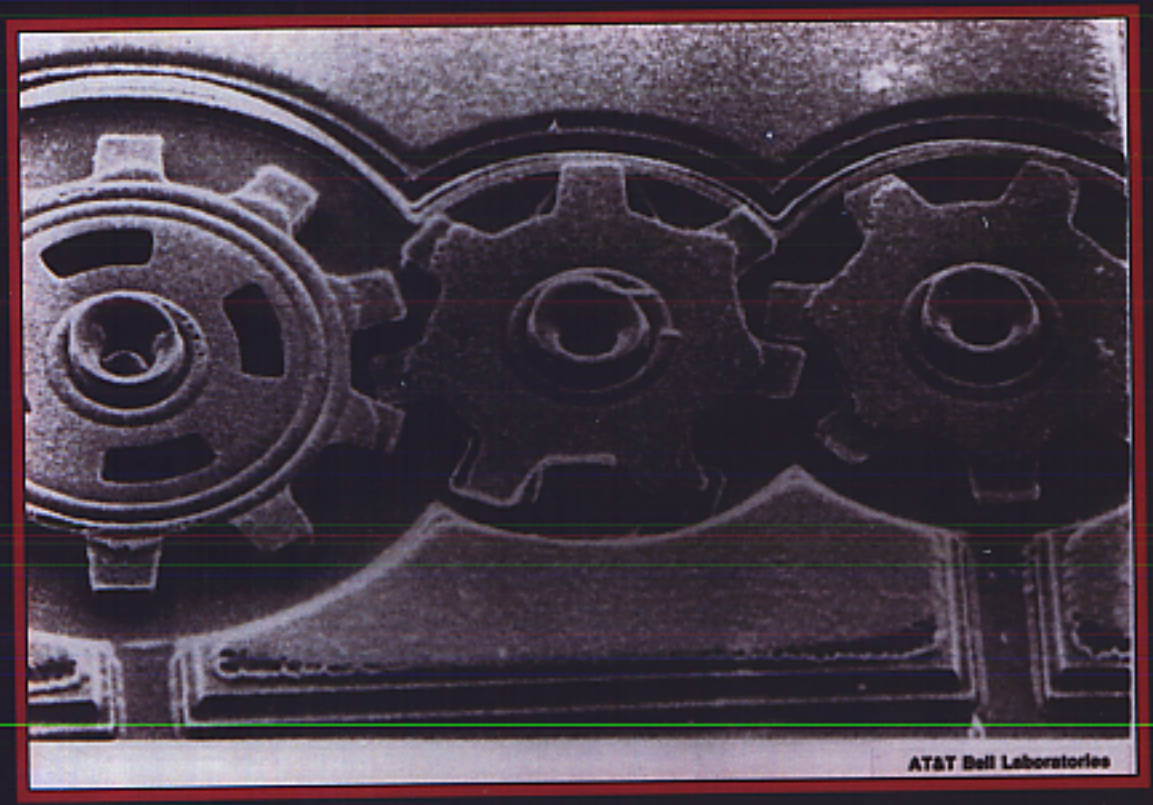
Silicon Micromachines for Science and Technology

David Bishop
Bell Labs, Lucent Technologies
Murray Hill, NJ

outline

- What are MEMS?
- Why are they important and useful?
- What are some applications in Technology?
  - -Lightwave Systems
  - -Acoustics
  - -Microwave Devices
- What are some applications in Science
  - -Magnetometers
  - -NSOMs
  - -Vortex Physics
- Conclusions

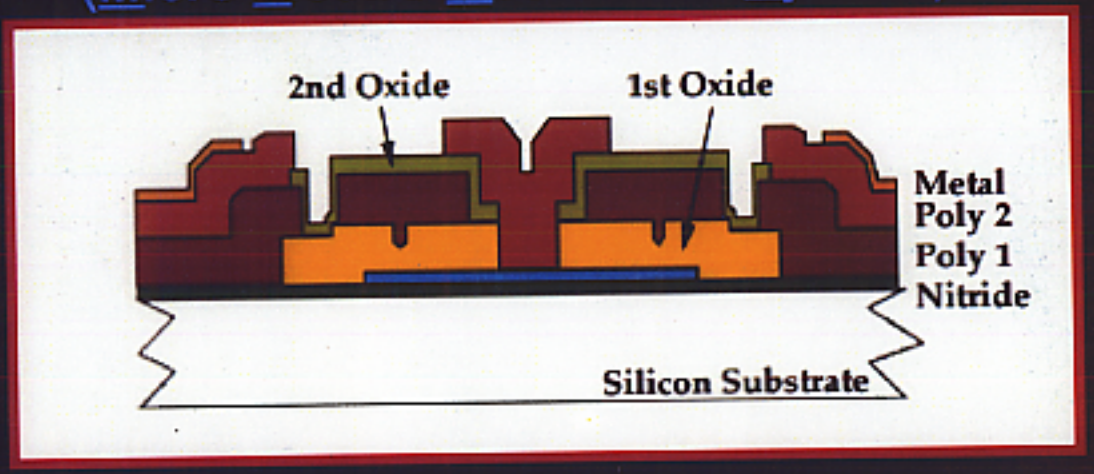
Early Surface Micromachined Device



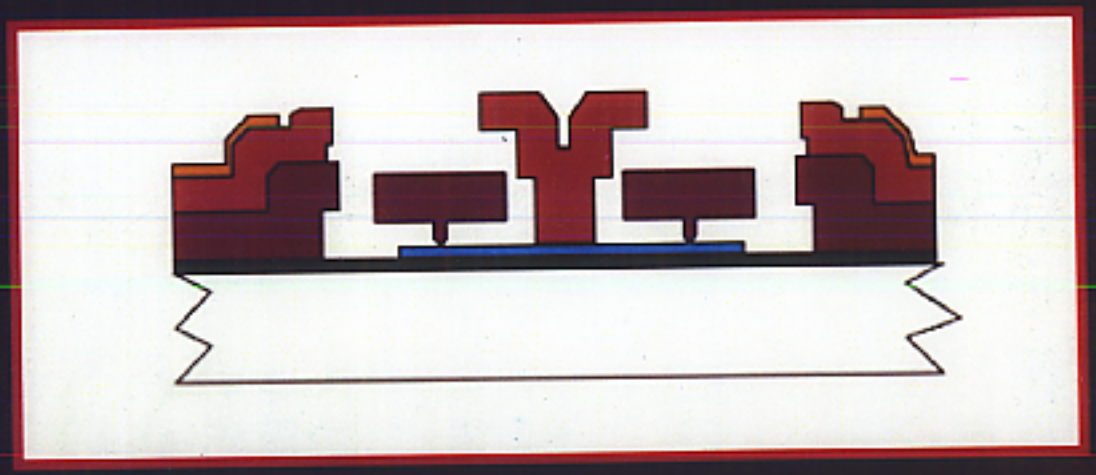
What is a MEMS Device and How is it Built?

(Micro Electro Mechanical System)

Device after all the films are deposited and patterned



Device after the oxide layers are etched away and the device is "released"



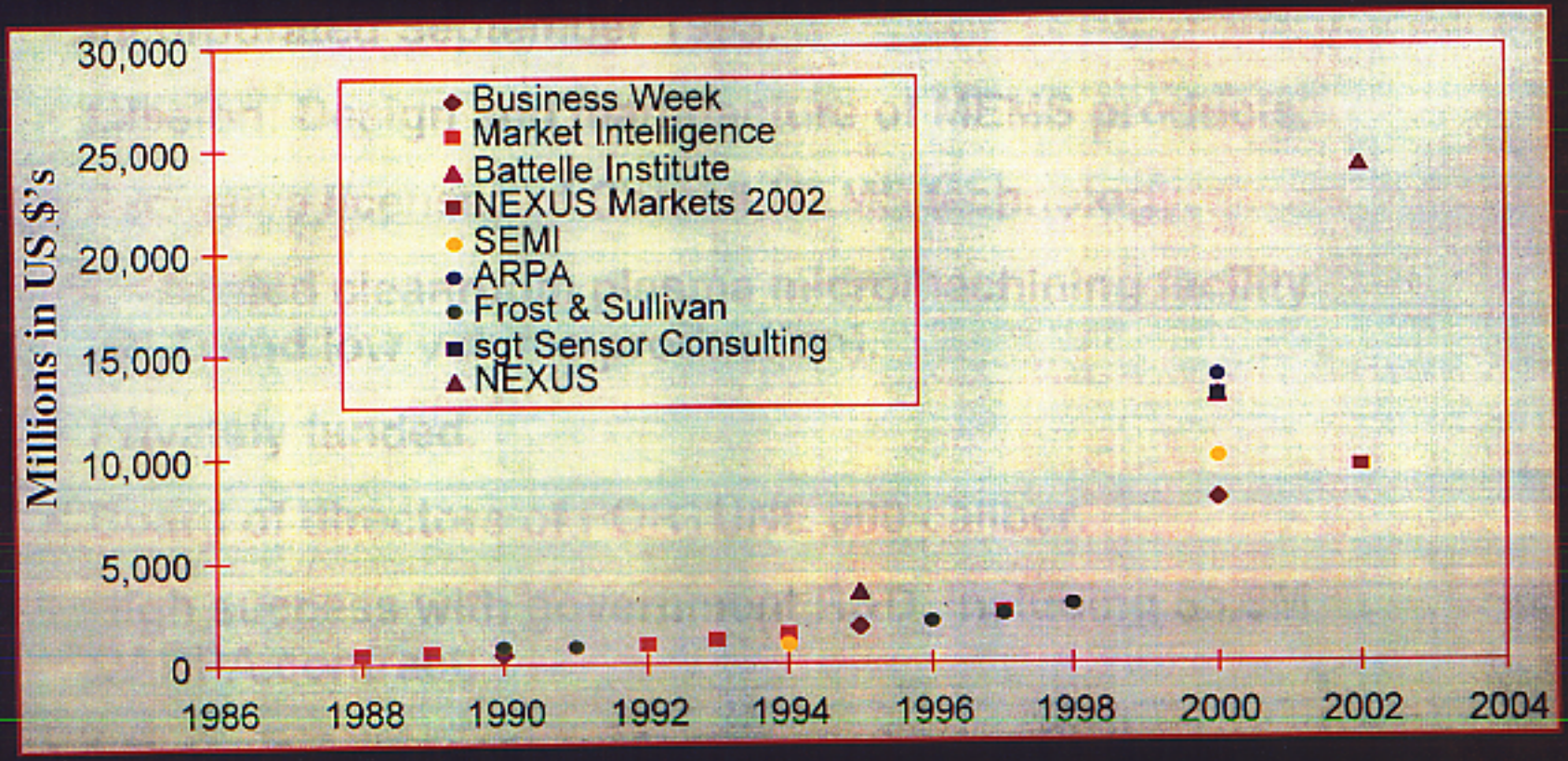
Because of the release step, these devices are capable of motion!

General Attributes of MEMS Devices

- Small and cheap to build
- Fabricated like an IC-can use IC tools
- Technology is easily scalable to large numbers of devices
- Easily integrated with analog and digital circuits
- Robust and long-lived, survive in hostile environments
- Dissipate small amounts of heat, work at low temps
- Extraordinary functionality-micro versions of most macro machines

MEMS will become the "new physics machine shop"

What is the Market for MEMS?



Much of this was forseen by Feynman...

There's Plenty of Room at the Bottom

Richard P. Feynman

1959

I imagine experimental physicists must often look with envy at men like Kamerlingh Onnes, who discovered a field like low temperature, which seems to be bottomless and in which one can go down and down. Such a man is then a leader and has some temporary monopoly in a scientific adventure. Percy Bridgman, in designing a way to obtain higher pressures, opened up another new field and was able to move into it and to lead us all along. The

dots on the fine half-tone reproductions in the Encyclopaedia. This, when you demagnify it by 25 000 times, is still 80 angstroms in diameter—32 atoms across, in an ordinary metal. In other words, one of those dots still would contain in its area 1000 atoms. So, each dot can easily be adjusted in size as required by the photoengraving, and there is no question that there is enough room on the head of a pin to put all of the Encyclopaedia Britannica

Infinitesimal Machinery

Richard Feynman

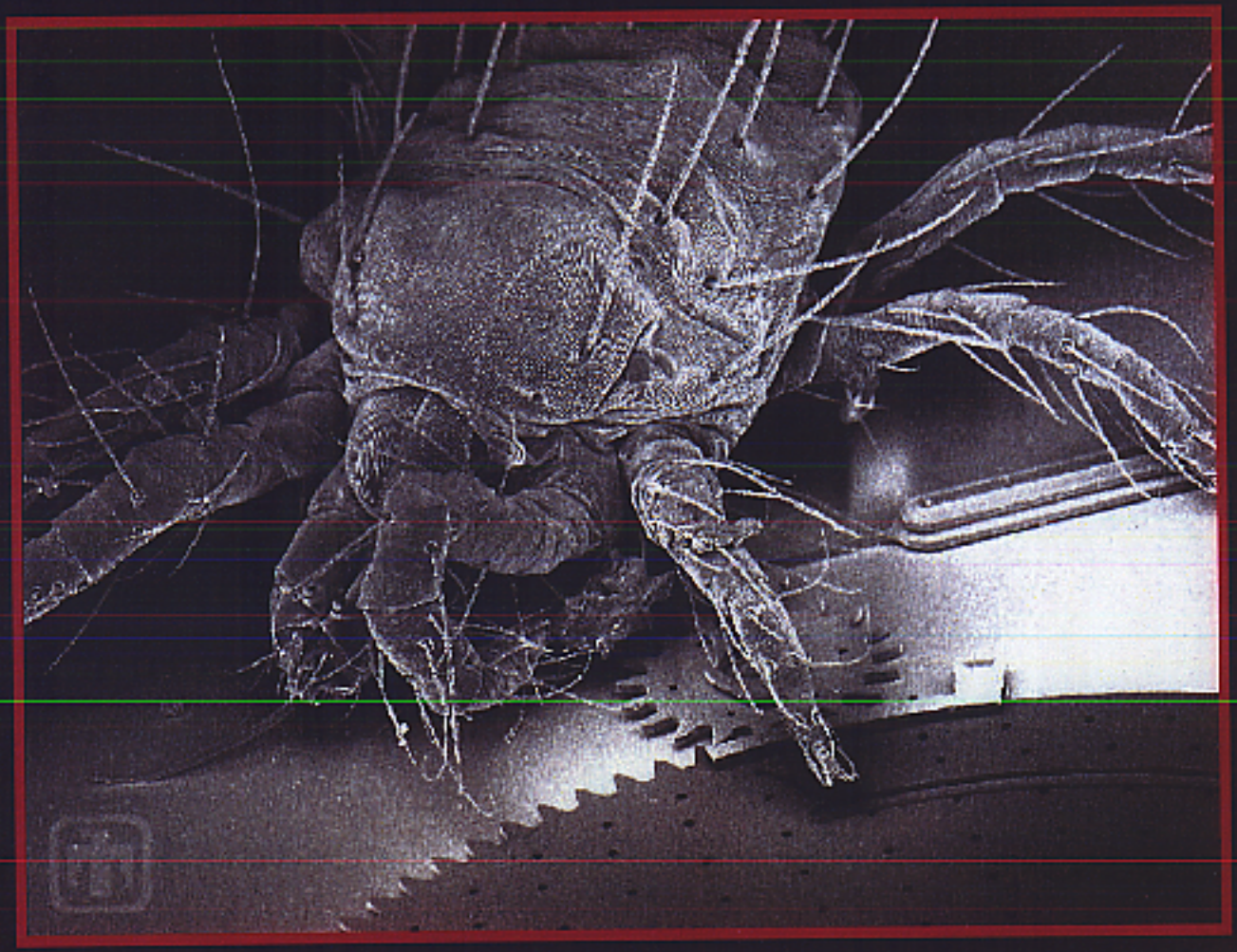
1983

Editor's Preface--This speech, delivered in 1983, is a sequel to the famous 1960 speech "There's Plenty of Room at the Bottom" (reprinted in J. Microelectromechanical Systems, *vol. 1, no. 1, pp. 60-66, 1992). It is remarkable in many ways. Feynman anticipates the sacrificial-layer method of making silicon micromotors, the use*

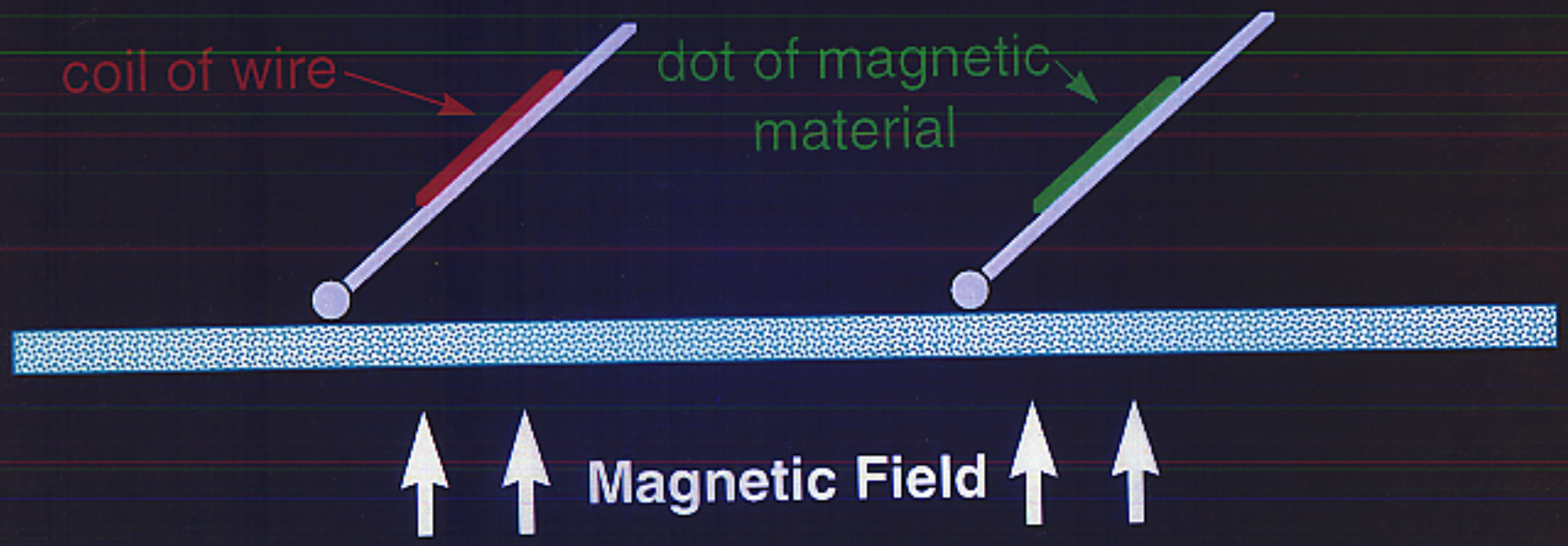
particularly those of South America and recently those of the South Pacific. At Caltech, he learned to decode Mayan hieroglyphs and took up art, becoming quite an accomplished draftsman—specializing in nude women. And he also does jogging.

Richard received the Nobel prize, but I believe it was for physics

Bug Bites Gear....

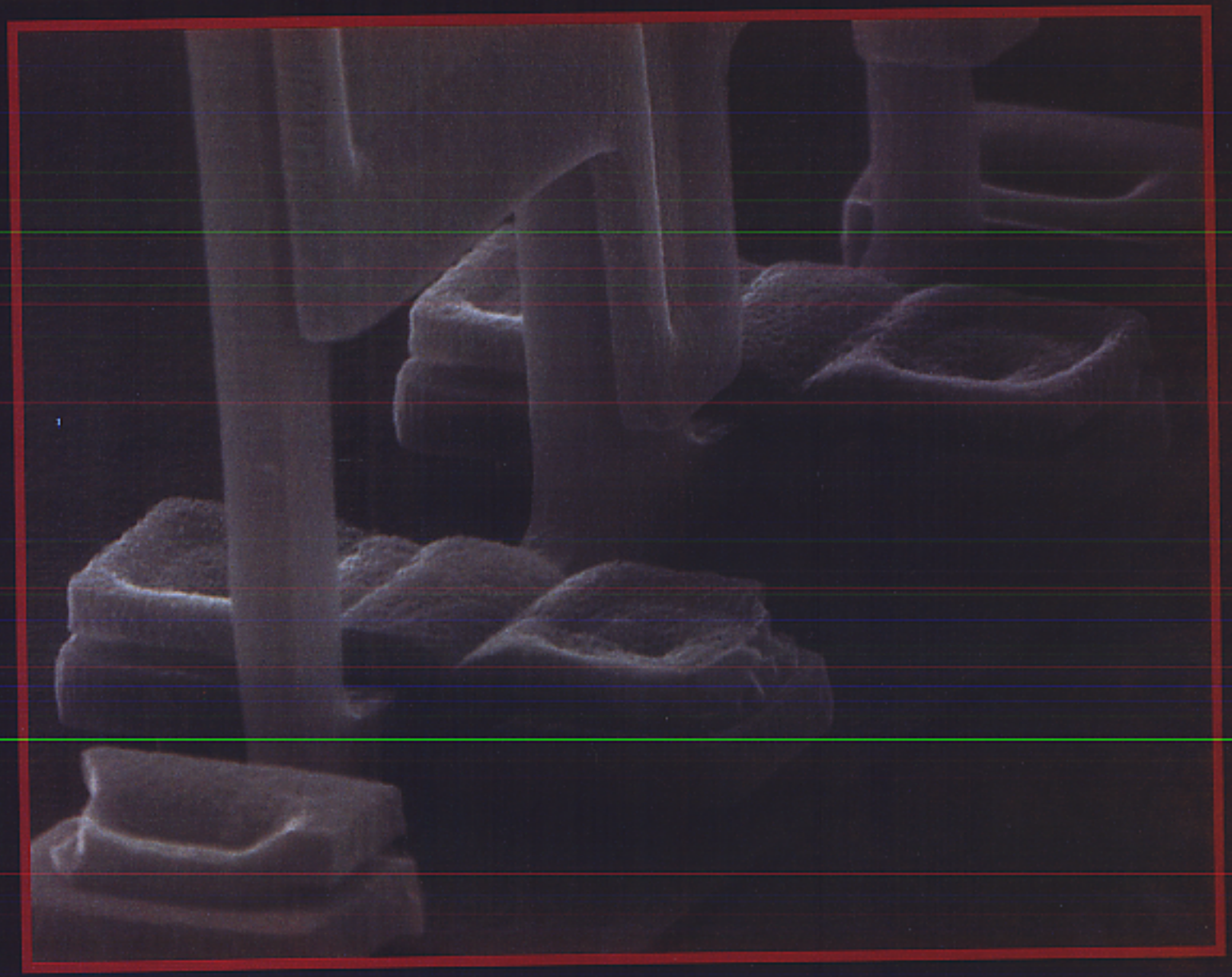


Can These Devices Self-Assemble?

