WELCOME TO THE COURSE ON MICROMACHINING

FOCUSED ION BEAM MACHINING

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ACKNOWLEDGEMENT

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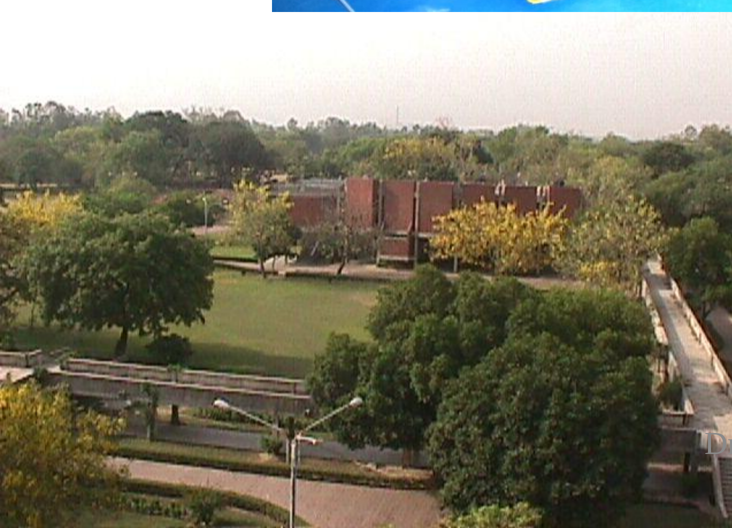
ORGANISATION

- **Introduction**
- **Ion Solid Interaction**
- **Focused Ion Beam**
- **Nanostructures fabricated by focused ion beam**
- **Characterization of nanostructures fabricated by FIB**

Energetic Ion Beams: A unique tool for micro and nano fabrication and futuristic technology development

Vishwas N Kulkarni
Department of Physics, IIT Kanpur



NANO-TECHNOLOGY AND ION BEAM MACHINING

- **NANO-TECHNOLOGY / NANO-MACHINING → TARGET OF ULTRAPRECISION MACHINING OF THE ORDER OF 1 nm. THE THEORETICAL LIMIT OF ACCURACY IN MACHINING EQUALS TO A FRACTION OF THE SIZE OF AN ATOM OR MOLECULE.**

- **ION BEAM MACHINING (IBM): MOLECULAR MANUFACTURING PROCESS BASED ON THE SPUTTERING OFF PHENOMENON.**

  -MATERIAL REMOVAL TAKES PLACE IN THE FORM OF REMOVAL OF ATOM OR MOLECULE FROM THE SURFACE OF THE WORK-PIECE.

- **THE PROCESSES CAN BE APPLIED TO THE MANUFACTURING OF ULTRA-FINE PRECISION PARTS OF ELECTRONIC AND MECHANICAL DEVICES.**

The core of all the modern technologies:

-fabrication of variety of sensors

- miniaturization

-integration

PRODUCT DEVELOPMENT CYCLE

Need → Design → machining processes → prototypes → tests → reliability-production – Marketing/utilization

Buzz words

Top-down /Bottom-up approaches

(Layered Mfg., Green Mfg., Environment Friendly Mfg.)

Microfabrication

Micromilling

microcutting

Assembling

……….

Ion - Matter Interaction

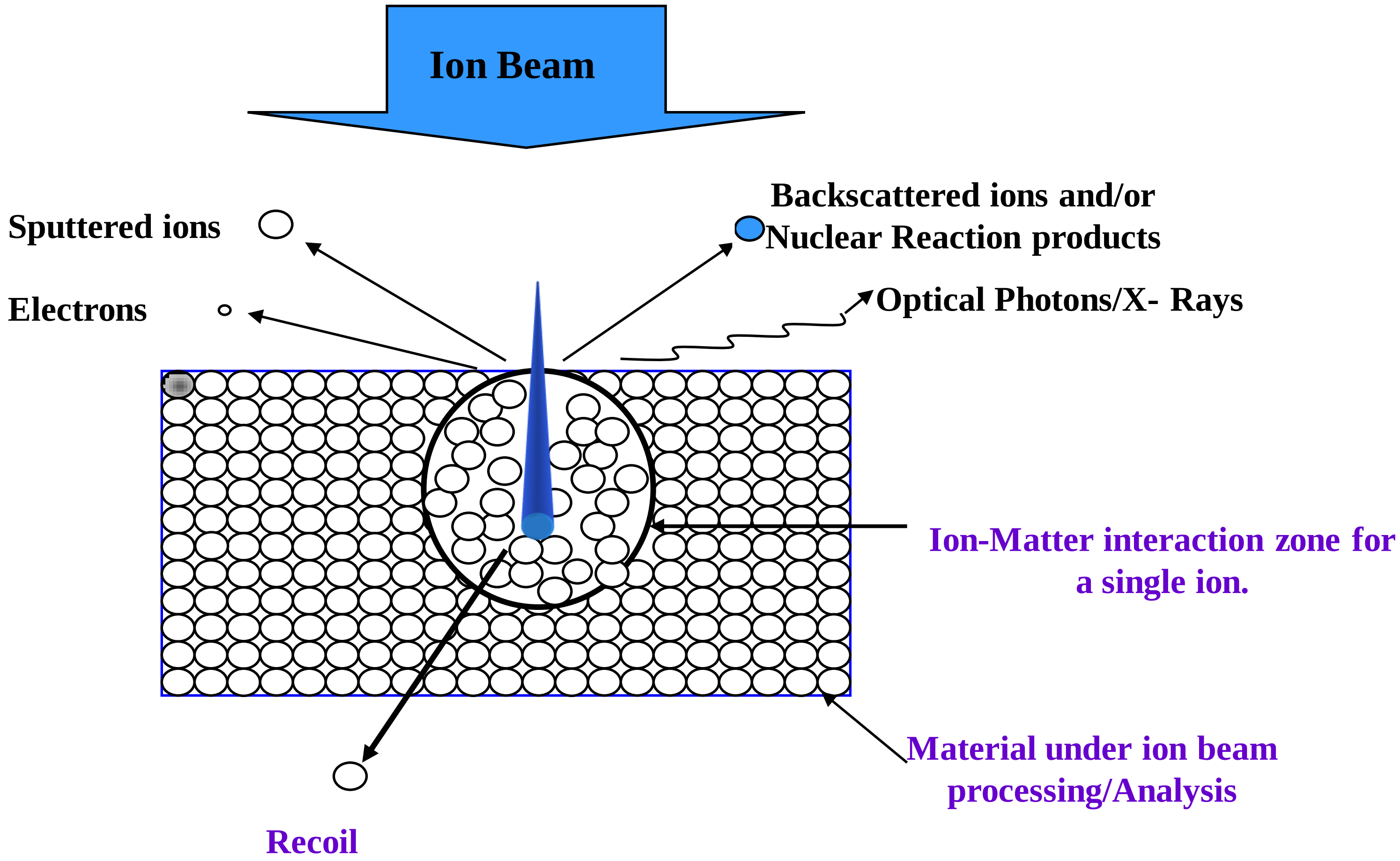
How the accelerators and ion beams become not only Relevant and alternative but indispensable as compared to the traditional engineering ways?

What is an Ion beam? :

A stream of energetic ions ranging in energy from few Electron Volt (eV) to several mega electron volts created by what is called as "particle accelerators " such as Van de Graaff, Cyclotron etc.

The first accelerator was developed in 1932 for Nuclear physics experiments. Subsequently the accelerator and ion beams found way in device technology (and revolutionized this area in microchip fabrication), materials Science and more recently in micro and nanofabrication.

Focused ion beams has become finest possible drill machine ever possible and it can create of the smallest brick as structural element


Ion Beam
Sputtered ions
Electrons
Backscattered ions and/or
Nuclear Reaction products
Optical Photons/X- Rays
Ion-Matter interaction zone for
a single ion.
Material under ion beam
processing/Analysis
Recoil

Ion beam induced processes

Depending on the **ion energy**, following interactions can happen:

- ✓ **Deposition**
- ✓ **Sputtering**
- ✓ **Re-deposition**
- ✓ **Implantation**
- ✓ **Backscattering**

Note: ***Not all effects are completely separable and this may lead to unwanted side effects for a specific application.***

MECHANISM OF MATERIAL REMOVAL IN ION BEAM MACHINING

- **SPUTTERING OFF: KNOCKING OUT ATOMS FROM THE WORK-PIECE SURFACE BY THE KINETIC ENERGY TRANSFER FROM INCIDENT ION TO THE TARGET ATOMS**
- **REMOVAL OF ATOMS WILL OCCUR WHEN THE ACTUAL ENERGY TRANSFERRED EXCEEDS THE USUAL BINDING ENERGY.**

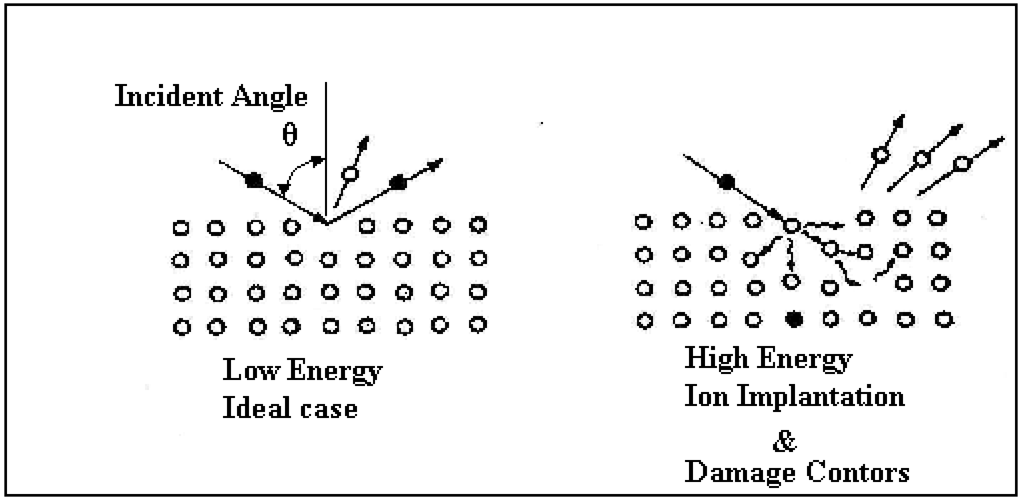
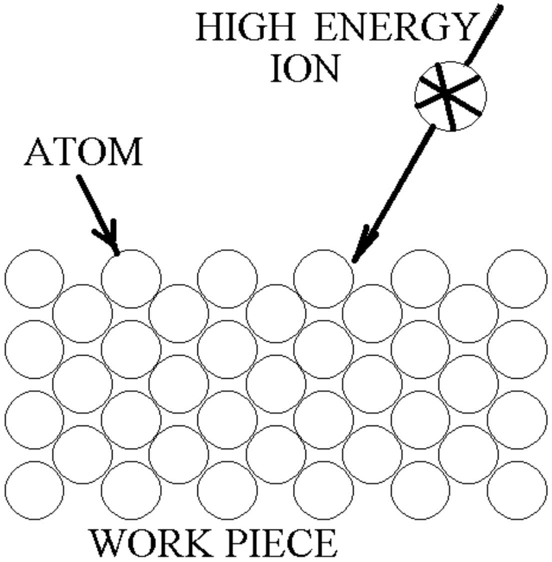
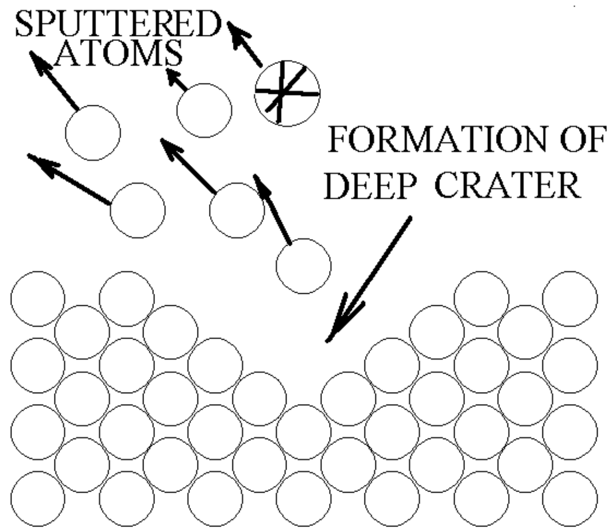
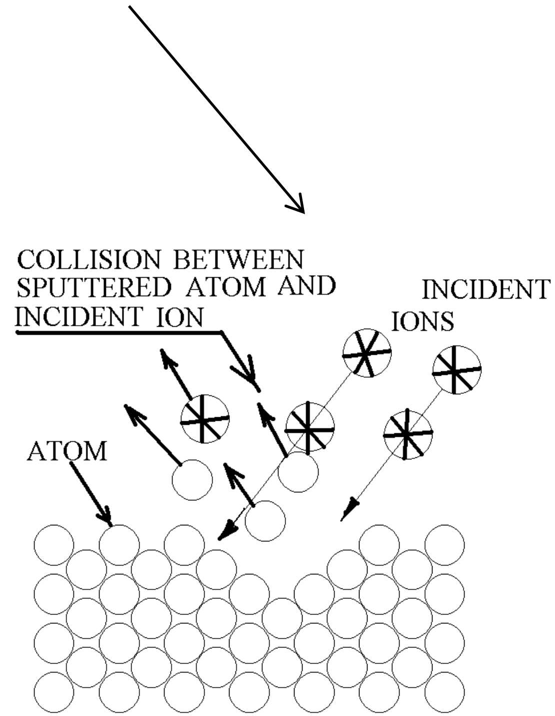


ILLUSTRATION OF THE MECHANISM OF MATERIAL REMOVAL IN IBM

- **AT SUFFICIENTLY HIGH ENERGY, THE CASCADING EVENTS WILL PENETRATE MORE DEEPLY INTO THE SOLID. SEVERAL ATOMS OR MOLECULES WILL BE EJECTED OUT AND THE BOMBARDING ION WILL BECOME IMPLANTED DEEP WITHIN THE MATERIAL**

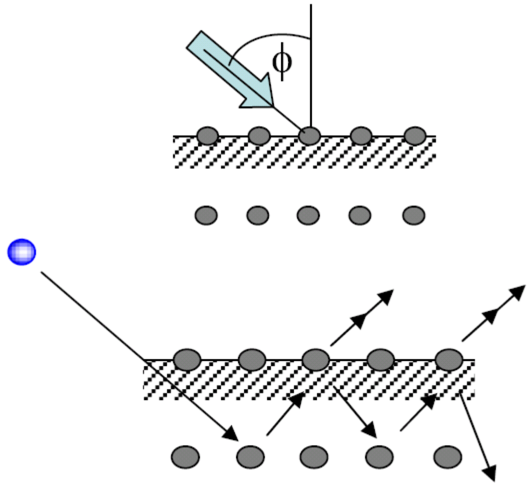






PROBABILITY OF COLLISION BETWEEN THE INCIDENT IONS AND SPUTTERED ATOMS BECOMES LARGER WITH INCREASING ION CURRENT DENSITY THAT CAUSES IRREGULAR MACHINING ON THE SURFACE.

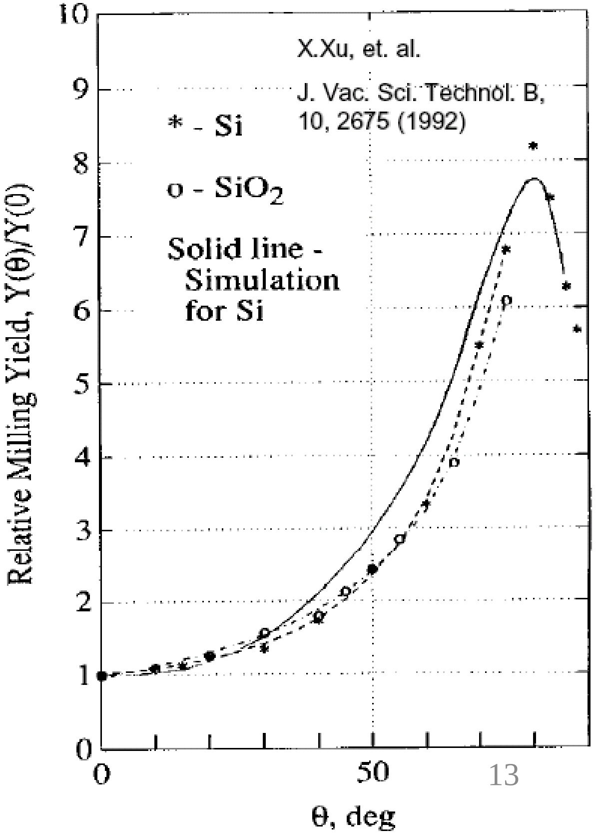
Sputtering Yield
Ion Incident angle dependence



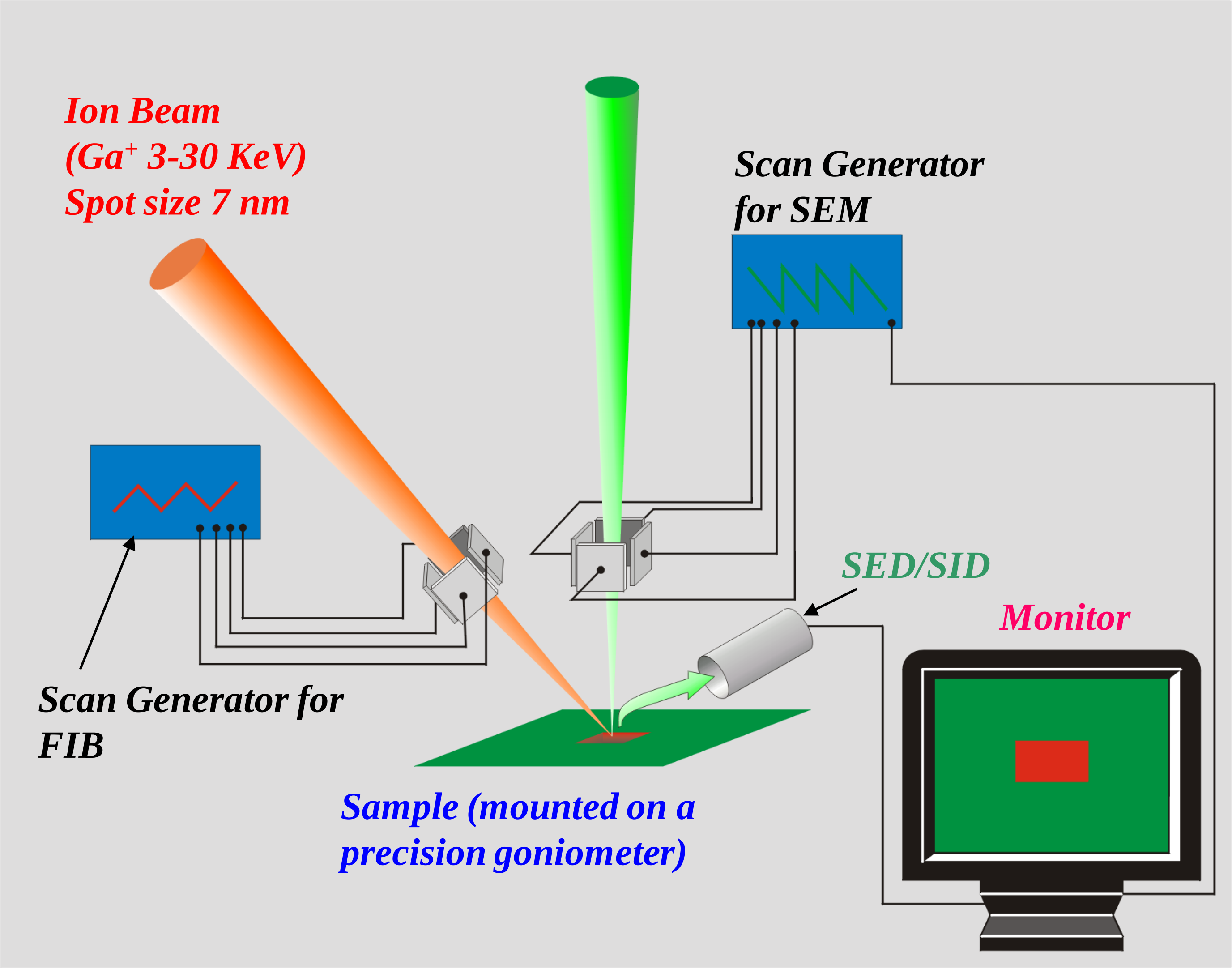
- **Generally increasing the incidence angle increases the sputter yield – Max around 80 degrees.**

- **As the angle of incidence increases from normal incidence, the possibility of the target atoms escaping from the surface during collision cascades, increases and eventually leads to increased sputter.**

- **After reaching a maximum the sputter yield decreases again as the ion approaches glancing incidence.**



Schematic Diagram of a Focused Ion Beam System



Ion Column

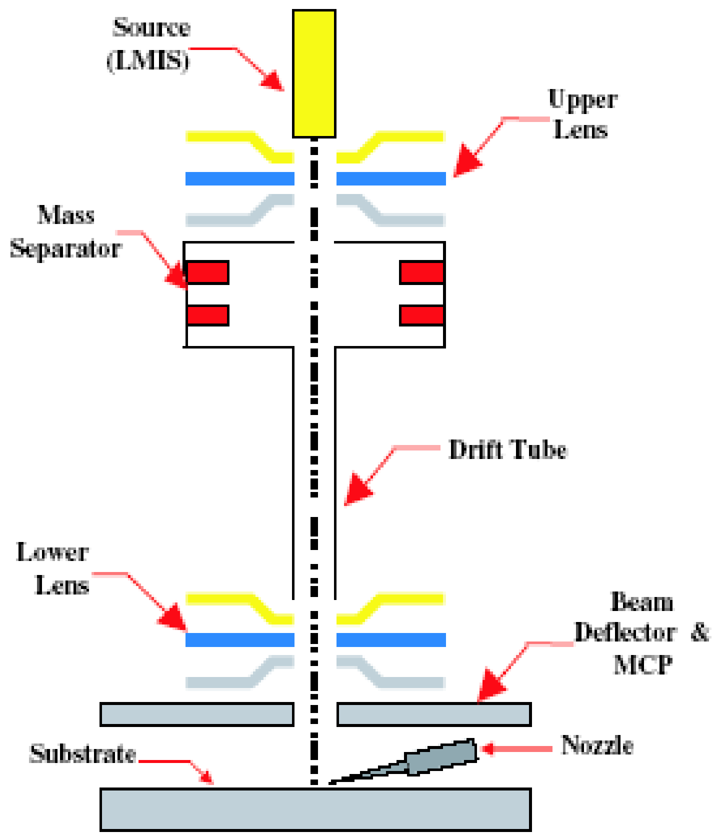


Figure 1. Schematic diagram of a two-lens FIB system.

- Mass separator is a setup that allows only the required amount of ions with a fixed mass-charge ratio to pass through.
- Below the mass separator there is a long and thin drift tube, which eliminates the ions that are not directed vertically.
- The lower objective lens helps in reducing the spot size of the beam and in improving focus.
- Finally there is the electrostatic beam deflector which controls the final landing location of the ions.

Focused Ion Beam System Components

- A Vacuum system and chamber
- A liquid metal ion source (LMIS)
- An ion column for milling and deposition
- A precision Goniometer for sample mounting and manipulation
- Imaging detectors
- A gas injection system to spray a precursor gas on the sample surface
- **An electron column for imaging**
- Scan generators for ions and electrons
- Computer control.

