EE 213, Microscopic Nanocharacterization of Materials
Lecture 10.
other micro-characterization using ion beams

Class website: https://ee213-winter16-01.courses.soe.ucsc.edu

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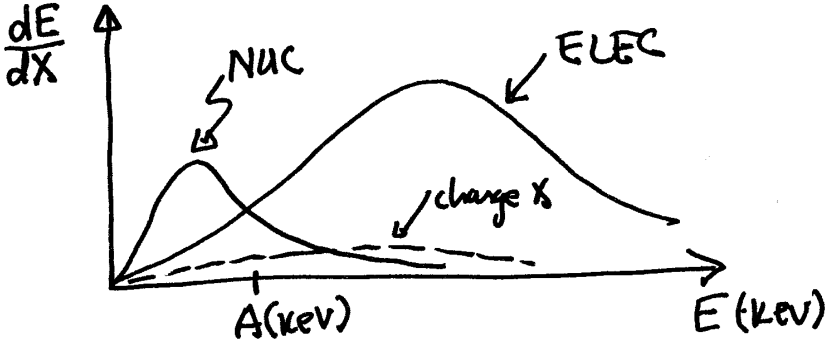
ION INTERACTIONS

three main components

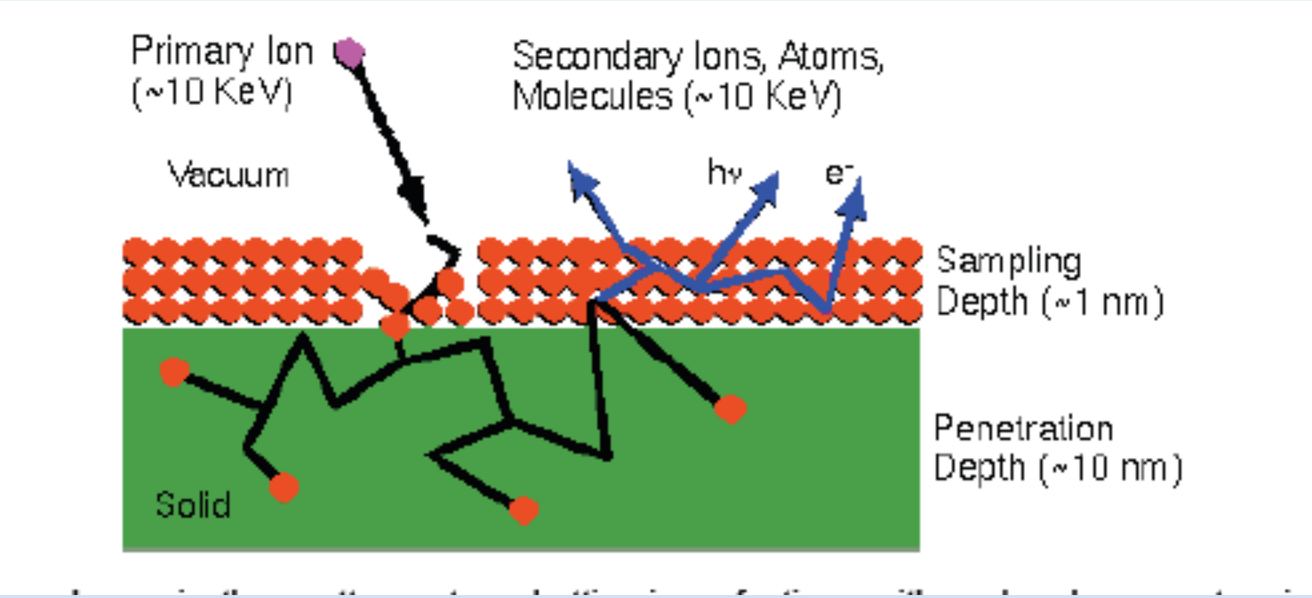
1. "nuclear" energy loss, dominates at low energies when $E < A$ keV
   at. wt inc. ion

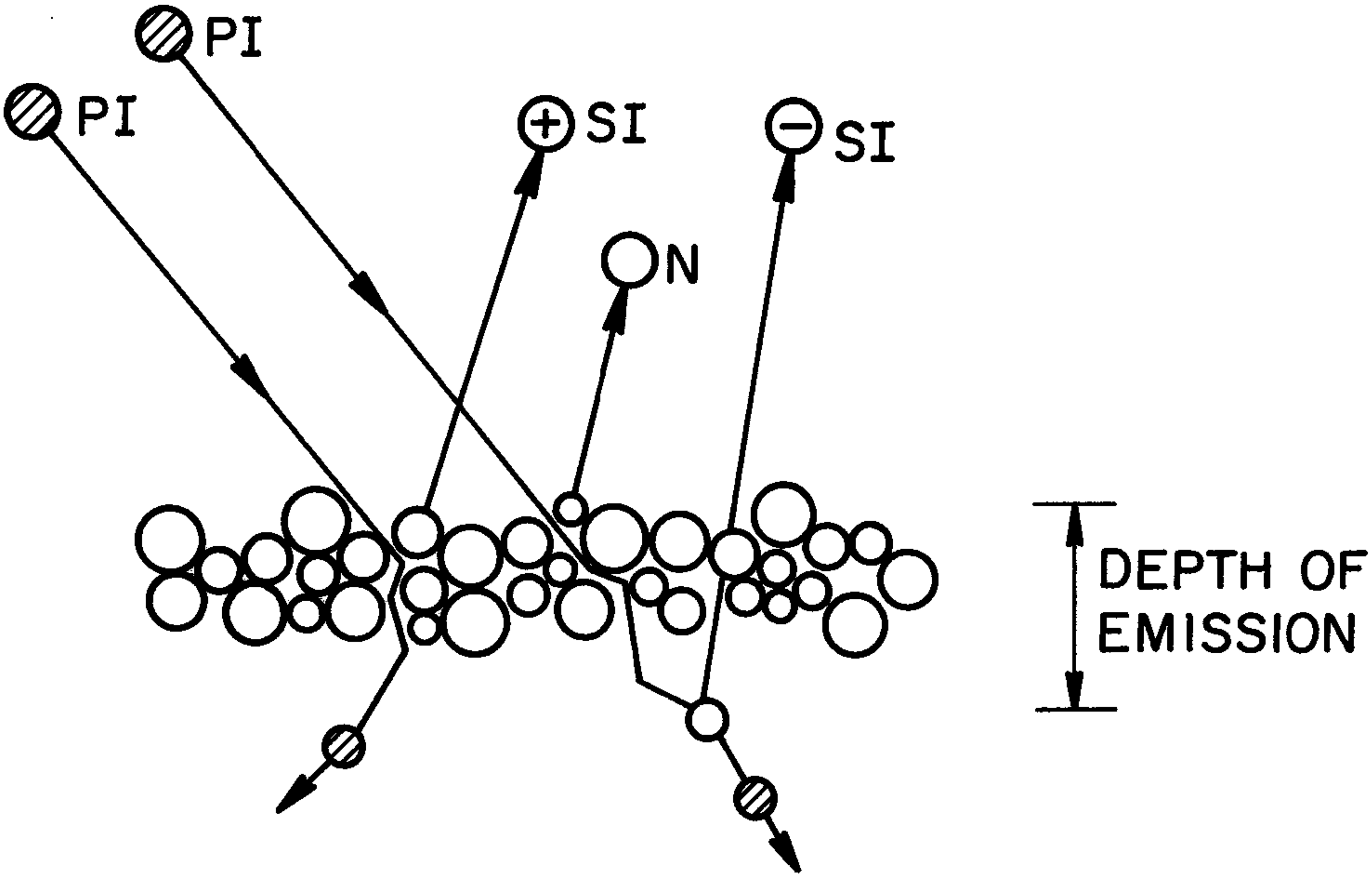
2. electronic energy loss
   interactions with atomic electrons
   (like "inelastic" electron scattering)

3. charge exchange
   $\lesssim$ 10% of total



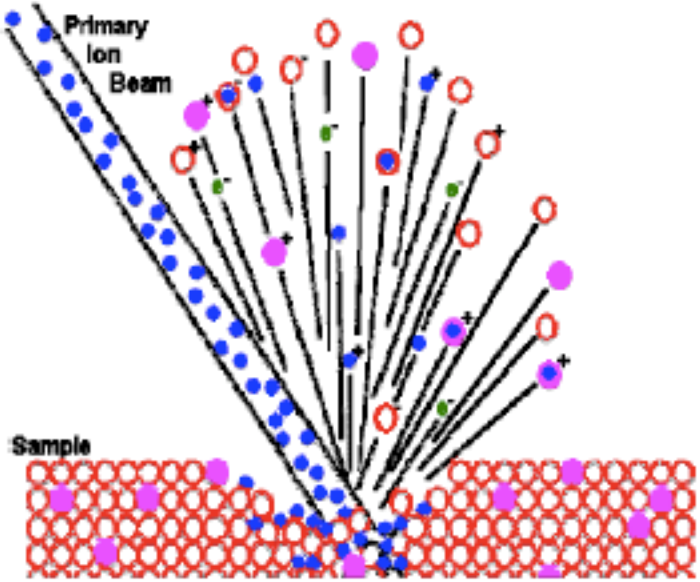
Sputtering


Primary Ion
(~10 KeV)
Secondary Ions, Atoms,
Molecules (~10 KeV)
Vacuum
hν
e⁻
Sampling
Depth (~1 nm)
Penetration
Depth (~10 nm)
Solid

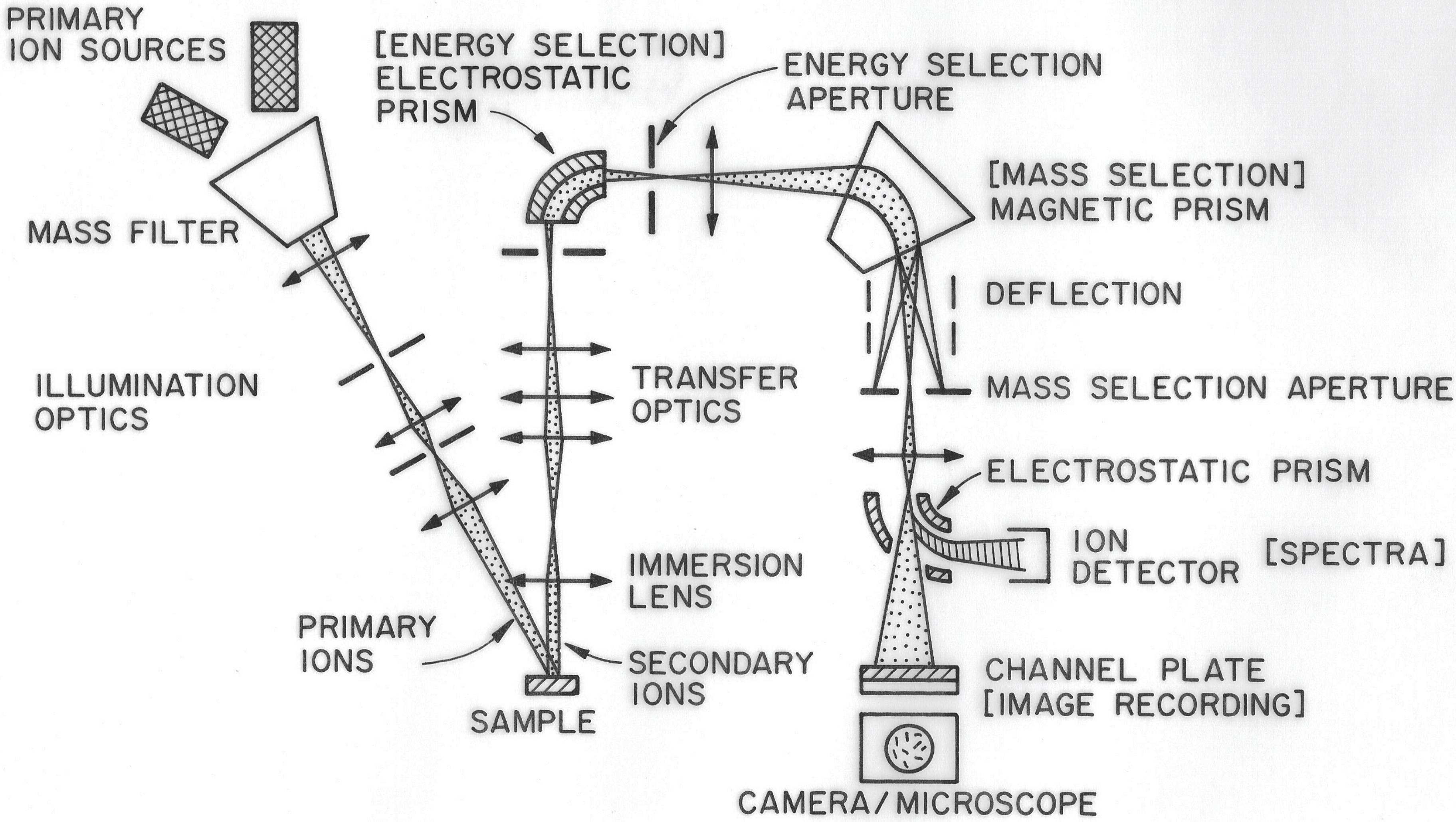

PI
PI
+ SI
− SI
N
DEPTH OF EMISSION

Primary Ion Beam

- **Interaction with the surface known as sputtering**
  - Amorphization of the surface
  - Implant Atoms
  - Secondary Particles are Ejected



http://pprco.tripod.com/SIMS/Theory.htm

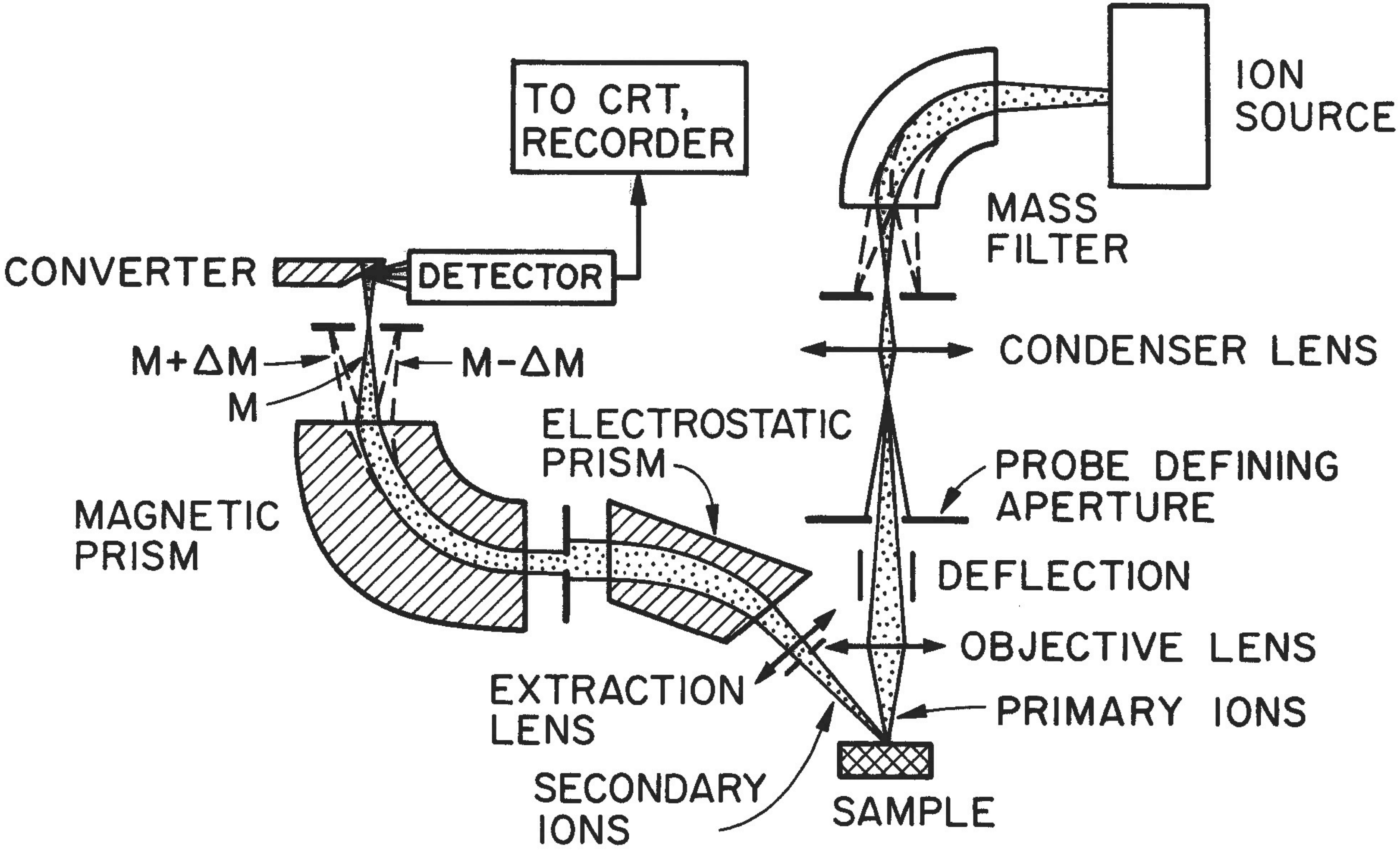


R. Castaing and G. Slodzian. J. Microscopy.1.(1962).395-410. (in French)

G. Slodzian. Surface Science.48.(1961)

SECONDARY ION MICROSCOPE

Global Image



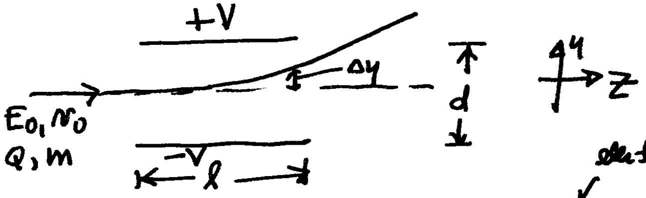
ION MICROPROBE

Scanning image

H. Liebl (1967). JAP.38.5277-5283.

energy selection by electrostatic field //

gen'l: ∥ plates



elec field

$$m\ddot{y} = q\mathcal{E}_y \longrightarrow \left[\begin{matrix}\dot{y}_0 = 0, & \dot{z}_0 = v_0 \\ y_0 = 0, & z_0 = 0\end{matrix}\right] \longrightarrow y = \frac{q}{2m}\mathcal{E}_y t^2$$

$$m\ddot{z} = 0 \longrightarrow \qquad z = v_0 t$$

$$\therefore y = \frac{q}{2m}\mathcal{E}_y\left(\frac{z_0}{v_0}\right)^2$$ but $E_0 = \frac{1}{2}m v_0^2$

$2E_0 = m v_0^2$

$\therefore$ $y = q\, E_y\, Z_0^2/4E_0$ $\mathcal{E}_y = \Delta V/d$

$\frac{E_0}{q}$

∥ defl $\propto \frac{1}{E_0}$ ∥ an energy deflector

for spherical plates $\Longrightarrow$ balance $\vec{F} = Q\vec{E}$ with centrip force

really E_0/q dependent ∥ get $\frac{2E_0}{r} = Q\mathcal{E}_0$ ∥ smaller E_0 get bent more //

$$\boxed{r = \frac{2E_0}{Q\mathcal{E}_0}}$$

diff than mag sector also. $BR = \frac{mv}{Q}$ ∥ momentum selector / a M/Q selector of energy must

ion microprobe (a "scanning" technique.
(in principle, simpler system / optics)

advantage: 1. can collect secondary electron image as well

NOTE // ≠ different erosion process.

in all ~~the~~ SIMS microprobe, topographic structure of sample surface can affect results.

doc camera

— shadowing
— redeposition

what are detection limits with SIMS?
- it varies with atom and matrix
- it varies whether + or − ions

show table //

example: in SiO₂ / Cu → $\lim = 5\times10^{13}/\mathrm{cm}^3$ with O_2^+
$\lim = 2\times10^{15}/\mathrm{cm}^3$ with Cs^-

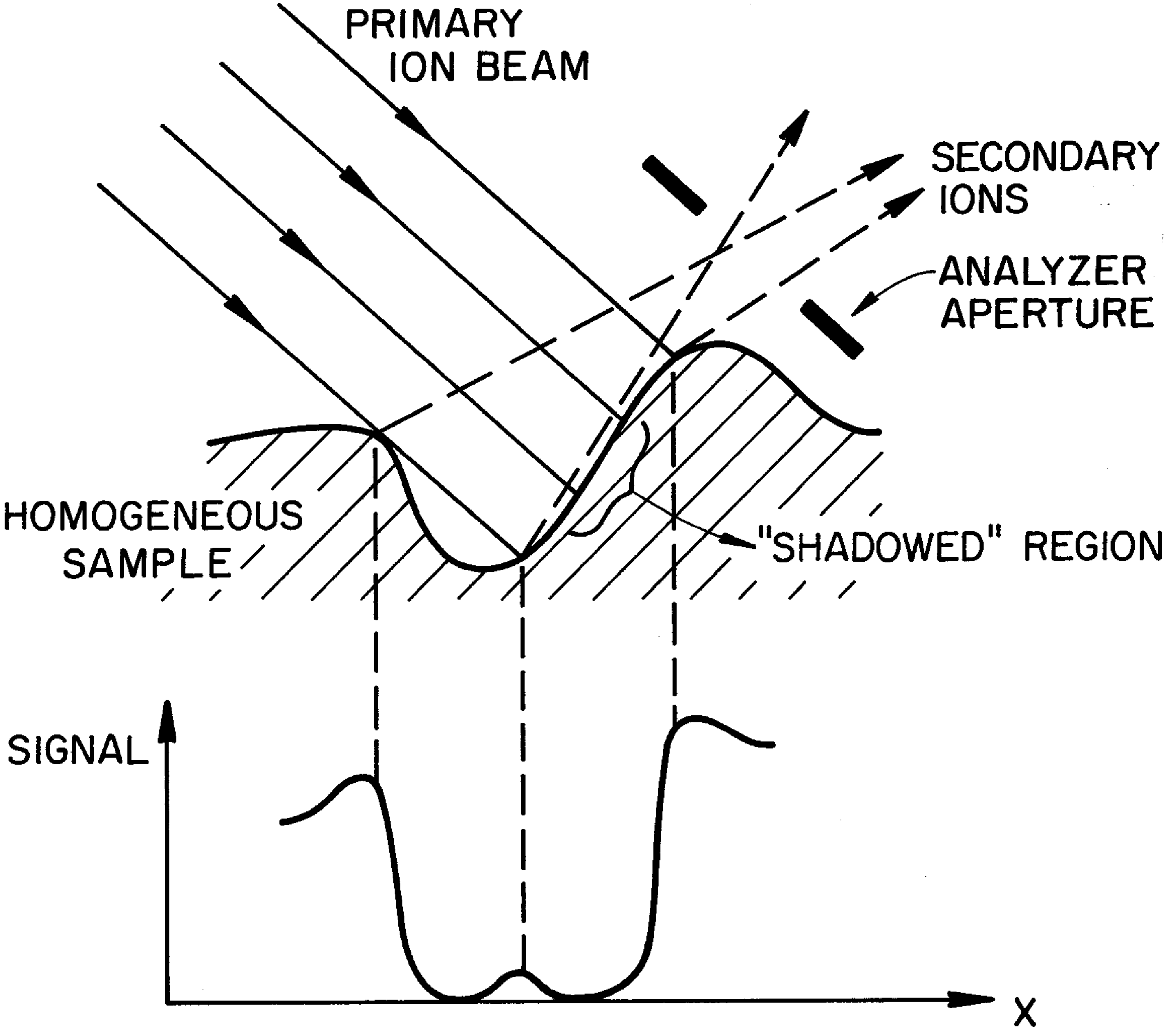
Si // $\rho = 2.7\ \mathrm{gm/cm}^3$
$A = 28$ amu
$n \cong 10^{-1}\times 6\times10^{23}$ atom/cm³
$\cong 6\times10^{22}/\mathrm{cm}^3$ //

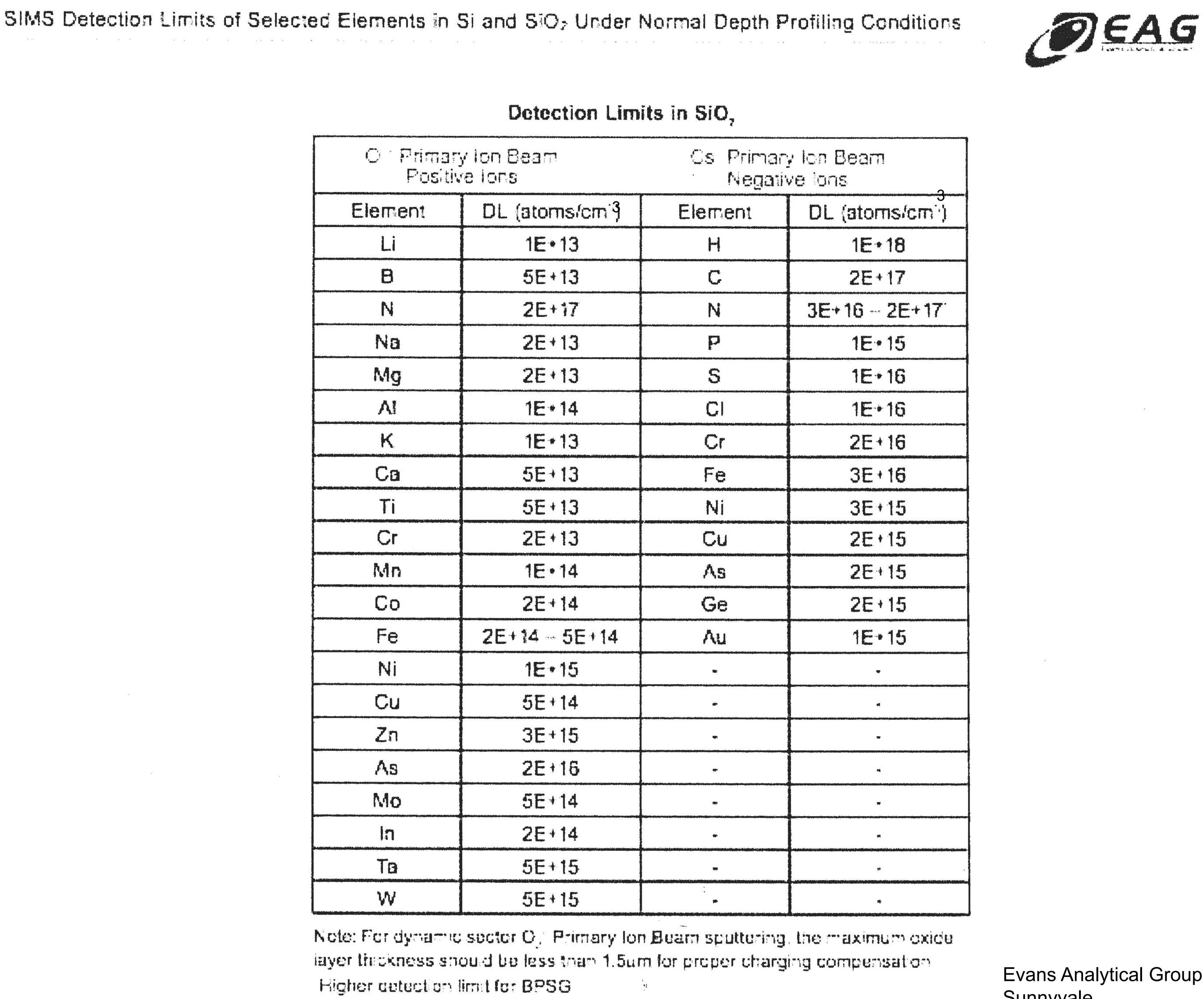
in Si / Cu → $\lim = 2\times10^{14}/\mathrm{cm}^3$ O_2^+
$\lim = 2\times10^{15}/\mathrm{cm}^3$ with Cs^-

NOTE / det limits are 10^{-6}–10^{-7} atom % or better —
almost a trace technique

Shadowing/Redeposition in SIMS

Rudenhauer and Steiger, Ultramicrsocpy. 24 (2-3).1988.p.115-123


PRIMARY ION BEAM
SECONDARY IONS
ANALYZER APERTURE
HOMOGENEOUS SAMPLE
"SHADOWED" REGION
SIGNAL
X



SIMS Detection Limits of Selected Elements in Si and SiO_2 Under Normal Depth Profiling Conditions

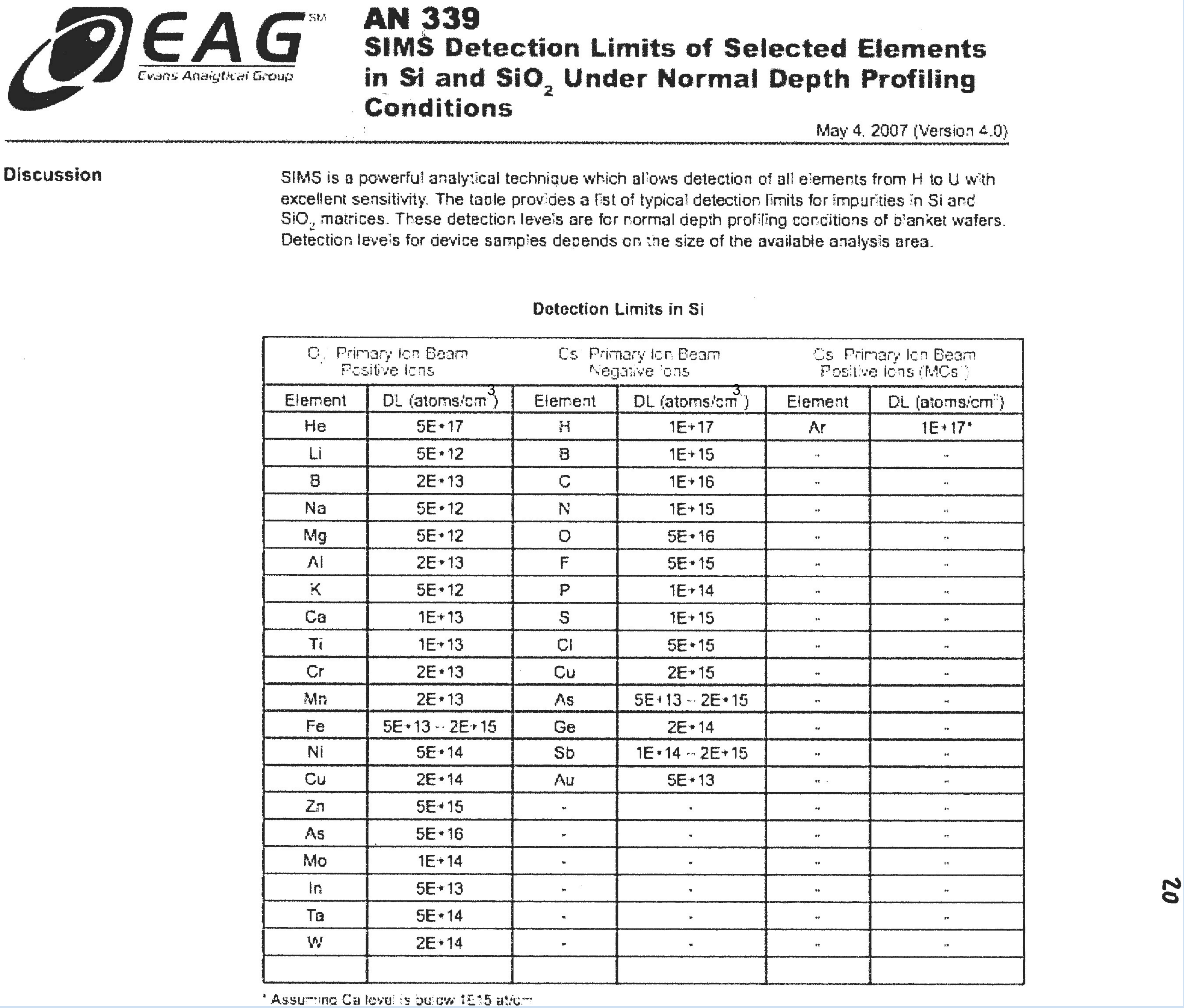
Detection Limits in SiO_2

O_2^+ Primary Ion Beam Positive Ions		Cs Primary Ion Beam Negative Ions	
Element	DL (atoms/cm^3)	Element	DL (atoms/cm^3)
Li	1E+13	H	1E+18
B	5E+13	C	2E+17
N	2E+17	N	3E+16 – 2E+17
Na	2E+13	P	1E+15
Mg	2E+13	S	1E+16
Al	1E+14	Cl	1E+16
K	1E+13	Cr	2E+16
Ca	5E+13	Fe	3E+16
Ti	5E+13	Ni	3E+15
Cr	2E+13	Cu	2E+15
Mn	1E+14	As	2E+15
Co	2E+14	Ge	2E+15
Fe	2E+14 – 5E+14	Au	1E+15
Ni	1E+15	-	-
Cu	5E+14	-	-
Zn	3E+15	-	-
As	2E+16	-	-
Mo	5E+14	-	-
In	2E+14	-	-
Ta	5E+15	-	-
W	5E+15	-	-

