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A Technical Introduction to The Orion He-Ion Microscope

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ALIS Corporation
A Carl Zeiss SMT Company

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Chief Scientist, International Business Development

December, 2006

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Topics for Today

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- **Brief Introduction to the Orion System**
  - The history
  - The system
- **The Ion Source**
  - A Three Atom Cluster
- **The Column Optics**
  - Designed for Sub-nm Resolution
- **Atomic Level Imaging System**
  - Imaging Modes
    - SE Detection
    - BSI Detection
    - Photon Detection

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Topics for Today

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- **Orion Applications**
  - High Resolution Imaging
  - Failure Analysis
  - Defect Review
  - CD Measurement
  - Mask Inspection/Characterization & metrology
  - Materials Characterization
    - Carbon Nanotubes
    - Magnetic Materials

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Introduction to the ALIS He-Ion Microscope

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- He-Ion source development started in 1992 (Micrion),
- To date, 40 man-years of research.
- $30M funding (DARPA, Sematech, Venture Capital & others).

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- Development work on ALIS technology began at Micrion, continued at FEI.
- Bill Ward left FEI in 2002, with a license for the technology, to begin the commercialization of the ALIS technology as the ultimate, high resolution microscope.
- ALIS Corporation was funded in March, 2005.
  – Grew to 36 employees by June 2006.
- Carl Zeiss SMT acquired all the stock of ALIS Corporation in July 2006.

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The Orion He-Ion Microscope October 2006

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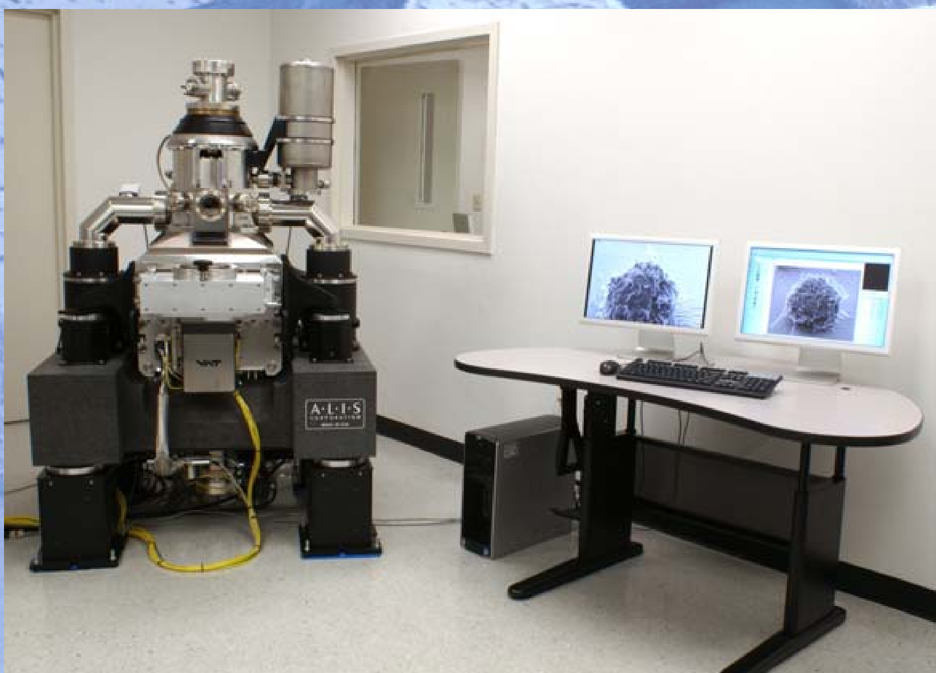

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The Orion He-Ion Microscope
February 2007

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The He Field Ion Microscope (FIM)

