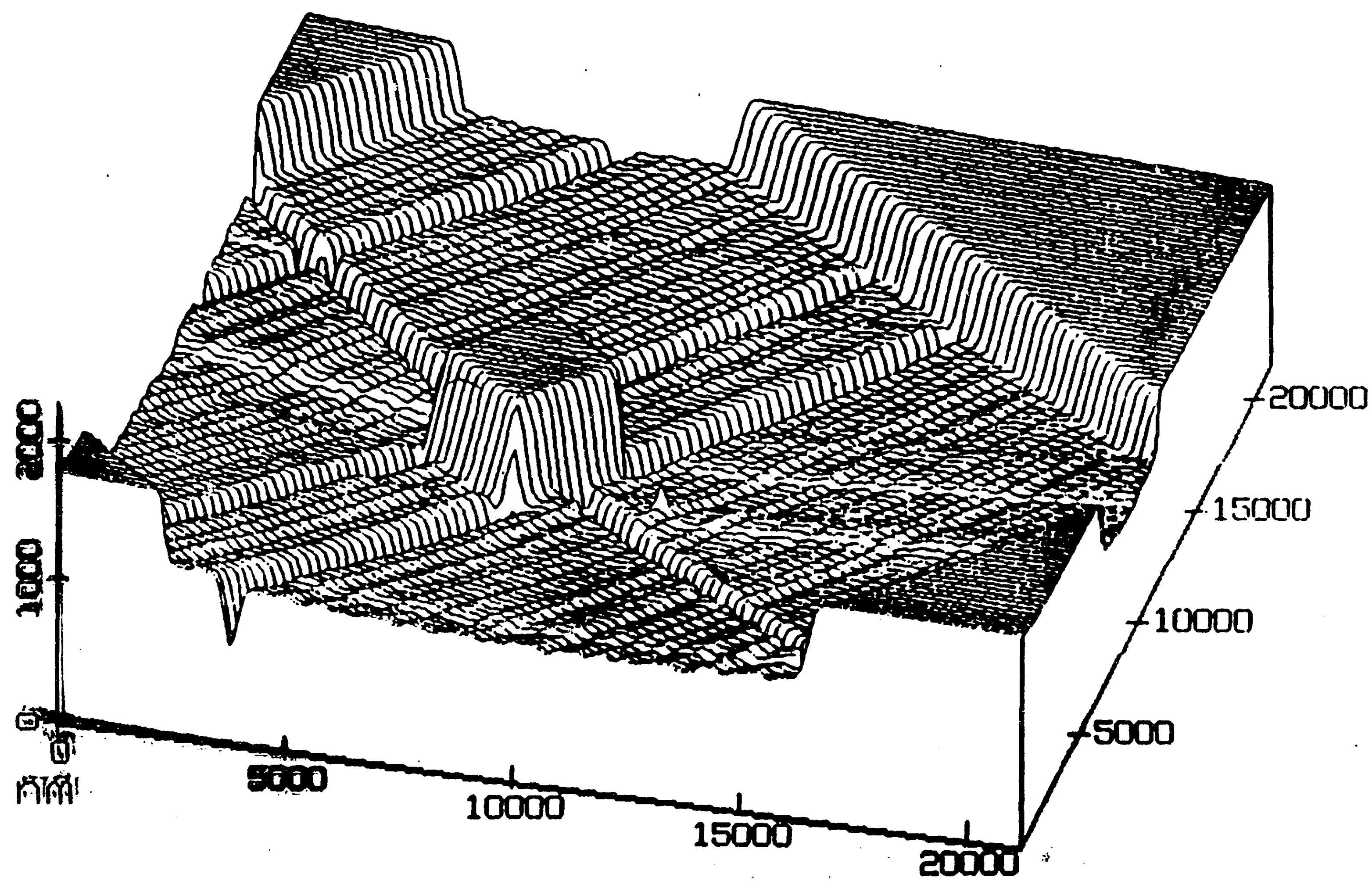
MICRO-OPTICAL DEVICES

- 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

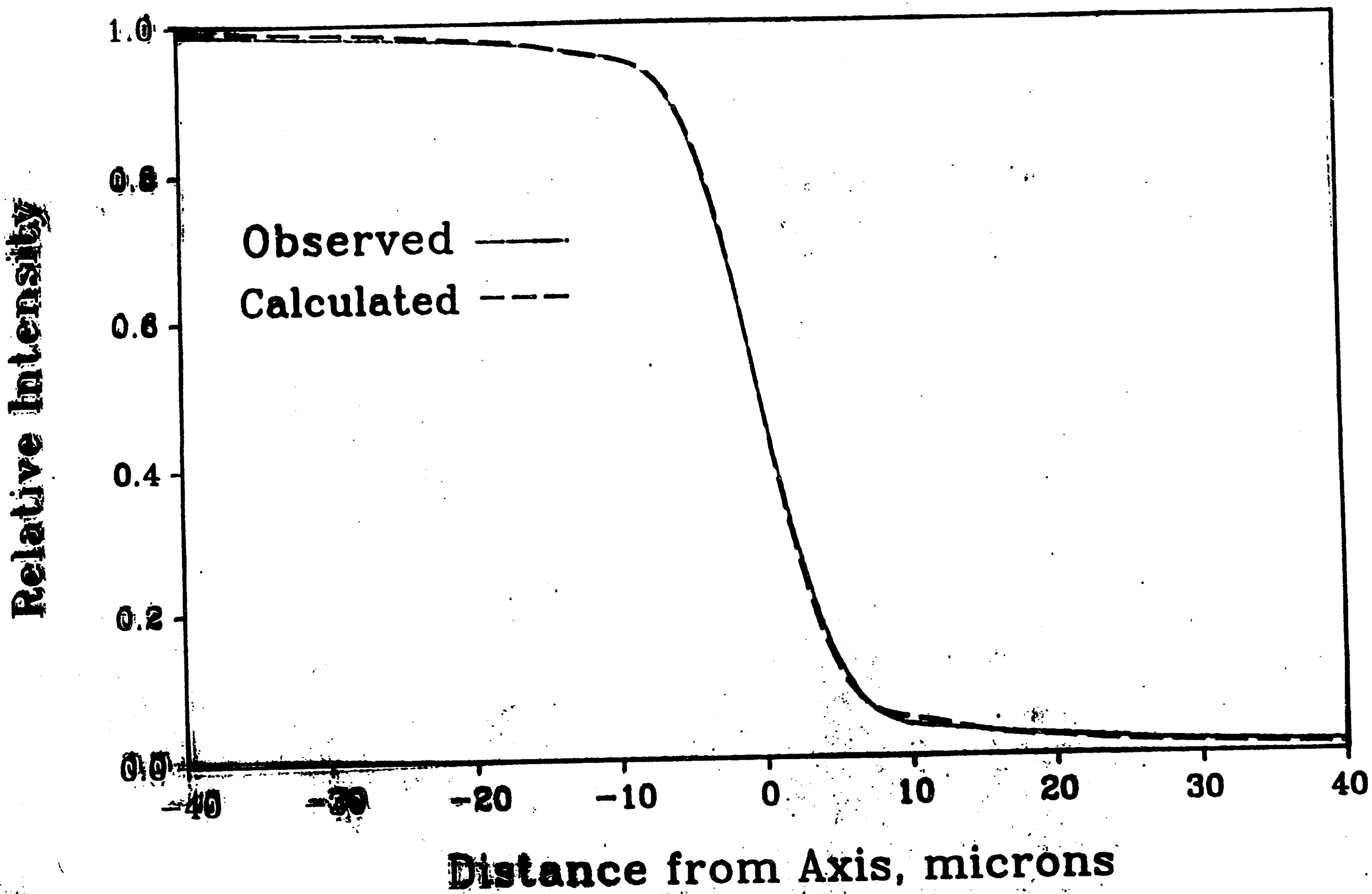


PMMA Pillar



Knife Edge Test of Diffractive Lens

Focal Length 1.49"   Diameter 0.10"



Microfabricated Grids for HESP

JPL/Caltech Technical Staff:

Michael Hecht (Task Manager)

Frank Grunthaner (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.

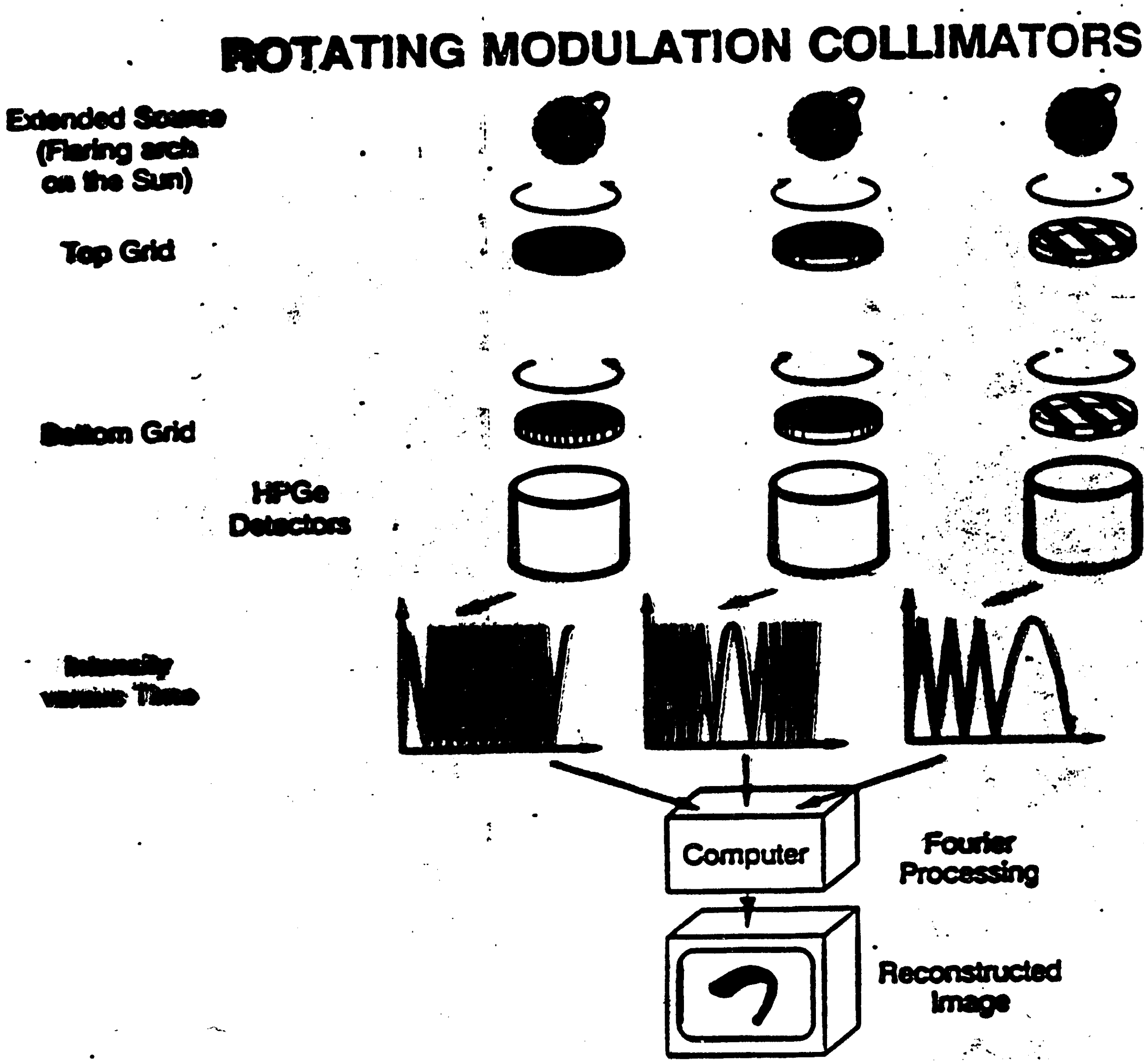


Figure [illegible]. Schematic representation of the Fourier-transform technique used to obtain images of solar flares with multiple rotating modulation collimators (RMC's).

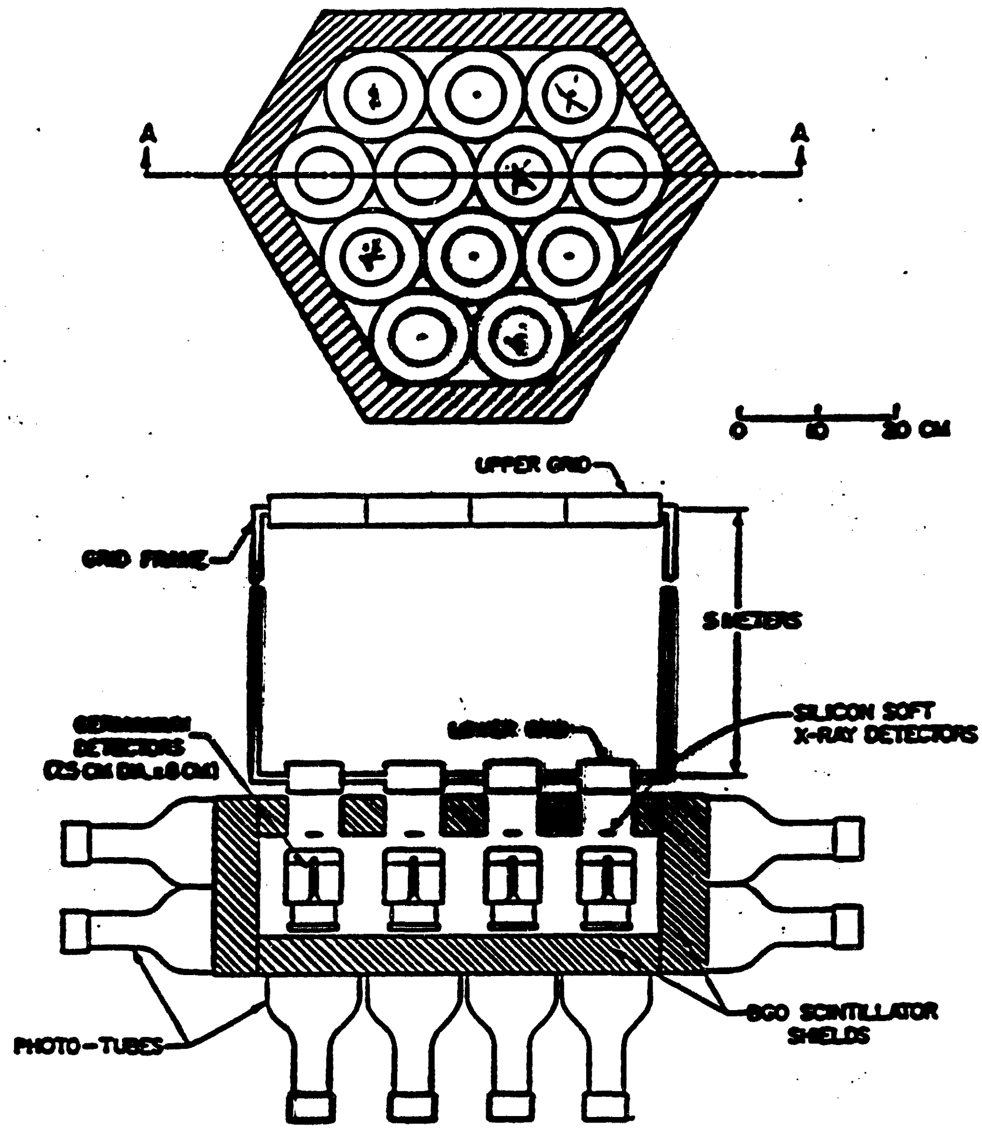


Figure 4.1. Schematic cross-sections of the High Energy Imaging Spectrometer (HEISPEC). The upper and lower tungsten grids separated by 5 m, form the rotating modulation collimators (RMC's). The two-segment germanium detectors provide high spectral resolution measurements from ~10 keV to 20 MeV. The combination of the Ge detectors and the bismuth germanate (BGO) shield extends the gamma-ray range to >200 MeV and provides spectral coverage from ~20 MeV to ~1 GeV. The silicon detectors cover the energy range from ~2 keV to ≳ 20 keV. The BGO shield and collimator form an active anti-coincidence shield to reduce the background.

[illegible] Grid Dimensions 20 April 1993

Collimator length (mm)	1750.
Bottom collimator diameter (mm)	71.0
Top collimator diameter (mm)	● [illegible]
Angular overlap (degrees)	0.300
Ratio of slit width to pitch	0.600

Collimator	1	2	3	4	5	6	7	8	9	10	11	12
FWHM Resolution (arcsec)	2.00	2.90	4.21	6.11	8.86	[illegible]	[illegible]	27.08	[illegible]	[illegible]	[illegible].70	120.00
Pitch (mm) ●	0.034	0.049	0.071	0.104	0.150	[illegible]	0.317	0.459	0.667	0.967	1.403	2.036
Slit width (mm)	0.020	0.030	0.043	0.062	0.090	[illegible]	0.190	0.276	0.400	0.580	0.842	1.222
Thickness (mm) ●	1.17	1.69	2.46	3.56	5.17	7.50	10.00	10.00	10.00	10.00	10.00	10.00
Field of View (deg.)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.58	2.29	3.32	4.81	6.97

Grid rim thickness (mm)	10.00
Grid density (g/cm^3)	19.30

Top grid weight (kg)	0.09	0.13	0.19	0.27	0.40	0.58	0.77	0.77	0.77	0.77	0.77	0.77
Total (kg)	6.28											
Bottom grid weight (kg)	0.06	0.09	0.13	0.19	0.28	0.40	0.54	0.54	0.54	0.54	0.54	0.54
Total (kg)	4.37											

Energy for 50.% transmission

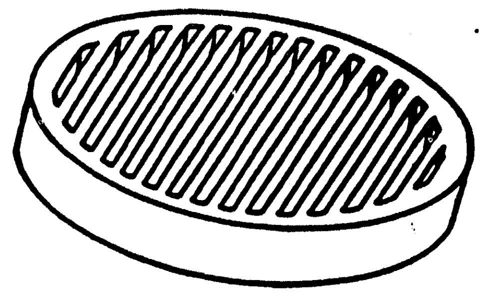
Energy (keV)	308.	379.	481.	648.	947.	1664.	0.	0.	0.	0.	0.	0.

Diffraction Energy limit (keV) with 10%, 50%, and 100% reduction in modulation amplitude
(0.0 = < .1 keV)

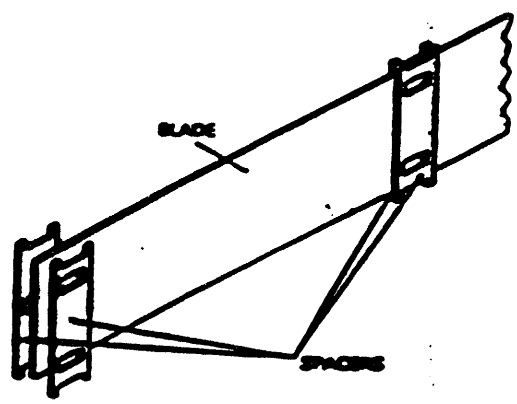
10% red, @ fundamental	13.1	6.2	3.0	1.4	0.7	0.3	0.2	0.0	0.0	0.0	0.0	0.0
10% red. @ 2nd harmon.	52.5	24.9	11.8	5.6	2.7	1.3	0.6	0.3	0.1	0.0	0.0	0.0
10% red. @ 3rd harmon.	118.1	56.1	26.6	12.7	6.0	2.9	1.4	0.6	0.3	0.1	0.0	0.0
50% red. @ fundamental	5.7	2.7	1.3	0.6	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0
50% red. @ 2nd harmon.	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. @ 3rd harmon.	50.9	24.2	11.5	5.5	2.6	1.2	0.6	0.3	0.1	0.0	0.0	0.0
100% red. @ 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. @ 2nd harmon.	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. @ 3rd harmon.	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)

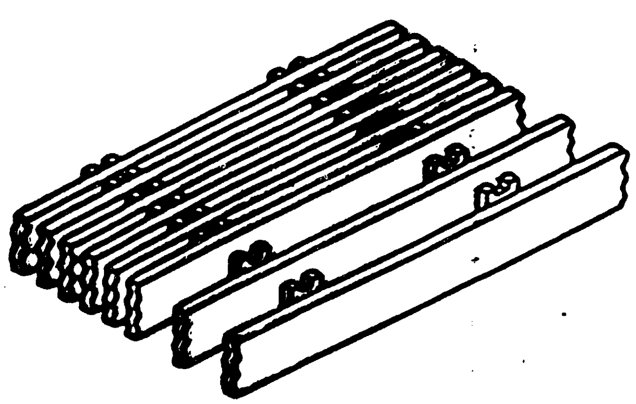
1st pk, fundamental	1.9	0.9	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1st pk, 2nd harmonic	7.5	3.6	1.7	0.8	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0
1st pk, 3rd harmonic	17.0	8.1	3.8	1.8	0.9	0.4	0.2	0.0	0.0	0.0	0.0	0.0



A. COARSE GRID MANUFACTURED
BY ELOX PROCESS.



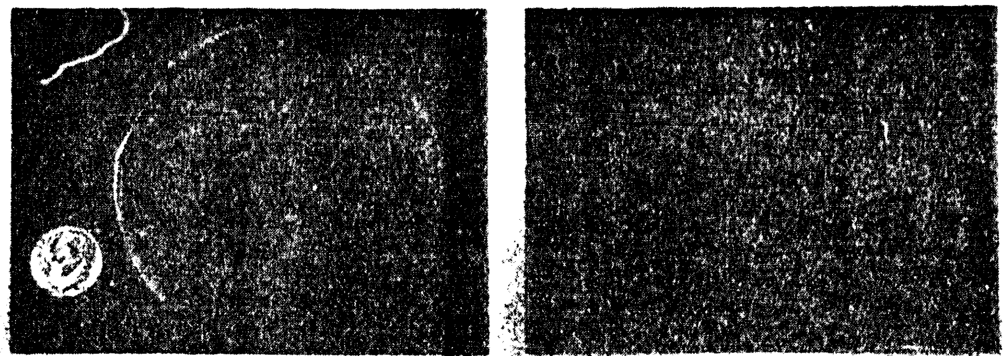
B. SECTION OF ACTUAL SINGLE BLADE
AND SPACERS FOR FINE GRID.



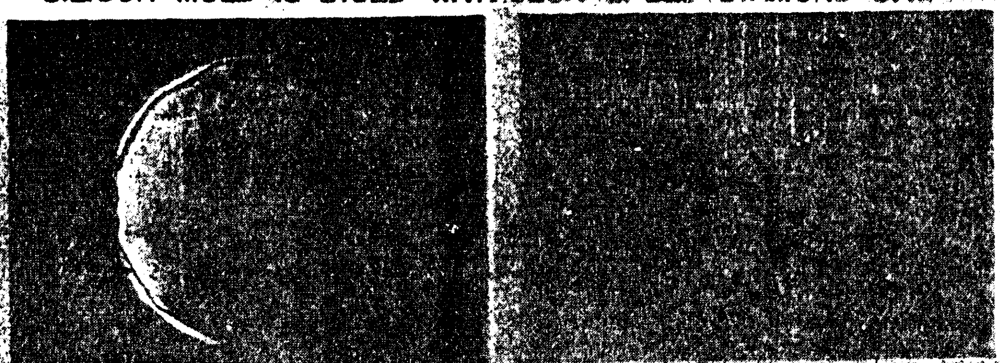
C. DESIGN CONCEPT FOR PACKET OF BLADES
AND SPACERS FOR FINE GRID.

Figure [illegible]: Illustration of two different grid fabrication techniques.