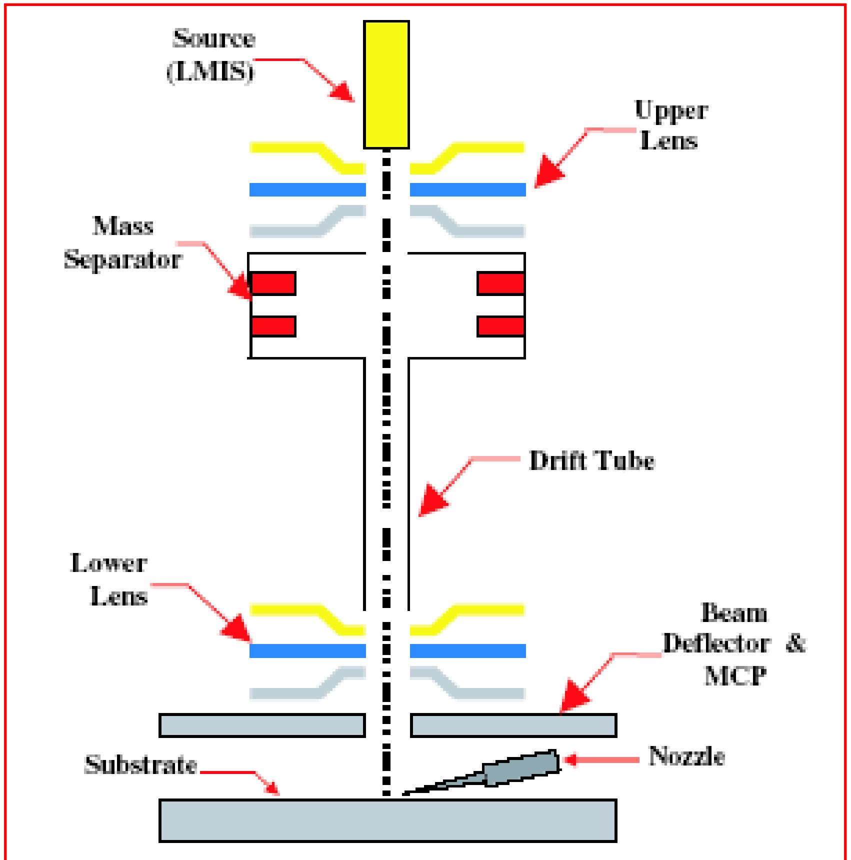
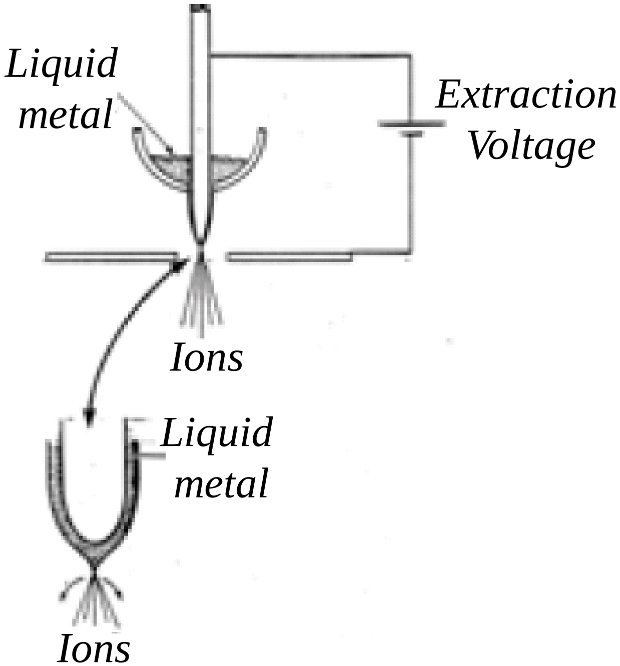


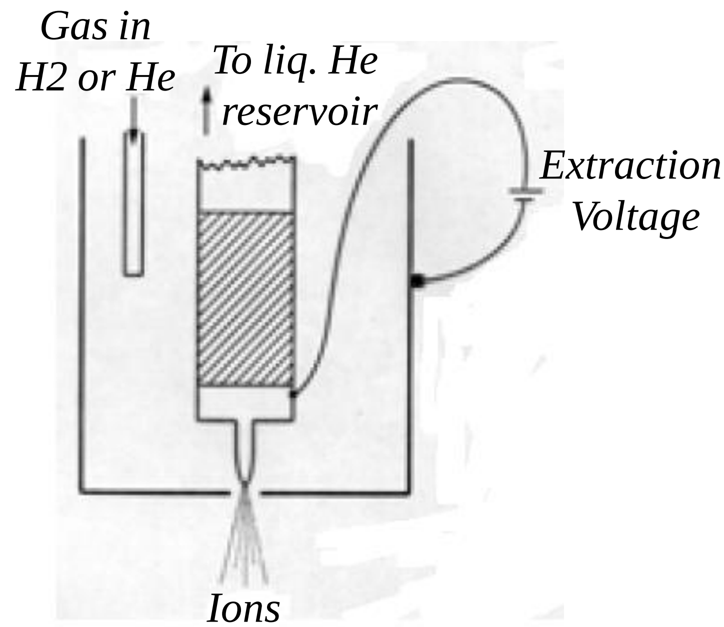
Figure 1. Schematic diagram of a two-lens FIB system.

Ion Sources

Liquid metal ion source



Gas field ion source



Type of ion source	Ion species	Virtual Source size (nm)	Energy spread, ΔE (eV)	Unnormalized brightness (A/cm^2sr)	Angular brightness (μA/sr)
Liquid metal	Ga^+	50	>4	3×10^6	50
Gas field ion (supertip)	H+, H_2^+,He^+, Ne^+ _ _ _	0.5	~1	5×10^9	35

Liquid metal ion source (LMIS)

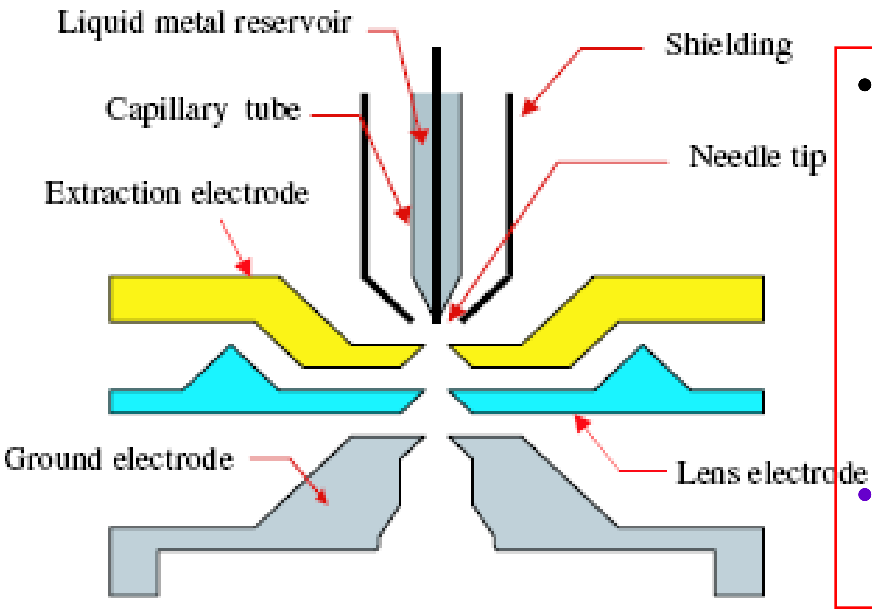


Figure 2. LMIS in a two-lens system.

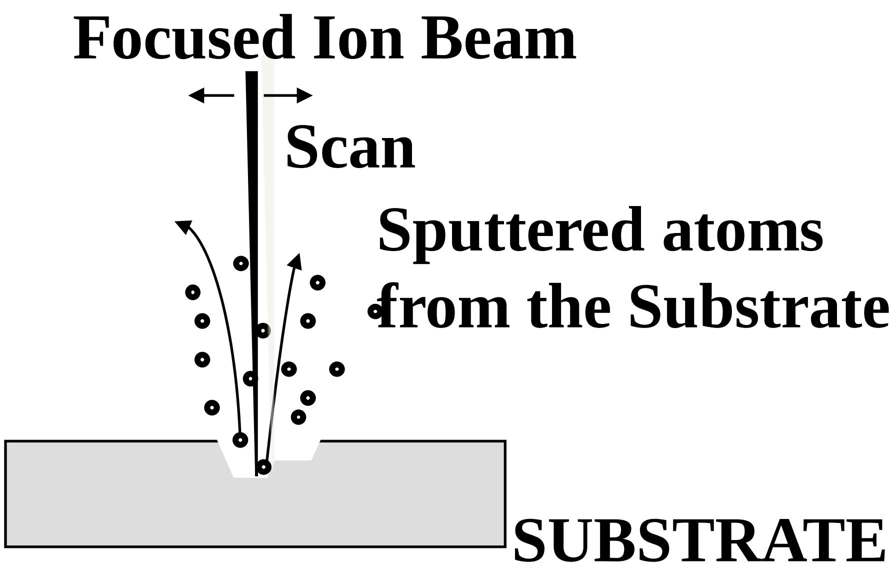
- LMIS Consists of a
  - **capillary tube with a needle through it**
  - **an extraction electrode and**
  - **a shielding.**
- **Capillary acts as a reservoir that feeds the metal to the tip.**

- Heated Ga flows and wets the needle having tip radius 2-5 µm.
- **A suppresser voltage [electric field (10^8 V/cm)] applied to the end of the wetted tip that causes the liquid Ga to form a point source (2-5 nm tip) in the shape of "Taylor cone".**
- **Conical shape forms because of electrostatic and surface tension force balance.**
- **An extraction voltage pulls Ga from the tip and efficiently ionizes it by field evaporation of the metal at the end of the Taylor cone.**

Basic Operating Modes

- ✓ **Emission of secondary ions and electrons**
  FIB Imaging (Low ion current)
- ✓ **Sputtering of substrate atoms**
  FIB Milling (High ion current)
- ✓ **Chemical interactions (Gas assisted)**
  FIB Deposition
  Enhanced Etching

FIB Milling



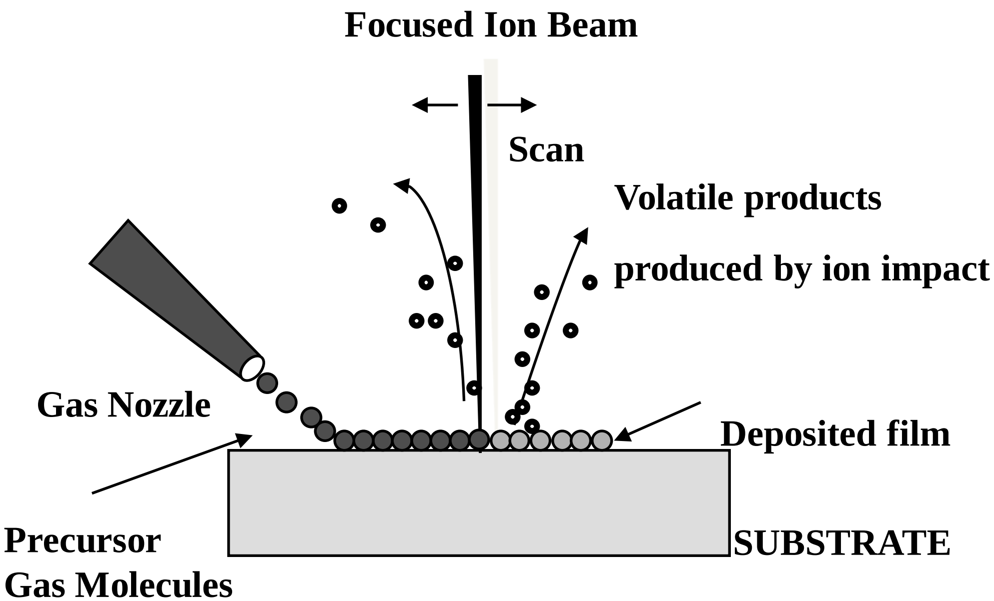
Nano-scale Milling

- For milling applications it is desirable that the incoming ions interact only with the atoms at the surface.
- If the ion energy (momentum) is adequate the collision can transfer sufficient energy to the surface atom to overcome its surface binding energy (3.8eV for Au and 4.7 eV for Si).

Note: There are other variants of the process like Reactive Ion Etching (RIE) where chemical species are incorporated and the process proceeds chemically

- **Interaction solely depends on momentum transfer to remove the atoms, sputtering is purely a physical process.**

FIB Deposition



Nanoscale Deposition

For FIB induced deposition, the necessary processes are

- ❑ **Adsorption of the chemical precursor gas onto the sample surface.**
- ❑ **Decomposition of gas molecules into volatile and non volatile products by focused ion beam.**

Focused ion beam scanning is our hand which defines the deposition area.

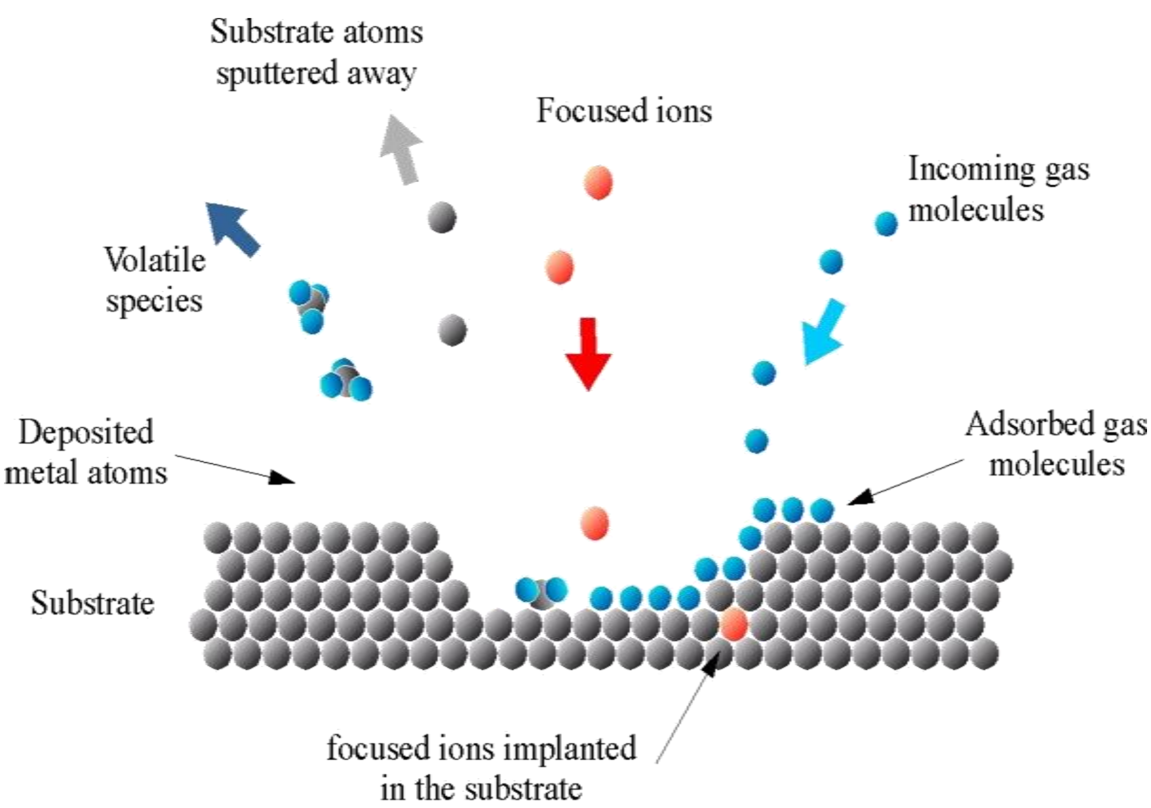
3 dimensional nanostructures can be fabricated using layer by layer deposition.

Precursor must have two properties, namely :

- ❑ **Sufficient sticking probability to stick to a surface of interest in sufficient quantity.**
- ❑ **Decompose more rapidly than it is sputtered away by the ion beam.**

WORKING PRINCIPLE OF ION BEAM MACHINING

Gas Injection System: Gas assisted etching

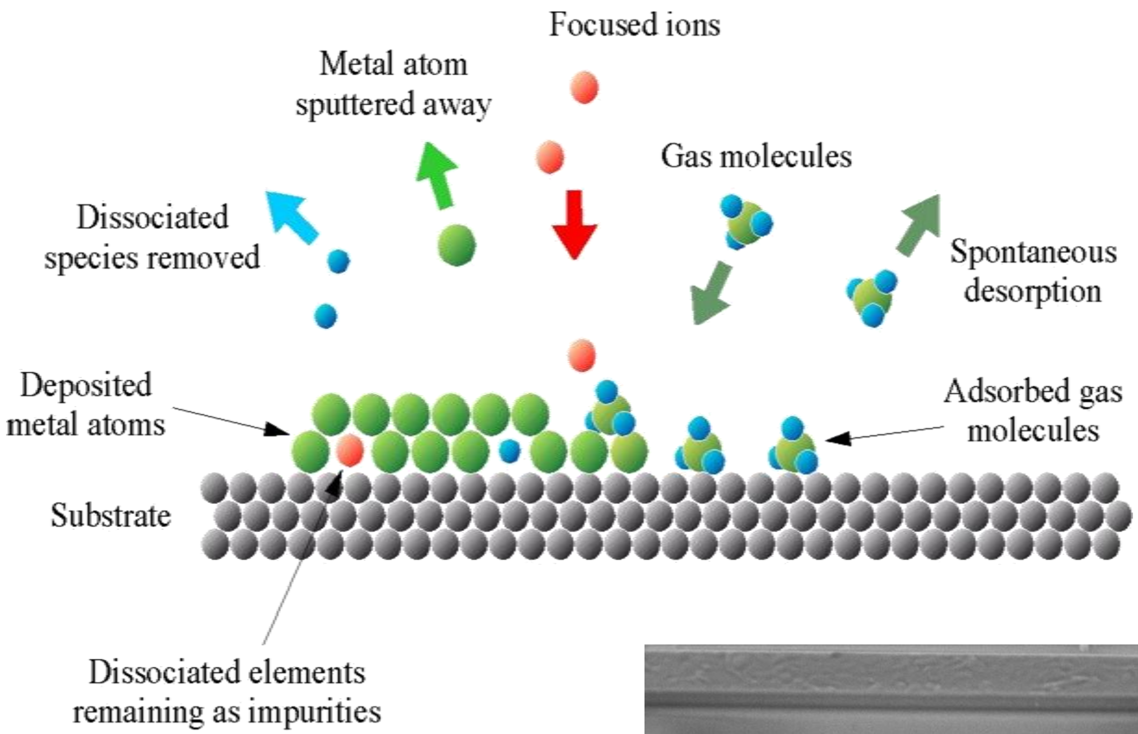


1. ADSORPTION OF THE GAS MOLECULES ON TO THE SUBSTRATE SUURFACE
2. ACTIVATION OF A CHEMICAL REACTION OF THE GAS MOLECULES WITH THE SUBSTRATE BY THE ION- / ELECTRON- BEAM
3. GENERATION OF VOLATILE REACTION- PRODUCTS : $GACl_3$ $SICl_4$ SIF_4
4. EVAPORATION OF VOLATILE SPECIES AND SPUTTERING OF NON-VOLATILE SPECIES

Available on CrossBeams:

XeF_2, H_2O

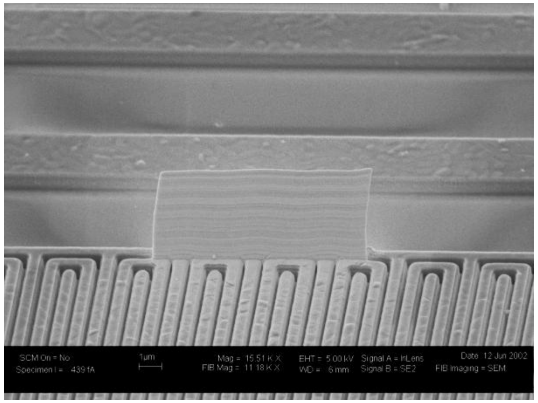
Gas Injection System: Deposition



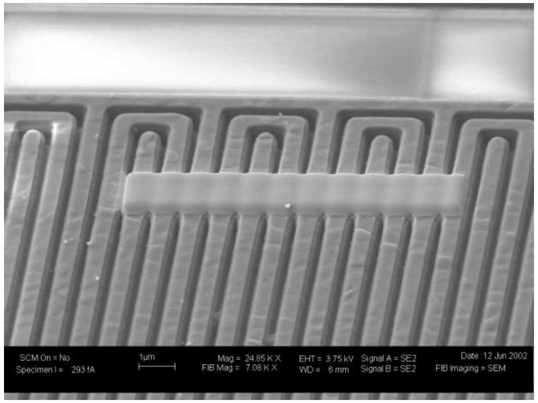
1. **ADSORPTION OF THE PRECURSOR MOLECULES ON THE SUBSTRATE**
2. **ION BEAM / E-BEAM INDUCED DISSOCIATION OF THE GAS MOLECULES**
3. **DEPOSITION OF THE MATERIAL / METAL ATOMS AND REMOVAL OF THE ORGANIC LIGANDS**

Available on LEO CrossBeams:

