Micro and Nano Systems for Space Exploration.

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Acknowledgments

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LIGA related pictures taken from work done at the Center for Advanced Microstructures and Devices (CAMD) at Louisiana State University, Baton Rouge.
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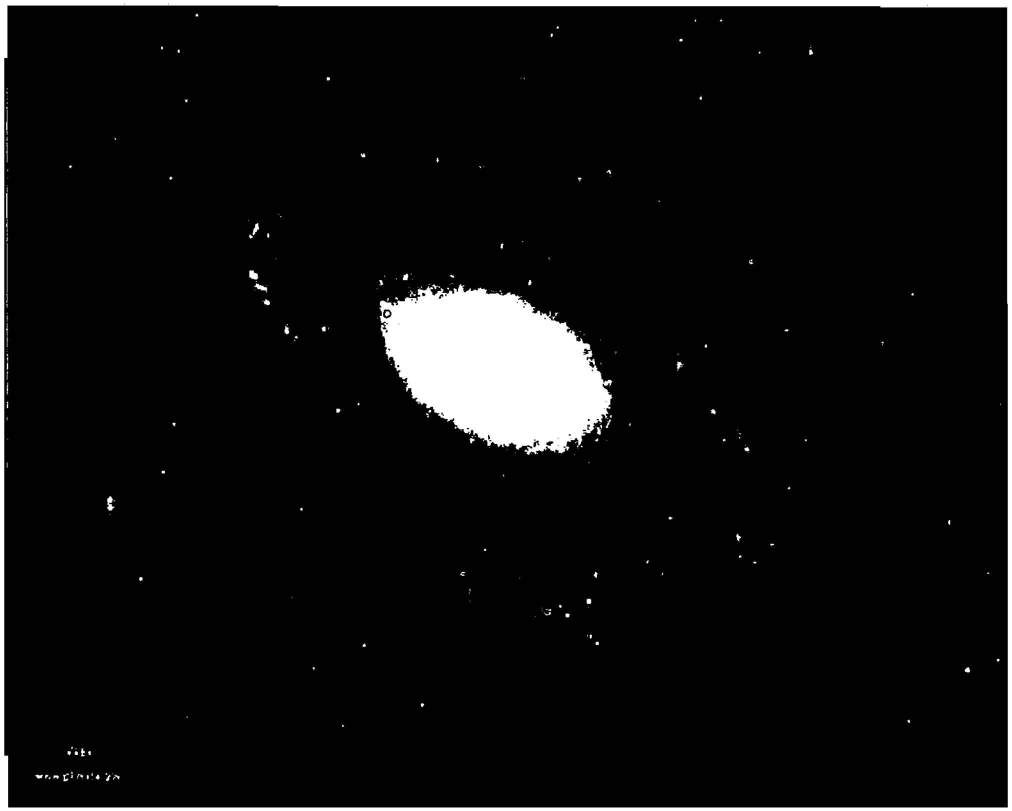
Exploration



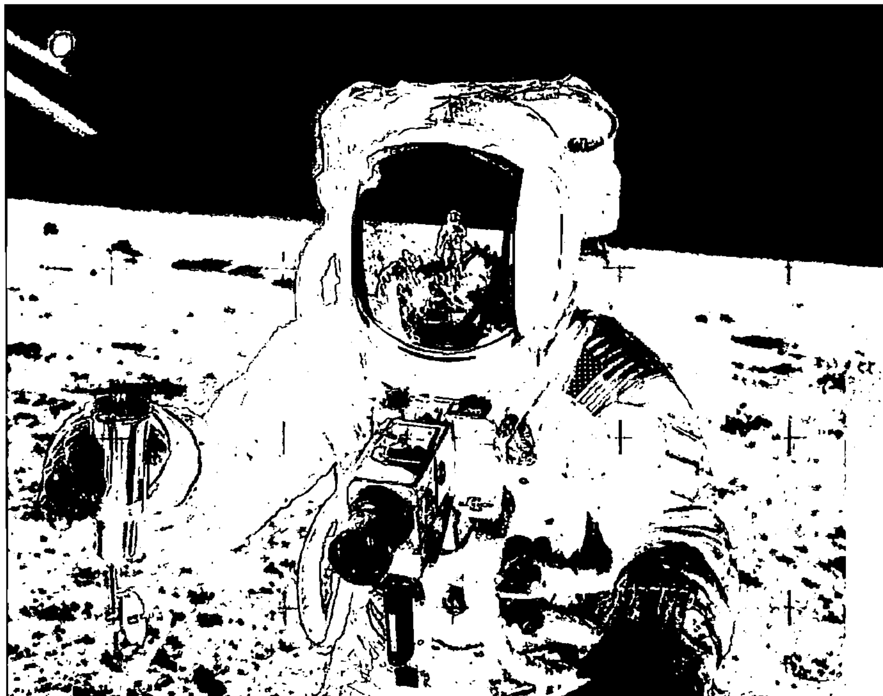
To improve life here;

To extend life to there;

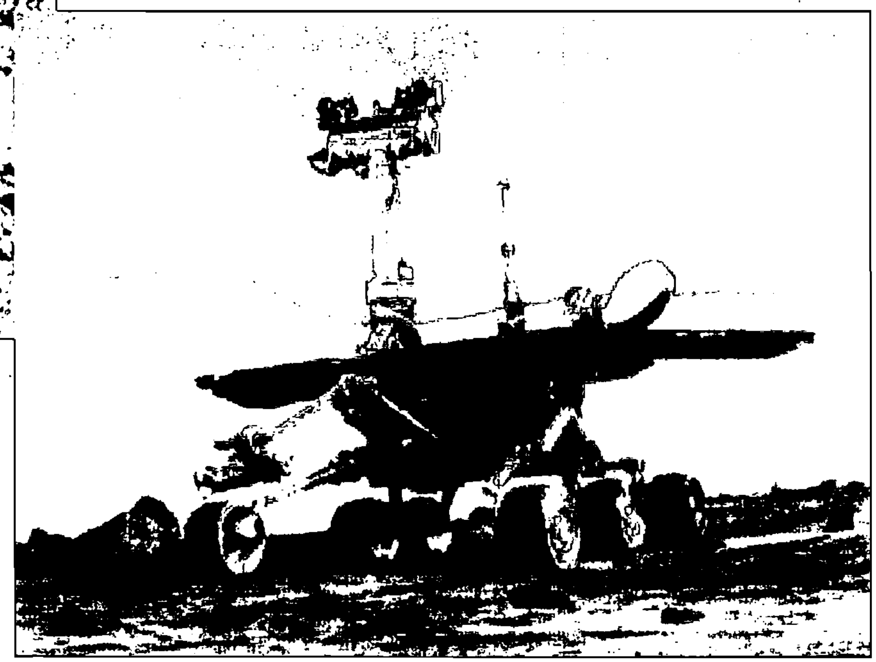
To find life beyond.

Exploration

In Situ Exploration



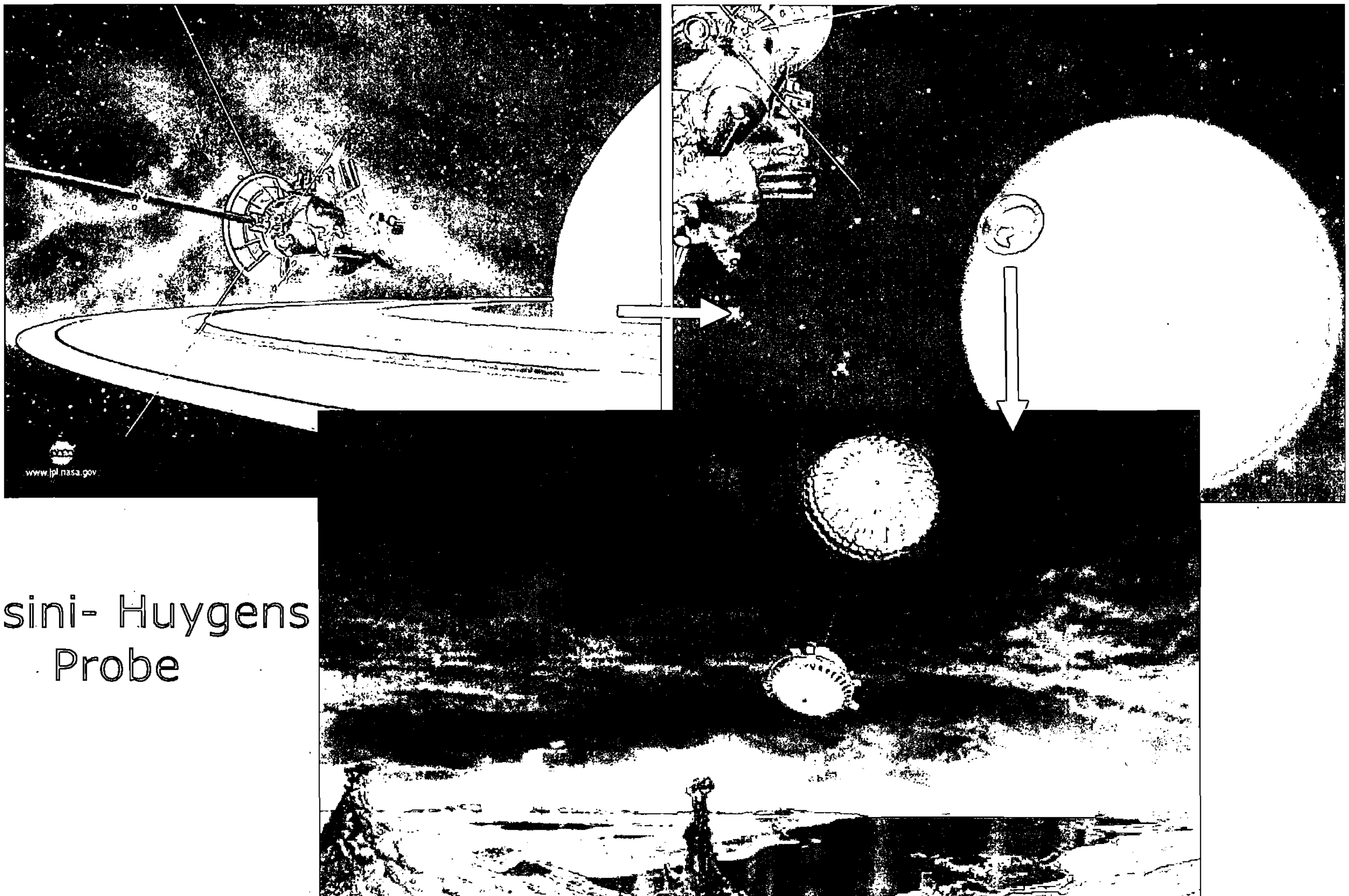
Humans



Robots
{Mars MER}

Exploration

In Situ Exploration



Cassini- Huygens Probe

Why Nano and Micro?

- Limited real estate on the landing platform
- Fixed power, mass, and volume budgets
- Missions are expensive
- Long journey times…"Are we there yet?!"
- When you are there you want to do much

So, make 'em smaller!

What are Nano and Micro?

Micro = 10^{-6} ... A million times smaller

Nano = 10^{-9} ... A billion times smaller

Human hair diameter is between 40 to 100 micrometers (or simply microns)

Have you noticed as the technology advances things get smaller, thinner, low-power consuming, longer lasting, and cheaper? Well, mostly.

Miniaturization

What can we accomplish in situ?

- Image - direct, microscopy

  E.g., Miniature- camera, microscope, SEM

- Analyze - composition, mineralogy, crystal structure

  E.g., Miniature- Gas Chromatograph and Mass Spectrometer, XRD/XRF

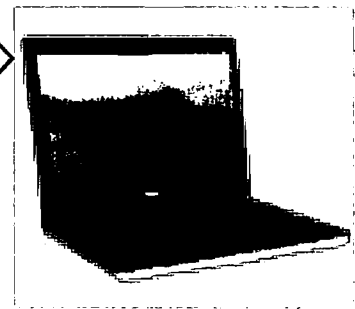
- Communicate

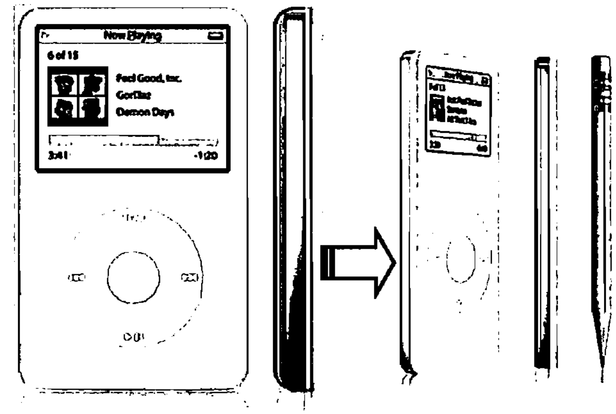
- Sample return - inertial guidance sensors

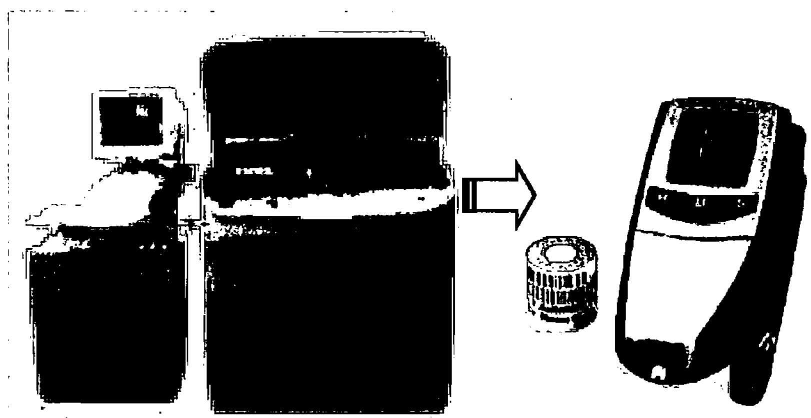
  E.g., Microgyroscopes

As Technology Advances…

ENIAC
1946 (5K/s, floor space 1,000 sq. ft.)