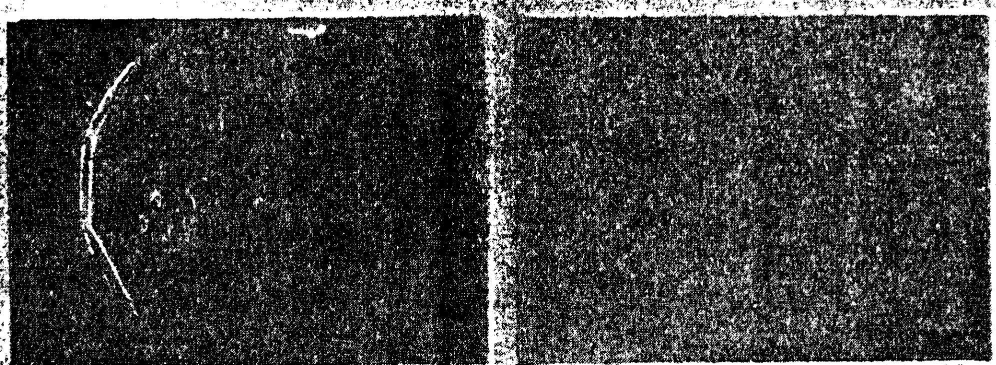
HESP GRID FABRICATION STAGES



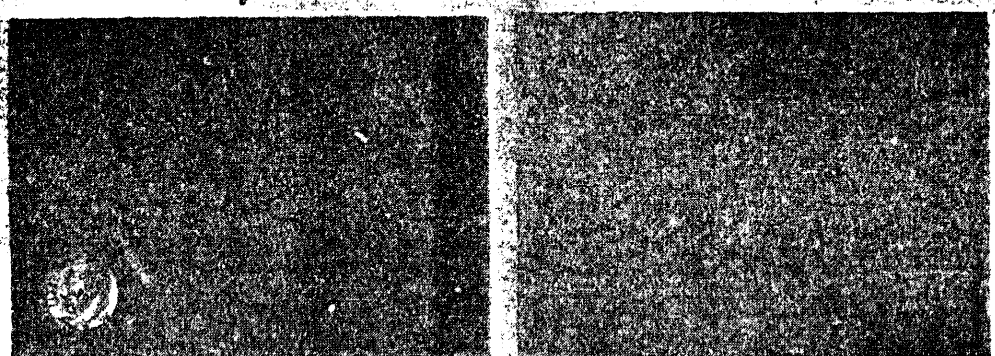
SILICON MOLD IS DICED WITH HIGH SPEED DIAMOND SAW



METAL IS ELECTROPLATED INTO SLOTS LEFT IN MOLD



SILICON/METAL SURFACE IS POLISHED FLAT



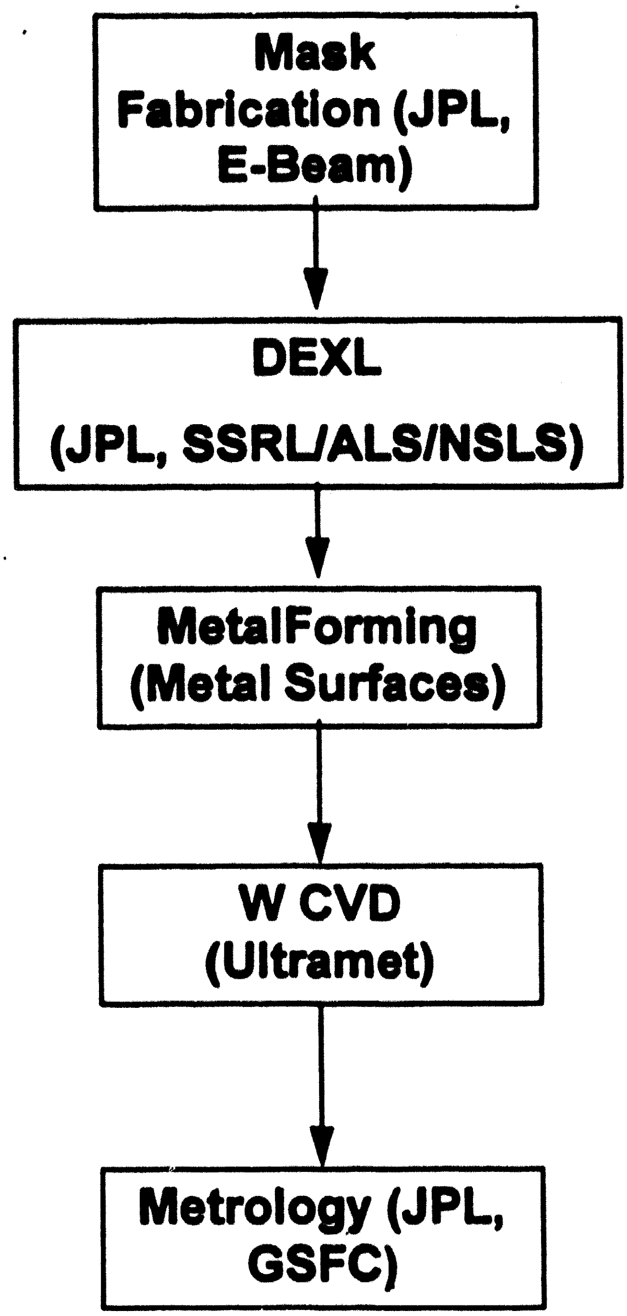
SILICON IS ETCHED AWAY LEAVING ALL METAL GRID

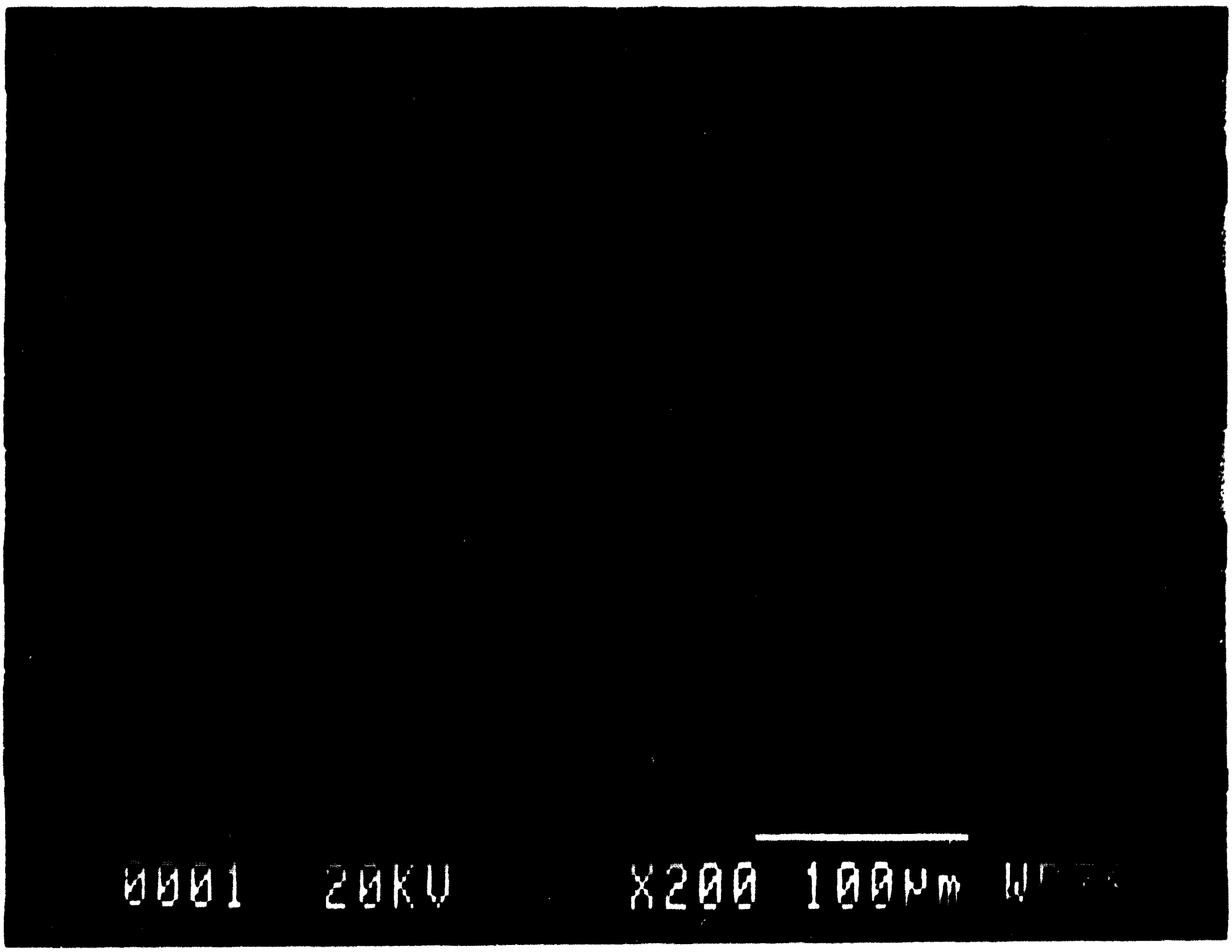
Work Performed by: M. Hecht, T. Kenny, F. Grunthaner, P.H. Siegel : California Institute of Technology Jet Propulsion Laboratory

[redacted]

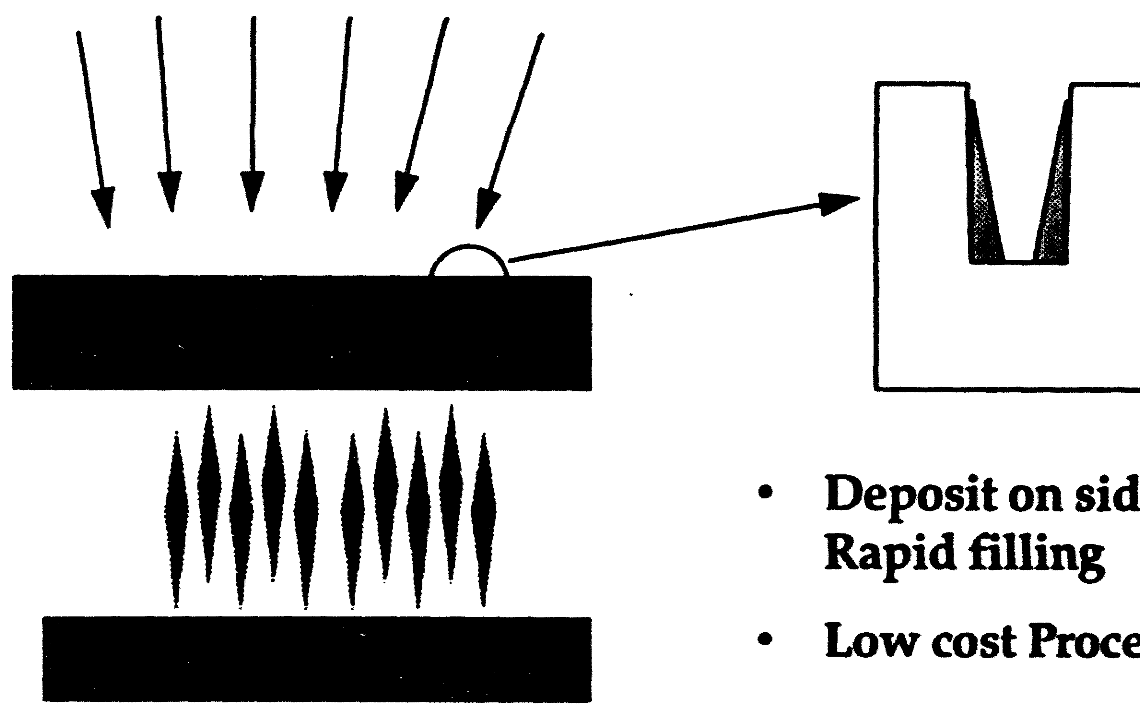
Silicon Micromachining

- **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 <u>each</u> 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 $L\sin\phi$ 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)

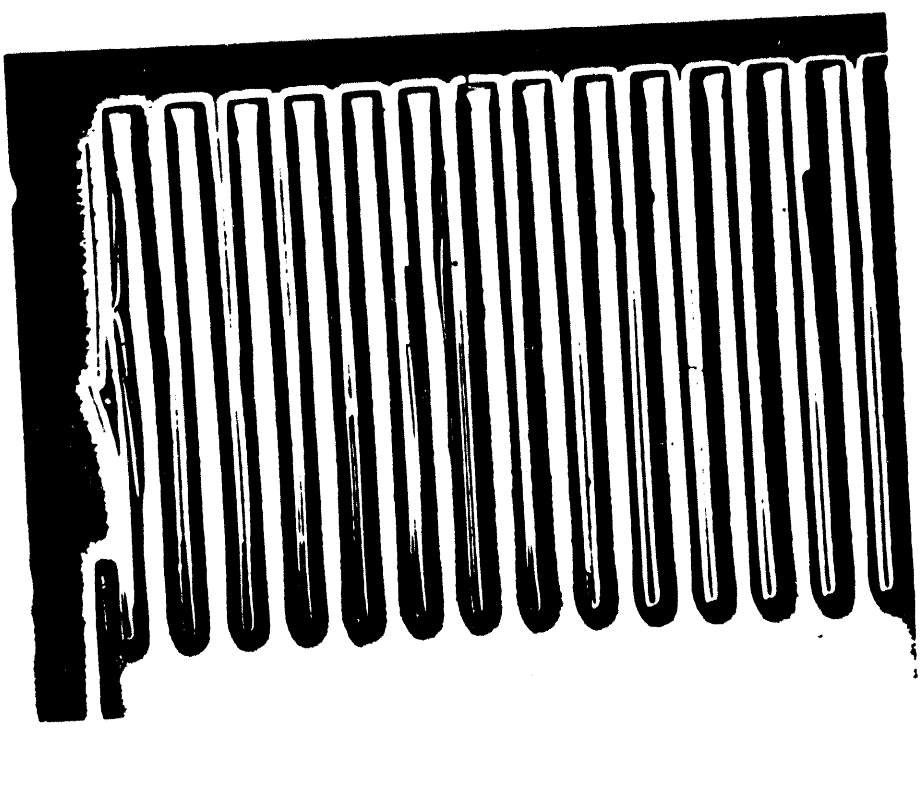

0001 20KV
X200 100µm

W CVD Process



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

Front 400X



Front 50X

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

Advanced Light Source Update

Brian Kincaid

PROJECT STATUS

ALS

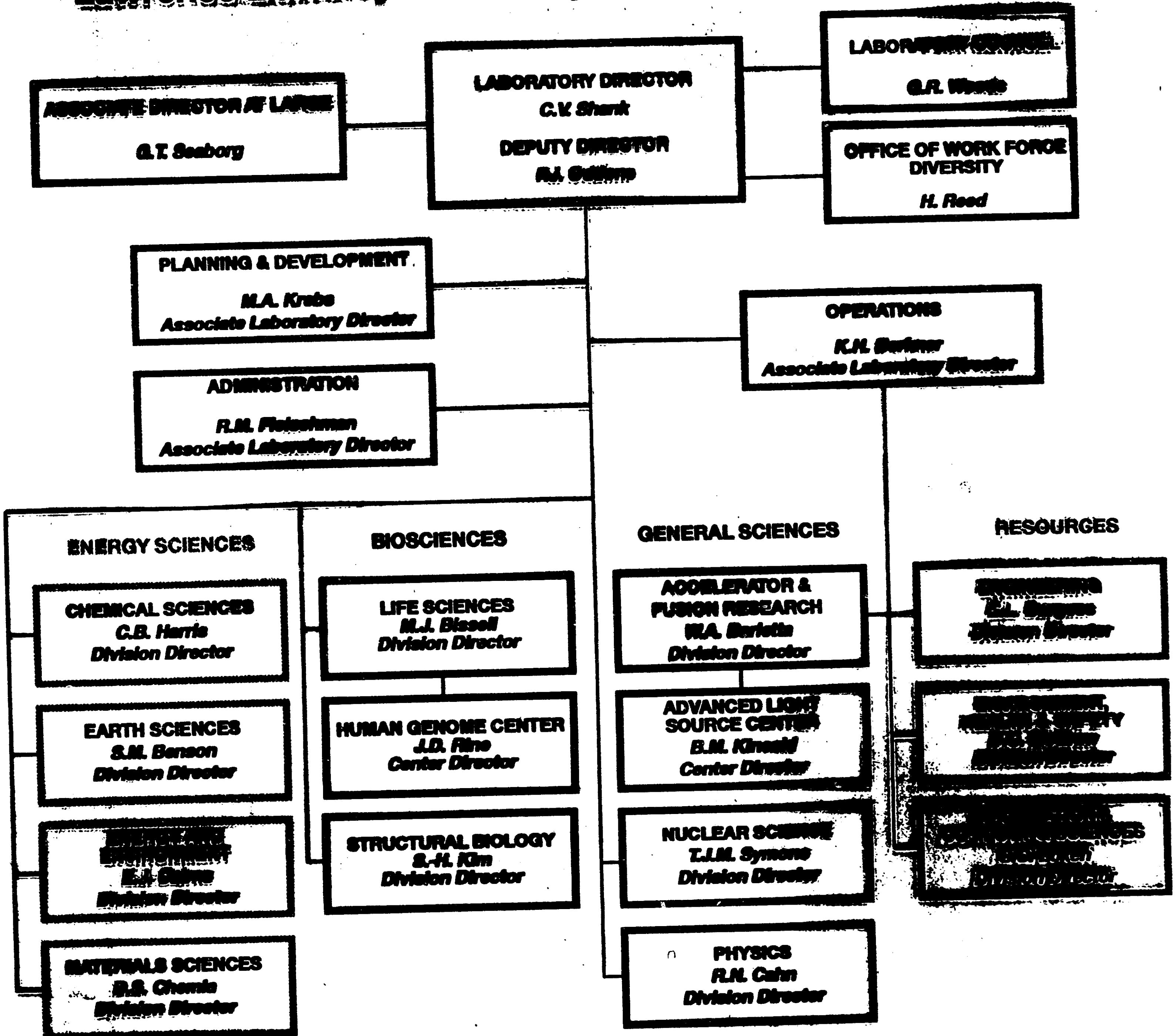
- On time
- On budget
- **It works!**

The Advanced Light Source

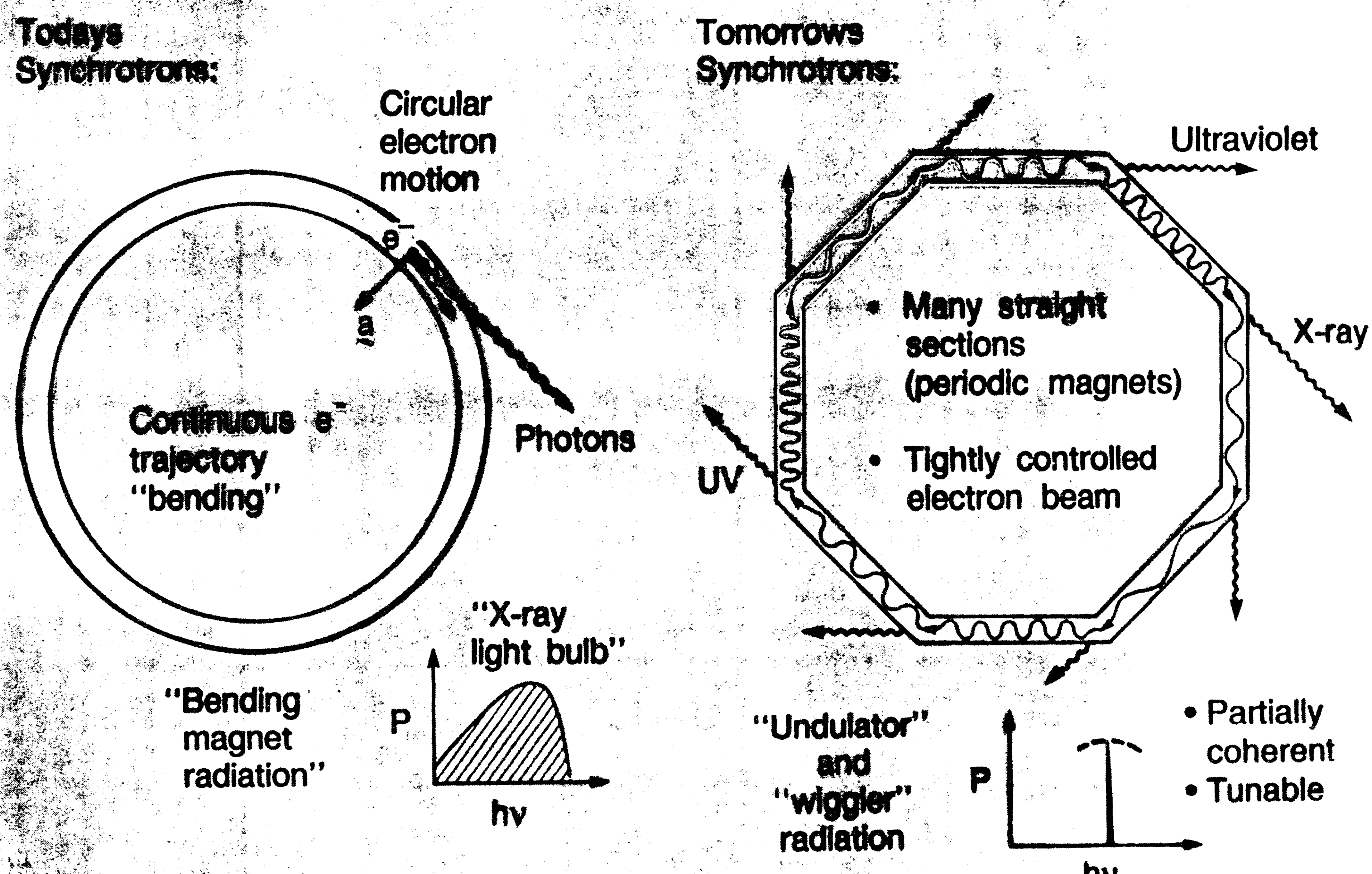
ALS

- 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

Lawrence Berkeley Laboratory • University of California



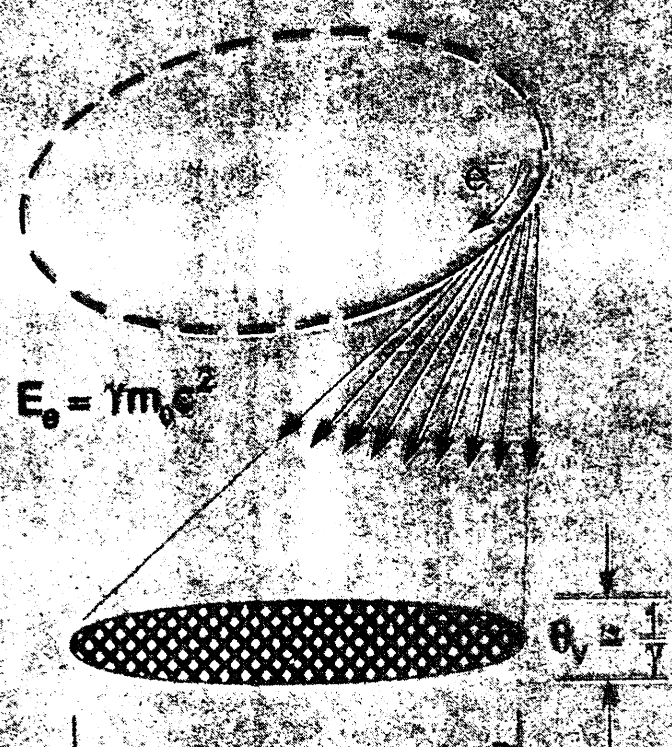
Evolution of Synchrotron Radiation



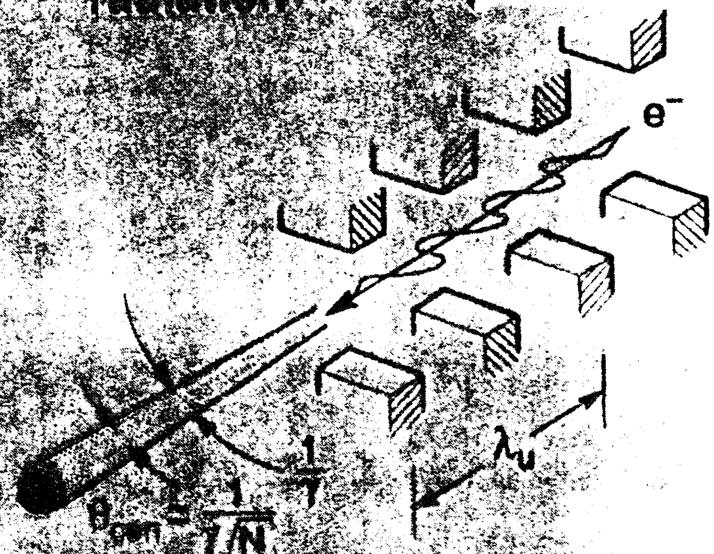
XBL 888-8937A

The ALS Has Both Undulators and Bending Magnets

Bending magnet radiation (sweeping searchlight)