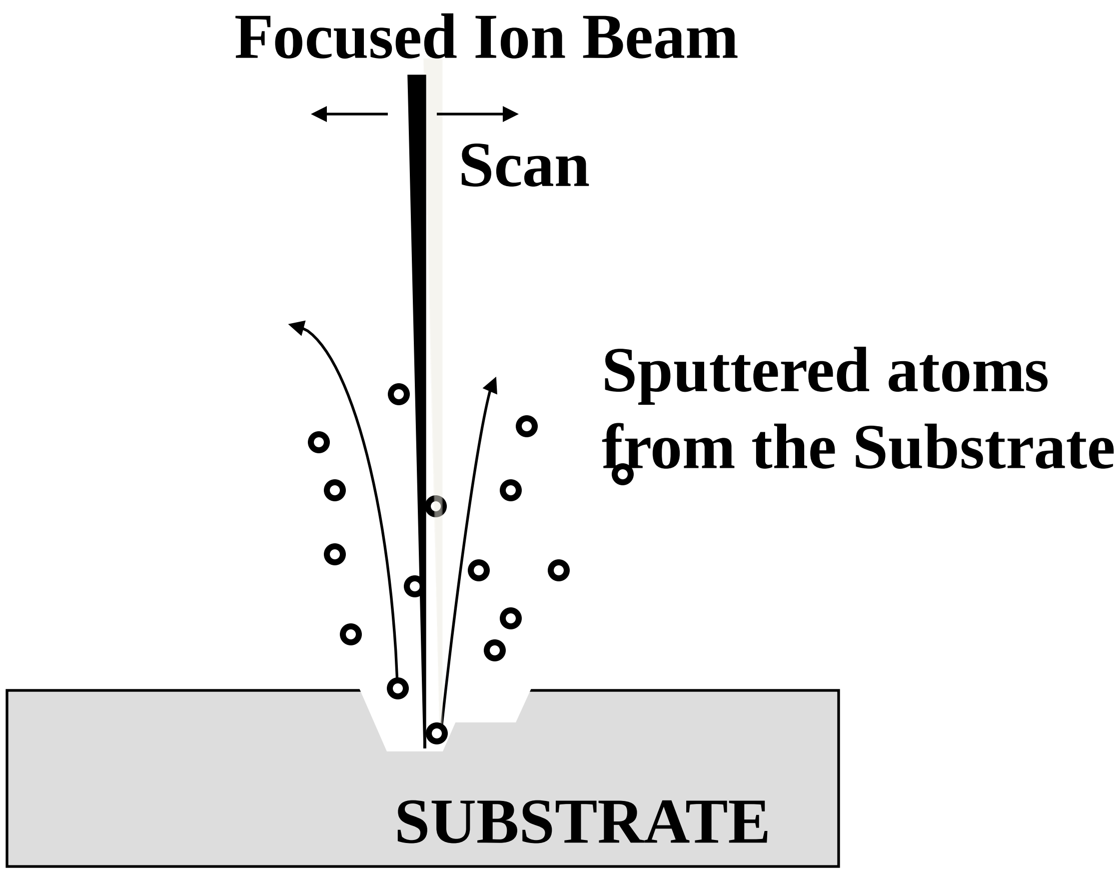
Metals:	W, Pt
Insulator:	SiO_2



Tungsten wall

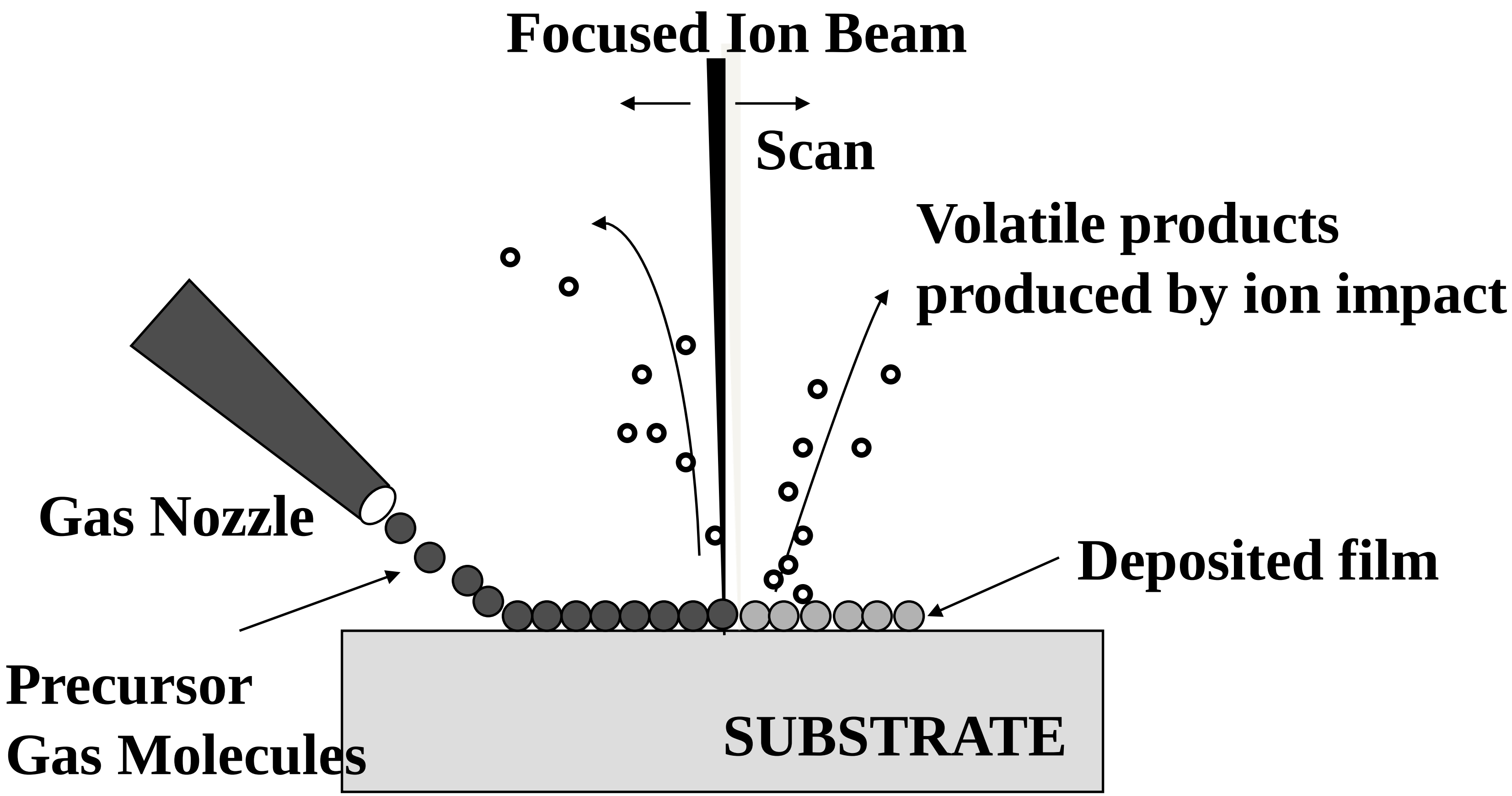


Tungsten deposition

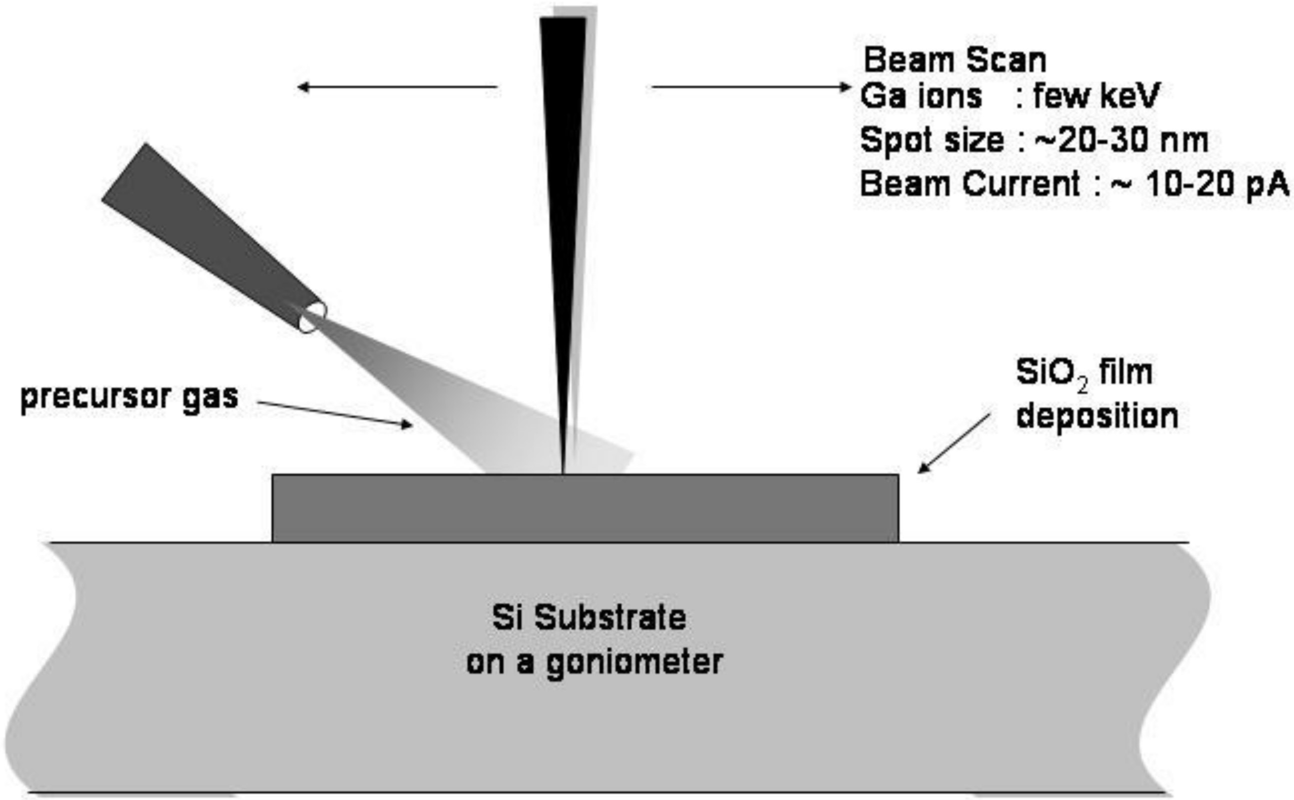


Nanoscale Milling by FIB

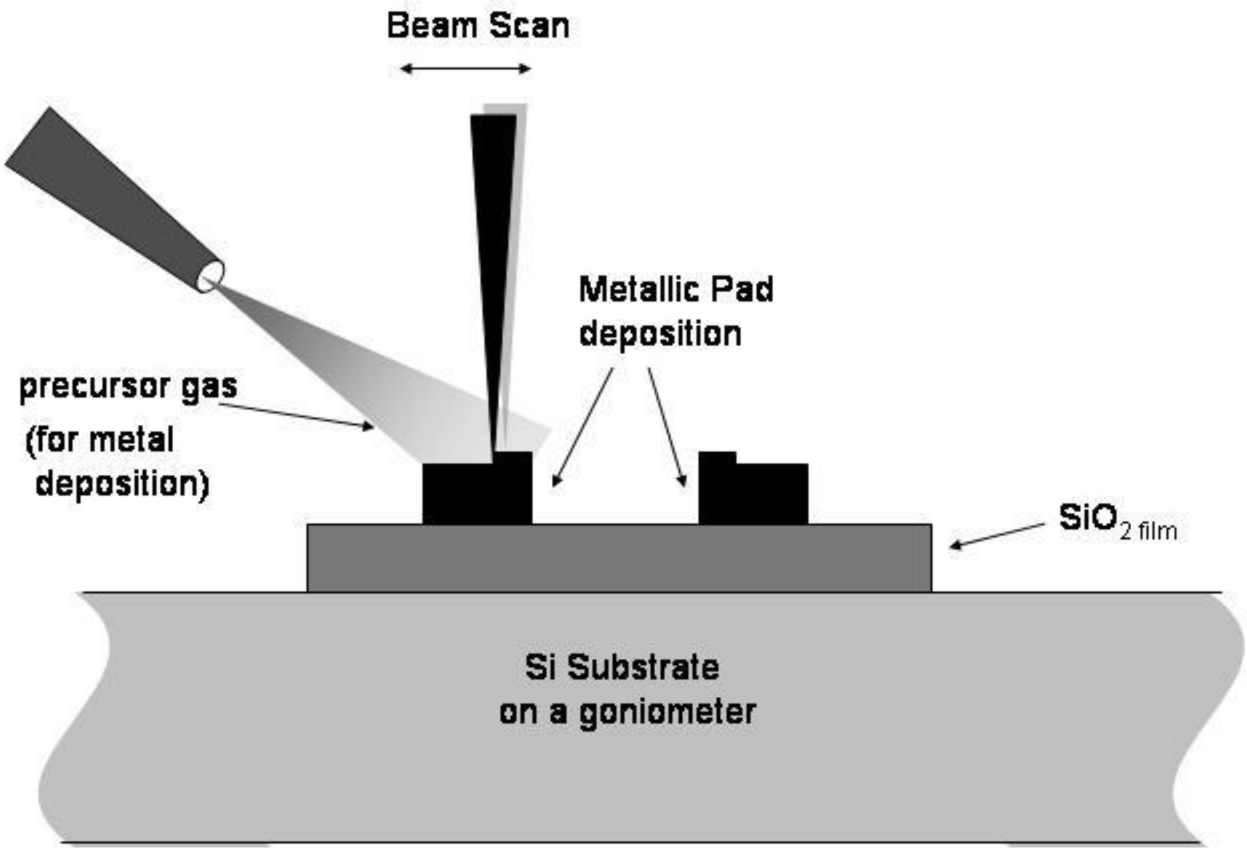
Typical material removal rate is about 1μm3 per second.



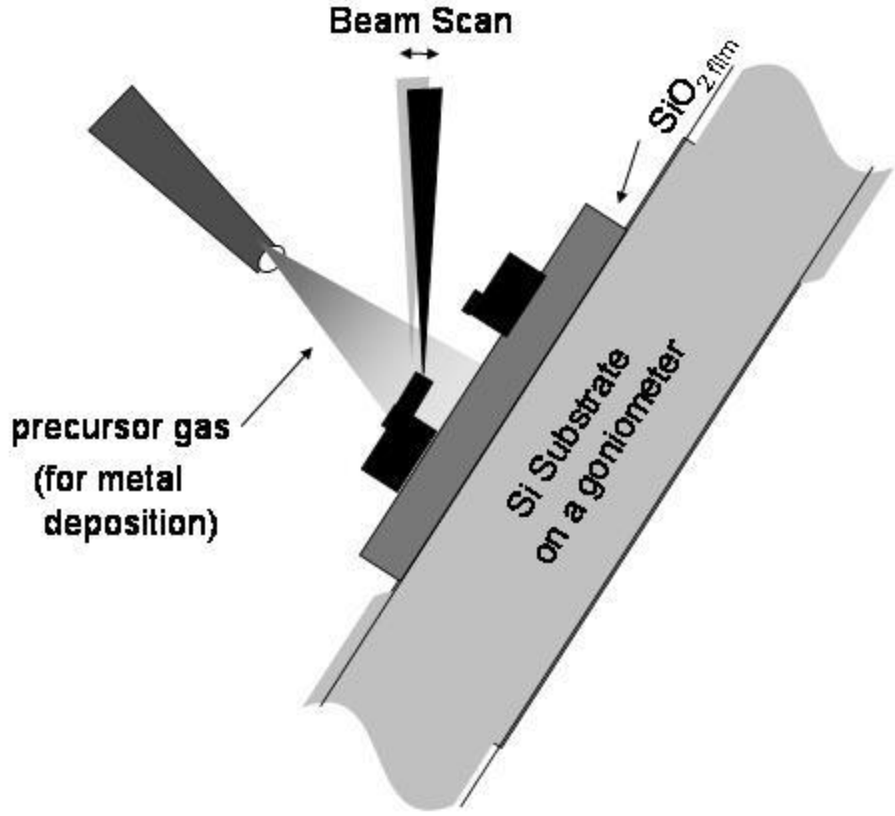
Nanoscale Deposition by FIB



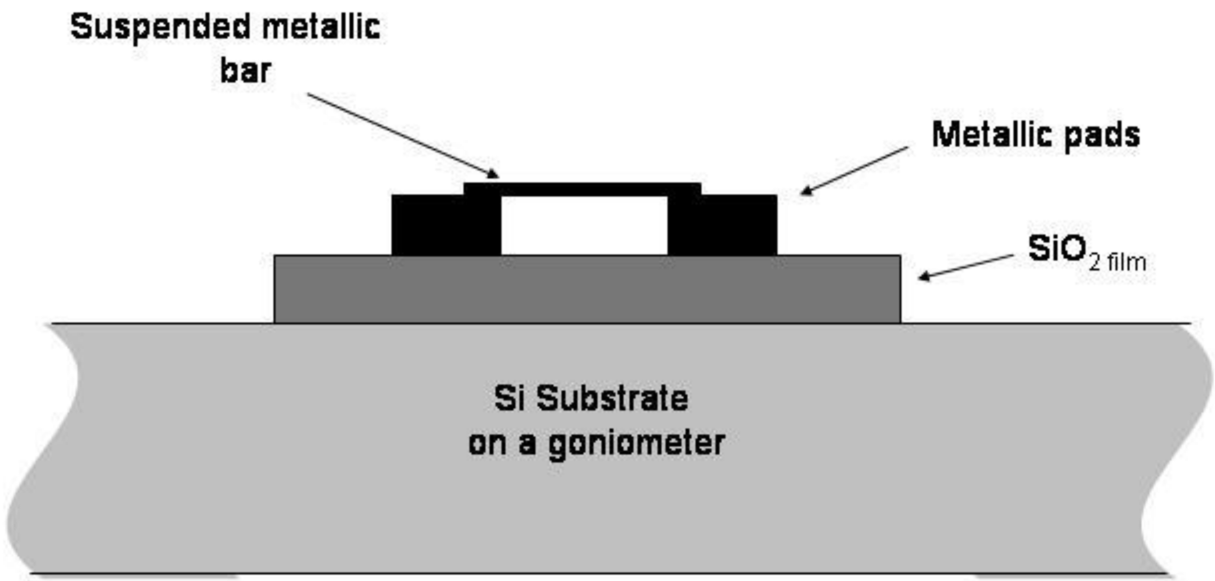
(a) Fabrication of a metallic microbridge (Pirani Gauge)
STEP 1 : Deposition of SiO_2 film



(b) Fabrication of metallic microbridge (Pirani Gauge)
STEP 2 : Deposition of metallic pads

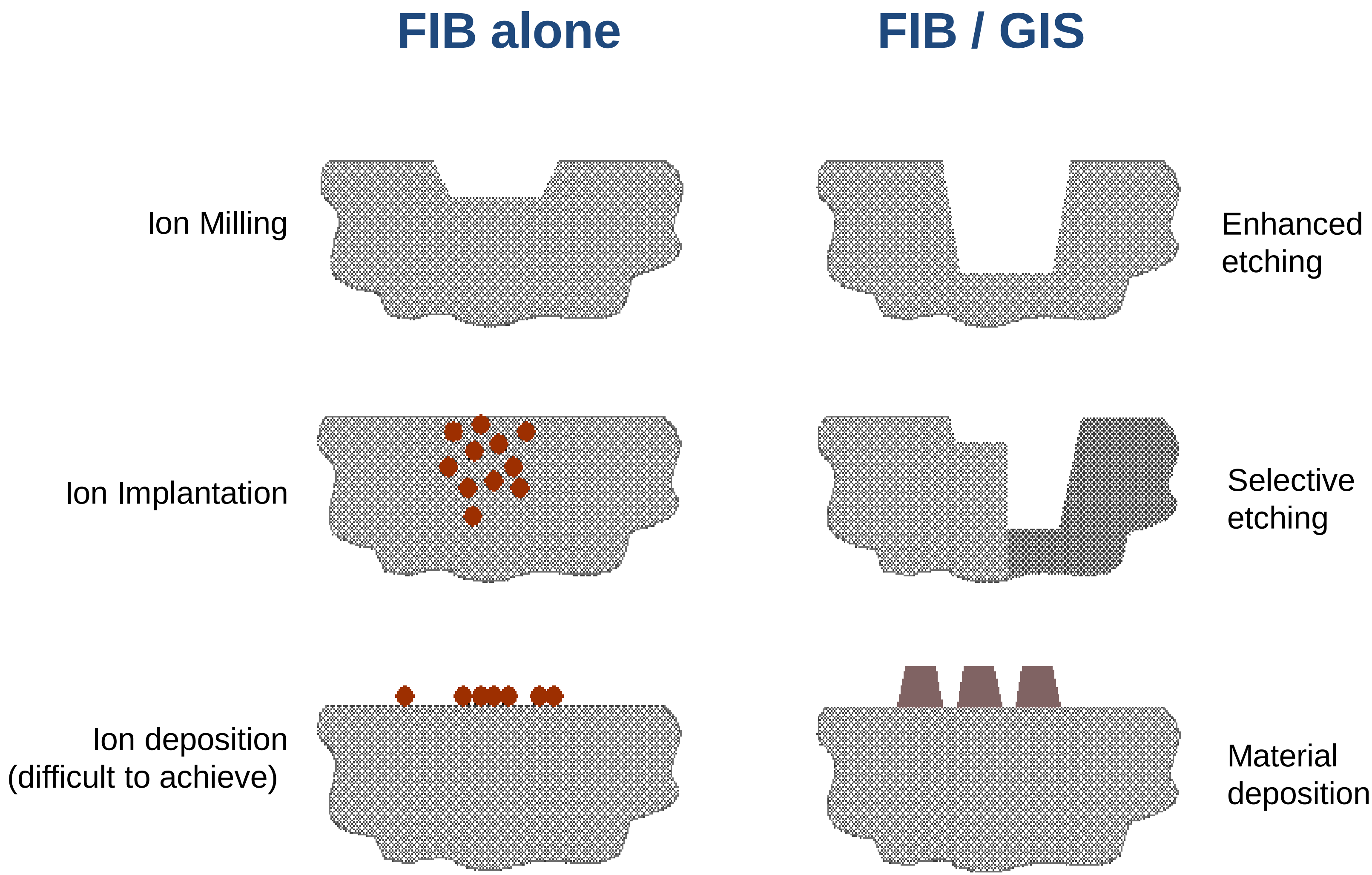


Fabrication of metallic microbridge (Pirani Gauge)
STEP 3 : Deposition of the bridge portion
(Tilts shown are not actual; only for illustration)

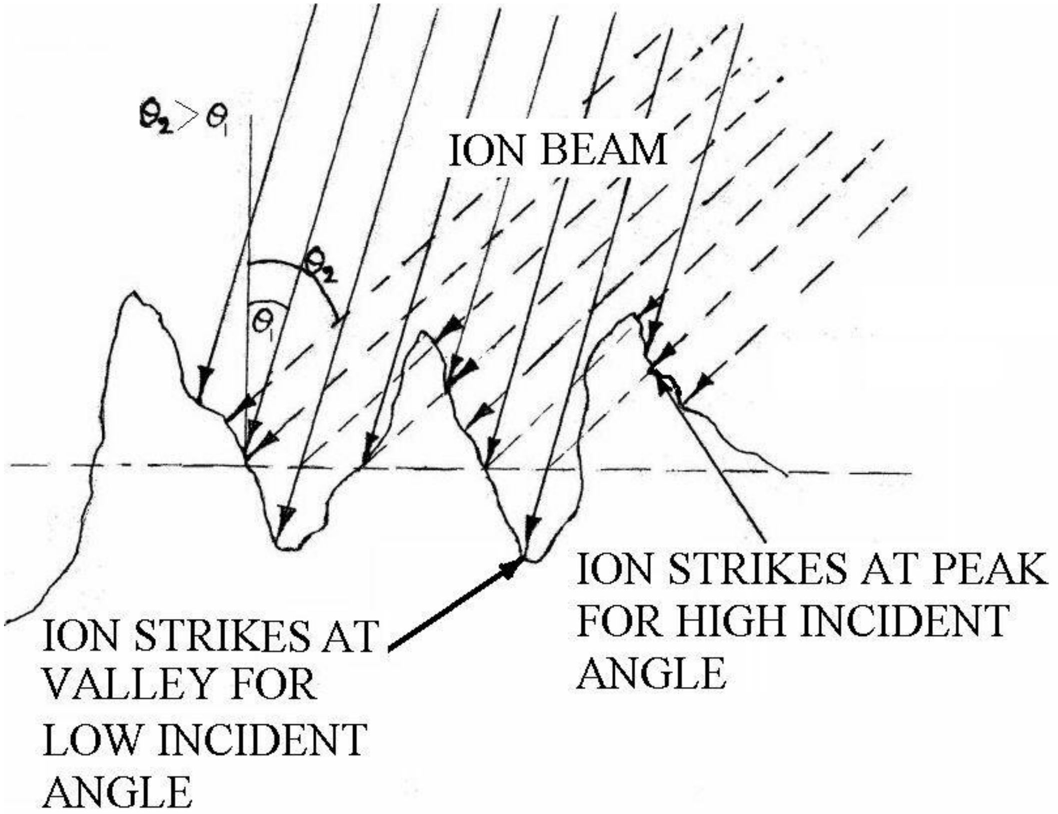


(d) Final structure of the metallic microbridge (Pirani Gauge)

Gas Injection System



EFFECT OF ANGLE OF INCIDENCE OF ION BEAM



♦ **AT VERY LARGE ANGLE OF INCIDENCE, SURFACE ROUGHNESS VALUE RAPIDLY DECREASES BECAUSE THE CONVEX PARTS OF SURFACE ASPERITIES ARE EASILY SPUTTERED BY THE OBLIQUELY INCIDENT IONS.**

ION BEAM MACHINING EQUIPMENT

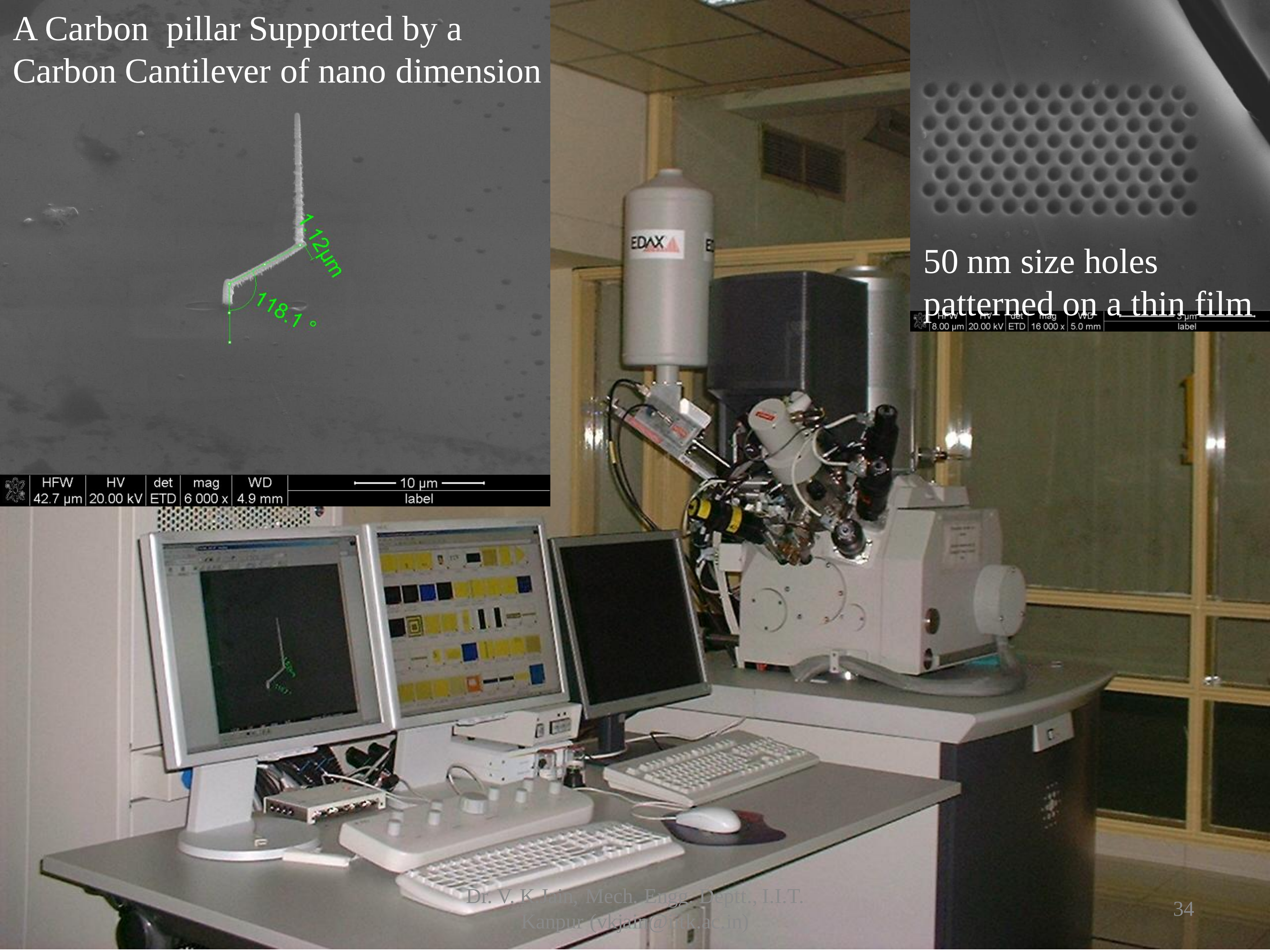
- **THE MOST COMMONLY USED ION SOURCE IS KAUFMAN ION SOURCE.**

- **MAJOR SECTIONS:**

  1. PLASMA SOURCE CHAMBER GENERATES IONS BY THE ELECTRIC DISCHARGE IN A LOW VACUUM (13 MPa) OF ARGON, KRYPTON, HELIUM, OR OXYGEN GAS.

  2. EXTRACTION GRID EXTRACTS ONLY ION FLUX FROM THE ION SOURCE AND A BROAD ION BEAM OF 80 mm CAN BE FORMED.

  3.WORKING CHAMBER IS KEPT AT HIGH VACUUM OF 1.2 MPa.