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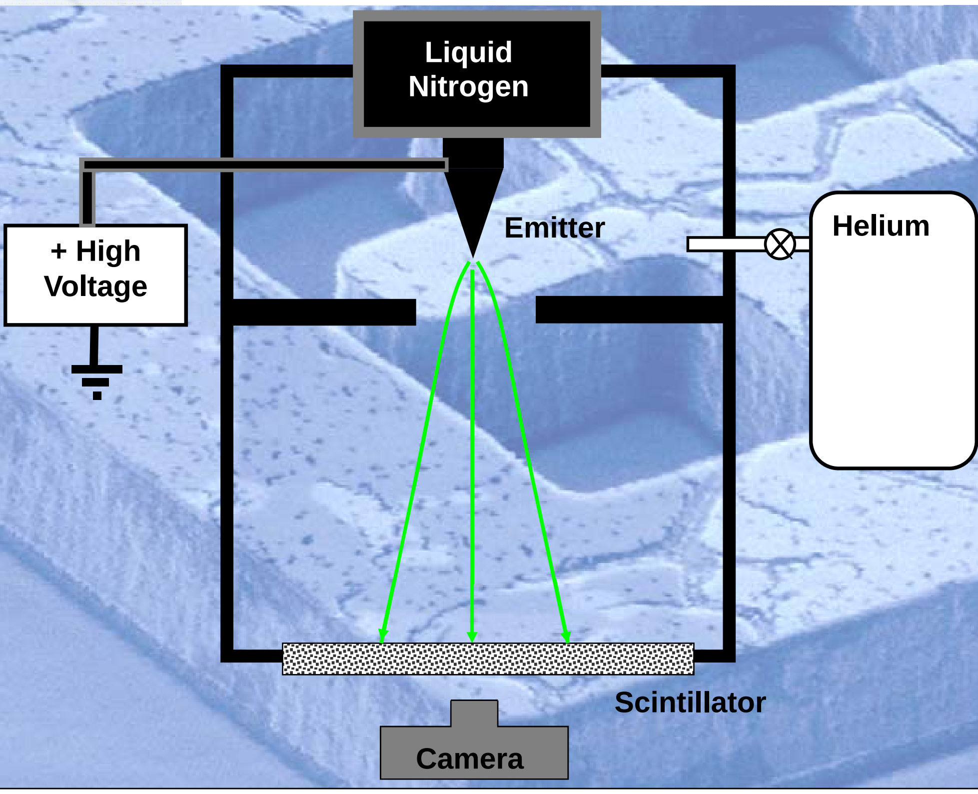

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ALIS Helium Ion Source From High Altitude

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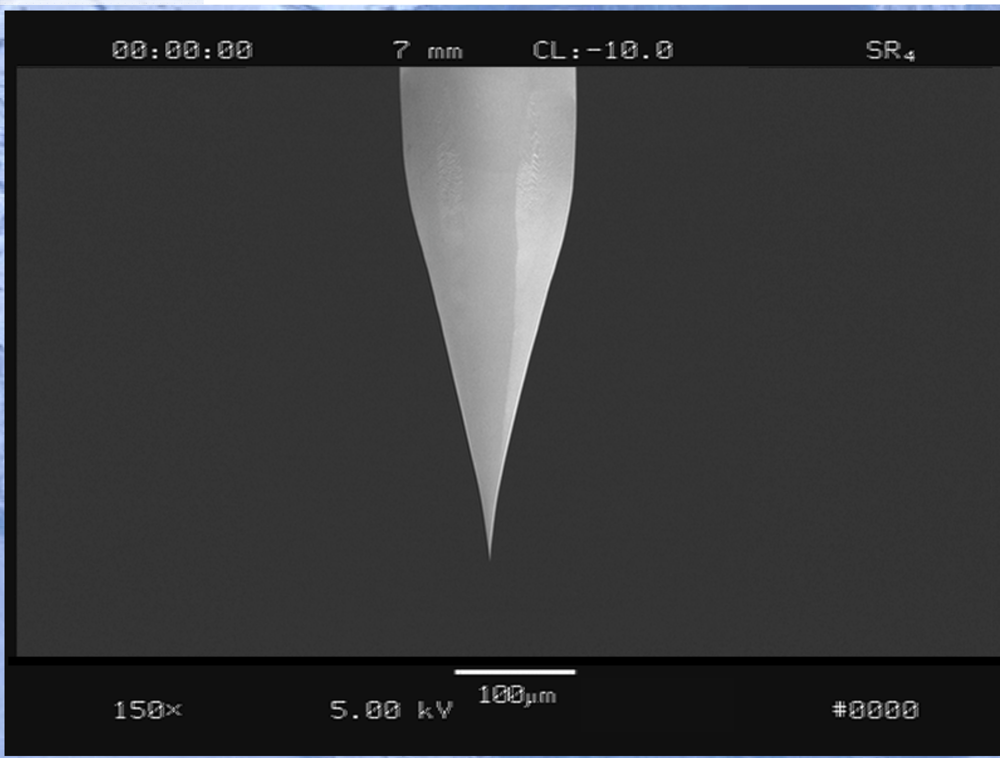

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Unsharpened ALIS Helium Ion Source – The Field Ion Microscope (FIM) Image