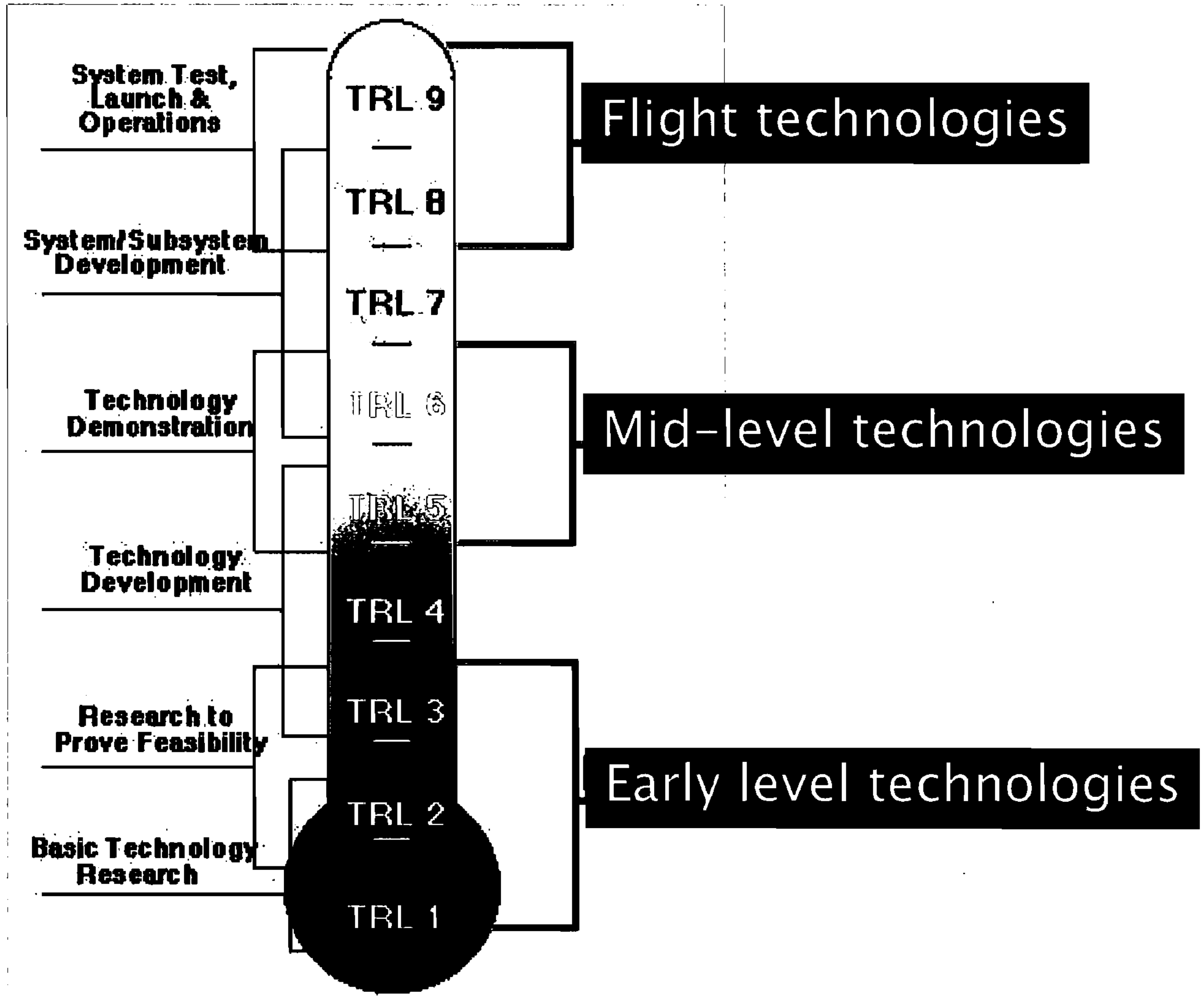




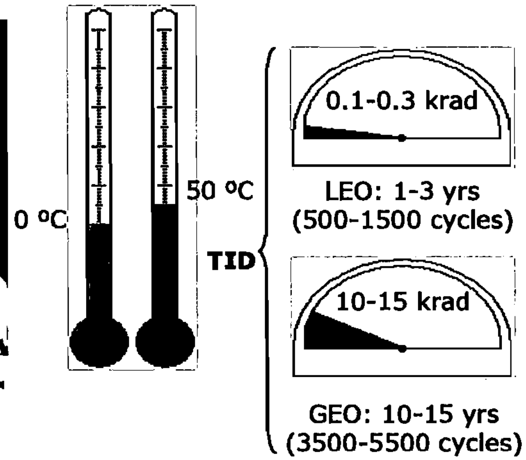
Miniaturization

In essence, it is not enough if only some components are made small; it is necessary to make the whole system or an instrument small!

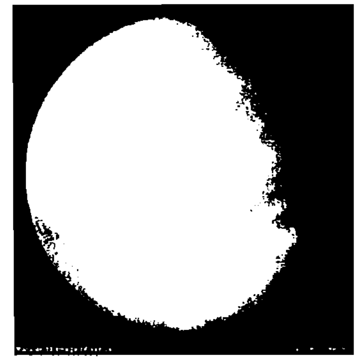
Technology Readiness Levels

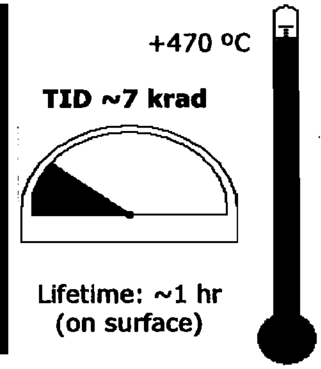


New Technologies for Challenging Environments

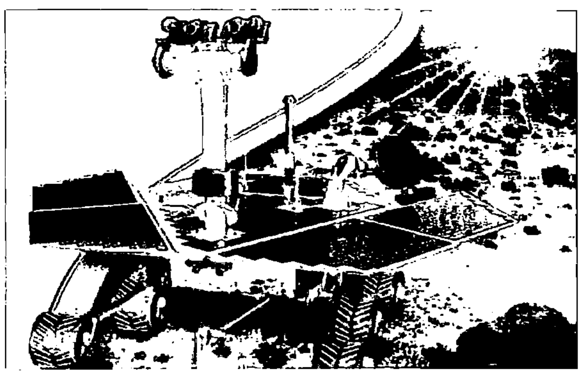


Earth Orbiter

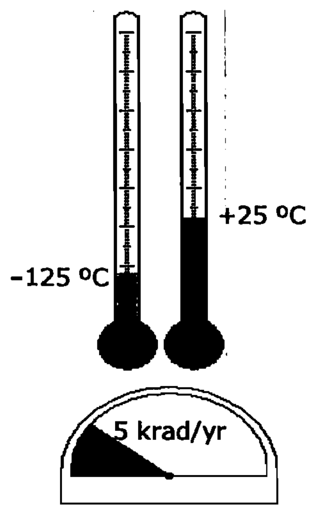




Venus

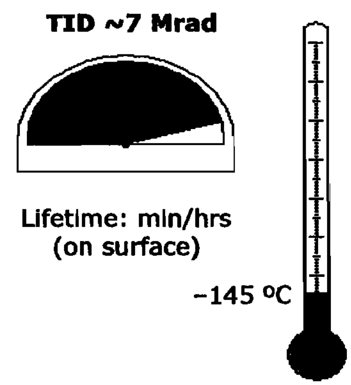


Mars Rover



Lifetime: 90 days

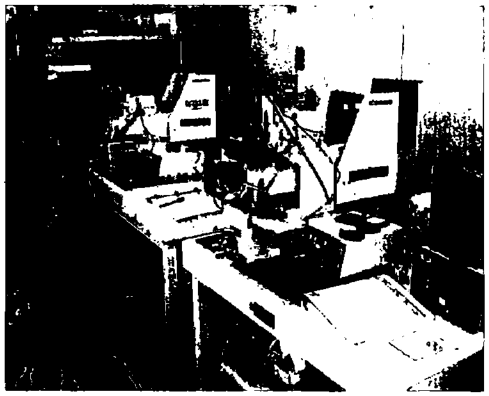
Europa



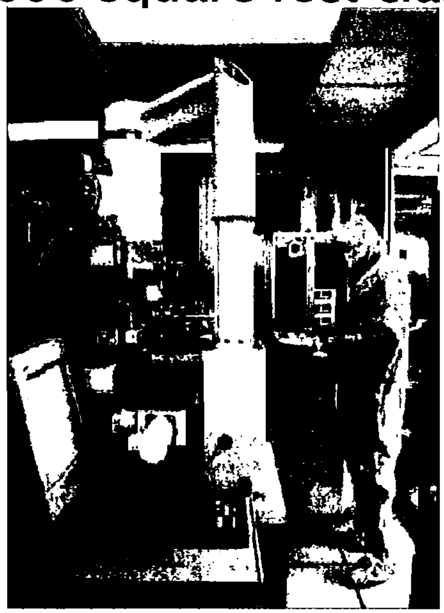
Where do we make them?

Micro Devices Laboratory

12,000 square feet class 10 cleanroom

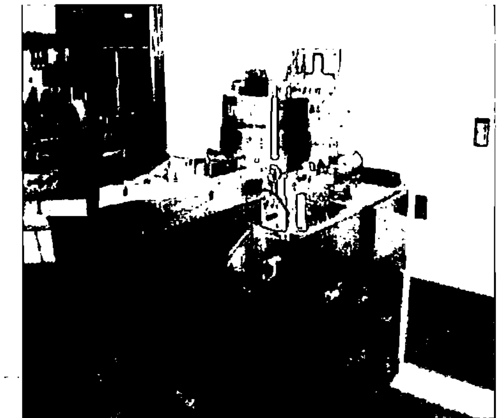


Contact lithography units

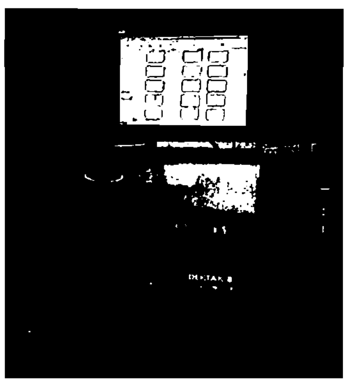


JEOL E-beam aligner

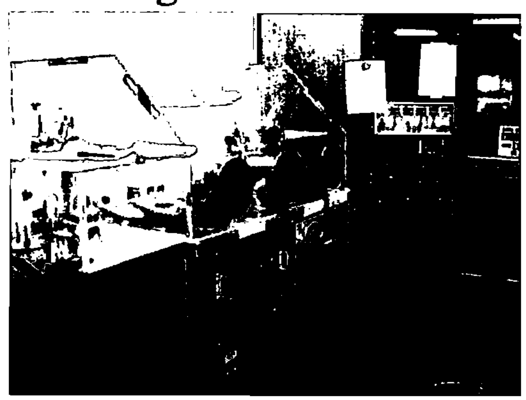
Conventional RIE etchers (CF_4/BCl_3)



New ICP etchers: high density, low pressure plasma (chlorine and fluorine chemistries)



Dektak profilometer



E-beam evaporator (Pt, Ti, Au electrodes)

How do we make them?