Undulator radiation



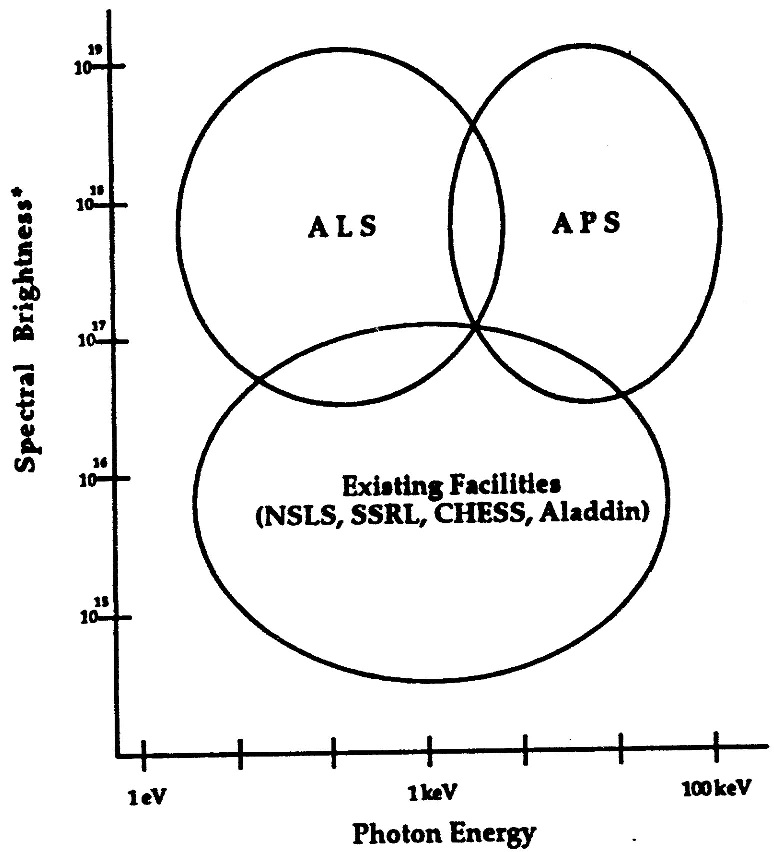
$$\lambda_x = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

In the central radiation cone:

$$\frac{\Delta\omega}{\omega} \simeq \frac{1}{N}$$

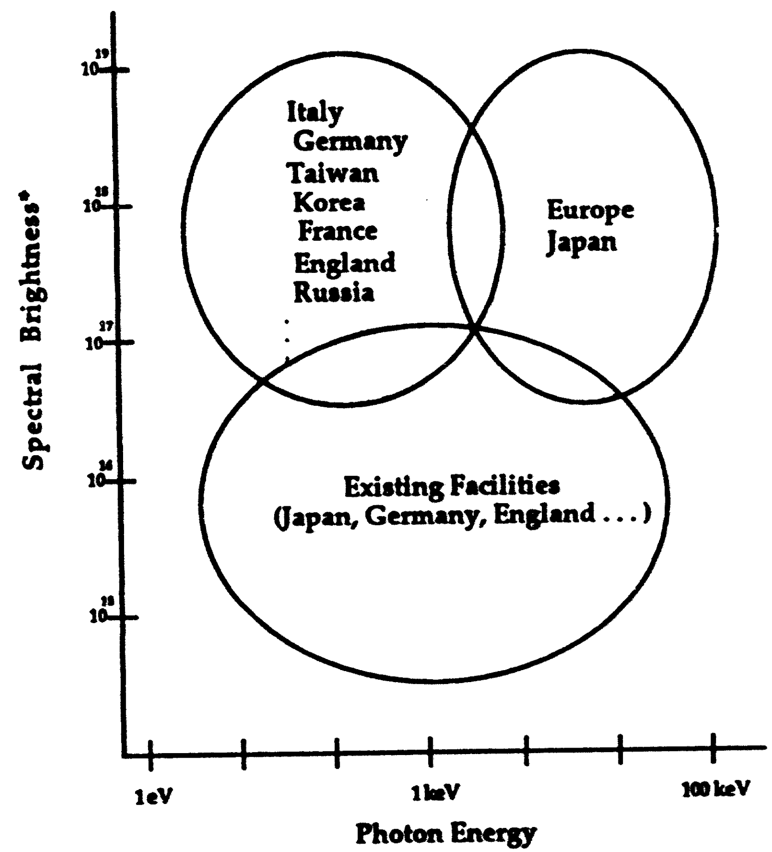
$$\theta_{cen} \simeq \frac{1}{\gamma\sqrt{N}}$$

The U.S. Scene



* Photons/mrad^2/mm^2/0.1% BW

Competition Overseas

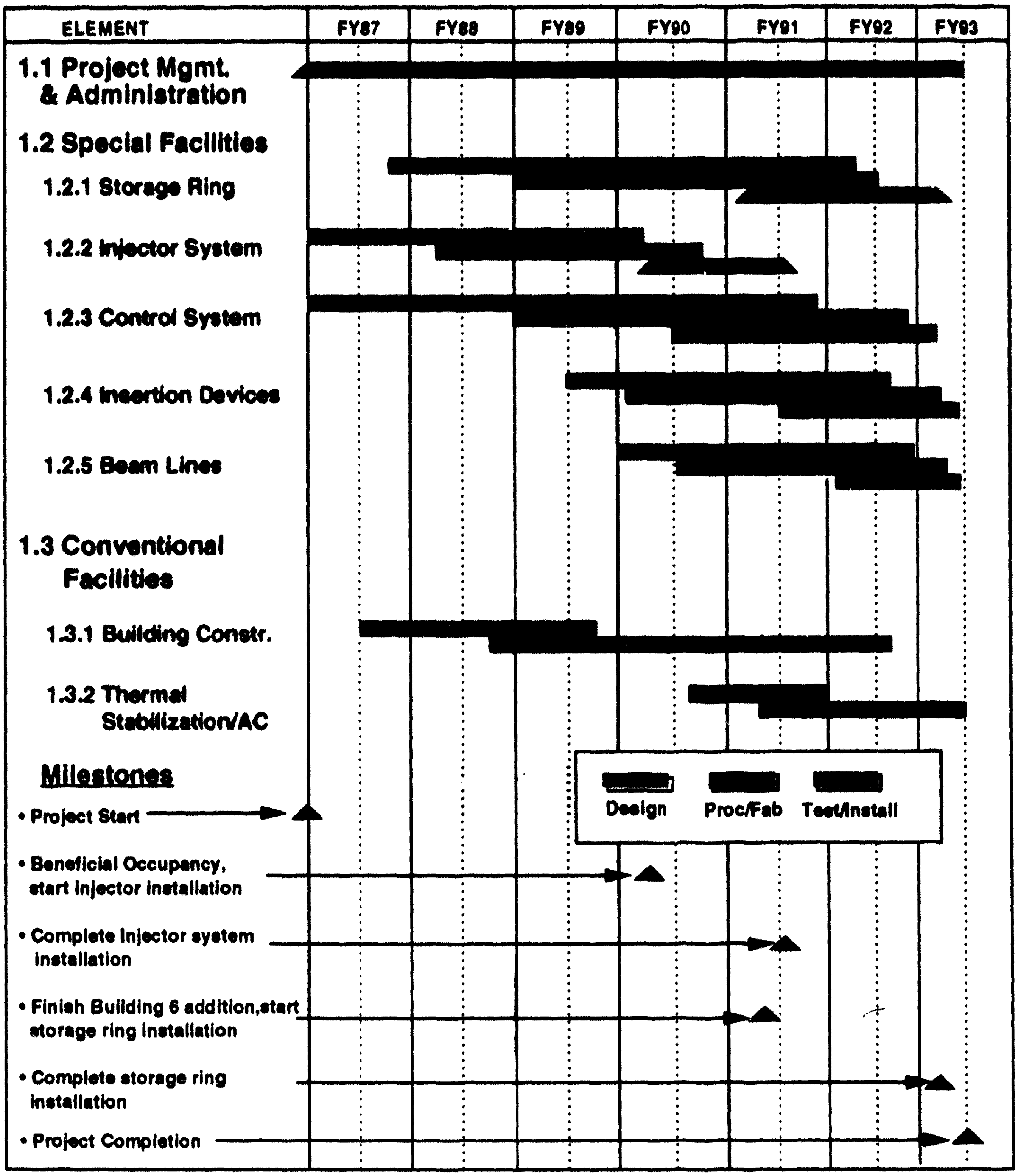


TEN MICROSCOPES ARE PLANNED FOR THE ALS

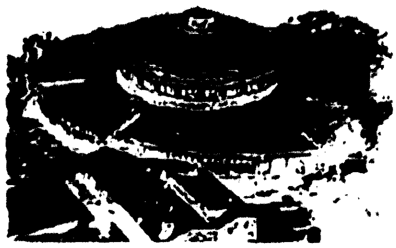
BEAMLINE	PHOTON SOURCE	TYPE OF MICROSCOPE	APPLICATION	P.I.
6.0	U3.9 Undulator	Scanning (2)	Biological & Materials Sciences	ALS (Attwood)
6.1	Bend Magnet	Zone Plate Imaging	Biological & Materials Sciences	Meyer-Ilse
7.0	U5 Undulator	Photoemission Imaging	Surface & Materials Sciences	Tonner/Ade
		Zone plate Scanning (fluorescence)	Surfaces, Materials Sciences & Polymers	Tonner/Ade
		Zone plate Scanning (photoemission)	Surface & Materials Sciences	Tonner/Ade
8.0	U5 Undulator	Zone plate Scanning	Surface & Materials Sciences	Stöhr
10.3	Bend Magnet	Microprobe (2)	Materials Sciences	Thompson
11.0	Elliptical Wiggler	Spin-polarized Photoemission	Magnetic Materials	Stöhr

Advanced Light Source

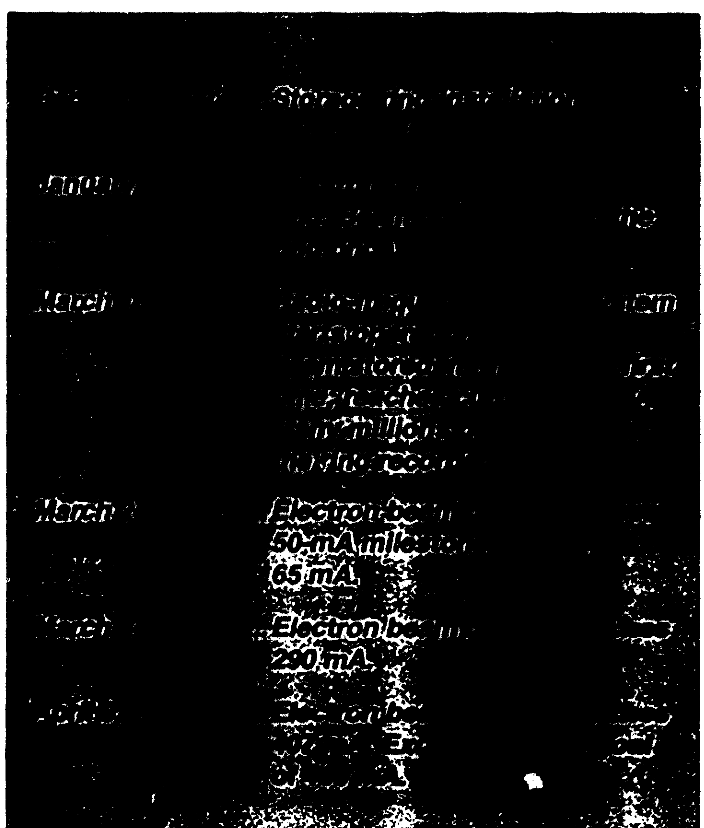
Advanced Light Source Schedule



Lawrence Berkeley Laboratory Scores Engineering Triumph



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.

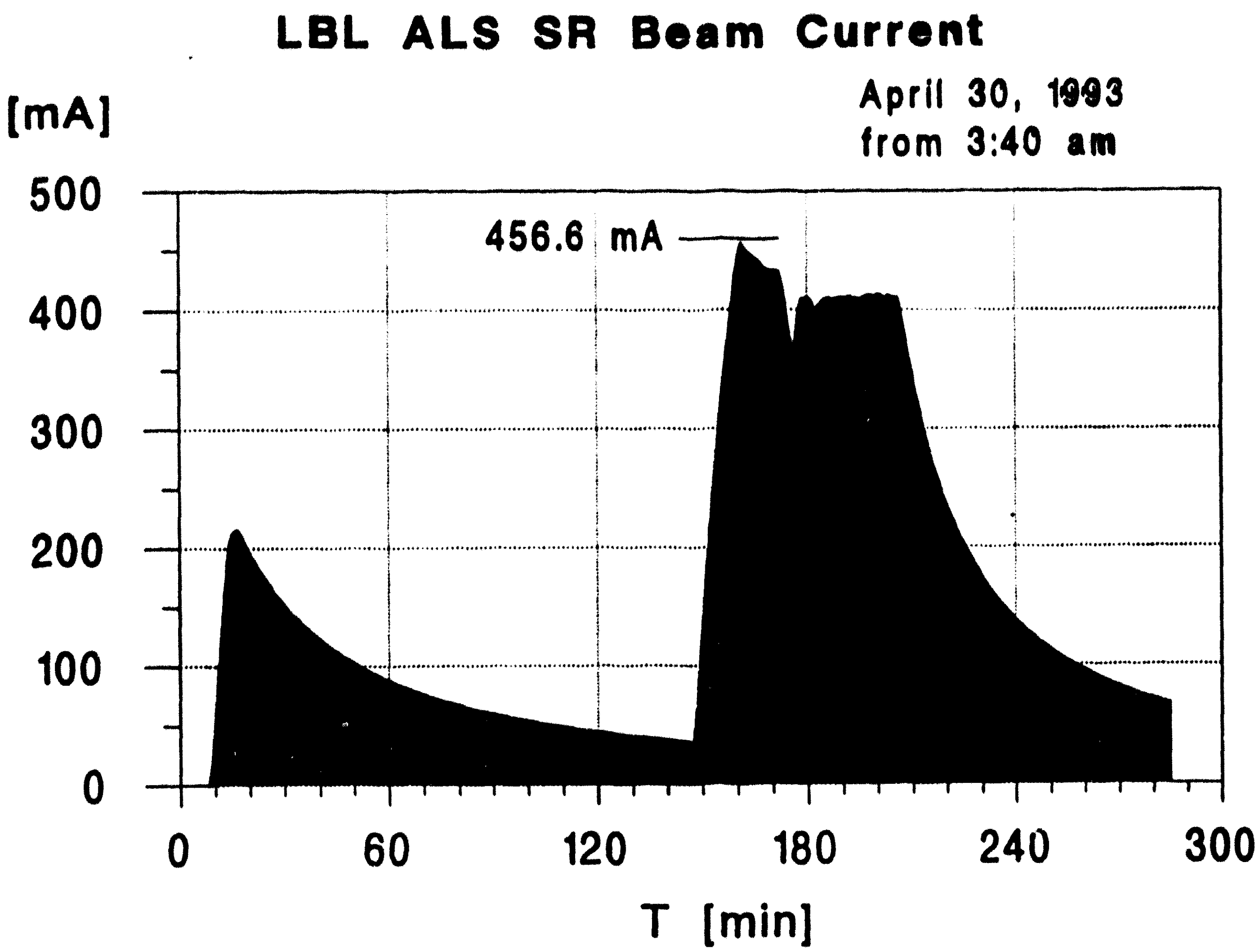


Built with $100 million in DOE construction funds, the ALS is a national user facility providing high-brightness beams of ultraviolet and soft x-ray light. It has been eagerly awaited by researchers in the physical, chemical, materials, and life sciences. Its principal component is a storage ring 200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



LBL ALS SR Beam Current
April 30, 1993
from 3:40 am
[mA]
500
400
300
200
100
0
456.6 mA
0
60
120
180
240
300
T [min]

178

Major Specifications for Accelerator Systems

Specification	Value	ALS
• 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)	

THE SECRETARY OF ENERGY
WASHINGTON, D.C.

March 30, 1993

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,

Hazel R. O'Leary

Department of Energy
Washington, DC 20585

JUN 28 1993

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 4700.1) 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: ____________________

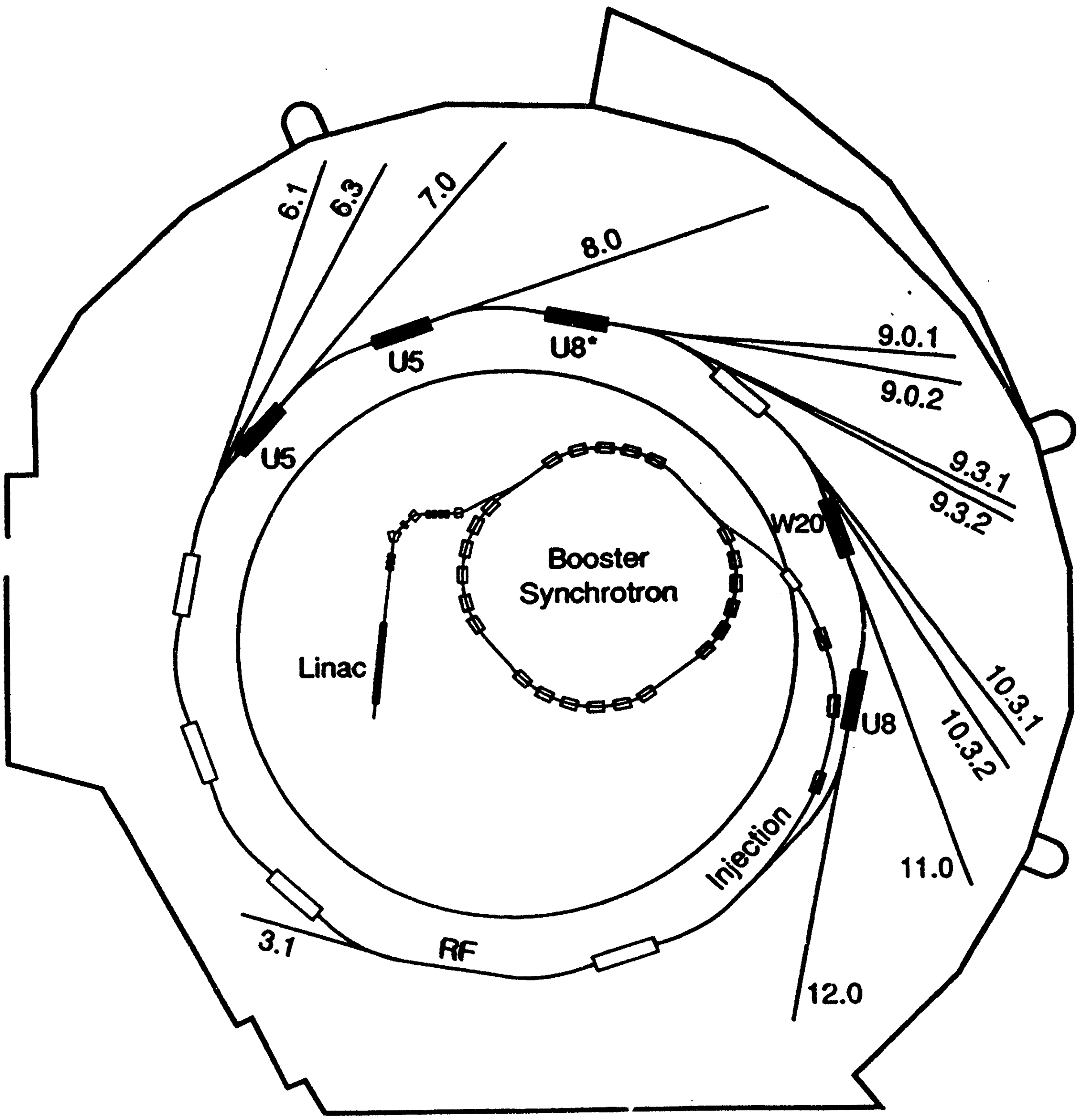
DATE: July 19, 1993

CONCURRENCES:

182

Comparison of Approximate Heat Flux Levels in Various Physical Processes

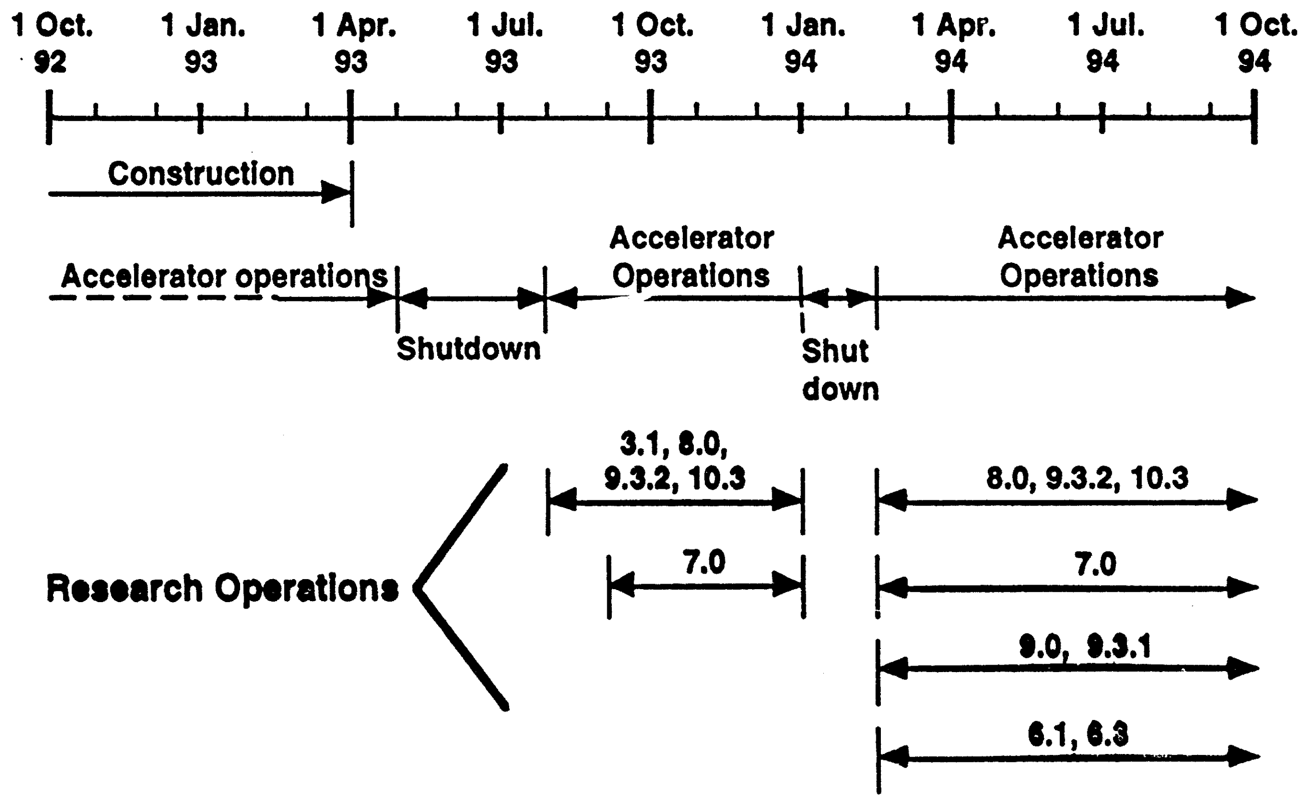
Process Or Component	Approximate Heat Flux (w/mm^2)
Meteor re-entry	100 to 500 — APS
Fusion reactor components	0.05 to 80
Sun's surface	60
Commercial plasma jet	20
Interior of rocket nozzle	10 — ALS
Fission reactor cores	1 to 2



* Will change to U10 in 1995

XBL 928-5341A

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

ALS

Plans ⟵⟶ | Projections ⟶

Beamlines

	1993	1994	1995	1996	1997	1998	1999	2000
IDT's	~~8~~ 2	3	5	6	7	8	9	10
BMT's	~~8~~ 2	5	5	8	12	16	20	24
Total	4	8	10	14	21	24	29	34

Users

	1993	1994	1995	1996	1997	1998	1999	2000
Users *Total*	~~150~~ 100	200	250	350	475	600	725	850
Users/Year	~~75~~ 50	100	125	175	240	300	360	425
Users on site	~~24~~ 16	32	40	56	76	96	116	136

Cars

	1993	1994	1995	1996	1997	1998	1999	2000
Cars on site	~~15~~ 10	20	25	35	48	60	72	85

Lab and Office Space

	1993	1994	1995	1996	1997	1998	1999	2000
Offices	~~12~~ 8	16	20	28	38	48	58	68
Office Space (sq. ft)	~~1,800~~ 1,200	2,400	3,000	4,200	5,700	7,200	8,700	10,200
Lab Space (sq. ft)	~~2,700~~ 1,800	3,000	4,500	6,000	7,800	9,000	10,400	13,200
Labs and offices (sq. ft)	~~4,500~~ 3,000	5,400	7,500	10,200	13,500	16,200	19,100	23,400

FS: June 5, 1992
(Update) FS: May 5, 1993

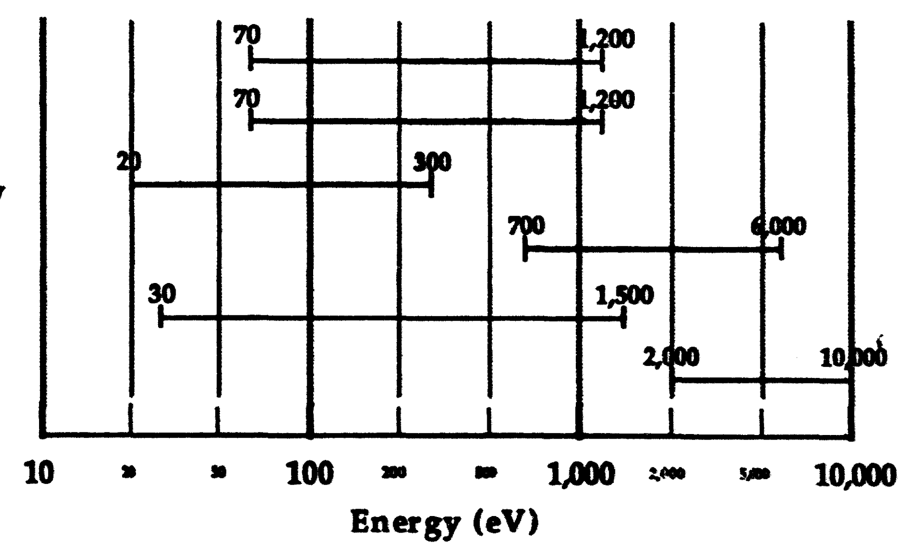
Advanced Light Source: Research Program

ALS

- 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

<u>Beamlines</u>

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



FS: April 15, 1993

. . . the end of the beginning.