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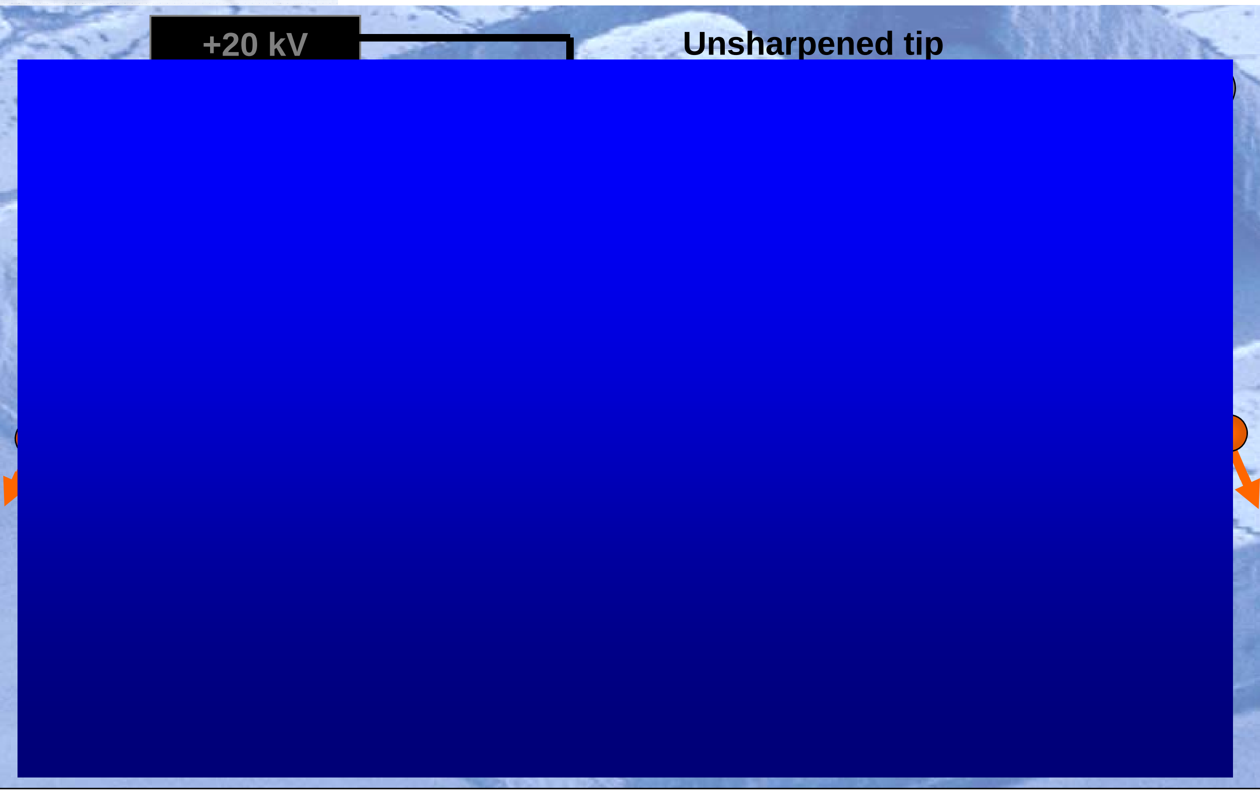

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Final ALIS Helium Ion Source – A Trimer, or 3 Atom Cluster - The Field Ion Microscope (FIM) Image

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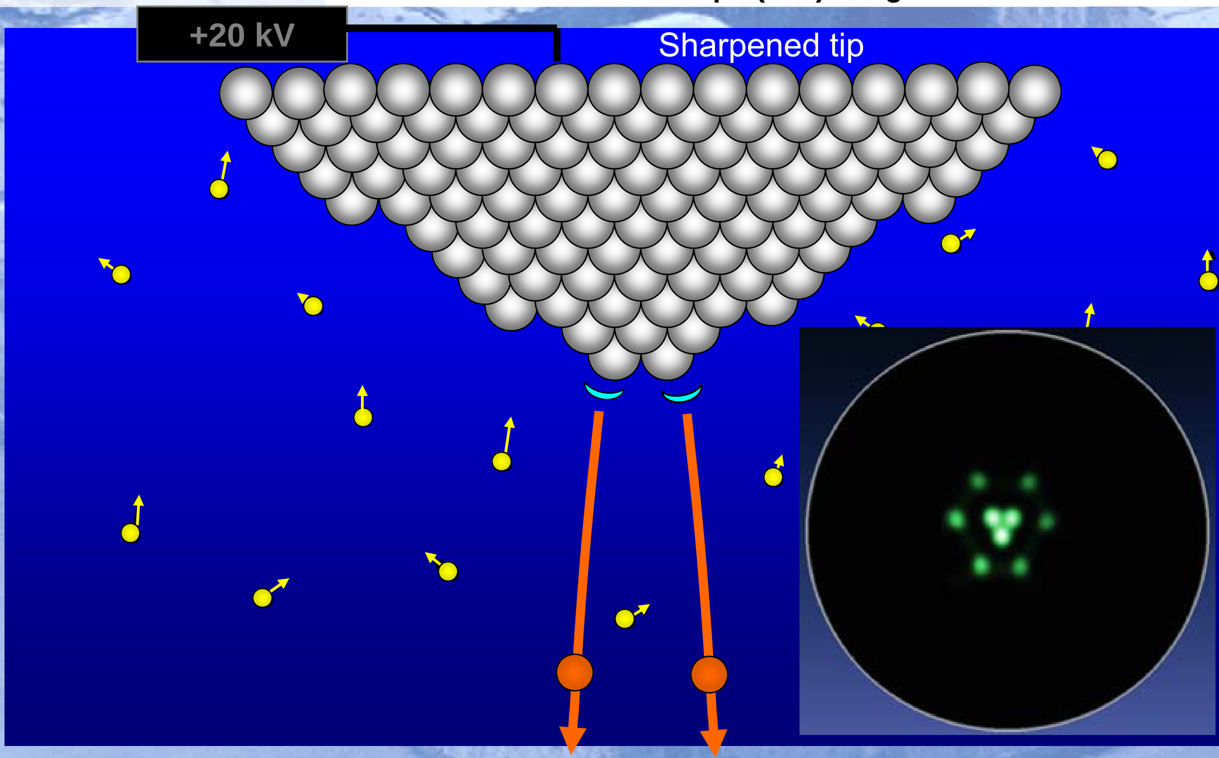