Lithography

e-beam lithography

UV- Lithography

X-ray Lithography / LiGA

Non-lithographic Techniques in Brief

Carbon Nanotube

Silicon Nanotips

Processing

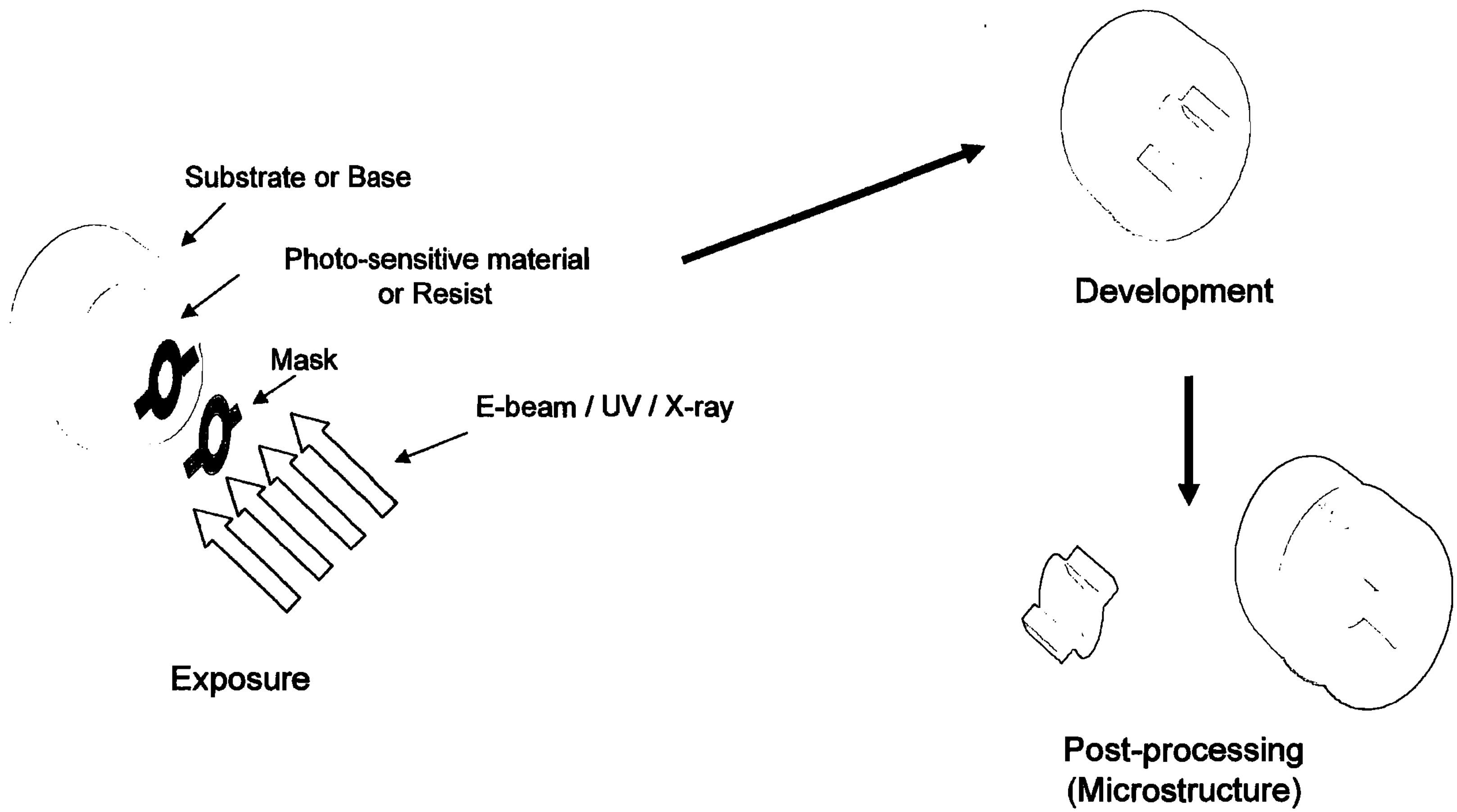
A combination of addition and subtraction of materials

Bulk Micromachining and Surface micromachining

How to make them?

Lithography

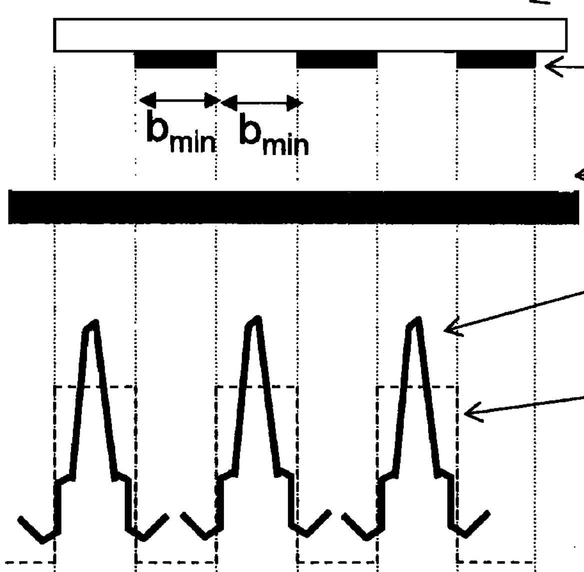
source → mask → photoresist → development → post-processing



How to make them?

Lithography

Important considerations…



Resolution

$$2\,b_{min} = 3\sqrt{\lambda\,[s + (1/2)\,z]}$$

s = gap between mask and the resist

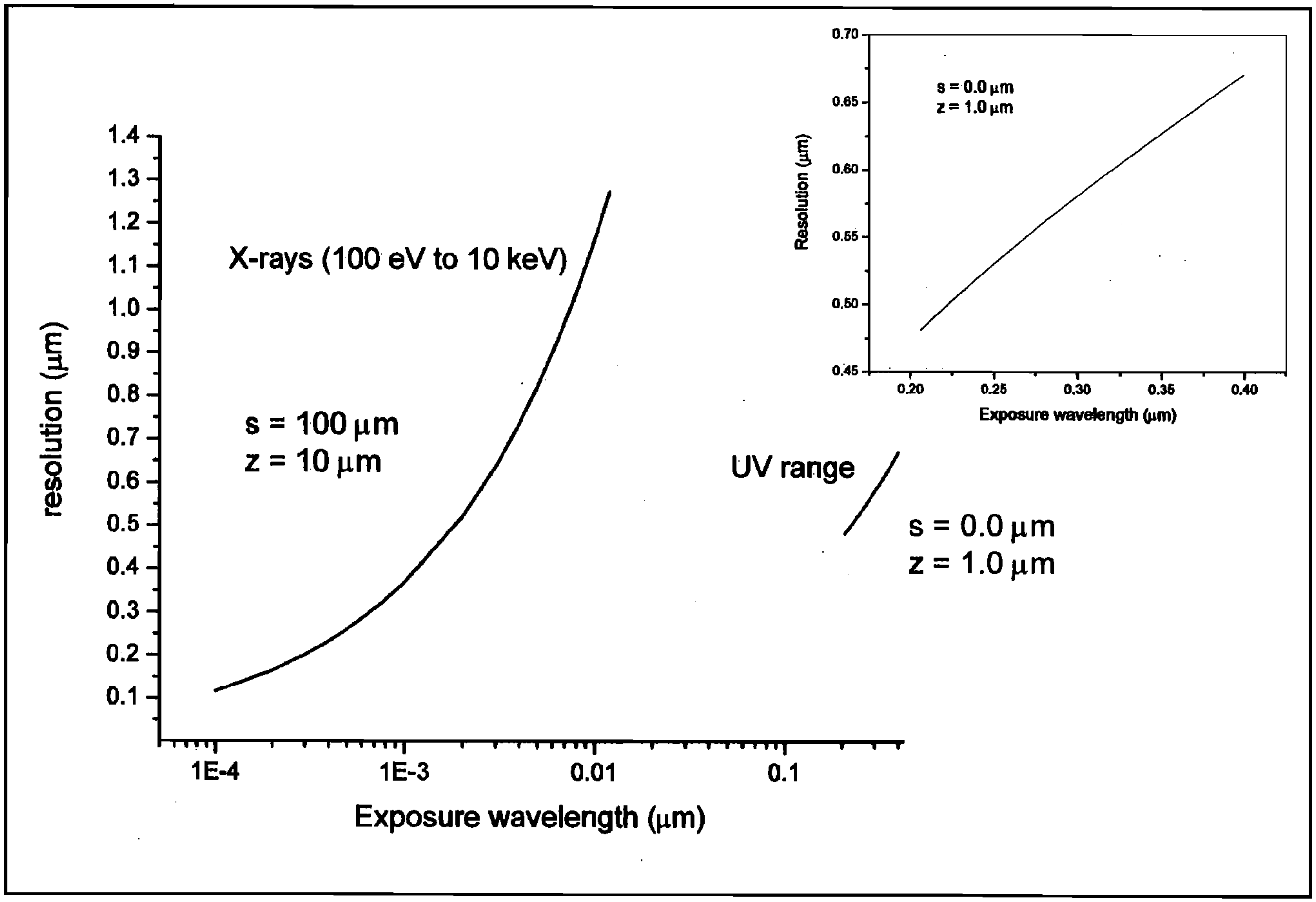
λ = exposure radiation wavelength

z = resist thickness

How to make them?

Lithography

Important considerations…



How to make them?

Lithography

Important considerations...

Actual resolution differs drastically from the theoretical resolution because of many factors

1) Diffraction limitation
2) Image broadening due to short DOF
3) Photoelectron spread (prevalent in e-beam, and X-rays)
4) Run-out distortions (X-rays mainly)
5) Penumbral blurring (UV and to certain extent X-rays)
6) Pattern deterioration due to resist and process characteristics

How to make them?

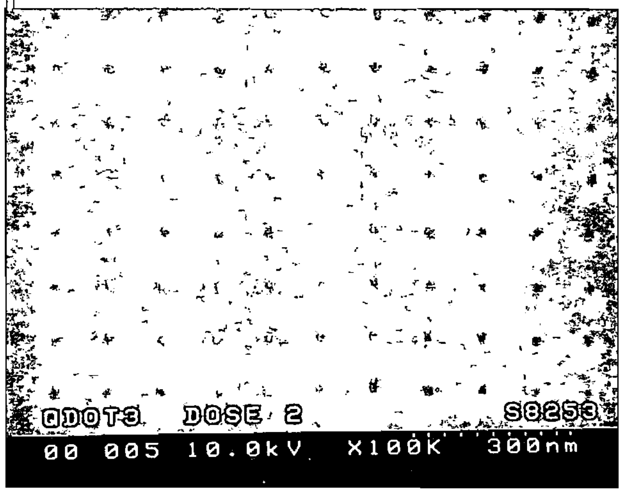
Lithography

E-Beam Lithography, briefly speaking:

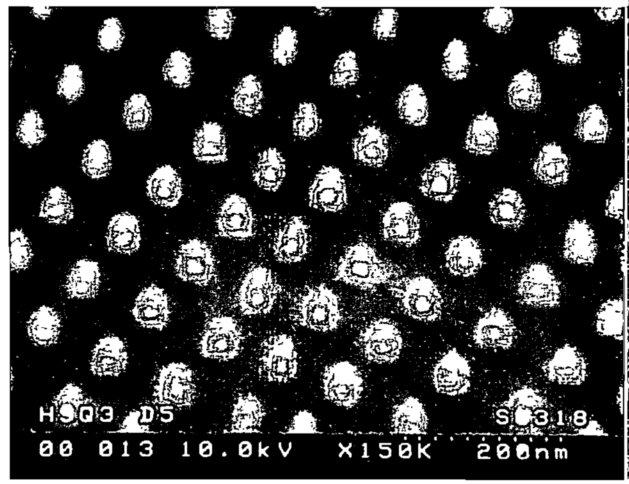
Focused electron beams are used to directly write highly resolved patterns into a resist.

- is a mask less process
- in fact, is used to generate masks for other types of lithography
- a mature technology
- highly accurate registration between multiple layers
- low defect densities
- low through put!
- constrained post processing

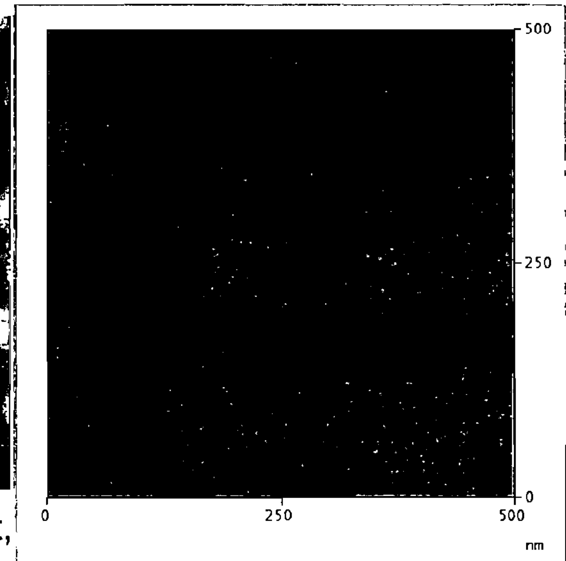
High-resolution E-Beam Lithography



~20 nm holes in positive resist



Dots in FOx-12 (HSQ) negative resist, 25 nm diameter x 70 nm tall



Shaped holes in ZEP-520 resist
{100 nm side triangles}

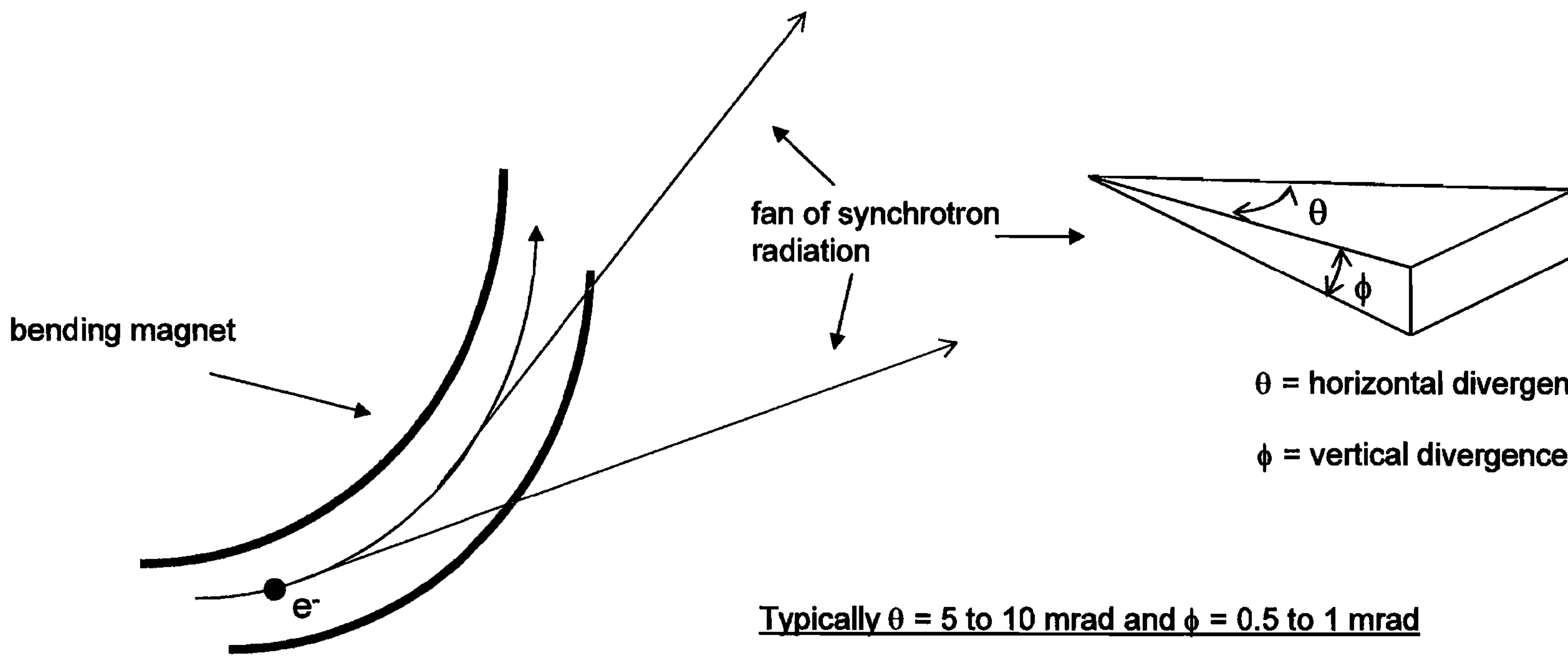
How to make them?