Note: For dynamic sector O_2^+ Primary Ion Beam sputtering, the maximum oxide layer thickness should be less than 1.5um for proper charging compensation

Higher detection limit for BPSG

Evans Analytical Group,
Sunnyvale



EAG Evans Analytical Group

AN 339
SIMS Detection Limits of Selected Elements in Si and SiO_2 Under Normal Depth Profiling Conditions

May 4, 2007 (Version 4.0)

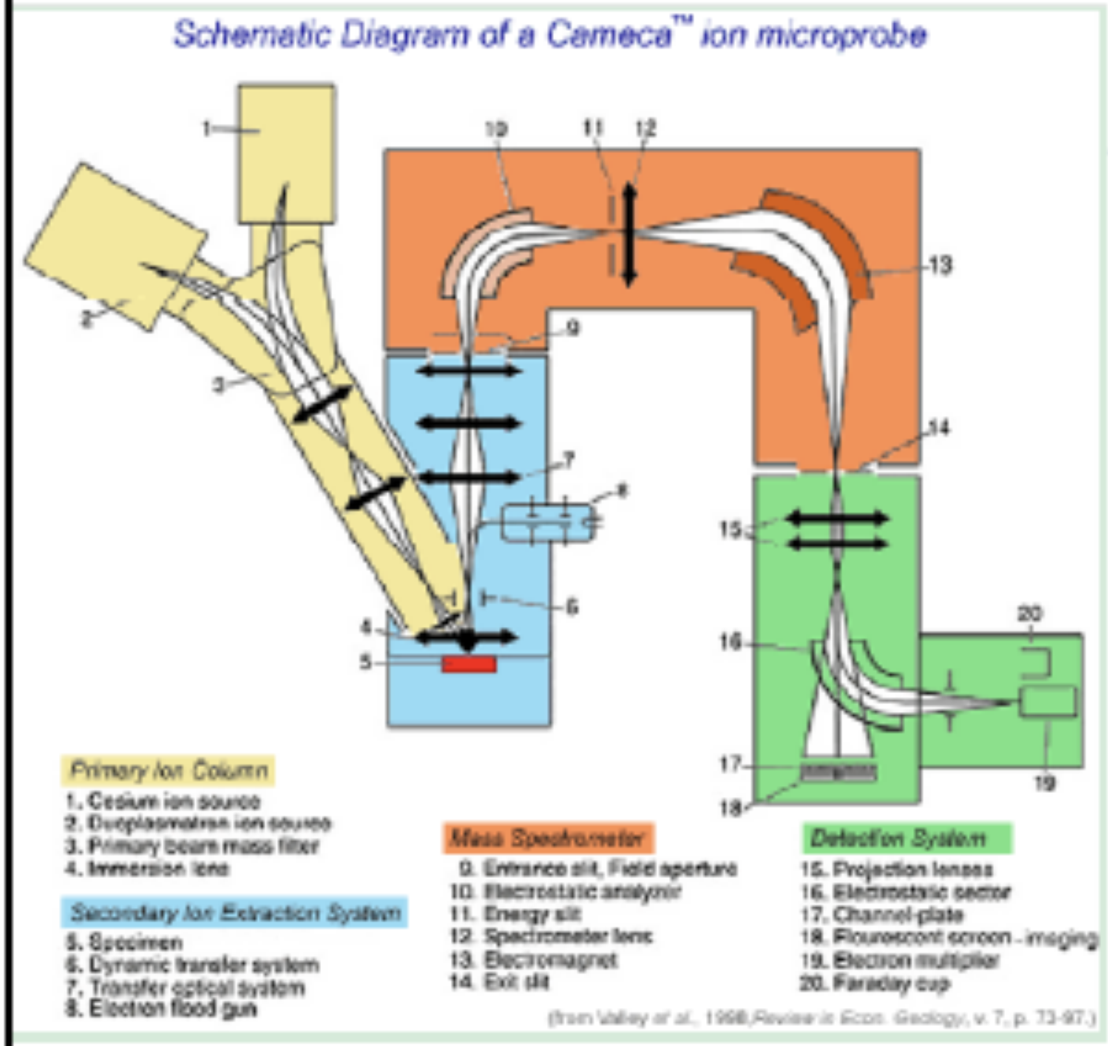
Discussion

SIMS is a powerful analytical technique which allows detection of all elements from H to U with excellent sensitivity. The table provides a list of typical detection limits for impurities in Si and SiO_2 matrices. These detection levels are for normal depth profiling conditions of blanket wafers. Detection levels for device samples depends on the size of the available analysis area.

Detection Limits in Si

O_2^+ Primary Ion Beam Positive Ions		Cs^+ Primary Ion Beam Negative Ions		Cs^+ Primary Ion Beam Positive Ions (MCs^+)	
Element	DL (atoms/cm^3)	Element	DL (atoms/cm^3)	Element	DL (atoms/cm^3)
He	5E+17	H	1E+17	Ar	1E+17*
Li	5E+12	B	1E+15	-	-
B	2E+13	C	1E+16	-	-
Na	5E+12	N	1E+15	-	-
Mg	5E+12	O	5E+16	-	-
Al	2E+13	F	5E+15	-	-
K	5E+12	P	1E+14	-	-
Ca	1E+13	S	1E+15	-	-
Ti	1E+13	Cl	5E+15	-	-
Cr	2E+13	Cu	2E+15	-	-
Mn	2E+13	As	5E+13 – 2E+15	-	-
Fe	5E+13 – 2E+15	Ge	2E+14	-	-
Ni	5E+14	Sb	1E+14 – 2E+15	-	-
Cu	2E+14	Au	5E+13	-	-
Zn	5E+15	-	-	-	-
As	5E+16	-	-	-	-
Mo	1E+14	-	-	-	-
In	5E+13	-	-	-	-
Ta	5E+14	-	-	-	-
W	2E+14	-	-	-	-

* Assuming Ca level is below 1E15 at/cm



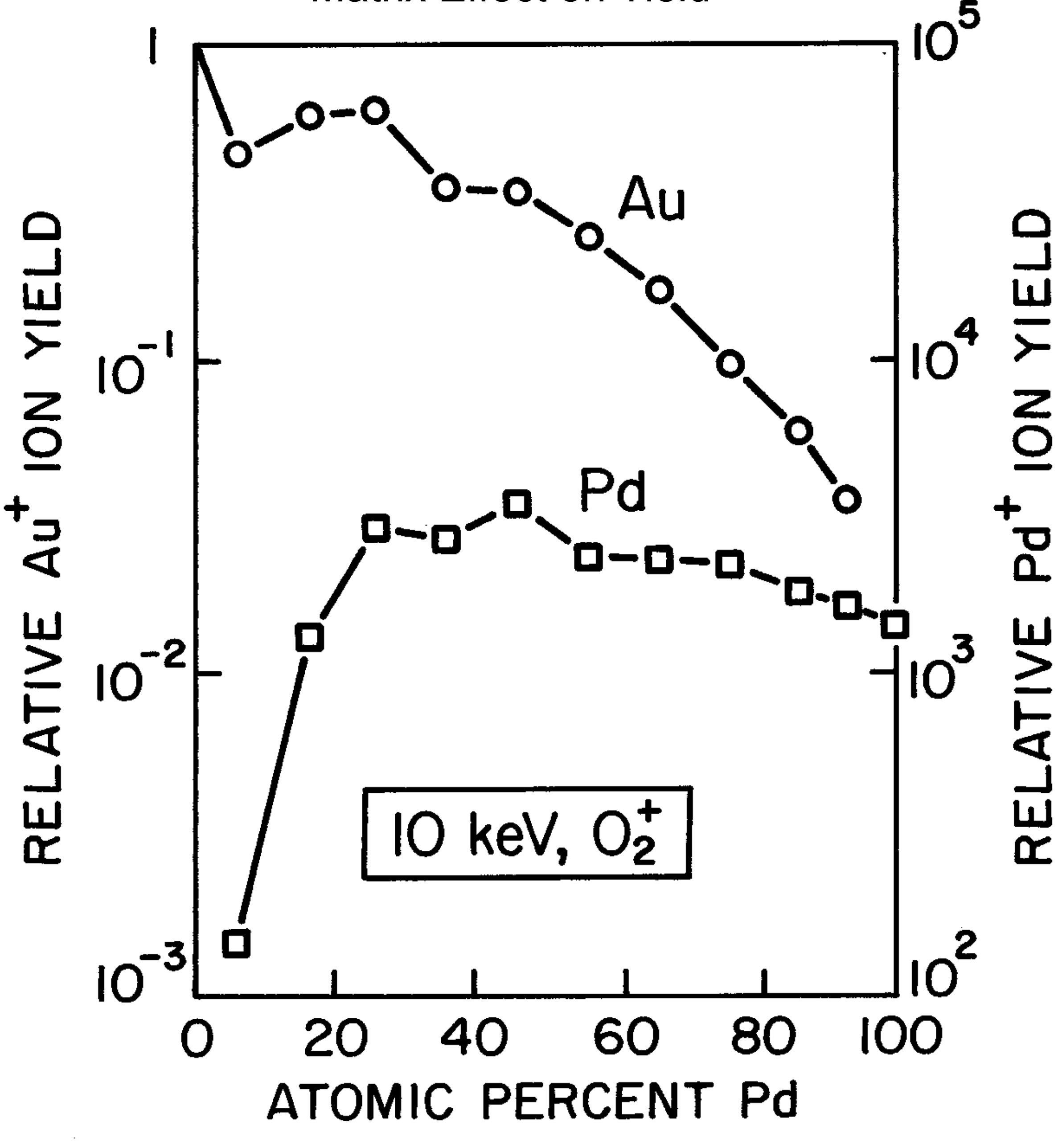
(from Valley et al., 1998, *Review in Econ. Geology*, v. 7, p. 73-97.)

Components

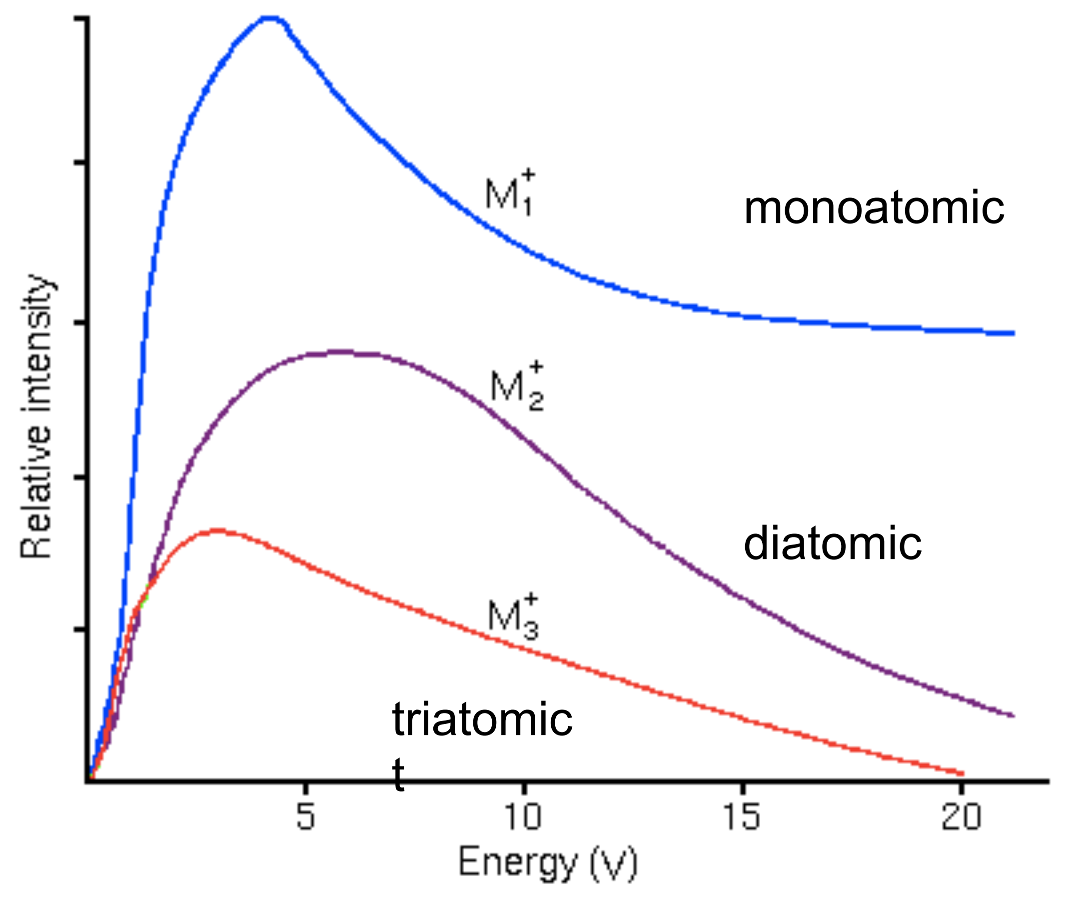
1. Ion Gun
2. Ion Gun
5. Target Sample
9. MS entrance slit
10. Electrostatic Analyzer
13. Electromagnet Sector
19. Electron Multiplier
20. Faraday Cup

T. Kelly, CAMECA

Matrix Effect on Yield



Secondary ion energy distributions

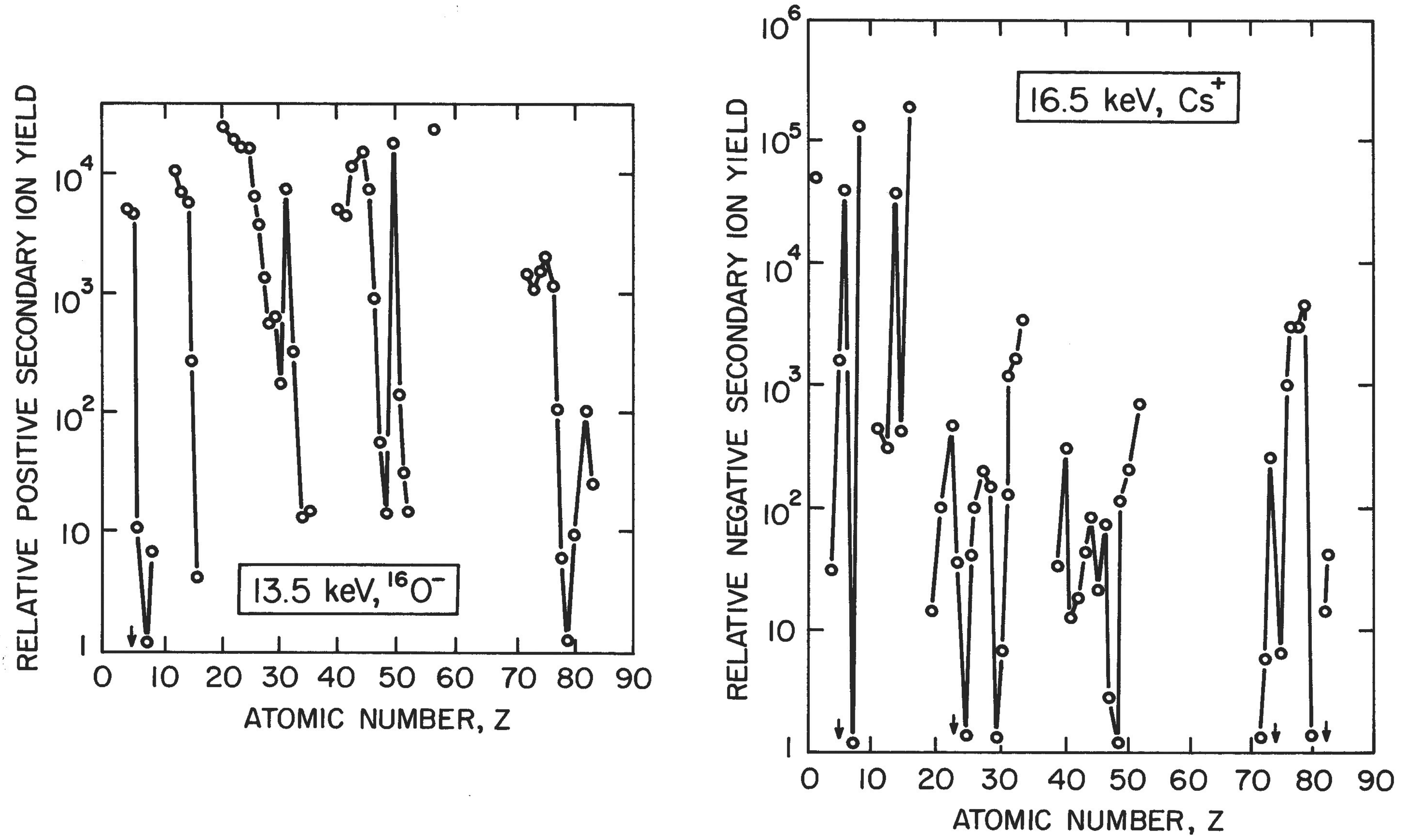


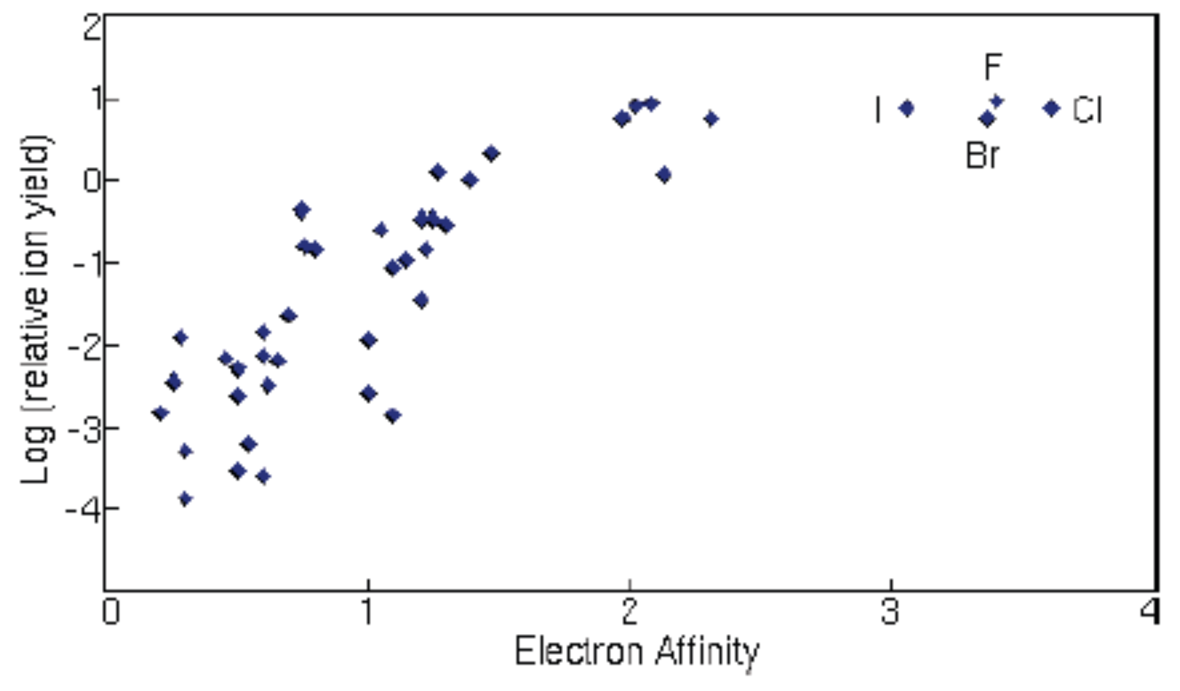
monoatomic

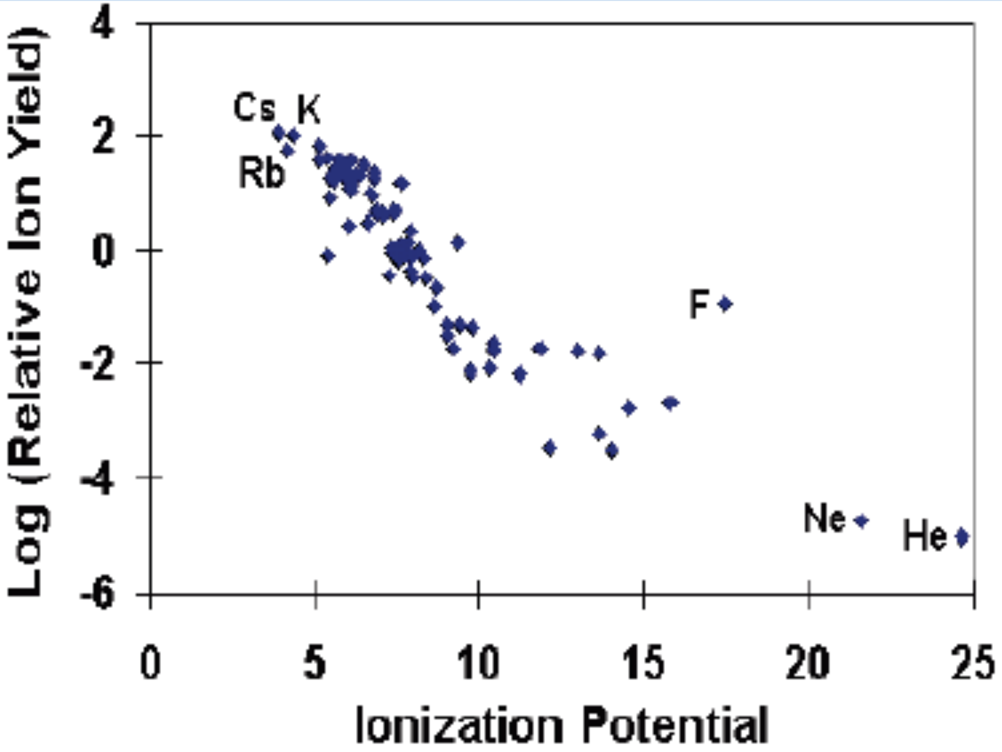
diatomic

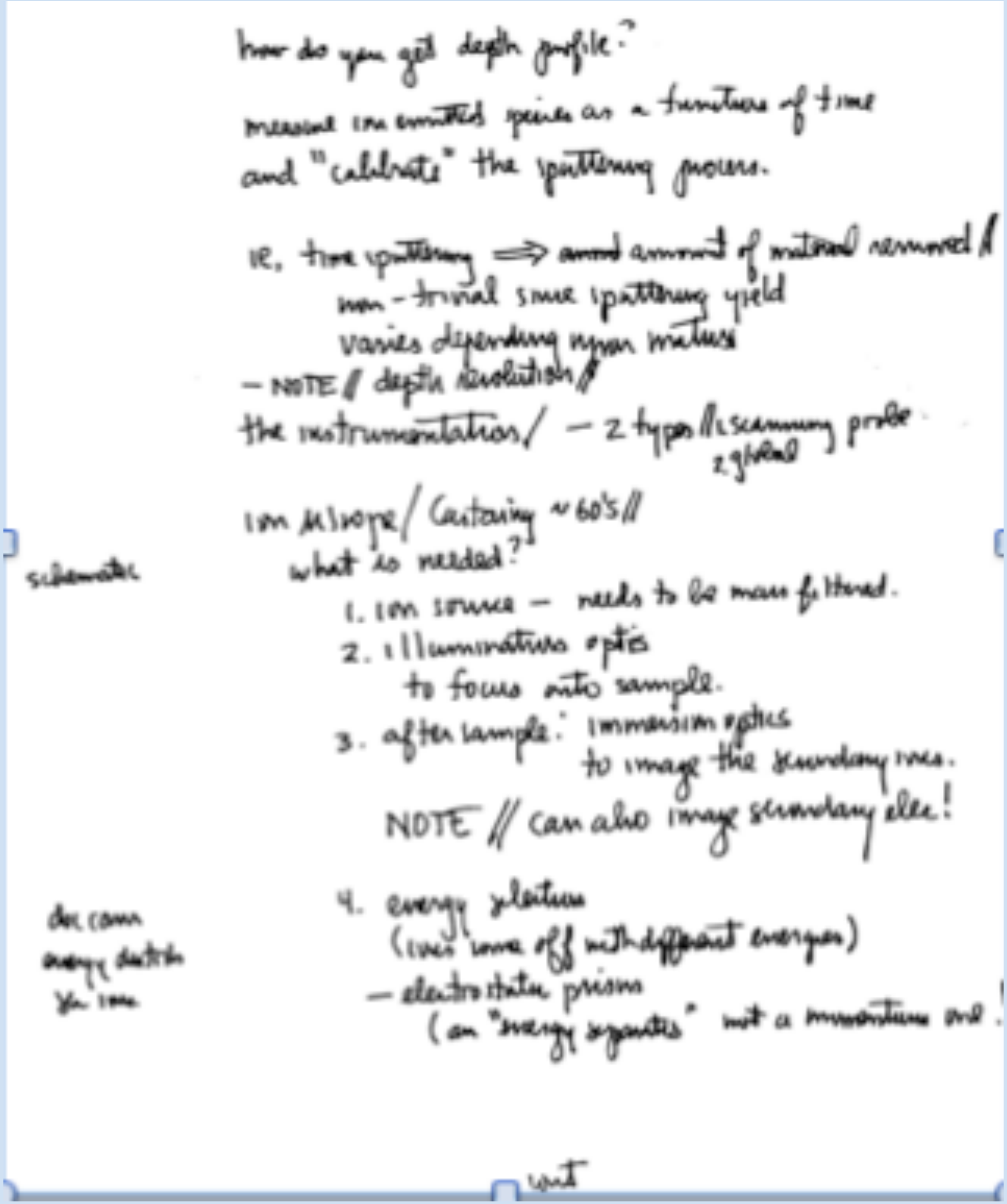
triatomic
t

Secondary Ion Yield Depends on Lots of Things




Log (relative ion yield)
Electron Affinity
2
1
0
-1
-2
-3
-4
0
1
2
3
4
F
I
Cl
Br


Log (Relative Ion Yield)
4
2
0
-2
-4
-6
Ionization Potential
0
5
10
15
20
25
Cs
K
Rb
F
Ne
He



how do you get depth profile?

measure ion emitted species as a function of time
and "calibrate" the sputtering process.

ie, time sputtering ⇒ ~~amnt~~ amount of material removed //
non-trivial since sputtering yield
varies depending upon material

— NOTE // depth resolution //

the instrumentation / — 2 types // 1. scanning probe
2. global

ion microscope / Castaing ~ 60's //
what is needed?

schematic

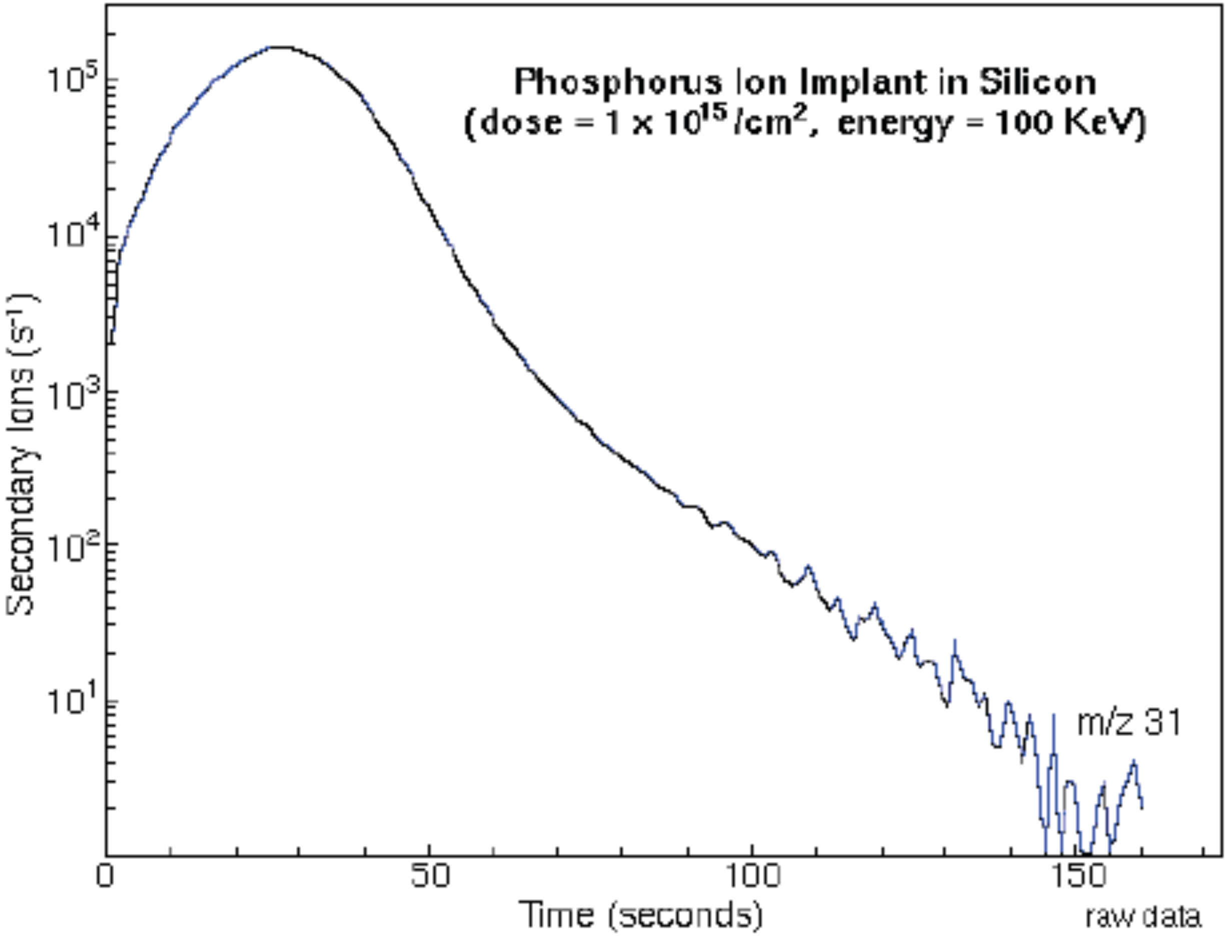
1. ion source — needs to be mass filtered.
2. illumination optics
to focus onto sample.
3. after sample: immersion optics
to image the secondary ions.