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The Field Ion Microscope- The beginning of the ALIS Ion Source

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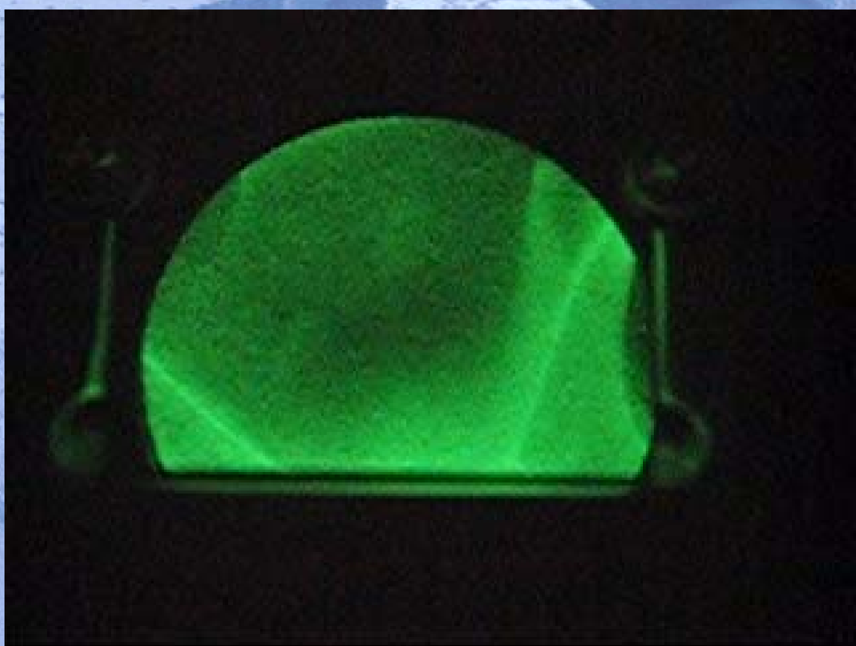

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The ALIS source fabrication process - one atomic shelf at a time

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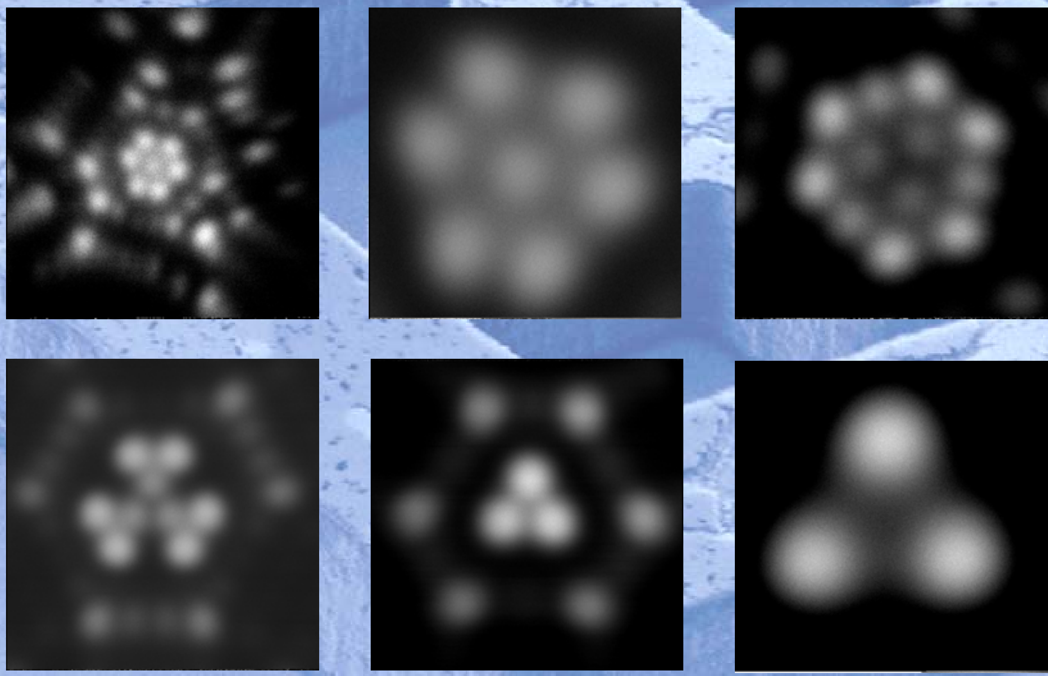