Lithography

X-Ray Lithography / LiGA:

We will focus on Synchrotron X-ray source.

Electrons moving at relativistic speeds when subjected to magnetic field emit high intensity, highly collimated, broad bandwidth radiation covering infrared to ultra hard X-rays



θ = horizontal divergence

ϕ = vertical divergence

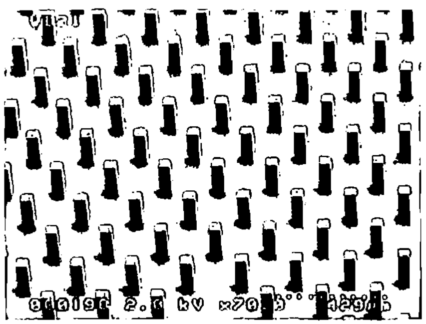
Typically θ = 5 to 10 mrad and ϕ = 0.5 to 1 mrad

How to make them?

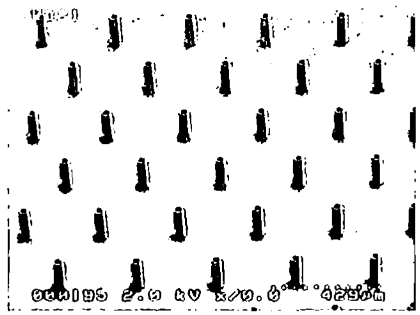
Lithography

X-Ray Lithography / LiGA:

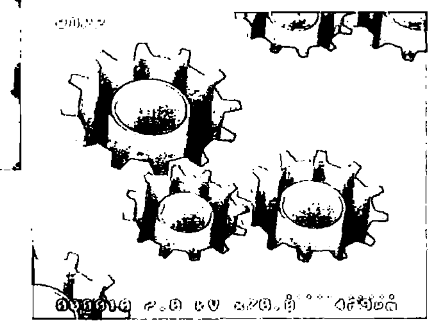
Some X-ray microfabricated structures: All have high-aspect ratios



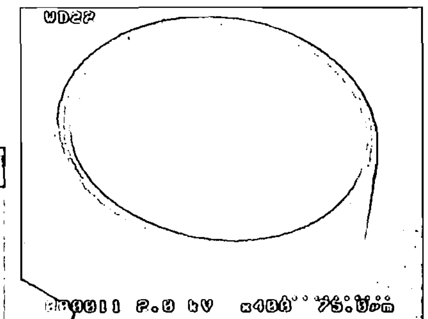
10:1



30:1



100:1



100:1

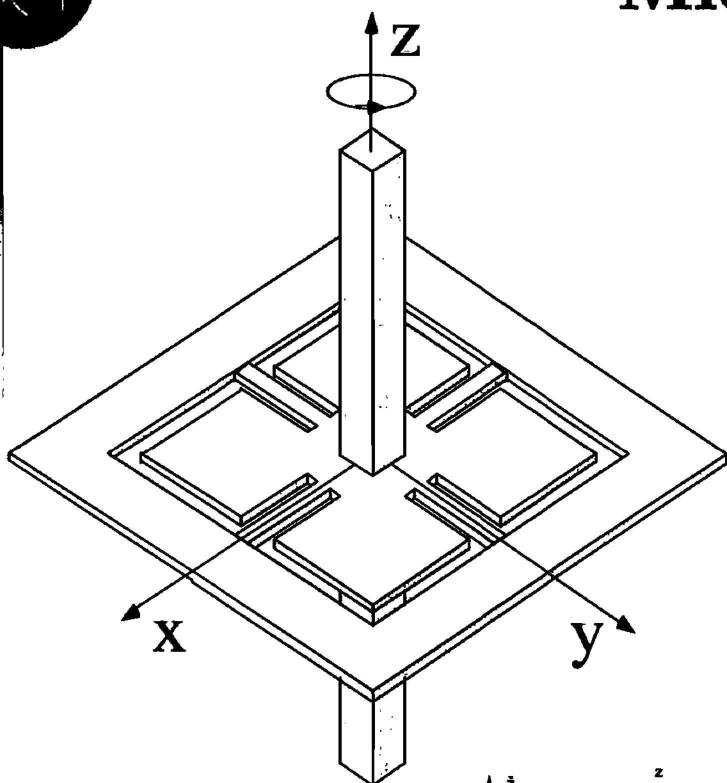
Courtesy: CAMD, Louisiana State University, Baton Rouge, LA, 1999 and 2000

Post-Processing: After development, the micro cavities are filled with metal through electroplating. Upon release from the substrate this electroplated part becomes a mold-insert that can be used to mass-produce its pattern through injection molding or hit embossing.

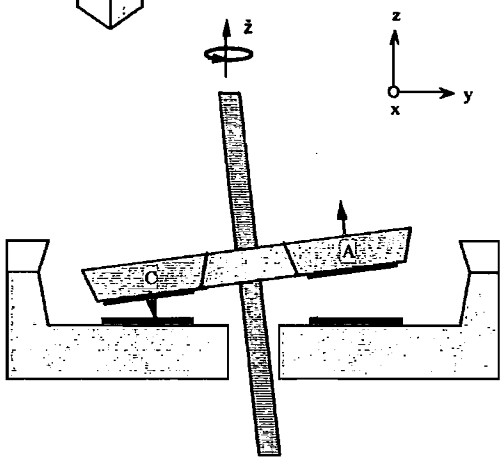
Many components have been made using the techniques described.

Two examples...

Micro Gyroscopes

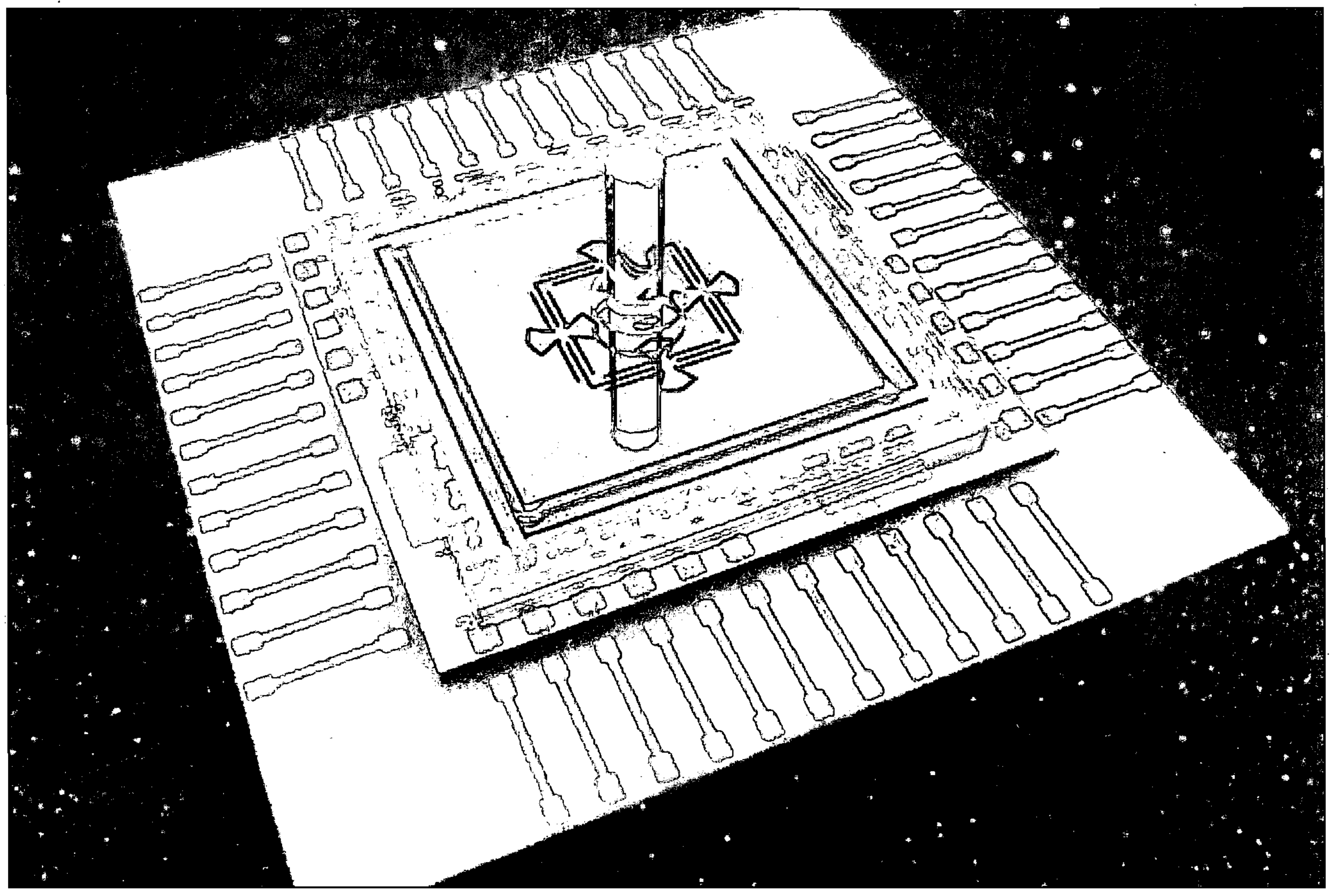


The Clover-leaf microgyroscope design is based on sensing the oscillatory movements of adjacent paddles in and out of the z-plane due to rotation about the z-axis.



- Symmetric structural design
- High Q resonator
- Large detection/drive area
- Precise bulk-micromachining
- Simple control electronics

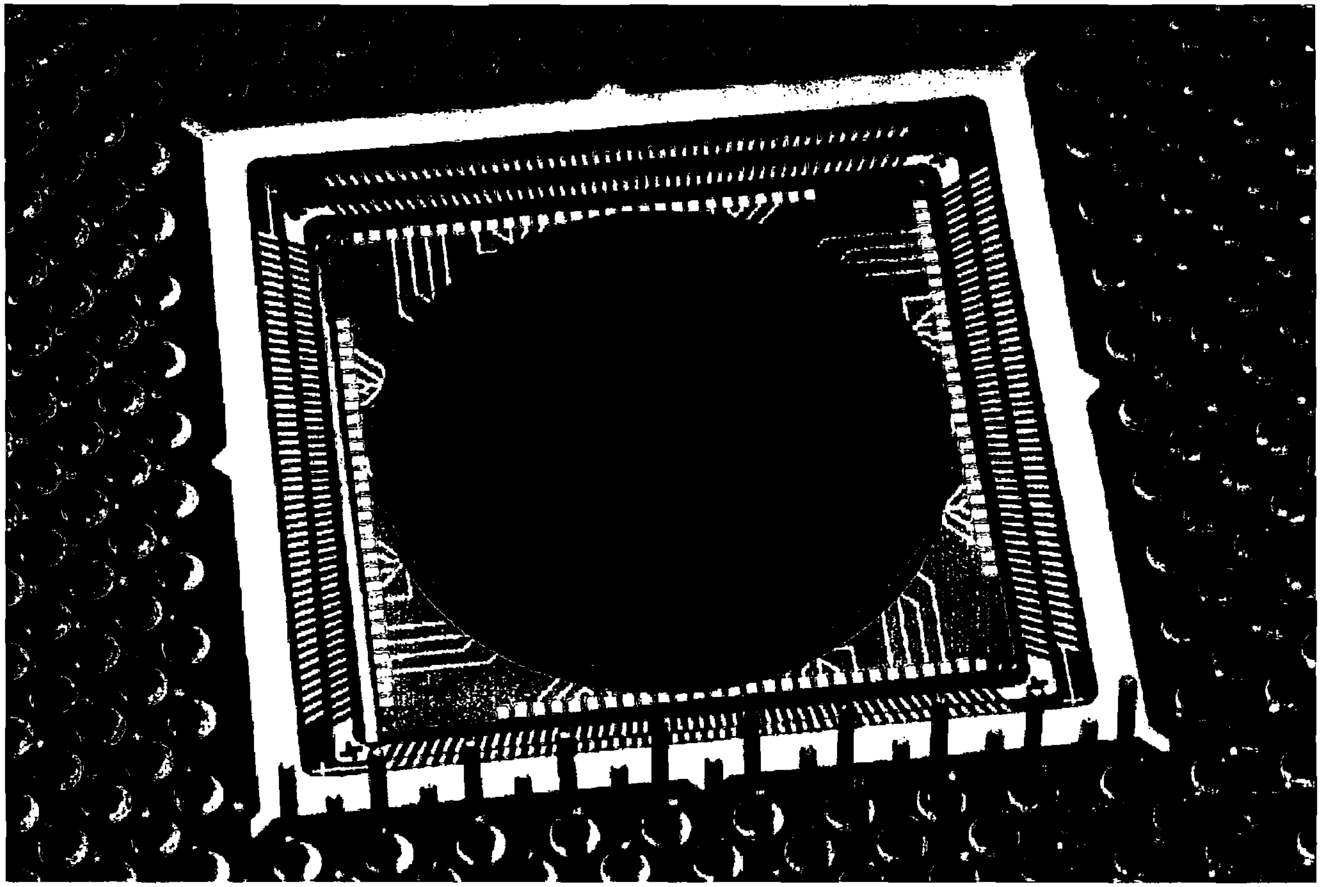
Micro Gyroscopes



MEMS microgyroscope for navigation and guidance

JPL's navigation grade post-resonating microgyroscope has one of the best performance characteristics. These microgyroscopes are being tested for sounding rocket missions and have strong potential for future sample return mission to Mars and elsewhere.