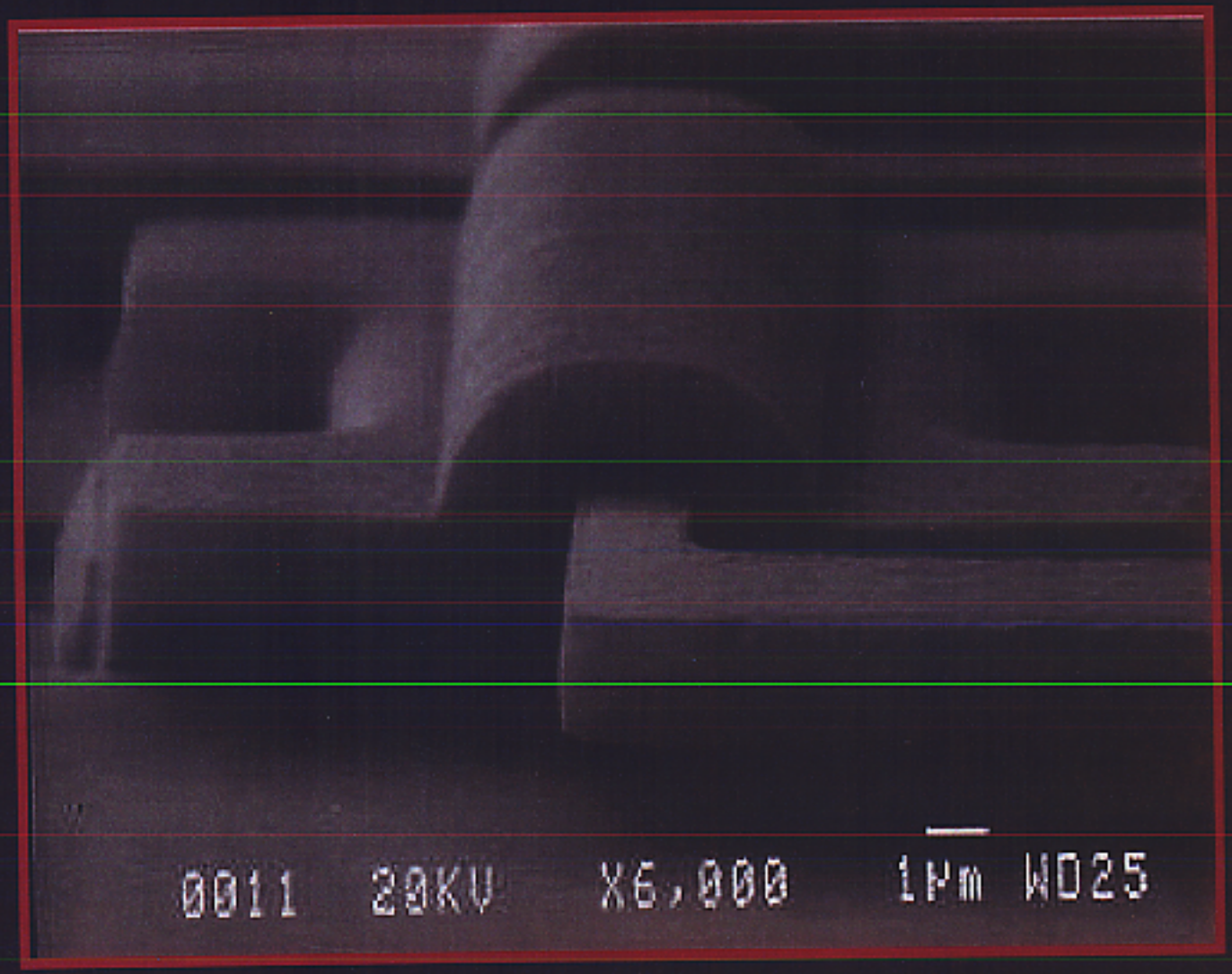


Can We Build Devices at the Wafer Scale?

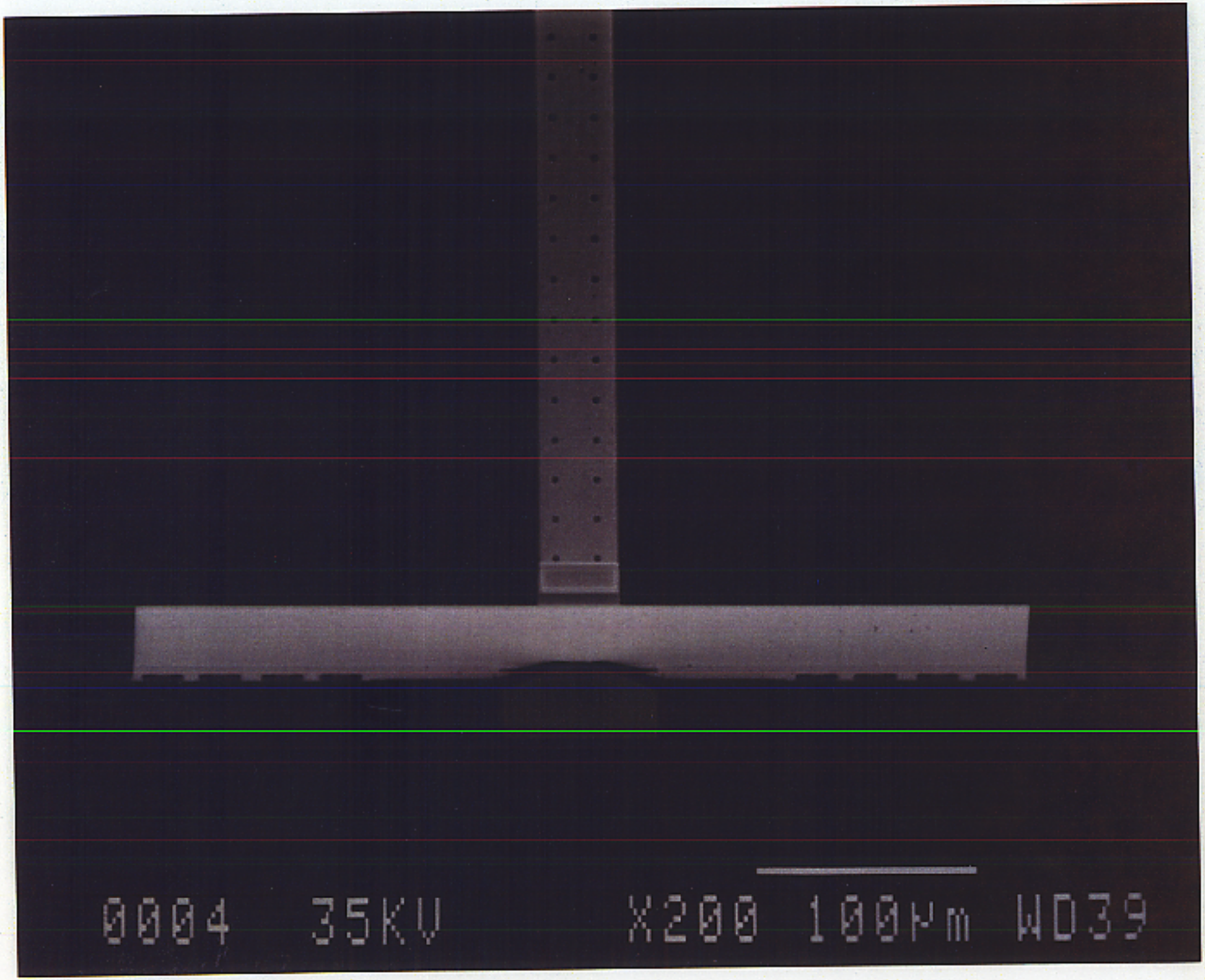
Close-up of Self-Assembling Hinge and Plate



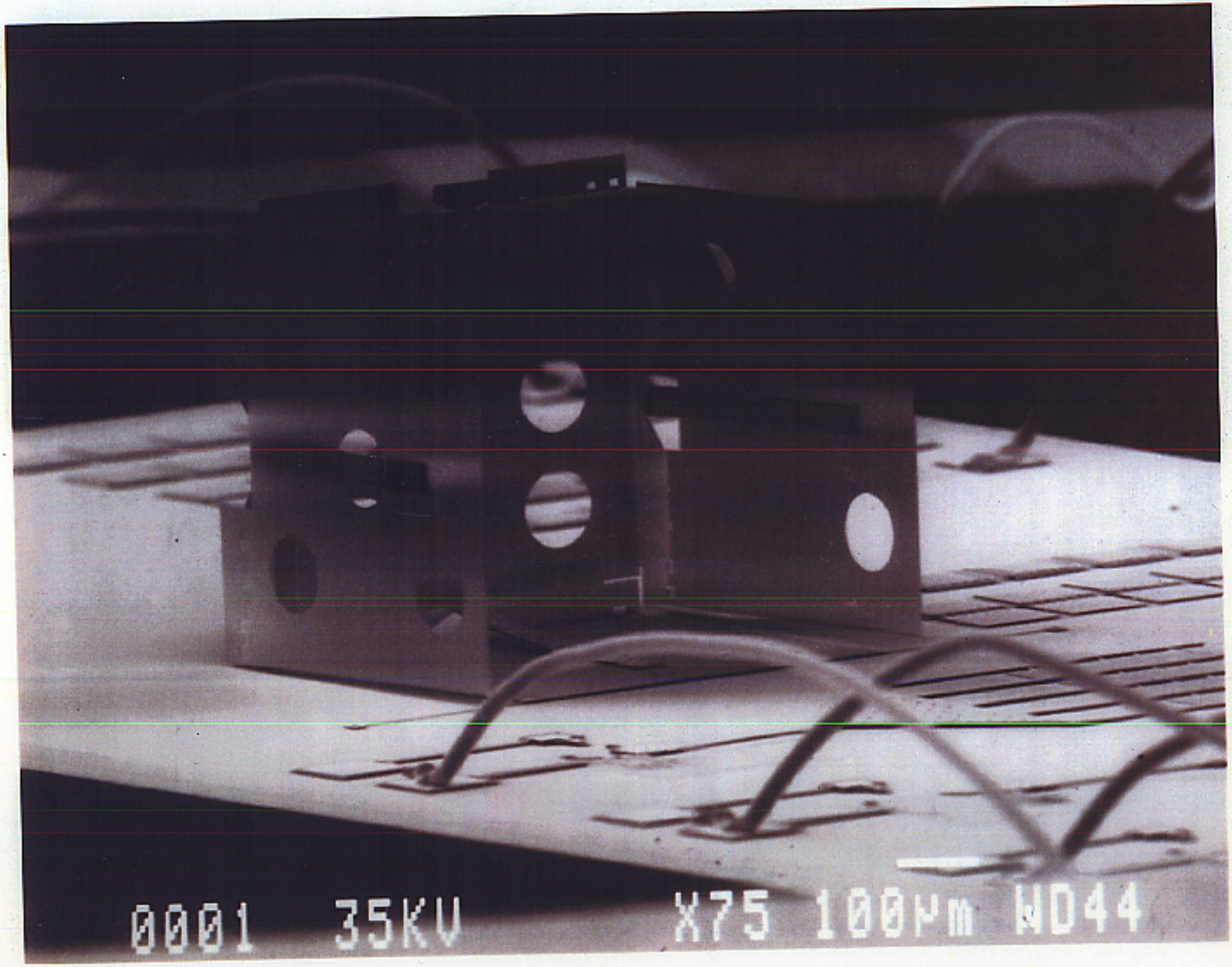
Microscopic Hinge



0002 35KV X650 10µm WD48


0004 35KV X200 100μm WD39

X1190 0061
WMOOM 1000M WO45
MXSE 3SXU
00001 10000


0001 35KV X75 100µm WD44

MicroMechanic at Work

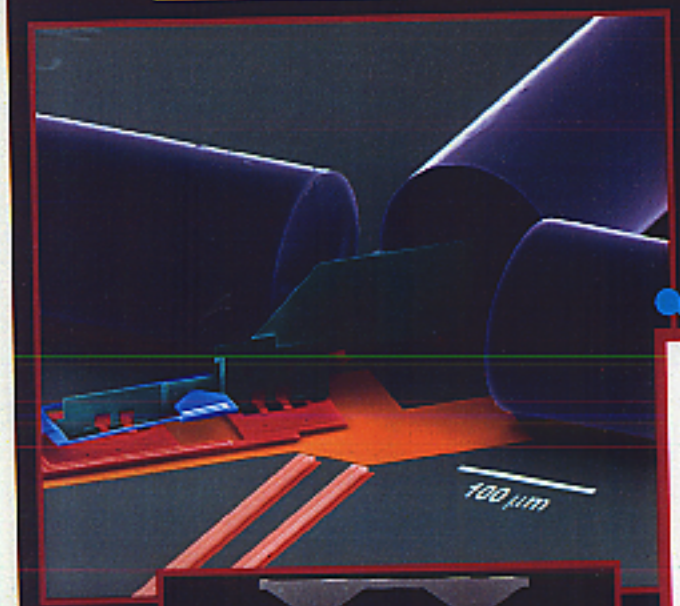
What are some Representative Technological Applications?

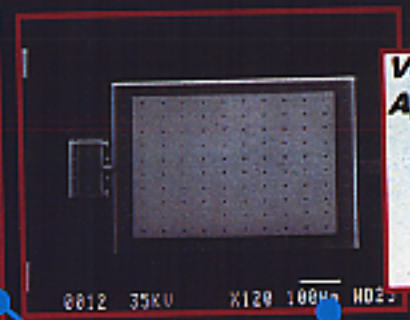
- Lightwave Systems:
  variable attenuators, switches, beam steering micromirrors, smart packages…..

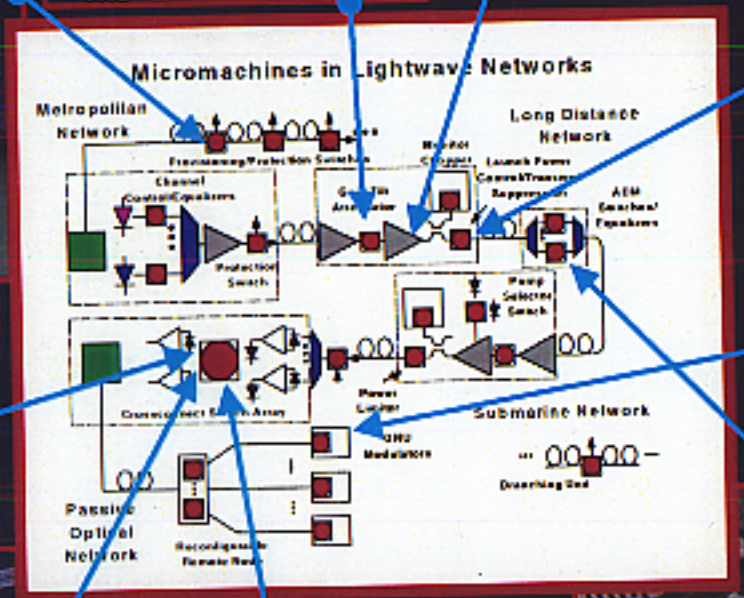
- Acoustics:
  micro-microphones, directional arrays, velocity microphones, inertial sensors for correction signals…

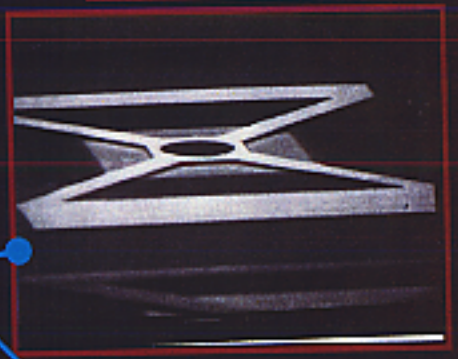
- Microwave Devices:
  varactors, inductors, transformers, relays, tank circuits, microwave switches, filters….

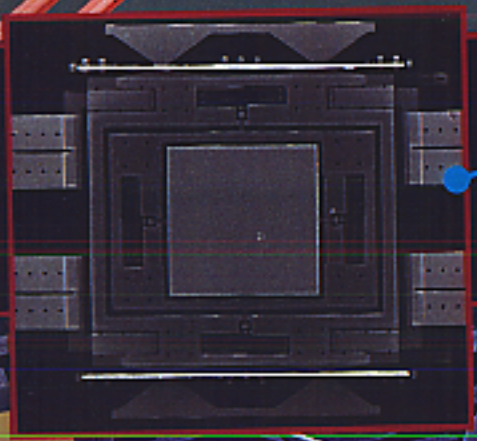
What Does Lucent's Effort in Optical MEMS Look Like?

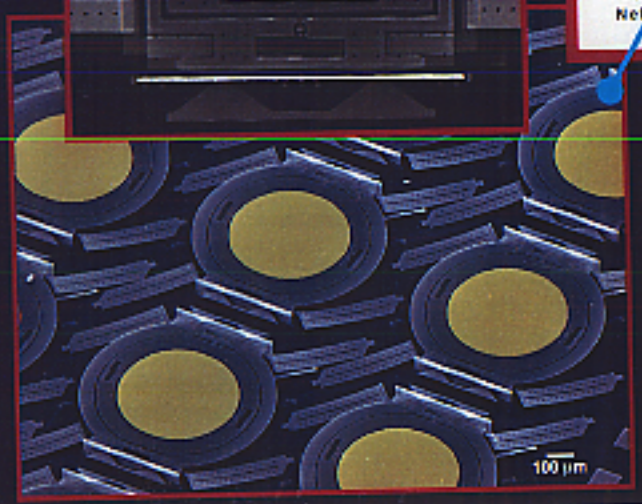


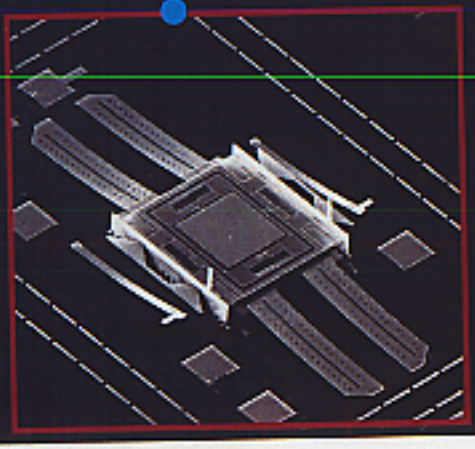


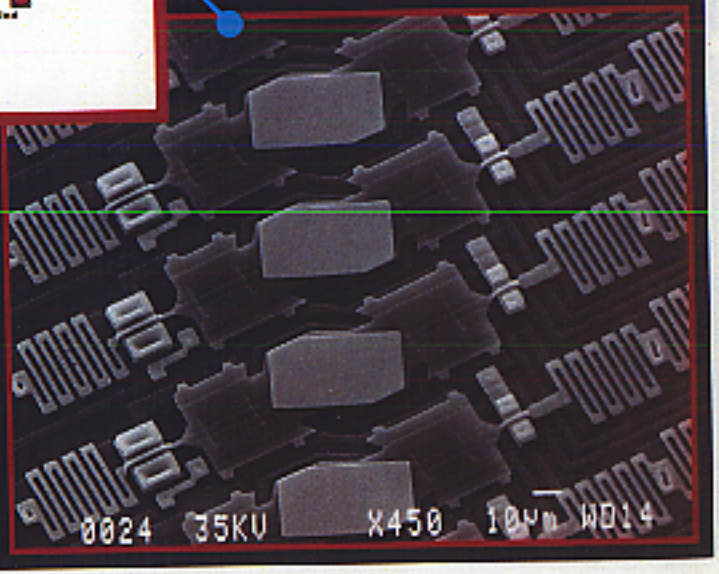




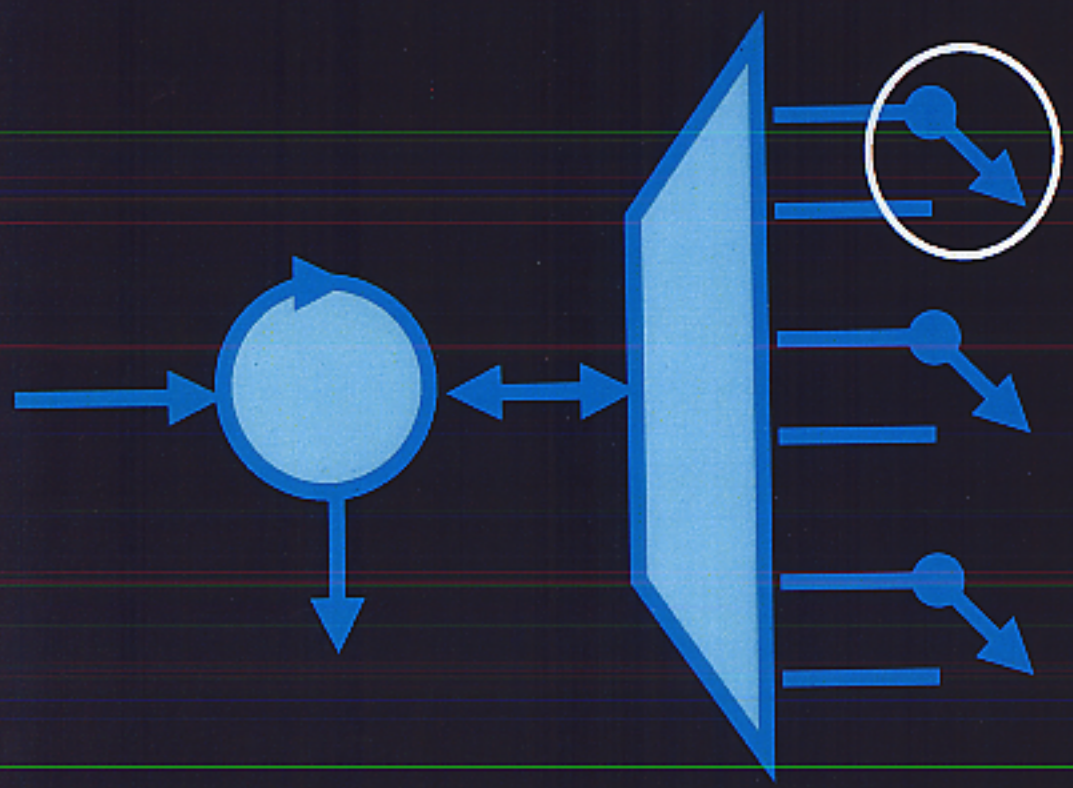








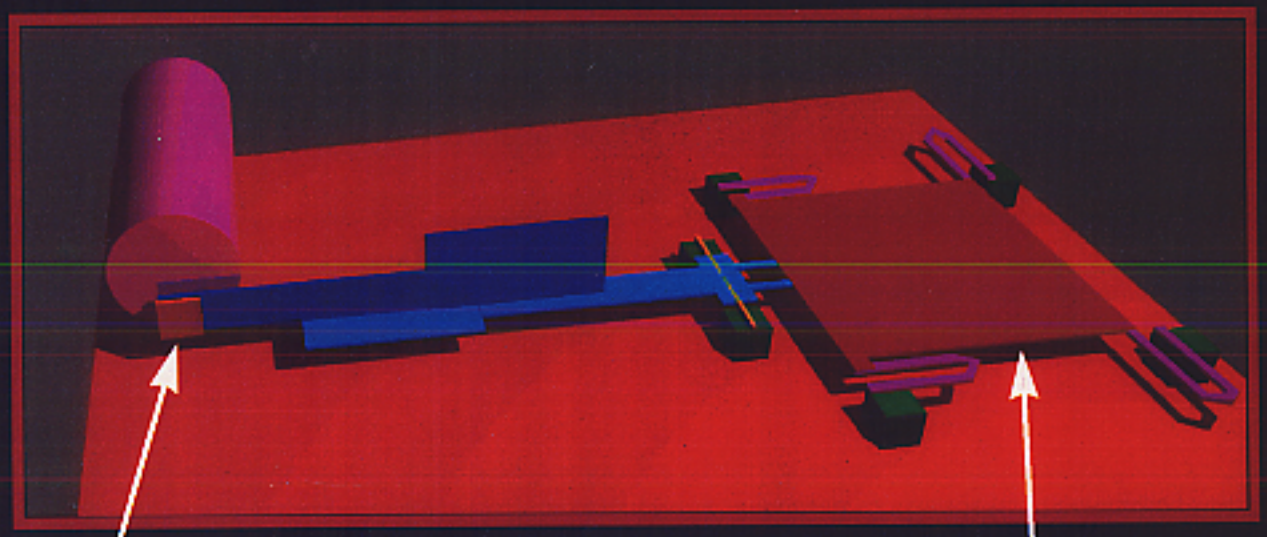
What are the Necessary Attributes of an Optical Switch?