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ALIS Helium Ion Source Summarized

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- **High Brightness: > 10^9 A/(cm^2 sr)**
- **Small Virtual Source Size (Sub-Angstrom?)**
- **Low Energy Spread (~0.5 eV)**
- **Diffraction Effects - Reduced Compared to an SEM**
- **Inert Gas - Electrically Inactive in Sample**
- **Long Source Life and Source Stability**

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Calculated Orion Beam Diameter vs. Beam Current

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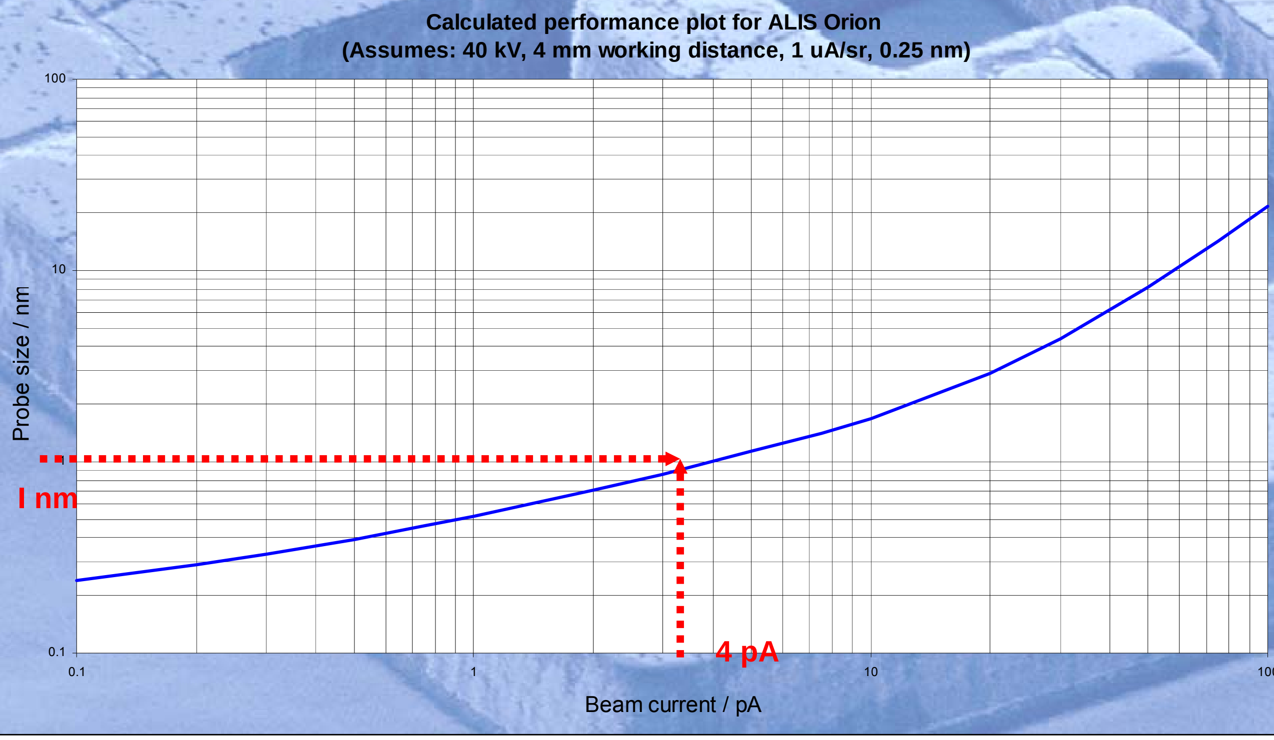

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ALIS SE Images: Long Depth of Field

Aluminum Crystals ~500um in depth

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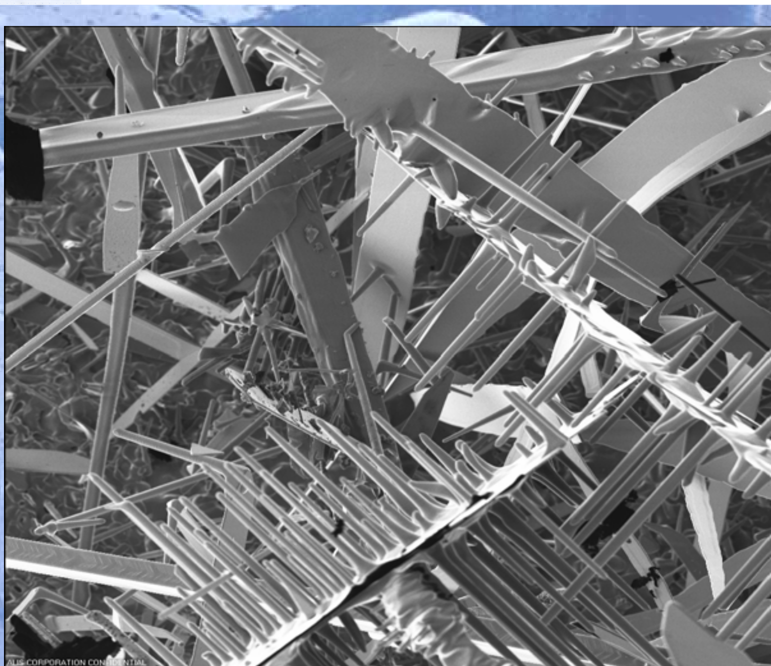