Micro Gyroscopes

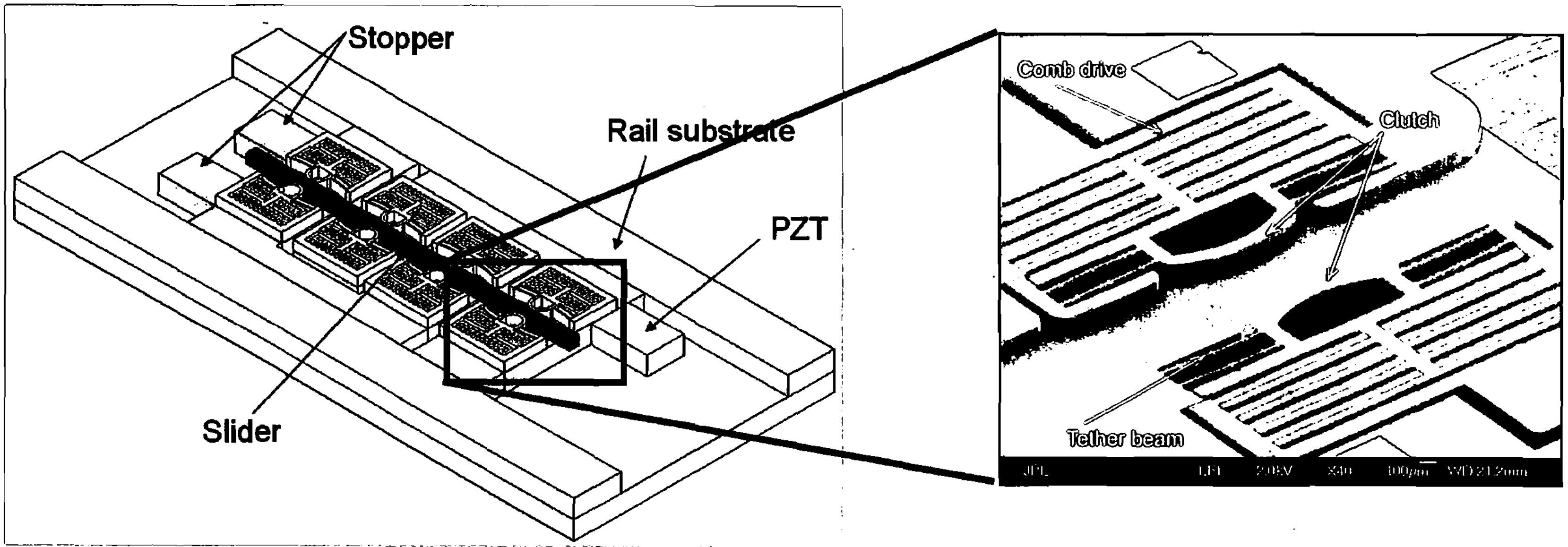


Even better disc-resonating microgyroscope

Our second generation microgyroscope uses a silicon disc as the resonating element. Not only do these add versatility to the range of applications because of their compact nature, but they are also more sensitive than post-resonating type. Disc-resonating gyroscopes have potential applications on future rovers, and in future sample returning missions.

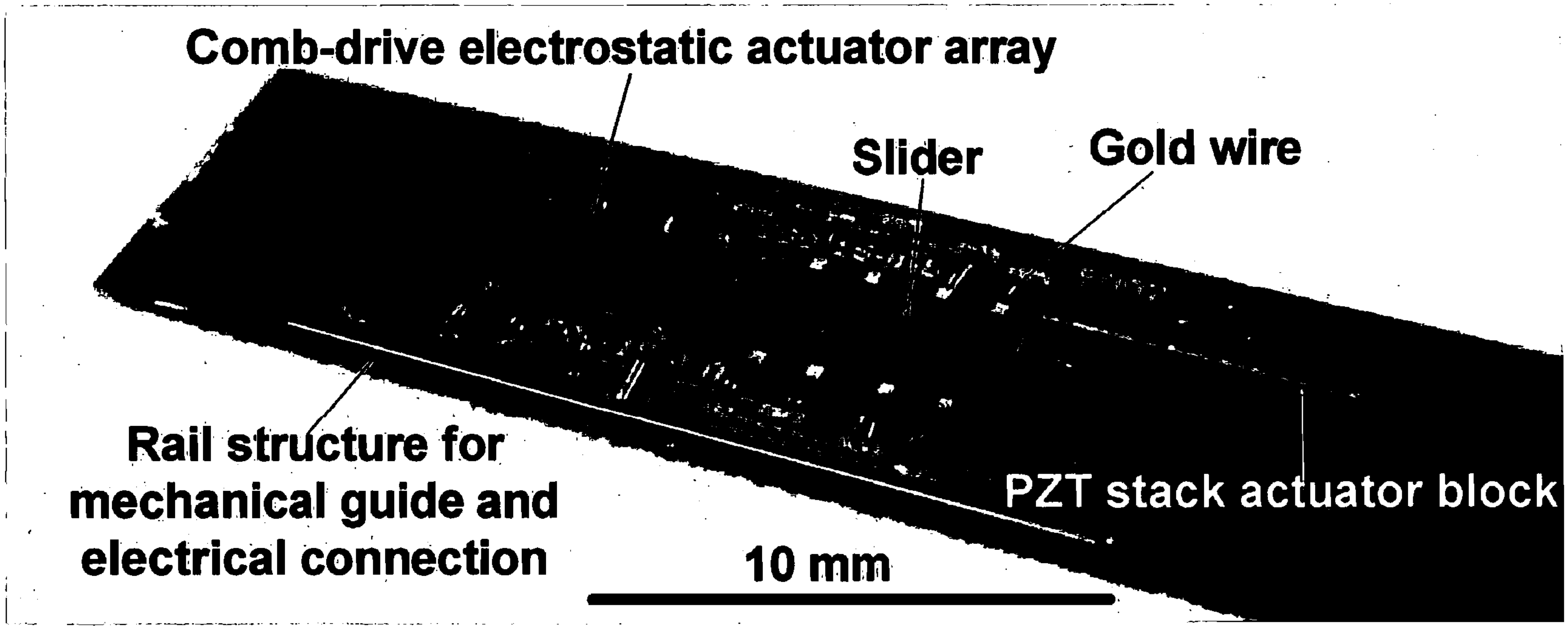
Inchworm Microactuator

Develop a precision silicon MEMS inchworm microactuator for a high-precision positioning/alignment applications as well as to achieve actuation in segmented large-area space telescopic mirror applications.



- Operation Temperature: 4 K ~ 370 K
- Stroke and Precision: > 1 mm and < 10 nm
- Clamping Force: > 10 mN
- Mean steady-state power: 100 μW
- Total volume: ~ 20 mm^3.

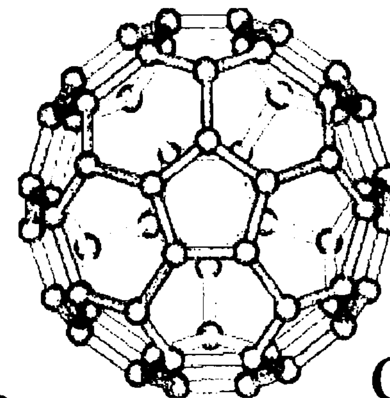
Inchworm Microactuator



Carbon Nanotubes and Silicon Nanotips

Carbon Nanotubes

Carbon nanotubes are fullerene related molecules.



C_{60}

Timeline

1991—discovered by Ijima in multiwalled form

1992—electronic structure predicted

1993—single walled tubes synthesized

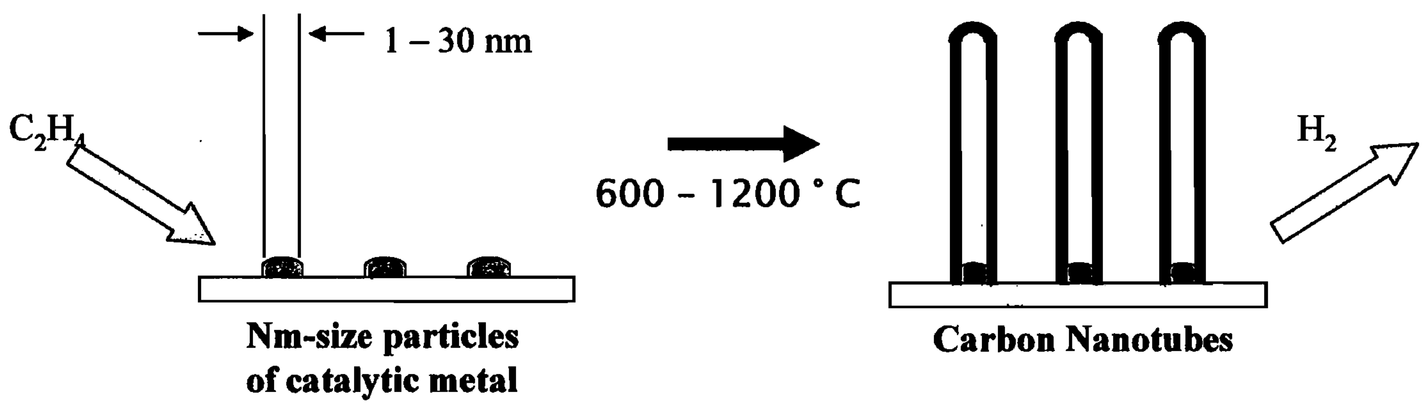
1995—field emission demonstrated

Etc.: hydrogen storage, nanoelectronic interconnects, superconductivity, quantum conductors, aligned tubes

Carbon Nanotubes

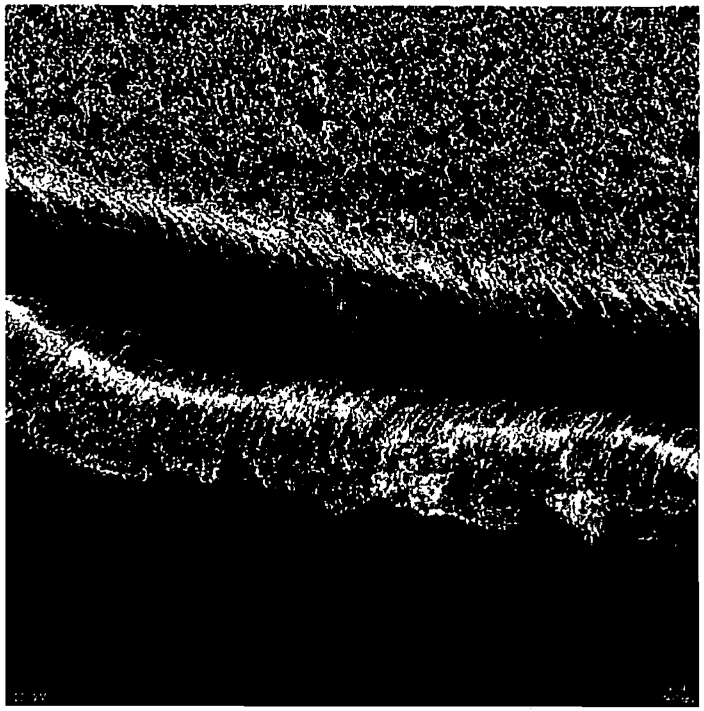
$$\text{Hydrocarbons } (C_nH_m) \xrightarrow[\text{600-1200 C}]{\text{Fe (or Ni, Co, etc.)}} C(s) + H_2$$