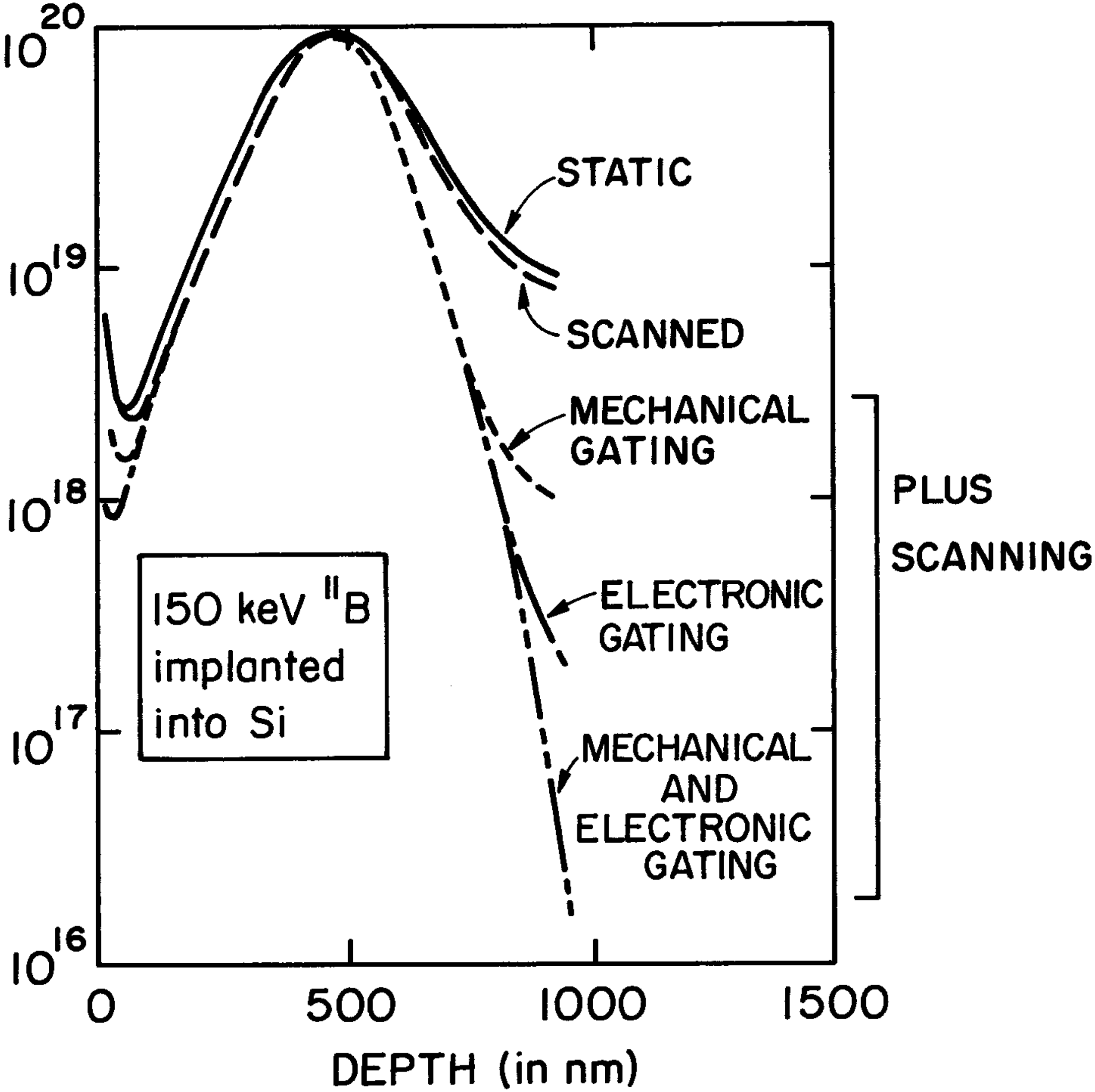
NOTE // can also image secondary elec!

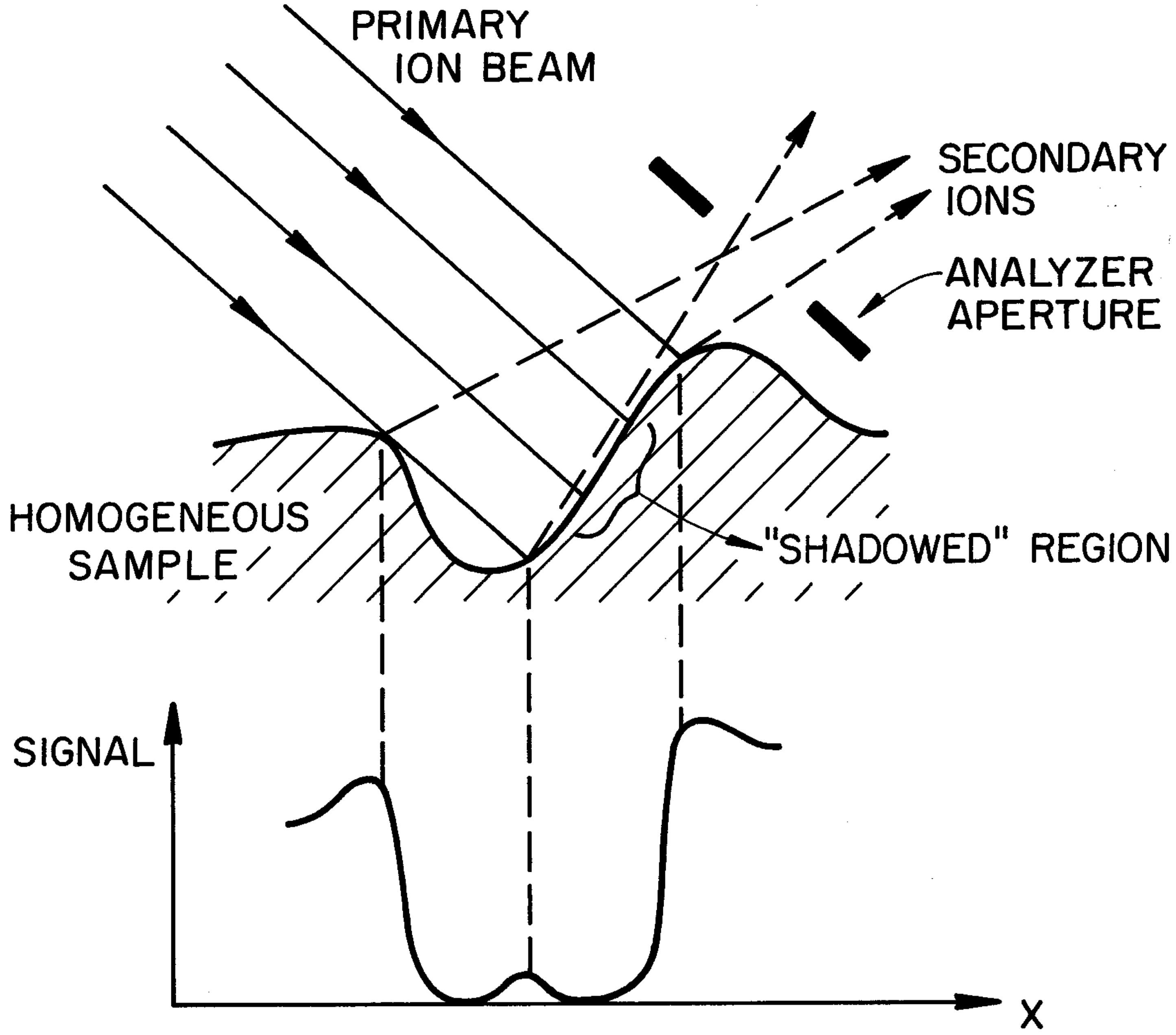
dc cam
energy dist'n
for ions

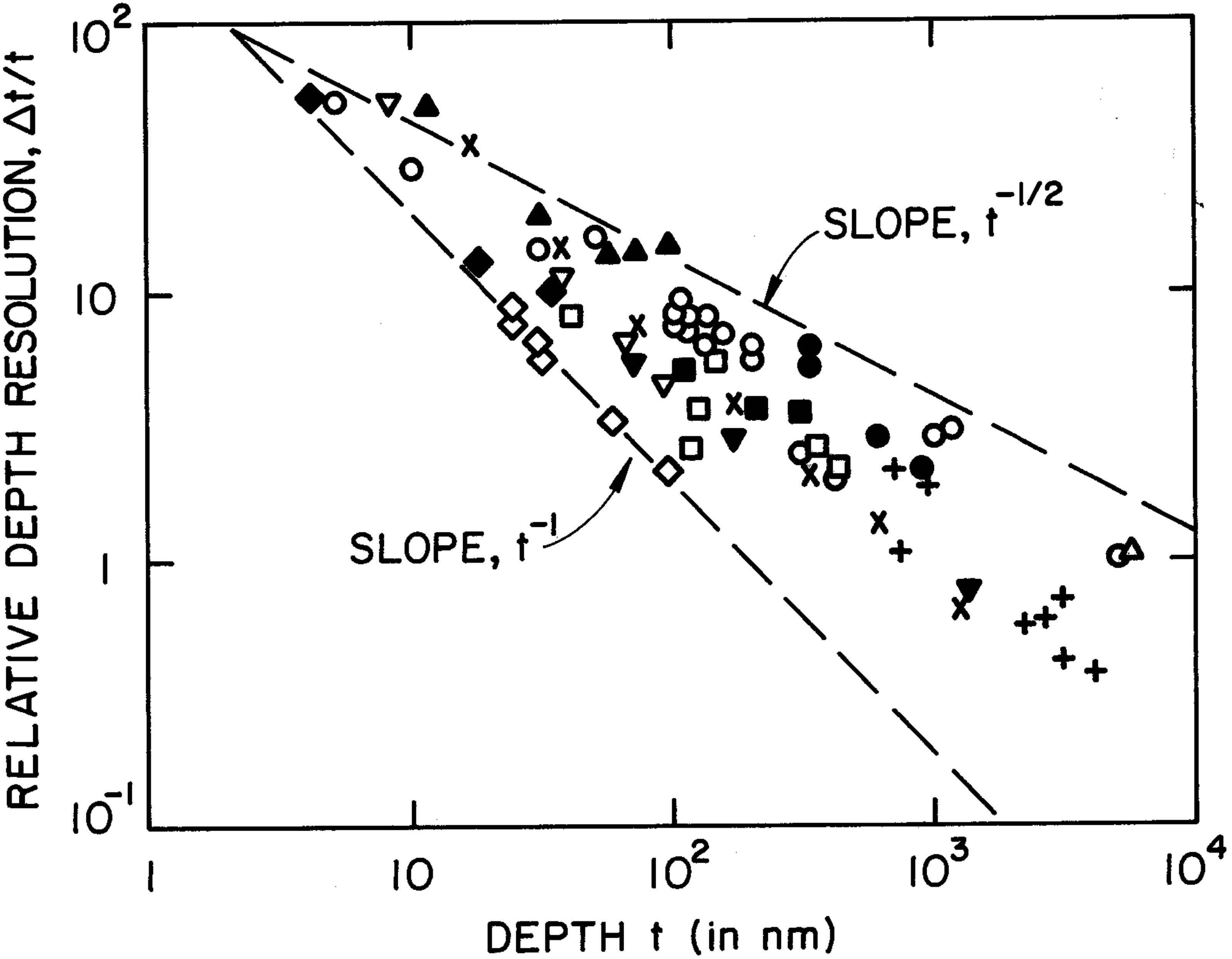
4. energy selection
(ions come off with different energies)
— electrostatic prism
(an "energy separator" not a momentum one!

wit

Phosphorus Ion Implant in Silicon
(dose = 1 x 10^{15} /cm^2, energy = 100 KeV)
Secondary Ions (s^{-1})
10^5
10^4
10^3
10^2
10^1
0
50
100
150
Time (seconds)
m/z 31
raw data

10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
0
500
1000
1500
DEPTH (in nm)
150 keV ^{11}B implanted into Si
STATIC
SCANNED
MECHANICAL GATING
ELECTRONIC GATING
MECHANICAL AND ELECTRONIC GATING
PLUS SCANNING


PRIMARY
ION BEAM
SECONDARY
IONS
ANALYZER
APERTURE
HOMOGENEOUS
SAMPLE
"SHADOWED" REGION
SIGNAL
X

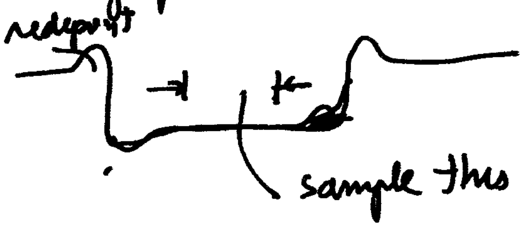

RELATIVE DEPTH RESOLUTION, Δt/t
DEPTH t (in nm)
10^2
10
1
10^{-1}
1
10
10^2
10^3
10^4
SLOPE, $t^{-1/2}$
SLOPE, t^{-1}

ASIDE 1 when depth profiling, tricks to eliminate artifacts due to redeposition, etc —

~~⇐~~ allows one to measure smaller concentration

— analyze from smaller area than probed

see doc cam pic



sample this only by ~~gatt~~ "gating"

* * *

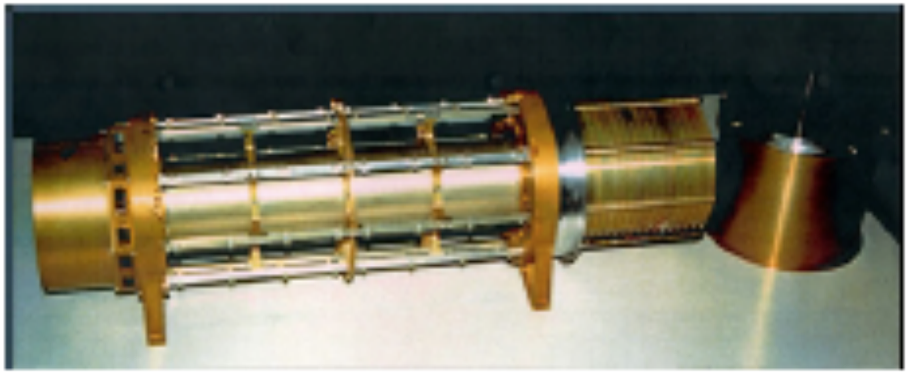
what is spatial resolution attainable?

1. depth ~5 nm
2. lateral ~10-50 nm

in addition:

3. all chem. elements can be observed, even H
4. separate isotopes can be measured (better mass res. than RBS)
5. destructive

- The COSIMA instrument onboard the European Space Agency's Rosetta spacecraft will be the first instrument to determine the composition of cometary dust with SIMS in 2014.



http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=12124

Secondary Ion Microscopy in Biology

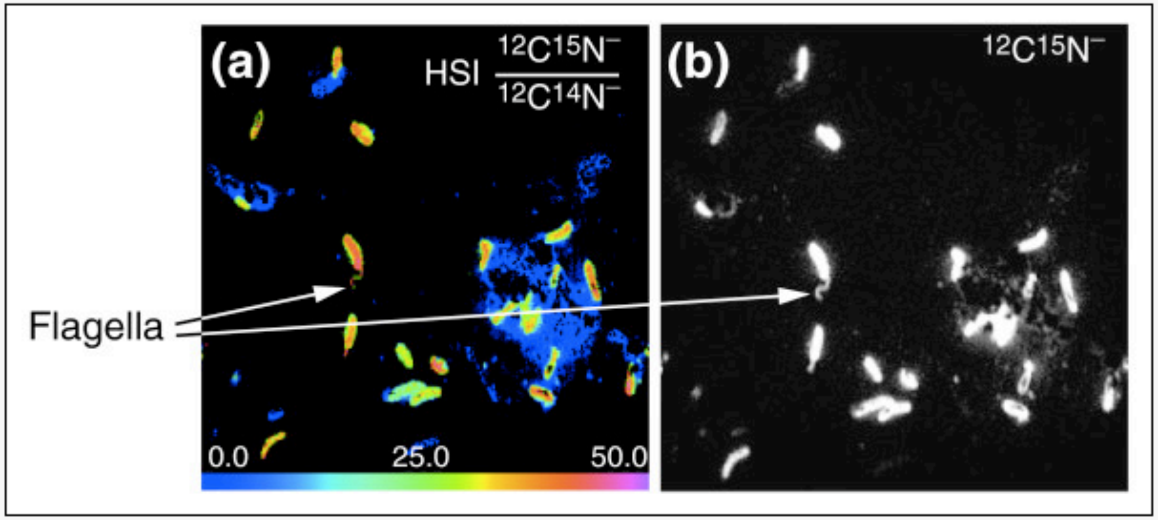
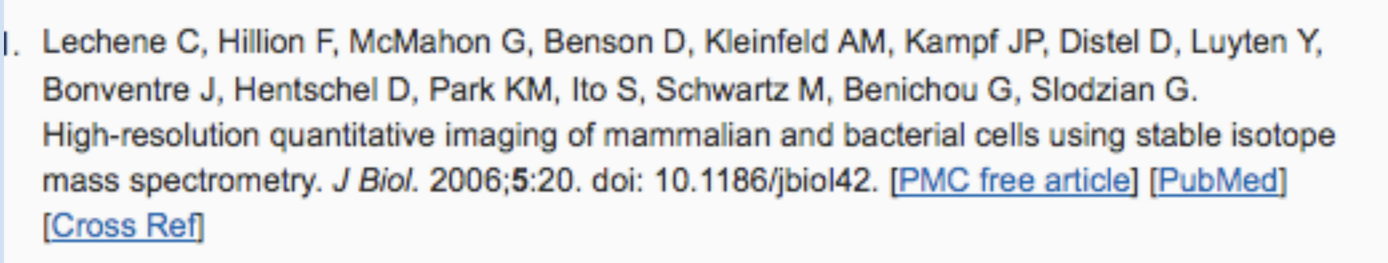


Figure 2

MIMS images of *Teredinibacter turnerae*, a nitrogen-fixing bacterium inhabiting a shipworm gill. The $^{12}C^{15}N/^{12}C^{14}N$ image (left) allows the uptake of ^{15}N by these organisms to be quantified. On the right, the image of $^{12}C^{15}N^-$ ions shows that sensitivity is sufficient to image the flagellum of this bacterium (arrowed) even though the flagellum diameter is estimated from the ion signal to be only about 10 nm. From [1].



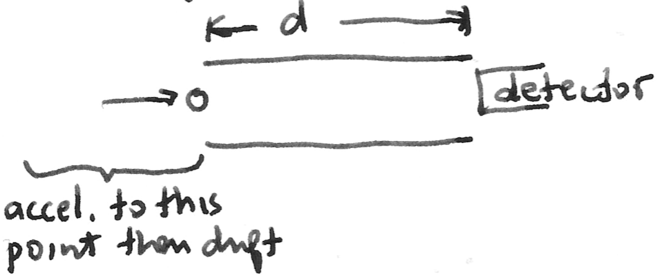
1. Lechene C, Hillion F, McMahon G, Benson D, Kleinfeld AM, Kampf JP, Distel D, Luyten Y, Bonventre J, Hentschel D, Park KM, Ito S, Schwartz M, Benichou G, Slodzian G. High-resolution quantitative imaging of mammalian and bacterial cells using stable isotope mass spectrometry. *J Biol.* 2006;**5**:20. doi: 10.1186/jbiol42. [PMC free article] [PubMed] [Cross Ref]

Time of Flight Characterization (TOF)

potential energy $E_p = \underset{\text{charge}}{Q}V$

kinetic energy $E_K = \frac{1}{2}mv^2$

send ions through a "drift" tube. field free space



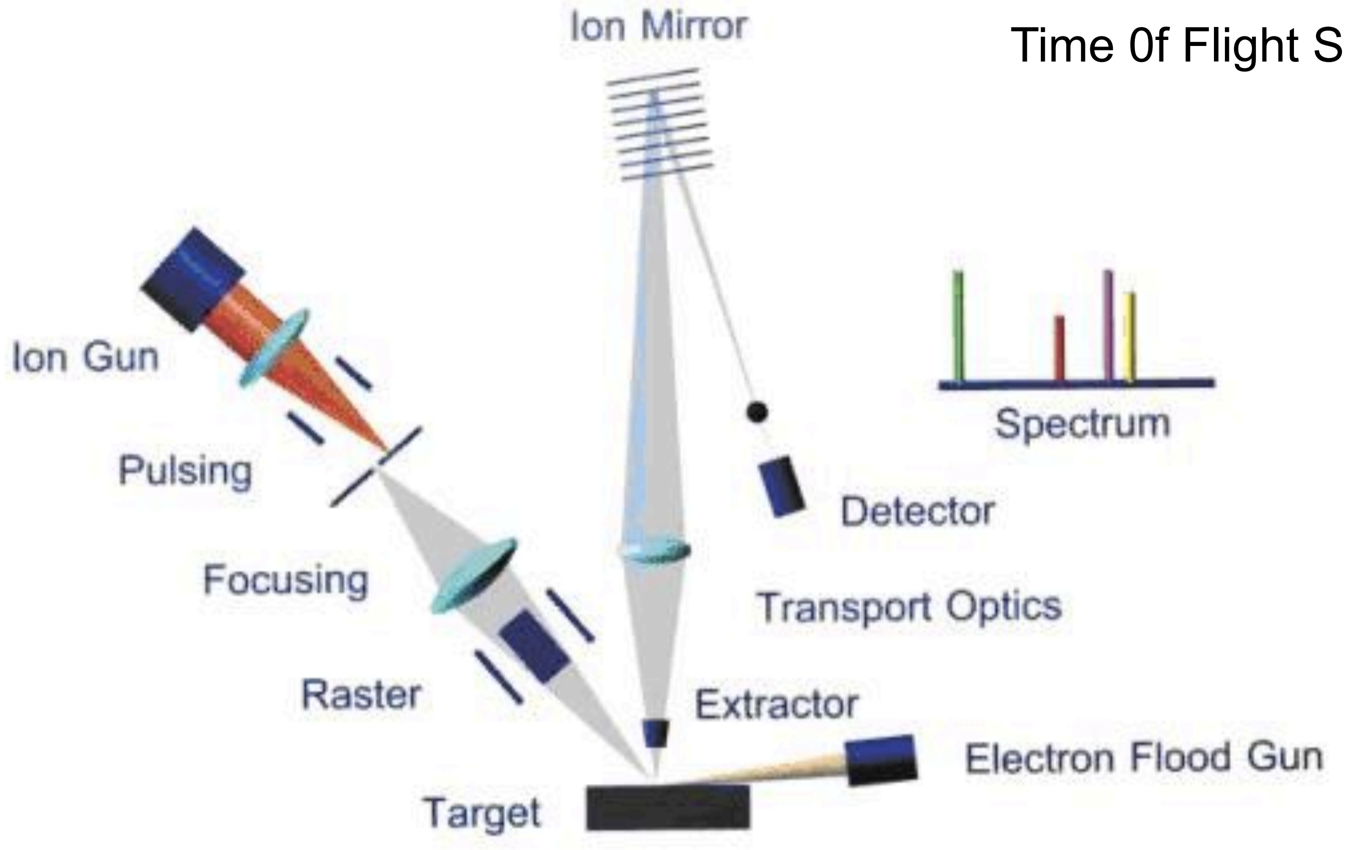
∴ $QV = \frac{1}{2}mv^2$ at tube entrance

time through drift tube $t = d/\overset{\text{ion velocity}}{v}$

∴ $QV = \frac{1}{2}m\left(\frac{d}{t}\right)^2 \Rightarrow \boxed{t = \frac{d}{\sqrt{QV}}\sqrt{\frac{m}{Q}}}$

‖ traverse time related to mass/charge ‖

Time 0f Flight SIMS



Schematic diagram of the CAMECA IonTOF ToF-SIMS instrument.

Time of flight SIMS

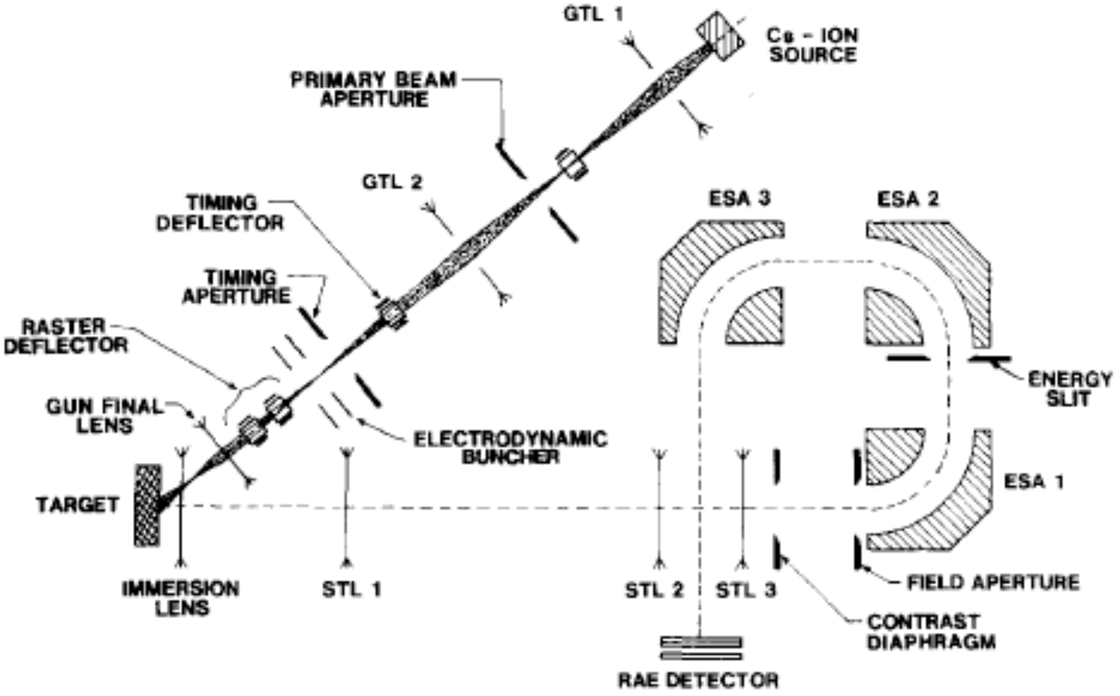
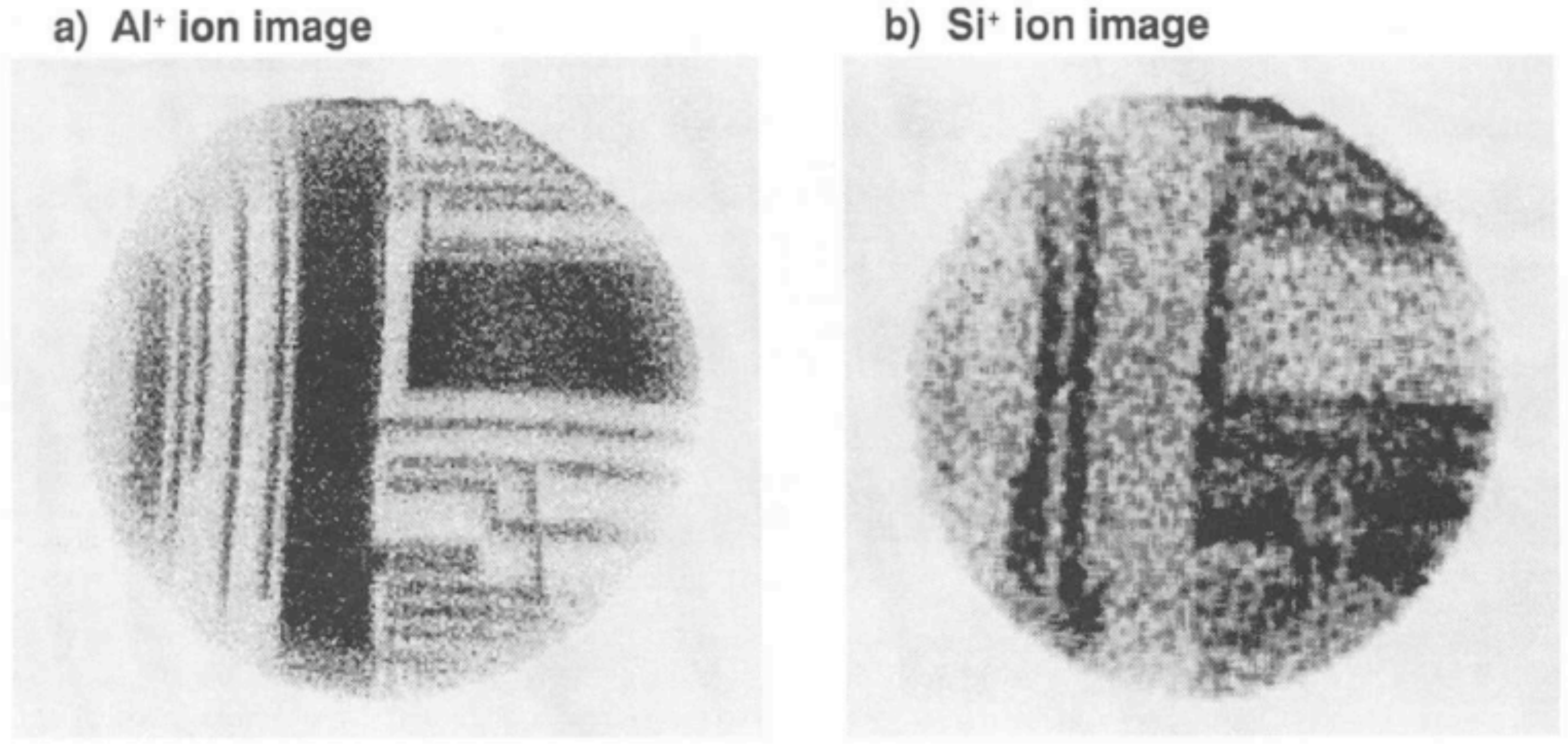


Figure 1. Schematic diagram of the Time-of-Flight secondary ion microscope.

From: Schueler, et.al. Vacuum. 41(1-4). 1990.p.1661-1664.

Time of Flight SIMS Microscopy



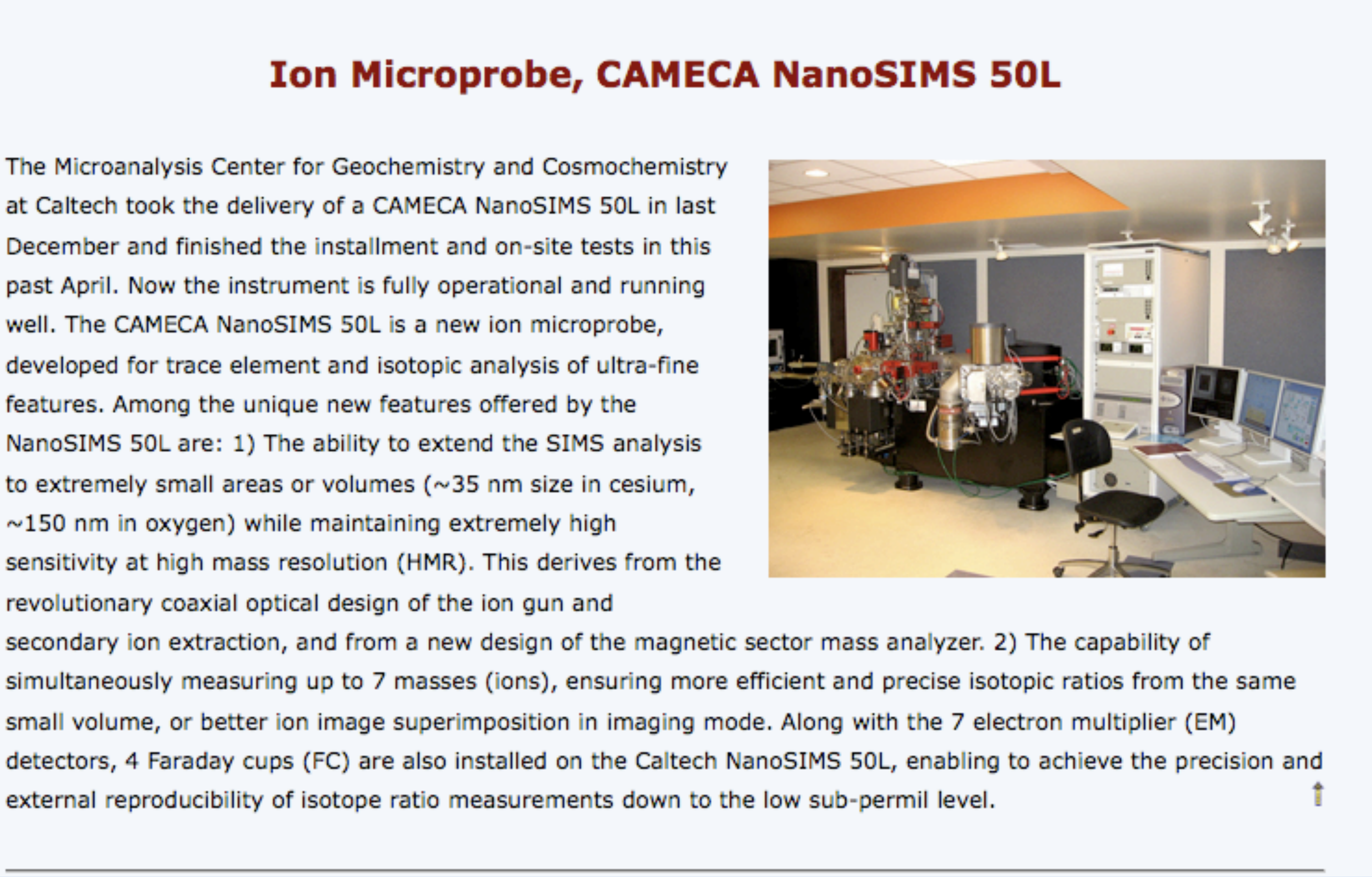
a) Al$^+$ ion image

b) Si$^+$ ion image

Figure 5. Secondary ion images of Al$^+$ (a) and ^{28}Si$^+$ (b) taken from a 250 μm diameter surface region of an Al–Si integrated circuit. The transmission reduction due to lateral energy filtering was approximately 30% for elemental secondary ion species.