ALIS images have a long depth of focus.
About 5X better than SEM under the same conditions.

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Sample Interaction Volume- What limits the resolution of SEMs?

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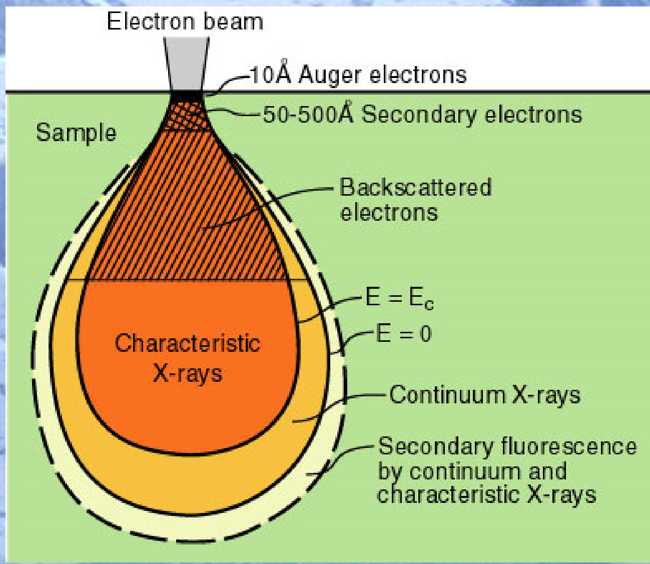
Secondary electrons:

Generated in a 50 to 500 Å region beneath the surface.

The spot size of the probe is not the limiting factor in resolution.



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Interaction Volume- The physics behind the resolution. (TRIM & Casino Modelling)

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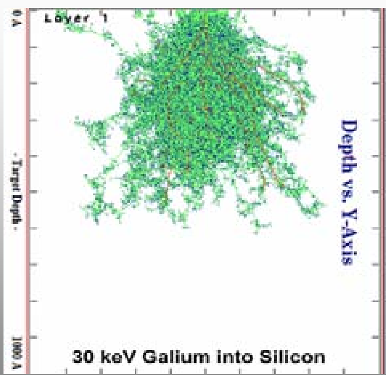
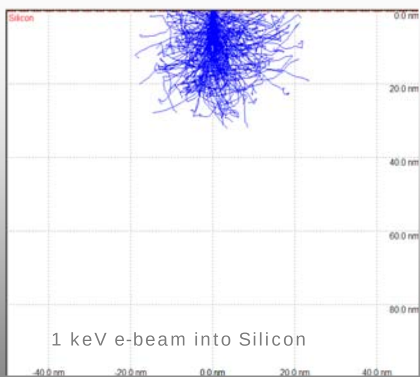
Gallium FIB



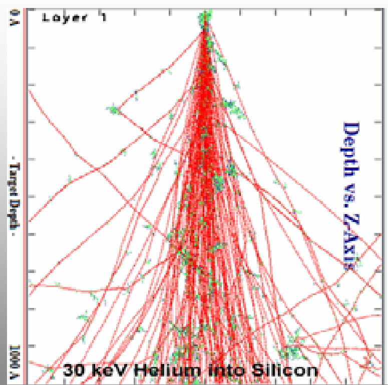
30 keV Gallium into Silicon: Image suffers from large interaction volume at the surface. Many SE's generated from recoils (green and blue).

Standard SEM



1 keV e-beam into Silicon: Image suffers from large interaction volume at the surface. Many SE's are really SE2.

Helium Ion Microscope



30 keV Helium into Silicon: Beam is well collimated beyond the SE escape depth. Recoil contribution is negligible.