A Carbon pillar Supported by a Carbon Cantilever of nano dimension

50 nm size holes patterned on a thin film

The 1500XB Specimen Chamber

Detector and accessory configuration

FIB column

Gemini column

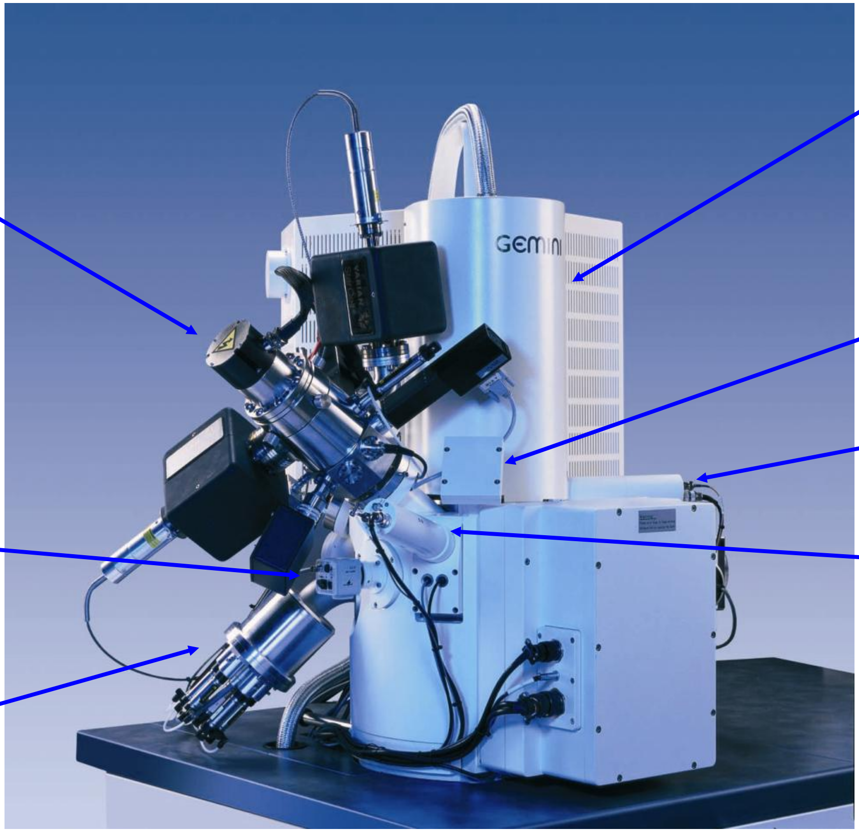
EDS - Detector

Inlens - Detector

CCD camera
& illumination

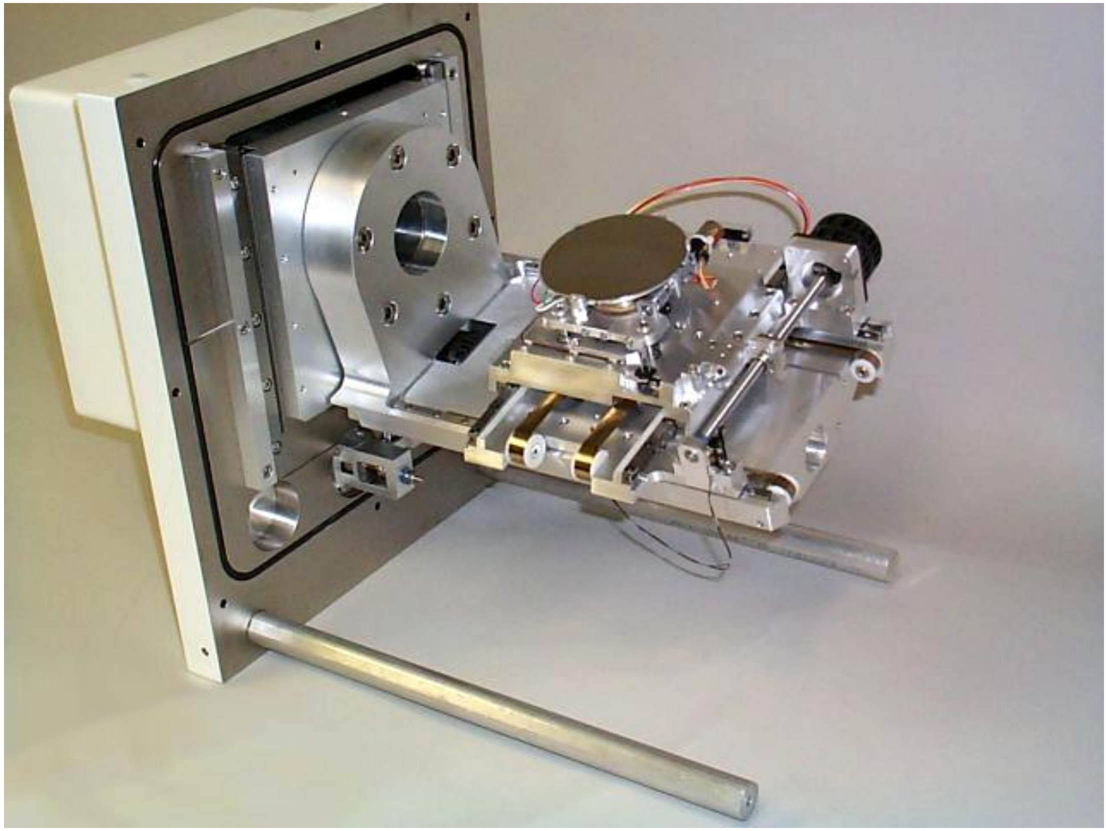
SE - Detector

Gas Injection System
(GIS)



LEO 1540XB equipped with FIB and a gas injection system for 5 different gases

Motorized 6-axes super eucentric specimen stage

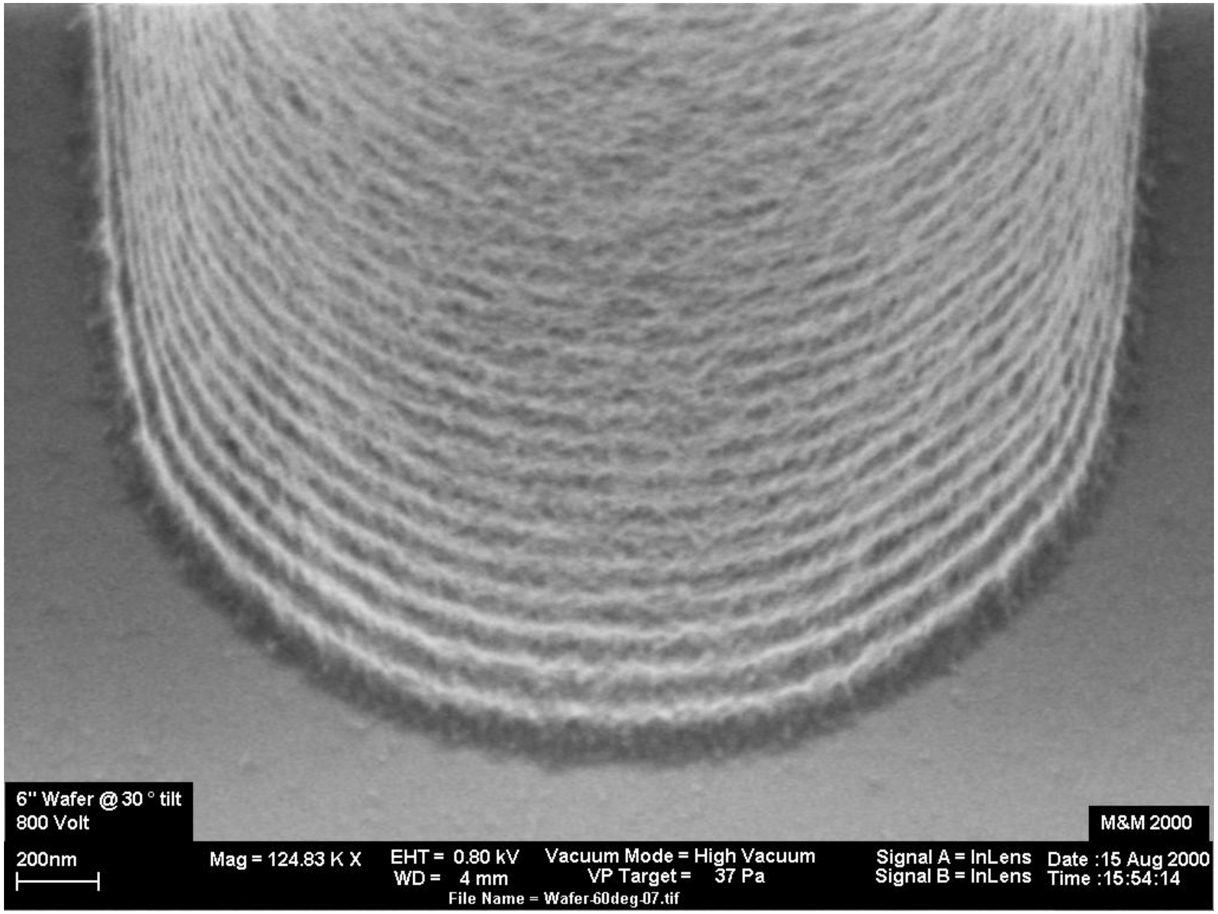


Eucentric specimen stage

- **Super eucentric stage**
  (all 6 axes motorized)
- **Movements:**
  X 152 (102) mm
  Y 152 (102) mm
  Z' 10 mm + Compueucentric
  Z 43 mm
  Tilt -15° to 62°
  Rot. 360°, compucentric rotation accuracy better than 15um.
  X/Y motion in the plane of tilt
- **Stage control**
  Dual joystick or optional hardware control panel

APPLICATIONS

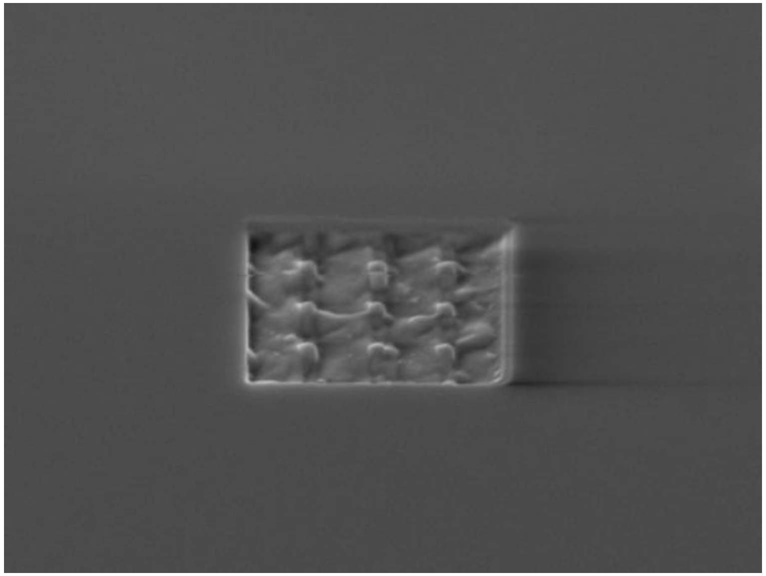
SEM Imaging



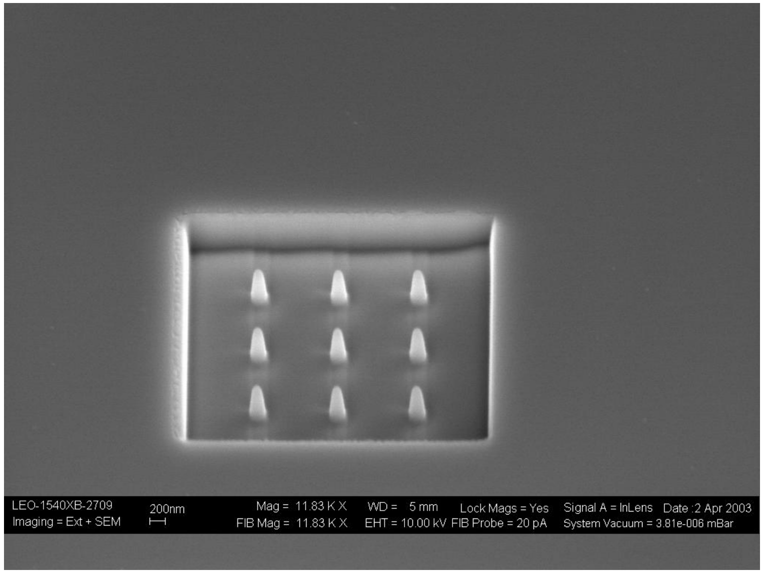
Resist structure on a silicon wafer

Gas Injection System
Gas assisted etch

PHOTONIC CRYSTAL IN GAAS

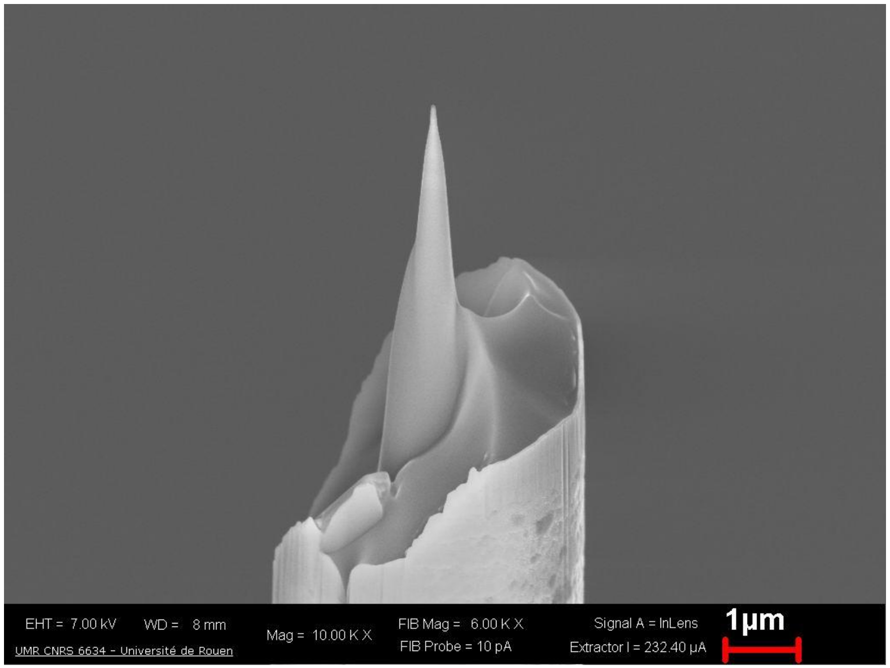


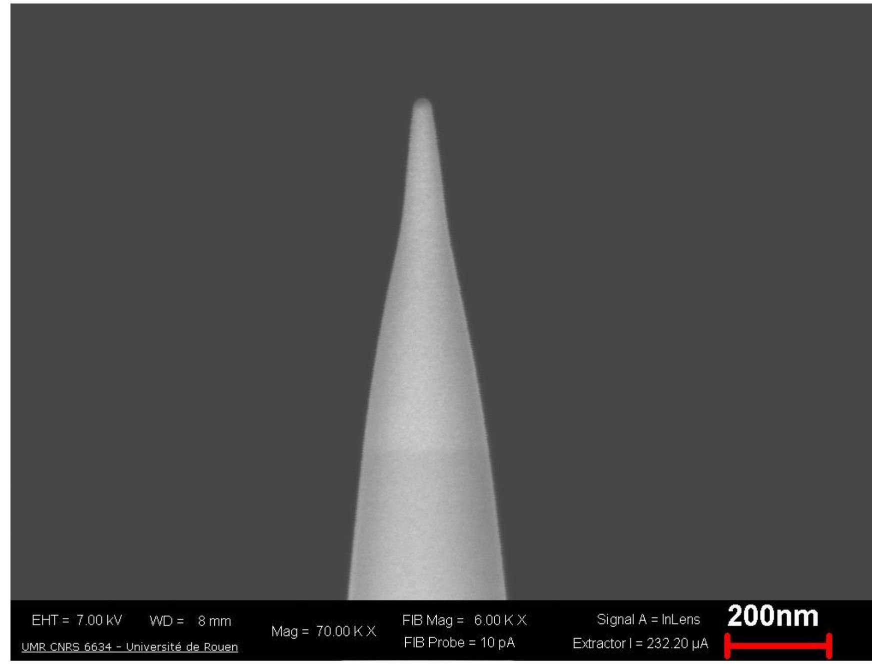
ION BEAM ONLY



ENHANCED ETCH WITH XEF_2

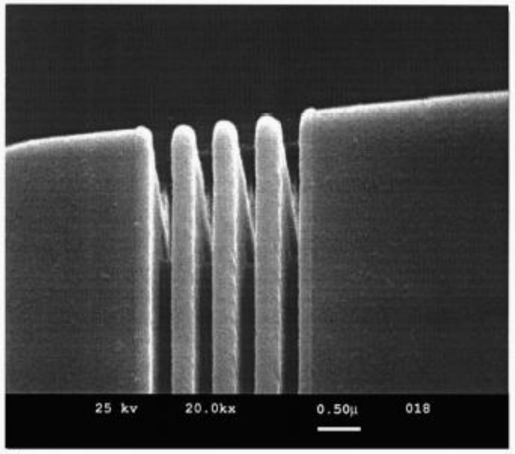
Micromachining





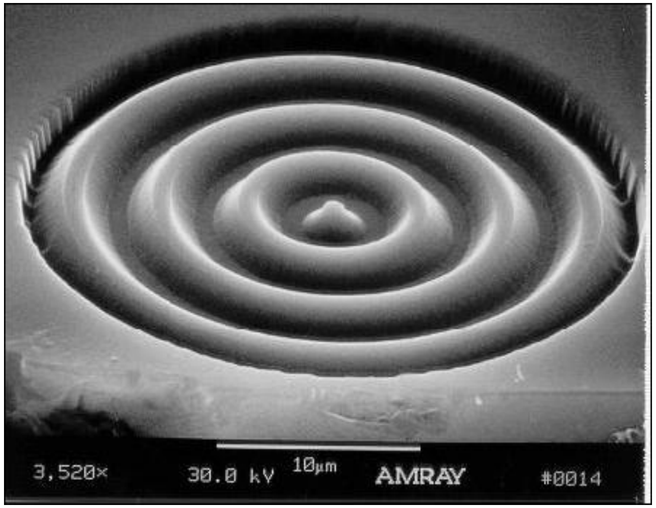
STM TIPS

SAMPLE COURTESY UNIVERSITY ROUEN



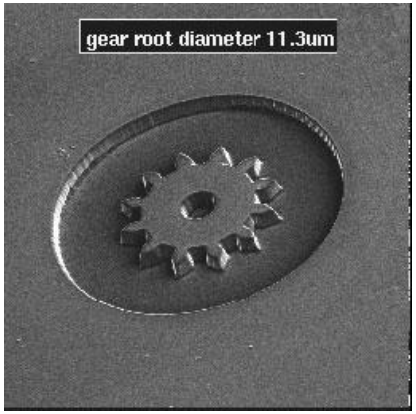
Fourth order grating structure

I. Chyr et al, J. Vac. Sci. Technol. B 17(1999) 3063



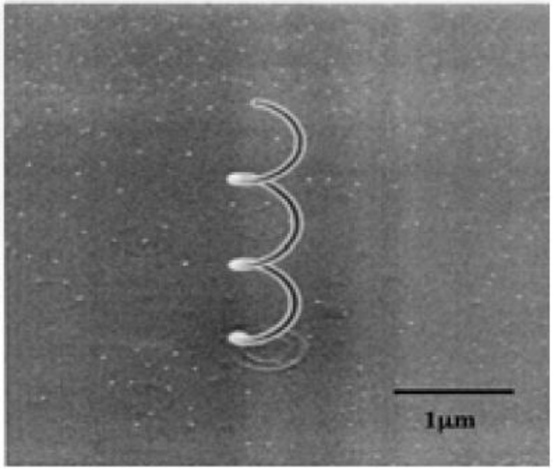
SEM image of sinusoidal annulus micro channels viewed at 60◦

*M Vasile et al, J. Vac. Sci. Technol. B **17** (1999) 3085*

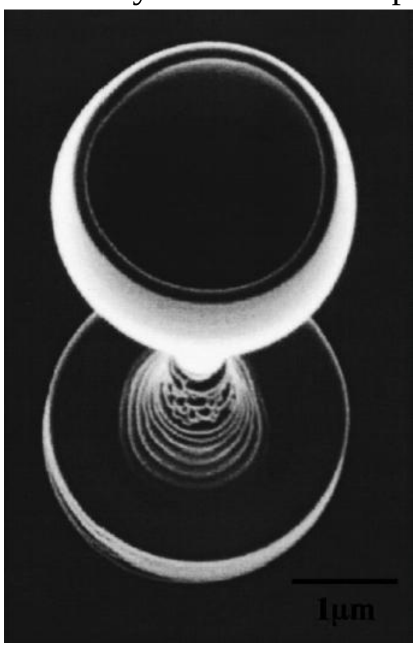


SEM image of gear structure milled with an ion dose of 5 nC μm^{-2}

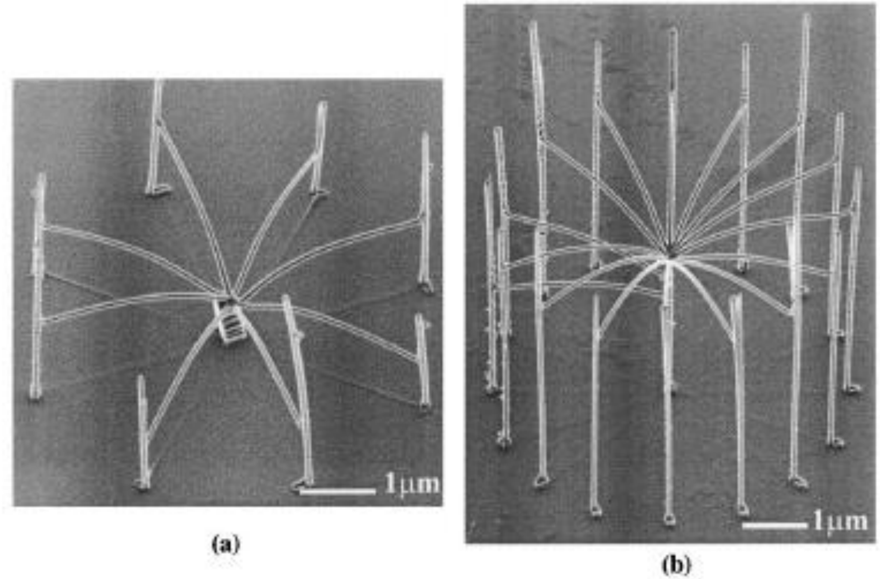
*Y Fu et al, Int. J. Adv. Manuf. Technol. **16** (2000) 600*



Coil 700 nm pitch, 80 nm line width, diamond like amorphous carbon, Fabricated by FIB induced deposition



Micro wine glass with 2.75 µm external diameter and 12 µm height.

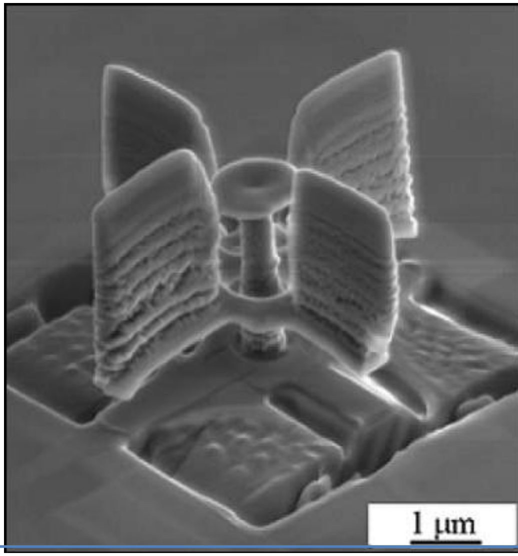


(a) Radial DLC free-space-wiring grown into eight directions from the center. (b) Radial DLC free-space-wiring grown into 16 directions from the center.

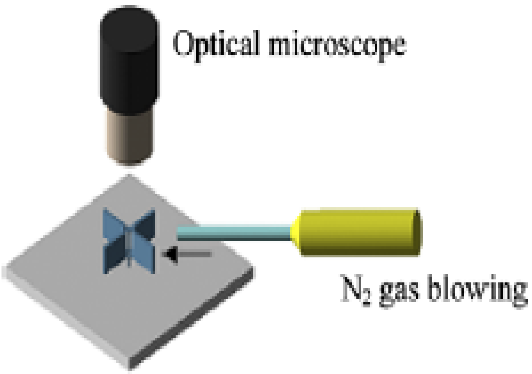
T. Morita et al, J. Vac. Sci. Technol. B ***21*** *(2003)*

Shinji Matsui et al, J. Vac. Sci. Technol. B 18(2000) 3181

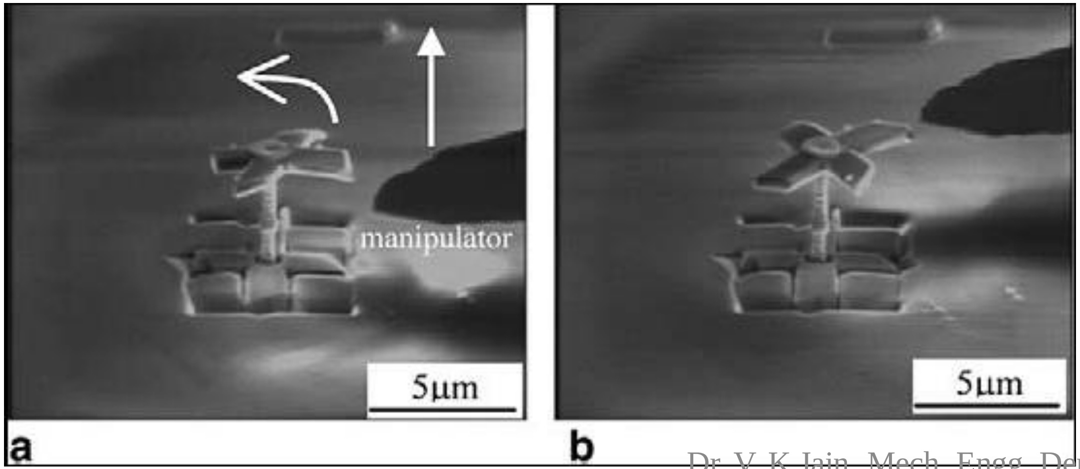
Micro-rotor



Four wings rotor with 6 µm diameter, 3 µm wing-height, 500 nm wing-width and 2.6 µm axis length.