From: Schueler, et.al. Vacuum. 41(1-4).1990.p.1661-1664.

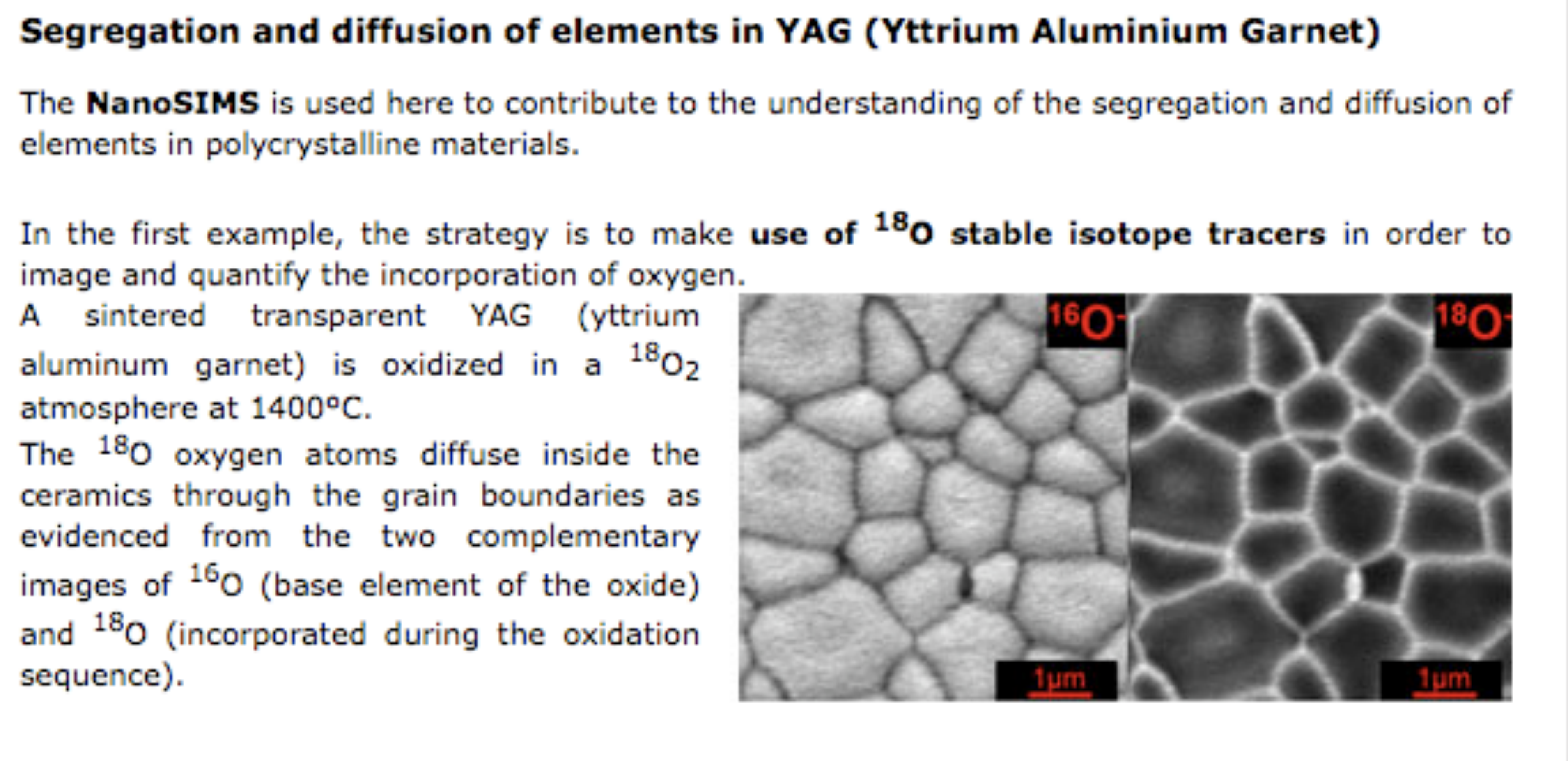
Commercial SIMS Instrument/ CAMECA



Ion Microprobe, CAMECA NanoSIMS 50L

The Microanalysis Center for Geochemistry and Cosmochemistry at Caltech took the delivery of a CAMECA NanoSIMS 50L in last December and finished the installment and on-site tests in this past April. Now the instrument is fully operational and running well. The CAMECA NanoSIMS 50L is a new ion microprobe, developed for trace element and isotopic analysis of ultra-fine features. Among the unique new features offered by the NanoSIMS 50L are: 1) The ability to extend the SIMS analysis to extremely small areas or volumes (~35 nm size in cesium, ~150 nm in oxygen) while maintaining extremely high sensitivity at high mass resolution (HMR). This derives from the revolutionary coaxial optical design of the ion gun and secondary ion extraction, and from a new design of the magnetic sector mass analyzer. 2) The capability of simultaneously measuring up to 7 masses (ions), ensuring more efficient and precise isotopic ratios from the same small volume, or better ion image superimposition in imaging mode. Along with the 7 electron multiplier (EM) detectors, 4 Faraday cups (FC) are also installed on the Caltech NanoSIMS 50L, enabling to achieve the precision and external reproducibility of isotope ratio measurements down to the low sub-permil level.

Nano SIMS



Segregation and diffusion of elements in YAG (Yttrium Aluminium Garnet)

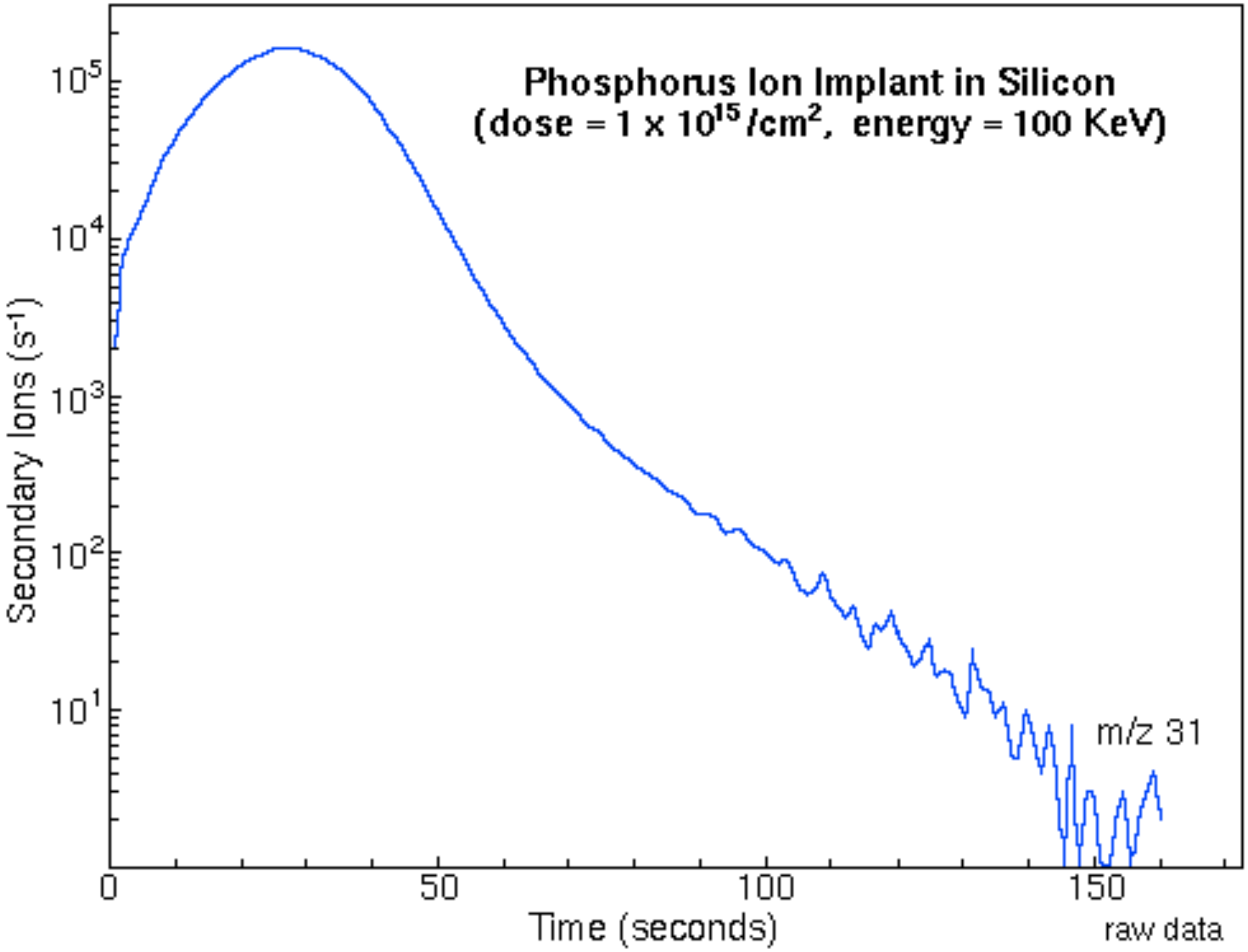
The **NanoSIMS** is used here to contribute to the understanding of the segregation and diffusion of elements in polycrystalline materials.

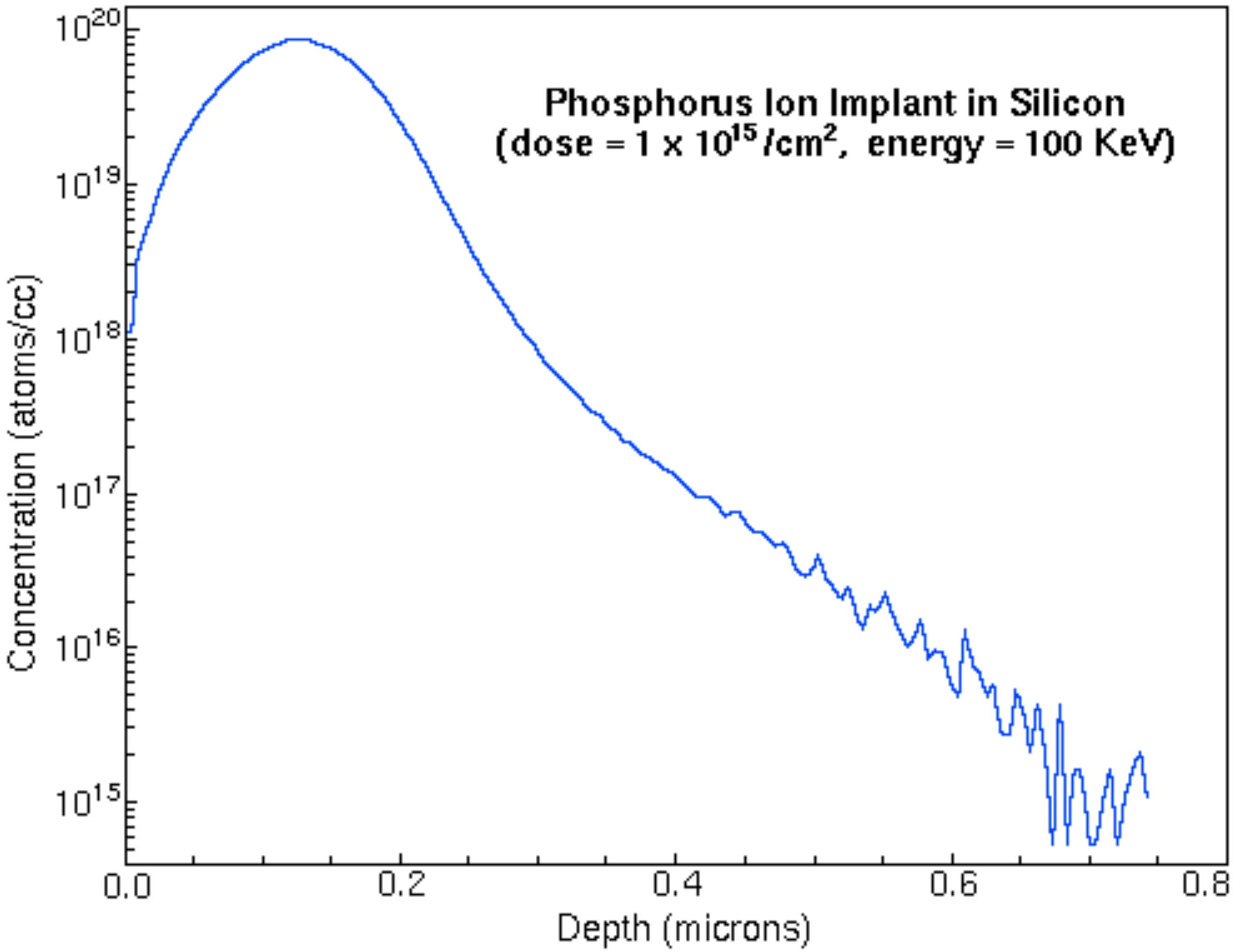
In the first example, the strategy is to make **use of ^{18}O stable isotope tracers** in order to image and quantify the incorporation of oxygen.

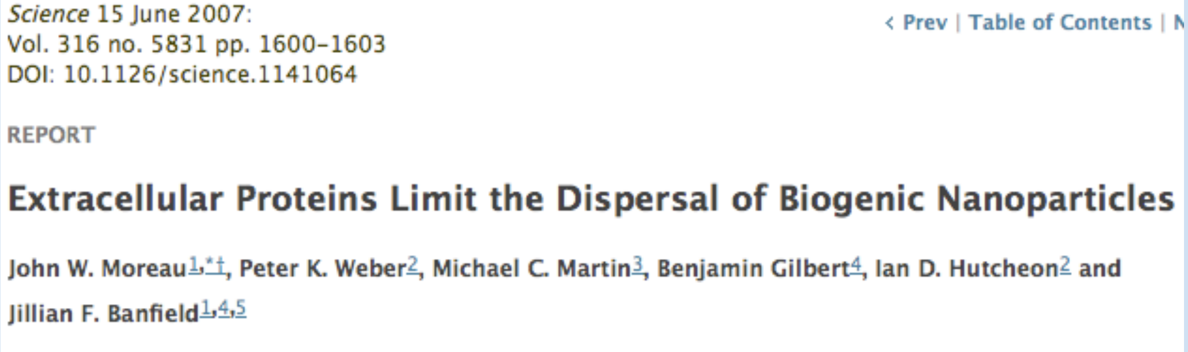
A sintered transparent YAG (yttrium aluminum garnet) is oxidized in a $^{18}O_2$ atmosphere at 1400°C.

The ^{18}O oxygen atoms diffuse inside the ceramics through the grain boundaries as evidenced from the two complementary images of ^{16}O (base element of the oxide) and ^{18}O (incorporated during the oxidation sequence).

Dr. Hajime Haneda, NIMS, Tsukuba, Japan


Phosphorus Ion Implant in Silicon
(dose = 1 x 10^{15} /cm^2, energy = 100 KeV)
Secondary Ions (s^{-1})
10^5
10^4
10^3
10^2
10^1
0
50
100
150
Time (seconds)
m/z 31
raw data


Phosphorus Ion Implant in Silicon
(dose = 1 x 10^15/cm^2, energy = 100 KeV)
Concentration (atoms/cc)
10^20
10^19
10^18
10^17
10^16
10^15
0.0
0.2
0.4
0.6
0.8
Depth (microns)



Science 15 June 2007:
Vol. 316 no. 5831 pp. 1600–1603
DOI: 10.1126/science.1141064

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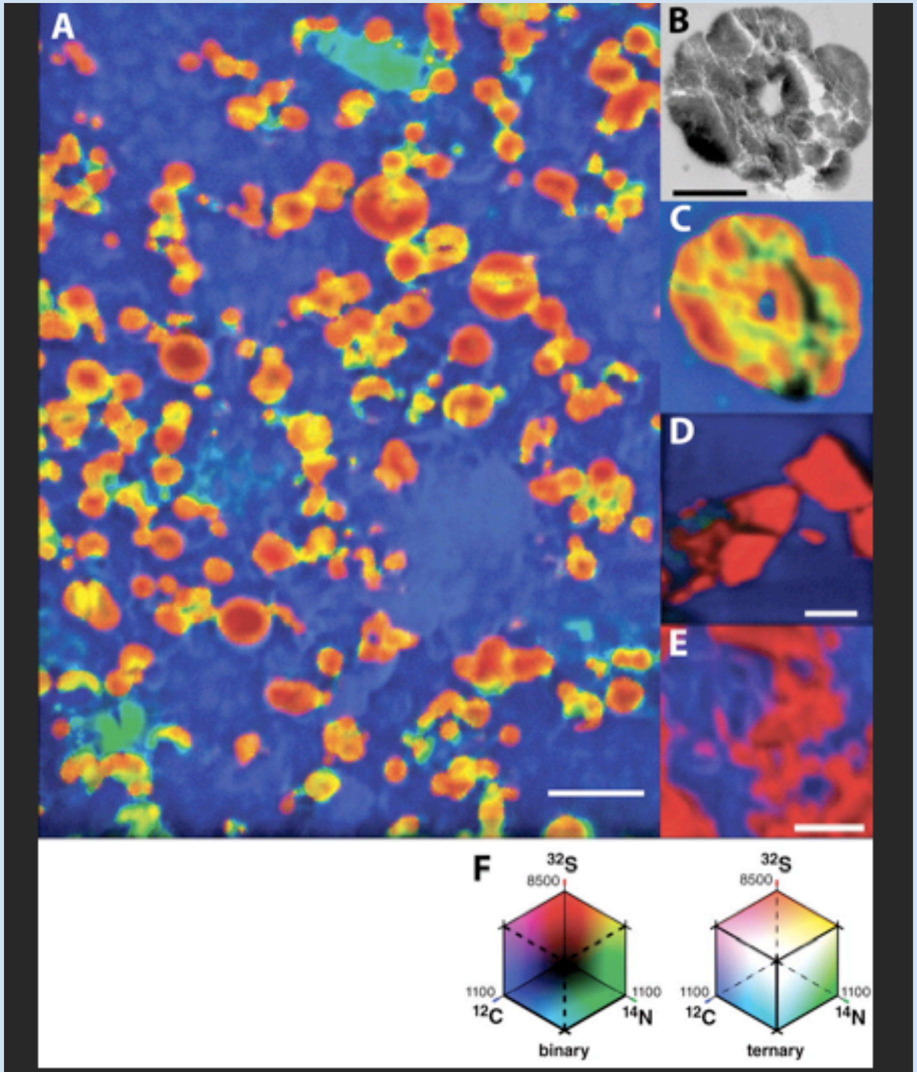
REPORT

Extracellular Proteins Limit the Dispersal of Biogenic Nanoparticles

John W. Moreau[1,*,†], Peter K. Weber[2], Michael C. Martin[3], Benjamin Gilbert[4], Ian D. Hutcheon[2] and Jillian F. Banfield[1,4,5]



Some References for SIMS Microscopy

G. Slodzian. Surface Science.48.(1961)

R. Castaing and G. Slodzian. (1962) J. Microscopy.1.395-410 (in French)

H. Liebl.(1967) J.A.P. 38.5277-5283.

R. Levi-Setti et. Al. (1986). Applied Surface Science. 26.249-264, (H+ probe)

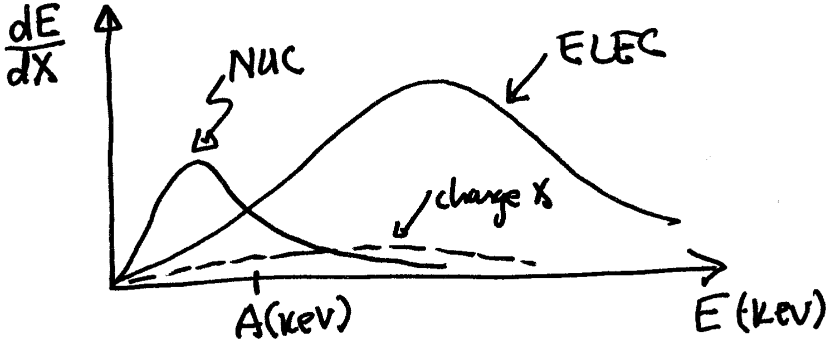
ION INTERACTIONS

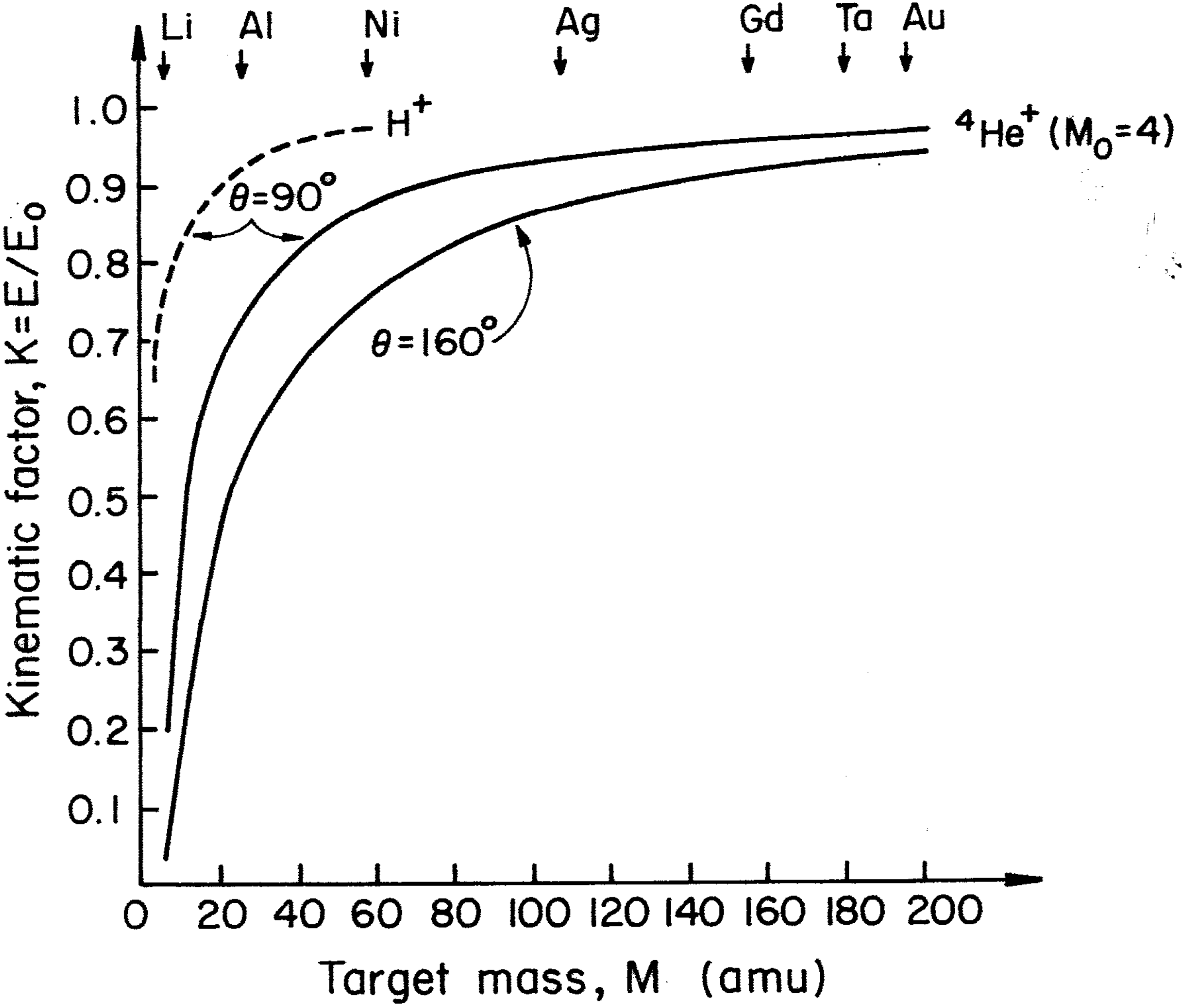
three main components

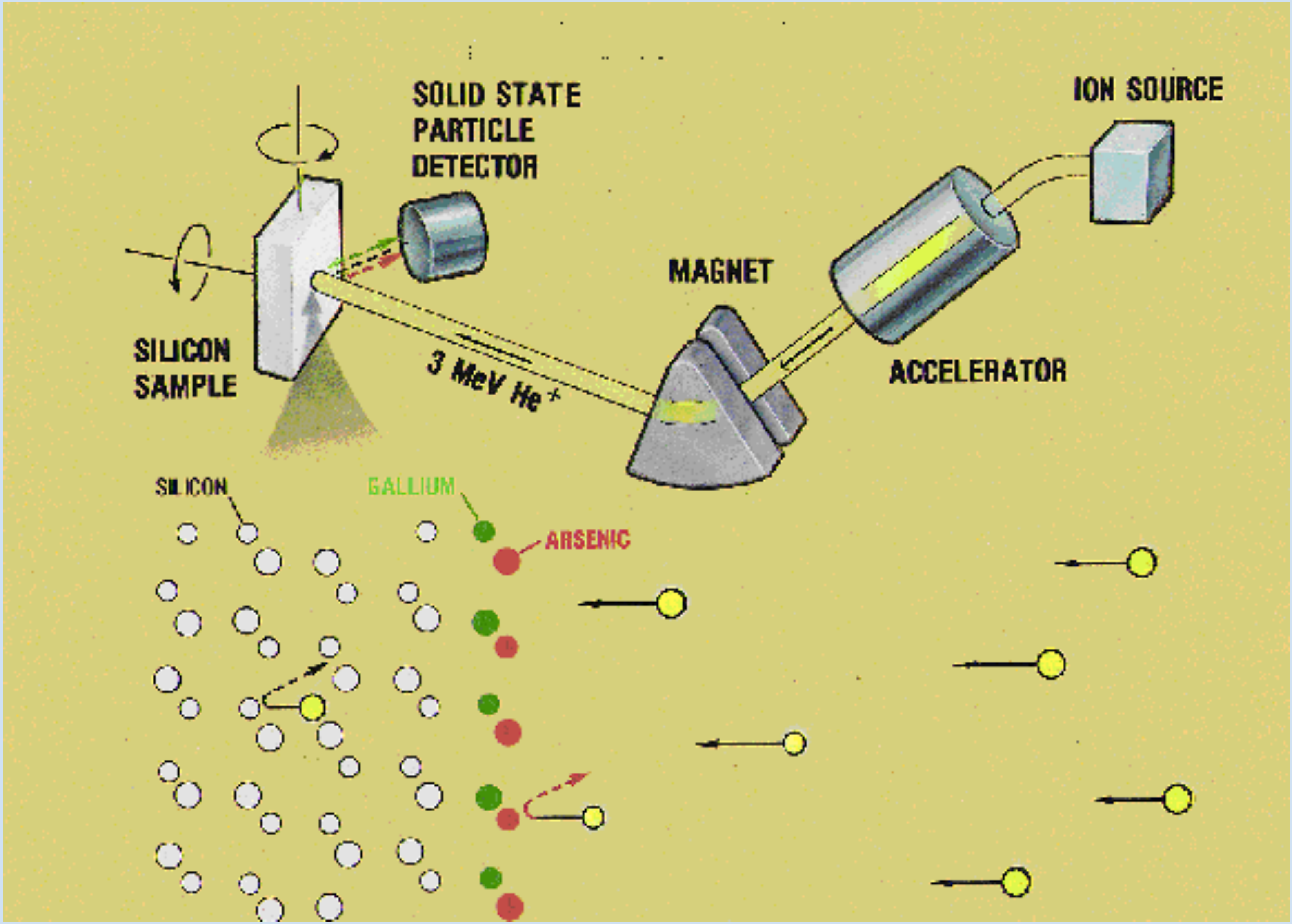
1. "nuclear" energy loss, dominates at low energies when $E < A$ keV
   ↑ at.wt inc-ion

2. electronic energy loss
   interactions with atomic electrons
   (like "inelastic" electron scattering)

3. charge exchange
   $\lesssim 10\%$ of total

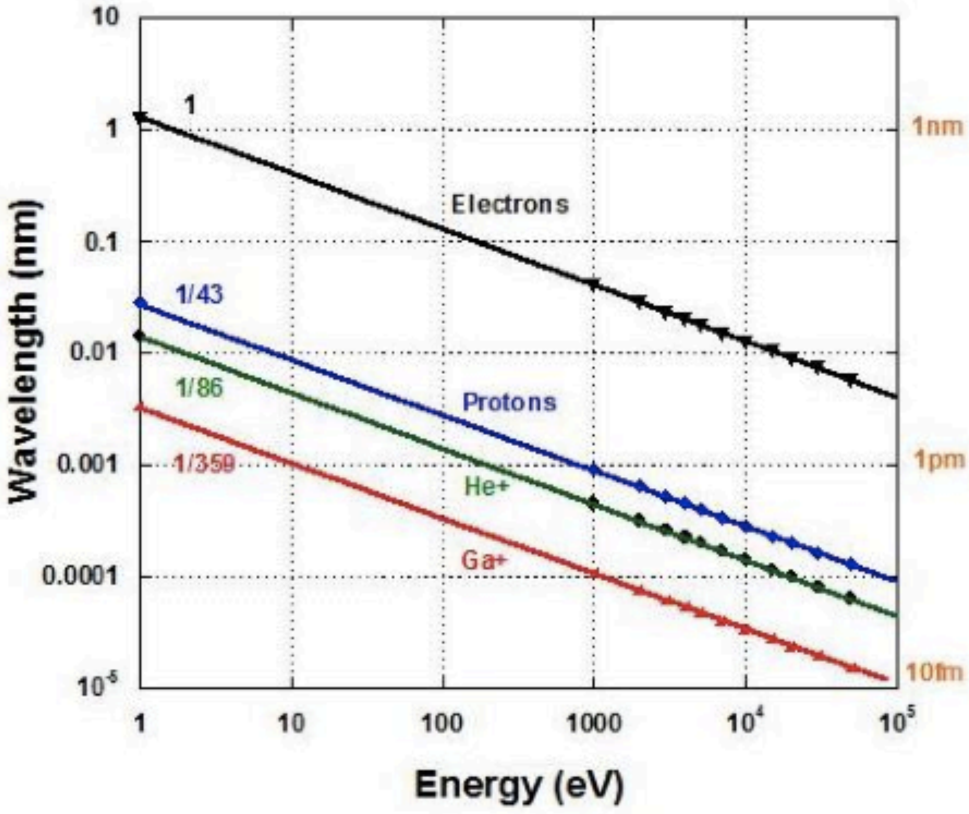



Li
Al
Ni
Ag
Gd
Ta
Au
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Kinematic factor, K = E/E$_0$
H^+
$^4He^+$ (M_0=4)
θ=90°
θ=160°
0
20
40
60
80
100
120
140
160
180
200
Target mass, M (amu)


SOLID STATE PARTICLE DETECTOR
ION SOURCE
MAGNET
ACCELERATOR
SILICON SAMPLE
3 MeV He+
SILICON
GALLIUM
ARSENIC

Why use ions?