- Low Insertion Loss
- High Contrast Ratio
- Low Cost
- Small Size
- Moderate Speed
- No PDL
- Flat Spectral Response
- Reliable
- Low Electrical Power
- Can be Scaled

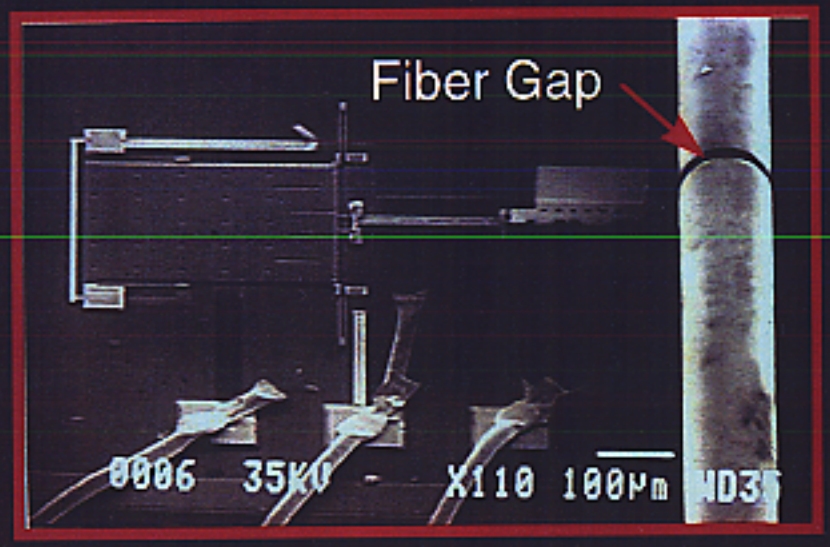
MEMS-Based Switches are an Ideal Choice!

Electrostatically Actuated Silicon Optical Shutter



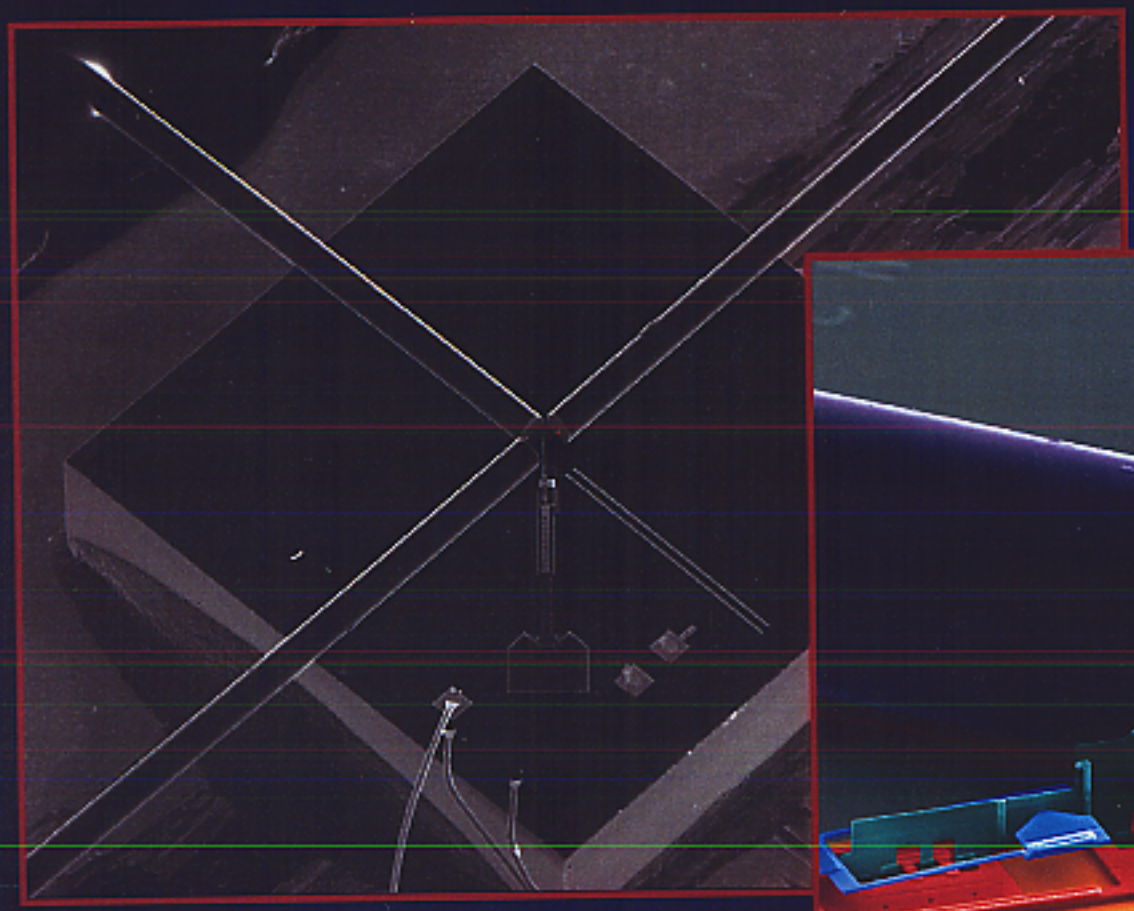
Gold Reflector Blocks Optical Path

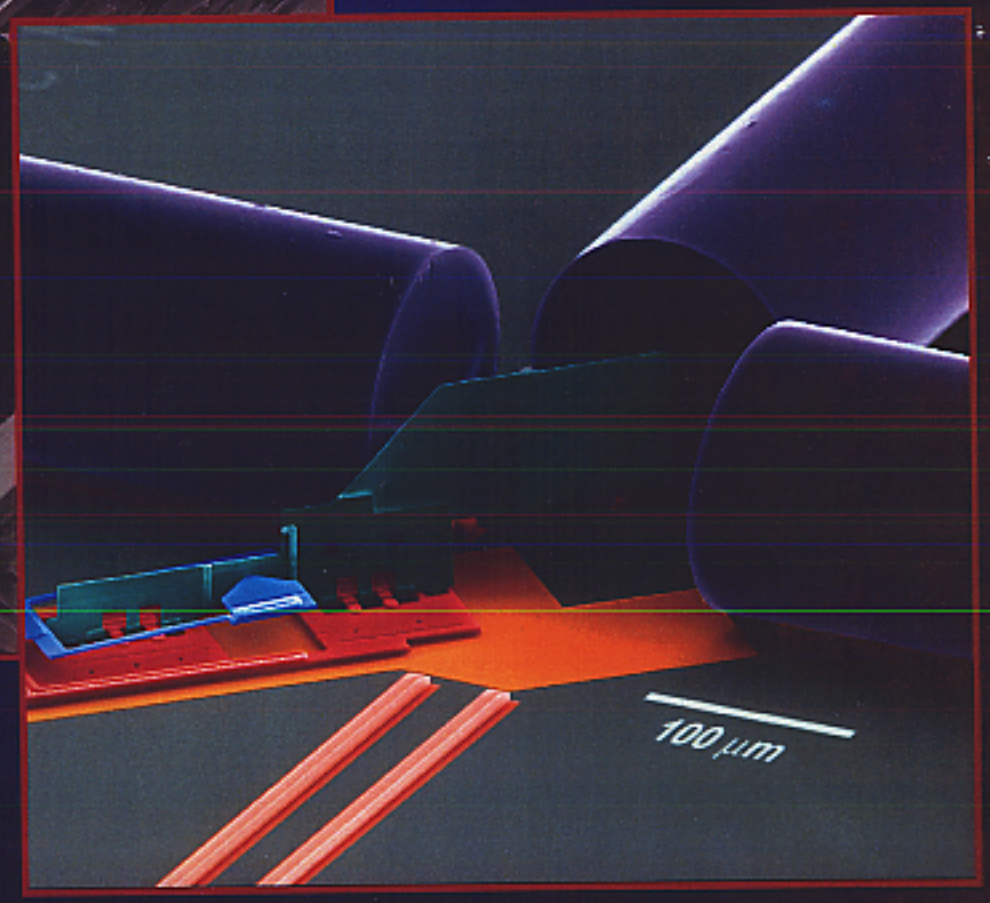
Spring-suspended capacitor plate



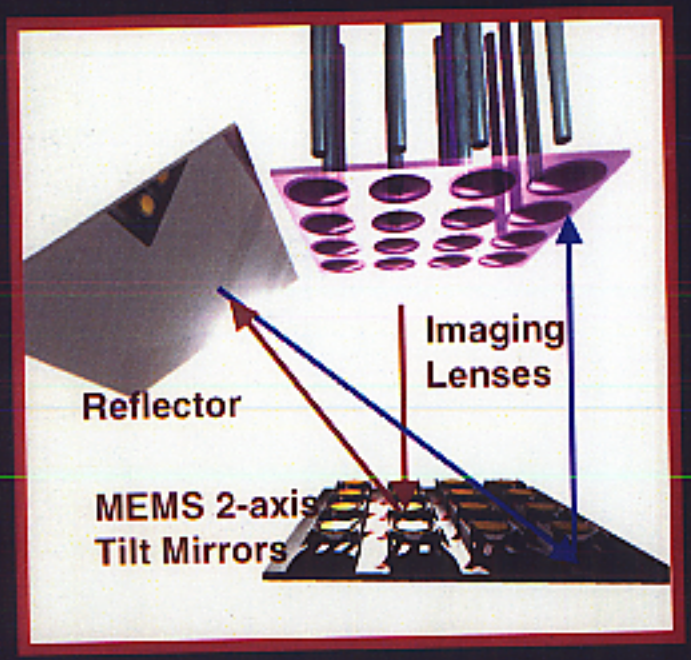
- 20µm fiber gap
- 0.5dB insertion loss
- ceramic dip package
- fiber connectorized
- <100 µsec switching time
- 1-20 volt operation
- low electrical power dissipation

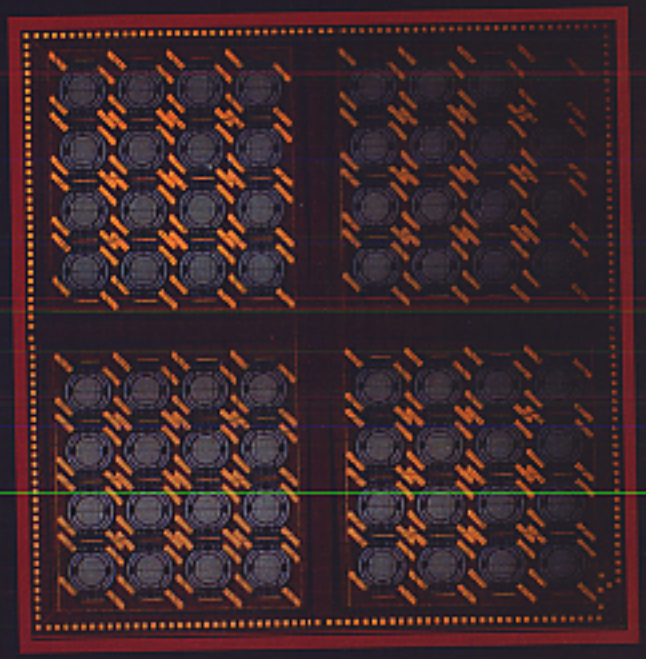
Lucent MEMS 1X2 Optical Switch



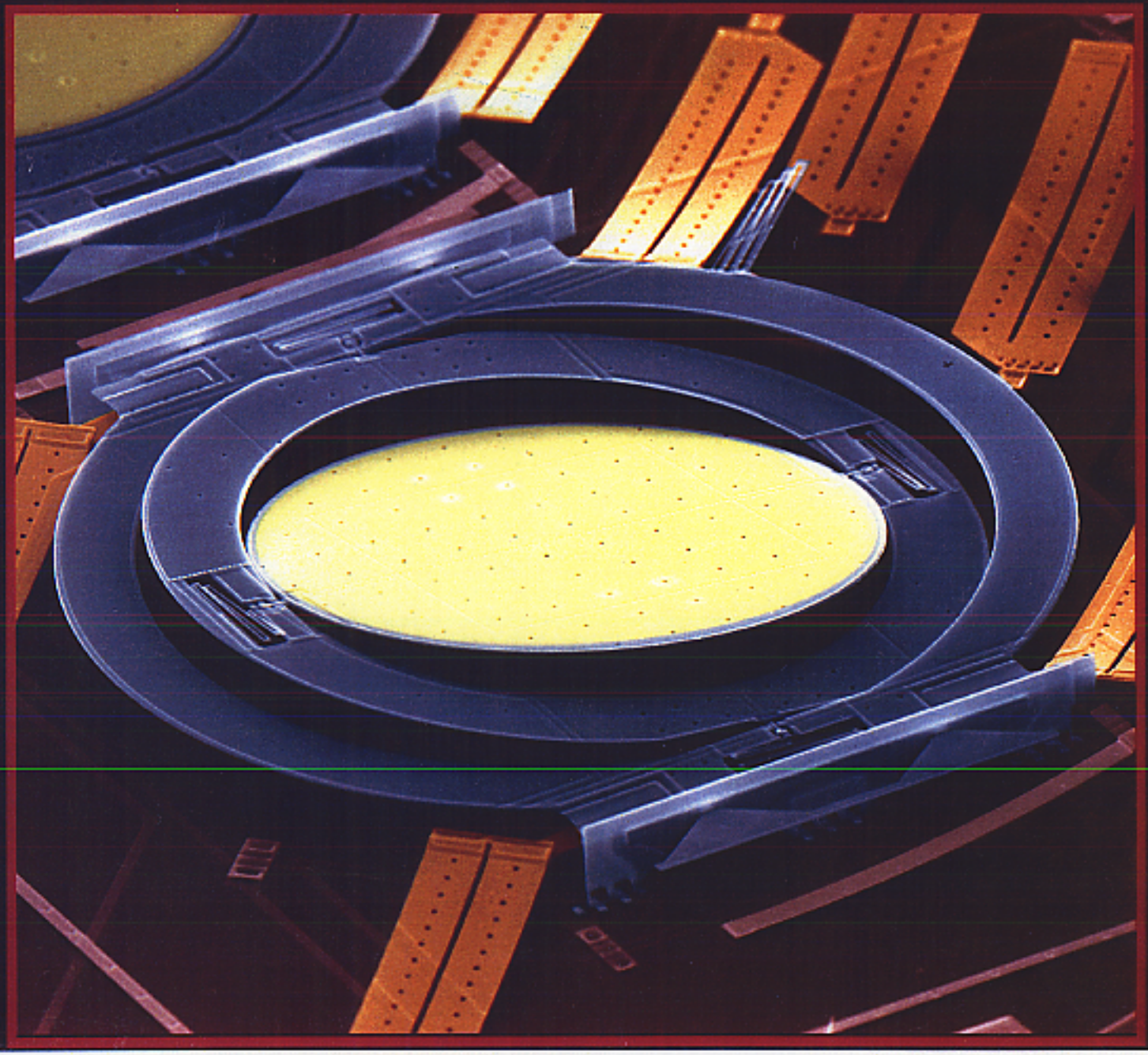


A Large MEMS Optical Crossconnect

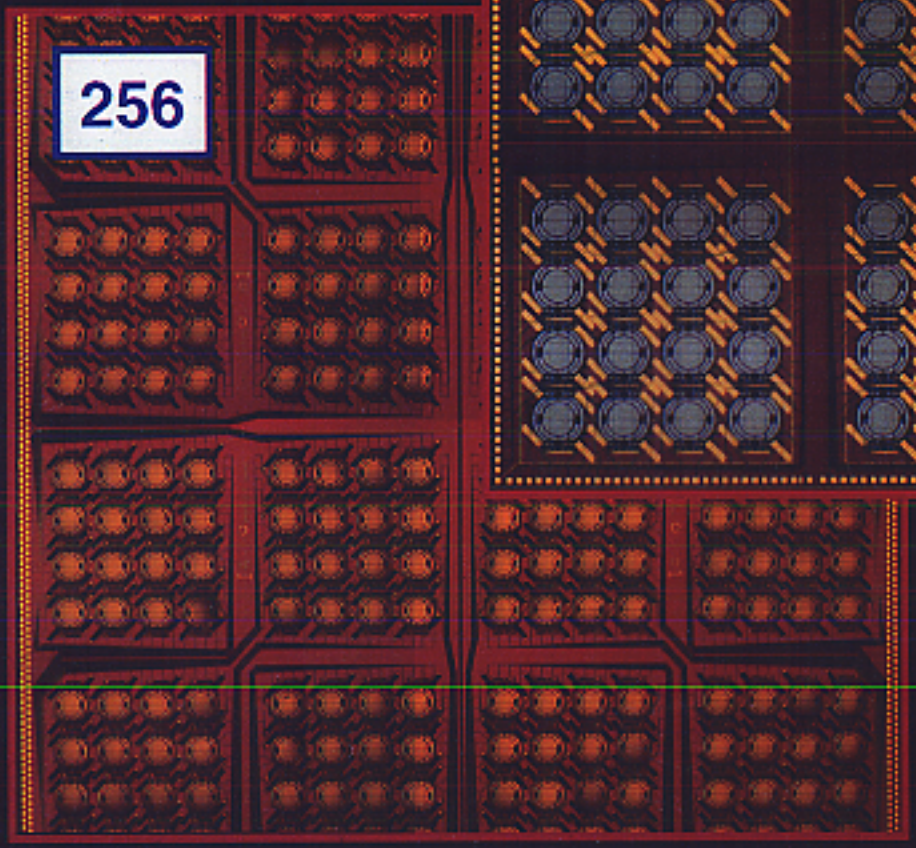


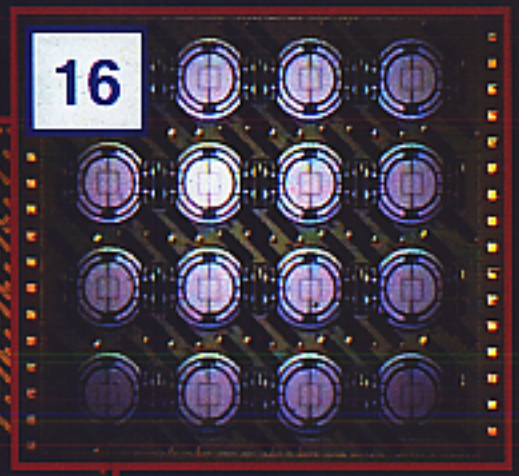


Lucent MEMS Optical CrossConnect Mirror-MicroStar™

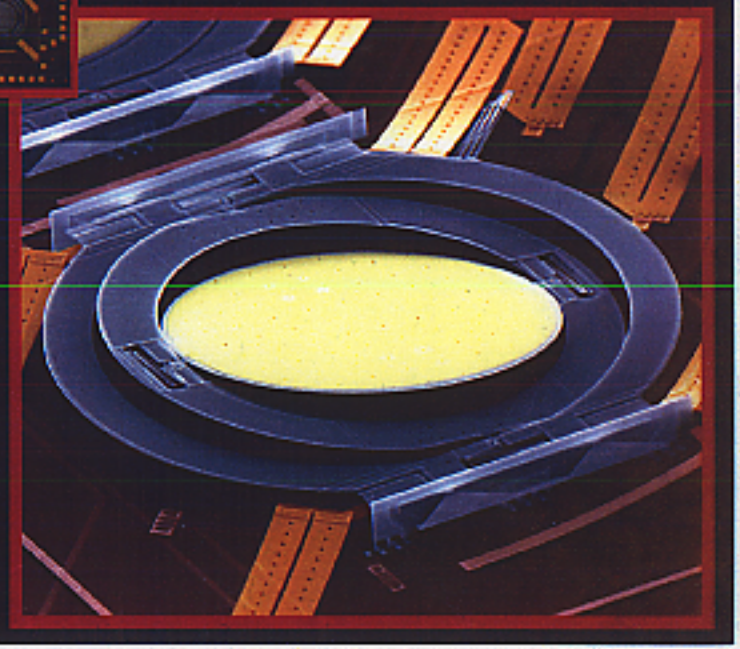


Lucent Micromirror Arrays

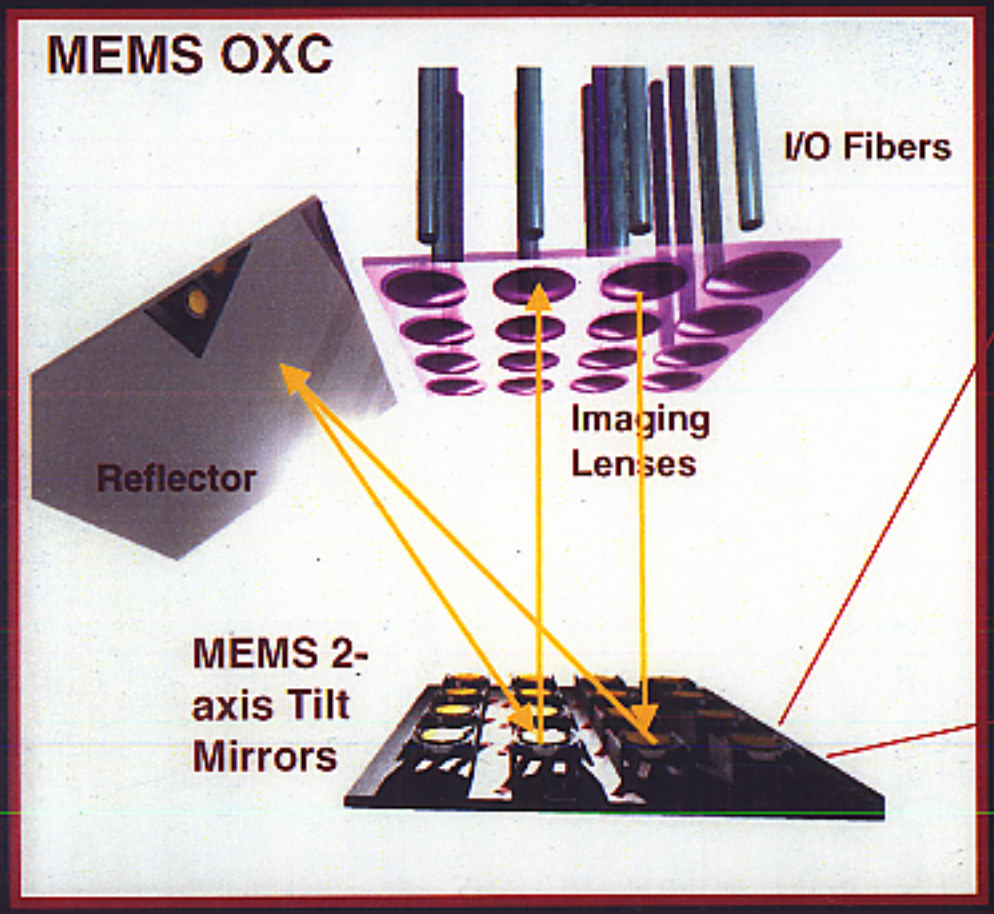




MicroStar Mirror



Lucent MEMS OXC



MEMS DEVICE:

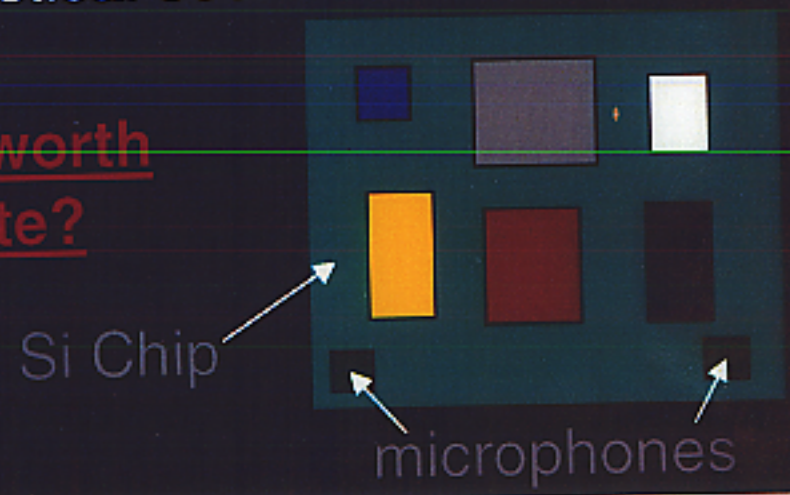
- 2-axis, angular range of > ±6°
- continuous, controlled tilt
- directly scalable to 256 mirrors (1024 in the long term)
- simple technology for rapid development / prototyping
- manufacturable

LambdaRouter MEMS All-Optical Crossconnect

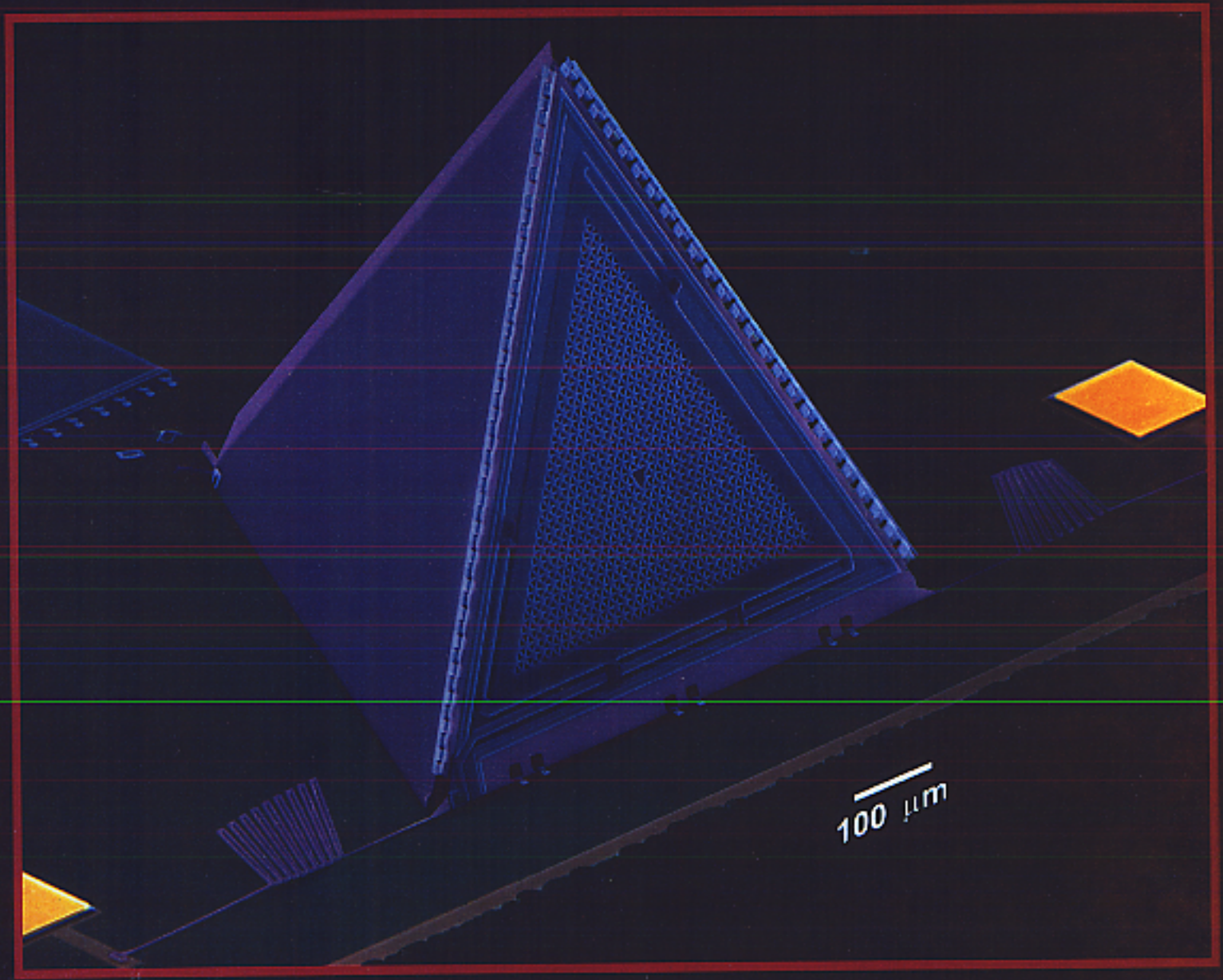
What Drives the Interest in a MEMS Microphone?

- As chips get bigger, there is more real estate for µphones
  - -Radio on a chip!
- Lithography allows µphones to be well matched
- Mixed signal chips put analog circuits close to µphones for high performance
- There is a strong desire for more functionality such as directional arrays for acoustical sound location

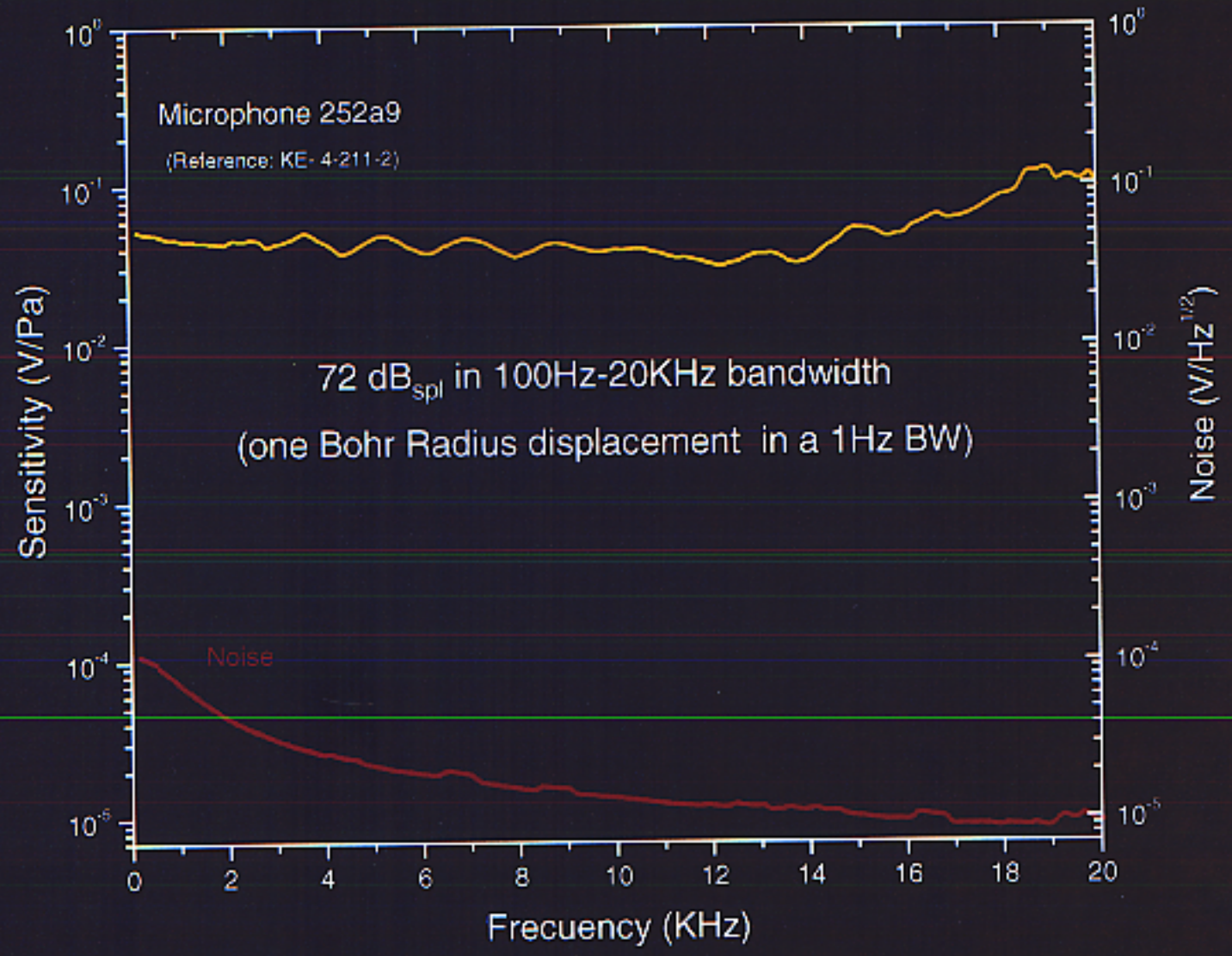
Will the functionality be worth the cost in Si real estate?

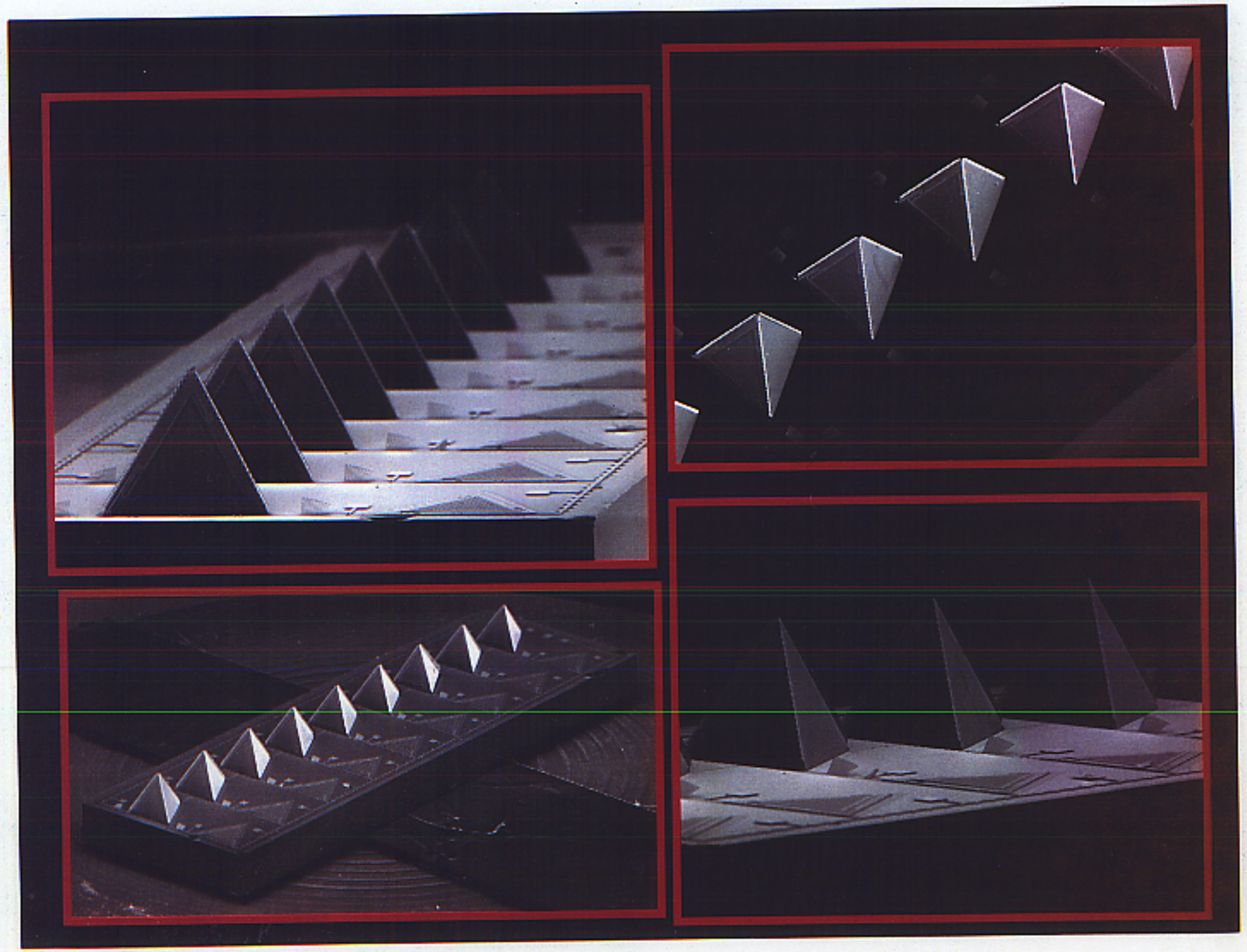


First Surface-Micromachined Si Microphone



Frequency Response



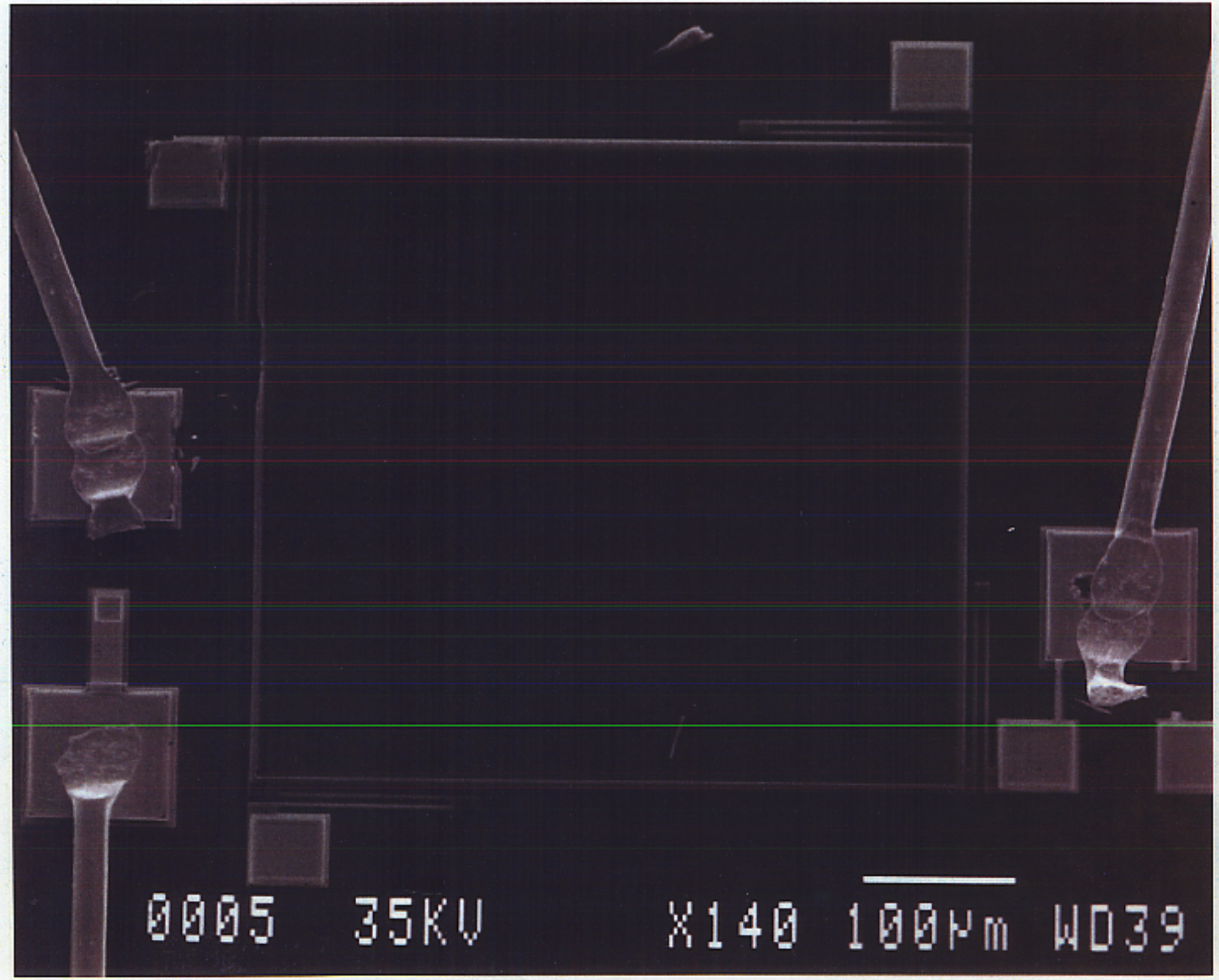


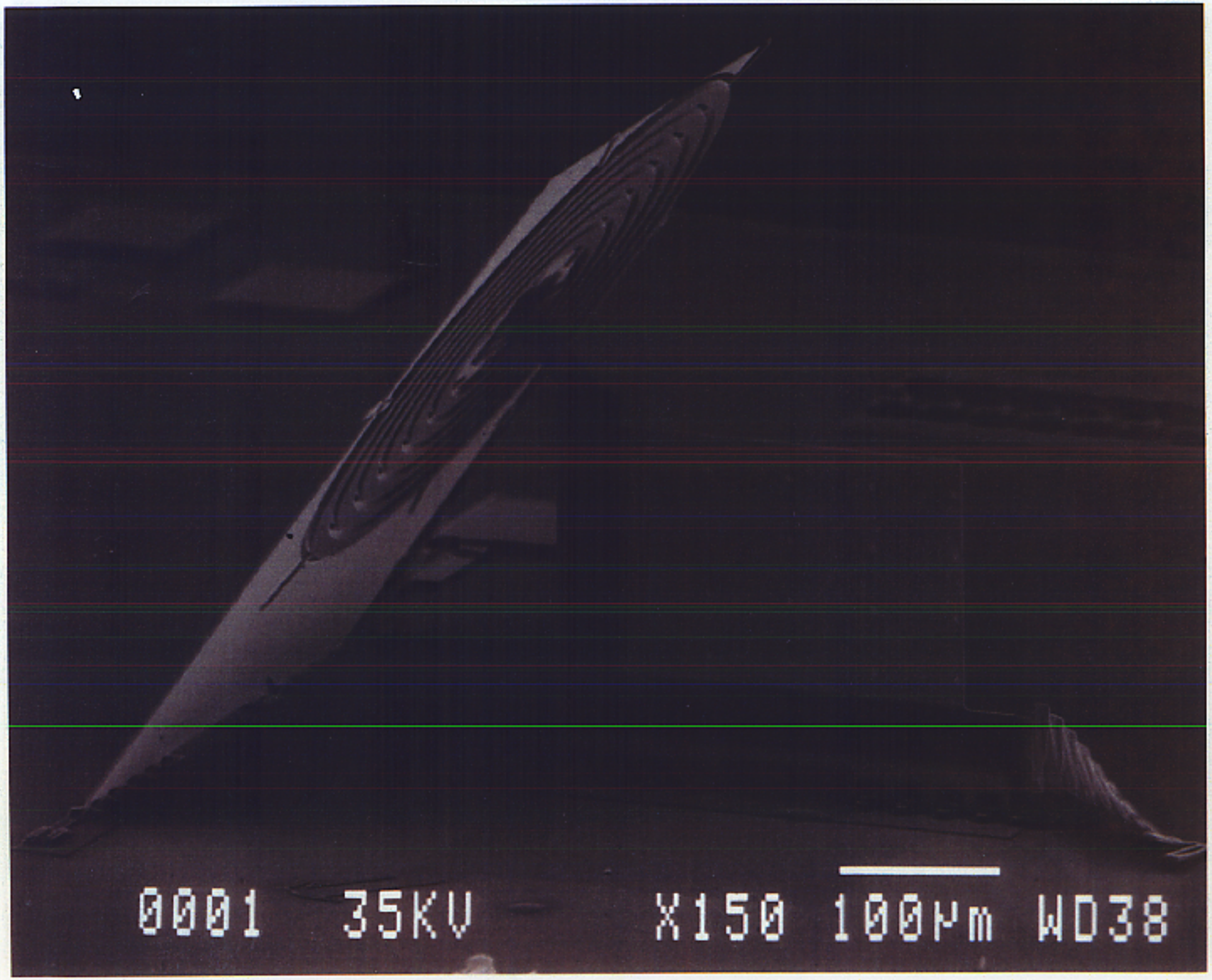
How will MEMS Impact Microwave Devices?