Institute for Micromachining

Robert Warrington
Louisiana Tech University

August 3, 1993

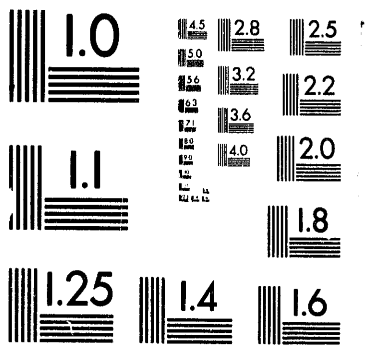
INSTITUTE FOR MICROMANUFACTURING

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.


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
7.1
8.0
9.0

3 of 3

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 synchrontron (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 reticles 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 micromaching 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 microsturctures 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.
(F) Process capability to be acquired/developed during 1991.

** 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, orifices to 25 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, toys, 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 modeule 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 miscroscopy 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.

(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.

** (F) 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.

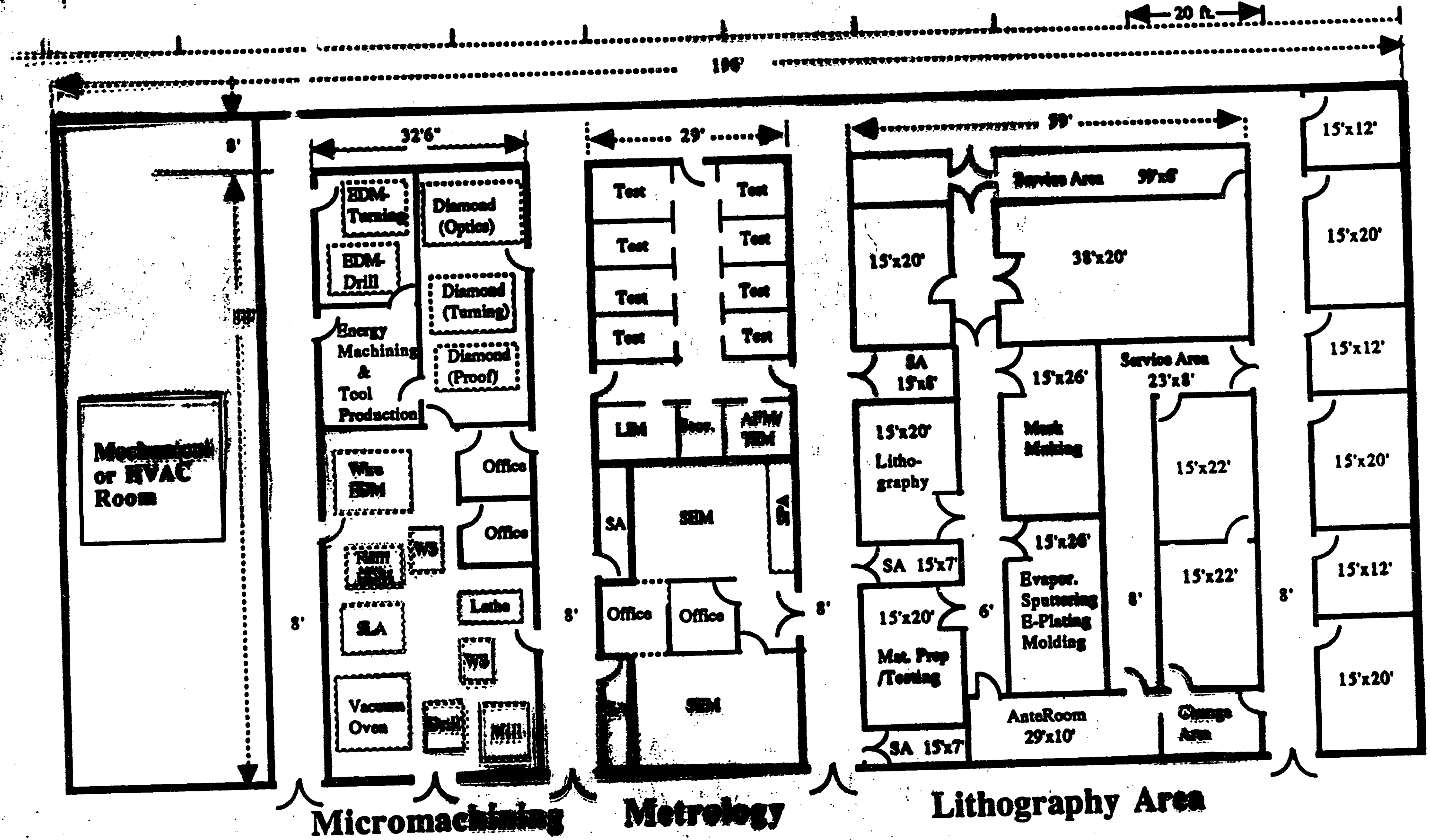
IN-PROCESS METROLOGY

** (F) 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.
(CH) Process capability currently being acquired/under development.
(F) Process capability to be acquired/developed during 1994.

La Tech University

Institute for Micromanufacturing



200

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

CAMD

The J. Bennett Johnston, Sr.
CENTER FOR ADVANCED MICROSTRUCTURES AND DEVICES
Louisiana State University

VOLKER SAILE
Director

CAMD MISSION

- Education
- Research (Basic & Applied)
- Industrial Applications (R&D, Prototype Fabrication, Manufacturing)
- Services (Chemical Analysis and Others)
- Anchor Tenant for Research Park

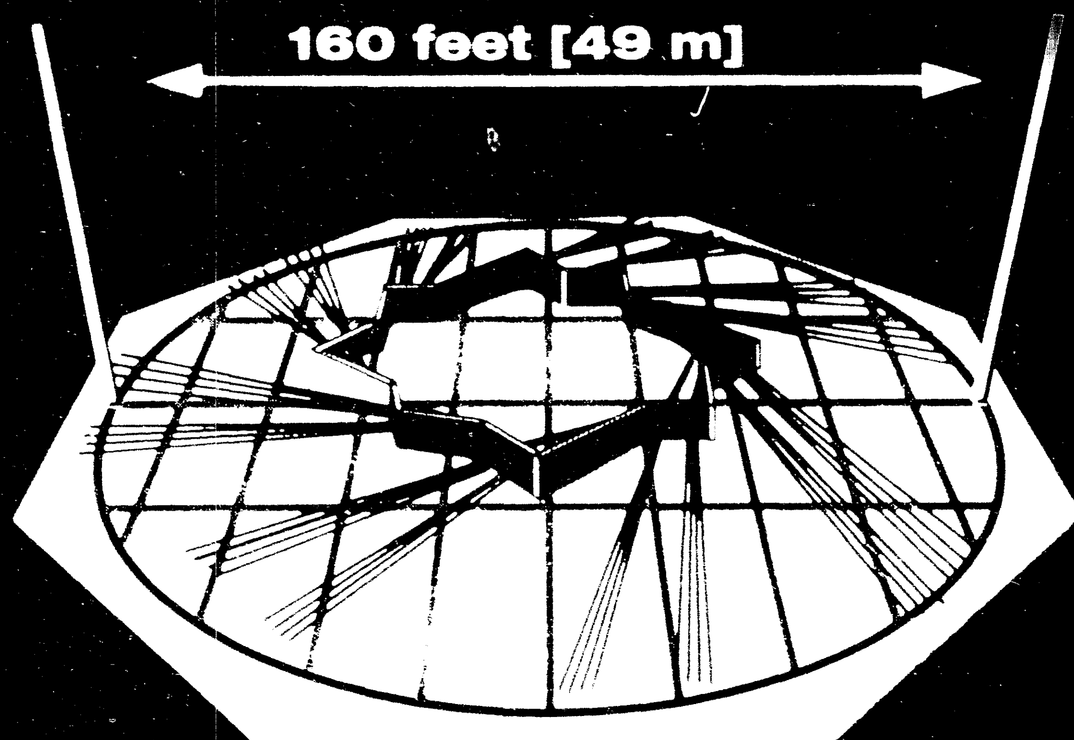
COLLABORATIONS/ COORDINATION

- 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

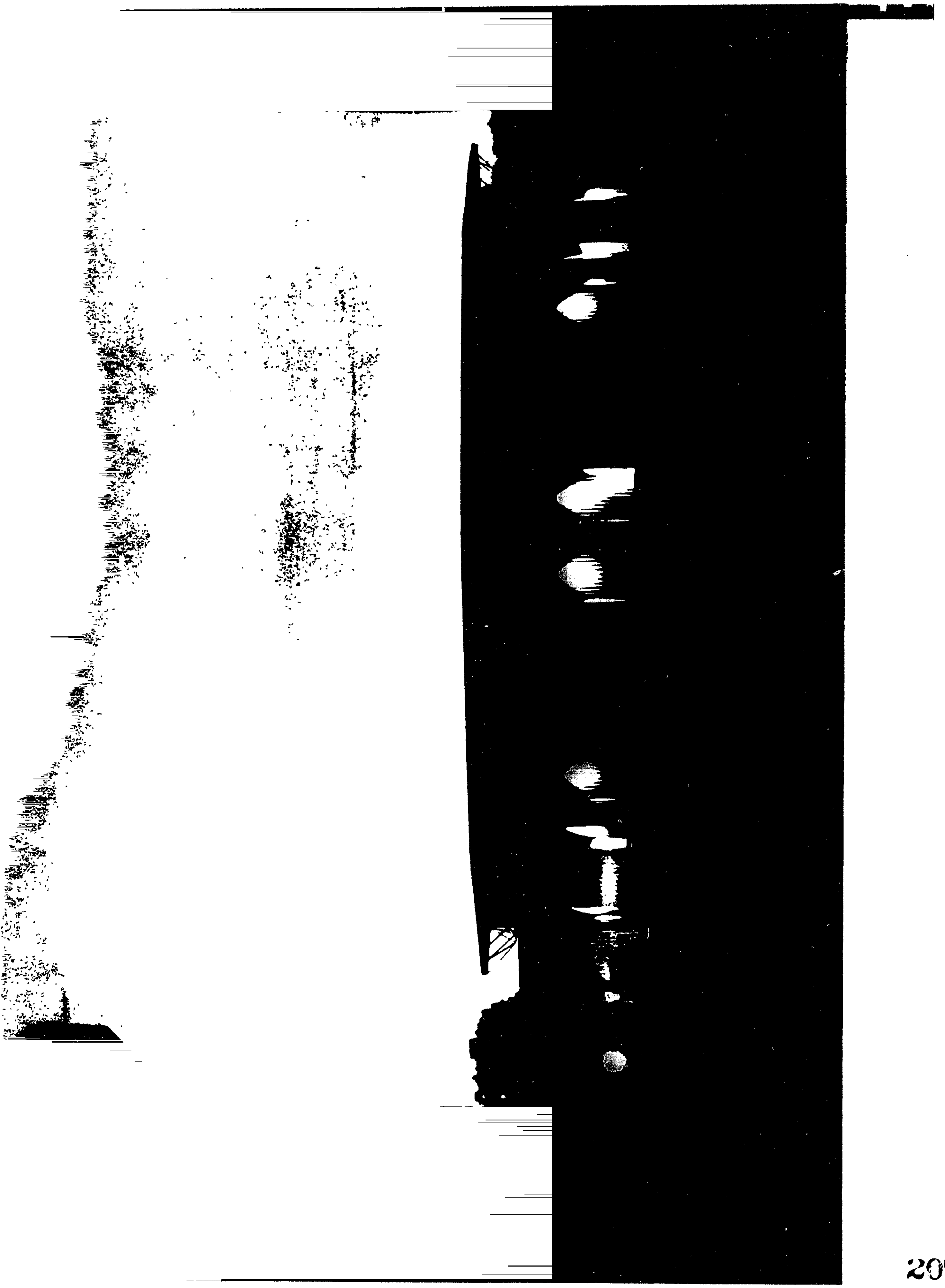
CAMD Status May, 1993

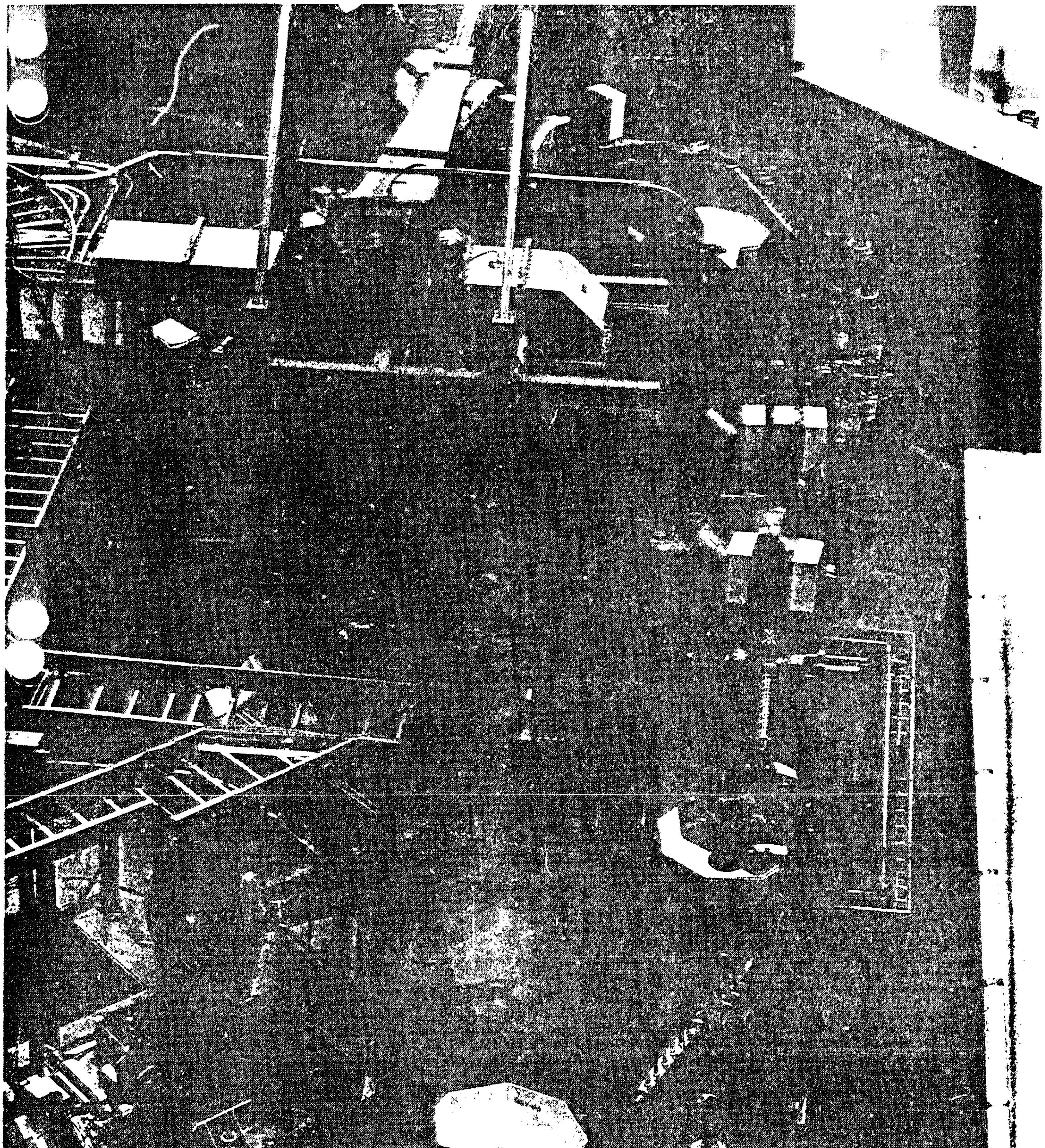
Building	completed, May 1991
Linac Injector	in Operation since 9/91
Storage Ring	first Injection Oct. 27/91 Beam ramped to 1.2 GeV June 3, 1992; 311 mA @ 1.3 GeV 10/22/92 157 mA @ 1.4 GeV 8/25/92 115 mA @ 1.5 GeV 8/25/92 200 mA @ 1.3 GeV Routine
Accept. of Acc. System	August 29, 1992
XRL Beamline	Commissioning
Basic Sciences Beaml.	Commissioning
LNLS Beamline	Operation
TNT Beamline	Delivery June 1993
SURA Beamline	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 aquired or funded
LIGA Stepper (Loui.Tech)	May 1994
SC-Wiggler	Proposal completed
Circ. Pol. Undulator	Proposal completed