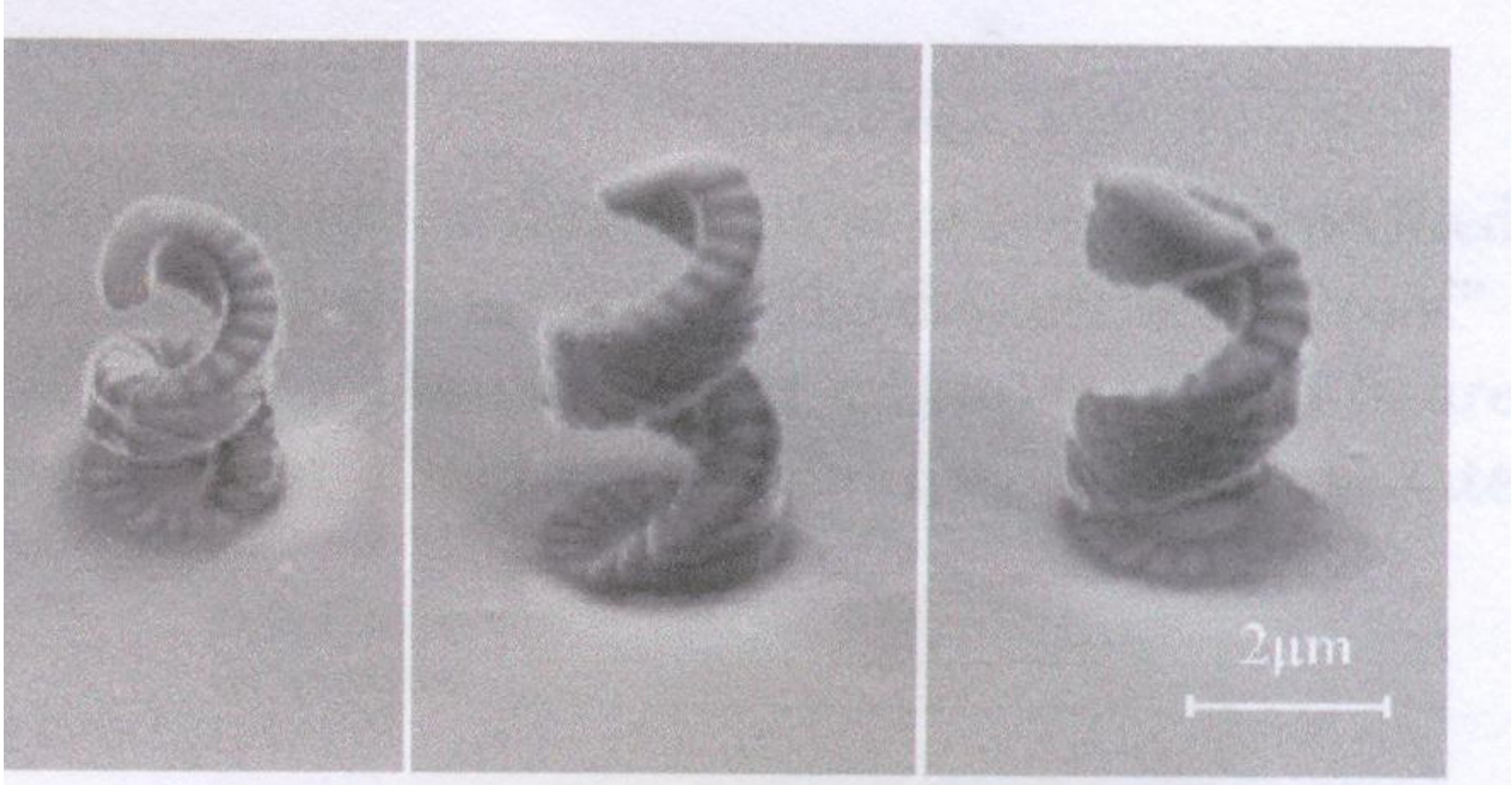


Moving mechanism of a flat rotor using N_2 gas flow



SEM images of the flat rotor movement by N_2 gas flow: (a) before moving; (b) after moving.

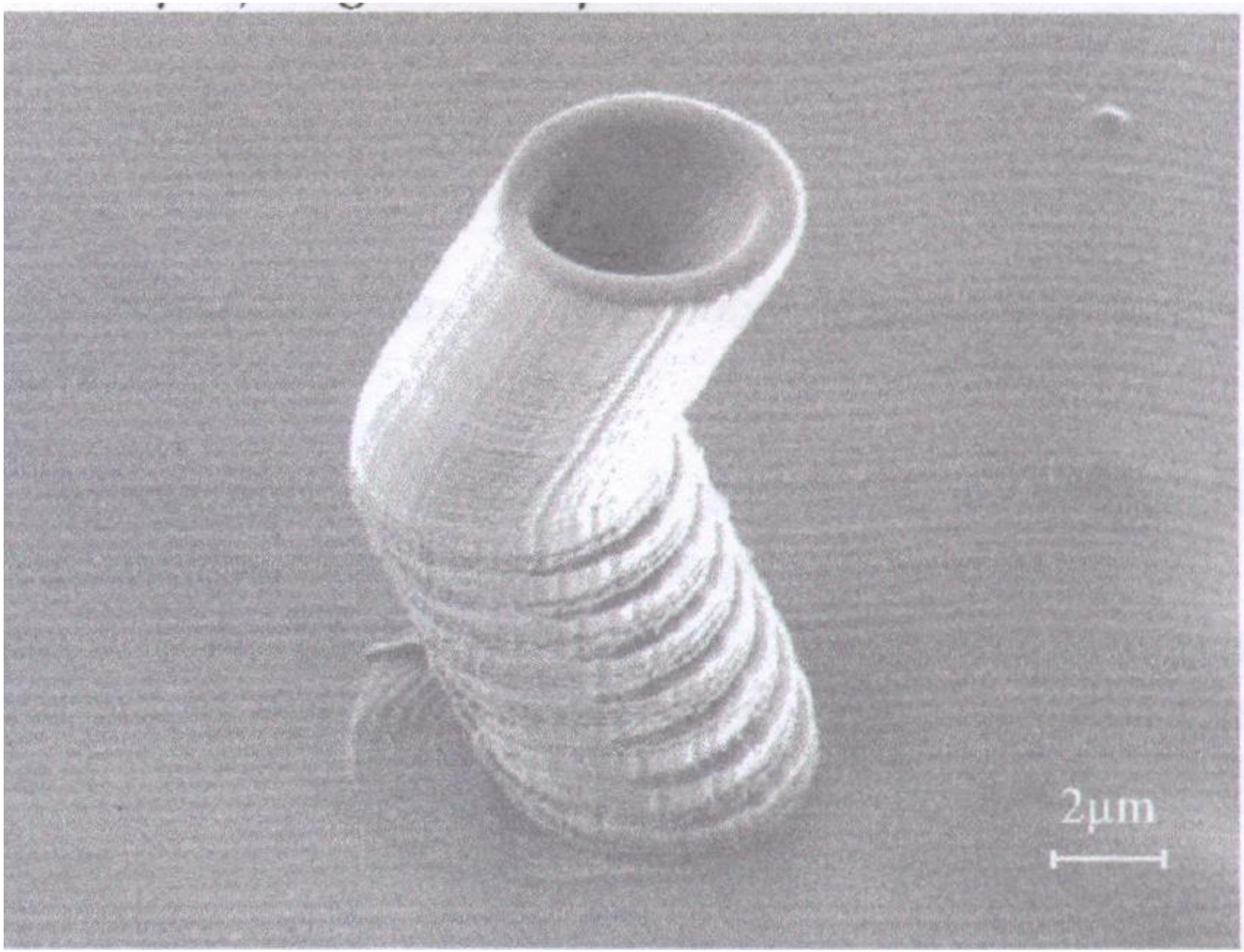
J.-y. Igaki et al., Microelectronic Engineering 83 (2006) 1221



Spiral shaped SiO2 depositions

Outer dia=2.4μ height= 3.5μ

(27 consecutive bitmap depositions, each consisting of a quarter ring, rotated over 20º with respective previous one)

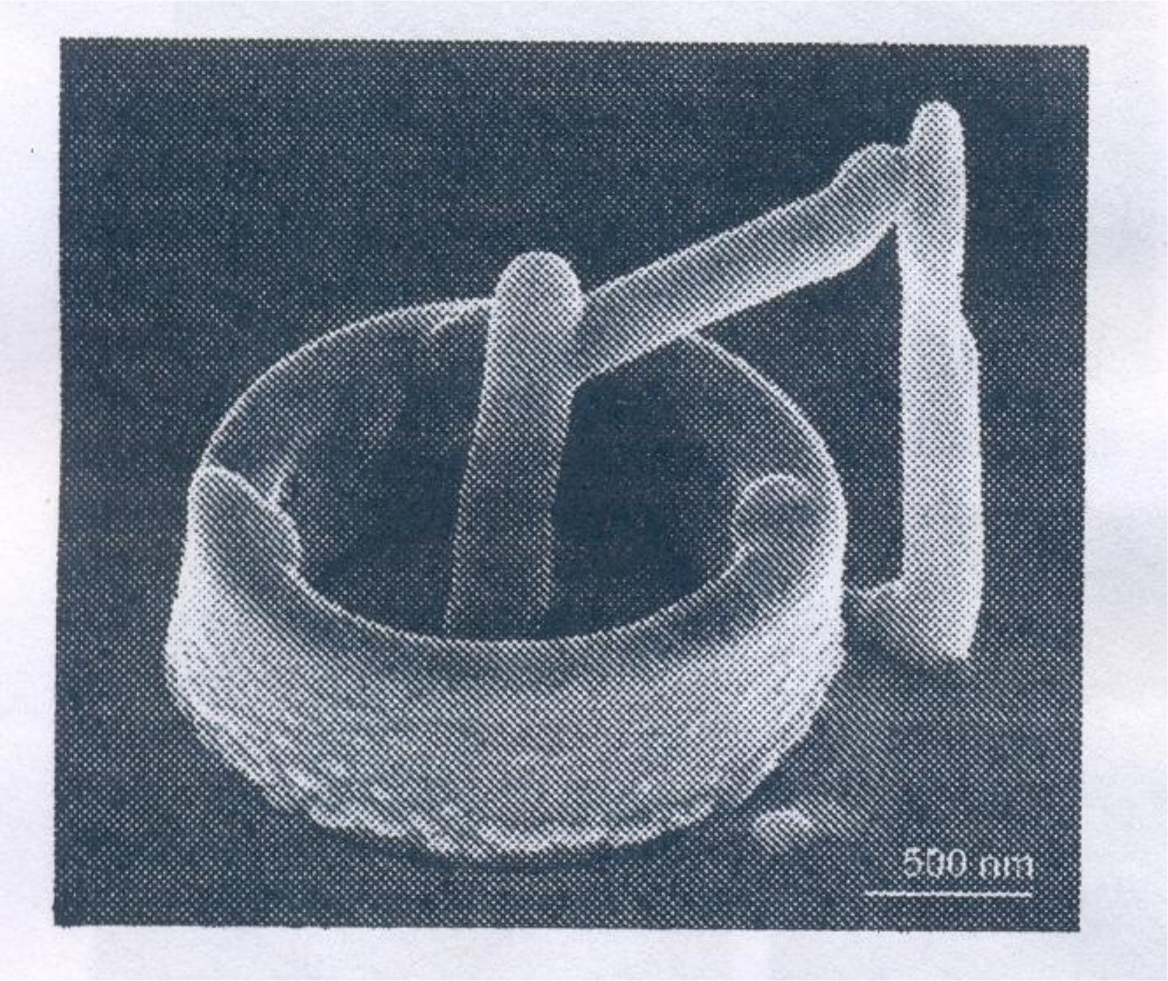


Bent Hollow Tube of SiO_2

Outer dia= 4.8 µm, height=14.5 µm

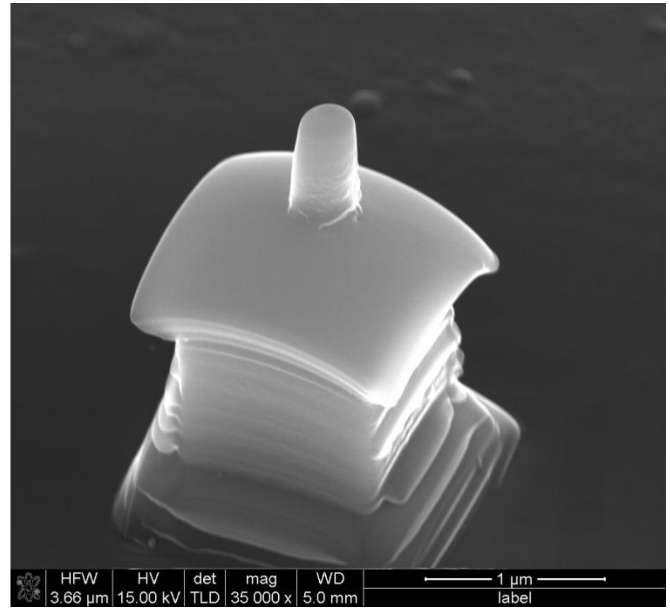
Lower part constructed by depositing 8 consecutive rings, translated wrt the previous

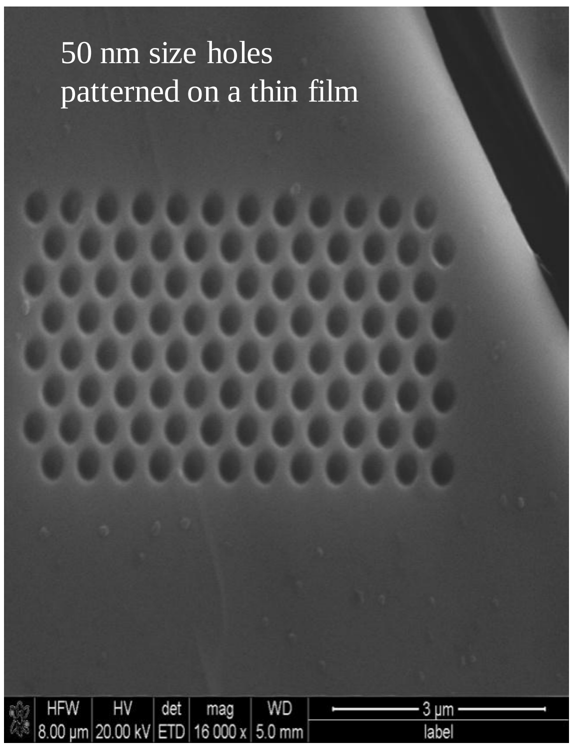
Upper part constructed with one deposition with continuous translation of the ion beam

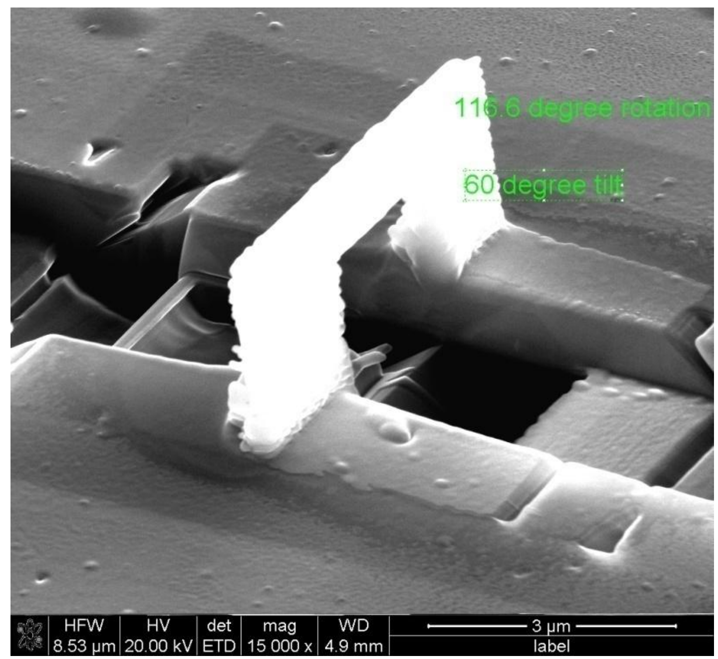


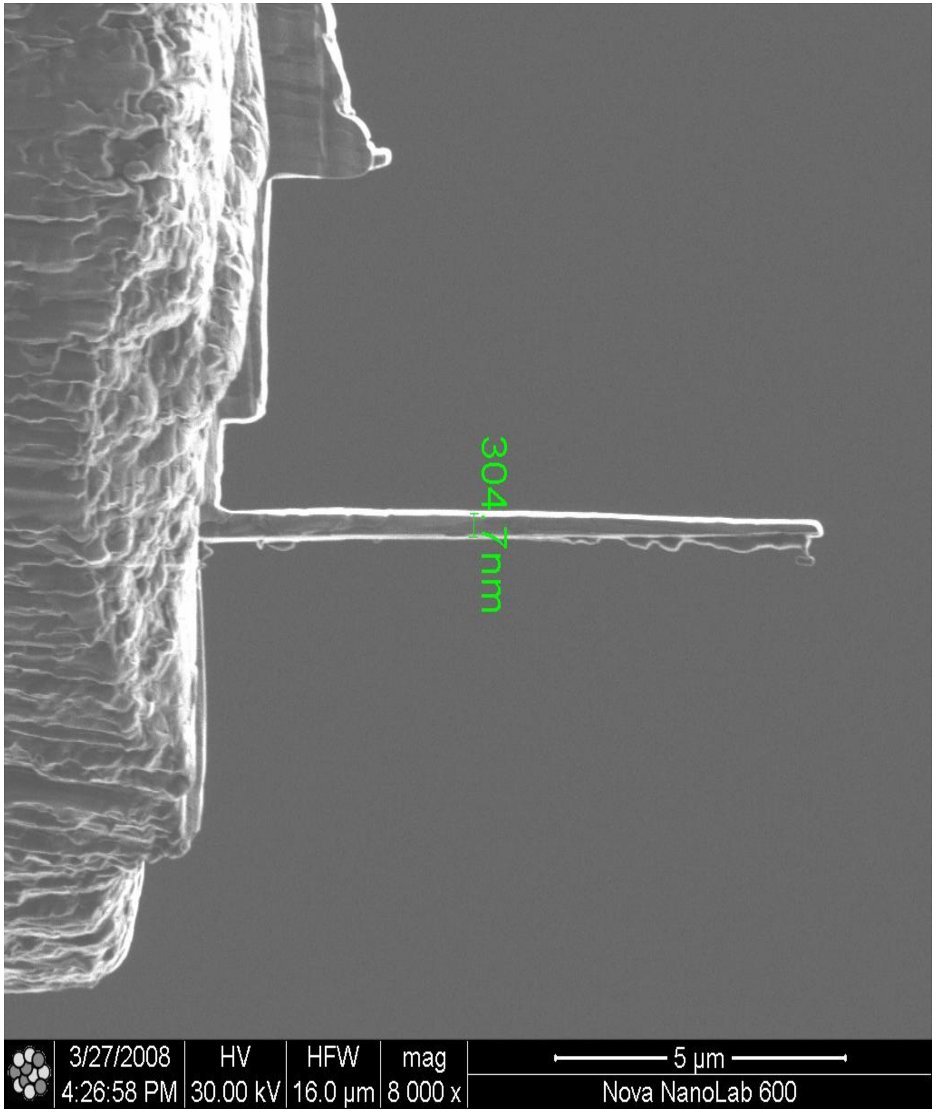
Micro-electrochemical cell fabricated by ion-beam deposition of Pt. Note the horizontal branch connecting the inner and outer electrodes

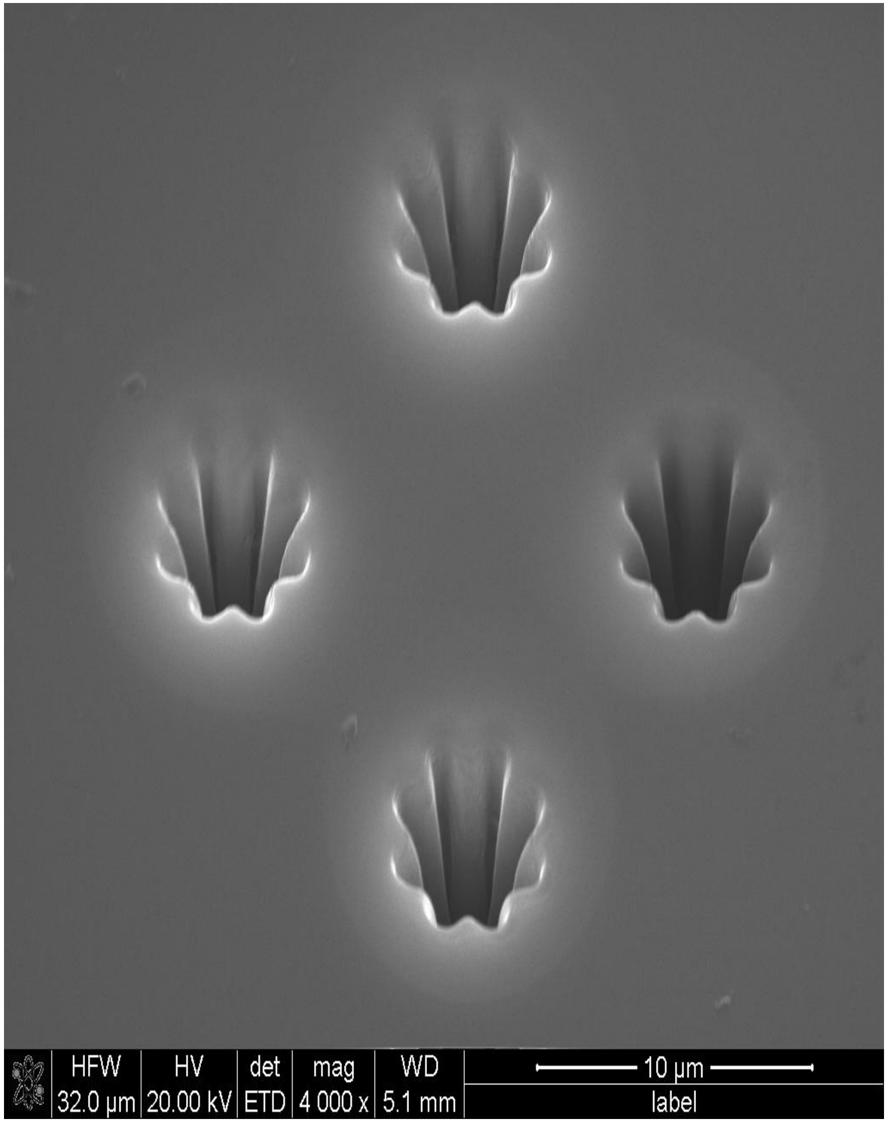
0.1 µm linewidth, 0.6 µm thick SAL601-ER7 resist pattern fabrication


HFW 3.66 µm
HV 15.00 kV
det TLD
mag 35 000 x
WD 5.0 mm
1 µm
label

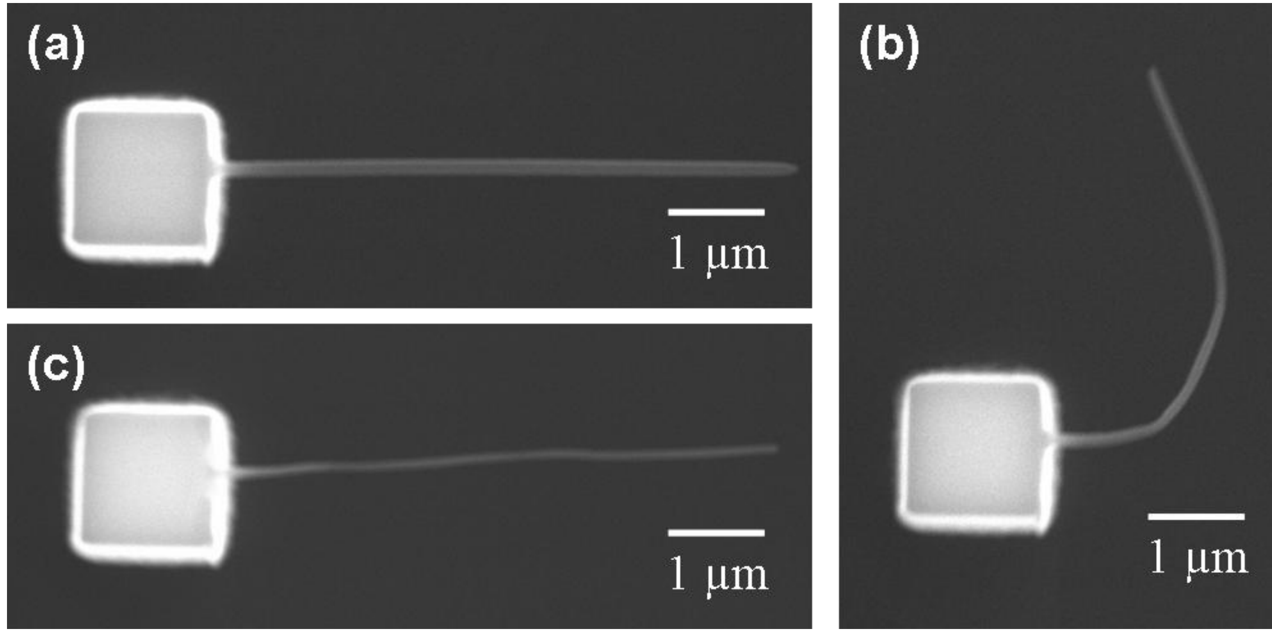

50 nm size holes
patterned on a thin film
HFW 8.00 µm
HV 20.00 kV
det ETD
mag 16 000 x
WD 5.0 mm
3 µm
label