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Orion Advantage – Highest Resolution in Secondary Electron (SE) Mode

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– Resolution < 1nm possible because:

- High Source Brightness: > 10^9 A/(cm^2 sr)
- Small Virtual Source Size (Sub-Angstrom)
- Low Energy Spread (~0.5 eV)
- No real contribution from diffraction aberrations ~
  - He ion wavelength 1/100th the e^- wavelength for comparable energies
- Extremely localized SE launch location due to low interaction volume
  - SE's have very low energy and short range in the sample
- Large Depth of Field

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Particles Ejected by He^+ & Their Implication to the User

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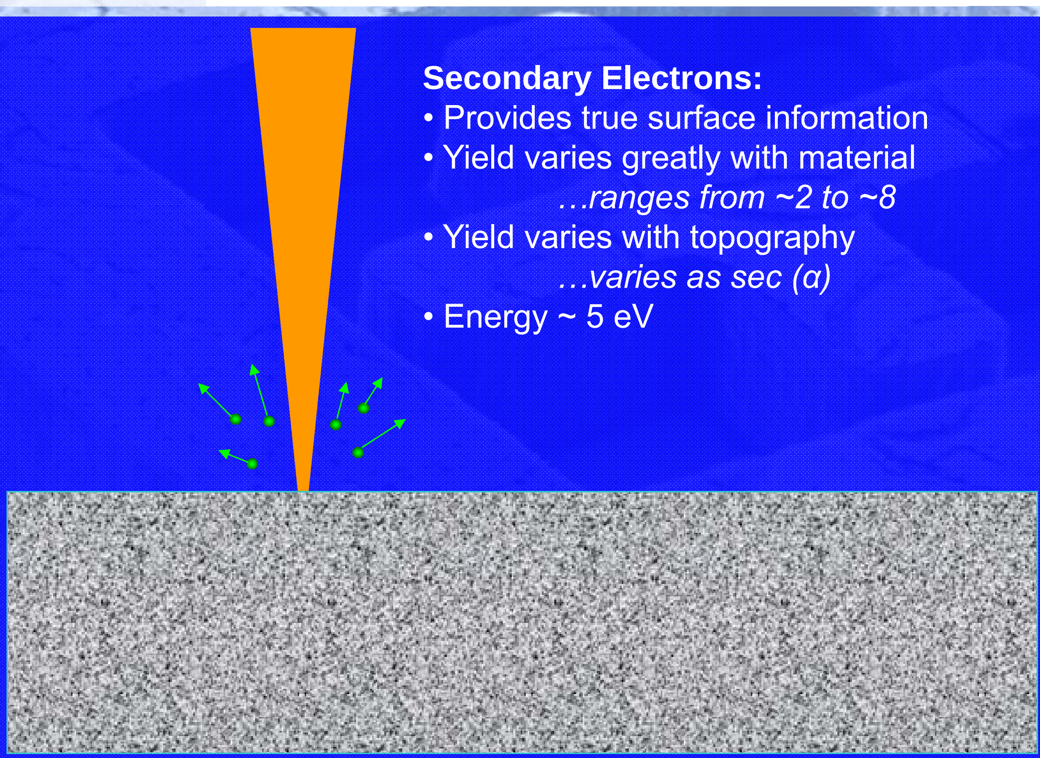
- **Secondary Electrons Imaging Mode (2 - 8 e^- per He^+);**
  - SE Video (gray) Level Contains Some Material Information
  - SE Voltage contrast mechanisms can contribute to image information
  - Prominent surface & topographical contrast
- **Back Scattered Helium Ions (1 per 100 He+, as He & He^+);**
  - RBI Rutherford backscatter (RBS) mode
  - Contains considerable material information
- **Sputtered Target Atoms;**
  - (~.02 per He+ for Silicon), 1/100th sputtered rate of 30 keV Ga
  - Long image times w/ little or no loss of material
  - No electrically active implantation
  - No fogged or washed out sample image
  - No change in electrical properties of the sample
- **Photons**
  - (~1 per 100 He^+);
  - Interesting Application as some organic and dielectric materials are translucent to photons
- **X-Rays (?)**
  - Uncharted region for exploration

ALIS Imaging Mode - SE



Secondary Electrons:
- Provides true surface information
- Yield varies greatly with material
  …ranges from ~2 to ~8
- Yield varies with topography
  …varies as sec (α)
- Energy ~ 5 eV

ALIS SE Characterization

Material	Z	M(amu)	Y_{SE} (E_{He} = 20 keV, α_{He} = 0)
Aluminum	13	27.0	5.31
Silicon	14	28.1	3.38
Titanium	22	47.9	4.65
Iron	26	55.8	4.55
Nickel	28	58.7	5.14
Copper	29	63.4	4.23
Indium	49	114.8	5.69
Tungsten	74	183.8	3.69
Rhenium	75	186.2	3.61
Platinum	78	195.1	8.85
Gold	79	197.0	5.17
Lead	82	207.2	5.57