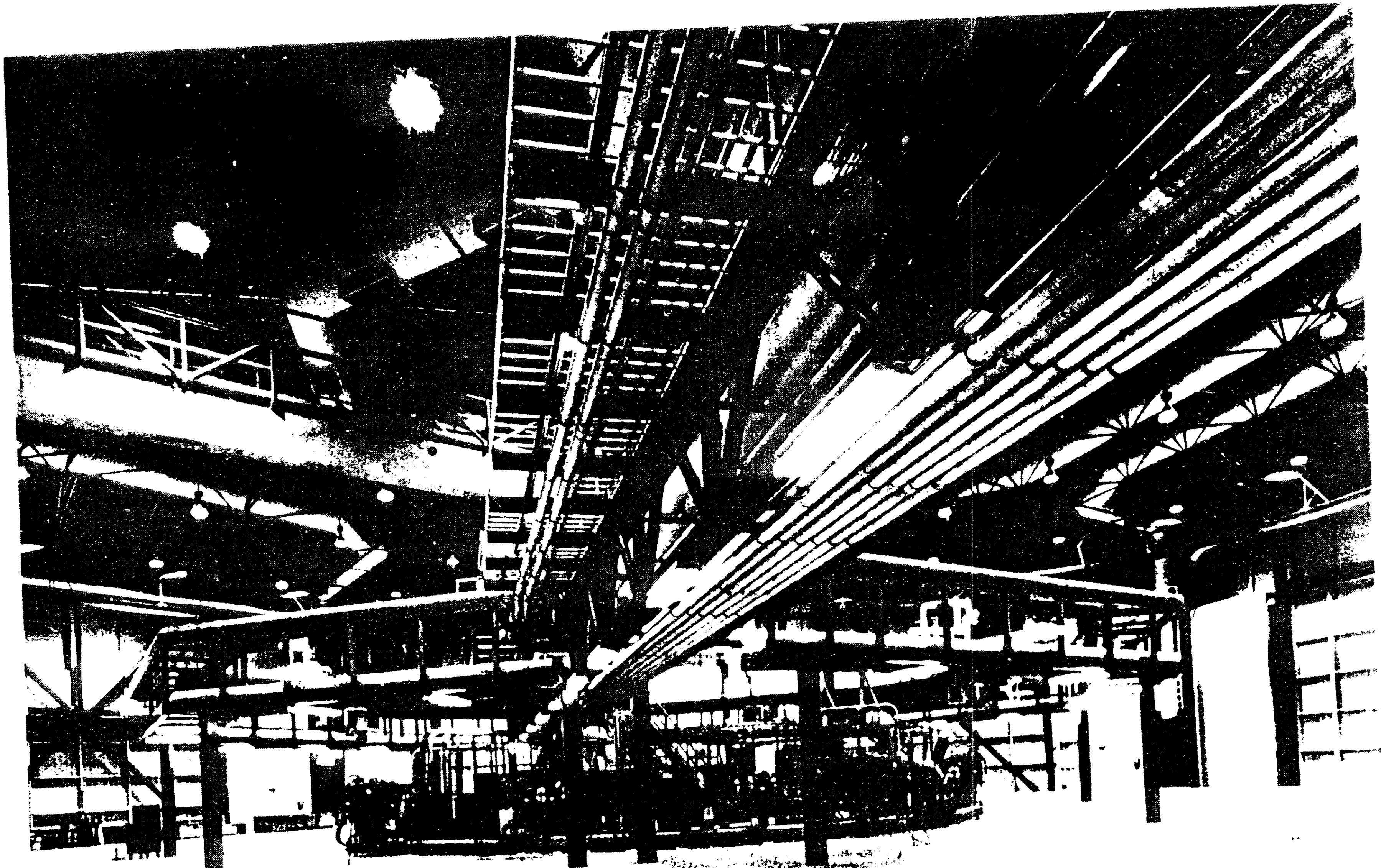
CAMD 1.2 -1.5 GeV SR SOURCE

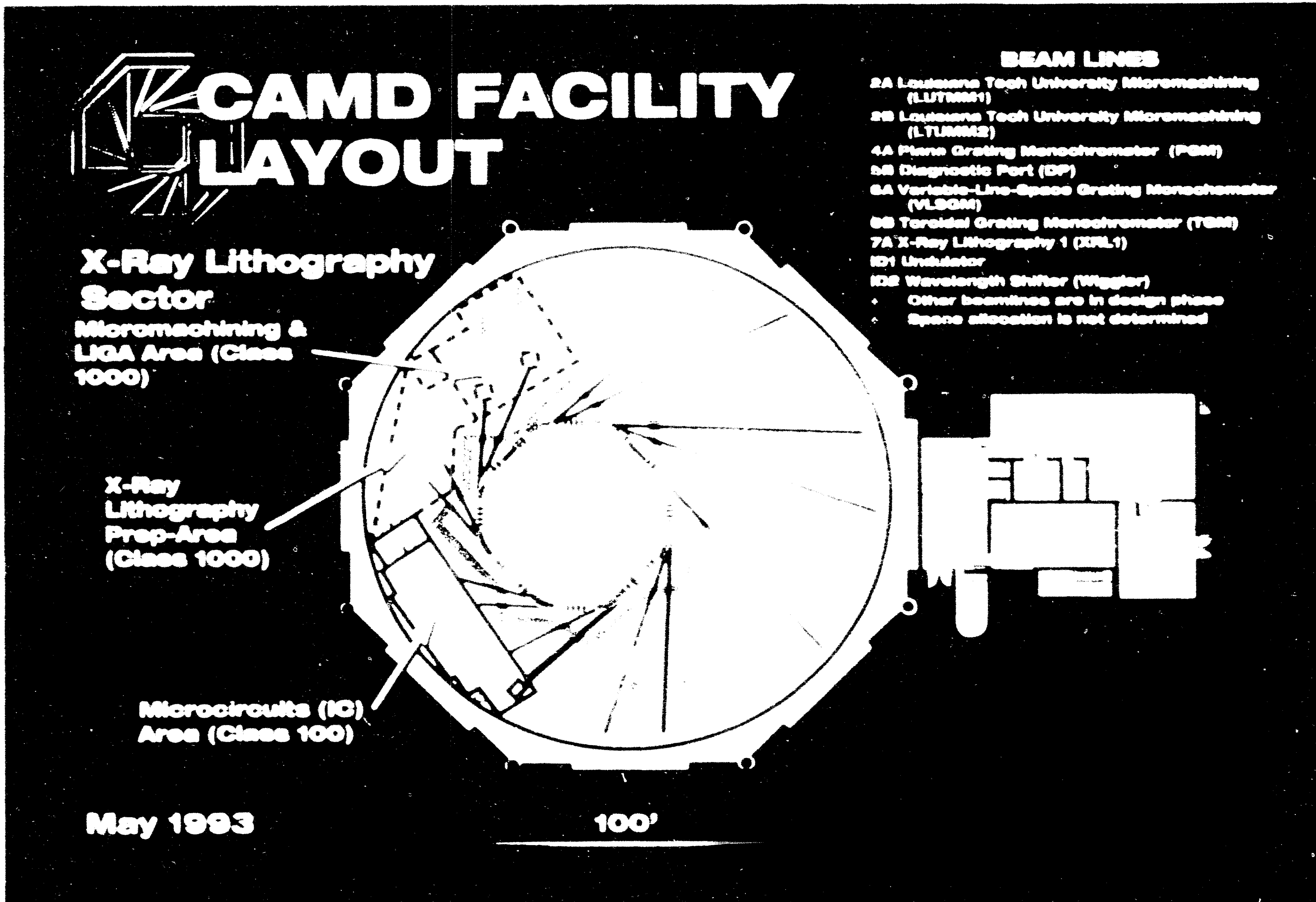


CAMD EXPERIMENTAL HALL





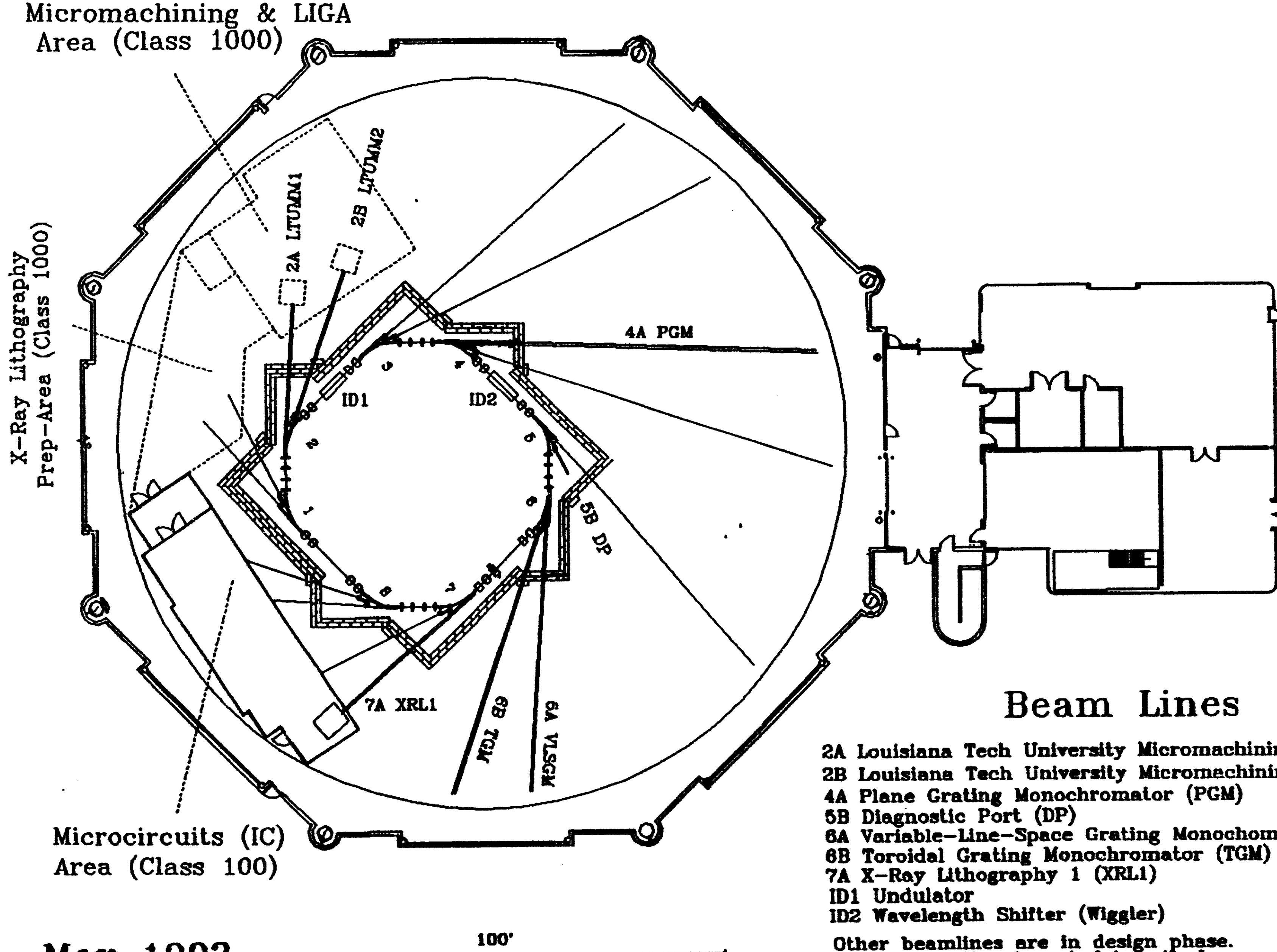




CAMD FACILITY LAYOUT
BEAM LINES
2A Louisiana Tech University Micromachining (LTUMM1)
2B Louisiana Tech University Micromachining (LTUMM2)
4A Plane Grating Monochromator (PGM)
5B Diagnostic Port (DP)
6A Variable-Line-Space Grating Monochromator (VLSGM)
6B Toroidal Grating Monochromator (TGM)
7A X-Ray Lithography 1 (XRL1)
ID1 Undulator
ID2 Wavelength Shifter (Wiggler)
Other beamlines are in design phase
Space allocation is not determined
X-Ray Lithography Sector
Micromachining & LIGA Area (Class 1000)
X-Ray Lithography Prep-Area (Class 1000)
Microcircuits (IC) Area (Class 100)
May 1993
100'

CAMD Facility Layout

X-Ray Lithography Sector

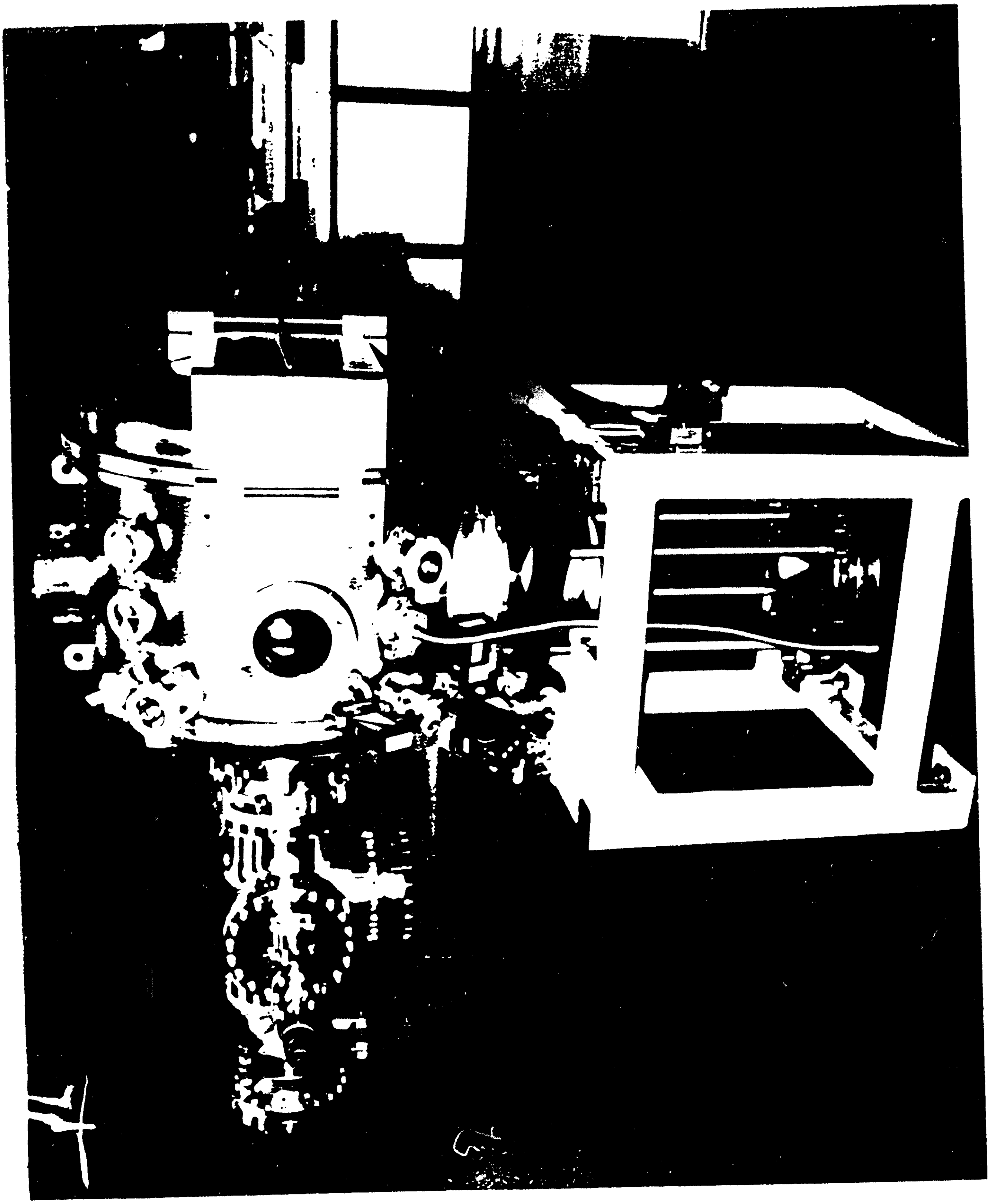


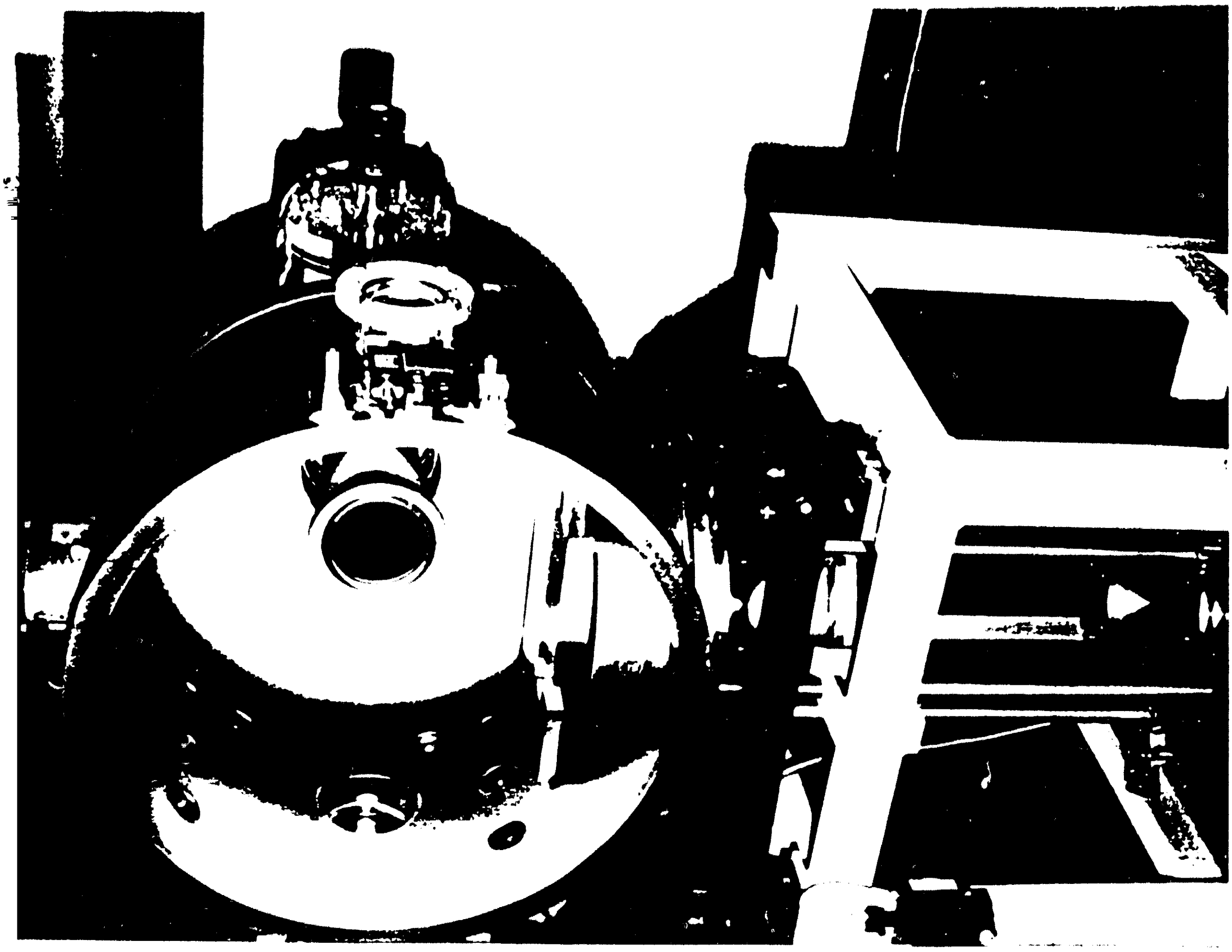
May 1993

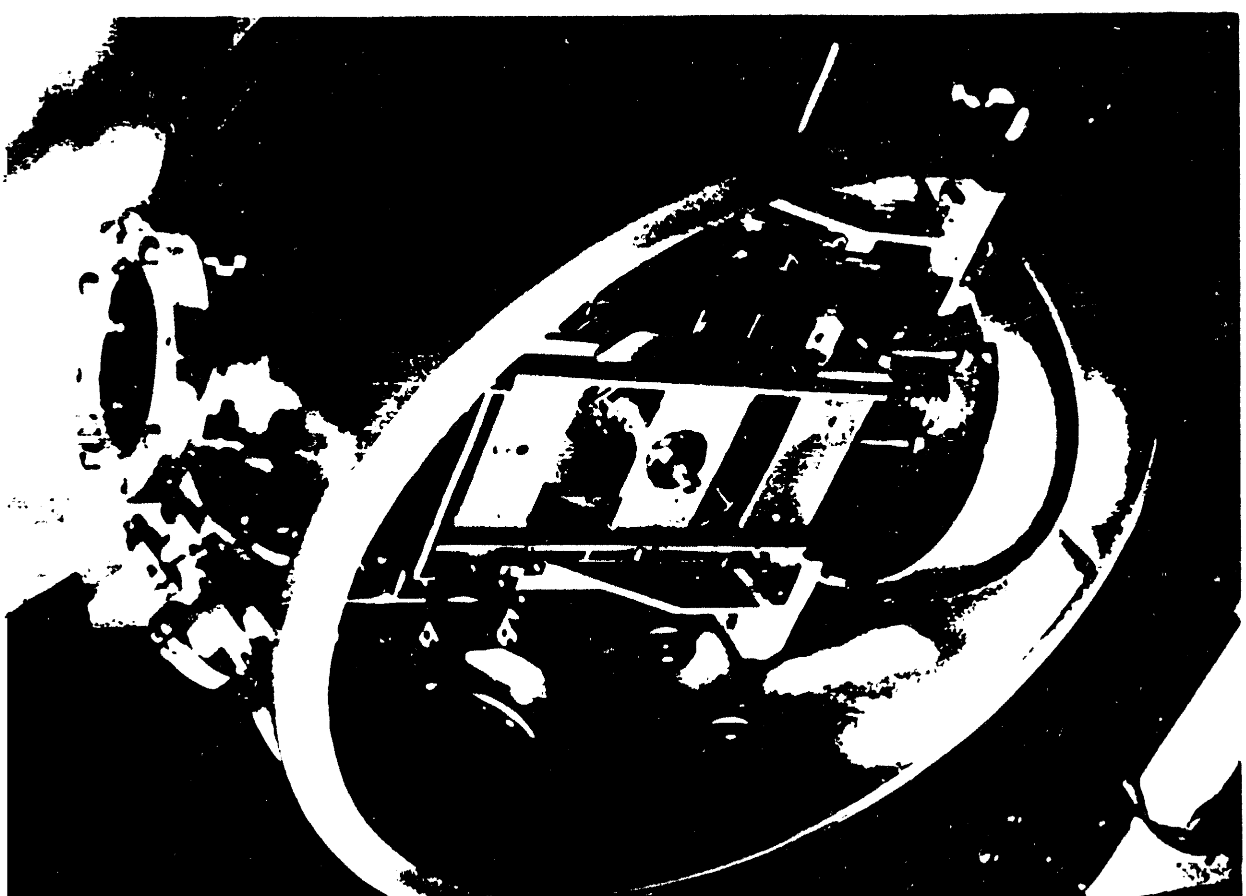
Beam Lines

2A Louisiana Tech University Micromachining (LTUMM1)
2B Louisiana Tech University Micromechining (LTUMM2)
4A Plane Grating Monochromator (PGM)
5B Diagnostic Port (DP)
6A Variable-Line-Space Grating Monochomator (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.







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

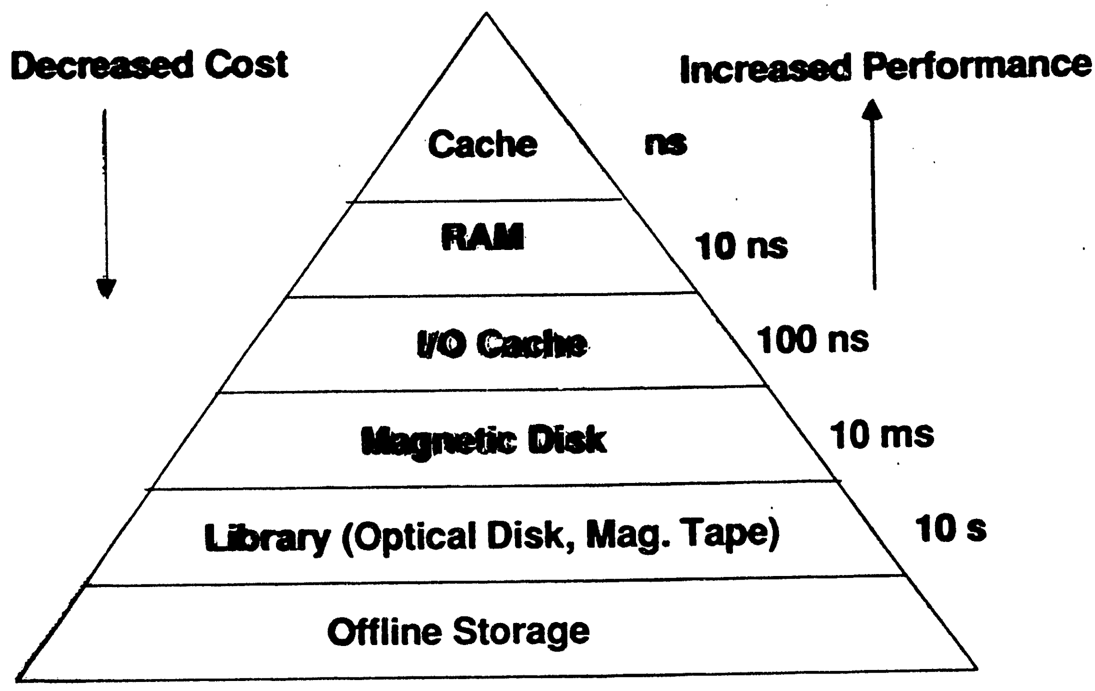
Longshen Fan
IBM Almaden

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



L.S.Fan (March 1993)

High-Performance Data Storage Systems

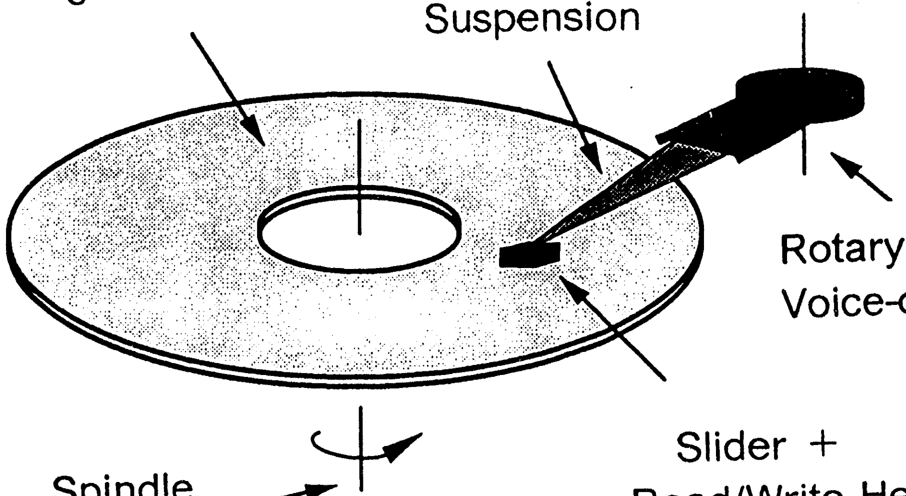
- 50% of the total system cost is in the storage system
- Bank of America, San Francisco, (4 large computers, IBM 3090)

  - 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



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

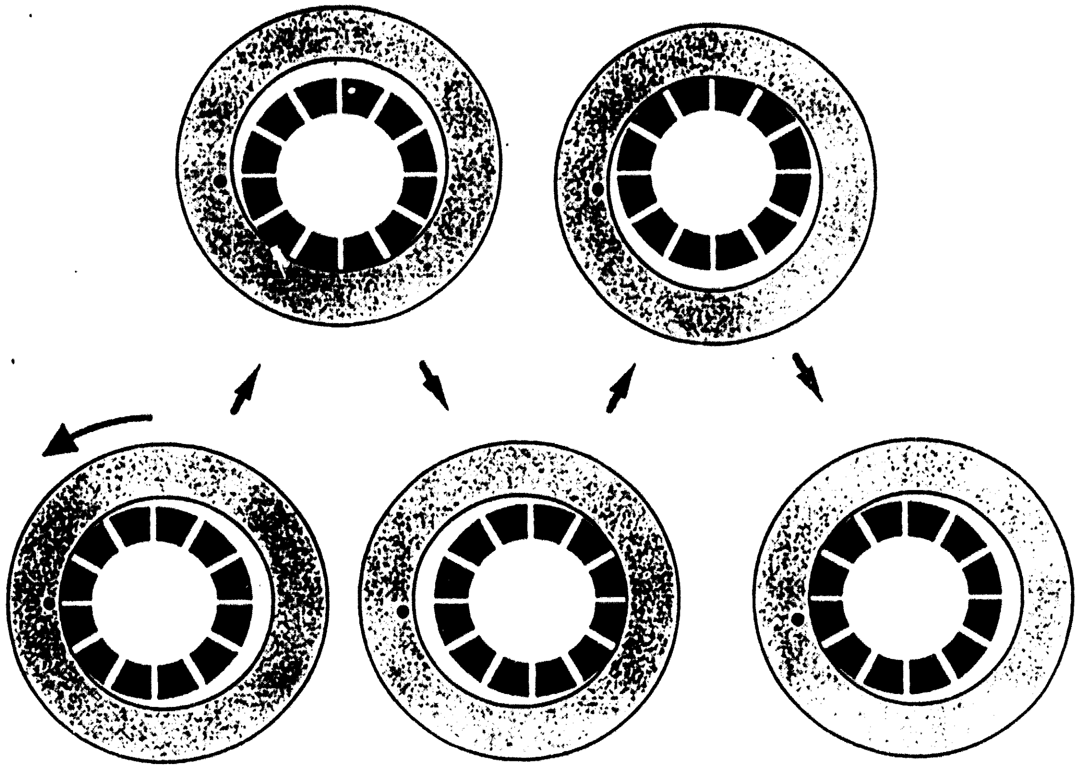
- Several groups (UCBerkeley, Case, MIT, U. Neuchatel, U. Michigan, Karlsruhe, U. Tokyo, IBM, ...)
- Primarily low-torque devices, commonly a few μm Si
- Potential torque improvements:
  - Wobble motor (harmonic motor)
  - Increase height
- IBM-Research/U. Tokyo collaboration; Furuhata, et al., 1993
  - 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.