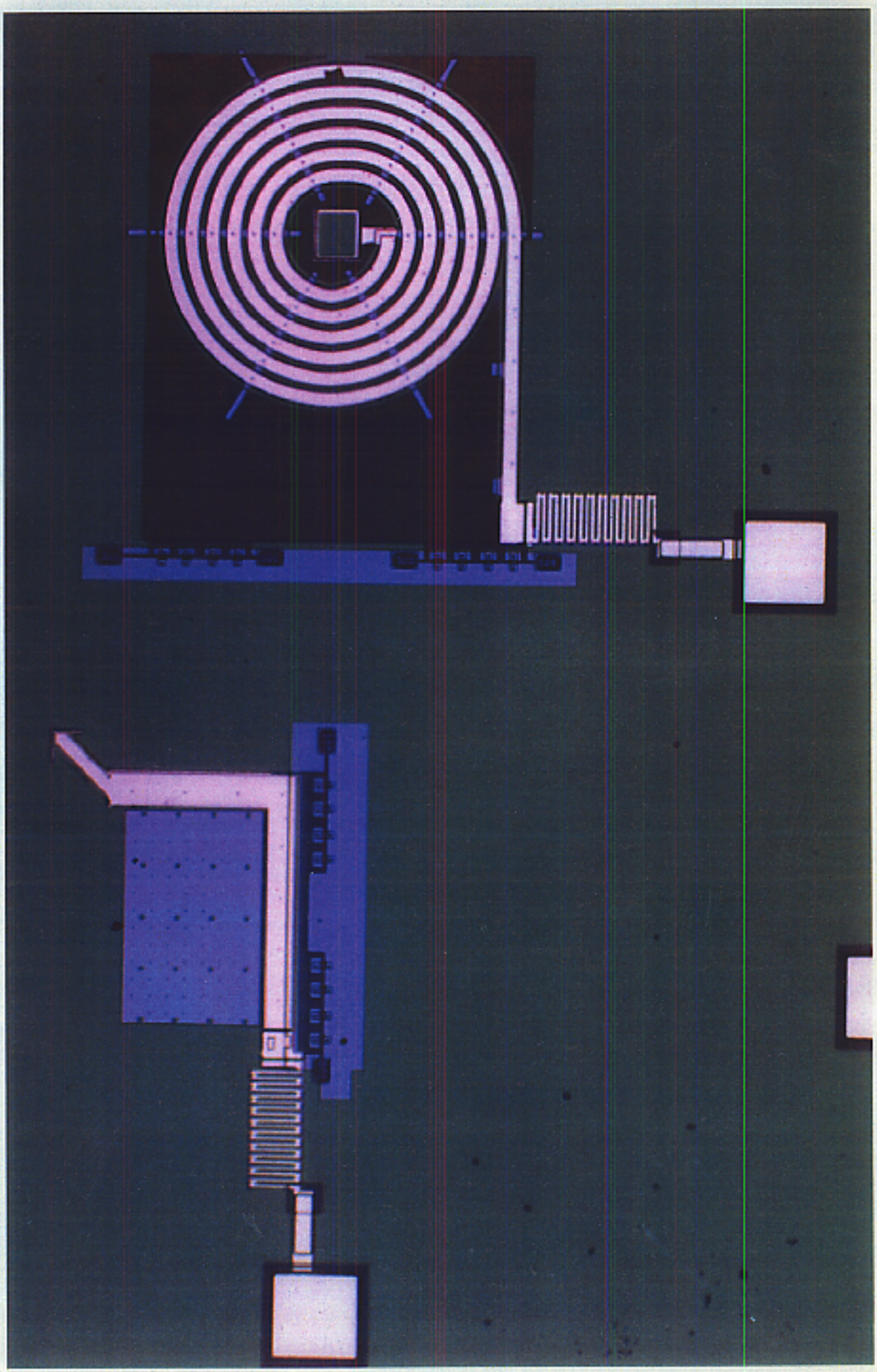
- The desire for a "Radio on a Chip" means one needs integrated devices such as switches for transmit/receive, varactors, inductors, transformers, tank circuits, filters….

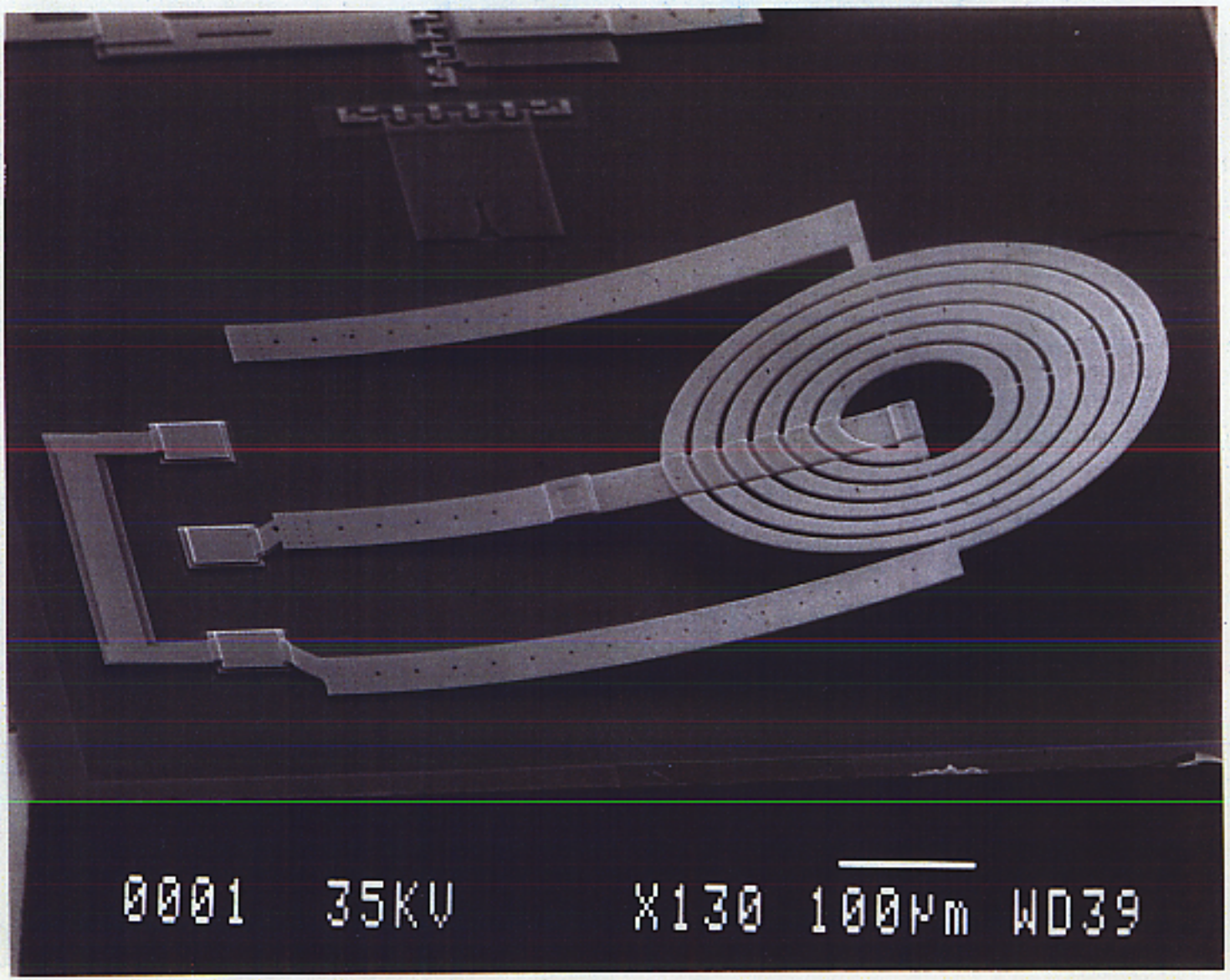
- In general, these devices need to be integrated with the electronic circuits, small, cheap, fast, compatible with the other IC processing….

MEMS is the perfect choice for this application.


0005 35KV X140 100μm WD39

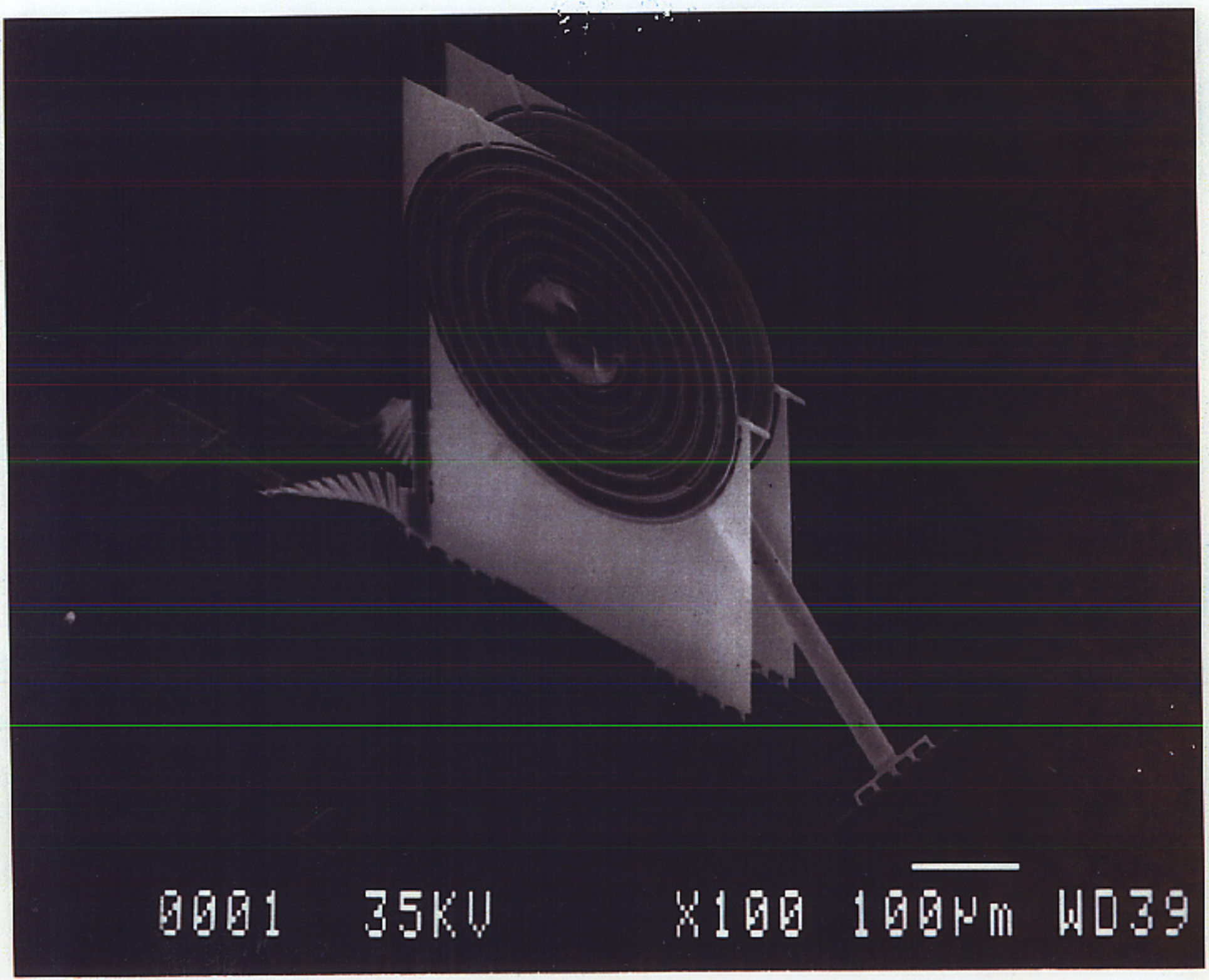

0001 35KV X150 100μm WD38





Lucent Technologies Proprietary
Use Pursuant to Company Instructions

Lucent Technologies
Bell Labs Innovation

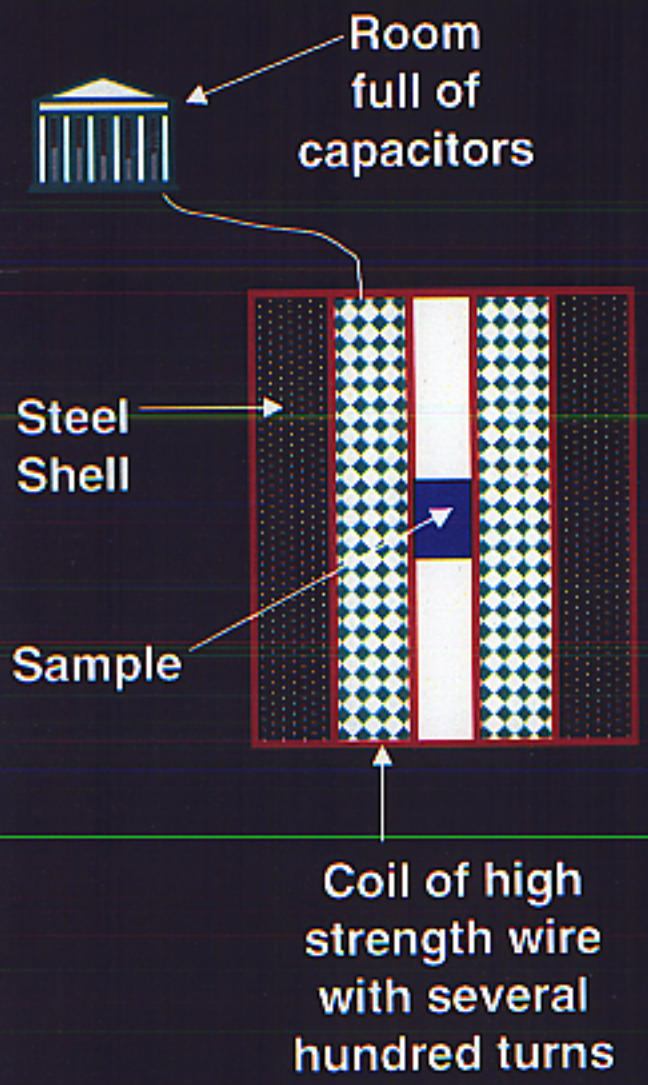

0001 35KV X100 100μm WD39

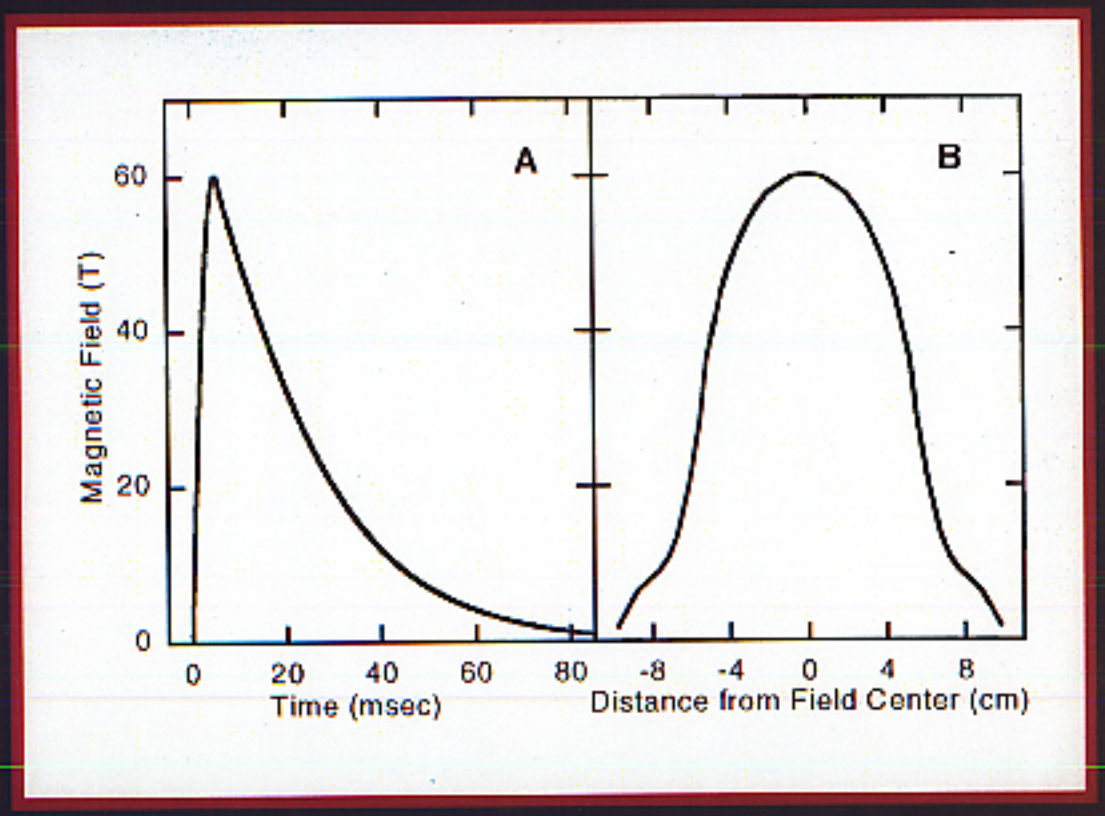
WD34
100µm
X50
35KV
0008

What are some Representative Scientific Applications?

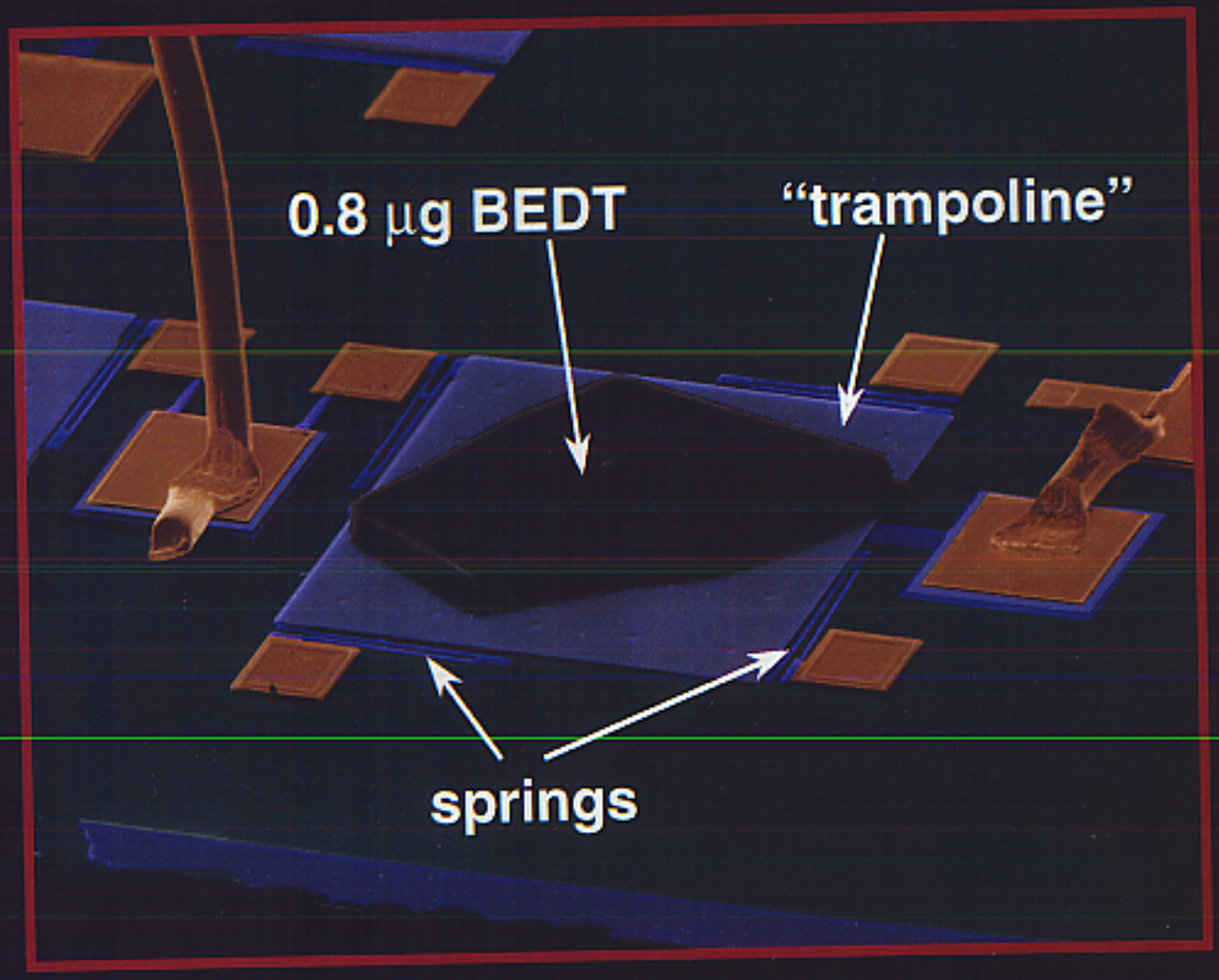
- Magnetometers for use in harsh environments
- Near-Field Scanning Optical Microscopes (NSOMs)
- Superconducting vortices and the observation of mesoscopic vortex physics
- Adaptive optics for astronomy
- Observation of the Casimir force

How to Build a 70T Pulsed Magnet

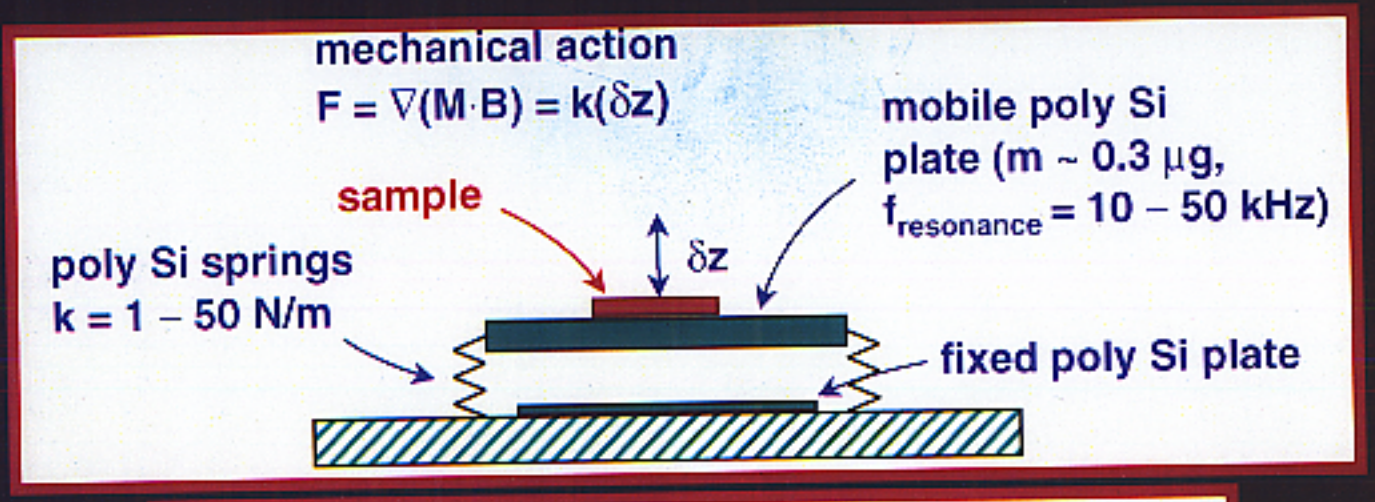


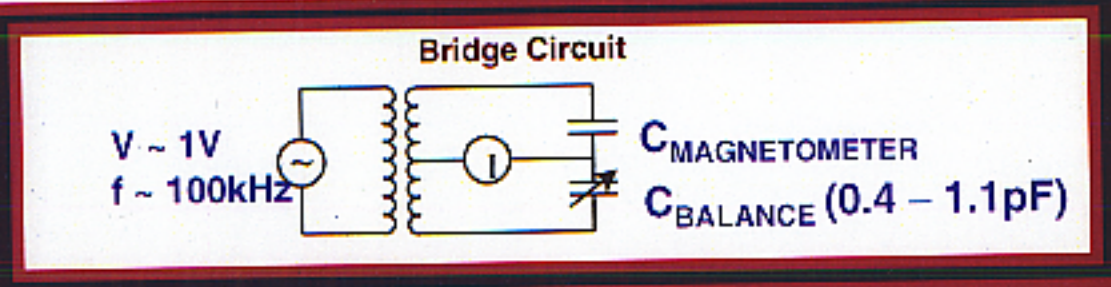


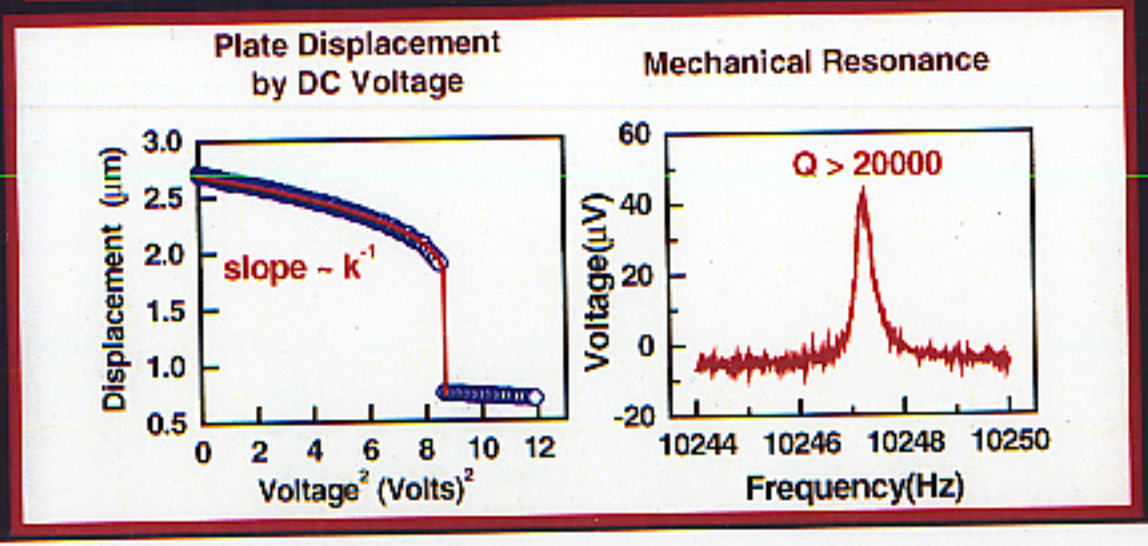
High Speed, High Sensitivity Magnetometer for use in 70T Pulsed Fields



How is the Magnetometer Operated?