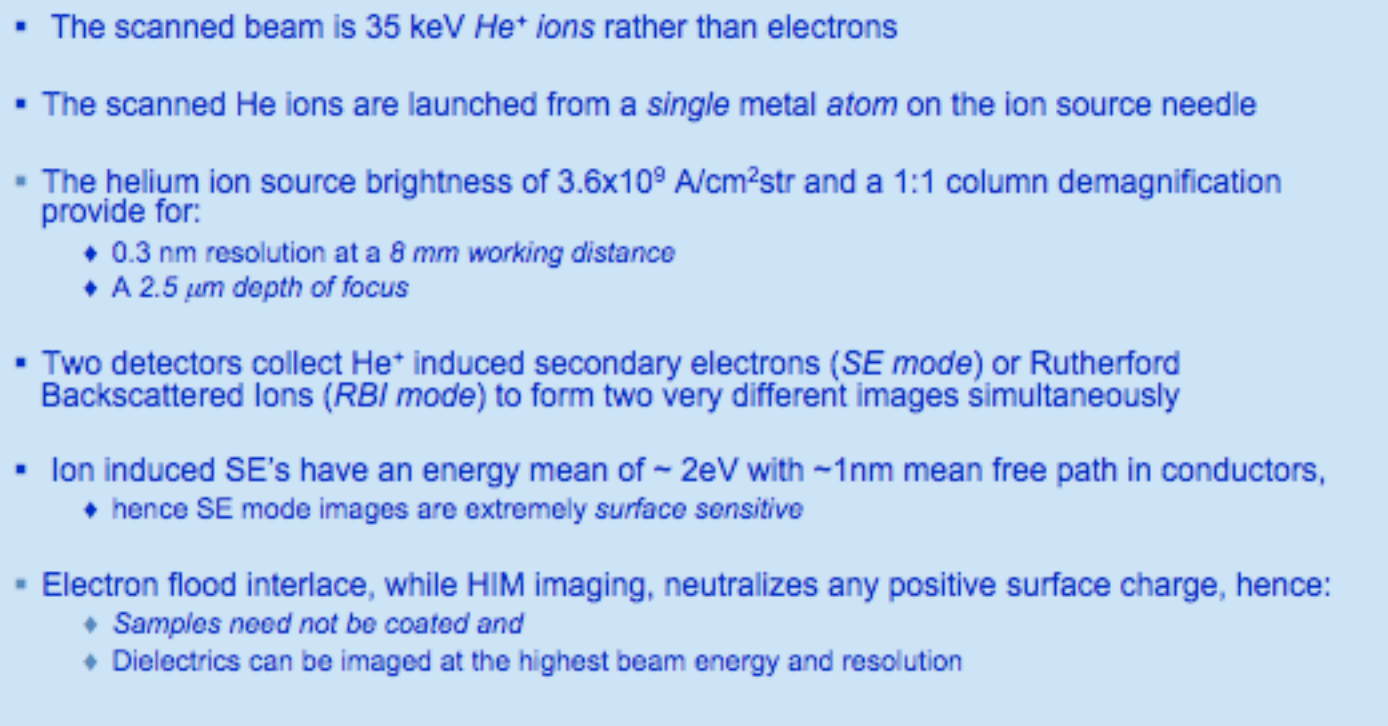
- Ions have wavelengths λ ~1% or less of that for electrons of same energy
- Diffraction limited spot size (=λ/α) is negligible
- Which ion to chose?
- H+ (proton) medium iSE yield, low sputter damage. Used by R.Levi-Setti with success (1970s)
- He+ - higher yields but more sputter. Good source available...



Wavelength (λ nm) of electrons, and protons, helium and gallium ions, as a function of energy

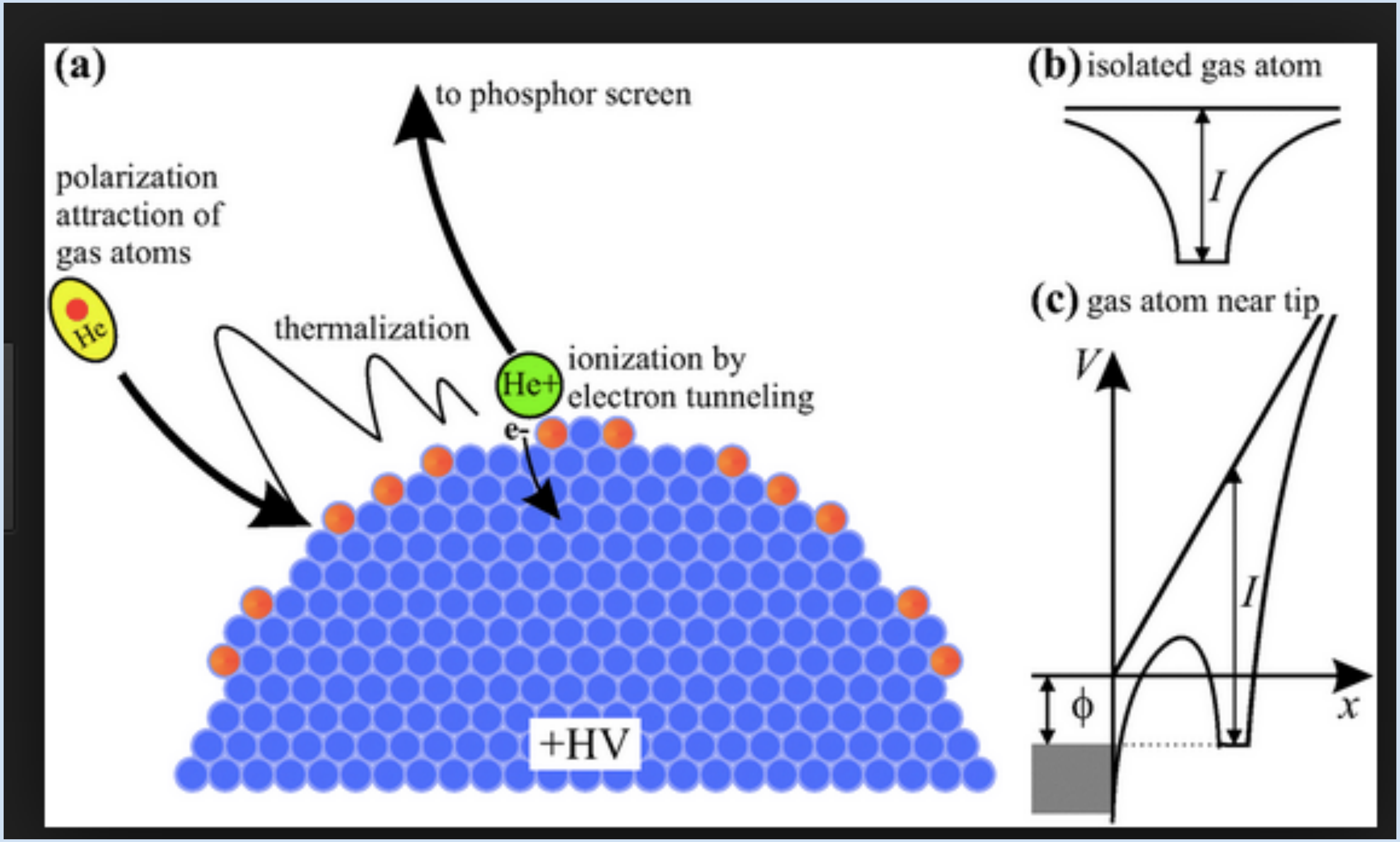
From D. Joy, ORNL

He Ion Beam Microscope
(combine SEM with RBS)



- The scanned beam is 35 keV *He^+ ions* rather than electrons
- The scanned He ions are launched from a *single* metal *atom* on the ion source needle
- The helium ion source brightness of 3.6×10^9 A/cm^{2}str and a 1:1 column demagnification provide for:
  - 0.3 nm resolution at a *8 mm working distance*
  - A *2.5 μm depth of focus*
- Two detectors collect He^+ induced secondary electrons (*SE mode*) or Rutherford Backscattered Ions (*RBI mode*) to form two very different images simultaneously
- Ion induced SE's have an energy mean of ~ 2eV with ~1nm mean free path in conductors,
  - hence SE mode images are extremely *surface sensitive*
- Electron flood interlace, while HIM imaging, neutralizes any positive surface charge, hence:
  - *Samples need not be coated and*
  - Dielectrics can be imaged at the highest beam energy and resolution

Field Ionization



Field Ion Microscopy

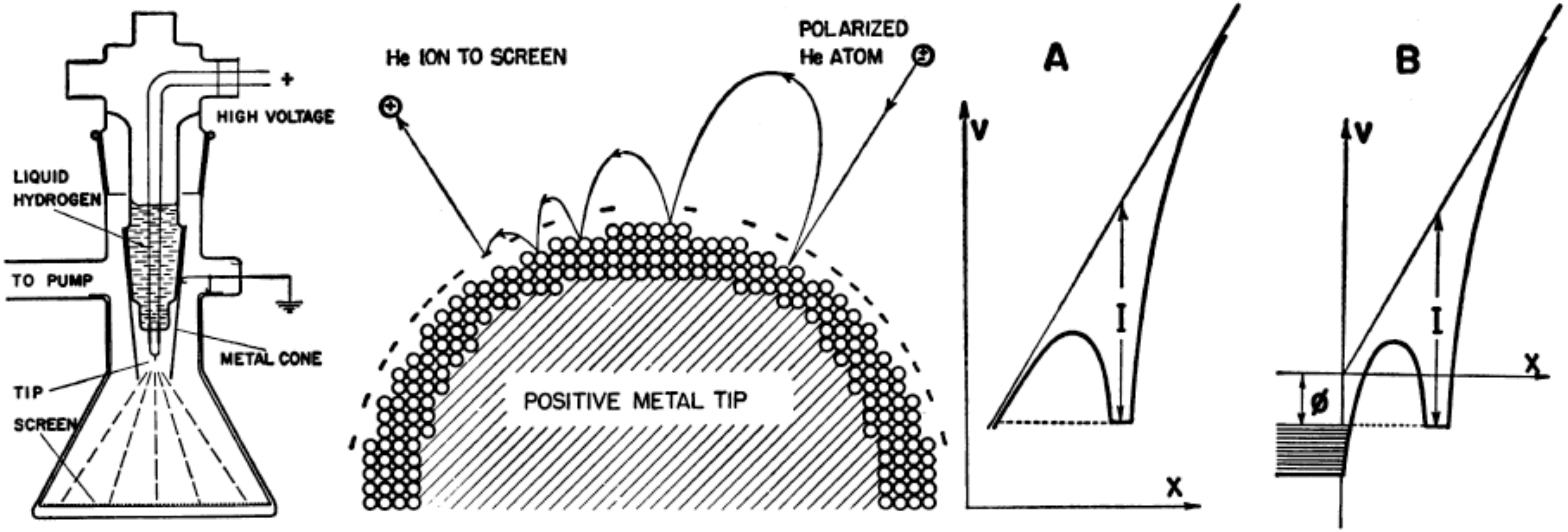


Fig. 1 (left). Schematic drawing of a field ion microscope. Fig. 2 (center). A polarized helium atom is attracted to the metal tip, is slowed down in a number of hops, and is ionized in the ionization zone (0.2 Å thick) over a protruding atom. The helium ion is accelerated toward the screen (see Fig. 1). Fig. 3 (right). (*A*) The potential funnel of an atom in a strong electric field; (*B*) the potential of an electron near the metal surface. Field ionization of the gas atom occurs when the electron from the ground state tunnels along the dotted line into the metal to the left.

E. W.Mueller, SCIENCE.149(#3684).1960.p.591-601..

Field Ion Micrograph: Platinum Tip

E. W. Mueller, *Science*. 149,591 (1965)

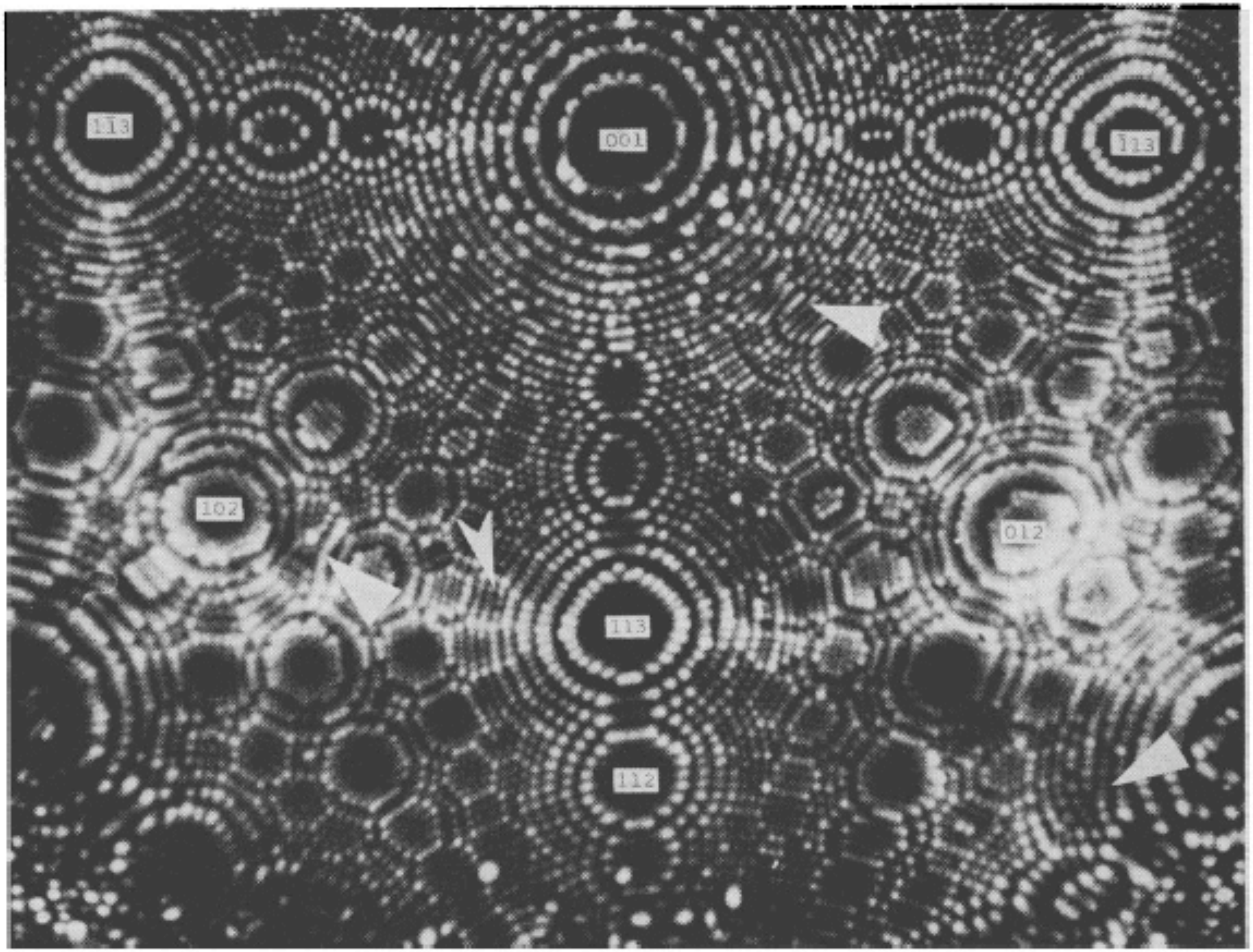
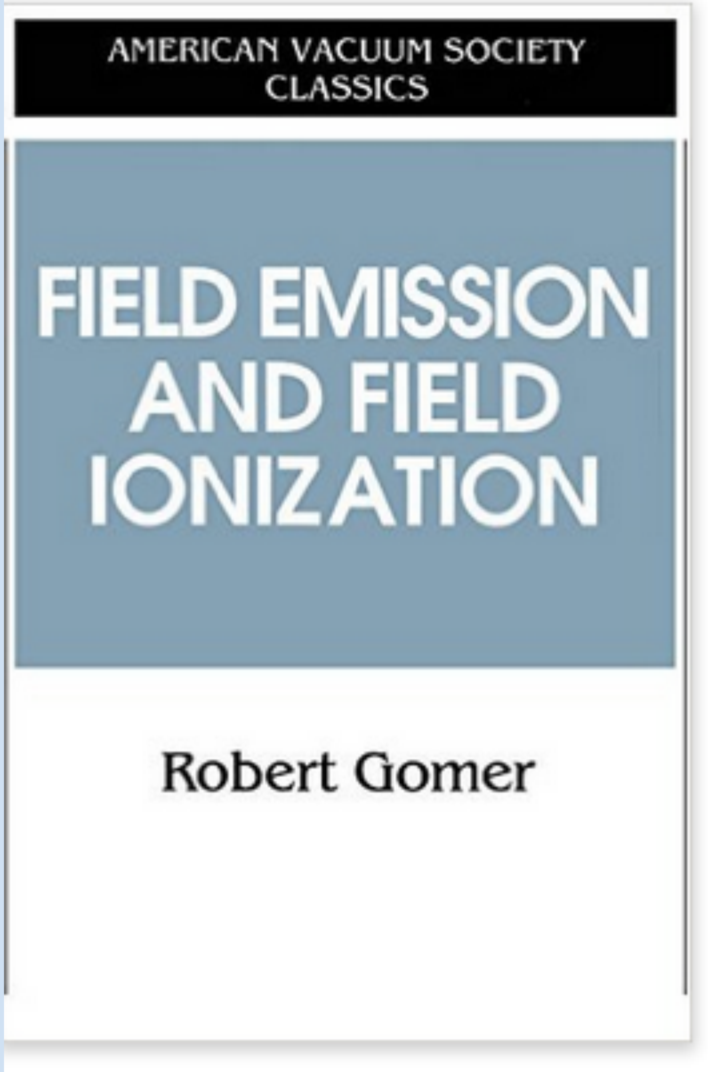


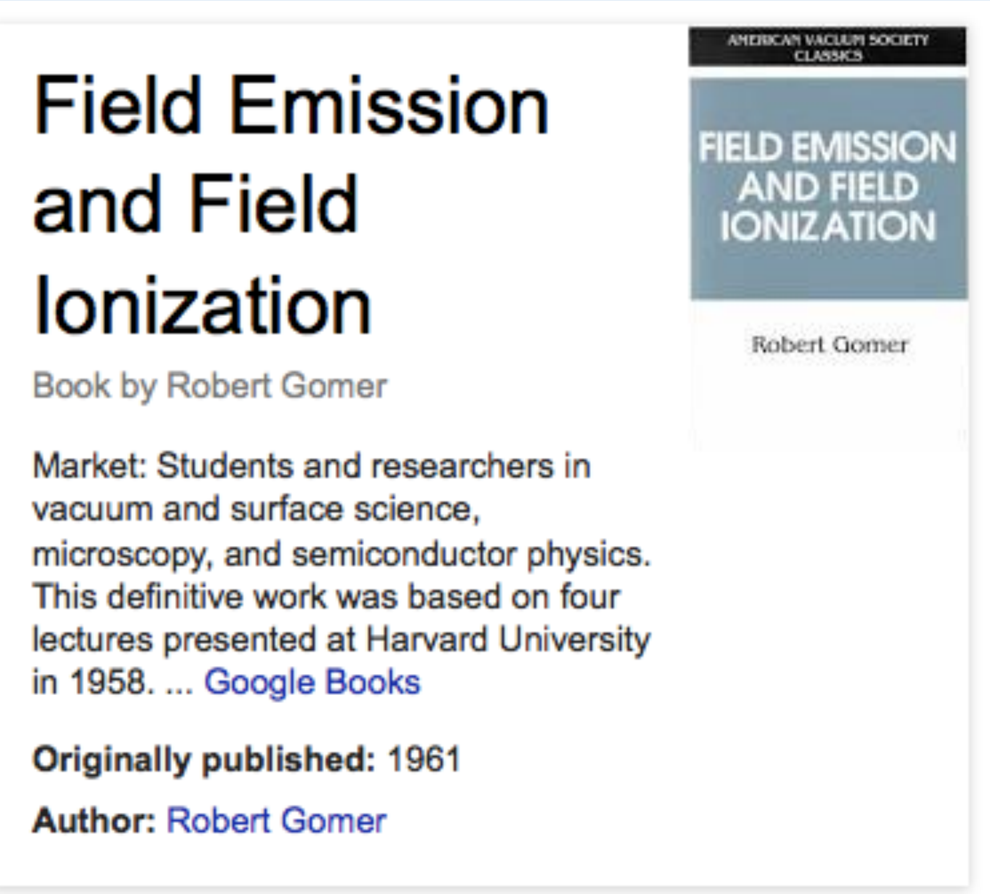
Fig. 13. Platinum crystal with a number of dislocations. The dislocation core near the (102) plane is decorated with an impurity atom, appearing as a bright spot. A vacancy is seen near the (113) plane.



AMERICAN VACUUM SOCIETY
CLASSICS

FIELD EMISSION
AND FIELD
IONIZATION

Robert Gomer



Field Emission and Field Ionization

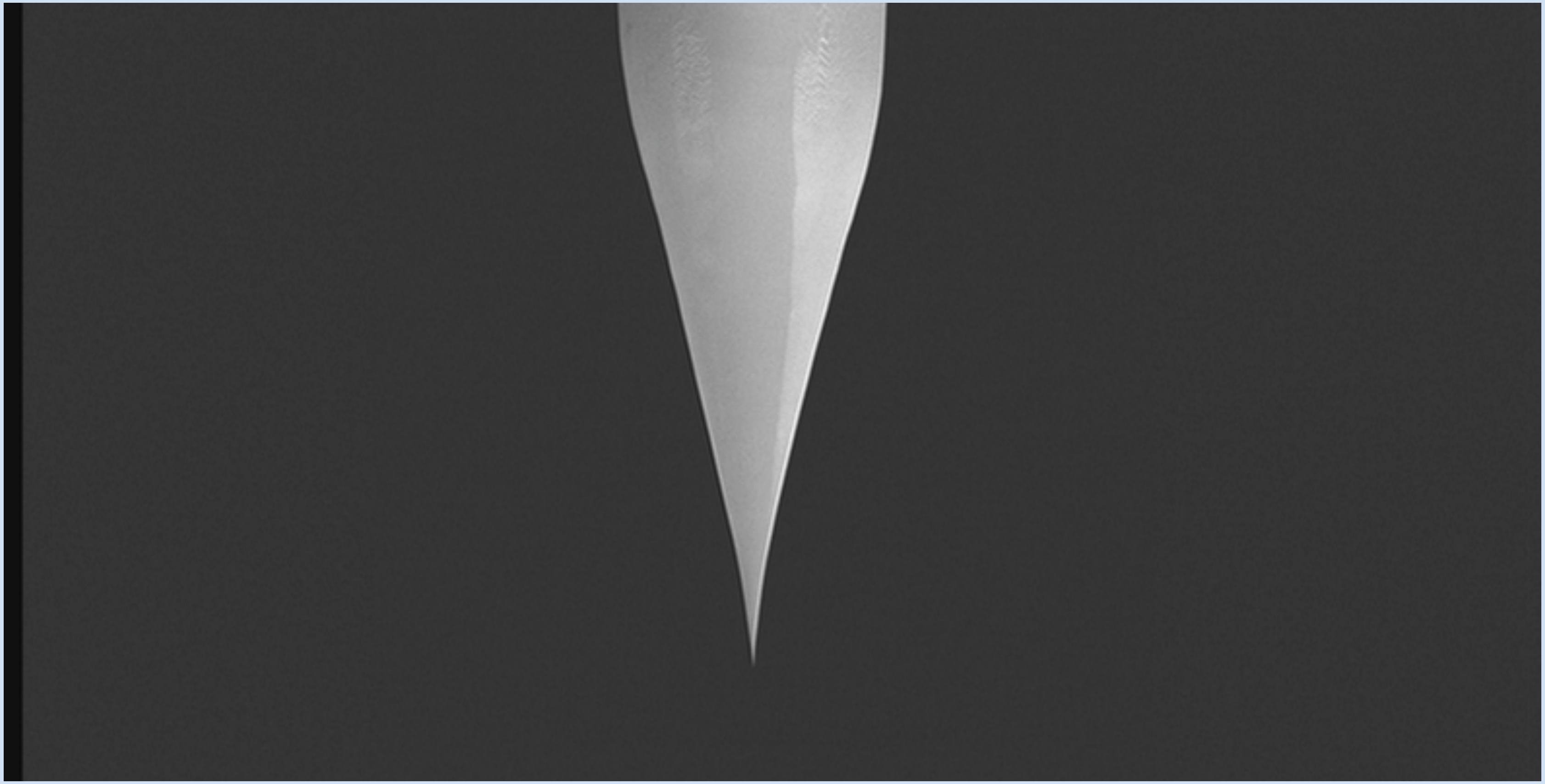
Book by Robert Gomer

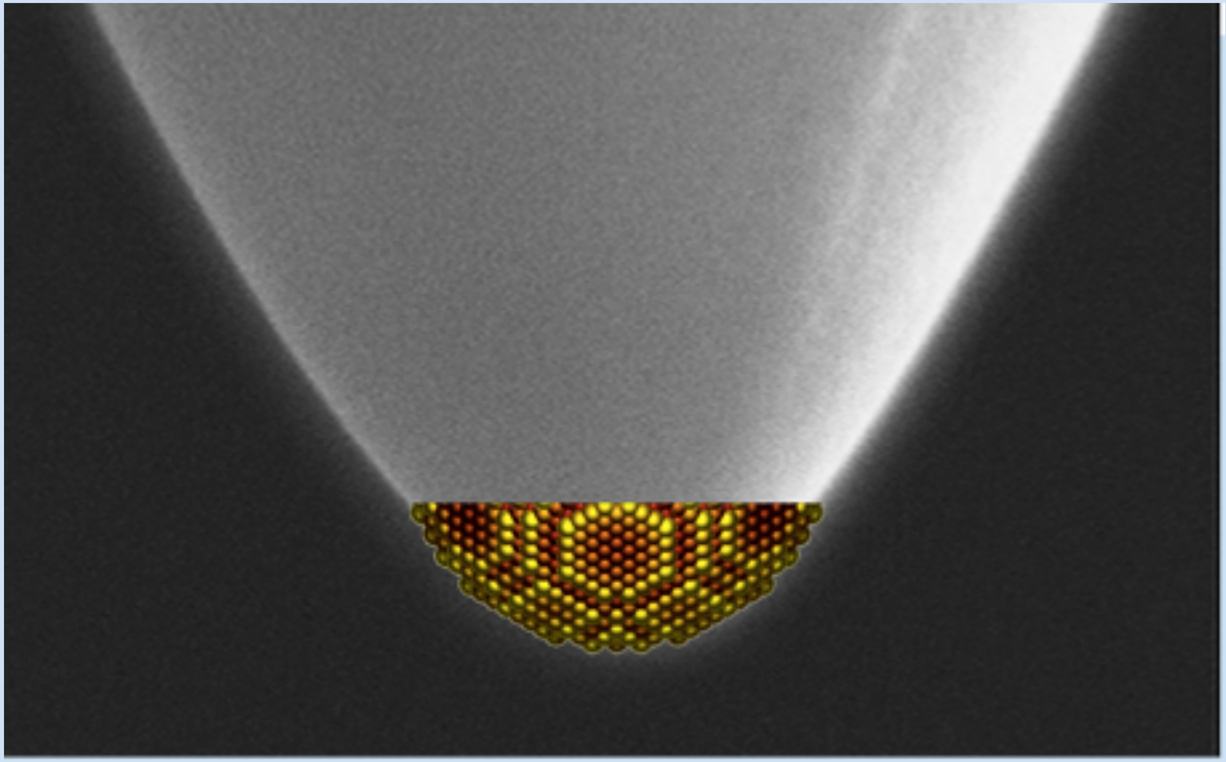
Market: Students and researchers in vacuum and surface science, microscopy, and semiconductor physics. This definitive work was based on four lectures presented at Harvard University in 1958. ... Google Books

Originally published: 1961

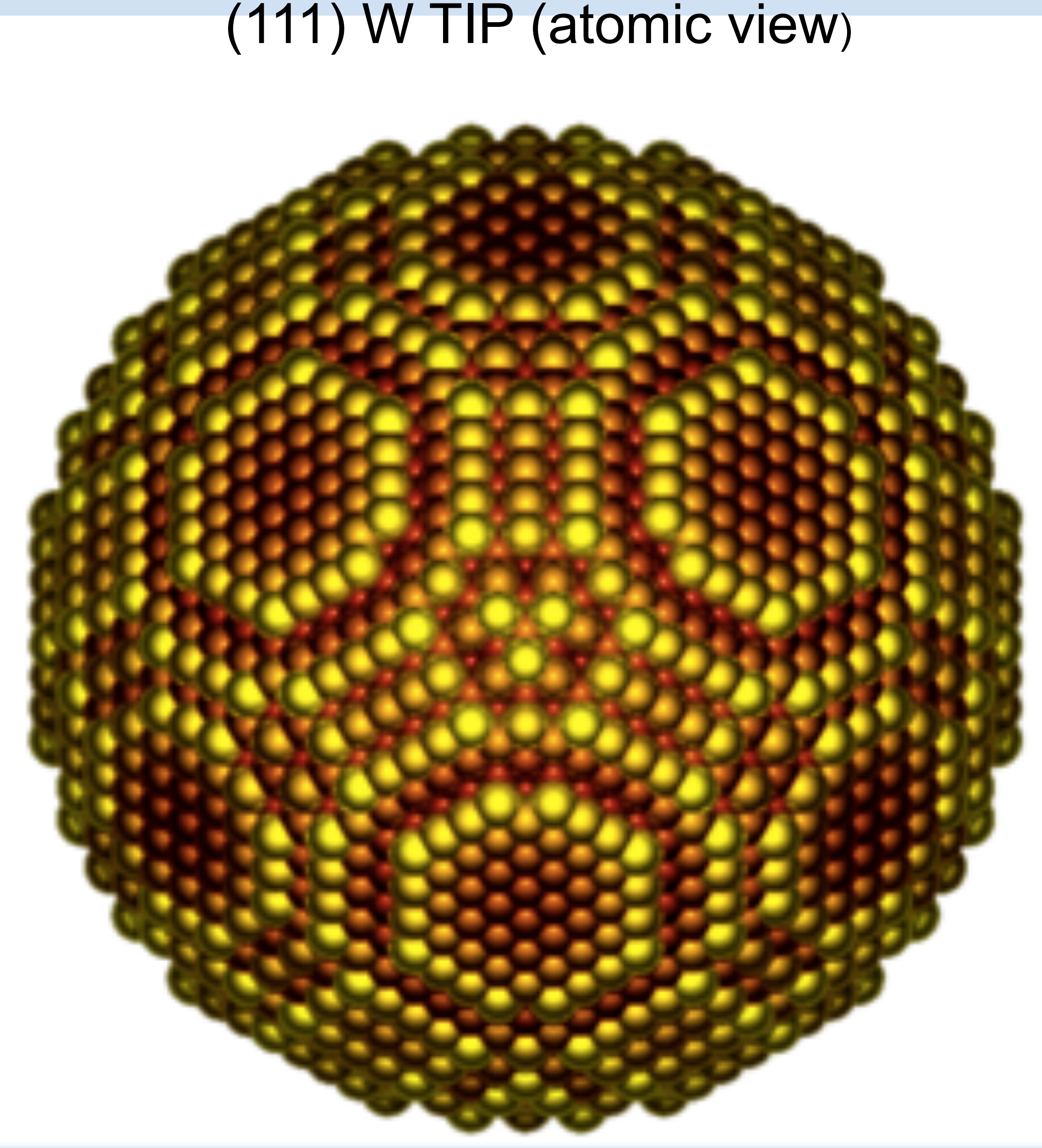
Author: Robert Gomer

Helium Ion Source

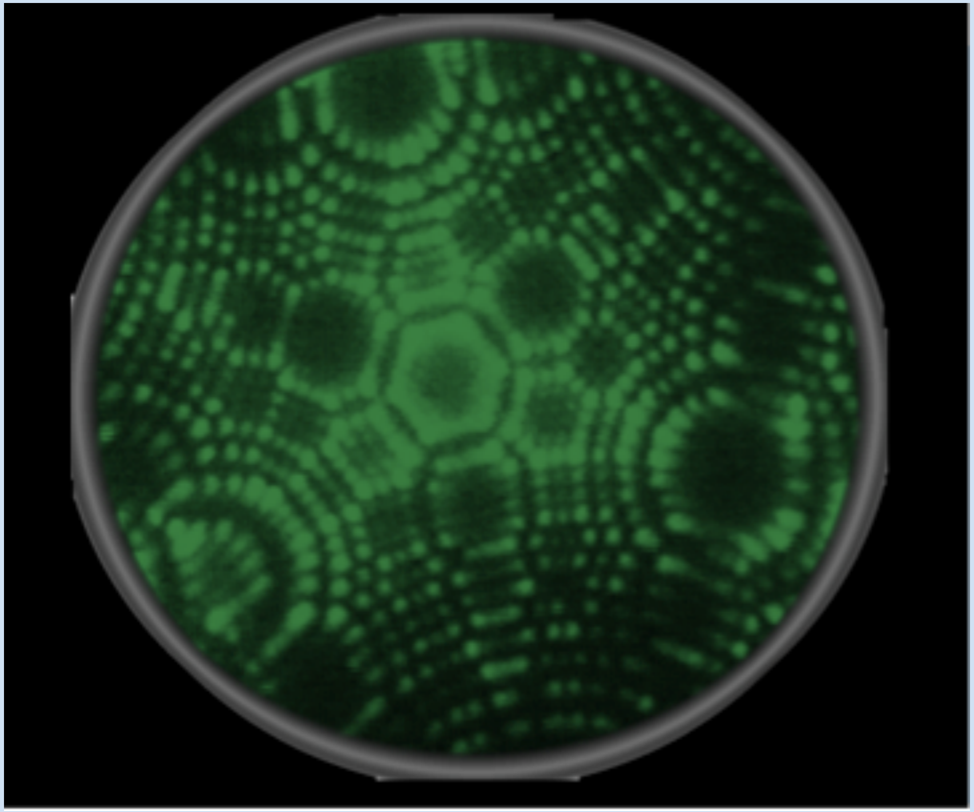




(111) W TIP (atomic view)