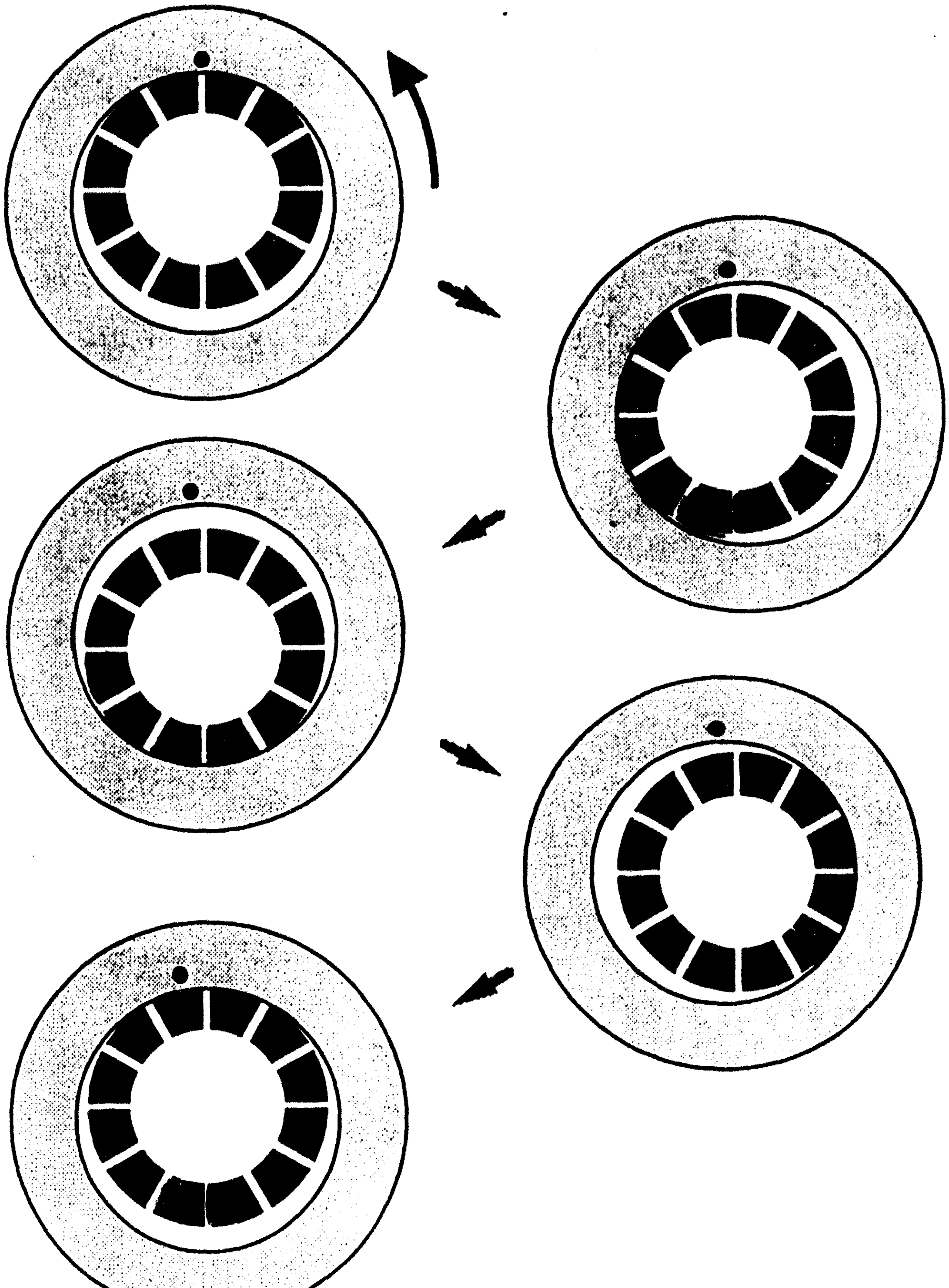
Microactuators for Storage

- Spindle motors for small disk
- Positioning actuator for small HSA
- Tracking fine actuator

ELECTROSTATIC WOBBLE MOTOR

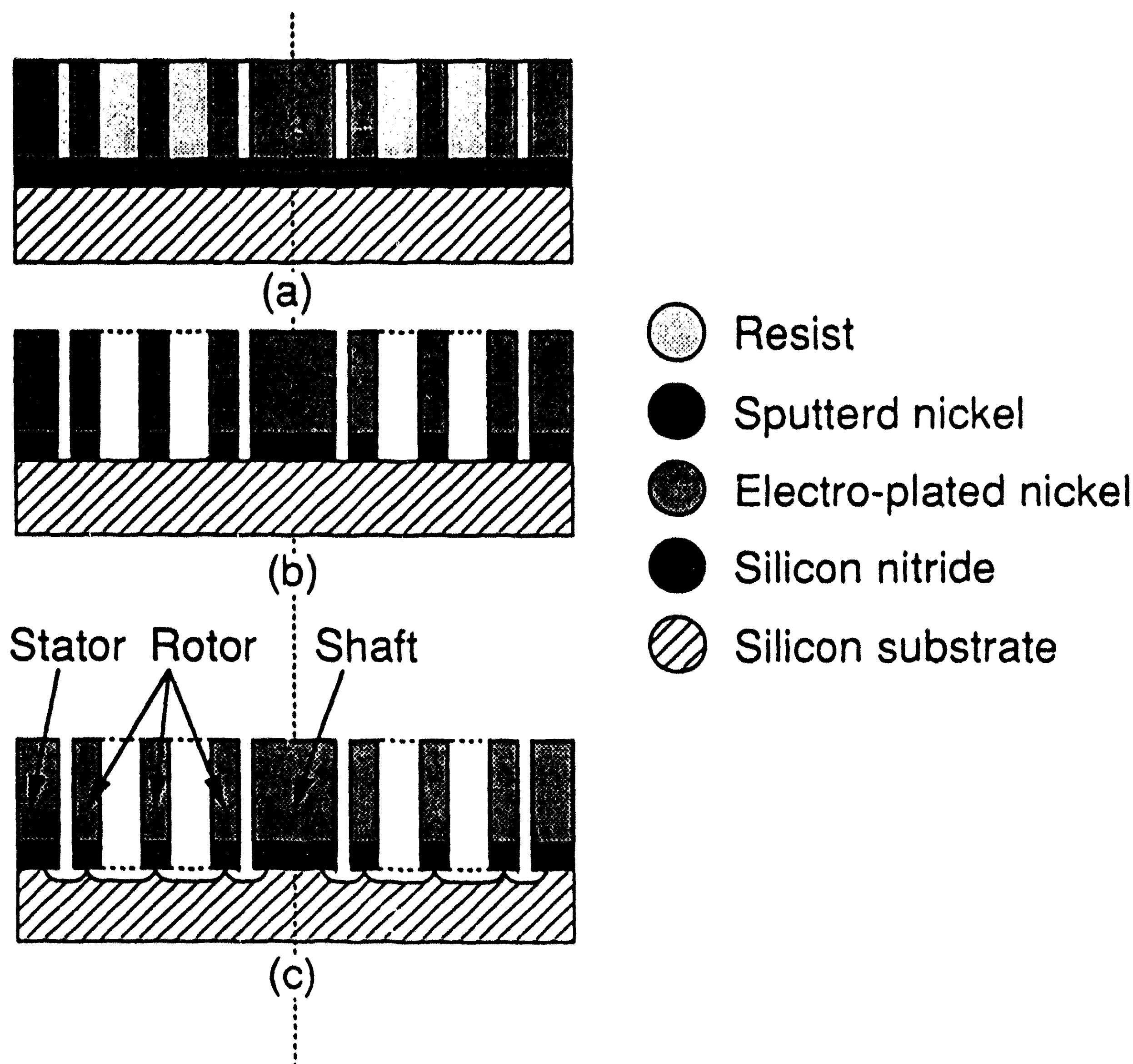
A complete electrical excitation cycle causes only a fraction of a rotation, effectively amplifying torque.





Micro motor

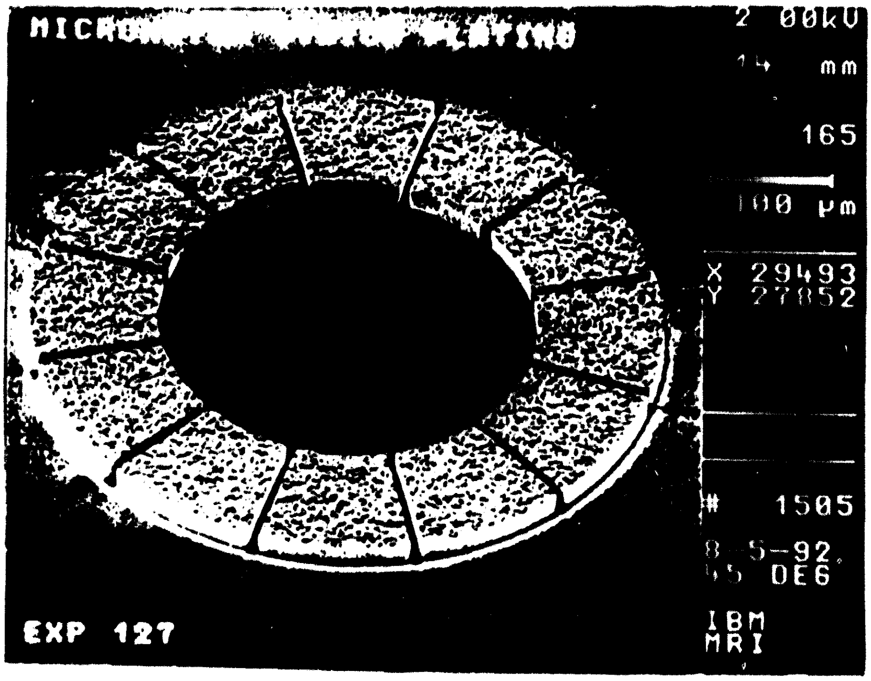
Fabrication sequence of low frictional drive

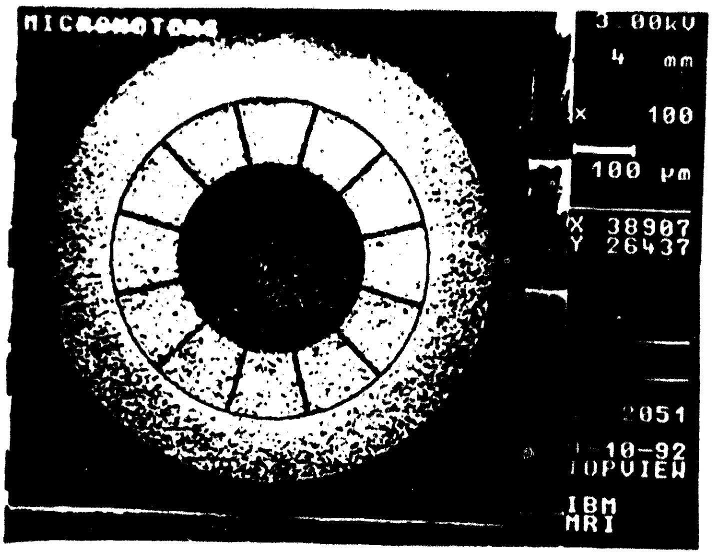


Plated Electrostatic Wobble Motor

T. Furuhata, T. Hirano, L. H. Lane, R. E. Fontana, L. S. Fan, H. Fujita, Feb., 1993

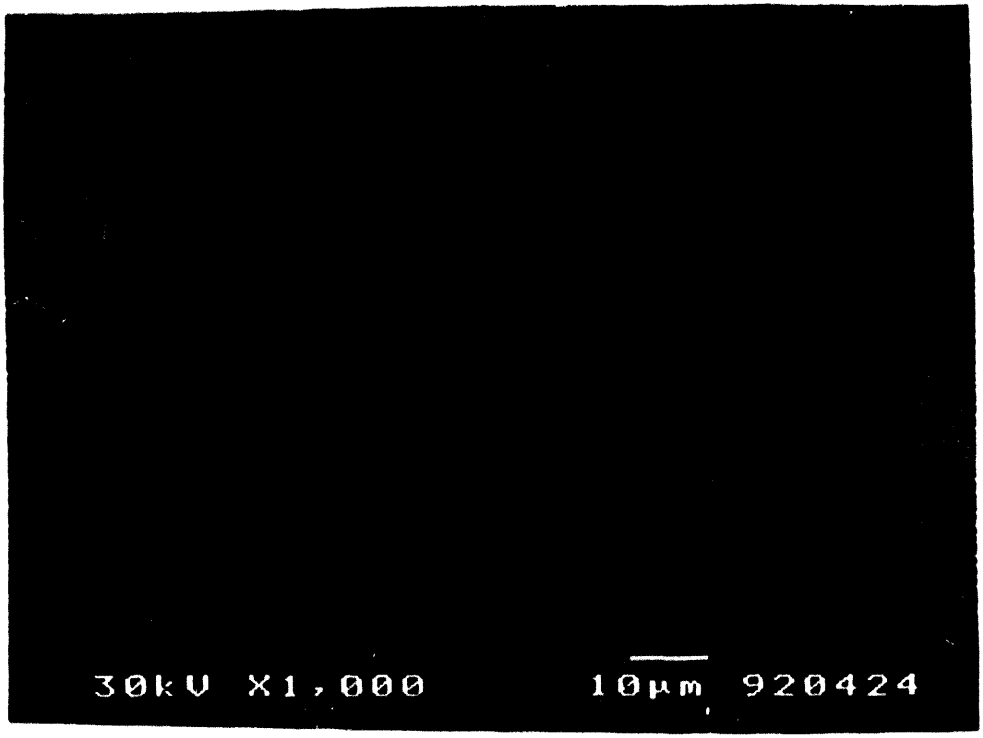
$T \propto r^3 V^2 h \Delta d^{-3}$

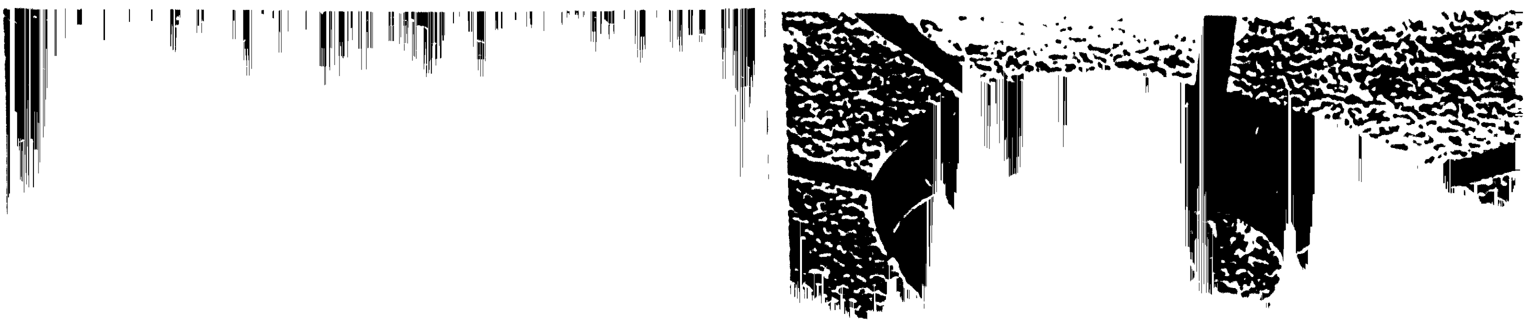




Plated Electrostatic Wobble Motor

T. Hirano, T. Furuhata, H. Fujita, Feb., 1993





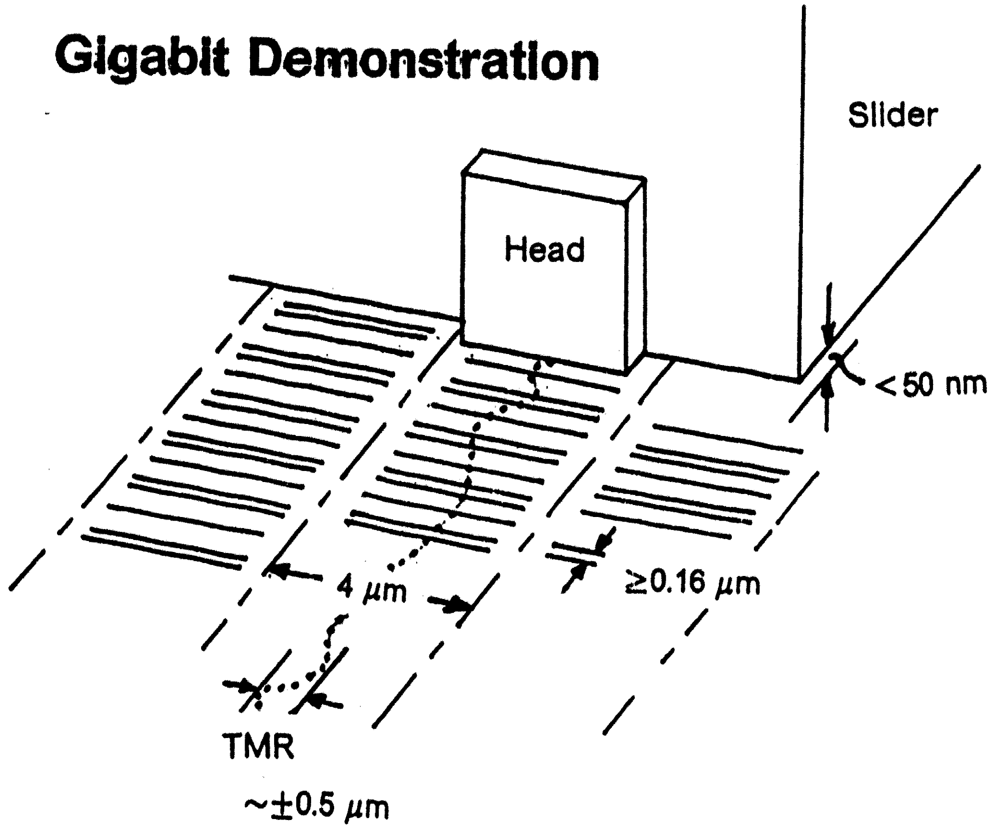
Shock, Acceleration Detectors

- Primarily to eliminate spurious writing

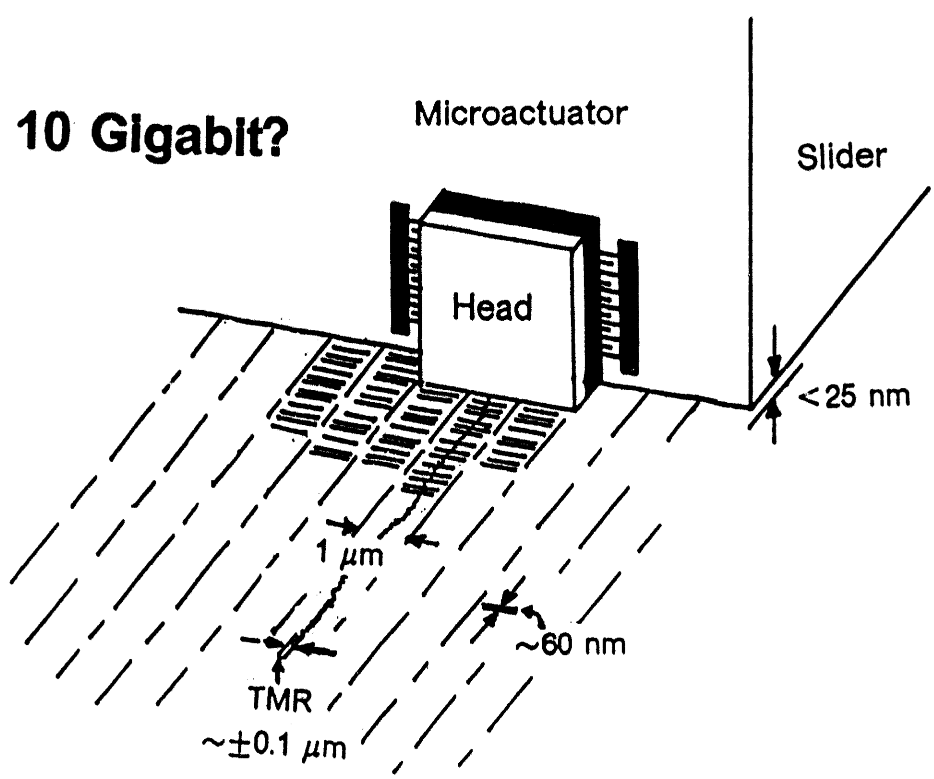
- Cost may limit sophistication of MEMS device

- Potential future application: accelerometer to assist in track following

Gigabit Demonstration

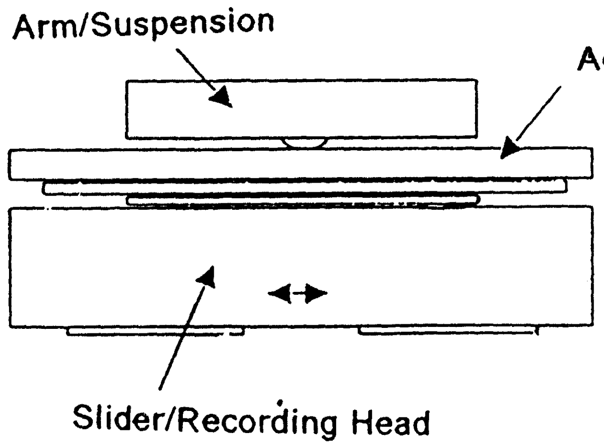


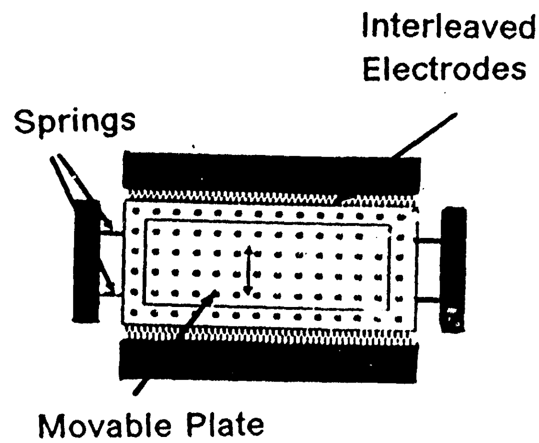
10 Gigabit?