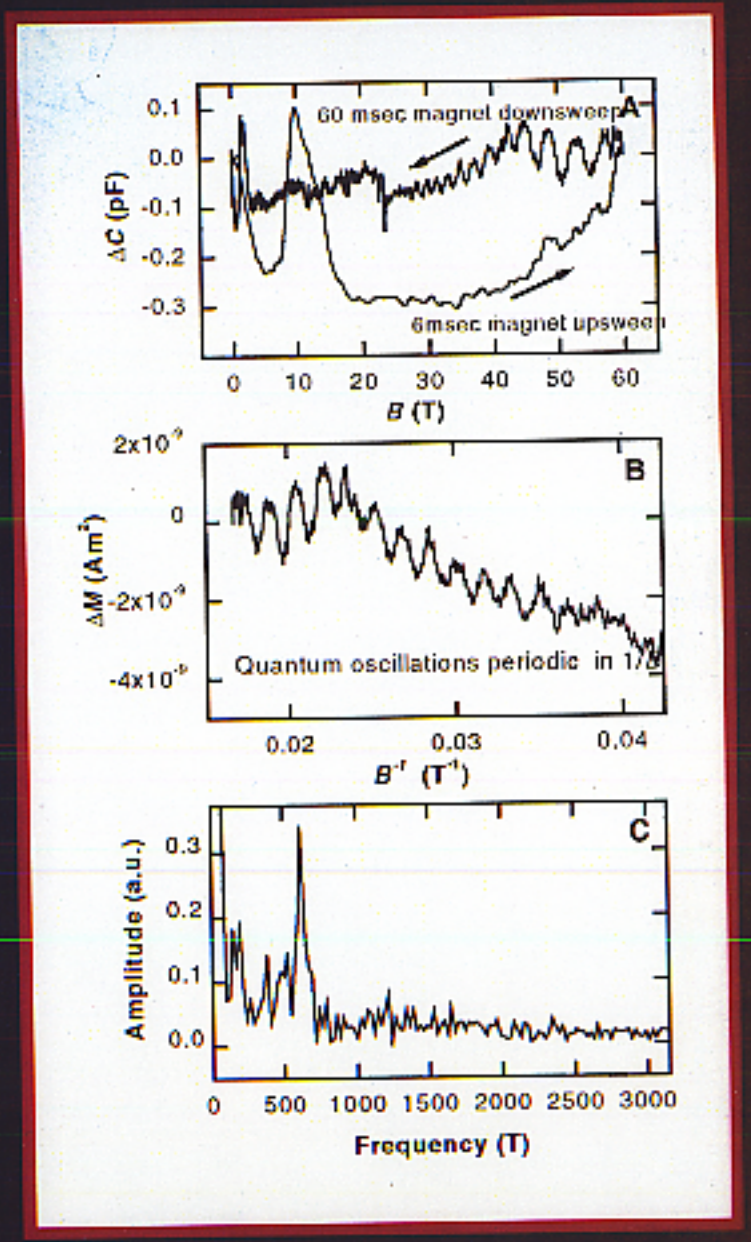


BEDT Magnetization Data in the 70T Pulsed Magnet

Capacitance *vs* Field

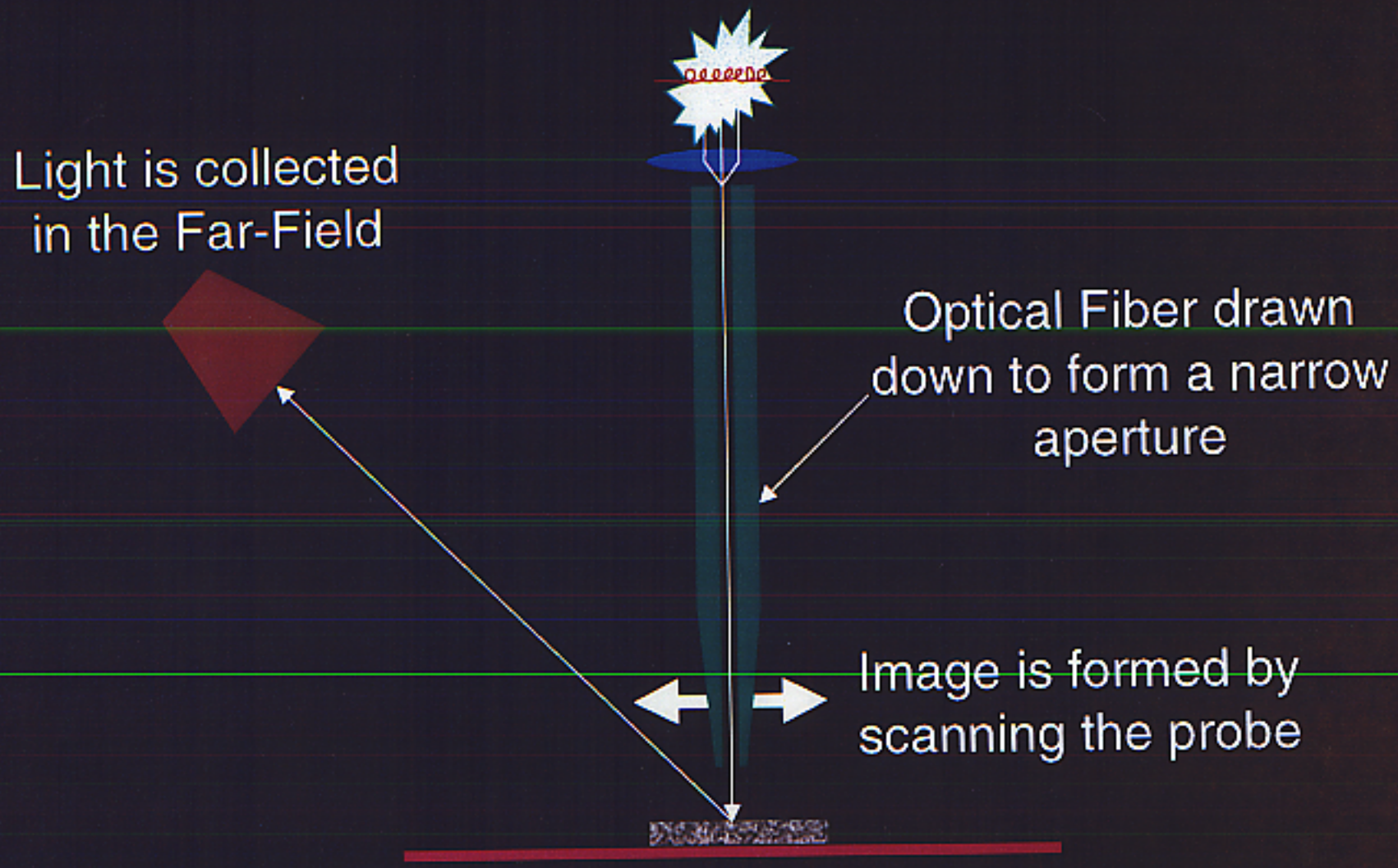
Magnetization *vs* 1/Field

Fourier Transform of M vs 1/Field

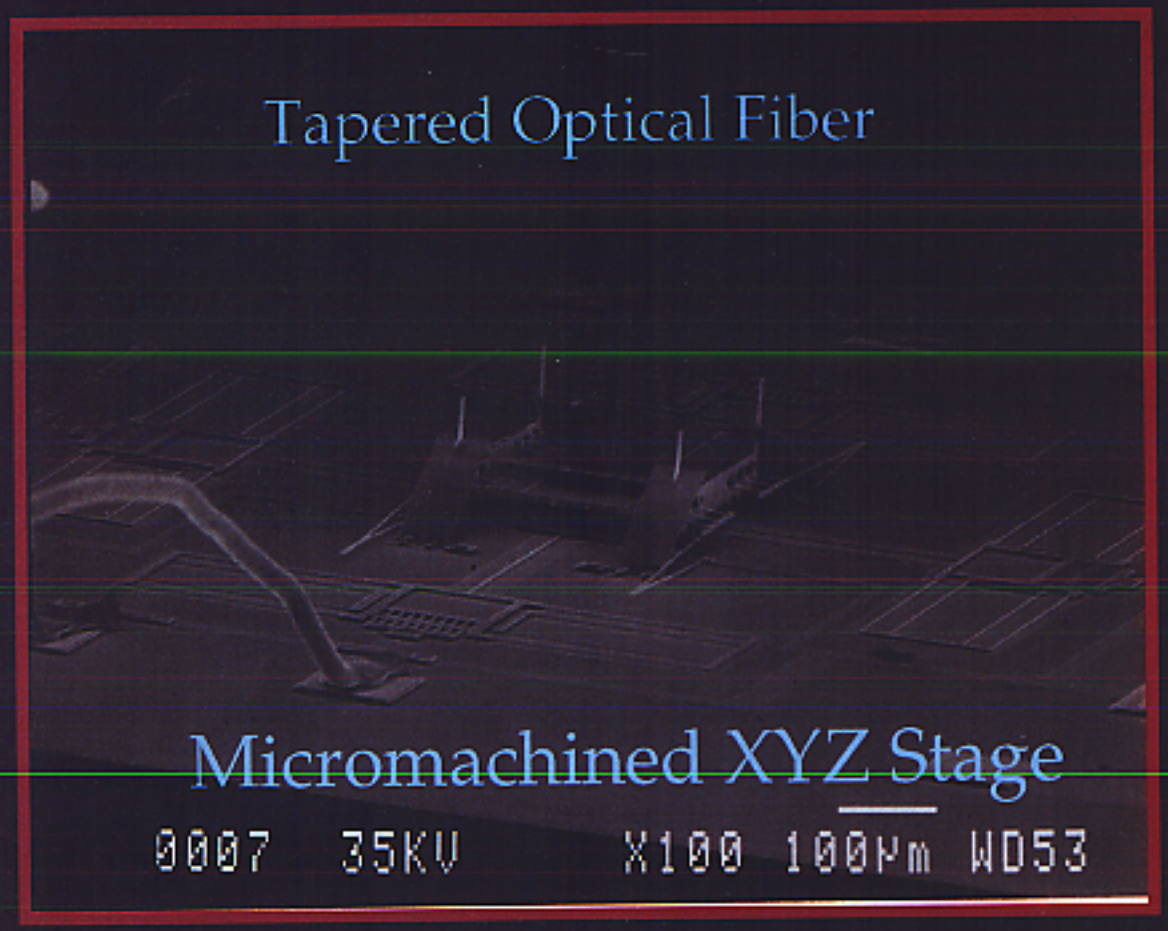


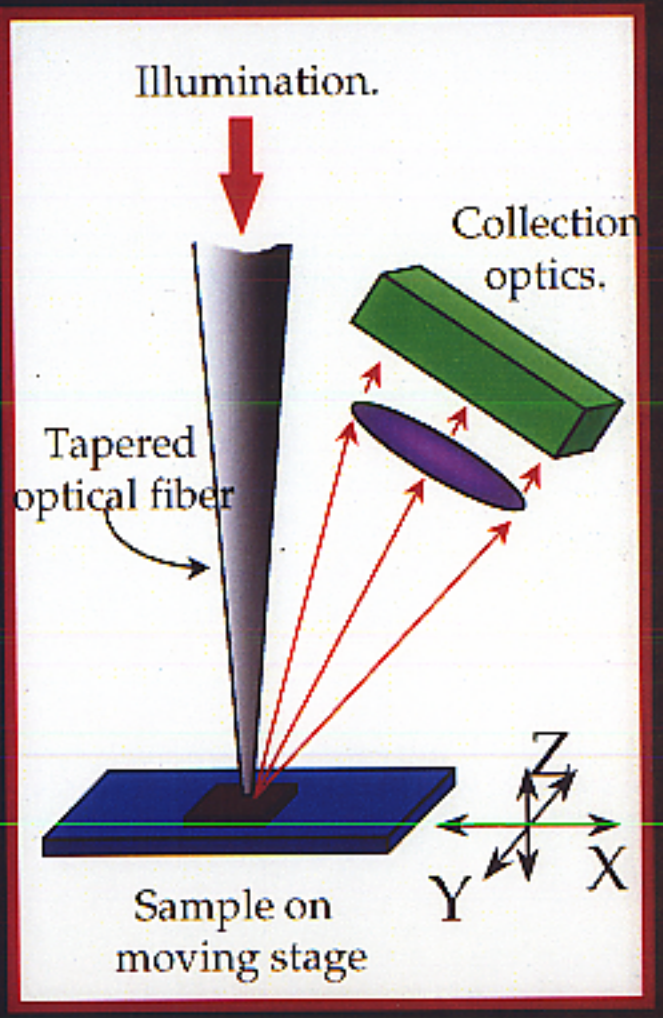
How Does an NSOM Work?