116.6 degree rotation
60 degree tilt
HFW 8.53 µm
HV 20.00 kV
det ETD
mag 15 000 x
WD 4.9 mm
3 µm
label

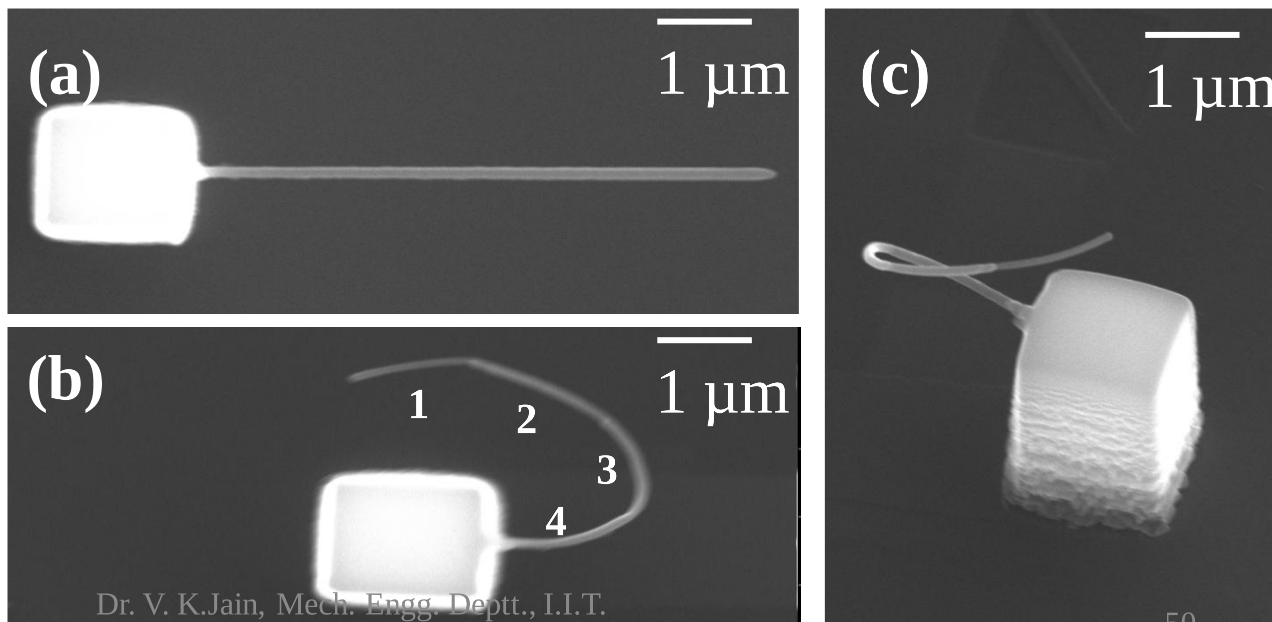

304.7nm
3/27/2008
4:26:58 PM
HV
30.00 kV
HFW
16.0 μm
mag
8 000 x
5 μm
Nova NanoLab 600


HFW
32.0 μm
HV
20.00 kV
det
ETD
mag
4 000 x
WD
5.1 mm
10 μm
label

Reversible Bending

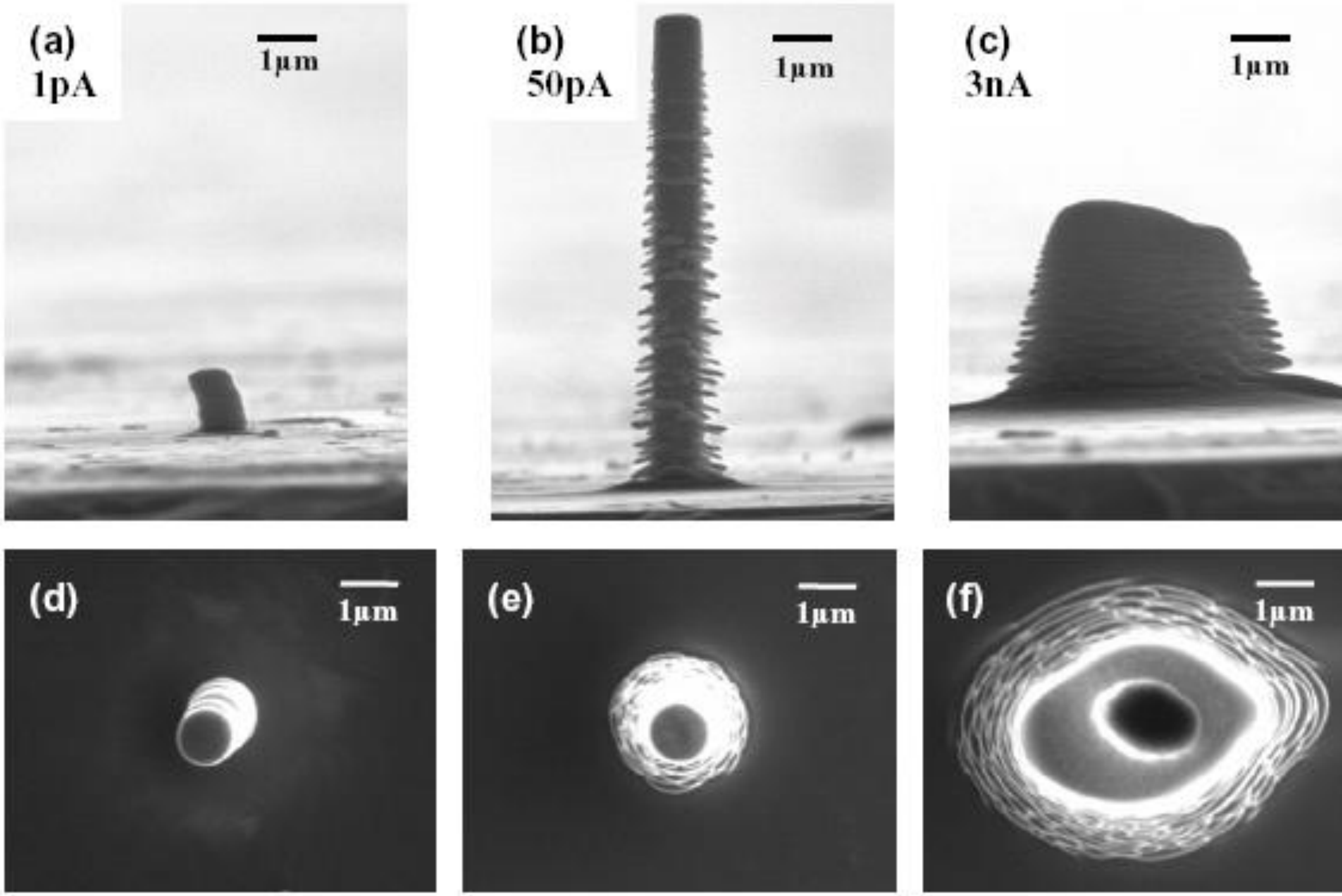


Piecewise Bending



Tripathi, Shukla, Kulkarni Nanotechnology 2008

30 keV Ga FIB grown Carbon Pillars

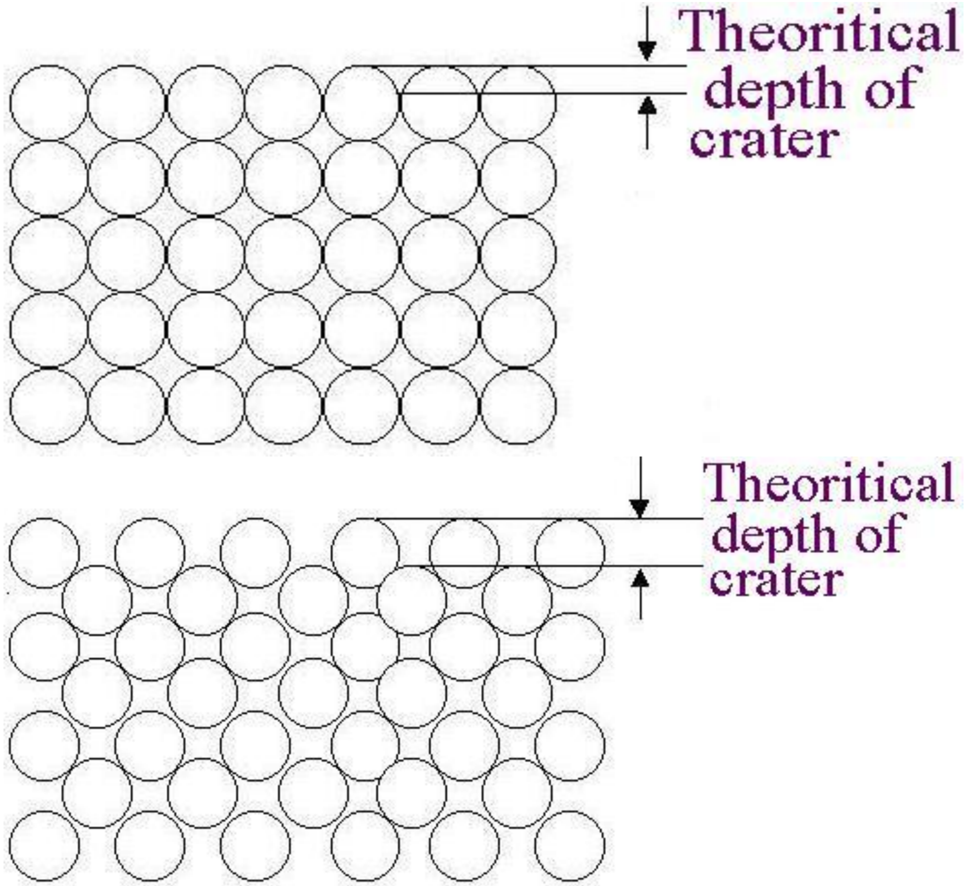


PARAMETRIC ANALYSIS OF IBM

PARAMETRIC ANALYSIS

* SURFACE FINISH
* MATERIAL REMOVAL RATE
* SURFACE TEXTURE

THEORITICALLY ACHIEVABLE SURFACE FINISH BY ION BEAM MACHINING



•**DPENDING ON THE CRYSTALINE STRUCTURE IT IS THEORITICALLY POSSIBLE TO ACHIEVE SURFACE FINISH IN THE ORDER OF A FRACTION OF THE SIZE OF AN ATOMS**

MACHINING CHARACTERISTICS

- **THE SPUTTERING YIELD IS THE MOST IMPORTANT MACHINING CHARACTERISTIC OF ION BEAM MACHINING.**
- **THE SPUTTERING YIELD S IS DEFINED AS THE MEAN NUMBER OF ATOMS SPUTTERED OFF FROM THE TARGET SURFACE PER INCIDENT ION.**
- **SPECIFIC SPUTTER MACHINE RATE V(θ) [(μm/h)/(mA/cm²)] AND SPUTTERING YIELD (‘S’) ARE RELATED AS:**

$$V(\theta) = 576 \times 10^9 \frac{S(\theta)}{n} \times \cos\theta \qquad (\mu m/h)/(mA/cm^2)$$

WHERE, n IS THE ATOMIC DENSITY OF THE TARGET MATERIAL IN ATOMS/cm³

TYPICAL MATERIAL REMOVAL RATE IN ION BEAM MACHINING

TABLE1: REMOVAL RATES BY IBM (SPENCER AND SCHMIDIT, 1972)

DATA : ARGON ION BEAM 60 TO 70^0 FROM NORMAL

Pressure = 3×10^{-4} Torr, Voltage = 6 kV, Current = 100 µA

Current density = 1 $mAcm^{-2}$ over 1 cm diameter area

Material	Removal (milling) rate, (µm hr^{-1})
Quartz	2
Garnet	1
Ceramic	1
Glass	1
Gold	2
Silver	3
Photo resist Material (KTFR)	1
Permalloy	1
Diamond	1

FACTORS AFFECTING MACHINING CHARACTERISTICS

- **WORK-PIECE MATERIAL : SPUTTERING YIELD IS A FUNCTION OF ATOMIC NUMBER, BINDING ENERGY, GRAIN SIZE, NO. OF ELECTRONS SHELL, ETC. OF THE WORK-PIECE MATERIAL.**

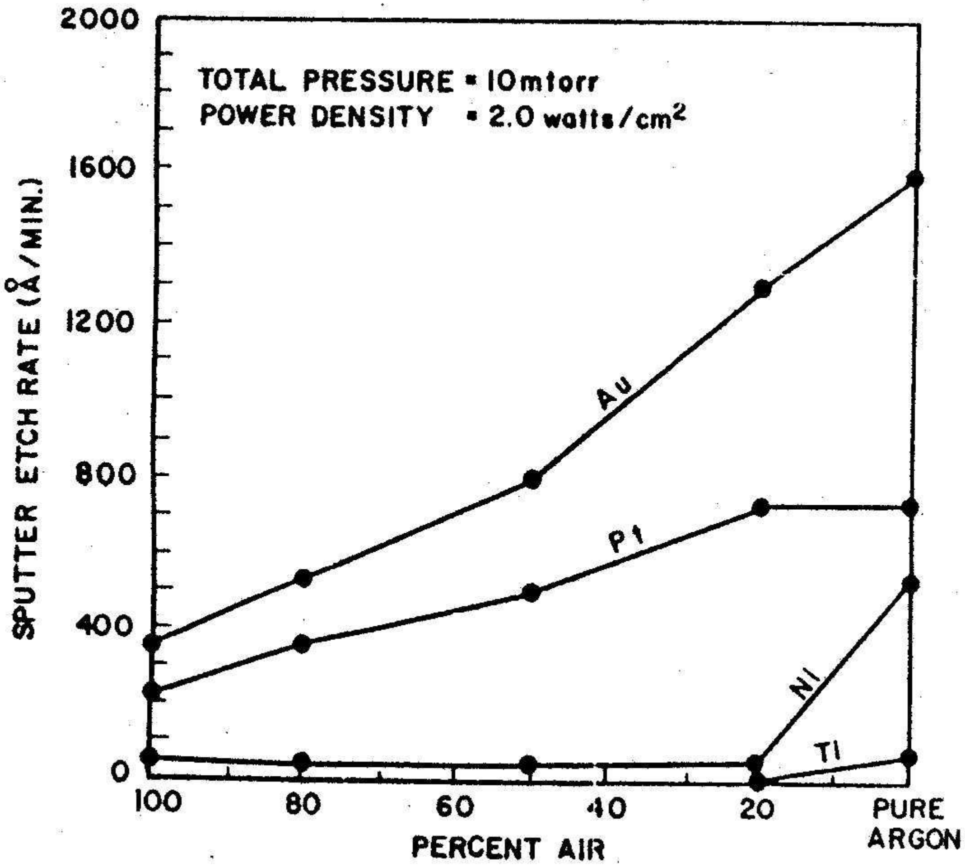
- **ION ETCHING GAS:**

❖ **THE SPUTTERING YIELD IS KNOWN TO BE DEPENDENT ON THE ATOMIC WEIGHT OF THE INCIDENT ION. IONS. HAVING HIGH ATOMIC NUMBER WILL YIELD HIGH MRR.**

✞ **SPUTTERING YIELD IS RELATED TO THE BINDING ENERGY OF THE ATOMS IN THE MATERIAL BEING ETCHED. IT IS POSSIBLE TO VARY ITS VALUE BY INTRODUCING REACTIVE GASES.**

✞ **OXYGEN WILL BE ABSORBED ON THE FRESH SURFACES OF MATERIALS LIKE TITANIUM, SILICON, ALUMINIUM AND CHROMIUM DURING ION ETCHING**

$\Rightarrow$ IT WILL FORM OXIDES AND WILL REDUCE ETCH RATE.

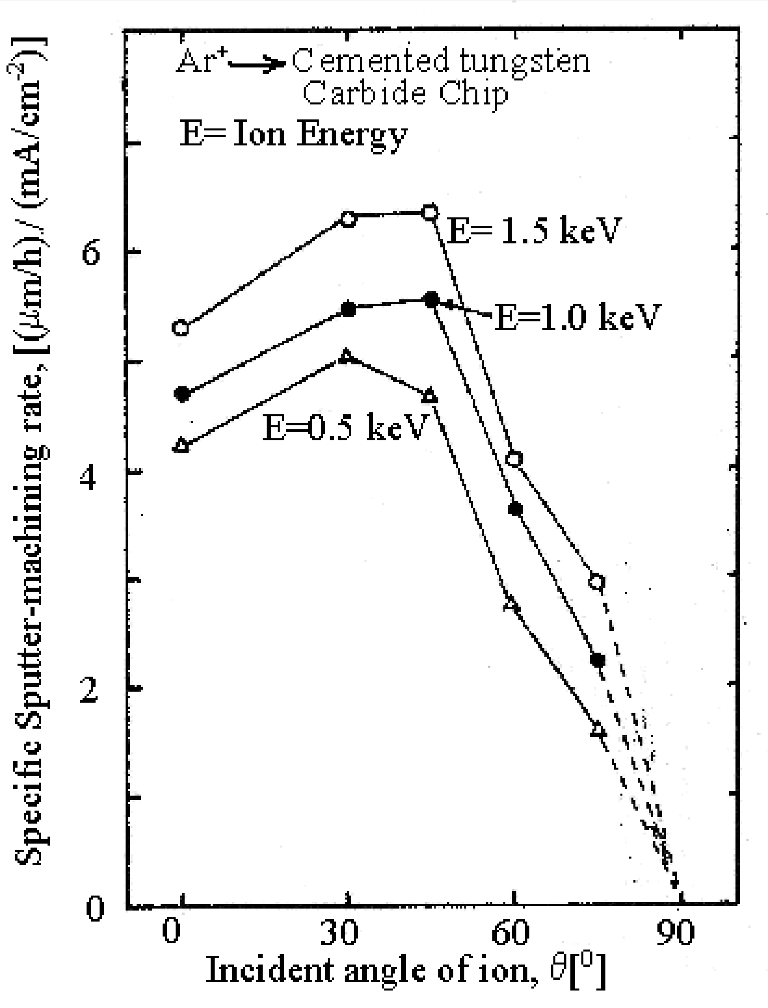


EFFECT OF OXYGEN / ARGON ON ETCH RATE (MILLER-SMITH,1976)

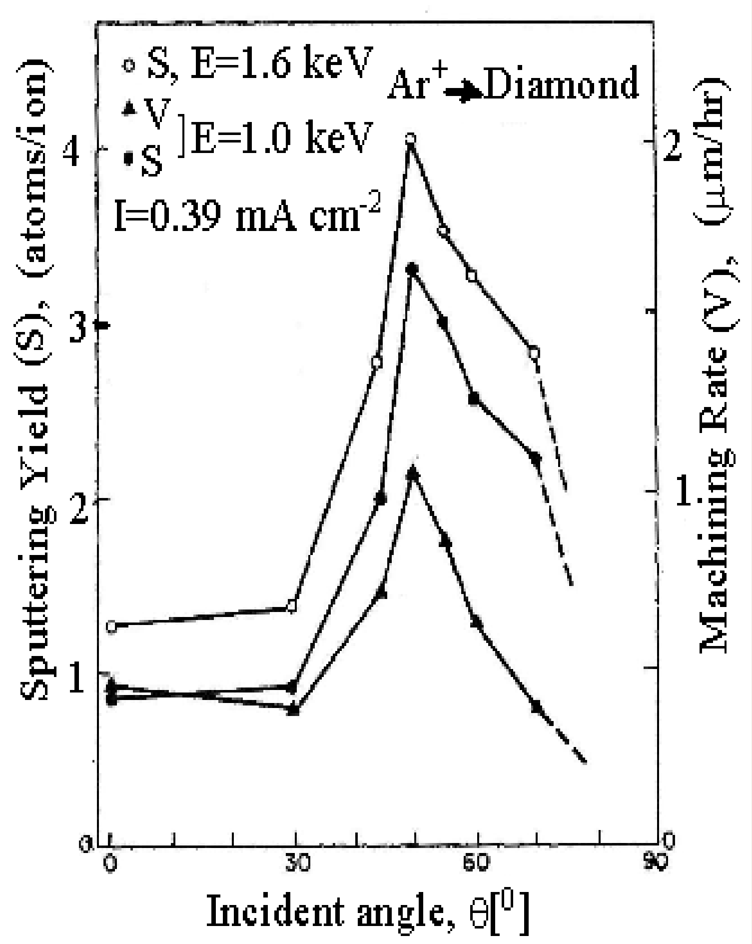
- **WHEN THE MACHINING CHAMBER IS FULL OF AIR, IT HAS MINIMUM ETCH RATE. AS THE CONTENT OF INERT GAS (PURE ARGON) INCREASES IN THE MACHINING CHAMBER, THE ETCH RATE ALSO INCREASES.**

- **ACTIVATED CHLORINE OR FLORINE CONTAINING SPECIES WILL REACT WITH THE ABOVE MATERIALS TO FORM LOOSELY BOUND OR EVEN VOLATILE COMPOUNDS AND THUS INCREASES ETCH RATE.**

•ANGLE OF INCIDENCE : SPUTTERING YIELD INCREASES GRADUALLY REACHES A MAXIMUM AT AN ION INCIDENCE ANGLE OF NEARLY 50^0 AND AFTER THAT DECREASES RAPIDLY.



.ANGULAR DEPENDENCE OF THE SPECIFIC SPUTTERING MACHINING RATE(TANIGUCHI, MIYAMOTO,1981)



ANGULAR DEPENDENCE OF SPUTTERING YIELD(MIYAMOTO,I,1987)

✞ AS THE ION INCIDENCE ANGLE INCREASES, MORE ATOMS OF THE WORK-PIECE CAN BE KNOCKED OUT OR SPUTTERED AWAY EASILY FROM THE SURFACE OF WORK-PIECE

✞ WHEN THE ION INCIDENCE ANGLE IS VERY HIGH, THE MACHINING RATE BEGINS TO DECREASE BECAUSE THE ION CURRENT DENSITY DECREASES BY COSθ AND THE NUMBER OF IONS REFLECTED FROM THE SURFACE OF THE WORK-PIECE WITHOUT SPUTTERING OFF ATOMS OF THE WORK-PIECE INCREASES .

- **ION ENERGY :**

✞ THE SPECIFIC SPUTTER-MACHINING RATES INCREASE LINEARLY WITH THE AMOUNT OF ION ENERGY AT ANY ANGLE OF THE INCIDENT ION. (SEE NEXT FIGURE)

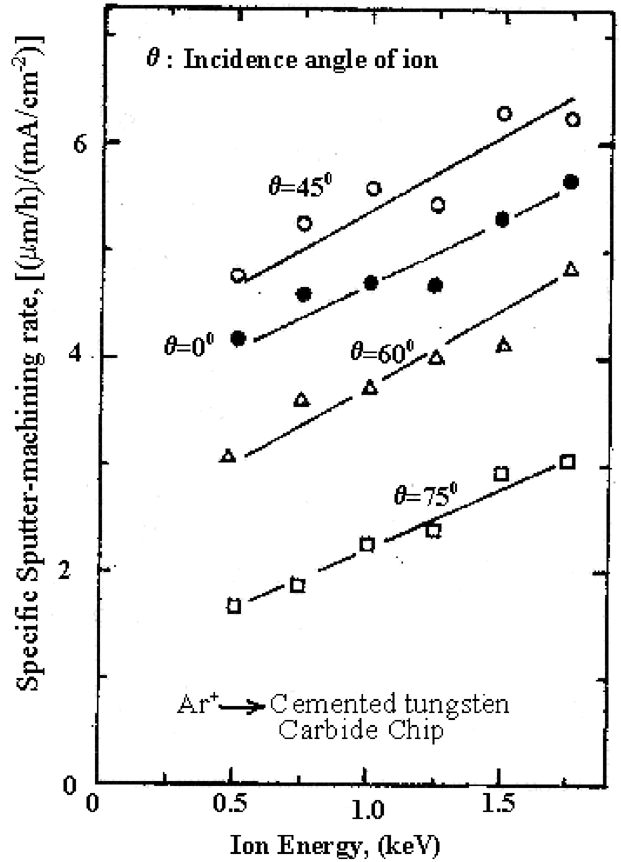
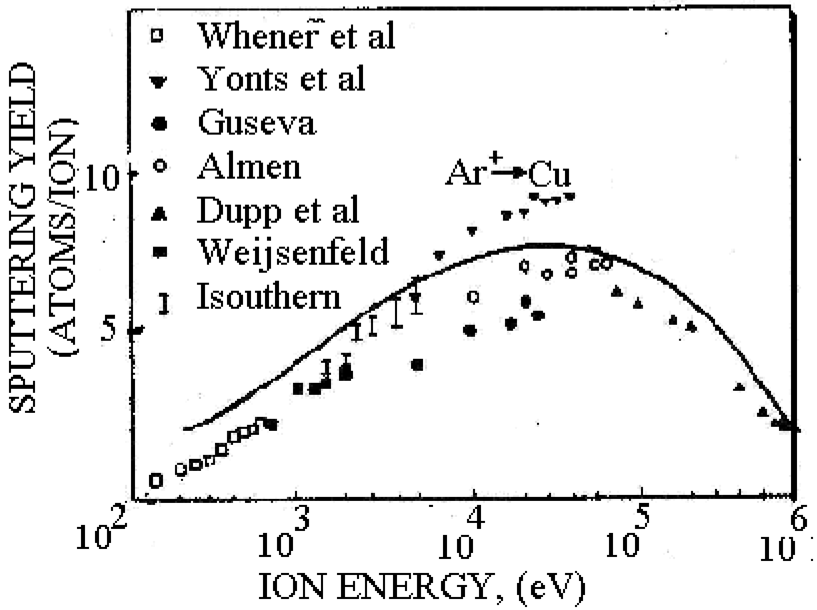


Fig. Ion energy dependence of the specific sputter-machining rate [1981,Taniguchi]

- **THE NUMBER OF ATOMS KNOCKED OUT BY THE INCIDENT IONS FROM THE TWO OR THREE ATOMIC LAYERS INCREASES WITH THE INCREASE IN THE ENERGY OF THE INCIDENT IONS**



SPUTTER YIELD AS A FUNCTION OF ION ENERGY IN LOW AND HIGH VOLTAGE RANGE

✞ABOVE 10^3 EV THE SPUTTERING YIELD INCREASES BUT THE RATE OF INCREASE IN SPUTTERING YIELD WITH ION ENERGY CONTINUES TO FALL, UNTIL IT REACHES TO A VERY HIGH VOLTAGE, APPROXIMATELY 10^5 EV.