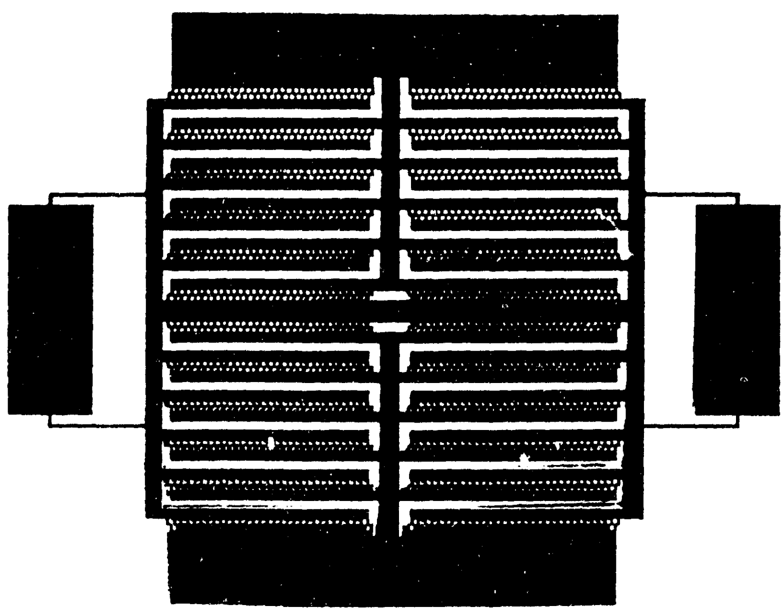


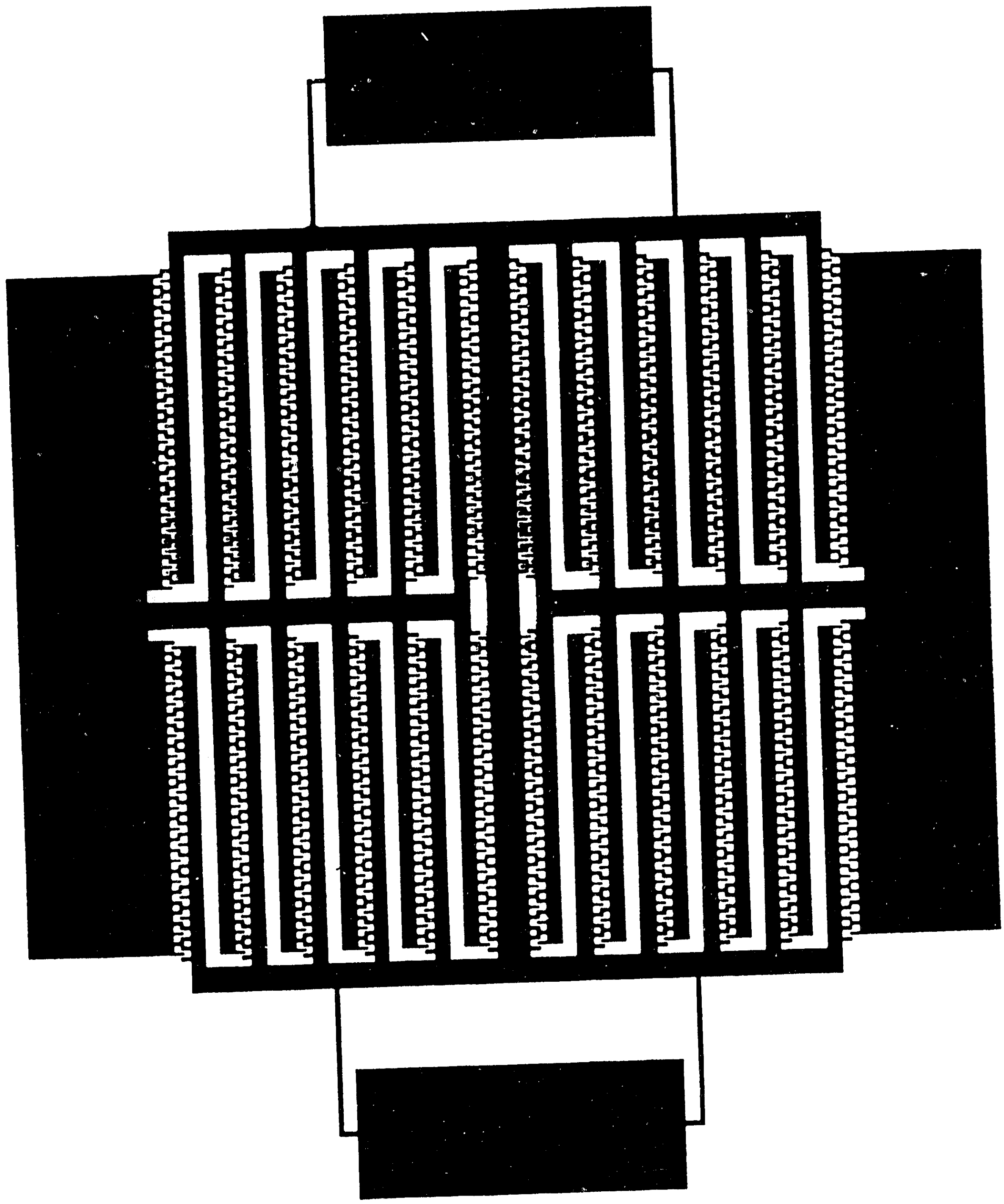
Microactuator for Two-Stage Track Registration Servo

- L. S. Fan, L. H. Lane, N. Robertson, L. Crawford, M. A. Moser, T. C. Reiley, W. Imaino, IBM; Feb. 1993.
- Slider motion
- Thick plated copper (20 μm); millimechanics

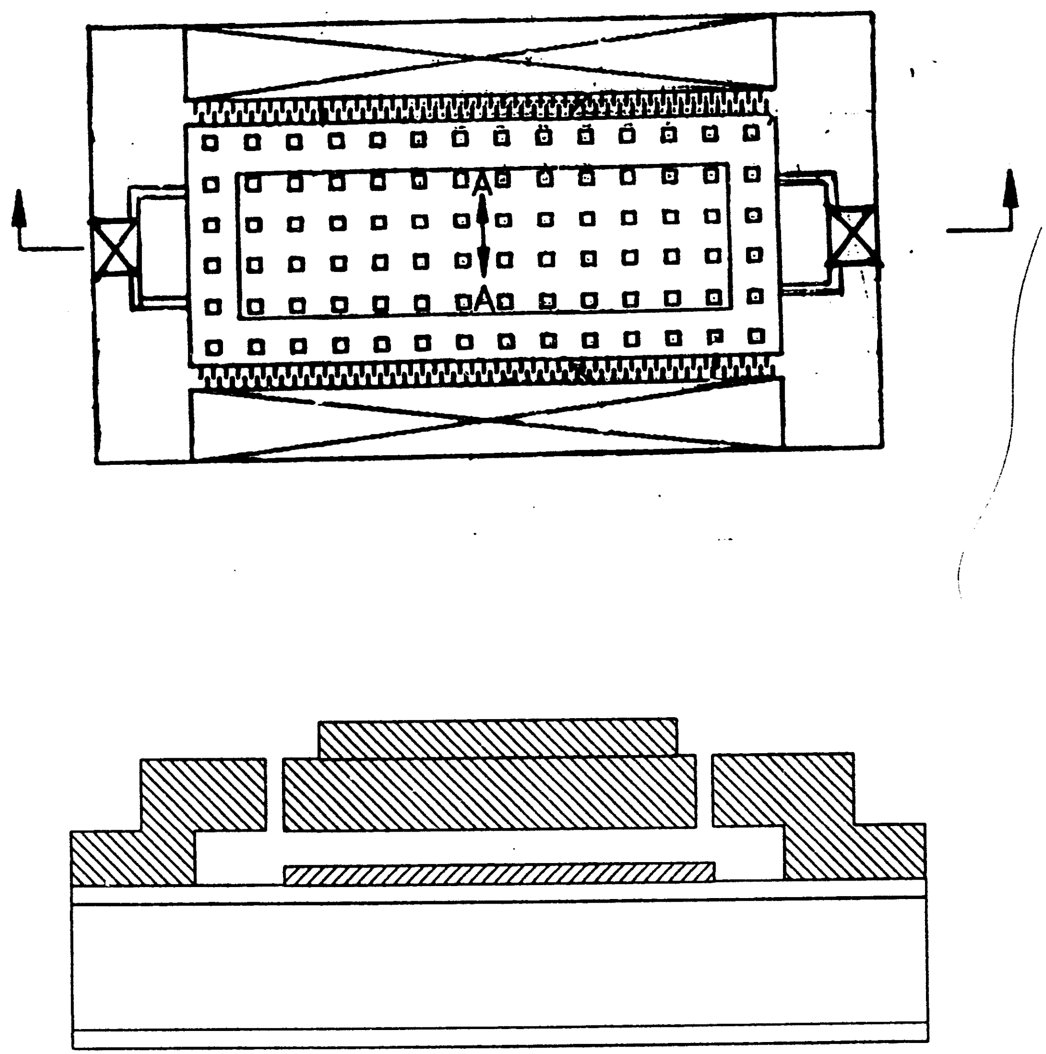




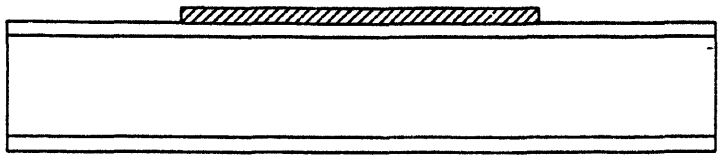




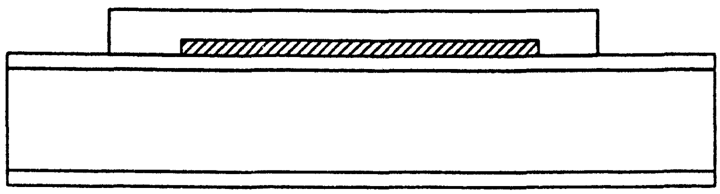
2.34



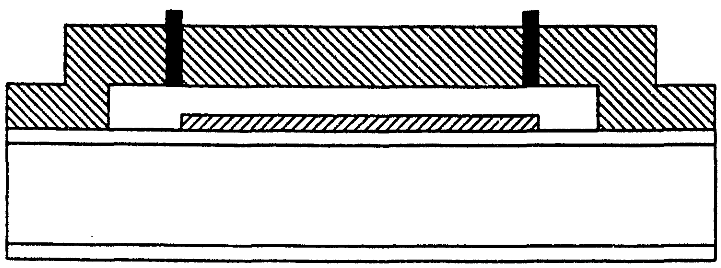
Top view and cross section of an electric crab-leg flexure.



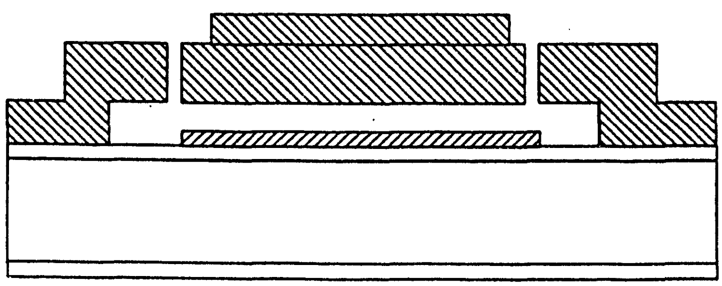
(a)



(b)



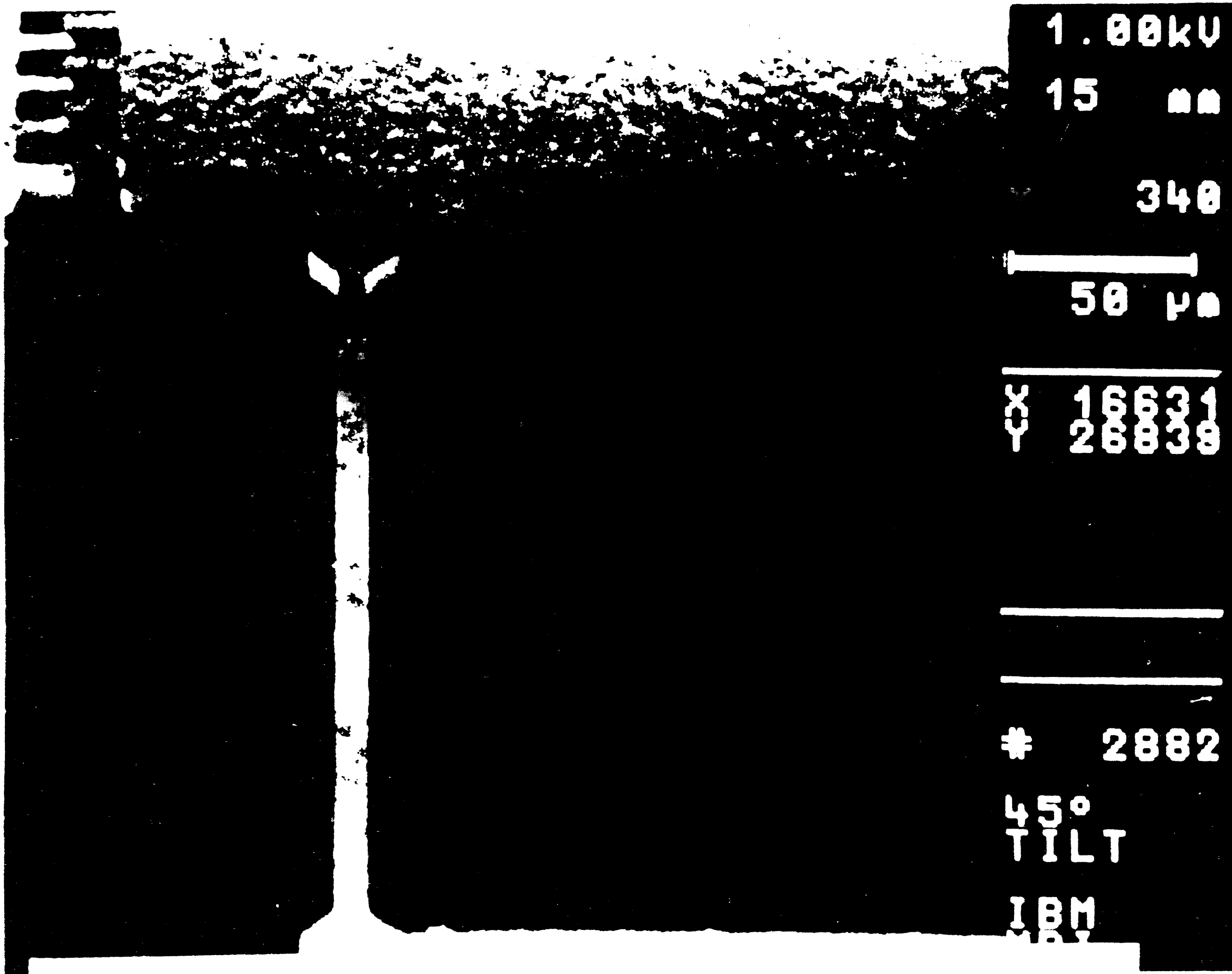
(c)



(d)

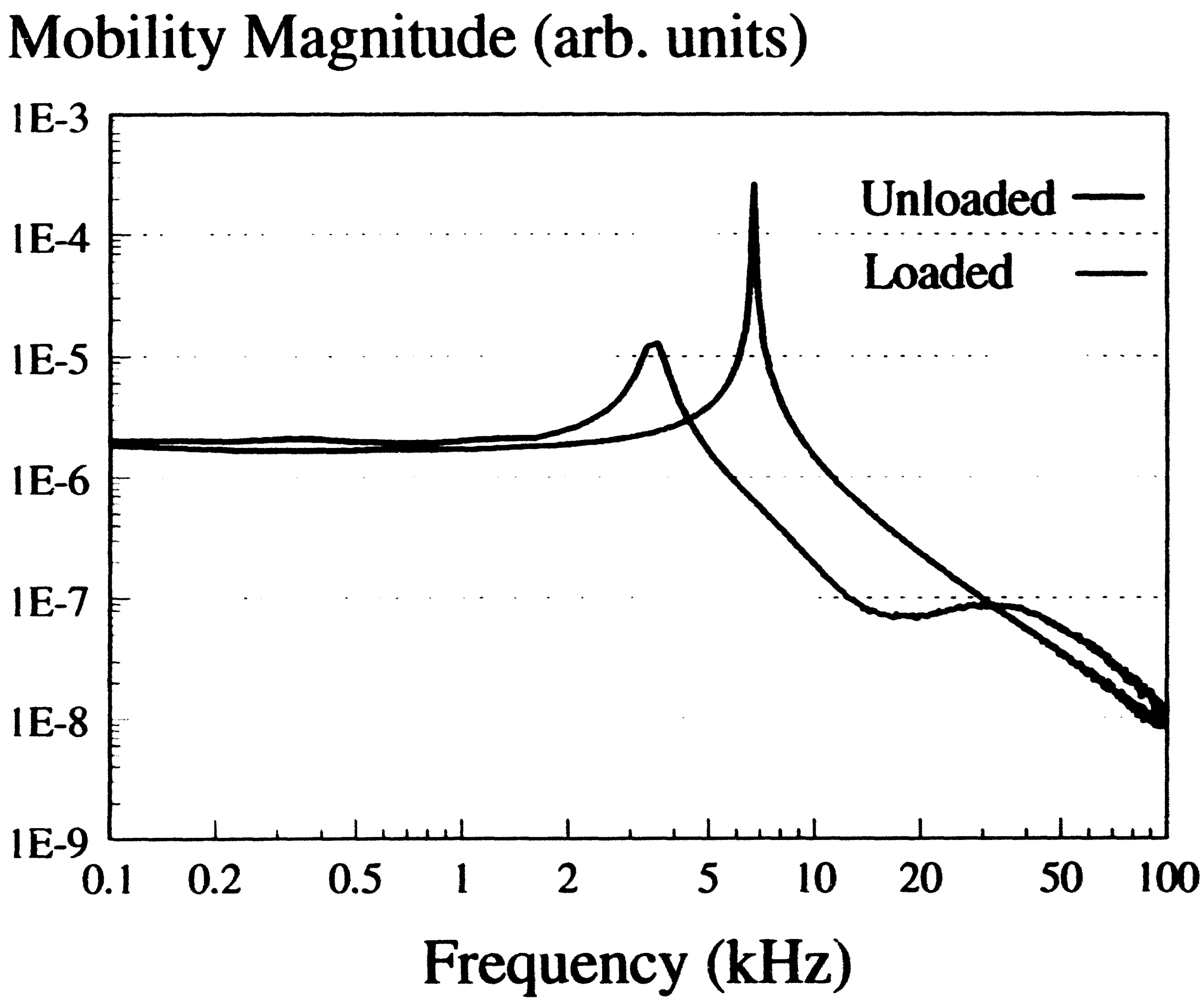
HIGH-ASPECT RATIO STRUCTURE

SEM micrograph of thick photoresist plating stencil for 2 μm gap electrodes.



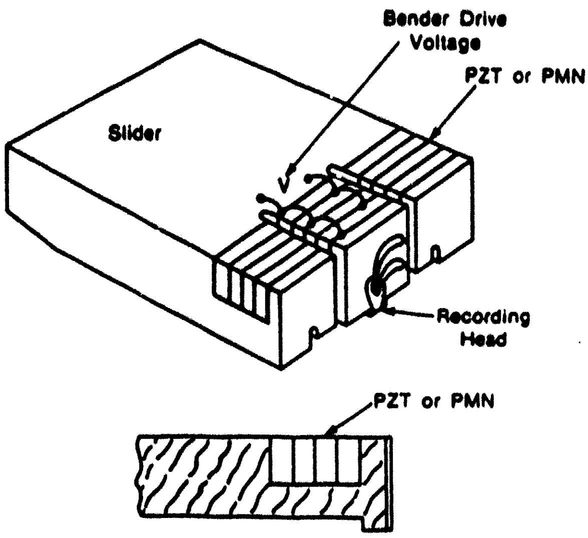
SEM micrograph of a microactuator.

Micro-Actuator Frequency Response Functions

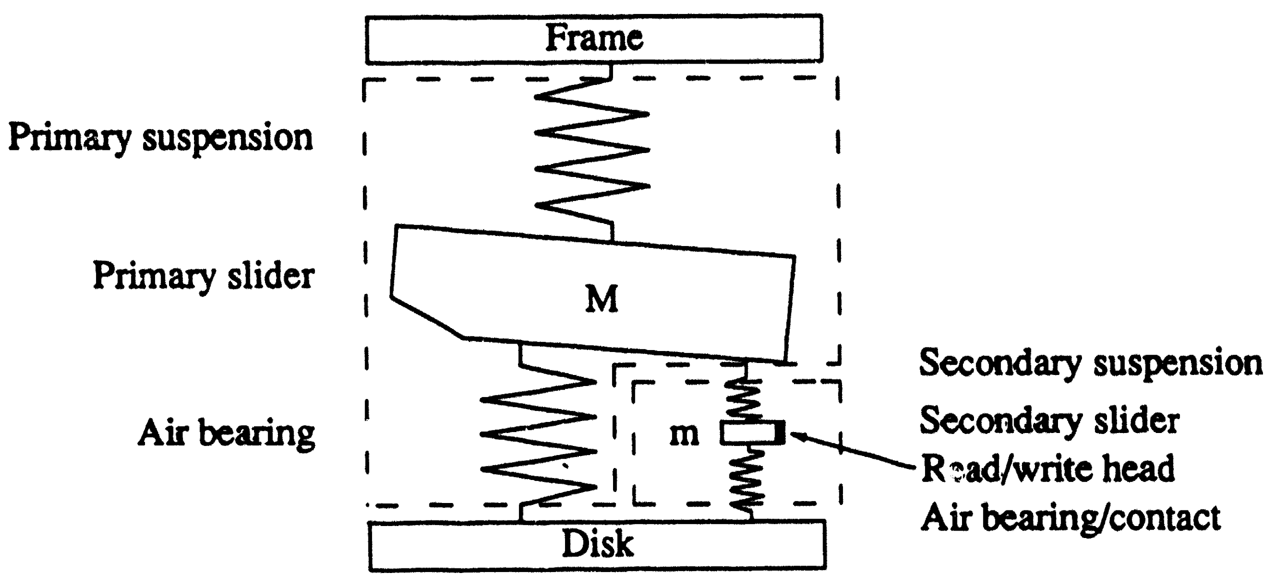


Flying Height Adjustment Techniques

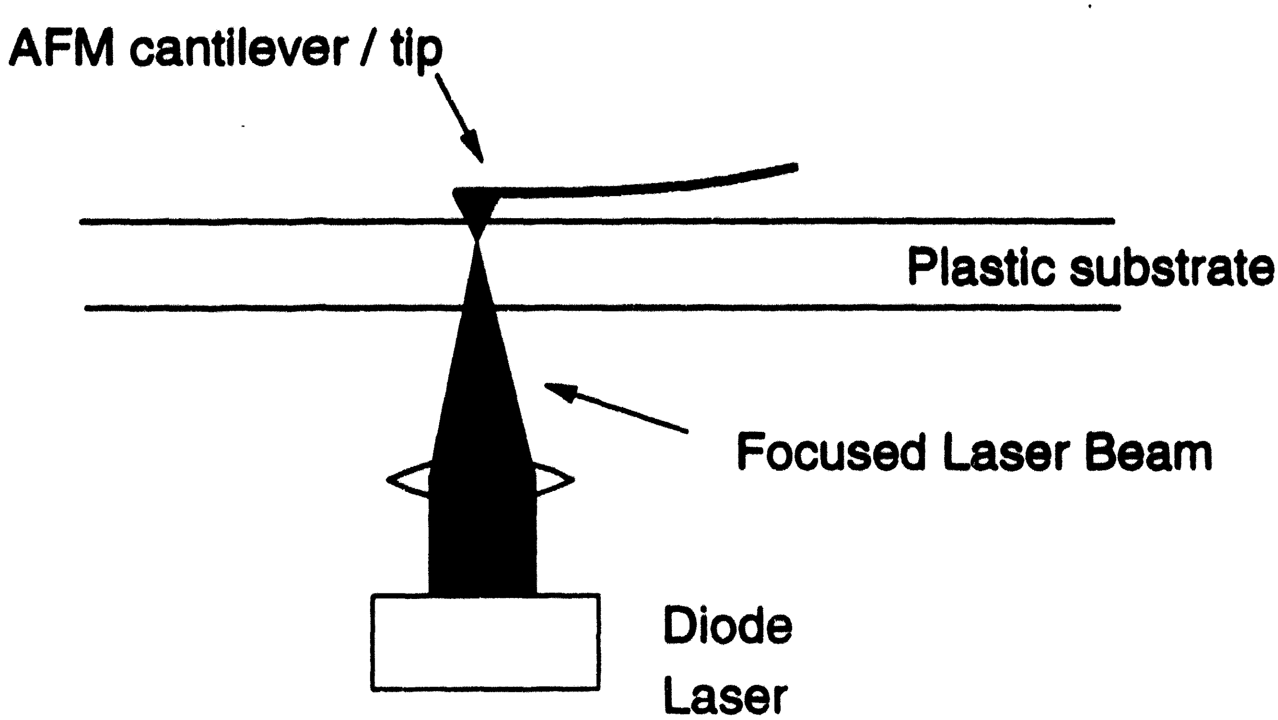
- C. Yeack-Scranton, et al., IBM, 1986: "Taildragger" piezoelectric bender to reduce head-disk spacing



- J. Wickert, et al, Carnegie-Mellon U., 1991: Dual slider with compliant interconnecting suspension



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

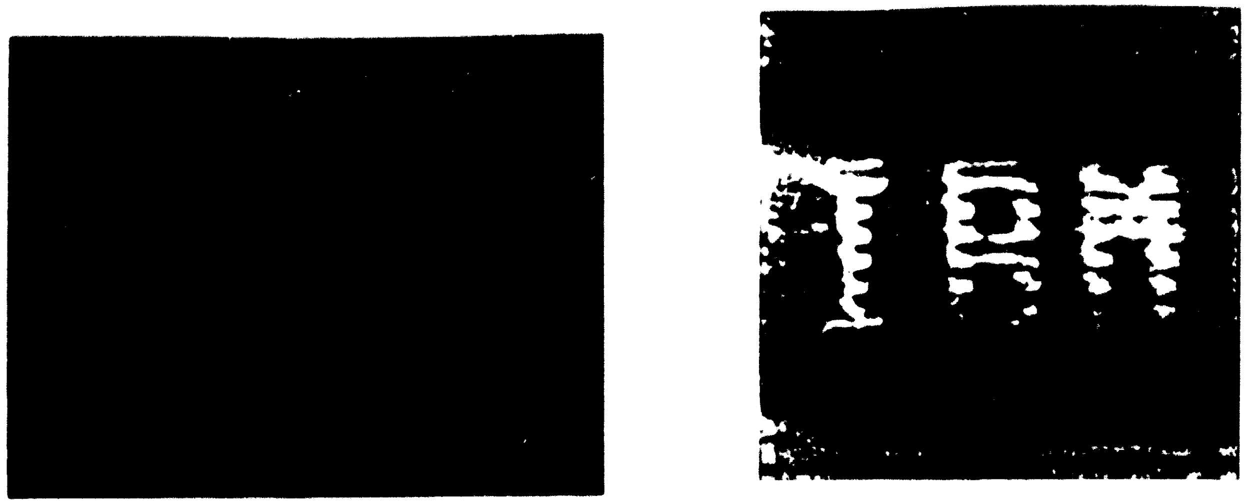


Figure 2 (a) AFM image of a pit written in PMMA. Pit is roughly 300 nm in diameter (b) AFM image of the IBM logo written between the grooves of an optical disk. The individual pits are approximately 100 nm in diameter.