CVD Growth Process

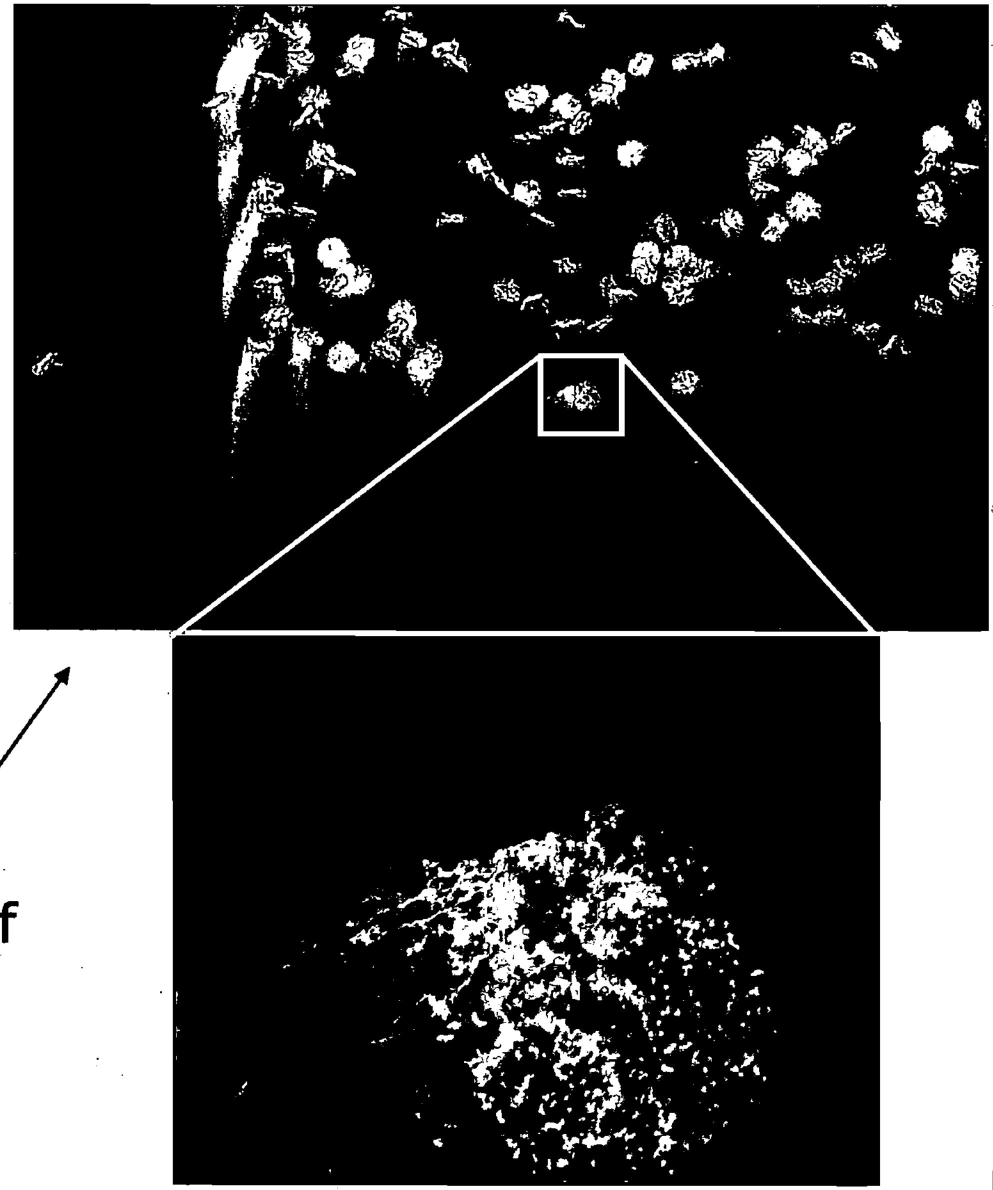


Size and position of catalytic particle determine size and position of resulting CNT

Carbon Nanotubes



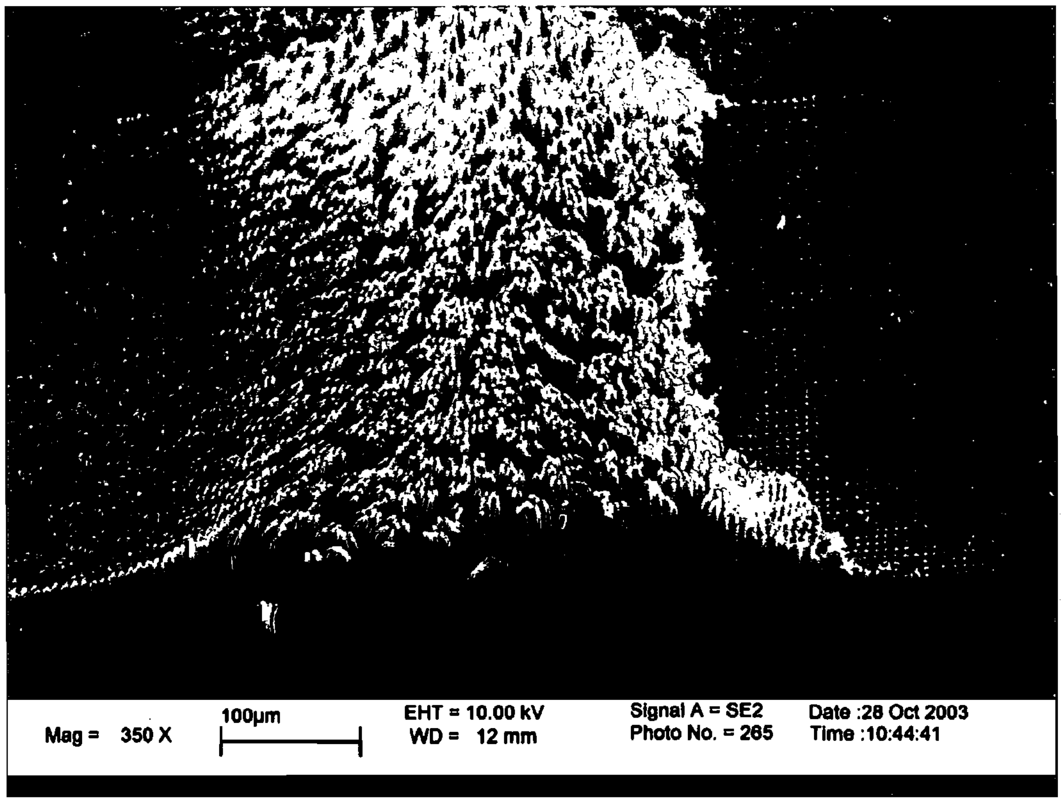
Dense forest of CNTs



Ordered arrays of CNTs

Carbon Nanotubes

CNT grown on sample with graded Fe thickness

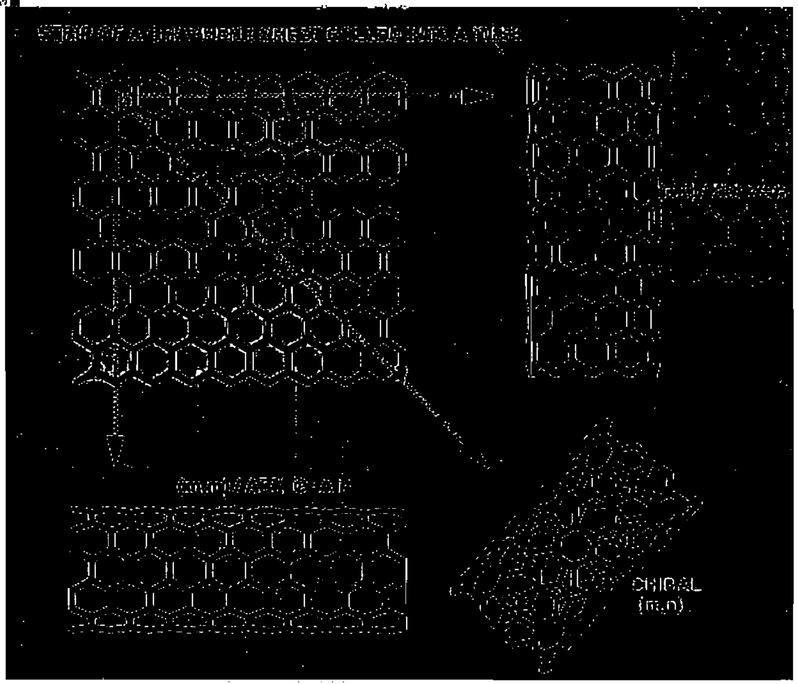


6 5 4 3 2 1 0

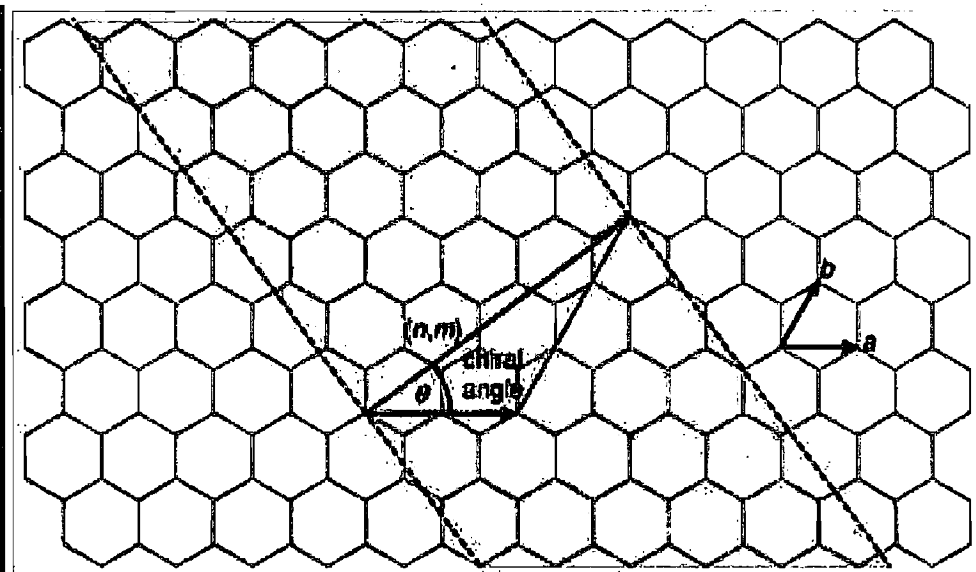
← **Fe catalyst thickness (nm)**

Carbon Nanotubes

Single-walled nanotubes- diameter 1 to 3 nm
Multi-walled nanotubes- diameter 4 to ~100 nm



Chirality is determined by rolling index: (n,m) which determines electronic properties.



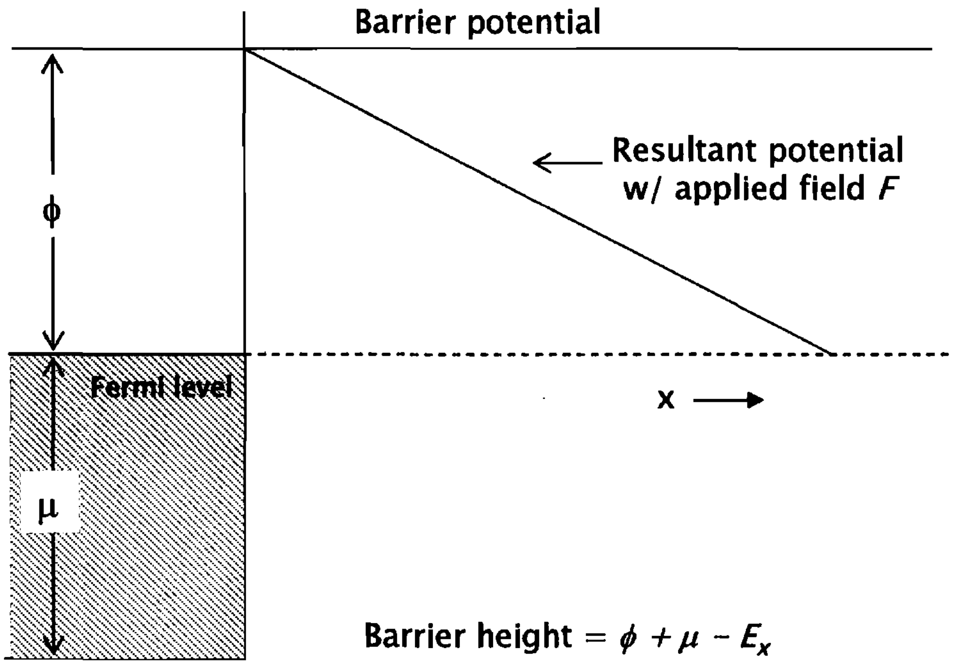
If: n = m ⇒ metallic

n − m = 3j {where j is an integer} ⇒ tiny-gap semiconductor *(virtually metallic at room temperature)*

Otherwise ⇒ large-gap semiconducting

Carbon Nanotubes

CNTs naturally have sharp tips. Sharp tips are attractive structures to generate electrons through field emission.



Barrier height $= \phi + \mu - E_x$

Barrier thickness $= (\phi + \mu - E_x) / (F.\ e)$

In thermionic and photoemissions, electrons are given sufficient energy to overcome the potential barrier at the metal surface.