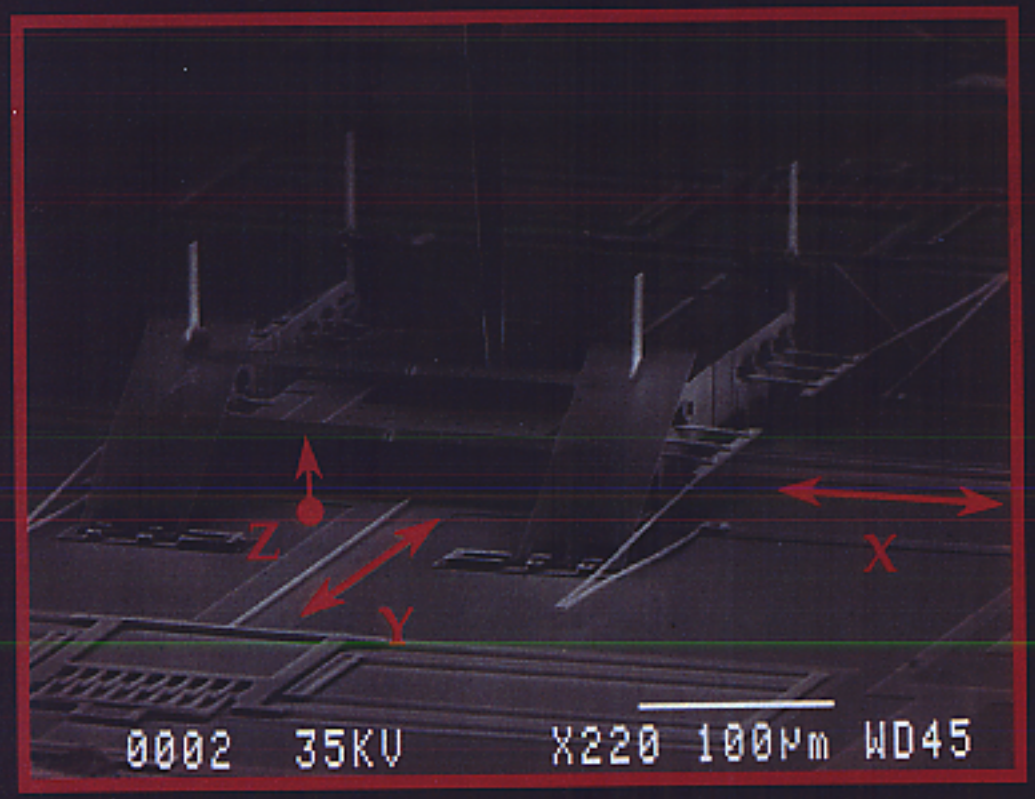
Near-Field Scanning Optical Microscope

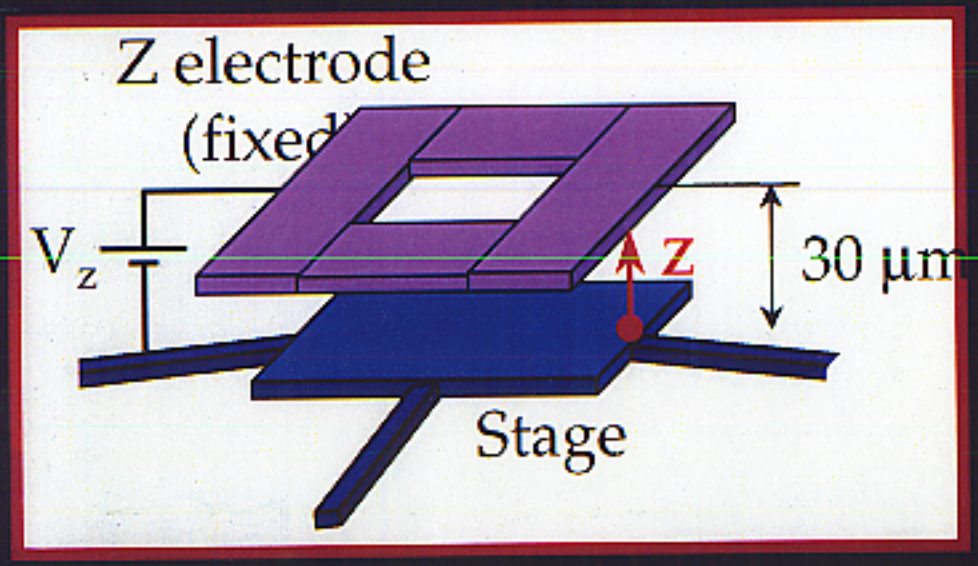


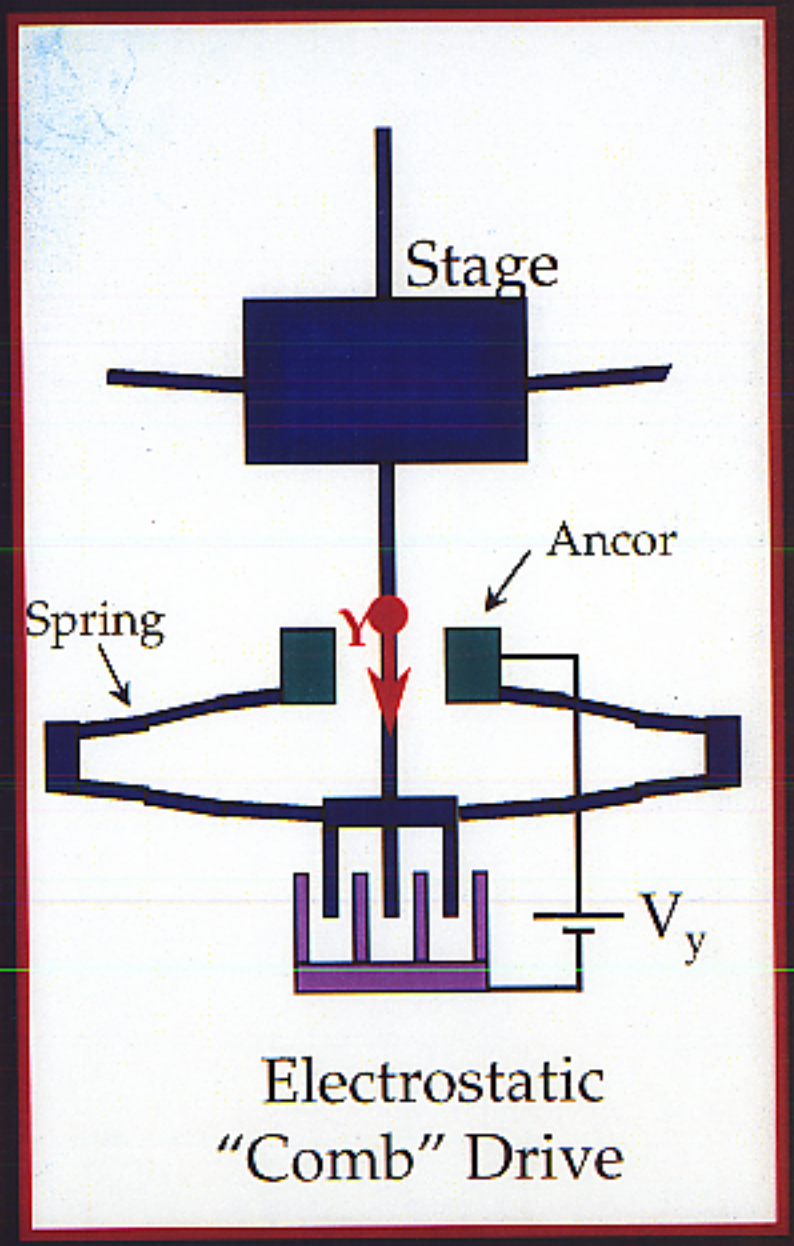
MEMS Micro-Microscope






Z
Y
X
0002 35KV X220 100Pm WD45


Z electrode
(fixed)
V_z
Z
30 µm
Stage


Stage
Ancor
Spring
Y
V_y
Electrostatic
"Comb" Drive

The Micromechanical NSOM

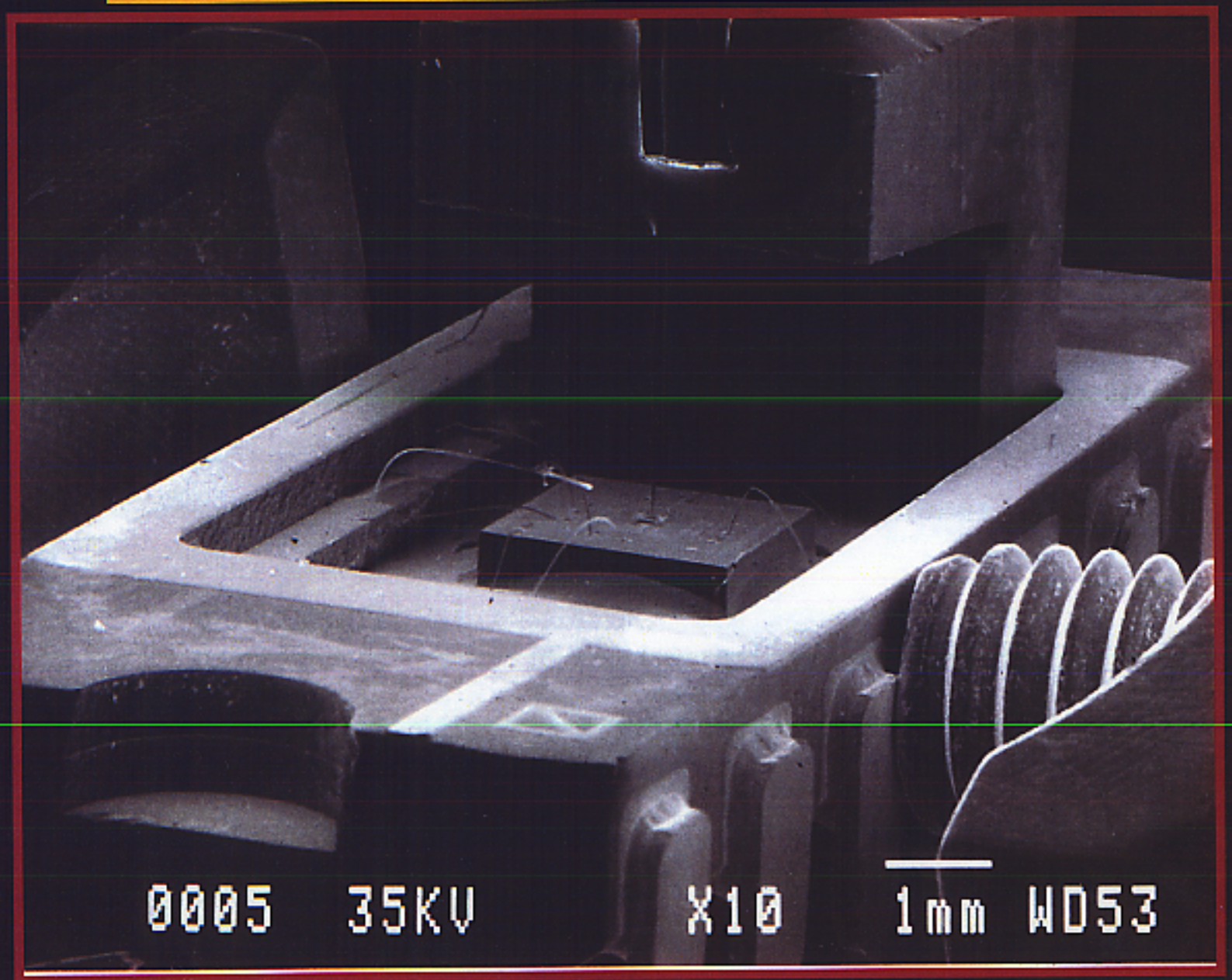
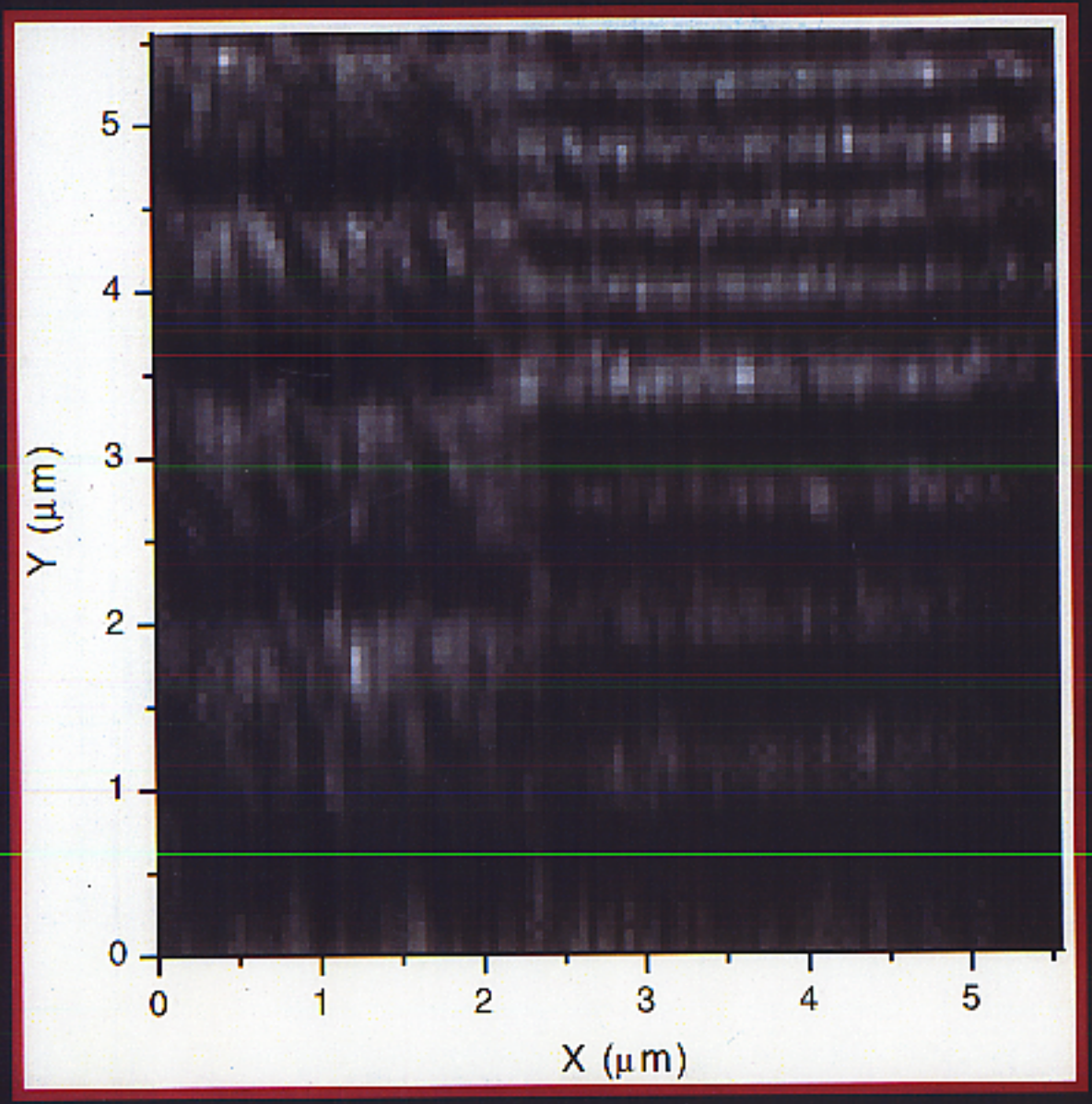


Image of a Test Pattern



6 May 1999

International weekly journal of science

nature

$8.95

www.nature.com

Mesoscopic vortex physics

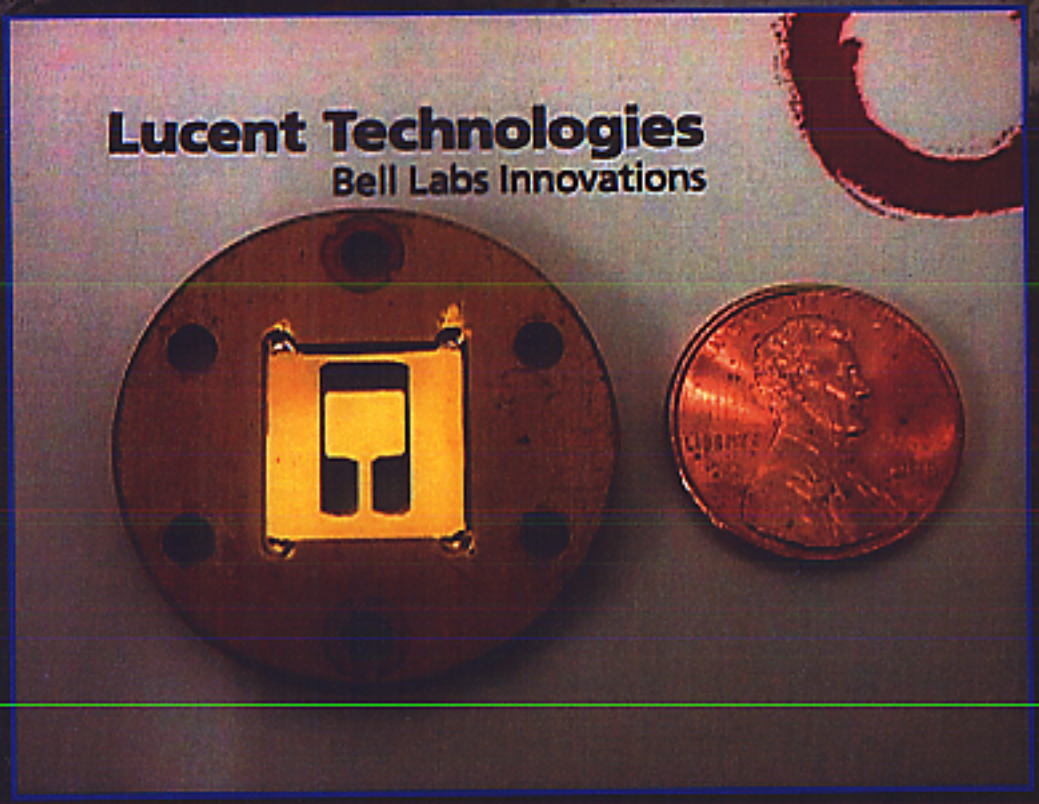
Early hominids
Cleverer than we thought

Making waves
Enteric neural reflexes

Petroleum stability
Cracking good markers

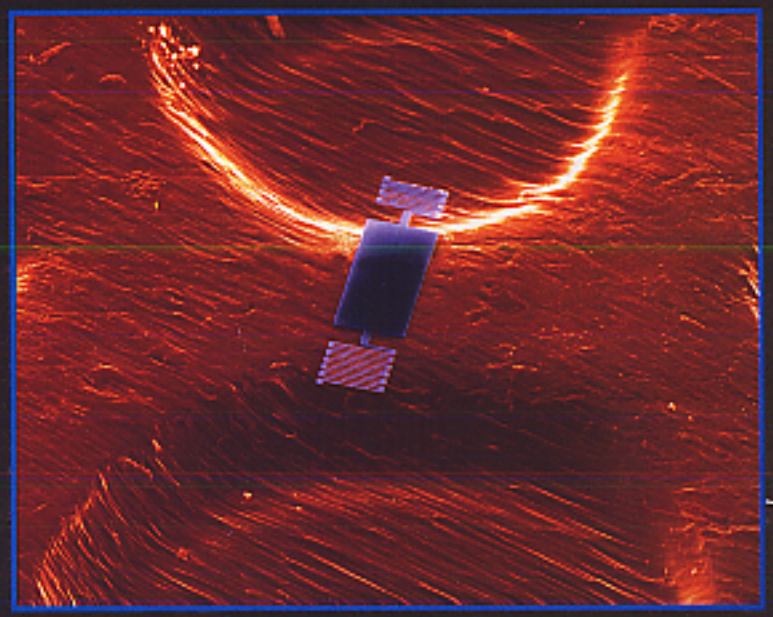
New on the market
Bioinformatics/Genomics

Traditional High-Q Mechanical Oscillator

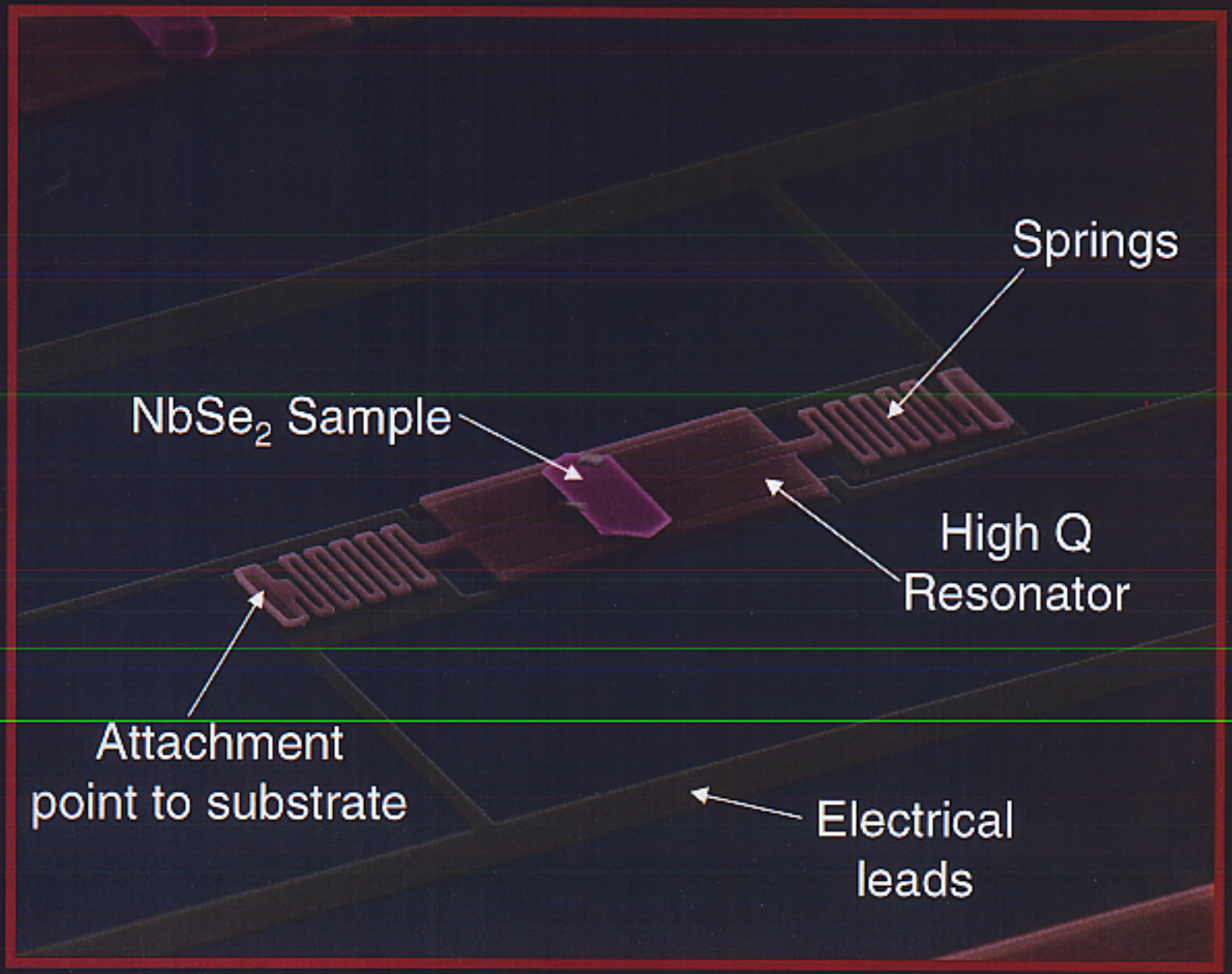


The Micro-Mechanical Oscillator on a Penny

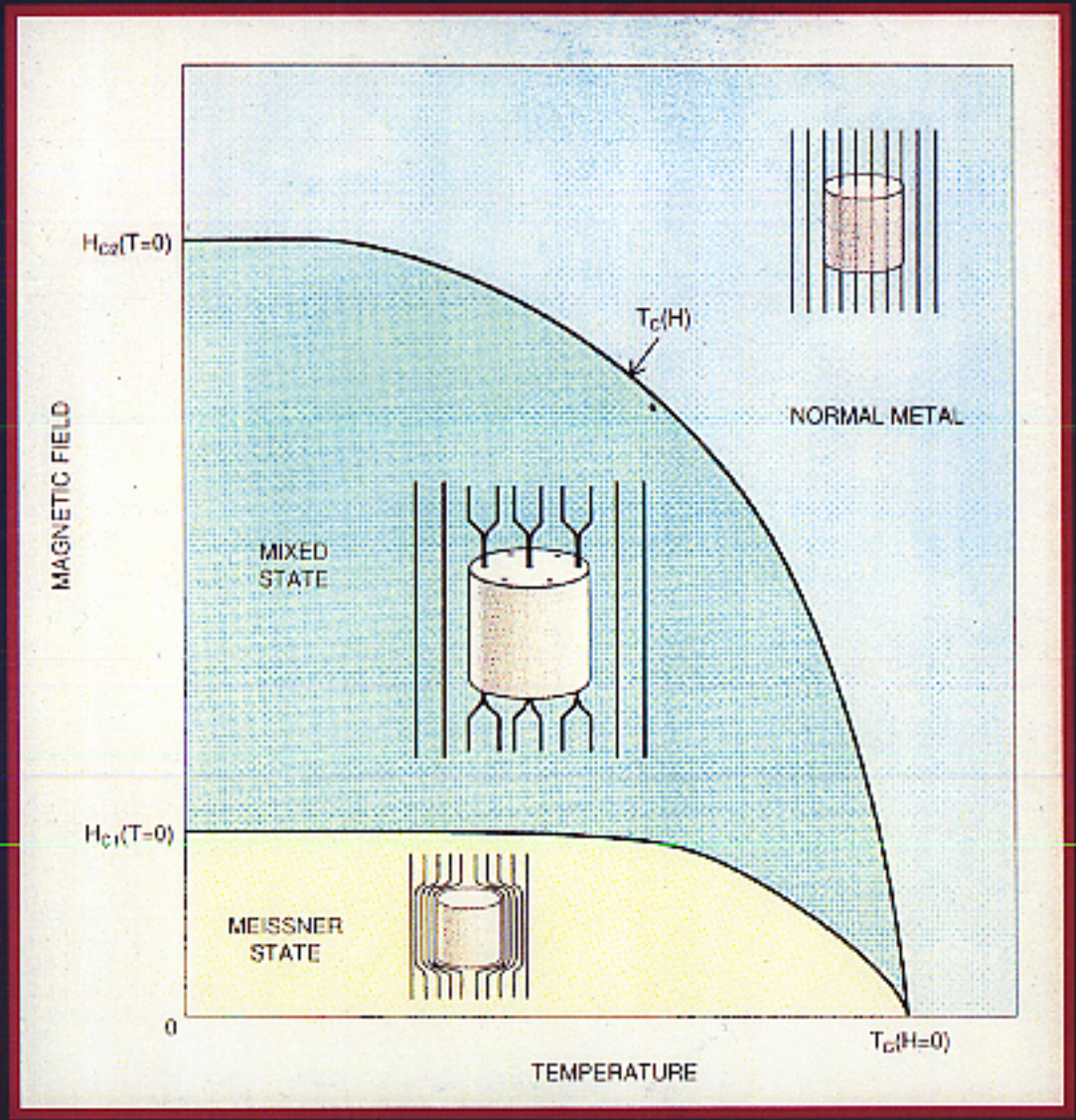
- Paddle Size: 50x100μm^2



MEMS High Q Oscillator for Vortex Physics

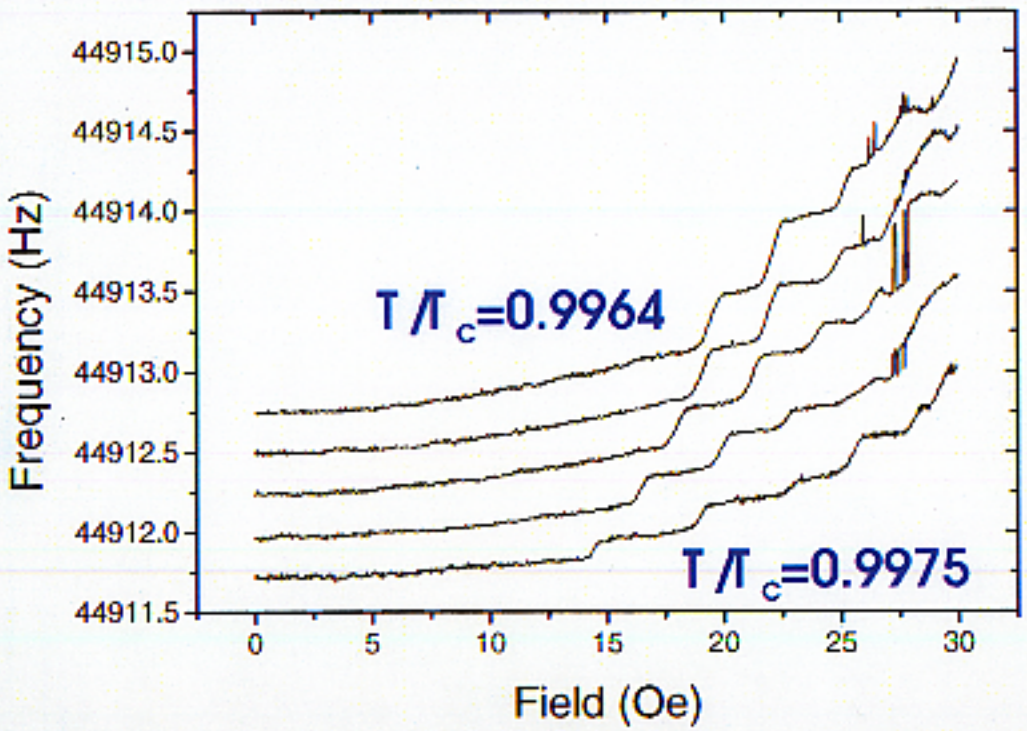


Pre-High Tc Phase Diagram for Type II Superconductors

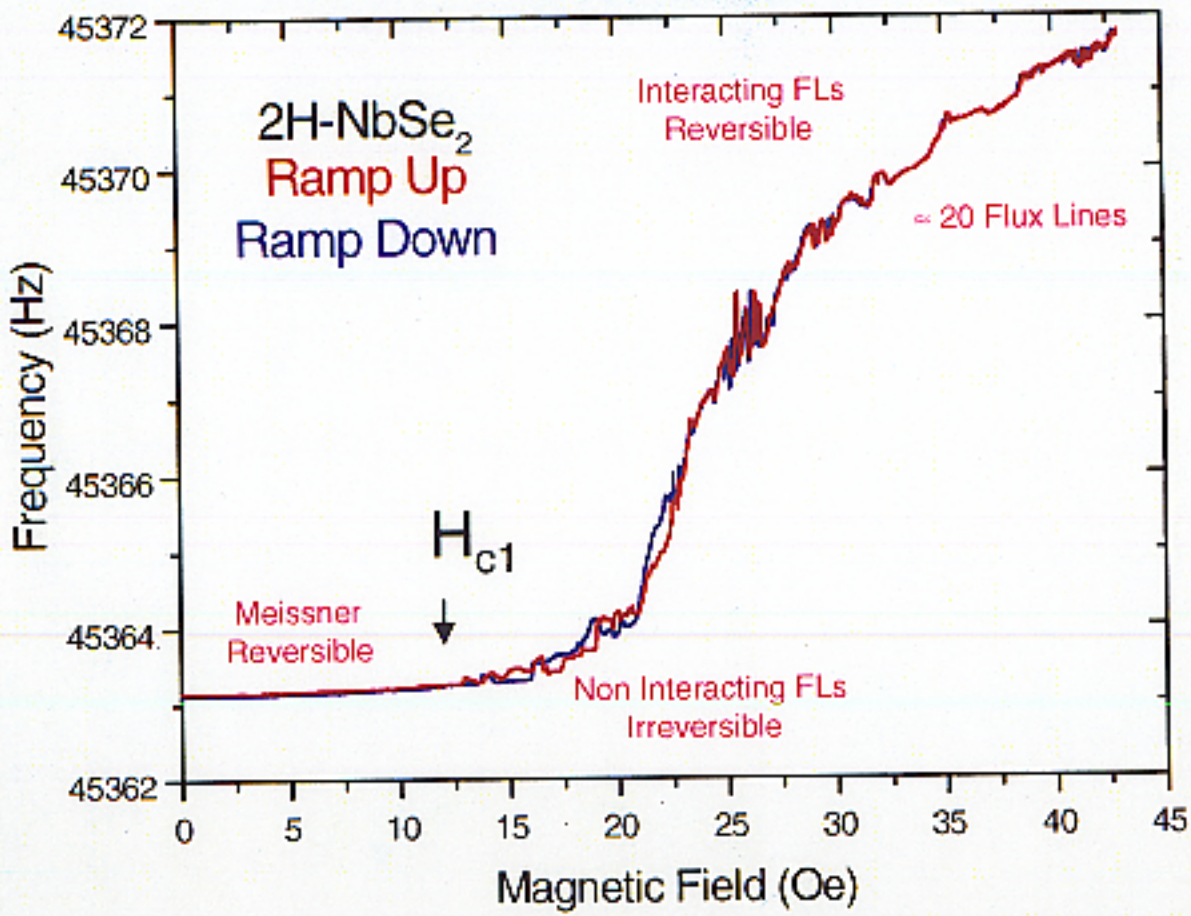


Temperature Dependence of B (H)