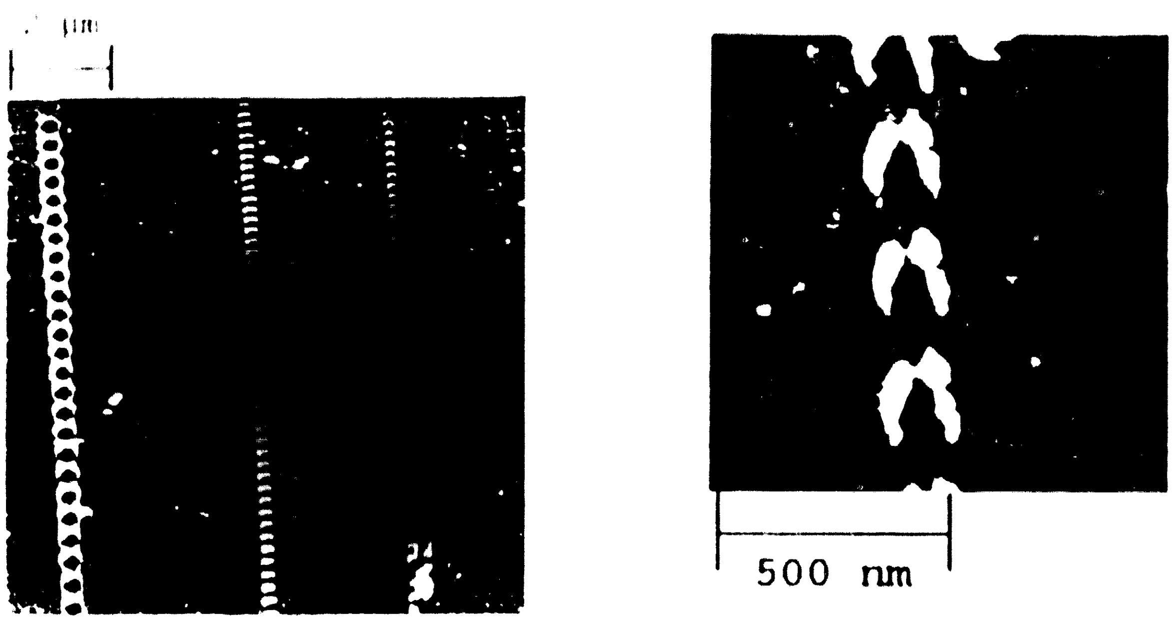


Figure 3 (a) AFM image of several tracks written on a rotating PMMA substrate (b) Blow up of one section of track

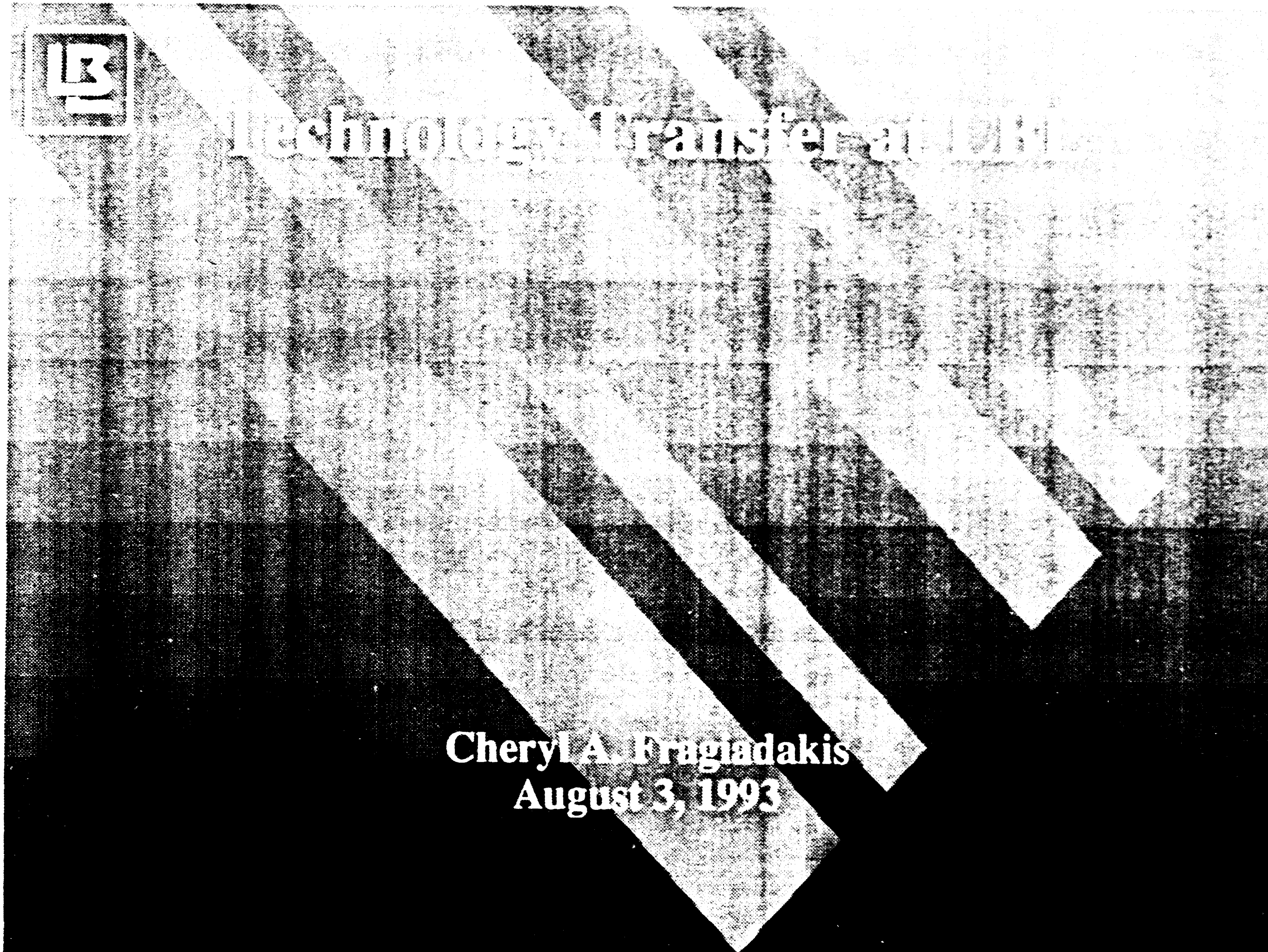
MEMS for DATA STORAGE

- 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

Technology Transfer at Lawrence Berkeley Laboratory

Cheryl A. Fragiadakis
Technology Transfer Department
LBL

August 3, 1993


Technology Transfer at LBL
Cheryl A. Fragiadakis
August 3, 1993

B... ...ership ... Achievement ...

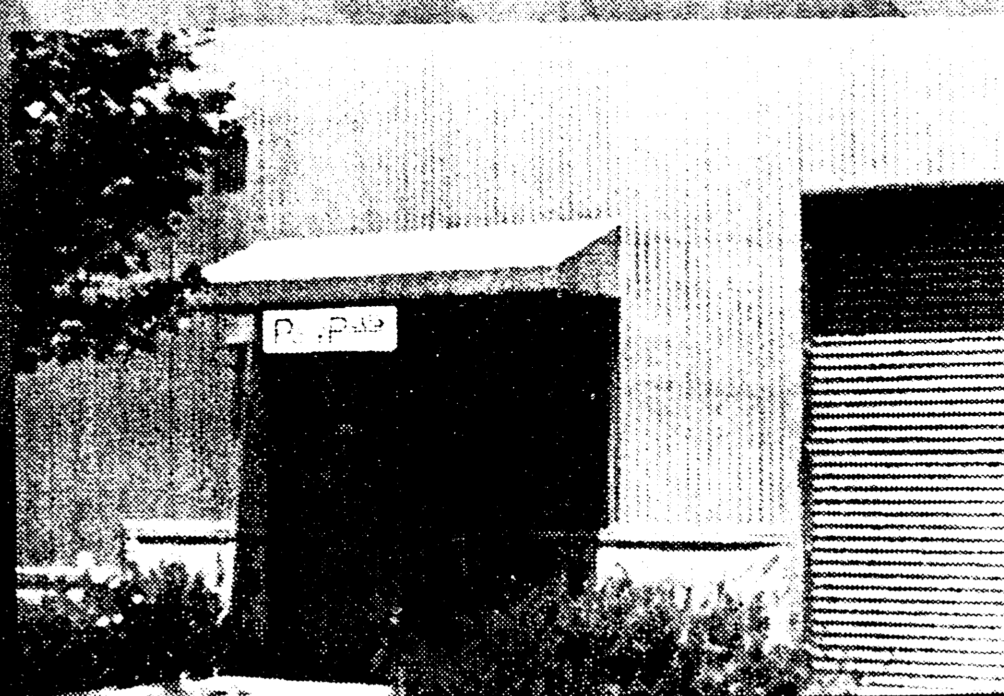
- Results-orient...
  - Techno... [illegible]
  - Respon... [illegible]
  - Match... [illegible]
- Managed ... [illegible]
  - Quality
  - Customers
  - Products

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

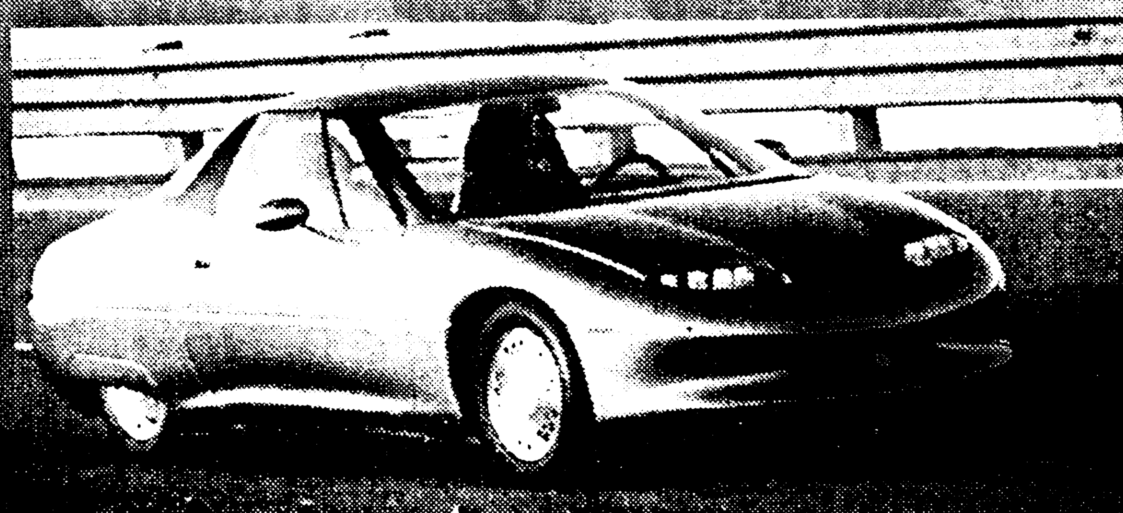
PolyPlus

- 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"



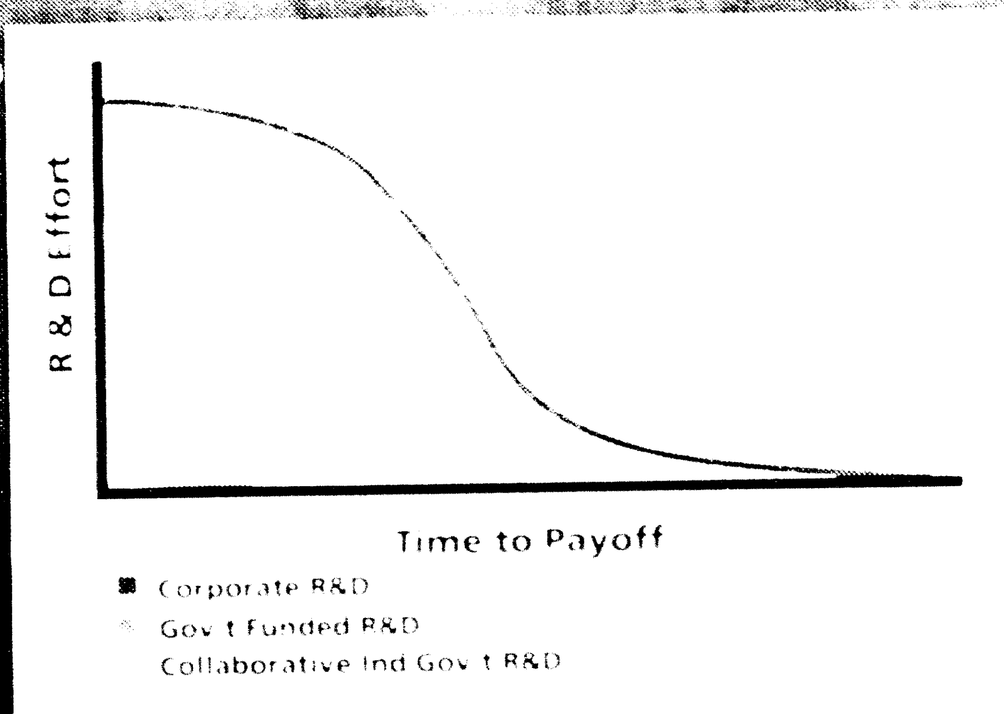
GM Prototype Electric Car

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

R & D "Gap"

- 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"



RA... ecuted In ...

Execute...

- Amgen
- AMTEX
- CIFE
- Conducti...
- EPRI
- IBM
- Glycomed
- Motorola
- Orion A.C.T.
- Seagate Magnetics
- USABC

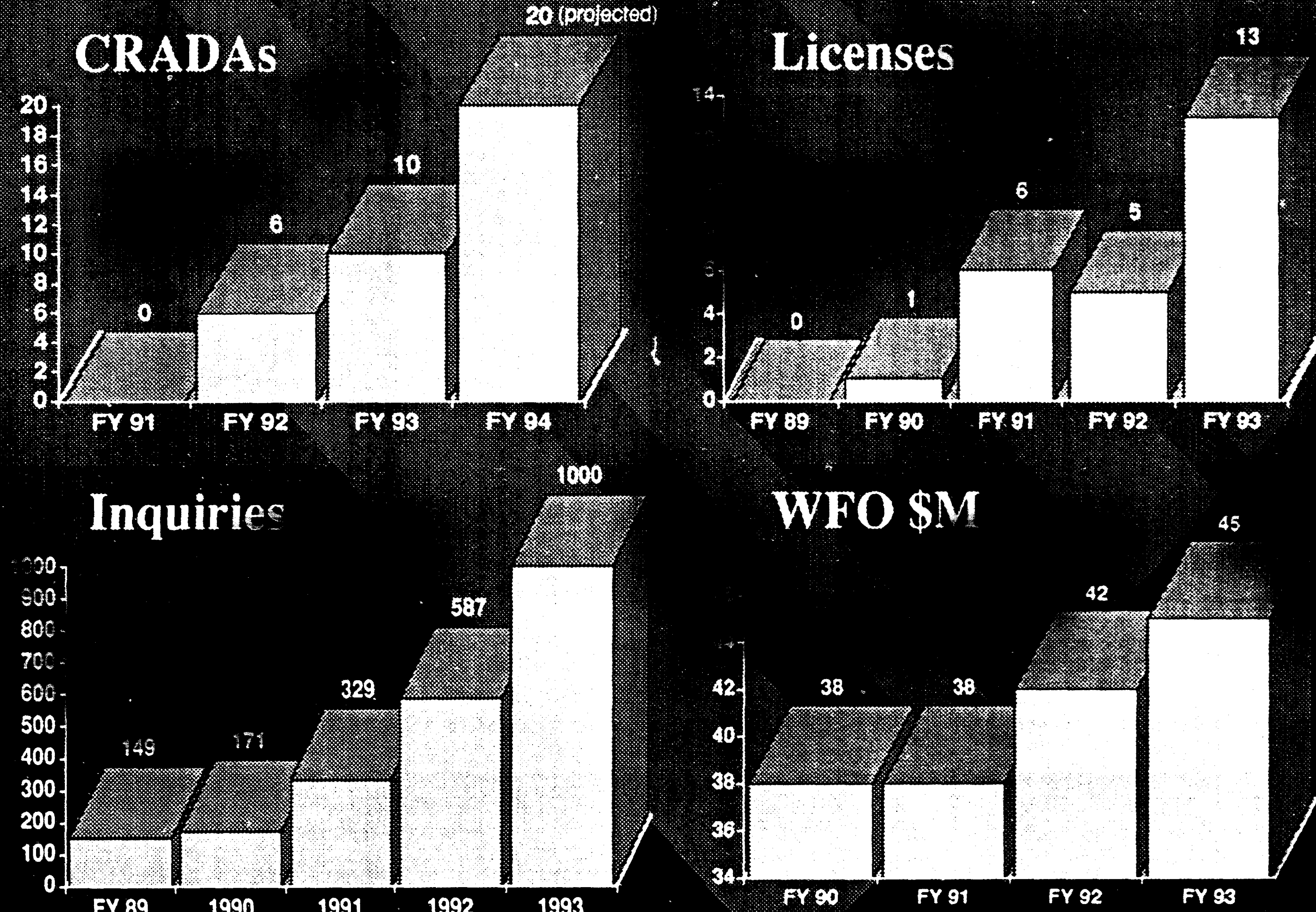
In P...

- Chemagnetic...
- Conducta...
- Chiron/C...
- Dow Chem...
- Du Pont
- Fusion Systems
- NYSERDA
- Oil and Gas Consortium
- Rouge Steel/Ford

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



(1993 Projected)

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

August 3, 1993

ATTENDANCE ROSTER

David Attwood
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Raul Beguiristain
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

James M. Bustillo
University of California, Berkeley
BSAC
497 Cory Hall
Berkeley, CA 94720
(510) 643-6690
(510) 642-2916

Sean Cahill
Menlo Park, CA

Jeanne Cherbeneau
Cherbeneau Associates
250 El Avenue
Berkeley, CA 94708

Patrick Cheung
University of California, Berkeley
BSAC
497 Cory Hall
Berkeley, CA 94720

Dino R. Ciarlo
Lawrence Livermore National Lab.
7000 East Avenue
Livermore, CA 94550
(510) 422-8872
(510) 422-2783

Bill Clark
University of California, Berkeley
BSAC
497 Cory Hall
Berkeley, CA 94720

Bob Crocker
Sandia National Laboratory
P. O. Box 969
Organization 8716
Livermore, CA 94551

Glen H. Dahlbacka
Lawrence Berkeley Laboratory
1 Cyclotron Road, 90-1070
Berkeley, CA 94720
(510) 486-5358
(510) 486-6457

Arthur B. Denison
Idaho Natl. Engineering Laboratory
EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415-220
(208) 526-1294
(208) 526-0690

Longshen Fan
IBM
650 Harry Road
San Jose, CA

Diane Fennell
Fennell Associates
441 Alameda Avenue
Half Moon Bay, CA 94019
(415) 726-3451
(415) 726-9019

Cheryl Fragiadakis
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720
(510) 486-7020
(510) 486-6457

Shoichi Furukawa
Case Western Reserve Univ
EEAP, Glennan T14A
10900 Euclid Avenue
Cleveland, OH 44106
(216) 368-5263
(216) 368-2668

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

August 3, 1993

ATTENDANCE ROSTER

Mitchell Halpern
SRI International
333 Ravenswood
Menlo Park, CA 94025

Michael H. Hecht
Jet Propulsion Laboratory
Mail Stop 302-231
4800 Oak Grove Drive
Pasadena, CA 91109
(818) 354-2774
(818) 393-4540

David Hicks
NCMS
3025 Boardwalk
Ann Arbor, MI 48108
(313) 995-4934
(313) 995-1150

Jill M. Hruby
Sandia National Laboratory
P. O. Box 969
Organization 8716
Livermore, CA 94551
(510) 294-2596
(510) 294-3410

Charles E. Hunt
Lawrence Livermore National Lab.
7000 East Avenue
Livermore, CA 94550
(510) 422-8354
(510) 422-2783

Keith Jackson
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720
(510) 486-6894

Hal Jerman
IC Sensors
1701 McCarthy Blvd.
Milpitas, CA 95035

Jack Judy
University of California, Berkeley
BSAC
497 Cory Hall
Berkeley, CA 94720

Tom Kenny
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

James F. Key
EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415-205
(208) 525-5397
(208) 525-5877

Chantal Khan-Malek
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720
(510) 486-6894

Brian Kincaid
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Jeffrey B. Kortright
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720
(510) 486-5960
(510) 486-4550

Abraham P. Lee
Lawrence Livermore National Lab.
P. O. Box 808, L-222
7000 East Avenue
Livermore, CA 94551
(510) 423-4524
(510) 422-2783

Michael A. Littlejohn
U.S. Army Research Office
P. O. Box 12211
Res. Triangle Park, NC 27709
(919) 549-4314
(919) 549-4310

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

August 3, 1993

ATTENDANCE ROSTER

Marc J. Madou
Microfabrication Application
3680 Bryant Street
Palo Alto, CA 94306
(415) 858-1663
(415) 858-1663

Karen W. Markus
MCNC
P. O. Box 12889
Res. Triangle Pk, NC 27709-288
(919) 248-1437
(919) 248-1455

Paul Matthews
Argonne National Laboratory
APS/RF
9700 S. Cass Avenue
Argonne, IL 60439

Shaun L. McCarthy
Ford Motor Company
P. O. Box 2053
M/D 3439-SRL
Dearborn, MI 48104
(313) 322-1355
(313) 248-3611

Werner Meyer-Ilse
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Dale Miller
Lawrence Livermore National Lab.
7000 East Avenue
Livermore, CA 94550
(510) 422-8782
(510) 422-2783

Richard S. Muller
University of California, Berkeley
Berkeley, CA 94720

Lawrence P. Muray
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road, 2-400
Berkeley, CA 94720
(510) 486-4447
(510) 486-4550

Phil Ross
Material Science Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720
(510) 486-6226
(510) 486-5530

Volker Saile
CAMD
Louisiana State University
3990 West Lakeshore Drive
Baton Rouge, LA 70803
(504) 388-8887
(504) 388-6954

Charles Shank
Lawrence Berkeley Laboratory
1 Cyclotron Road, 50A-4133
Berkeley, CA 94720
(510) 486-5111
(510) 486-6720

Chris Steffani
Lawrence Livermore National Lab.
P. O. Box 808
Mail Stop L-332
Livermore, CA 94550

Thomas L. Swain
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road, 46-161
Berkeley, CA 94720
(510) 486-5644
(510) 486-4873

Ron Tackaberry
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Scott Taper
Office Technology Licensing
2150 Shattuck Avenue #510
Berkeley, CA 94704

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

August 3, 1993

ATTENDANCE ROSTER

Stan R. Trost
Lawrence Livermore National Lab.
P. O. Box 808, L-119
Livermore, CA 94550
(510) 423-5864
(510) 422-8277

James H. Underwood
Center for X-Ray Optics
Lawrence Berkeley Laboratory
1 Cyclotron Road, 2-400
Berkeley, CA 94720.0
(510) 486-4958
(510) 486-4550

Robert O. Warrington
Louisiana Tech. University
Inst. for Micromanufacturing
Ruston, LA 71272
(318) 257-2357
(318) 257-3999

Richard M. White
University of California, Berkeley
Berkeley, CA 94720

October 1993

DATE
FILMED
2/4/94

END