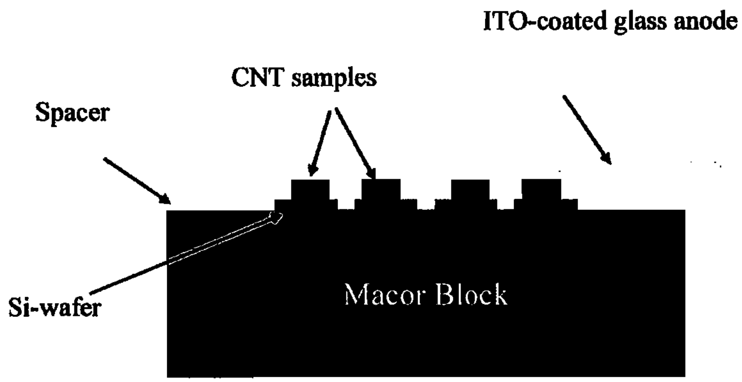
In field emission the barrier itself is deformed strongly through application of an external field that unexcited electrons can tunnel out.

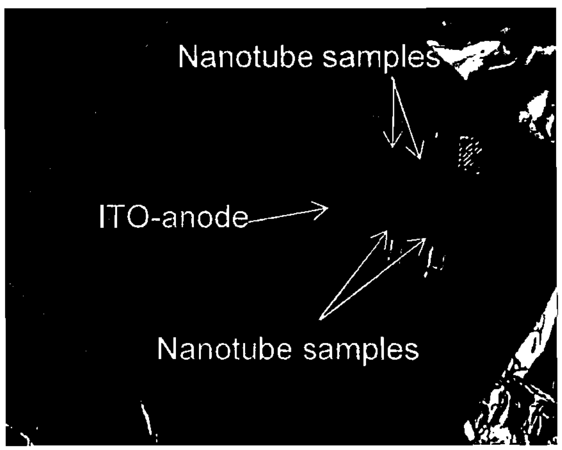
Carbon Nanotubes

CNT field emission sources are advantageous over the state-of-the-art.

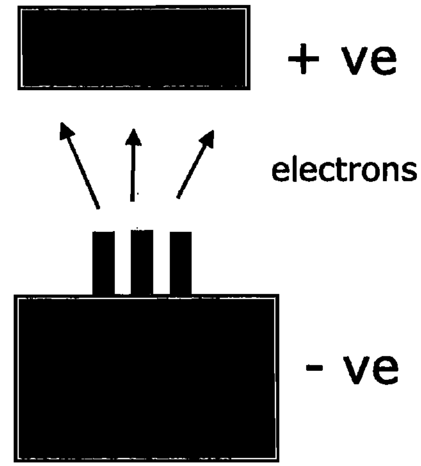
- Low operating voltage
- Low power consumption
- High current density (amperes/cm^2)
- Room temperature operation
- Very small size
- Light weight
- Conducive for integration into miniature instruments

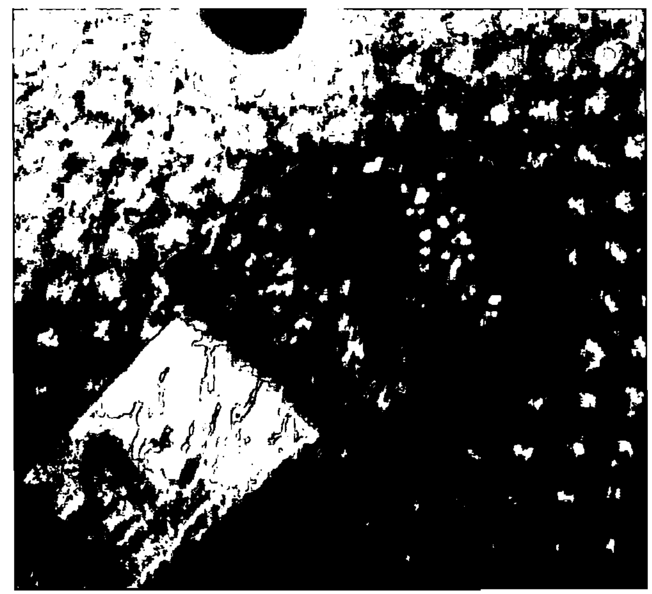
CNT Field Emitters





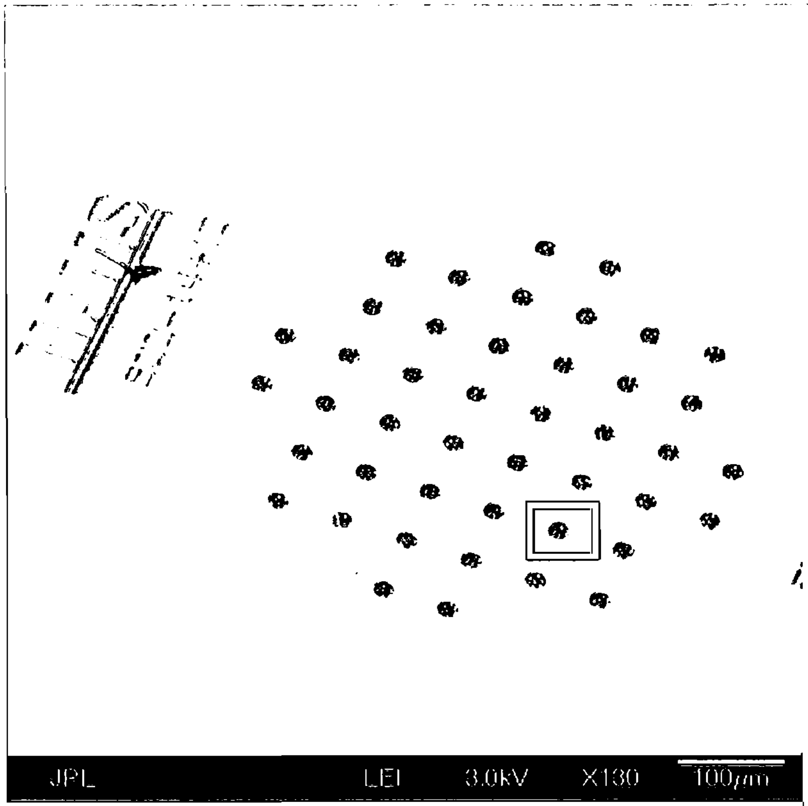
Diode mode setup



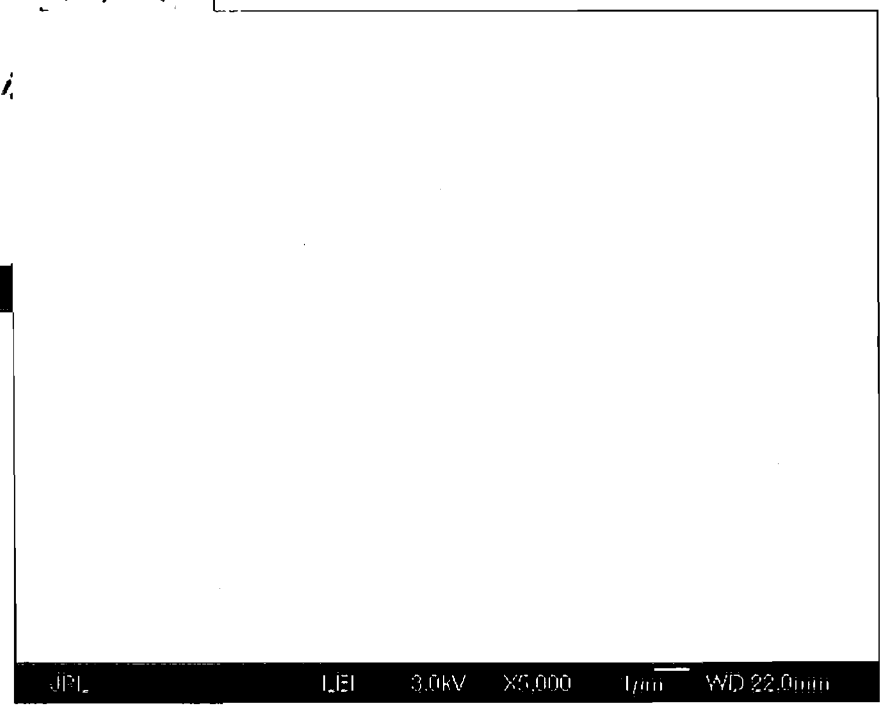


CNT Field Emitters

Monolithically gate-integrated CNT bundle array electron source



Close-up of a gate aperture.



E-Beam Microsystems

Miniature instruments need miniature electron sources...

- Next generation miniature X-ray Diffraction and X-ray Fluorescence instruments – for X-ray production
- Miniature mass spectrometers – for gas ionization sources
- Terahertz frequency vacuum tube oscillators and amplifiers – electron source
- Radiation insensitive vacuum electronics
- Next generation miniature Scanning Electron Microscope and Energy Dispersive X-ray Spectroscope – electron source

E.g., XRD / XRF

X-Ray Diffraction (XRD)

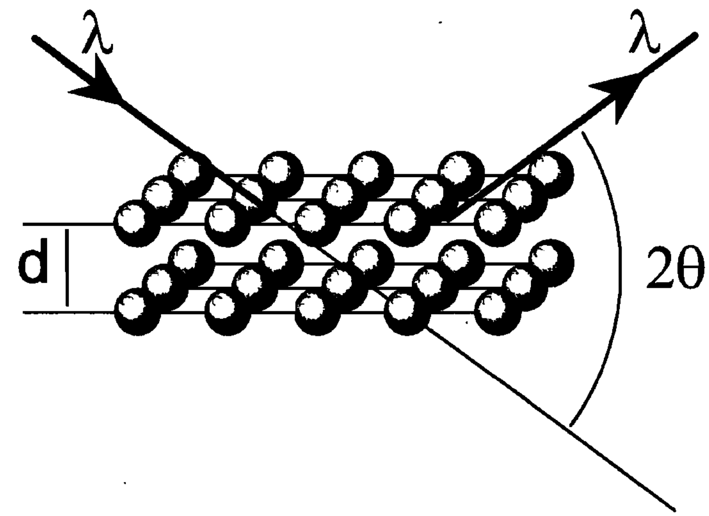
- To perform mineralogical characterization
- Smaller the beam spot, sharper is the diffraction data.
- Is a definitive mineralogy detection technique

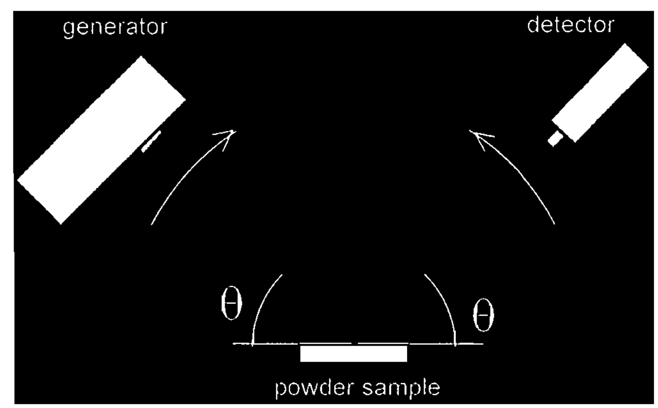
X-Ray Fluorescence (XRF)

- To detect elemental composition
- Higher incident photon flux, in principle, gives better S/N ratio (detector response speed limited).
- Needs both reflected fluorescence as well as transmitted in combination with a beam stop diode to perform quantitative analysis

X-Ray Diffraction

- X-rays reflected from the crystal planes are measured.
- Bragg's law n λ =2d·sinθ
- Conventionally, a source and a detector are moved to capture signal at all possible angles.