(Curves Shifted for Clarity)



Field Ramps Below Tc

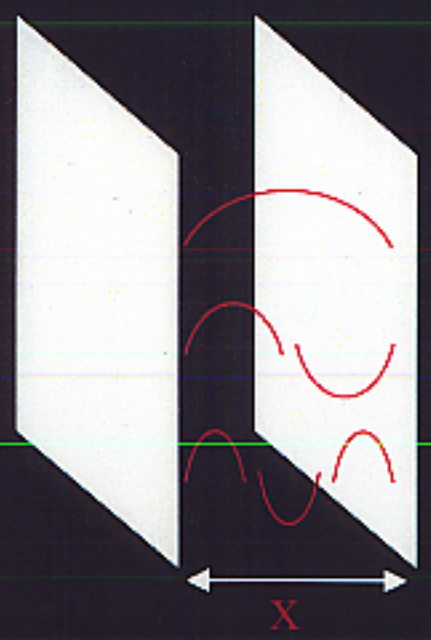


Casimir Force

attractive force between two uncharged conducting surfaces arising from zero point fluctuations of the electromagnetic field

Energy for each mode: $E_{n,\omega} = (n + 1/2)\hbar\omega$

Total zero point energy: $E_{total} = \sum_{\omega} \frac{1}{2}\hbar\omega$



$$F = -\frac{dE_{total}}{dx} = -\frac{\pi\hbar c}{240x^4}$$

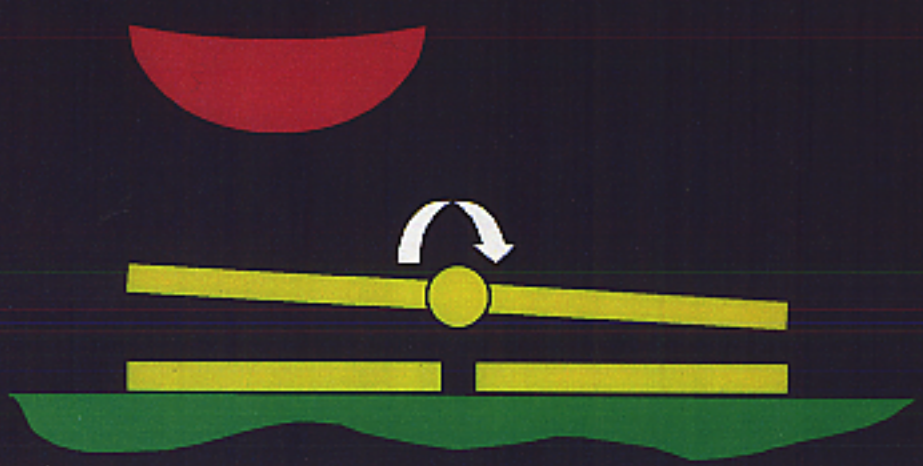
Between 2 μm thick silicon plates.

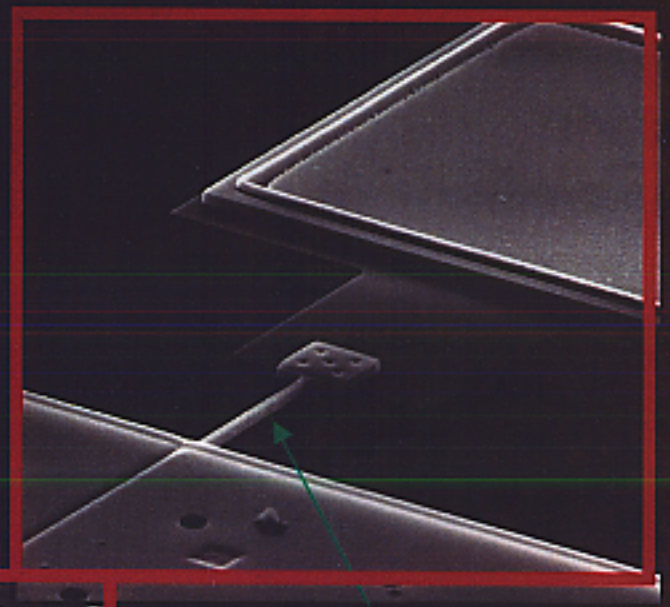
At 1 μm, ~ gravitatonal attraction

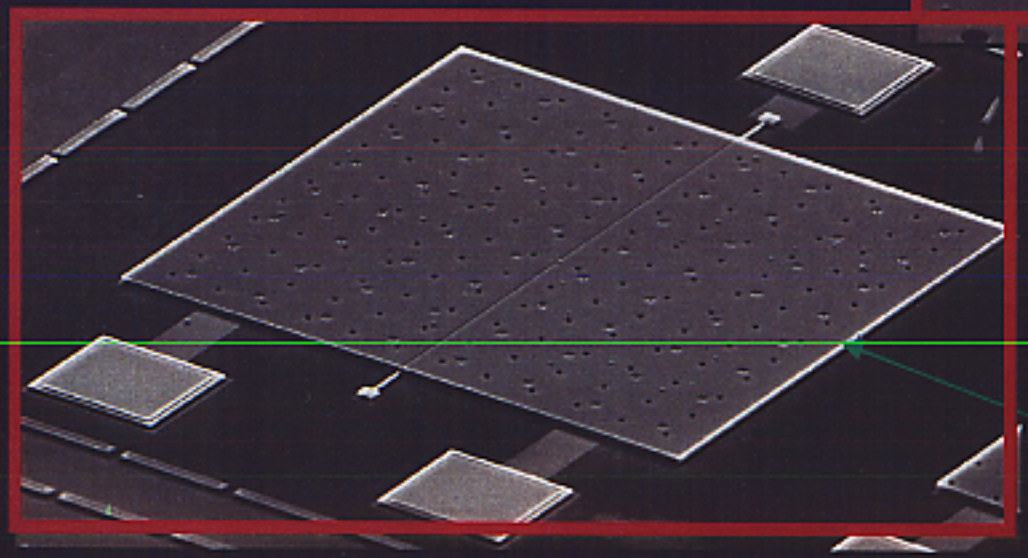
At 10 nm, 10^8 times larger, ~ 1 atmosphere of pressure.

Non-ideal surfaces: finite conductivity, roughness

MEMS torque sensor





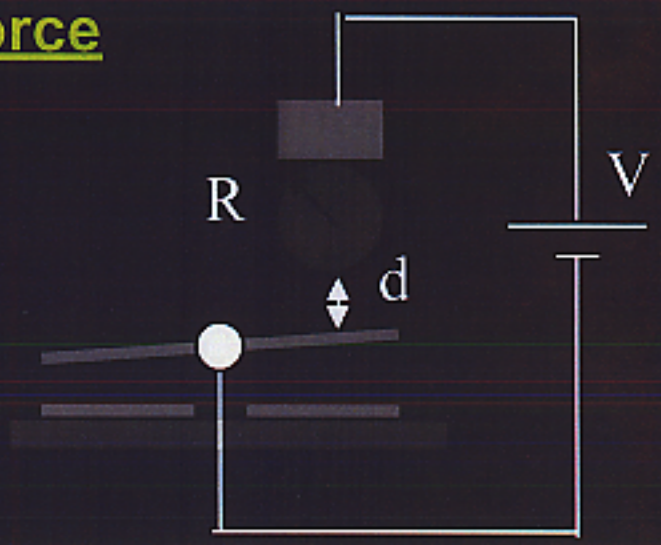


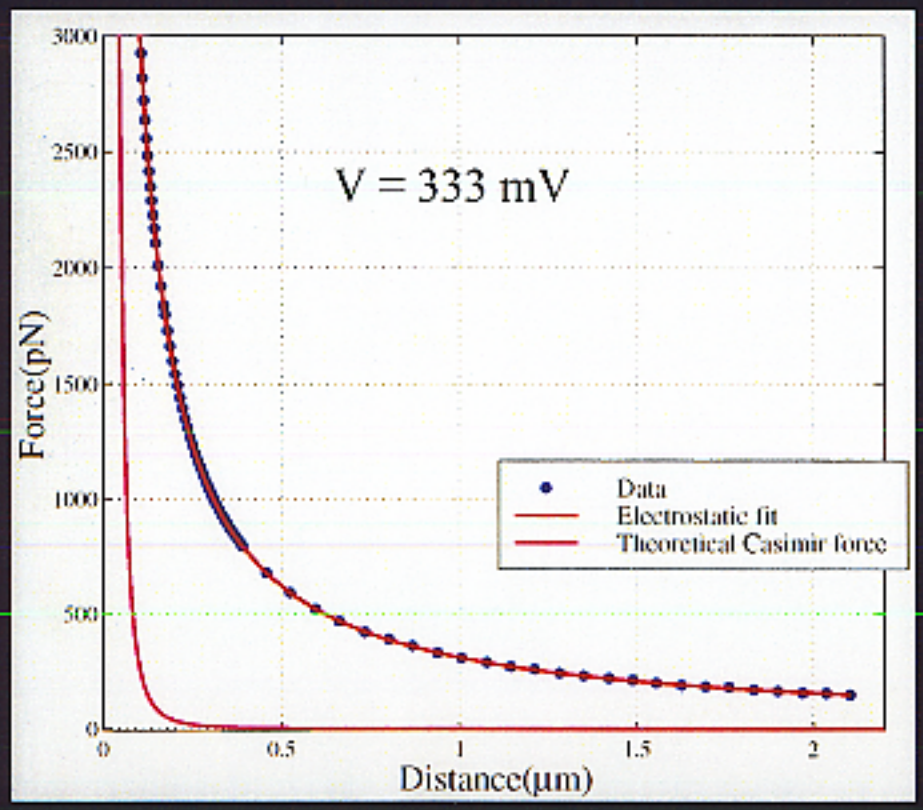
Torsional rod
cross section: 2 x 2 um^2

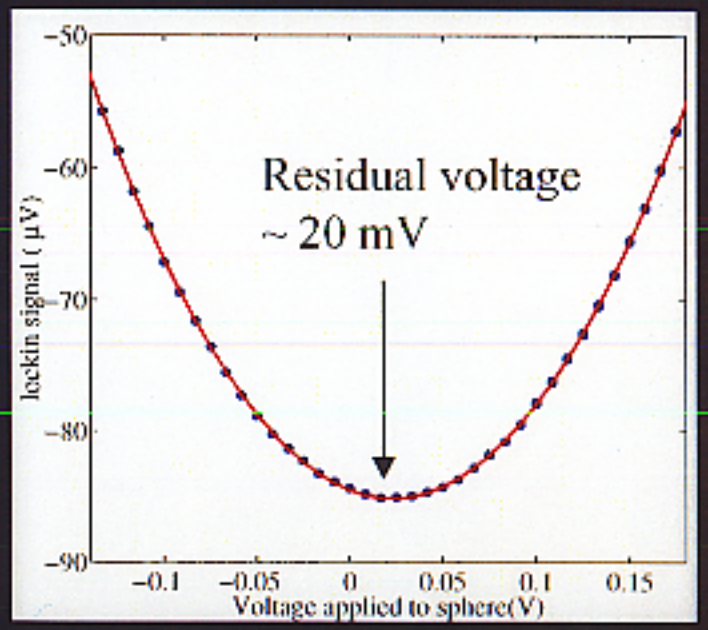
poly-Si plate:
500 µm x 500 µm x 3.5 µm

Calibration by electrostatic force

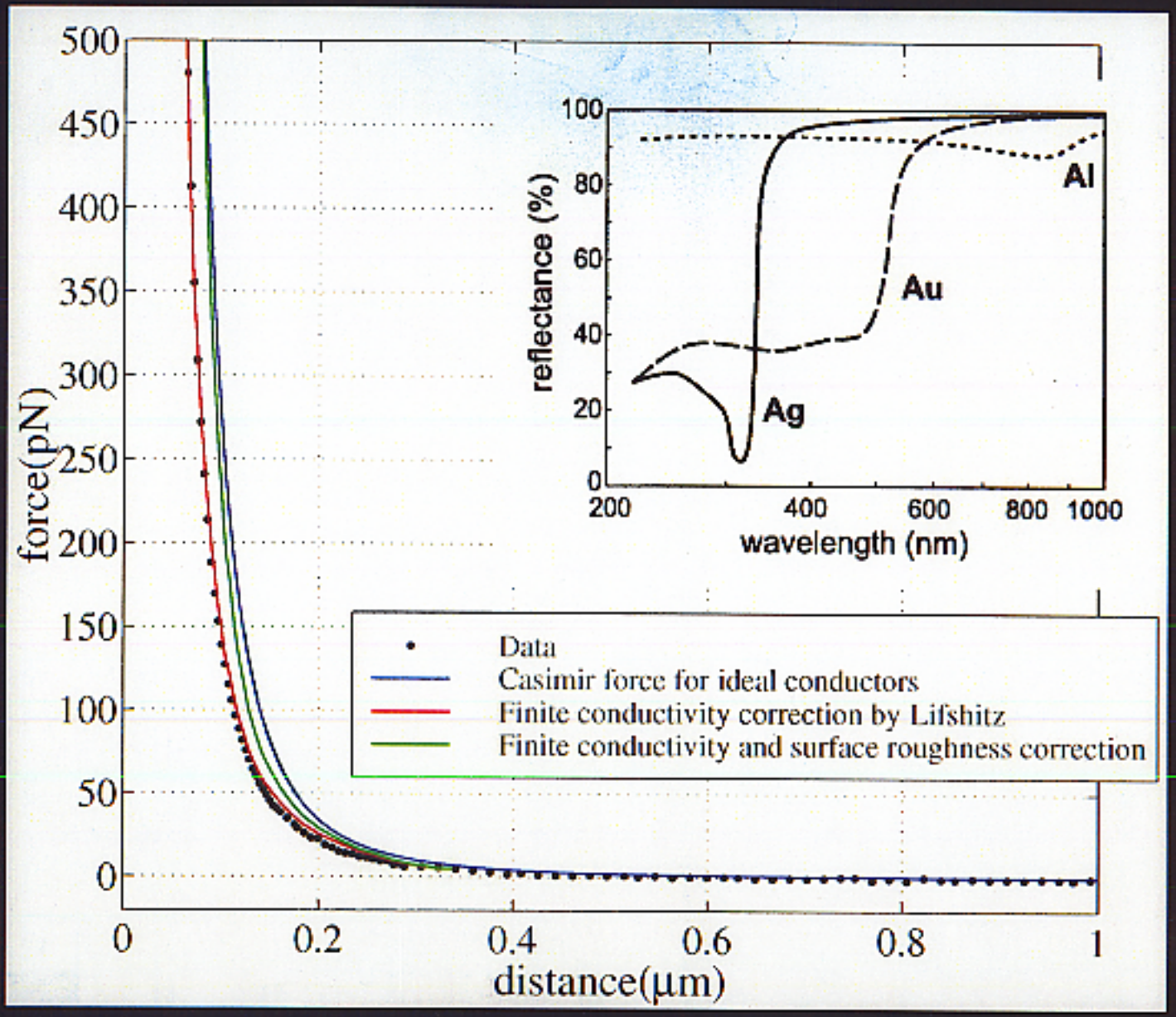
$$F = \varepsilon \pi R \frac{V^2}{d}$$



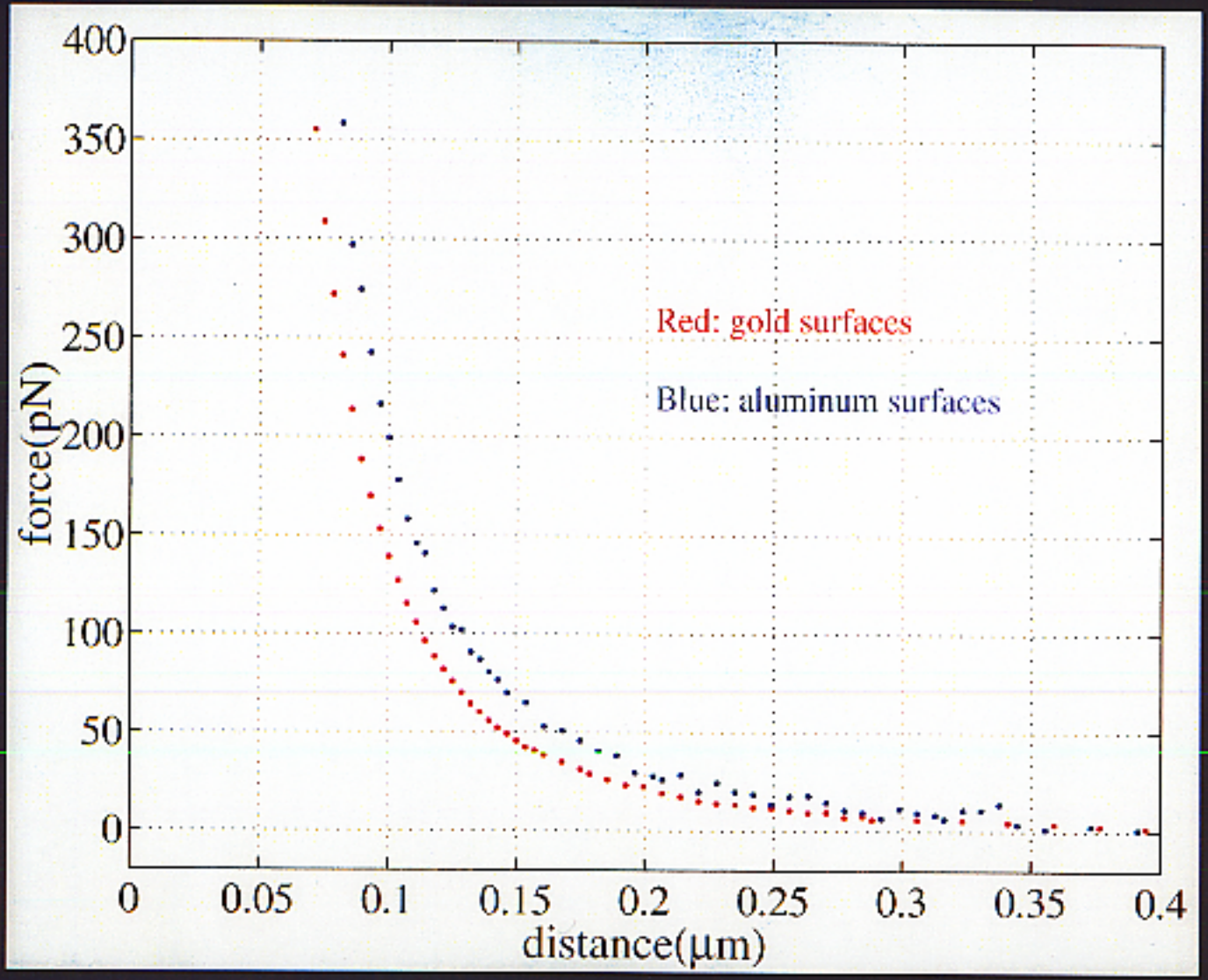




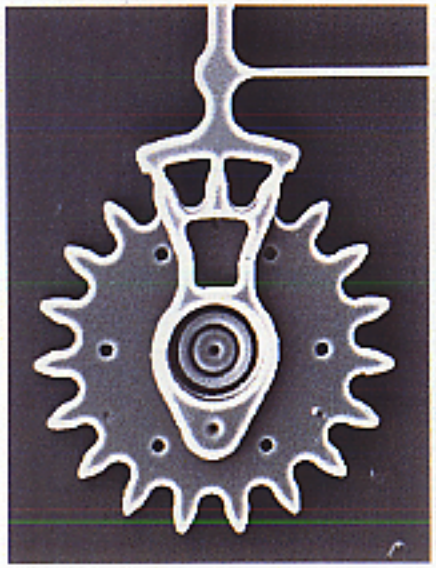
Attraction between gold surfaces



Comparison of Casimir force between Gold and Aluminum surfaces



Macro and Micro: Is the Physics of Failure the Same?



		Factor	
Length:	7 m	~2×10^{5}	4×10^{-5} m
Weight:	10500 kg	10^{16}	10^{-12} kg
Power:	1.35×10^{5} W	~2×10^{10}	6×10^{-6} W
Rev. to Fail:	5×10^{8}	~10	7×10^{9}
Maturity:	100 years	10	10 years

What is the Future?

Many of us believe that micromechanics will have as profound an impact on our lives as has microelectronics. In every facet of technology from optics, medicine, wireless communications, chemistry, automobiles, TV and many more, micromechanics is changing the landscape. Science is also being changed in that new ways of measuring things are being enabled.

The 21st century will be the "Era of Micromachines"