Field Ion Micrograph of the Unshaped Emitter



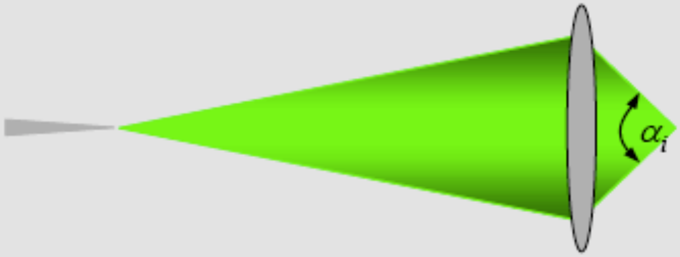
Probe Size: $d_P = \sqrt{(M \cdot d_g)^2 + d_S^2 + d_C^2 + d_d^2}$

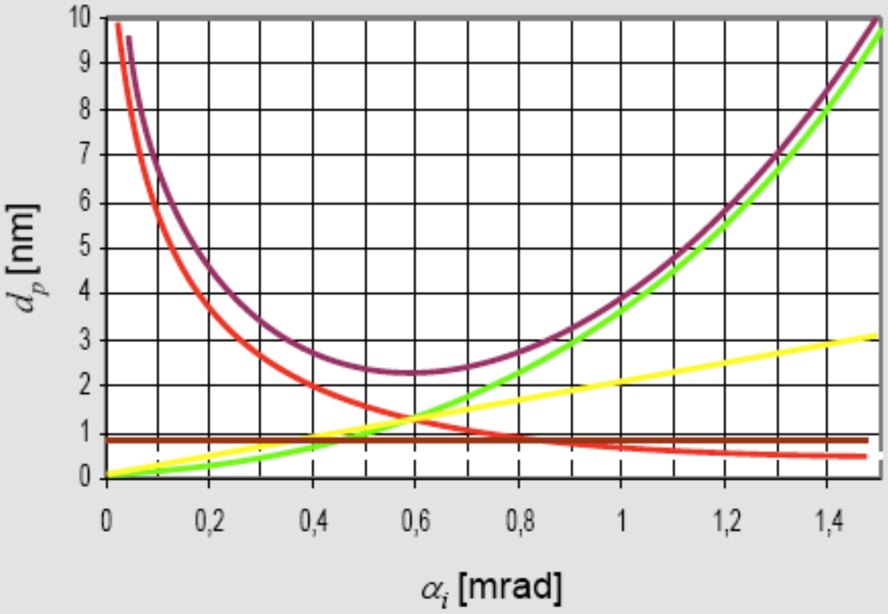
Demagnified source: $d_{So} = M \cdot d_g$

Spherical aberration: $d_S = 0.5\,C_S\,\alpha_i^3$

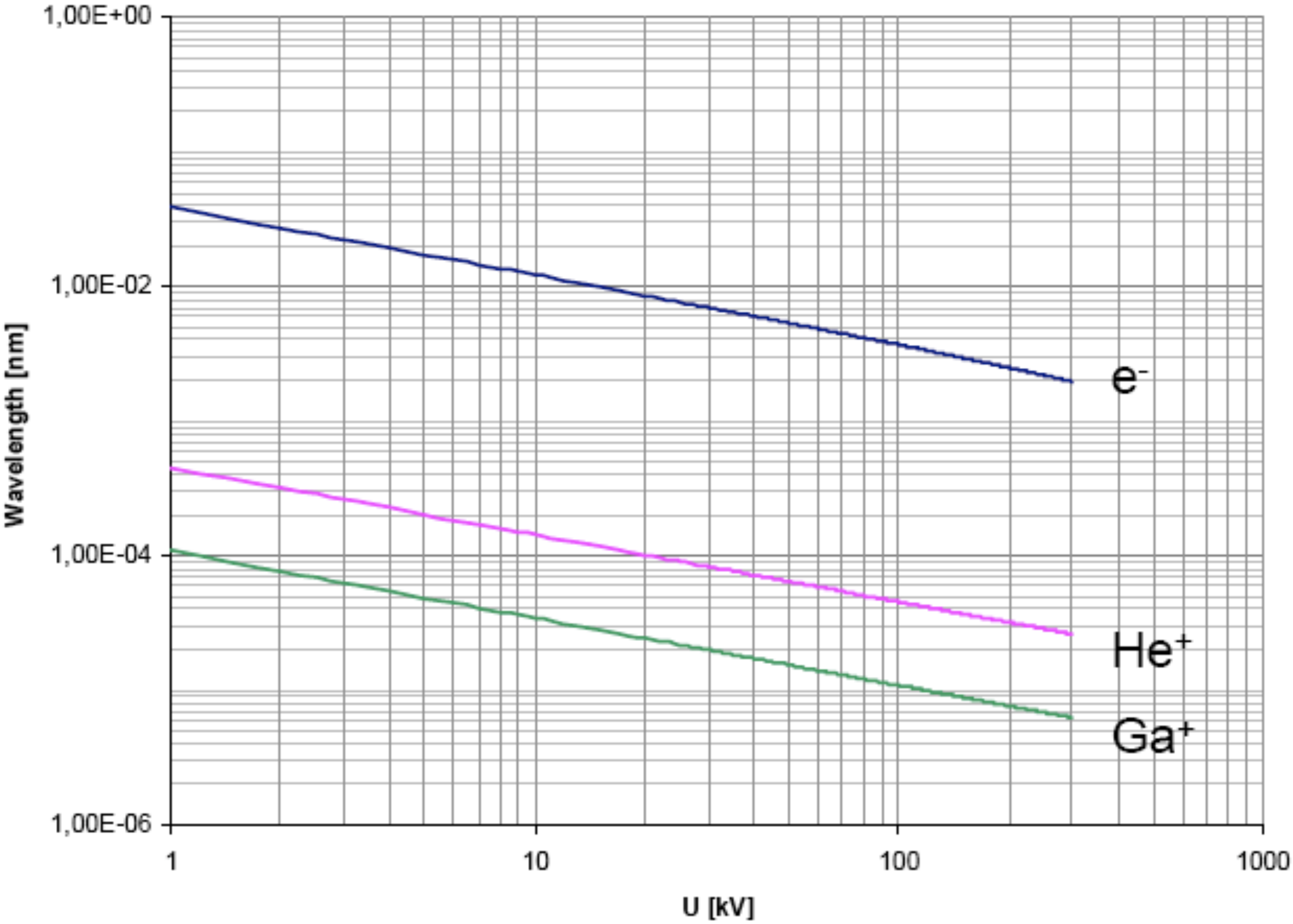
Chromatic aberration: $d_C = C_C \dfrac{\Delta U}{U} \alpha_i$

Diffraction Error: $d_d = 0.6 \dfrac{\lambda}{\alpha_i}$





Superposition of the aberration discs


1,00E+00
1,00E-02
1,00E-04
1,00E-06
Wavelength [nm]
1
10
100
1000
U [kV]
e-
He+
Ga+

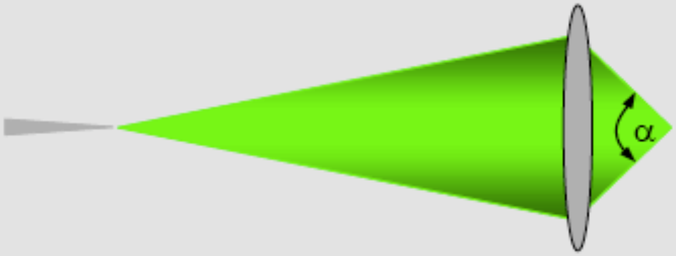
Probe Size: $d_P = \sqrt{(M \cdot d_g)^2 + d_S^2 + d_C^2 + d_d^2}$

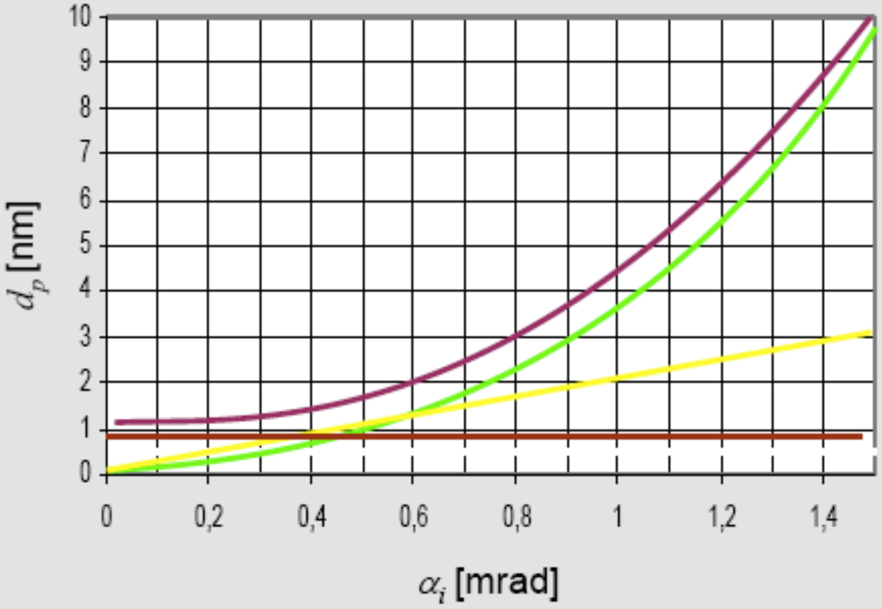
Demagnified source: $d_{So} = M \cdot d_g$

Spherical aberration: $d_S = 0.5 C_S \alpha_i^3$

Chromatic aberration: $d_C = C_C \dfrac{\Delta U}{U} \alpha_i$

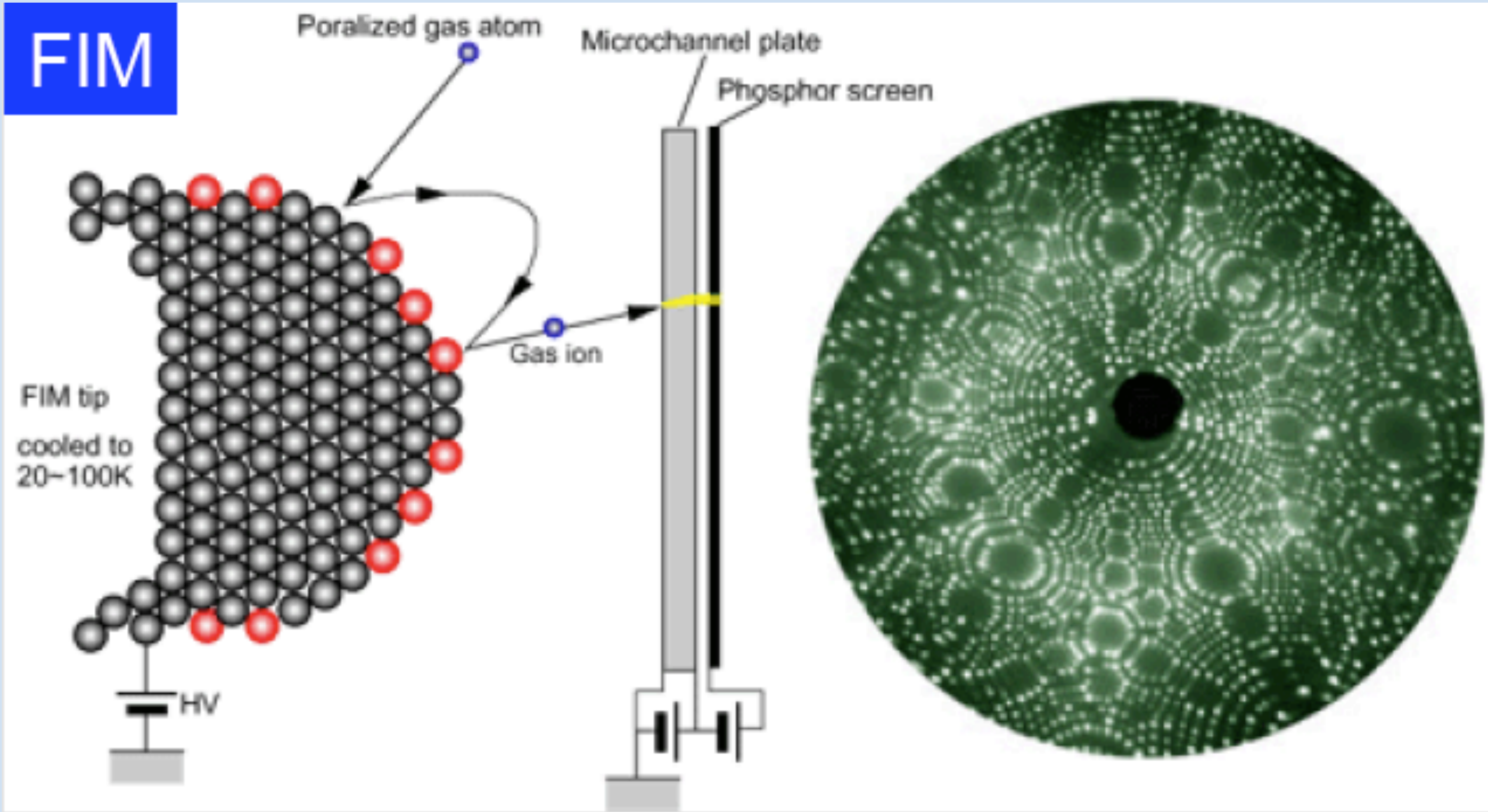
~~*Diffraction Error:* $d_d = 0.6 \dfrac{\lambda}{\alpha_i}$~~





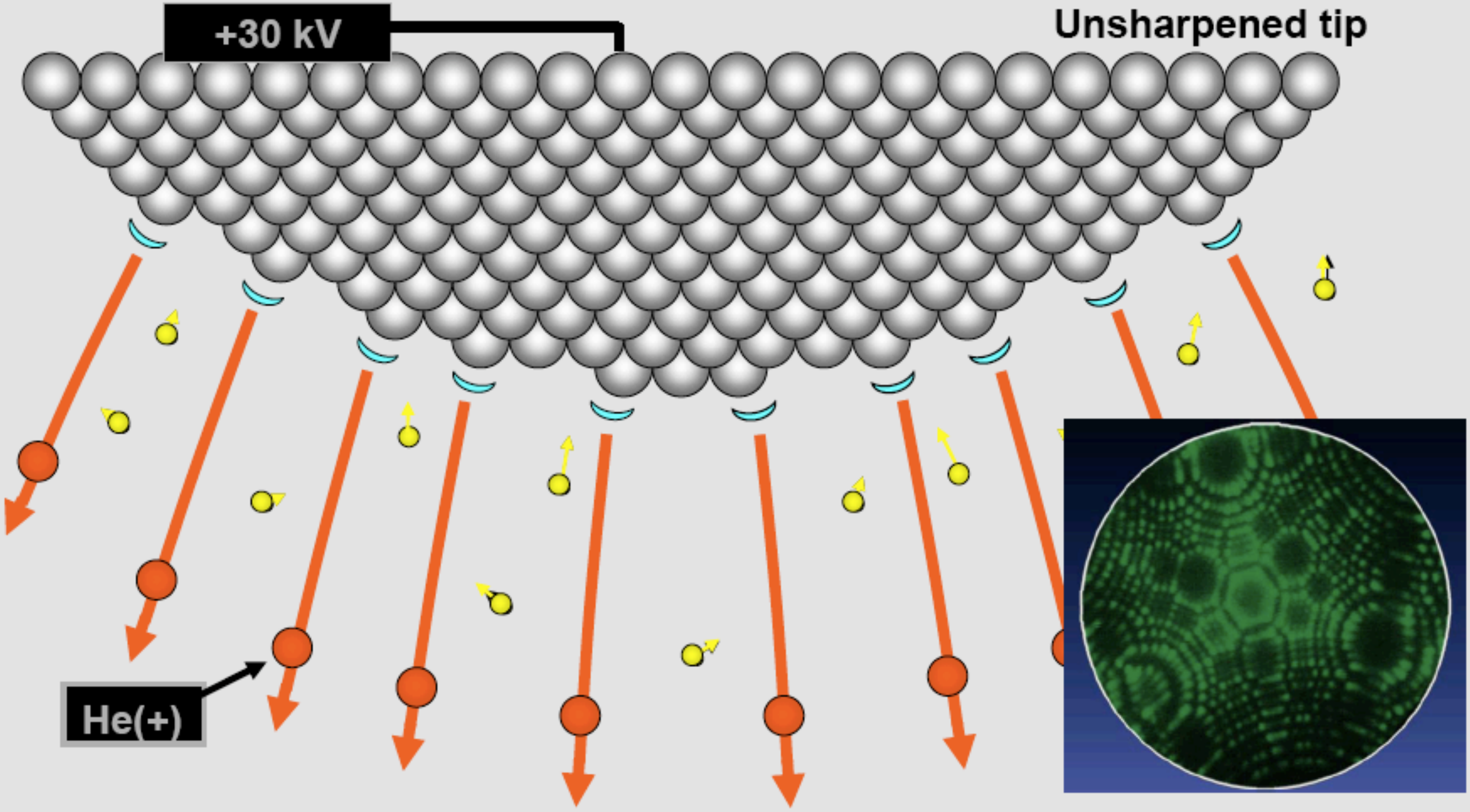
Superposition of the aberration discs

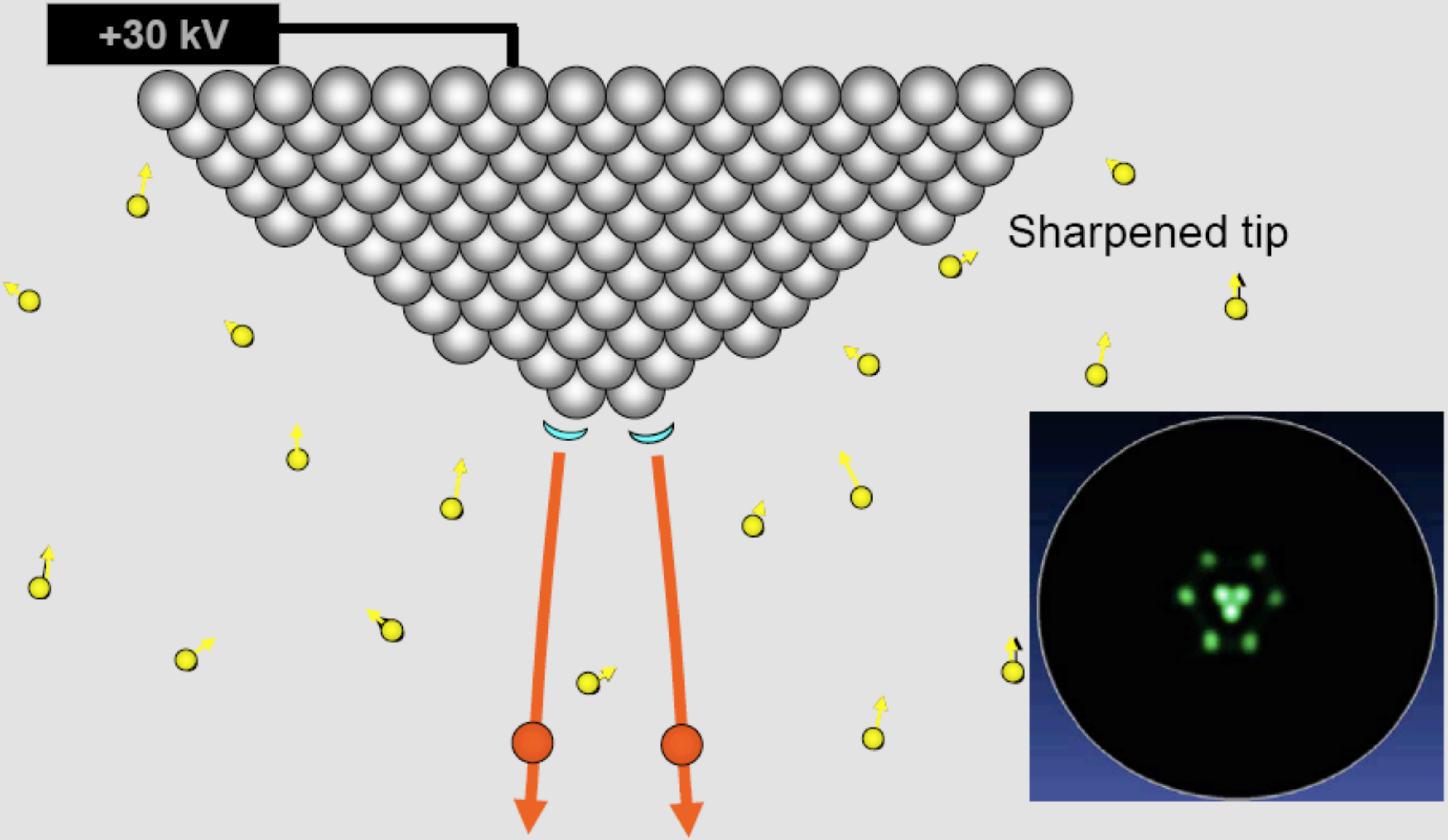
FIM



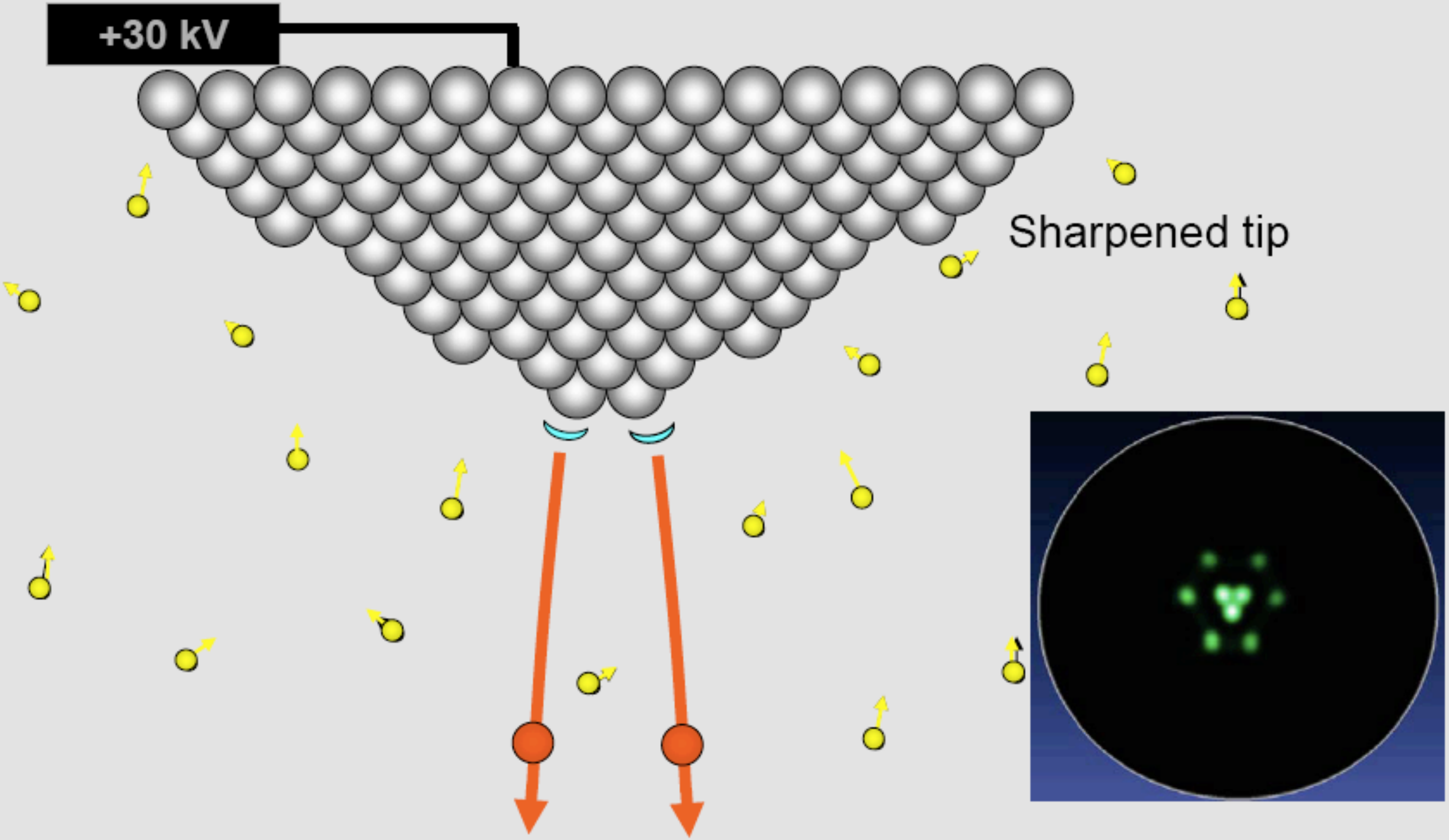
Schematics of a field ion microscope

Unsharpened tip



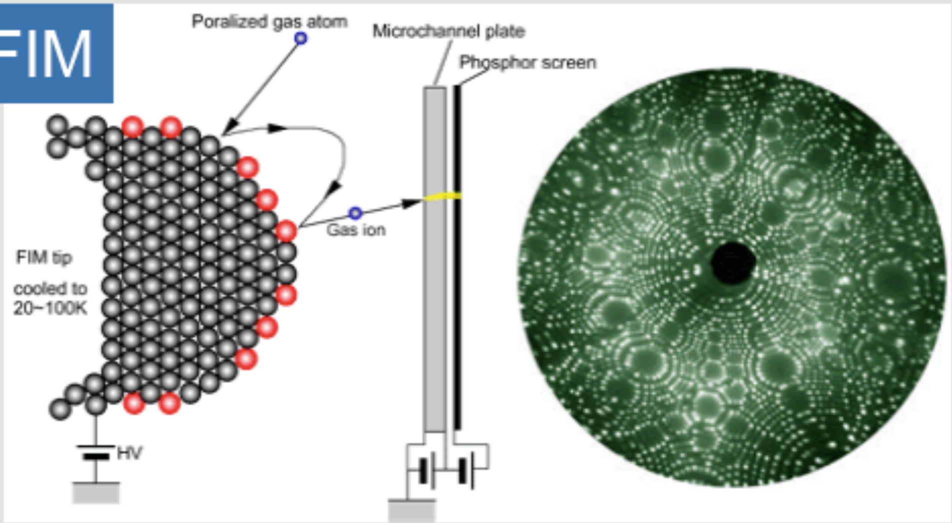


Carl Zeiss NTS, Peter Gnauck

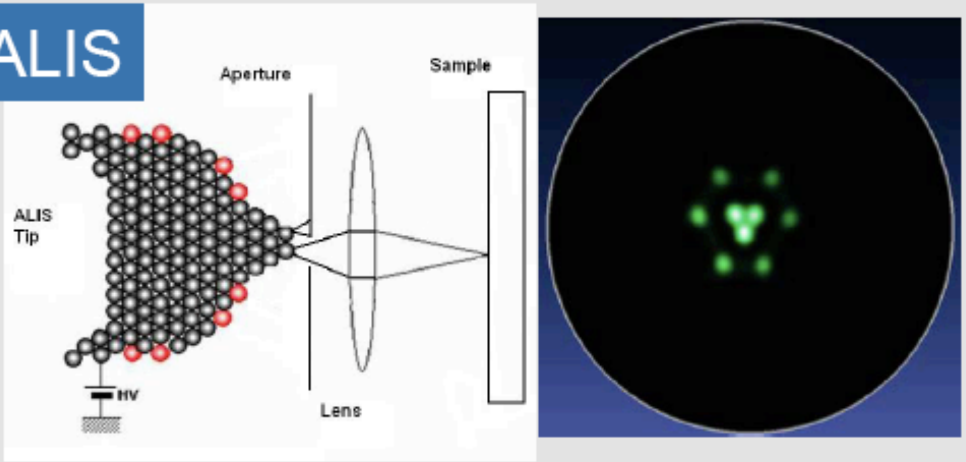


Sharpened tip

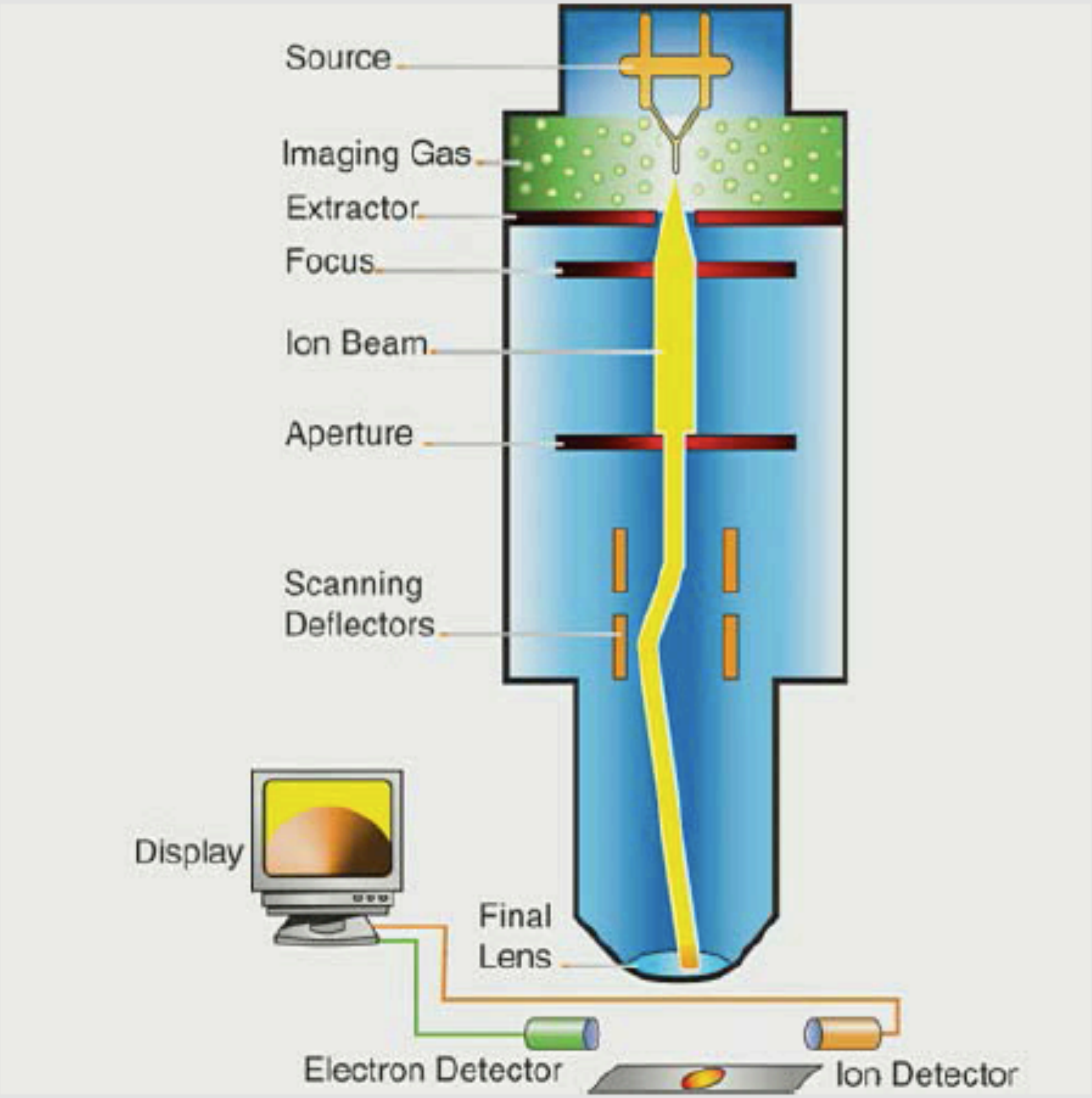
FIM

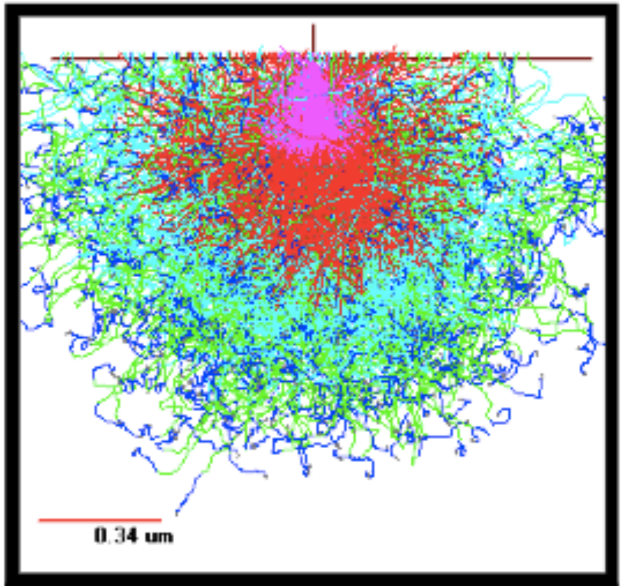


ALIS



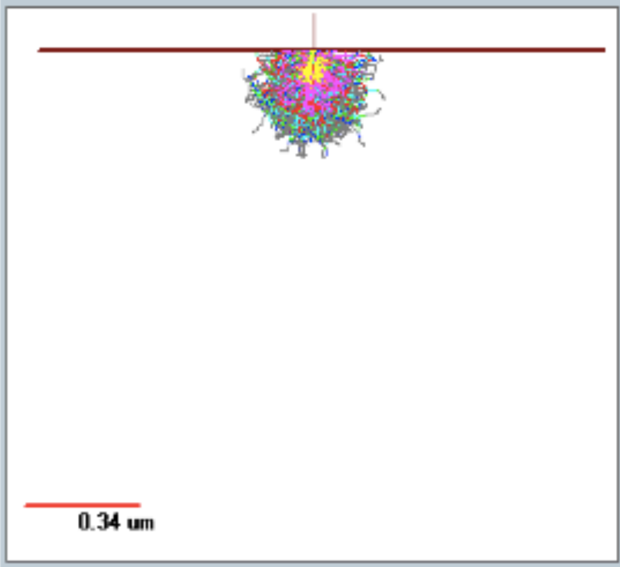
- FIM tip created via chemical etching
- ALIS tip formed with additional reshaping
- 3 atom shelf called the “trimer” created through field evaporation
- Single atom selected to form the final probe
- Results in a sub-angstrom virtual source with high brightness (4×10^9 A/(cm^2 sr)) and low energy spread (<1eV)