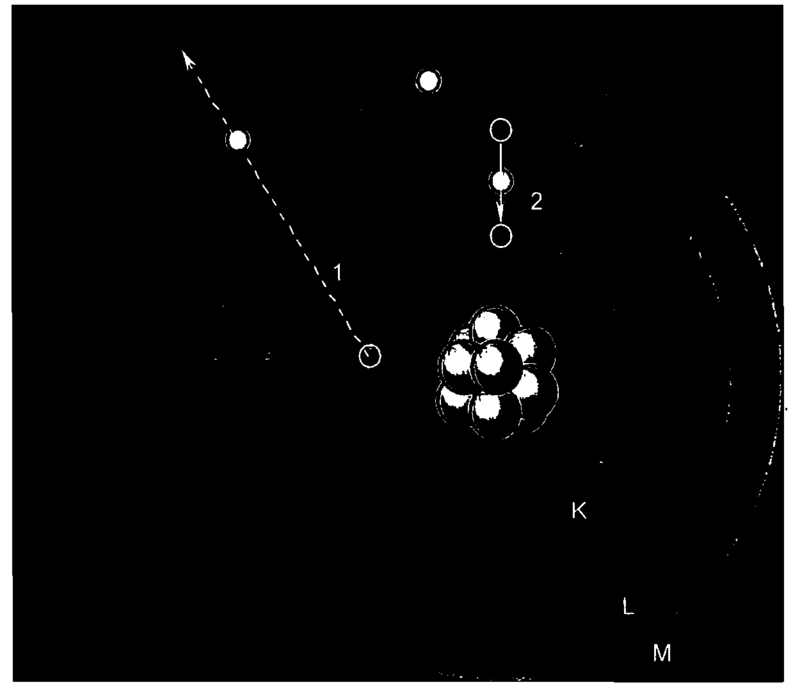




X-Ray Flourescence

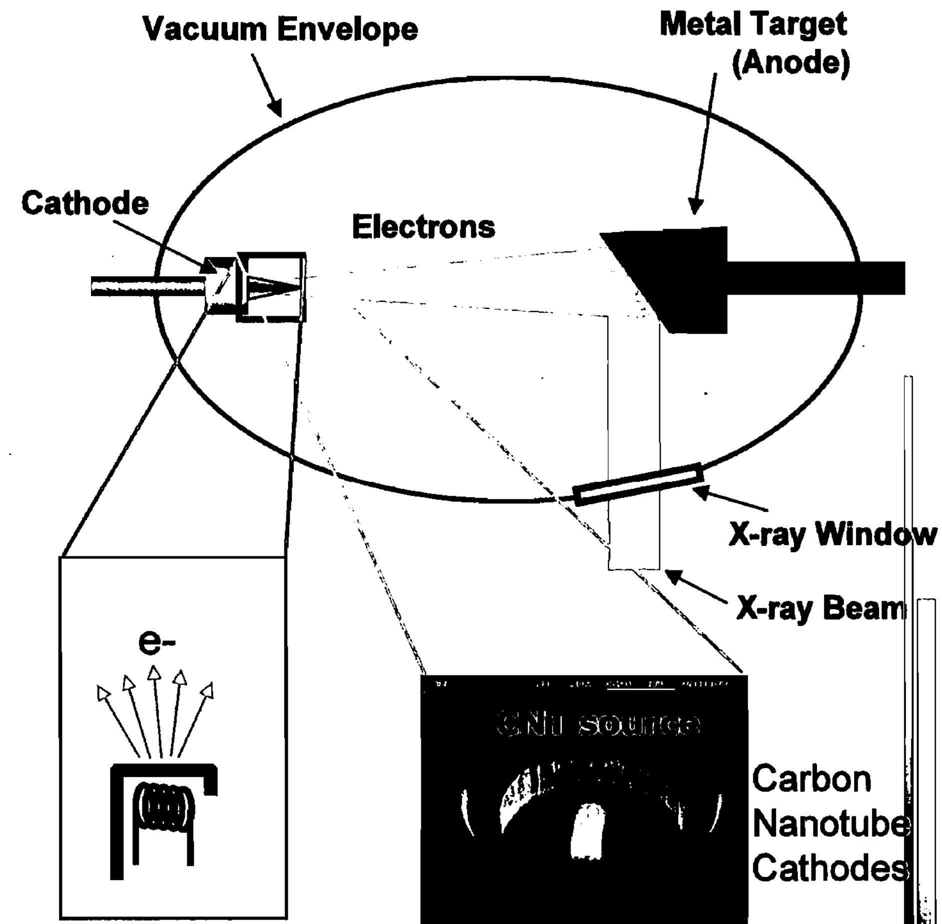
- X-ray photons of energy hν, knock off K-shell (high interaction cross section) electrons causing a vacancy. Vacancy is filled by electrons from the higher shells resulting in a photon of "difference" energy, hν' (fluorescence photons)

- These fluorescence photons are characteristic of the element.



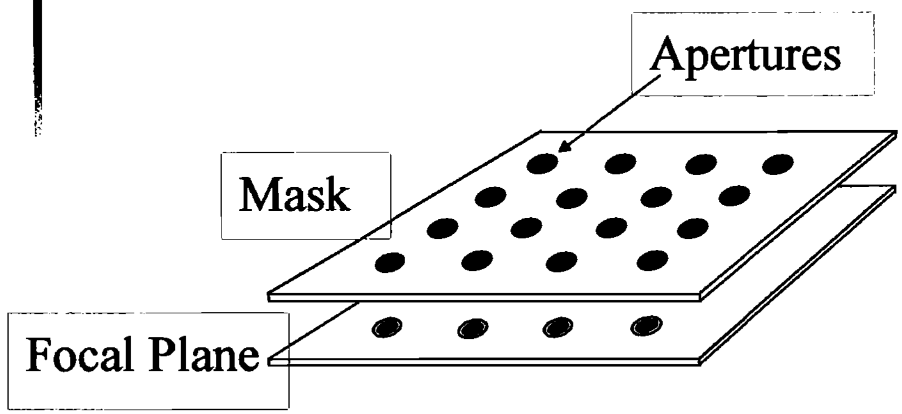
Miniature X-Ray Tube

- Accelerated electrons bombard with a metal target to produce a continuous X-ray spectrum (Bremsstrahlung) as well as characteristic X-ray lines.

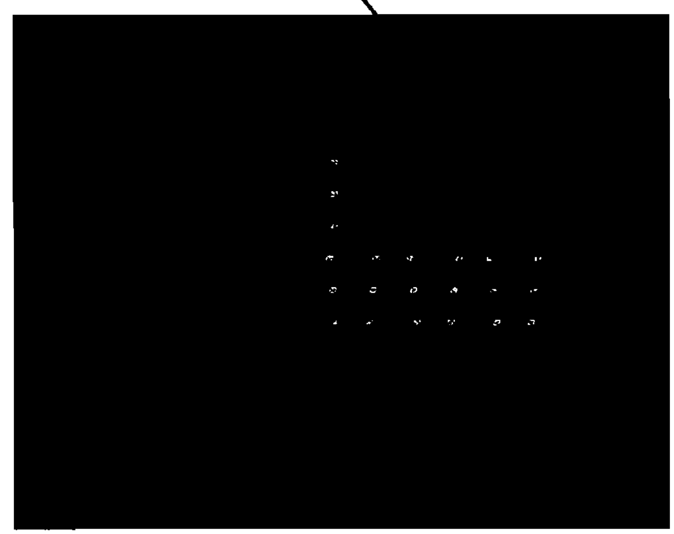


Ghost Images on Mars Sun Sensor

Using Sun's position to navigate



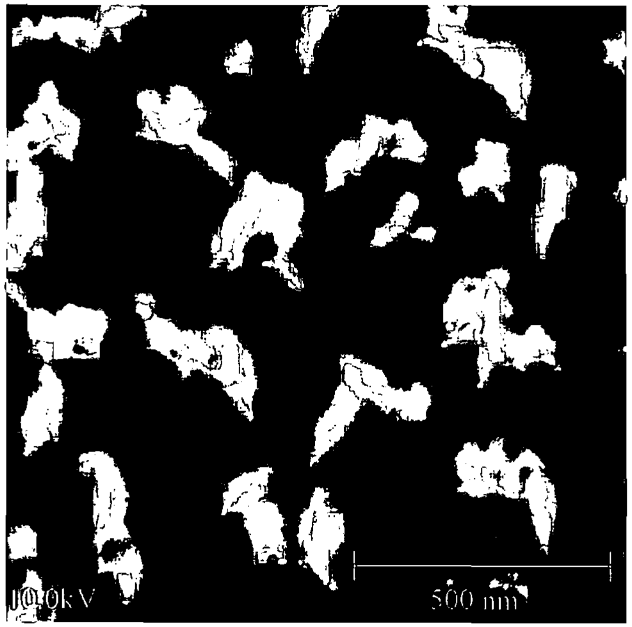
Internal reflections between the mask plate and the APS focal plane caused ghost images severely decreasing the accuracy.



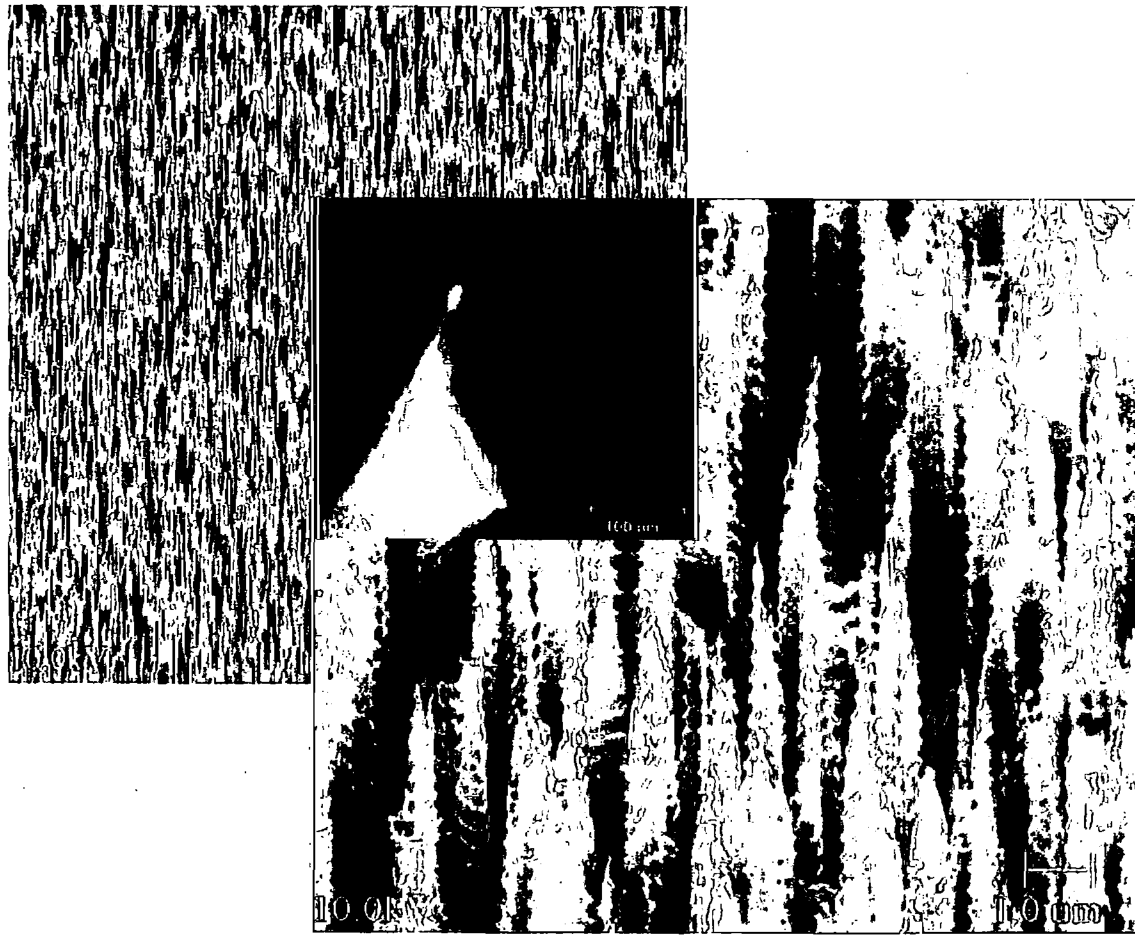
Selectively covering the backside of the mask plate with Si-nanotips removed the ghost image problem entirely!

Light Trapping

Silicon Nanotip Anti-Reflection Coating

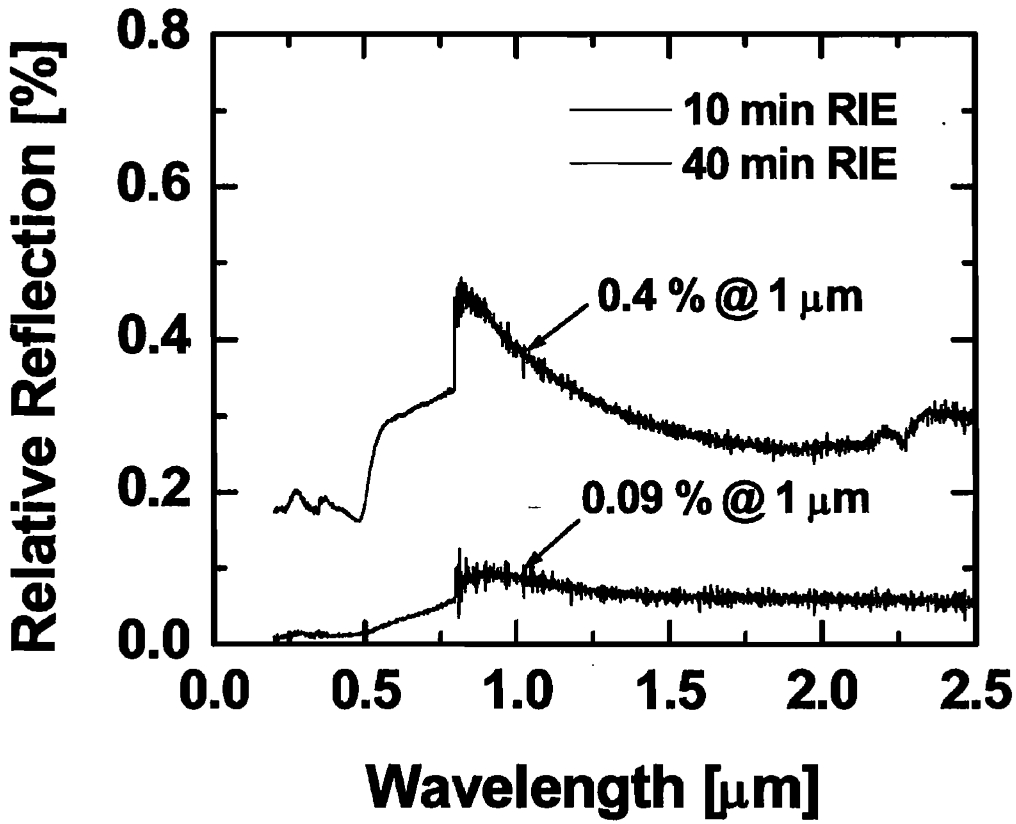


RIE- Polymer Grass



DRIE- Silicon Nanotips

Silicon Nanotip Anti-Reflection Coating



Successfully used in Mars Micro Sun Sensor to remove ghost images.

Thank you!