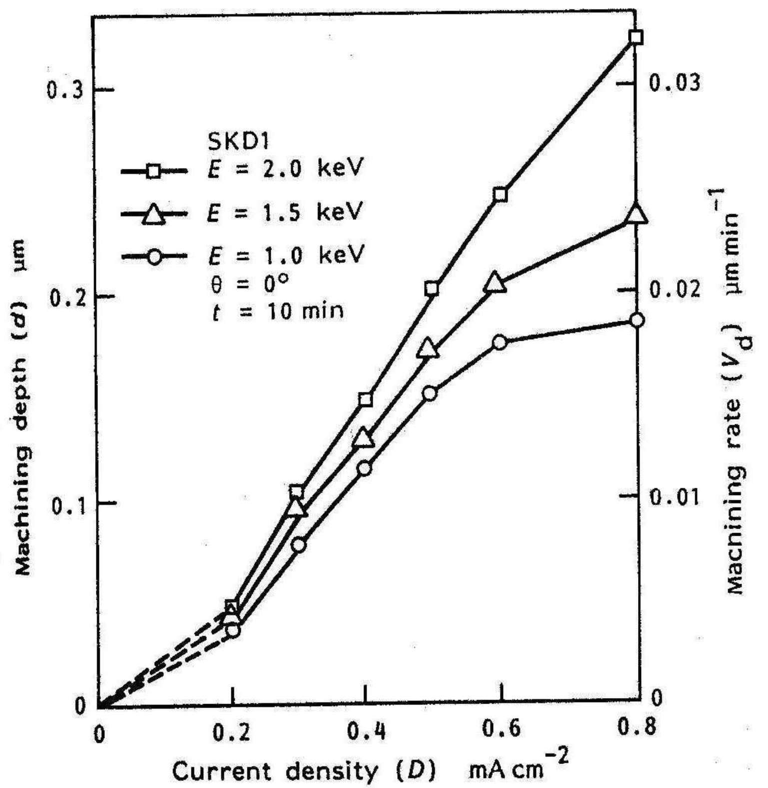
✞ THE SPUTTERING YIELD STARTS TO DROP BEYOND MAXIMA DUE TO IMPLANTATION EFFECT.

- **CURRENT DENSITY :**

❖ **MACHINING DEPTH INCREASES WITH INCREASE IN CURRENT DENSITY. HOWEVER, IT LARGELY DOES NOT DEPEND ON THE ION CURRENT DENSITY WITH SMALL ION ENERGY**

✞ **THE INCIDENT IONS LOSS THEIR KINETIC ENERGY DUE TO COLLISION WITH THE SPUTTERED IONS, AND ITS PROBABILITY BECOMES LARGER WHEN THE CURRENT DENSITY IS HIGH. THIS PHENOMENON IS SUPERSEDED BY INCREASE OF THE INCIDENT ION VELOCITY OR ION ENERGY.**

SKD-1=>HIGH CHROMIUM HIGH CARBON STEEL FOR GAUGES



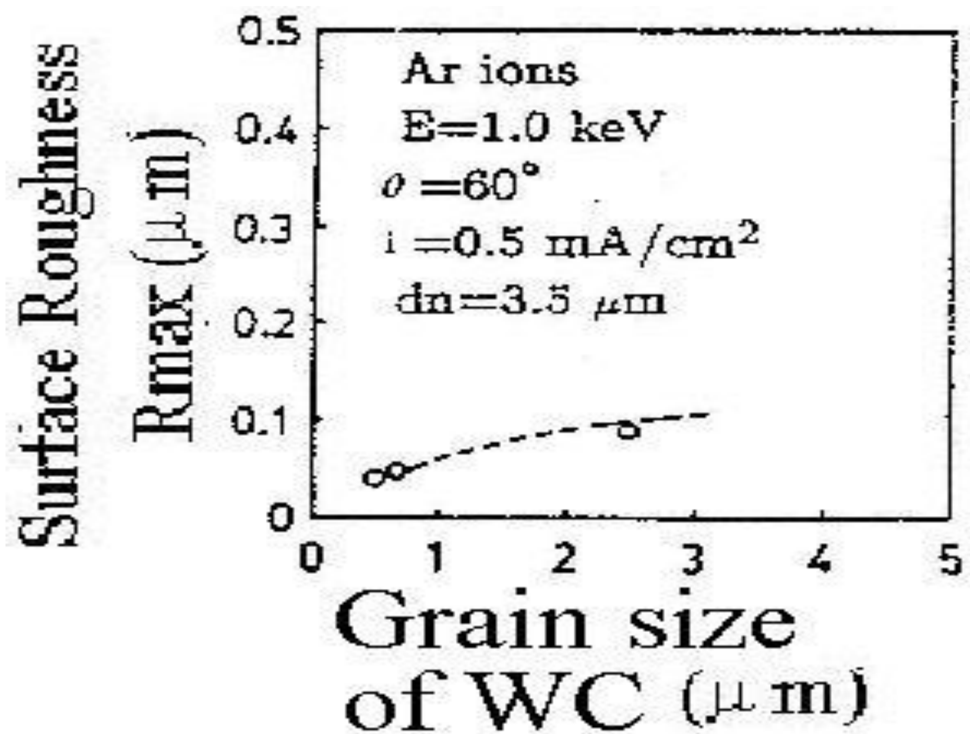
EFFECT OF CURRENT DENSITY ON SURFACE ROUGHNESS AT DIFFERENT ION ENERGIES (SHIMAT.,1990)

SURFACE FINISH IN ION BEAM MACHINING

FACTORS AFFECTING SURFACE FINISH

Workpiece material : SUCCESS OF THE ION BEAM POLISHING DEPENDS CRUCIALLY ON THE **GRAIN SIZE AND INITIAL MORPHOLOGY** OF THE SURFACE.

♦ SURFACE ROUGHNESS OF THE WORK-PIECE INCREASES WITH INCREASING GRAIN SIZE OF TUNGSTEN CARBIDE (WC).

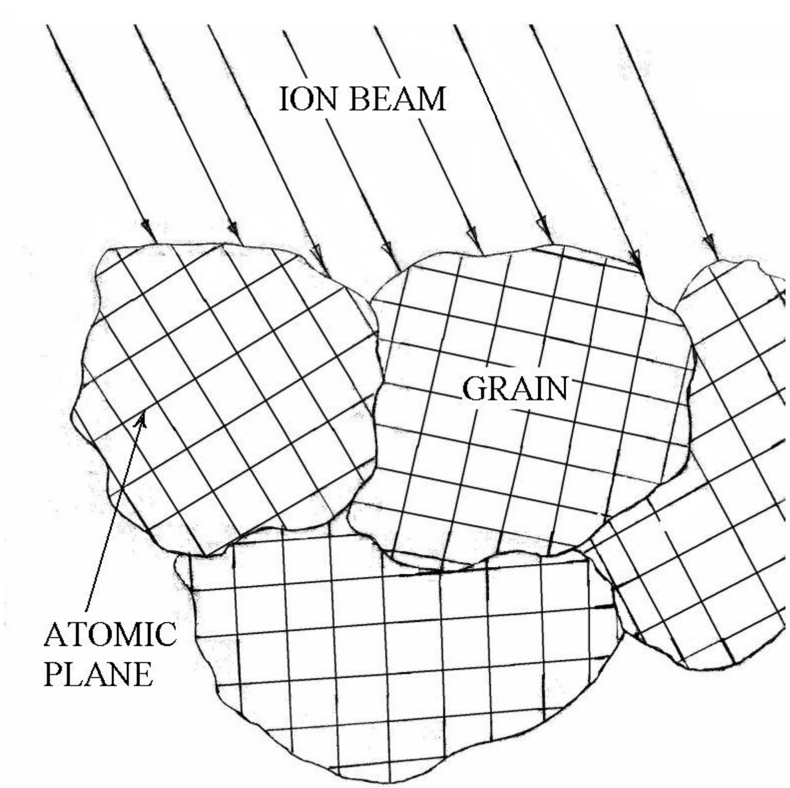


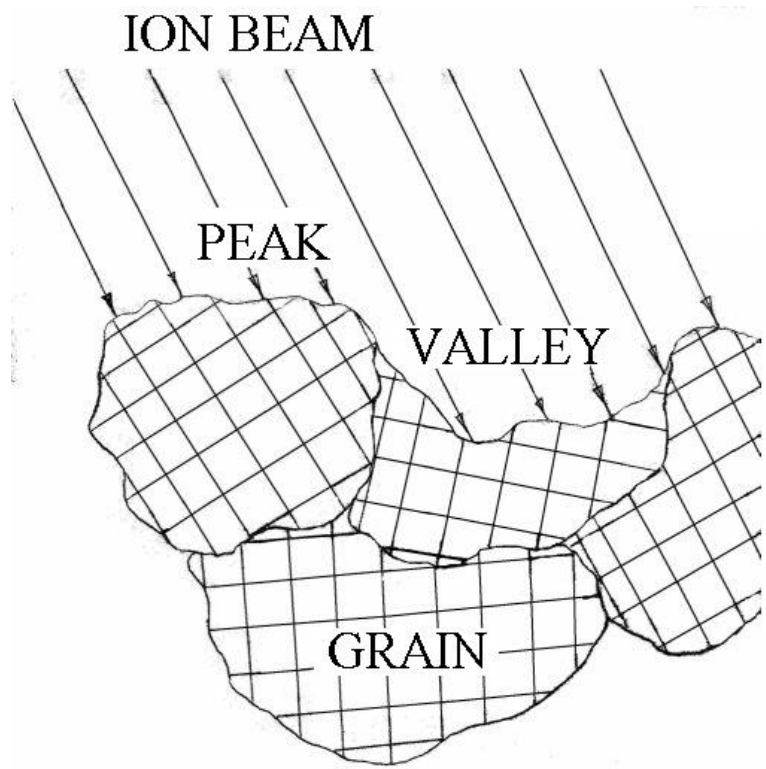
GRAIN SIZE DEPENDENCE OF THE SURFACE ROUGHNESS (MIYAMOTO.1993)

EFFECT OF GRAIN SIZE

- ♦ WITH VERY SMALL GRAIN SIZE, THE MACHINING RATE OF EACH GRAIN WILL BE ALMOST THE SAME, AND THEREFORE UNIFORM MACHINING OVER THE SURFACE WILL TAKE PLACE.

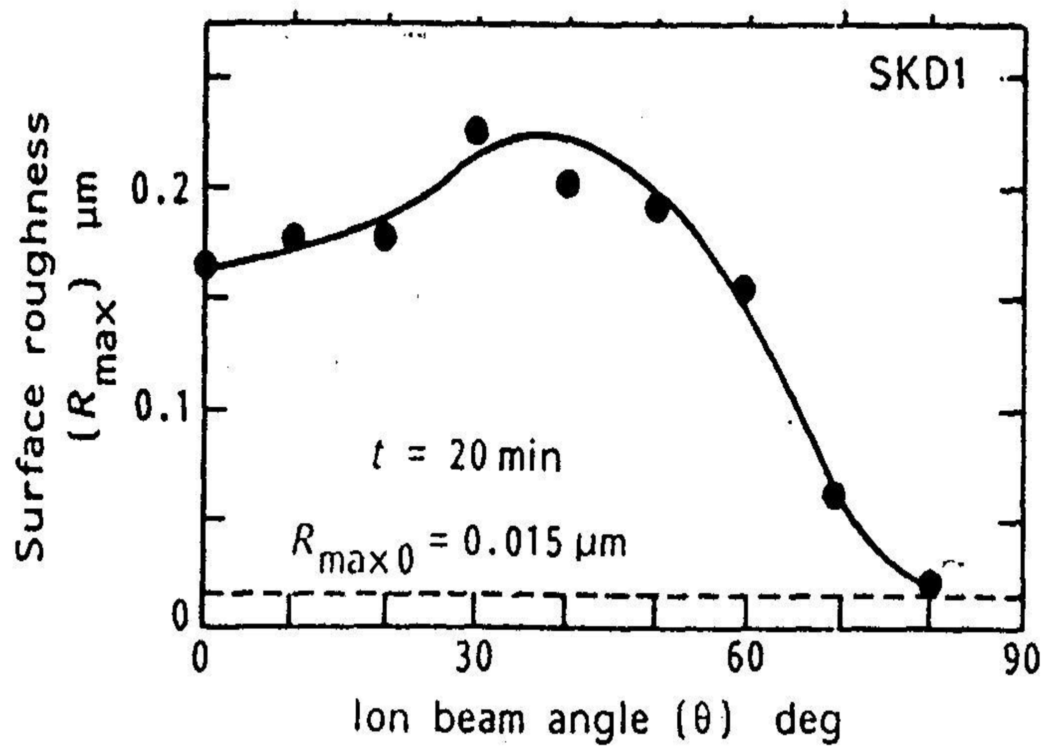
- ♦ FOR LARGE GRAIN SIZE, THE DIFFERENCE BETWEEN THE MACHINING RATES OF THE GRAINS RESULTS IN THE INCREASE IN VALUE OF SURFACE ROUGHNESS.





ANGLE OF INCIDENCE :

- AFTER AN INITIAL INCREASE, AN INCREASE IN ANGLE OF INCIDENCE SURFACE ROUGHNESS , DUE TO INCREASE IN THE MATERIAL REMOVAL RATE.



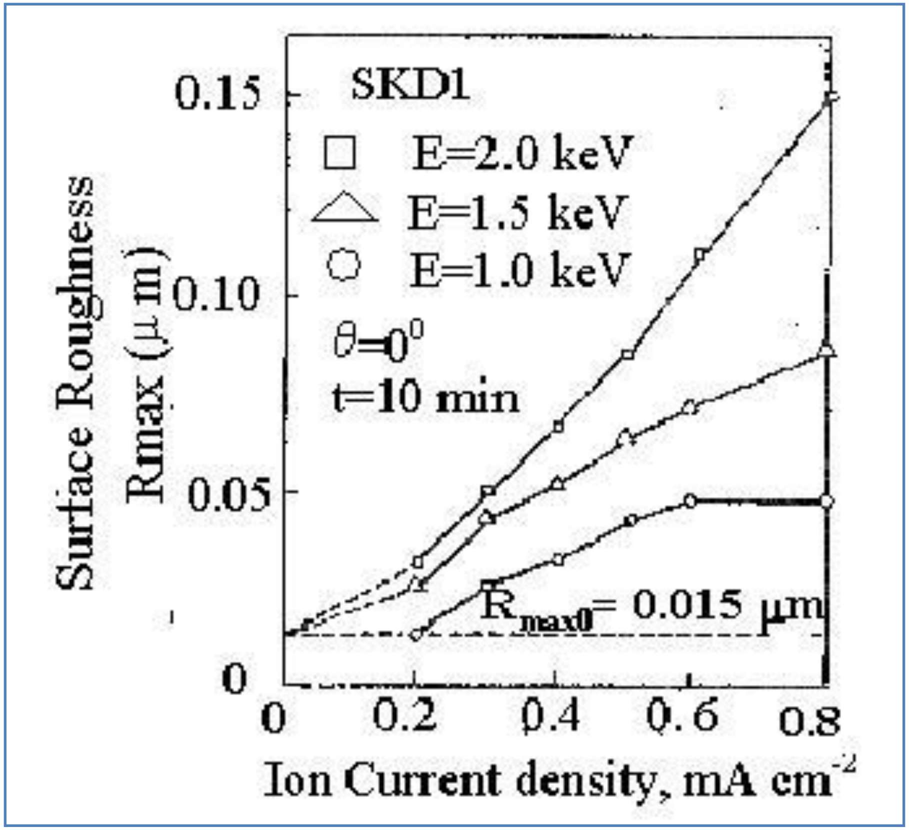
EFFECT OF ION BEAM INCIDENCE ANGLE ON SURFACE ROUGHNESS
(SHIMA,T.1990)

CURRENT DENSITY AND ION ENERGY:.

▪FOR LOW CURRENT DENSITY AND ENERGY, THE SMALLER VALUE OF SURFACE ROUGHNESS

♦ FOR THE SAME ENERGY IF THE CURRENT DENSITY IS HIGH SURFACE ROUGHNESS IS HIGH.

♦ PROBABILITY OF COLLISION BETWEEN THE INCIDENT IONS AND SPUTTERED ATOMS BECOMES LARGER WITH INCREASING ION CURRENT DENSITY THAT CAUSES IRREGULAR MACHINING ON THE SURFACE.



EFFECT OF CURRENT DENSITY ON SURFACE ROUGHNESS AT DIFFERENT ION ENERGIES (SHIMAT.,1990)

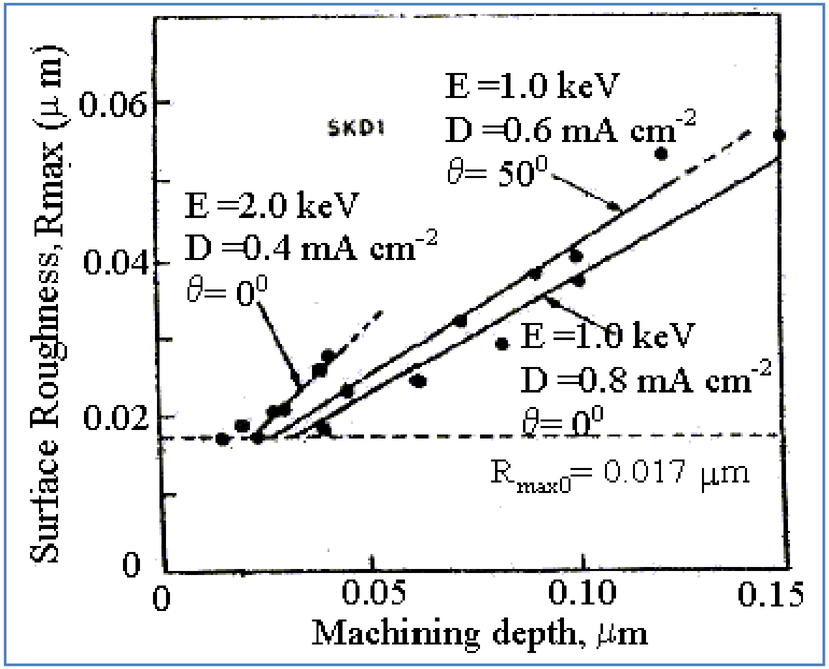
Predicaments During Finishing By Ion Beam Machining

- ♦ RE-DEPOSITION OF THE SPUTTERED MATERIAL ONTO THE SIDE OF STEEP SLOPES AS WELL AS ON THE MACHINED SURFACE
- ♦ IT REQUIRES HIGH VACUUM MACHINING CHAMBER.
- ♦ SURFACE ROUGHNESS MAY INCREASE

BY ION BEAM MACHINING FOR THE SURFACE HAVING THIN FILM OF OXIDE LAYER.

♦ SURFACE ROUGHNESS INITIALLY REMAINS CONSTANT UPTO THE MACHININ DEPTH OF APPROXIMATELY 30 nm

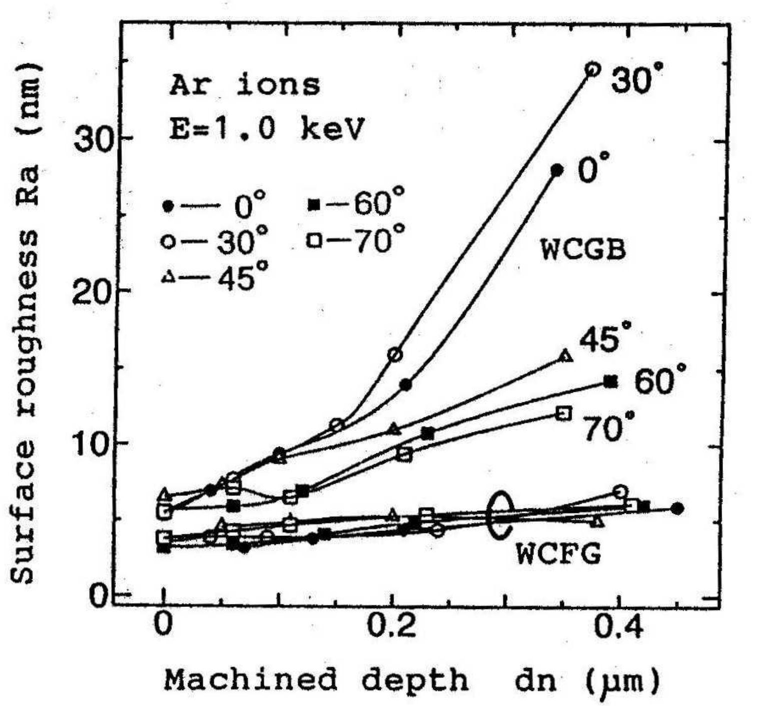
♦ AS THE MACHINING PROGRESSES, LARGE GRAIN STRUCTURE ARE EXPOSED THEREFORE SURFACE ROUGHNESS VALUE INCREASES.



SURFACE ROUGHNESS INCREASES BY ARGON ION BEAM MACHINING FOR SKD-1 (SHIMAT.,1990)

ARGON ION BEAM MACHINING FOR CEMENTED CARBIDE(MIYAMOTO I.,1993)

♦ **WHILE MACHINING CEMENTED CARBIDE, THE DIFFERENCE BETWEEN THE ION BEAM MACHINING RATES OF WC GRAIN AND THAT OF THE COBALT BINDER RESULTS IN A ROUGHENING OF WORK-PIECE SURFACE**



WCGB=>tungsten carbide gauge block, grain size 2-3 μm

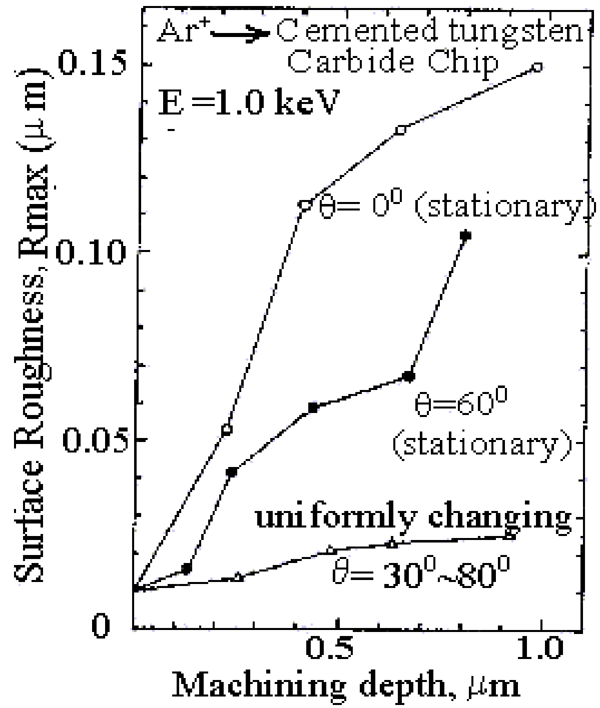
WCFG=>tungsten carbide chips, grain size 0f 0.5 μm.

♦ **THE WORK-PIECE HAVING COARSE GRAIN OF TUNGSTEN CARBIDE IS ROUGHENED FASTER THAN THAT OF THE WORK-PIECE HAVING FINE GRAIN SIZE**

ANGLE OF INCIDENCE OF IONS

♦ SURFACE QUALITY OF CEMENTED CARBIDE CAN BE IMPROVED BY UNIFORMLY CHANGING THE ANGLE OF INCIDENCE.

♦ DUE TO UNIFORMLY CHANGING OF INCIDENT ANGLE OF THE IONS, ADJACENT GRAINS OF TUNGSTEN CARBIDE WILL BE ERODED WITH THE SAME AVERAGE RATE, AND THE GRAINS OF THE COBALT AND TUNGSTEN CARBIDE WILL ALSO BE ERODED WITH NEARLY THE SAME RATE.