Source
Imaging Gas
Extractor
Focus
Ion Beam
Aperture
Scanning Deflectors
Display
Final Lens
Electron Detector
Ion Detector



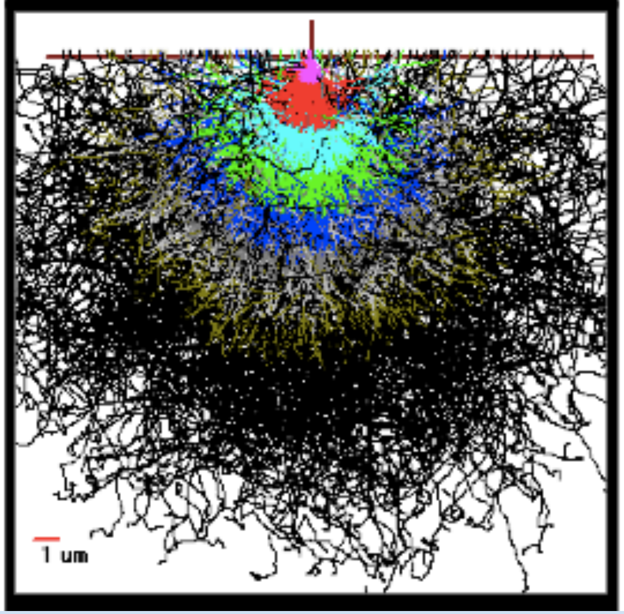
←e^- He$^+$→

10keV Si



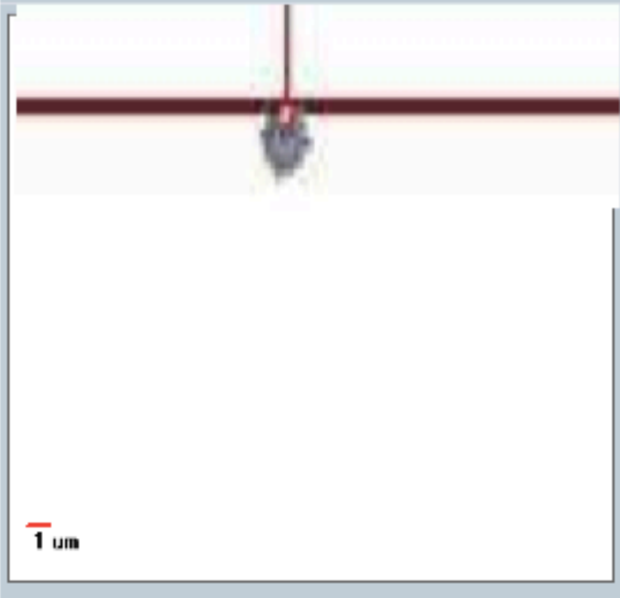
Electron and ion trajectories plotted on the same size scale

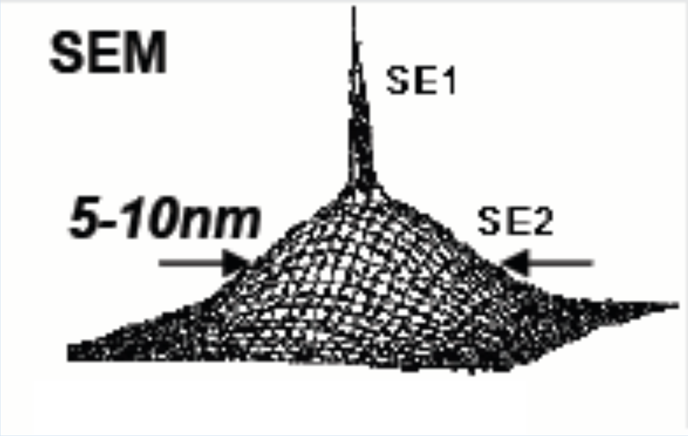
Range Ratio @E (Electron/Ion) ~ E



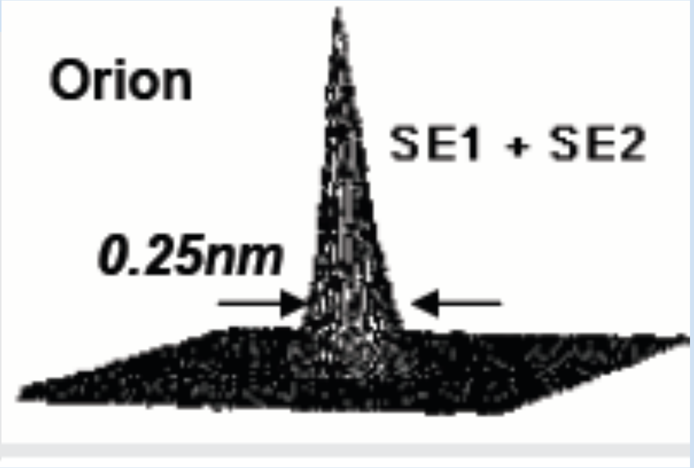
←e^- He$^+$→

30keV Si



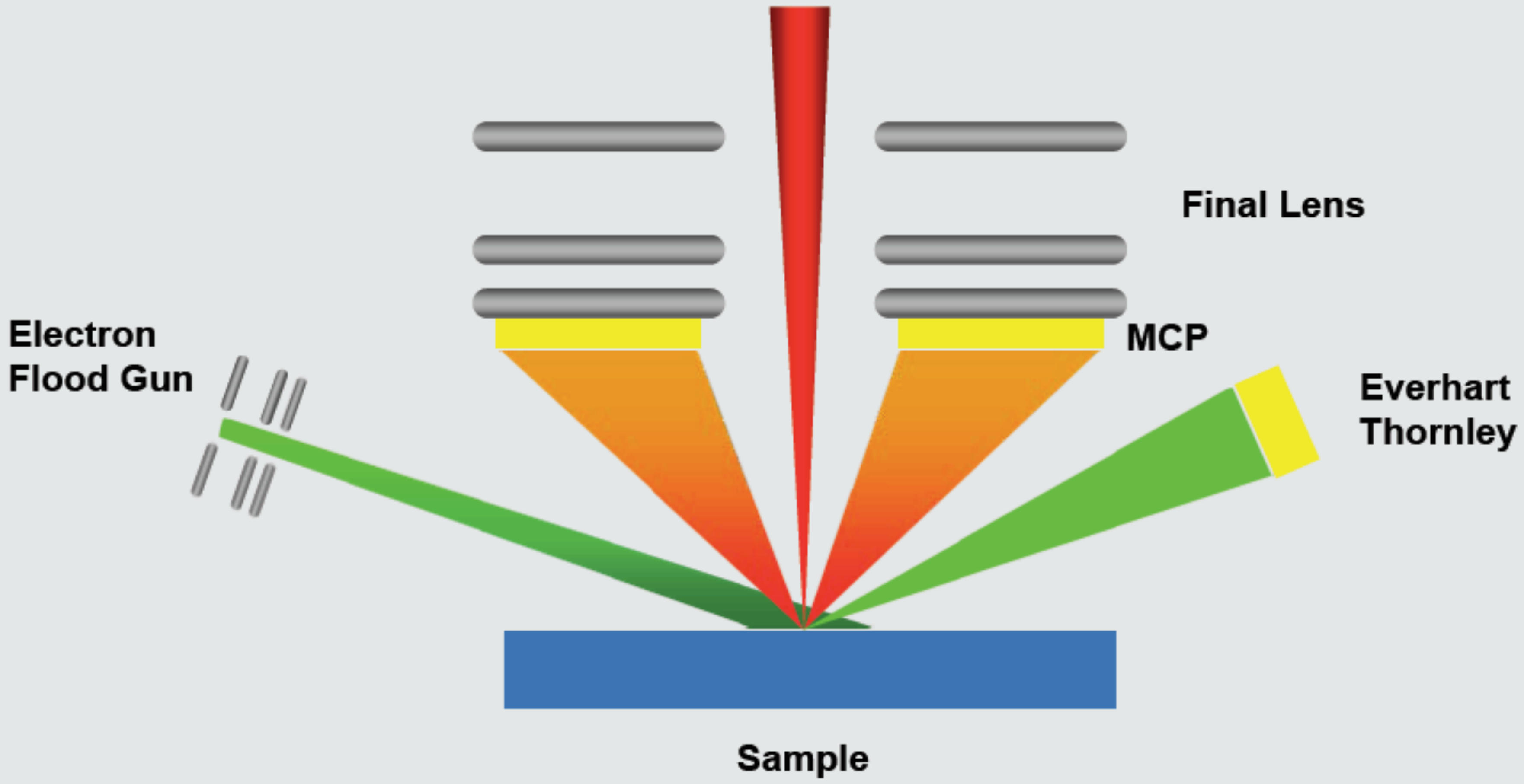


e beam induced secondary electrons



He ion induced secondary electrons

SE1 are produced directly by the primary beam
SE2 are produced by the backscattered beam as it exits sample


Final Lens
Electron
Flood Gun
MCP
Everhart
Thornley
Sample

The Helium Ion Microscope

- Similar in concept to the SEM but different in crucial details..
- Uses a He+ (or other) ion instead of electrons

ZEISS ORION
installed at Harvard Courtesy
Dr. David Bell

Secondary Electrons

Surface Information

Yield varies with material (range ~2-8)

SE image provides both topographic information and material contrast

Typical Energy ~5 eV

SE Yield Ranges from 3 to 8

Escape Depth ~ nm

Backscattered Ions

Material Information

Scatter yield varies as Z^2 of target

Scatter energy varies with mass of target (similar to RBS)

Typical Energy ~ several keV

Typical Yield ~ 0.1% to 3%

Minimal Topographic Information

Immune to surface charging

Transmitted Ions

Provides material information.

Scatter cross section varies with $\sim Z^2$ of the target

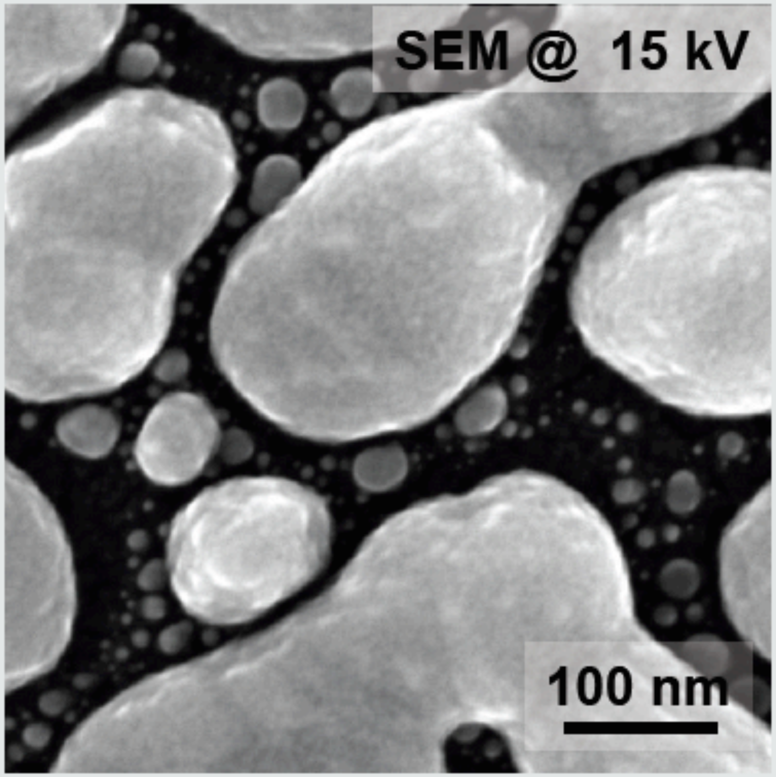
Provide crystallographic information

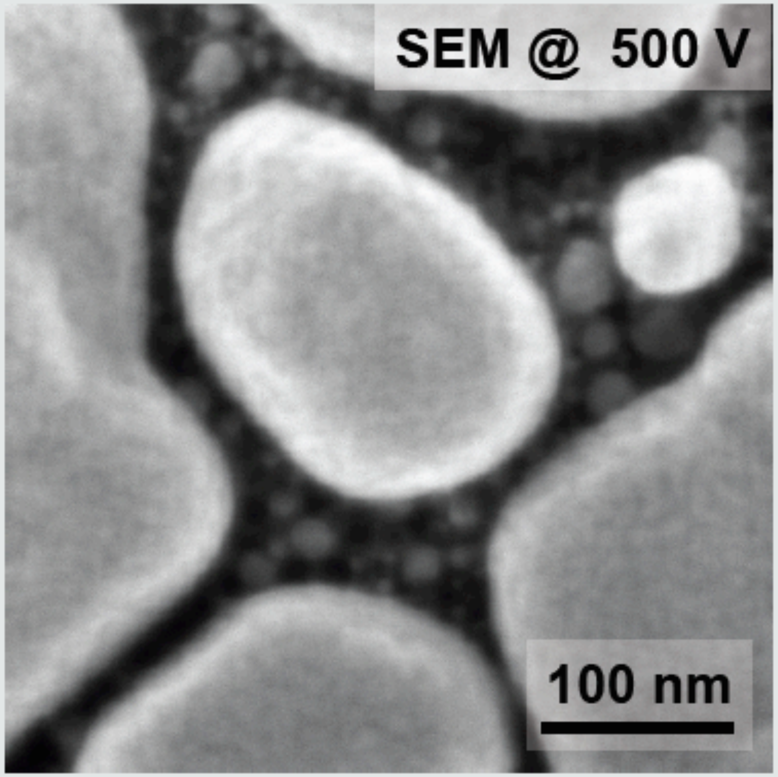
Other Contrast Mechanisms

Channeling Contrast

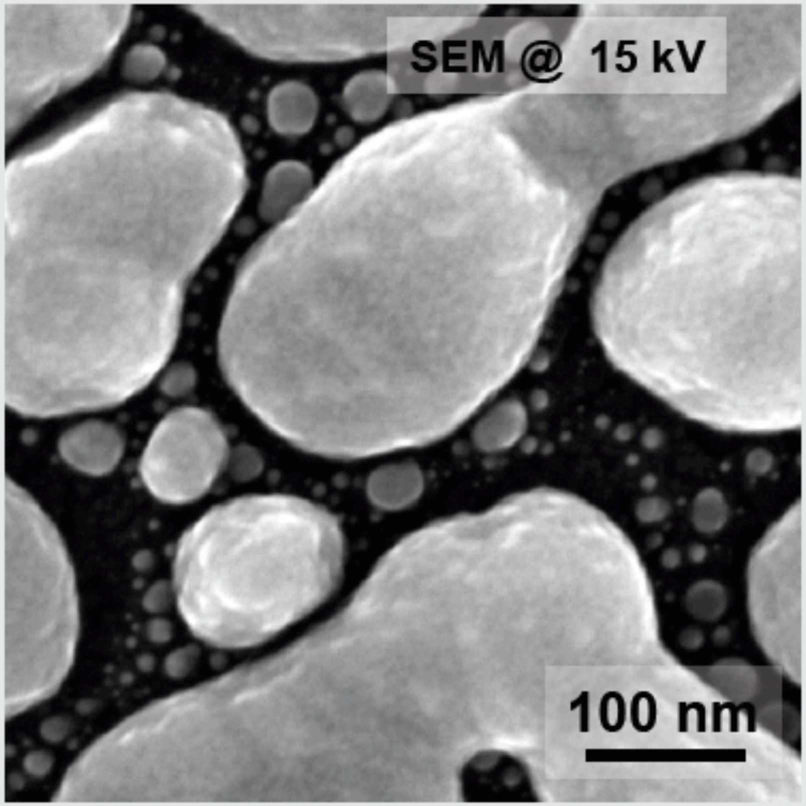
Voltage Contrast

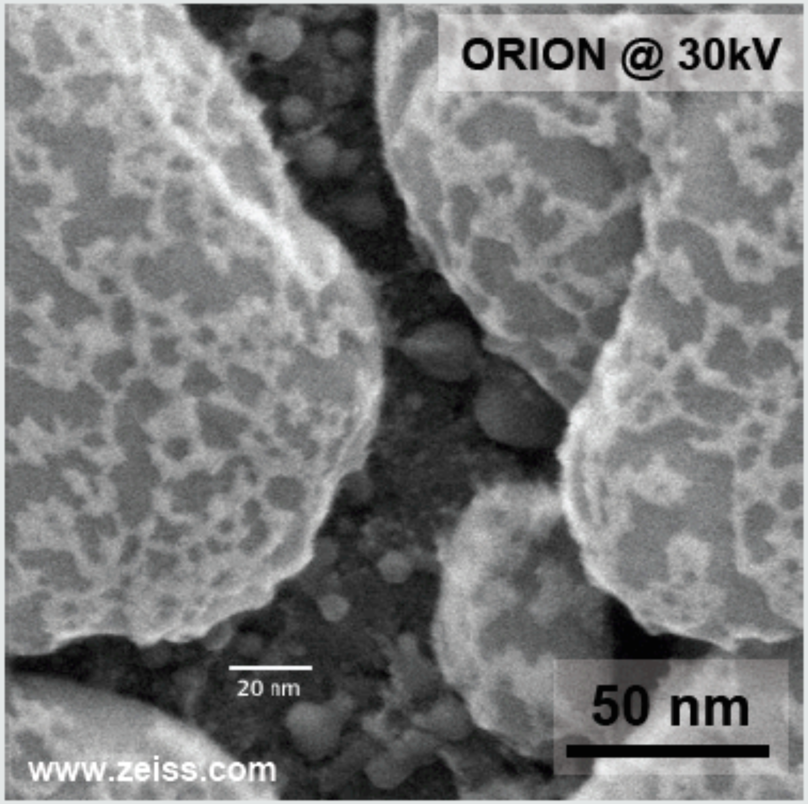
Photon Imaging “Ion luminescence”



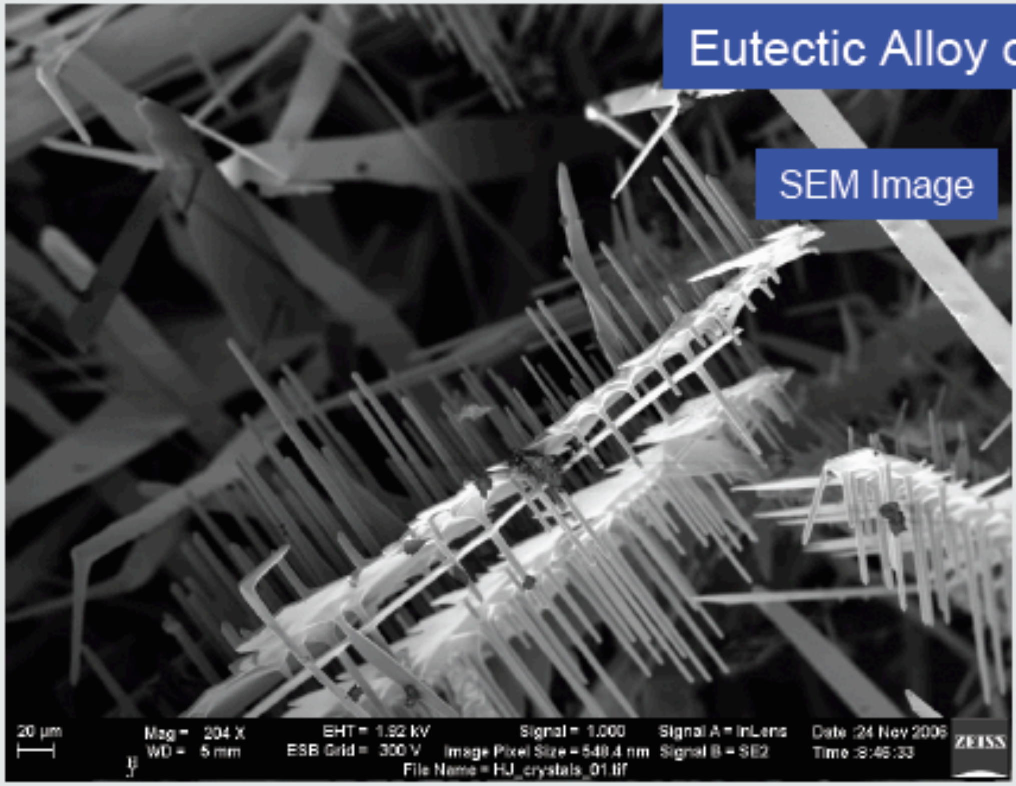


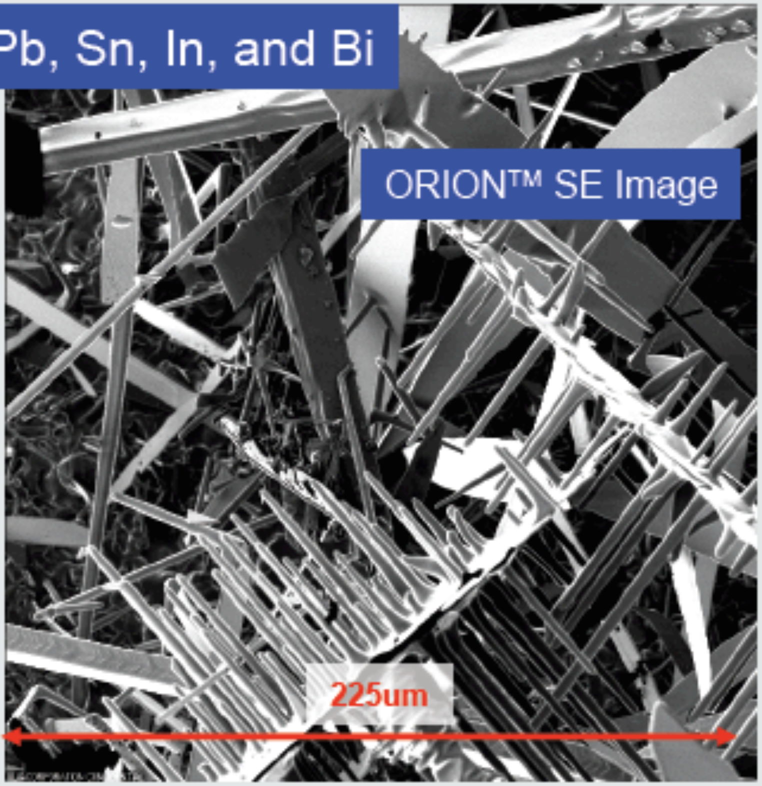
sample courtesy of Al Lysse, Carl Zeiss SMT Inc., US


SEM @ 15 kV
100 nm


ORION @ 30kV
20 nm
50 nm
www.zeiss.com

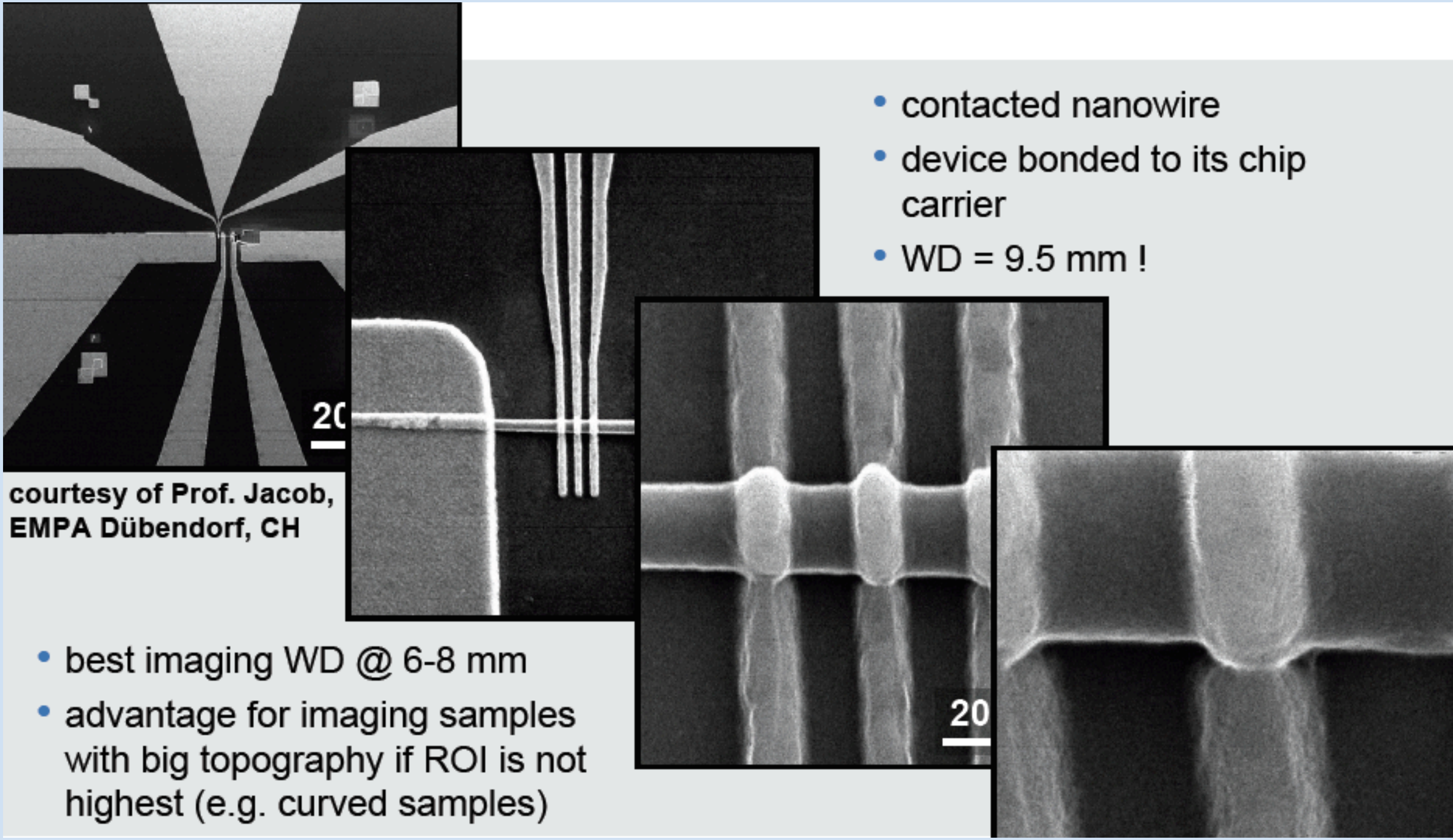
Eutectic Alloy of Pb, Sn, In, and Bi


SEM Image


ORION™ SE Image

Depth of Field inversely proportional to Half Angle (α_i) of incident beam

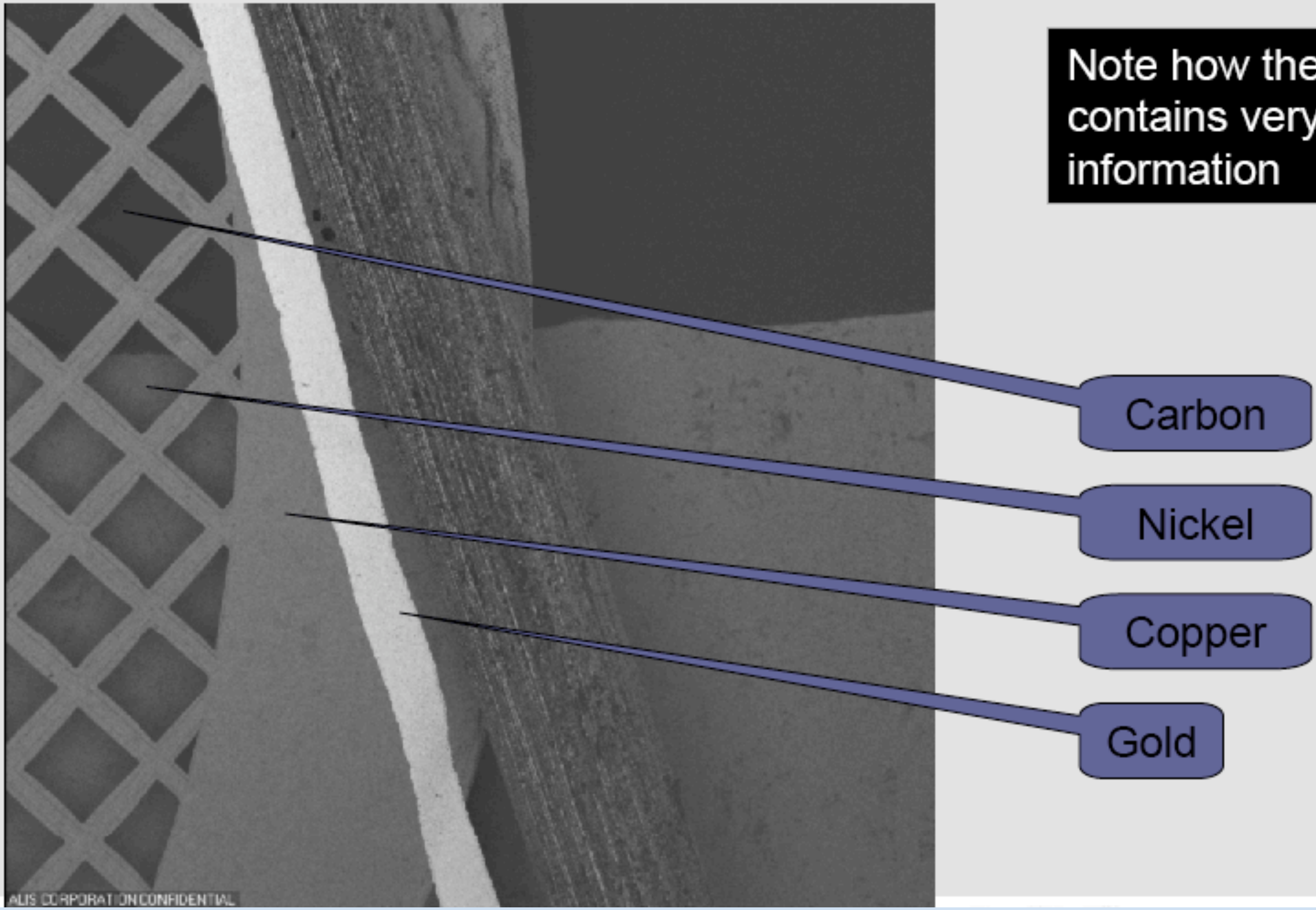
- contacted nanowire
- device bonded to its chip carrier
- WD = 9.5 mm !