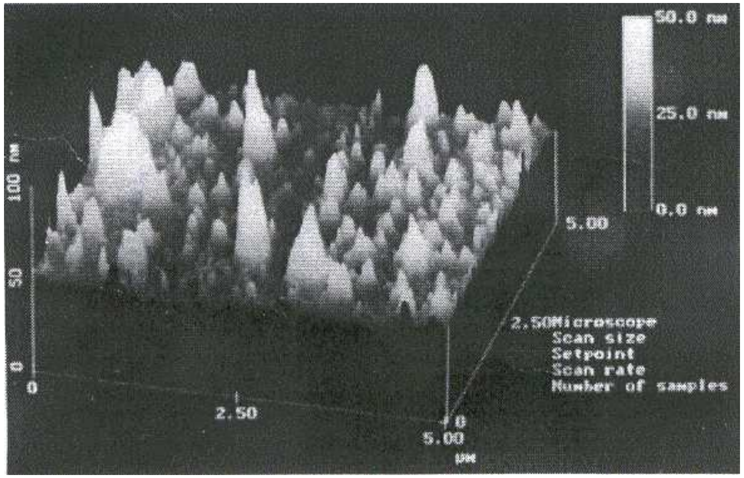


IMPROVEMENT OF SURFACE ROUGHNESS BY UNIFORMLY CHANGING THE ANGLE OF INCIDENCE (TANIGUCHI N,1981)

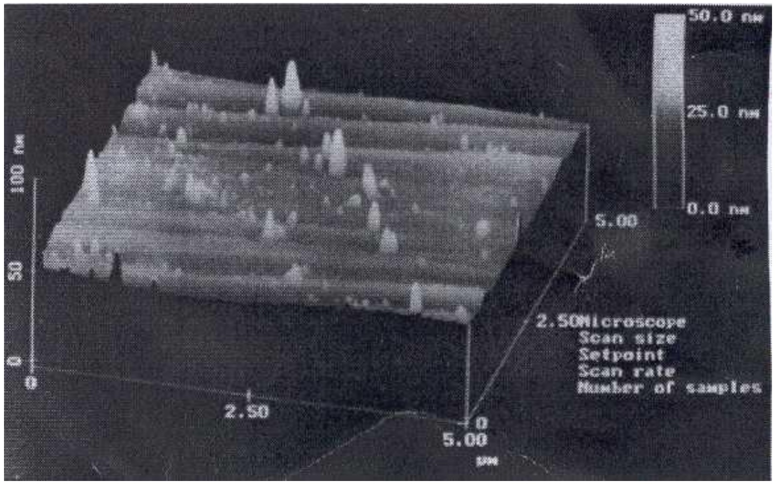
♦ TYPE OF ION SOURCE:

=>SURFACE ROUGHNESS AFTER ION BEAM MACHINING USING AN ECR-TYPE (ELECTRON CYCLOTRON RESONANCE) APPARATUS IS ABOUT FOUR TIMES LESS THAN THAT USING A KAUFAN TYPE APPARATUS.

=>DUE TO AN ELECTRODE-LESS DISCHARGE SYSTEM, THE ION SOURCE CAN PRODUCE BEAMS OF EXCELLENT UNIFORMITY AND STABILITY.



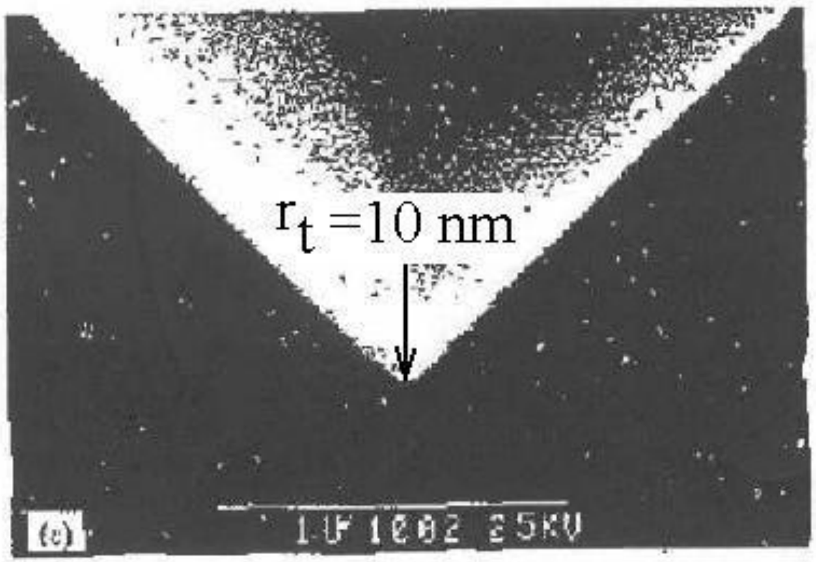
ION SOURCE: KAUFMAN TYPE



ION SOURCE: ECR TYPE

AFM IMAGE OF DIAMOND (100) AFTER OXYGEN ION BEAM MACHINING (KIYOHARA S.,1996)

DIAMOND STYLI AFTER BEING POLISHED BY ARGON ION BEAM (VASILE M,1996)



E=10 kev

current density = 0.5 mA/cm^2

Machining Time=13 hrs

- **DIAMOND STYLI FOR PROFILOMETER WERE SHARPENED USING KAUFMAN TYPE ION SOURCE TO THE TIP RADIUS OF 10 nm**

CONCLUSIONS

- ♦ ION BEAM MACHINING IS AN IDEAL PROCESS FOR NANO-FINISHING OF HIGH MELTING POINT HARD AND BRITTLE MATERIALS SUCH AS CERAMICS, SEMICONDUCTORS, DIAMOND ETC.
- ♦ AS THERE IS NO LOAD ON THE WORK-PIECE WHILE FINISHING , IT IS ALSO SUITABLE FOR FINISHING OF VERY THIN OBJECTS, OPTICS AND SOFT MATERIAL.
- ♦ SURFACE ROUGHNESS INCREASES WITH INCREASE IN SIZE OF THE GRAIN STRUCTURE, ION ENERGY AND CURRENT DENSITY. SURFACE MORPHOLOGY HAS SIGNIFICANT EFFECT ON THE FINAL SURFACE FINISH.
- ♦ SURFACE ROUGHNESS INCREASES FOR INCIDENT ANGLE FROM 0^0 TO 50^0 THEN DECREASES RAPIDLY.
- ♦ NON-HOMOGENEITY IN GRAIN STRUCTURE MAY RESULT IN ROUGHENING OF THE WORK-PIECE SURFACE BY ION BEAM MACHINING BUT THAT CAN BE OVERCOME BY CHANGING THE MACHINING CONDITIONS.
- ♦VERY LESS AMOUNT OF MATERIAL REMOVAL NEEDED TO ACHIEVE THE FULL POLISHING.

THANK YOU

ION BEAMS

Analysis

- Rutherford Backscattering
- Channeling
- Proton and Heavy Ion Induced X-ray Emission
- Resonant Scattering
- Nuclear Reactions
- Forward Scattering (Elastic Recoil)
- Ion Beam Induced Charge Microscopy

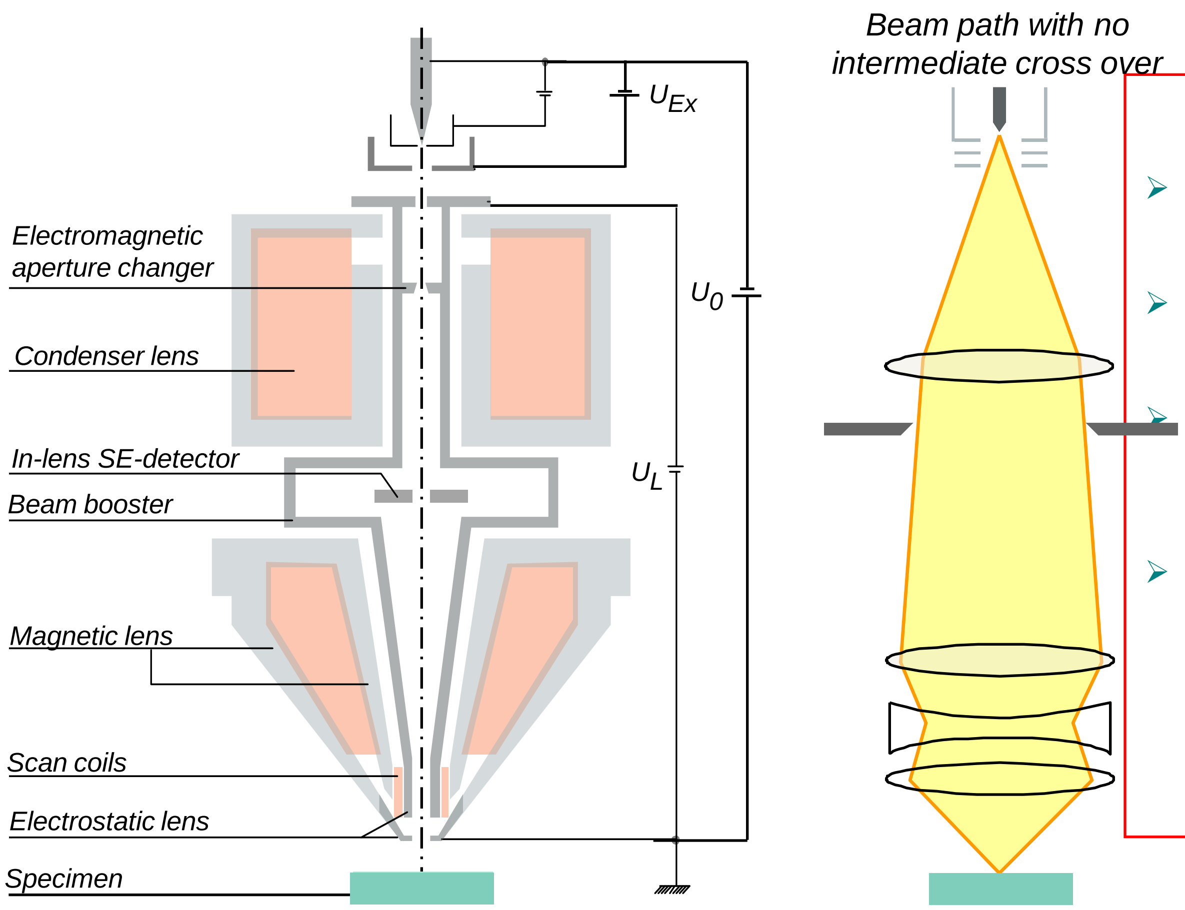
Engineering

- **Ion Implantation**
- **Tribology**
- **Ion Beam Mixing**
- **Lithography**
- **Deposition by cracking of molecules under ion impact**
- **Micro and nano machining and fabrication of microcomponents**
- **Size and shape control of nano Structures**
- **Ion Beam Sculpting**
- **Radiation bystander effects (single ion irradiation effects in biological cells)**

Ion Beam Tool Kit for Engineering and Analysis

Electron Optics

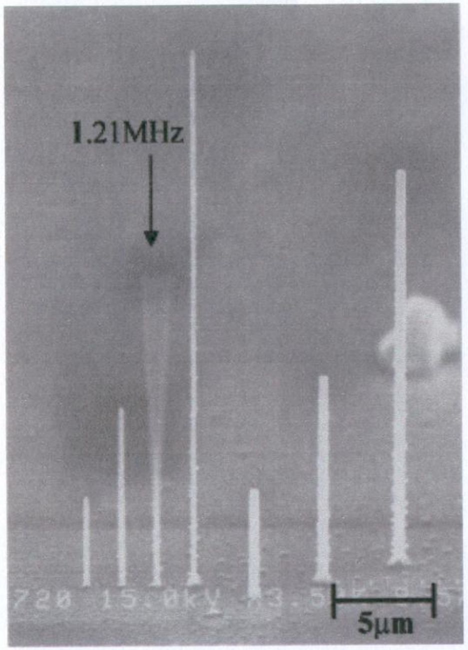
Operating principle of the Gemini column



FEATURES

- **HIGHLY STABLE THERMAL FEG**
  < 0.5 % /H VARIATION
- **LOW BEAM NOISE**
  < 1 %
- **CROSS OVER FREE BEAM PATH**
  NO SIGNIFICANT BOERSCH EFFECT,
  HIGH DEPTH OF FIELD
- **BEAM BOOSTER**
  SUPERB IMAGE RESOLUTION THROUGHOUT THE WHOLE BEAM ENERGY RANGE, PARTICULARLY DOWN TO 100 EV.
  HIGH RESISTANCE TO AMBIENT MAGNETIC STRAY FIELDS

FIB deposition for nanoscale structures



Amorphous carbon pillars **deposited** with 30 keV Ga FIB + phenanthrene gas CVD.

SEM image of vibration induced by a piezo device with resonant frequency of 1.21 MHz

$$f = \frac{\alpha\beta^2}{2\pi L^2}\sqrt{\frac{E}{16\rho}}$$

E=600 GPa

J. Fujita, et al., J. Vac. Sci. Technol. B 19 (2001) 2834

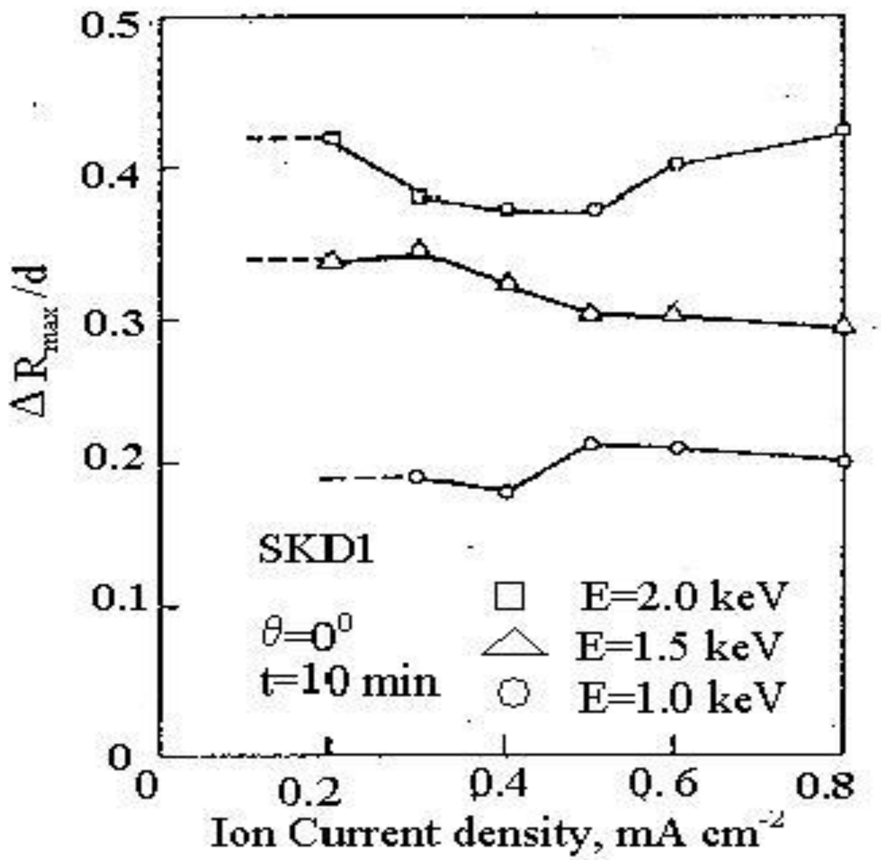
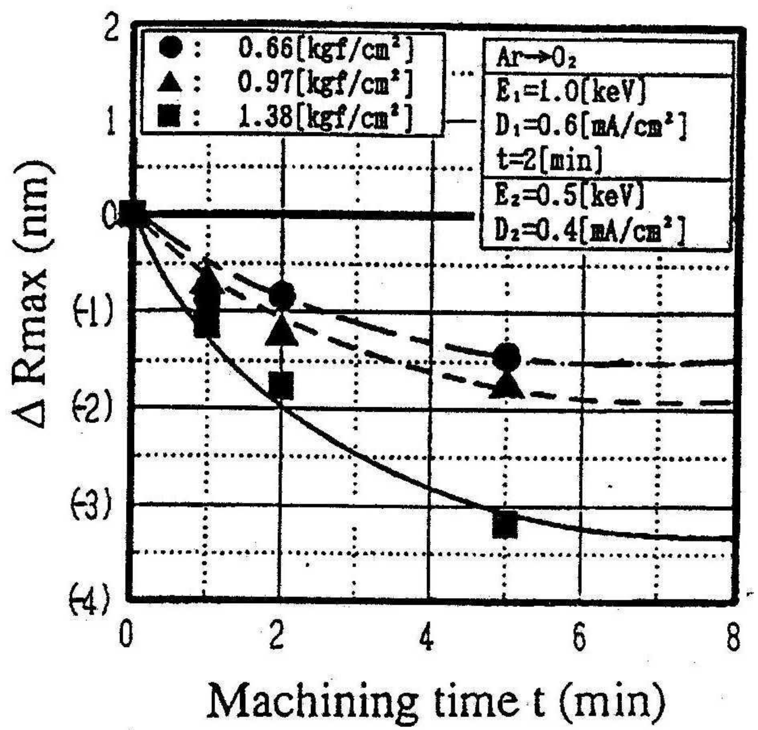


Fig. Effect of ion current density on different ion energies(Shima,T.1990)

♦ **HIGHER THE ENERGY, LARGER IS THE VALUE OF $\Delta R_{MAX}/d$, BUT WITH THE CHANGE IN CURRENT DENSITY, THE VALUE OF $\Delta R_{MAX}/d$ IS ALMOST CONSTANT**

METHODS FOR IMPROVEMENT IN SURFACE FINISH

♦ USE OXYGEN ION BEAM FOR THE MATERIAL TO QUICKLY FORM FINE GRAINED OXIDE LAYER . OXYGEN IONS ARE LIGHTER THAN ARGON IONS.



work-piece (SKD-1)

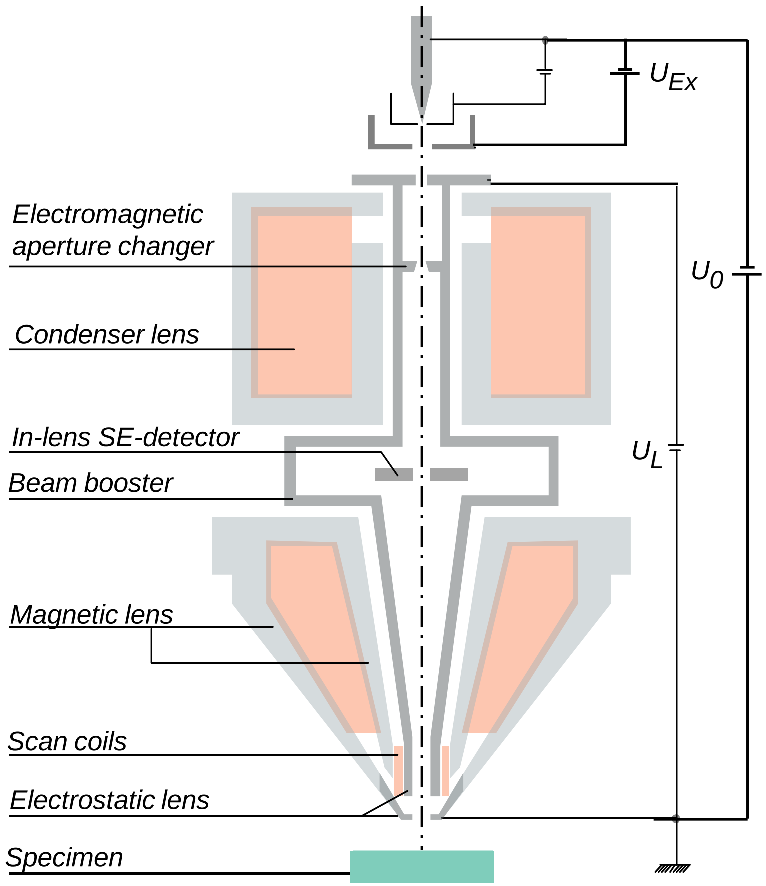
ΔR_{max} = **FINAL SURFACE ROUGHNESS - INITIAL SURFACE ROUGHNESS**

CHANGE IN SURFACE ROUGHNESS BY OXYGEN ION BEAM POST MACHINING (T.KAZUYOSHI,1995)

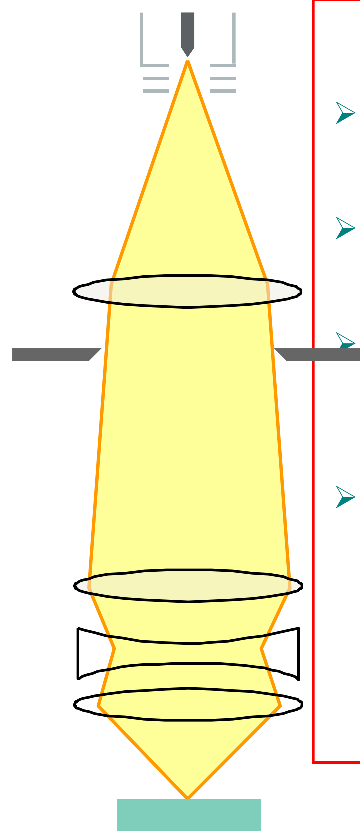
♦ **DECREASE IN SURFACE ROUGHNESS BY OXYGEN ION BEAM MACHINING AFTER PRE-MACHINING BY ARGON ION BEAM.**

Electron Optics

Operating principle of the Gemini column



Beam path with no intermediate cross over



FEATURES

- **HIGHLY STABLE THERMAL FEG**
  < 0.5 % /H VARIATION
- **LOW BEAM NOISE**
  < 1 %
- **CROSS OVER FREE BEAM PATH**
  NO SIGNIFICANT BOERSCH EFFECT,
  HIGH DEPTH OF FIELD
- **BEAM BOOSTER**
  SUPERB IMAGE RESOLUTION THROUGHOUT THE WHOLE BEAM ENERGY RANGE, PARTICULARLY DOWN TO 100 EV.
  HIGH RESISTANCE TO AMBIENT MAGNETIC STRAY FIELDS

ION BEAM MACHINING EQUIPMENT

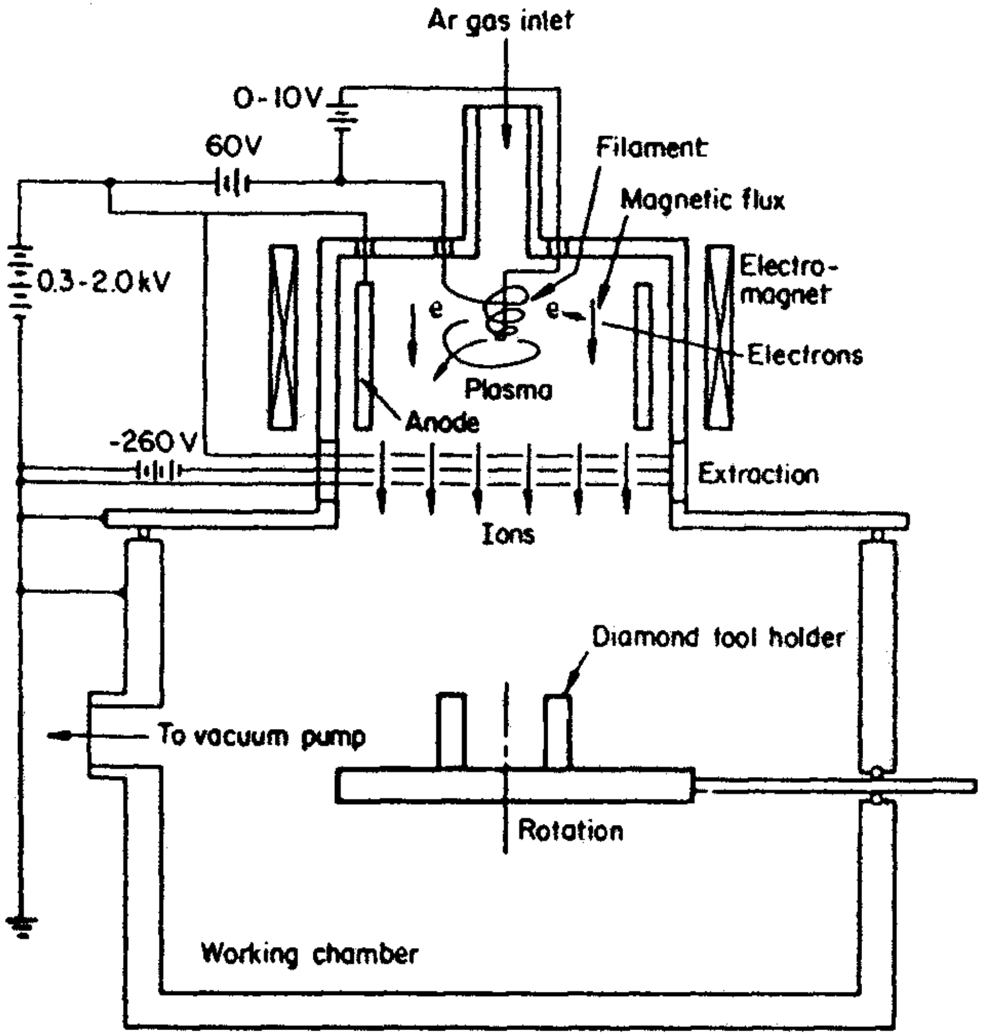


Fig.Ion beam machining apparatus (Miyamoto,I,1987)