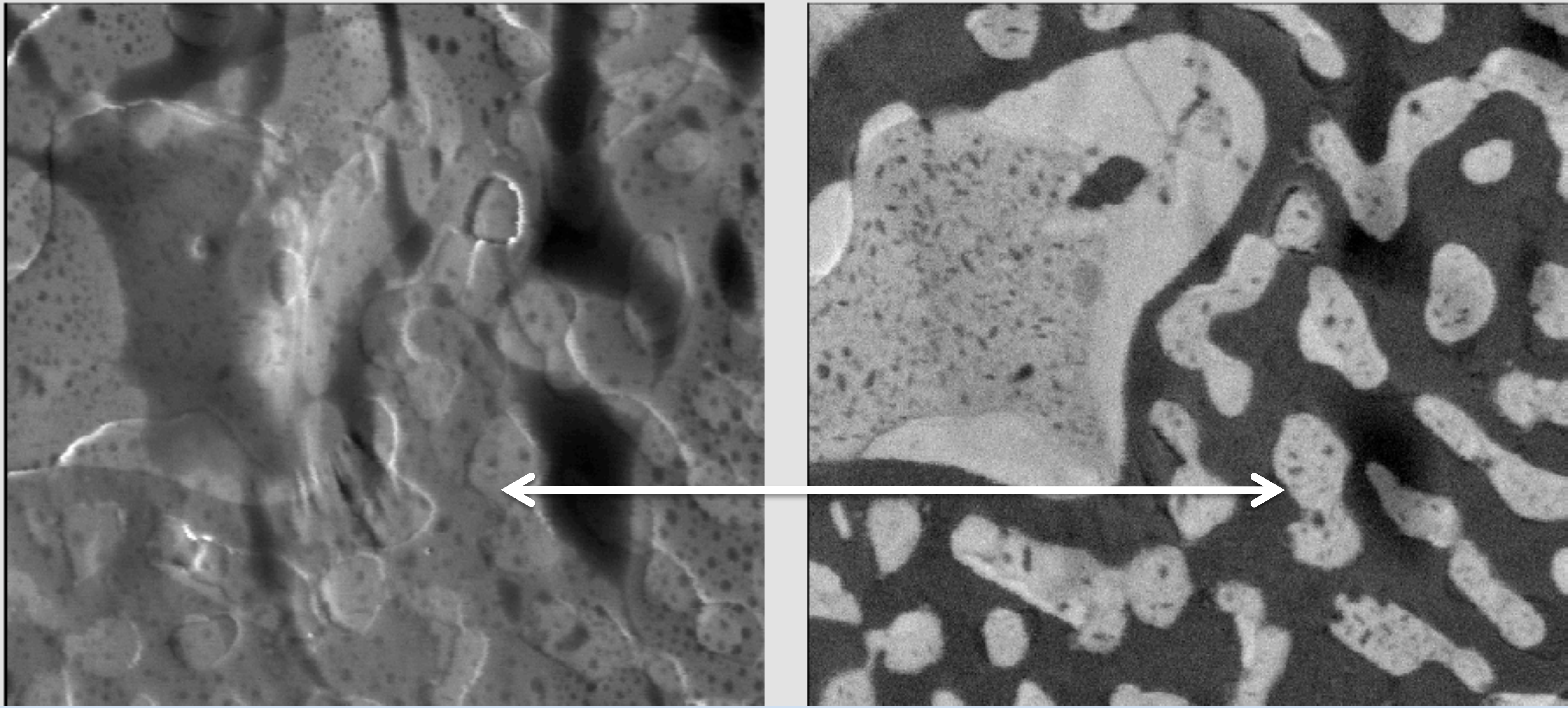


courtesy of Prof. Jacob,
EMPA Dübendorf, CH

- best imaging WD @ 6-8 mm
- advantage for imaging samples with big topography if ROI is not highest (e.g. curved samples)

Note how the RBI image contains very little edge information

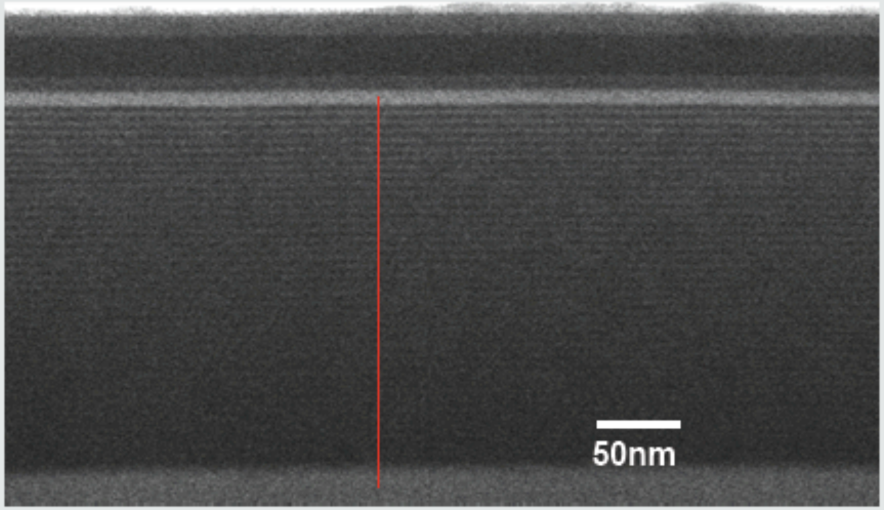


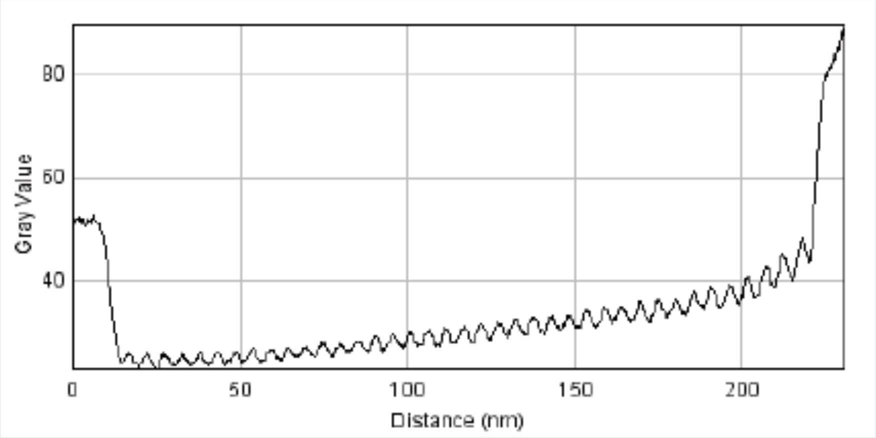


SE image

He Ion Backscattered image

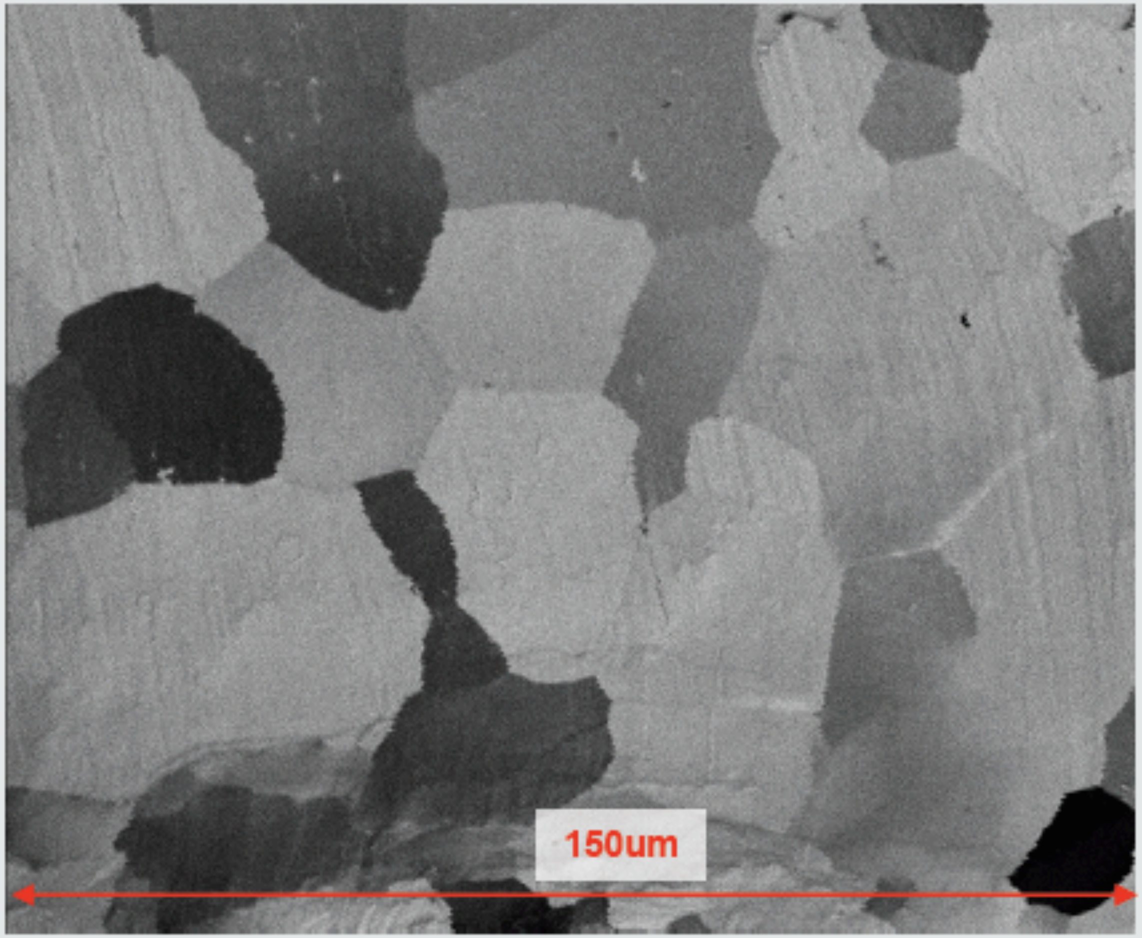
From P. Gnauck, Zeiss



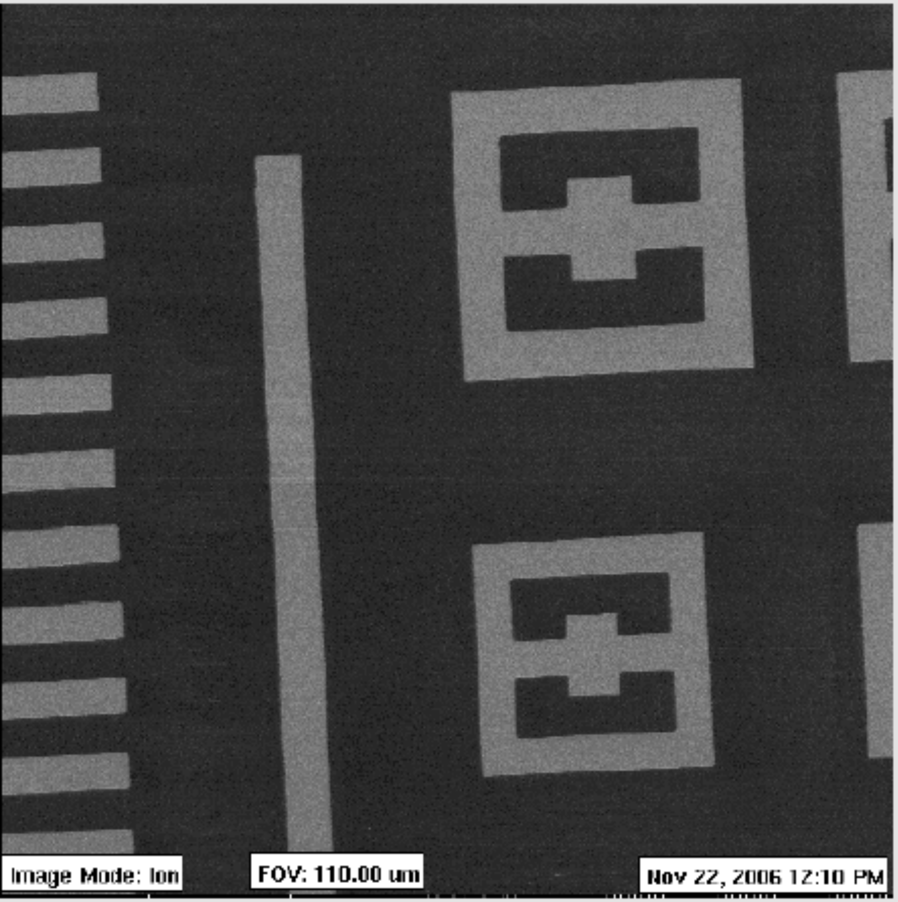


- Transmission Ion imaging performed with a "Conversion Style" detector
- Transmission image of EUV mask clearly shows the absorber stack, the cap layer, and the multi-layers
- An improved detector in development which will allow both bright and dark field imaging

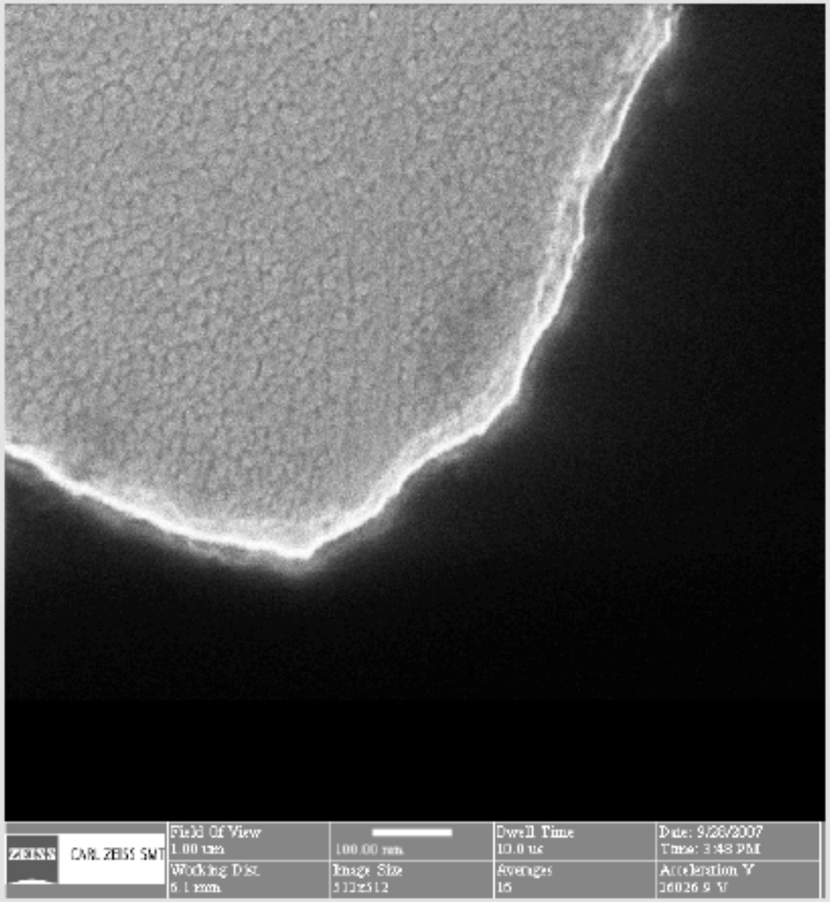
Channeling Contrast



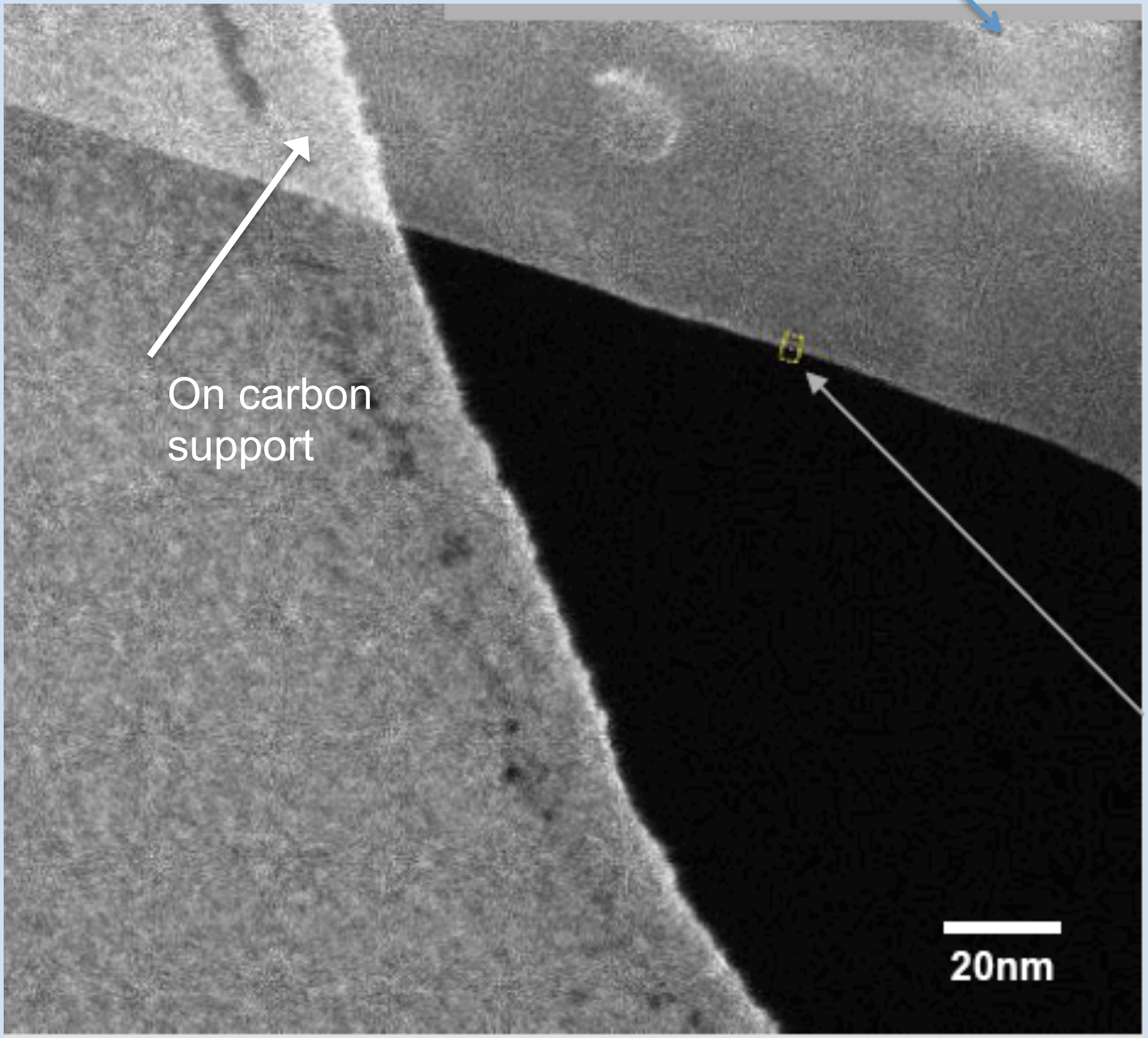
Contrast differences due to grain orientation



Backscattered ions have high energy
and are impervious to surface charging

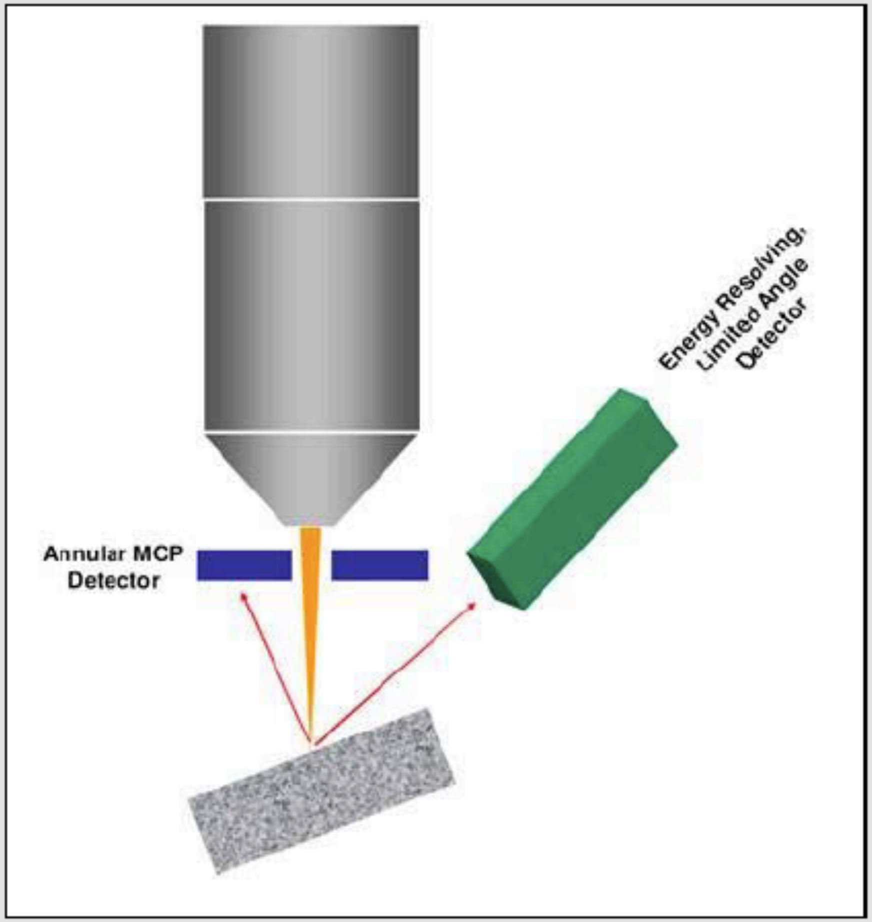


Charge control in Secondary electron
mode using an electron flood gun



Self supporting

Asbestos Fiber on Holey Carbon Film



- Virtually no X-ray production → use backscattered helium for materials characterization

- Cross section for scattering (RBI Yield, Imaging)

$$\sigma \propto \frac{Z^2}{E_0^2}\frac{1}{\sin^4(\theta)}$$

- Backscatter Energy for spectroscopy

$$E_B = E_0\left(\frac{\sqrt{M_2^2 - M_1^2\sin^2\theta} + M_1\cos\theta}{M_1 + M_2}\right)^2$$

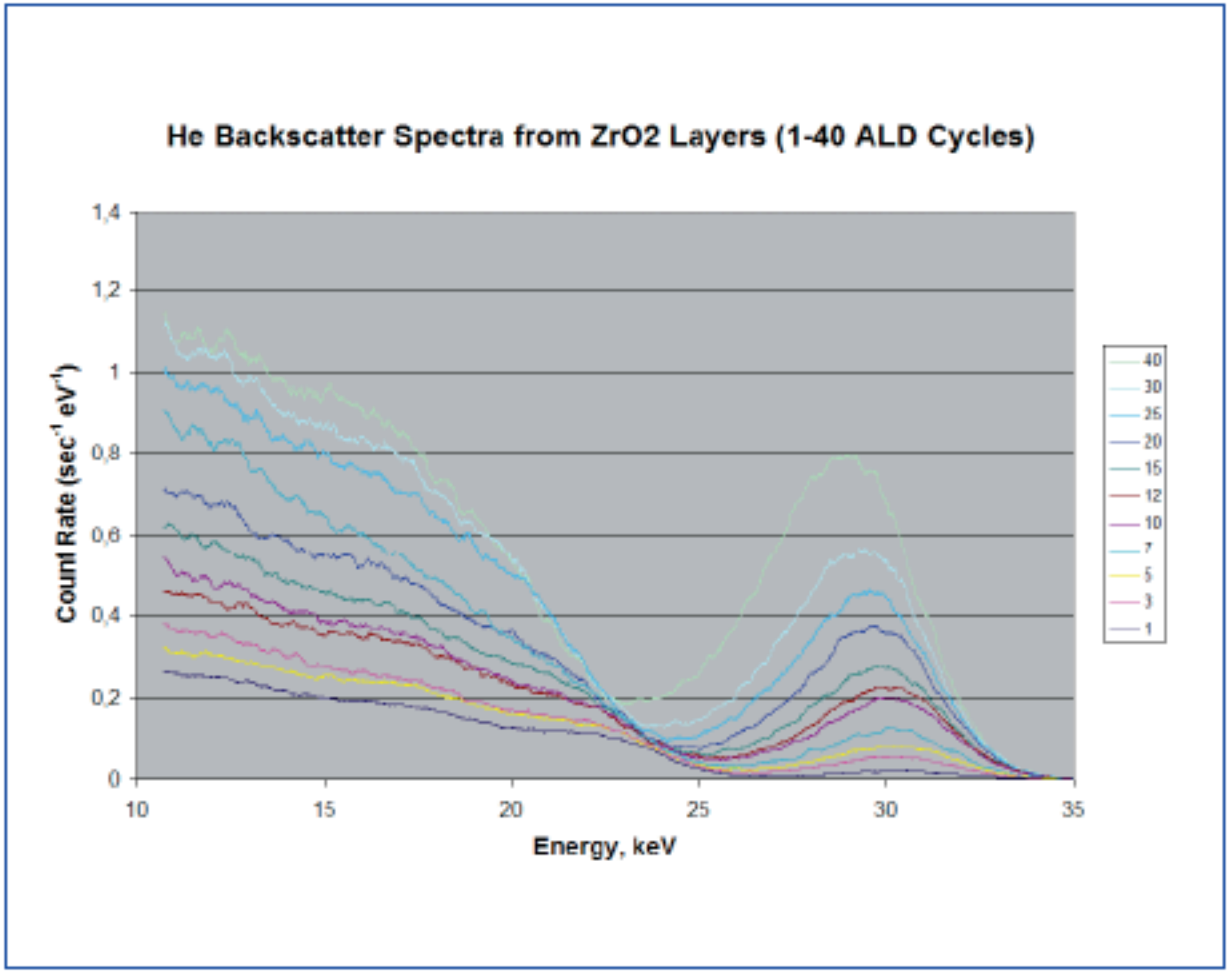
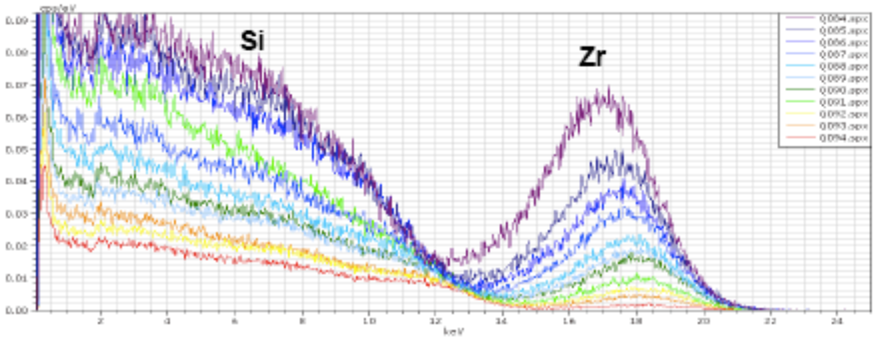
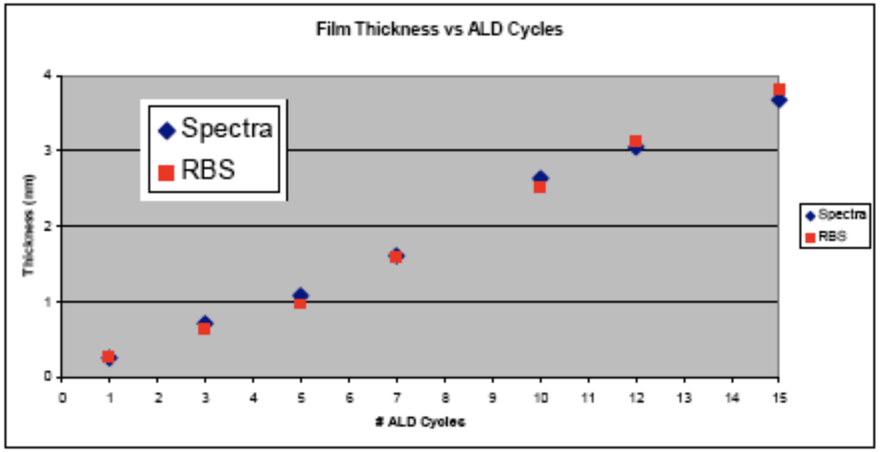


Figure 1: Helium backscatter spectra from a set of ZrO_x films on silicon. The legend indicates the number of ALD cycles used to grow the various films. Samples provided courtesy of Dr. Steffen Teichert, Qimonda (Dresden, Germany).

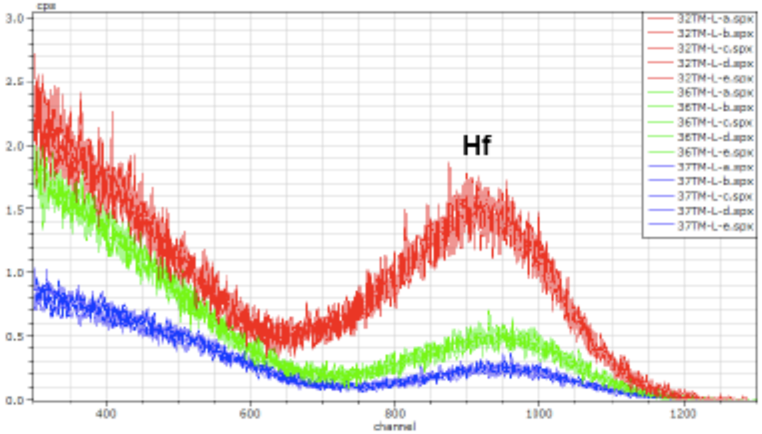
ZrO_2 on SiO_2

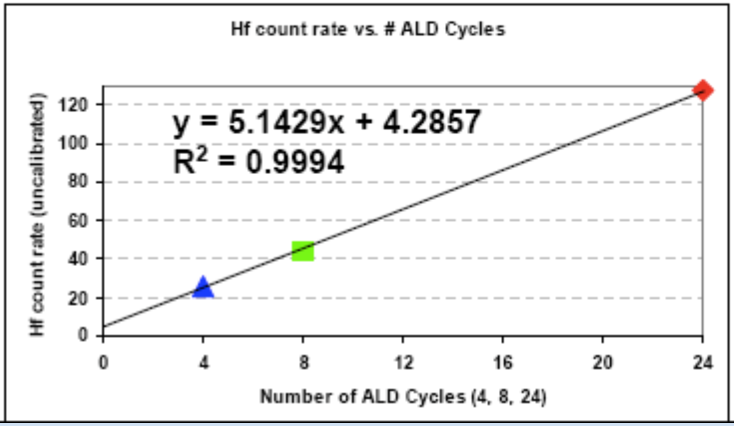




Correlation between low voltage RBS and MeV RBS

HfO_2 on SiO_2





$y = 5.1429x + 4.2857$

$R^2 = 0.9994$

From B. Thompson, Zeiss

- The Helium ion microscope is based upon a gas field ionization source.
- Unique properties :
  - high resolution
  - different contrast mechanisms (SE and RBI mode)
  - large depth of focus
  - high surface sensitivity
  - strong channeling contrast.
- The helium ion microscope can be used for fabrication.
- Disadvantages:
  - Source stability
  - Beam induced damage
  - Not fully developed technology

References for Helium Ion Microscopy

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