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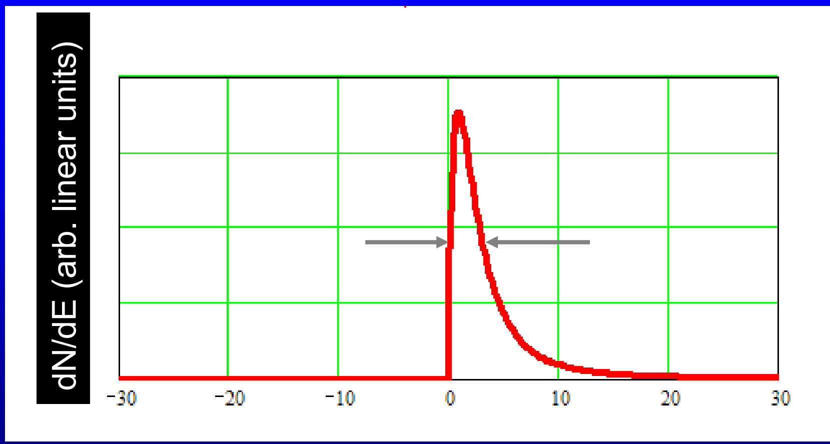
ALIS SE Characterization – No High Energy Backscattered Electrons



FWHM of dN/dE for a typical metal - ranges from 3 to 8 eV
Result – No high energy electrons to blur e^- resolution

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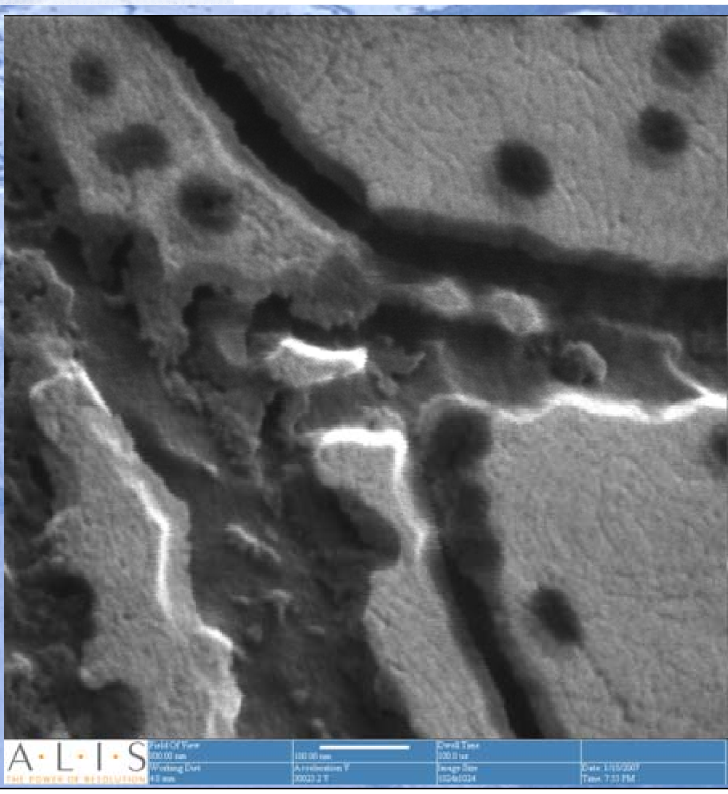
ALIS SE Image: Surface of Material and Topography Contributions



ALIS images offer rich surface information.

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ALIS SE image: Gold on carbon

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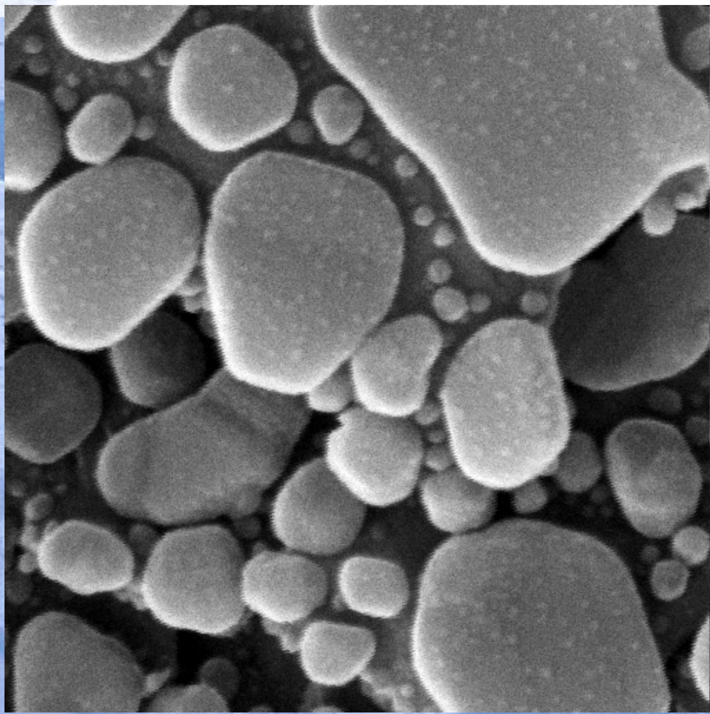

Gold condensate on carbon: 1 um FOV.

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Carbon Nanotubes
(Provided by Prof. Brendan Griffin Univ. W. Australia)

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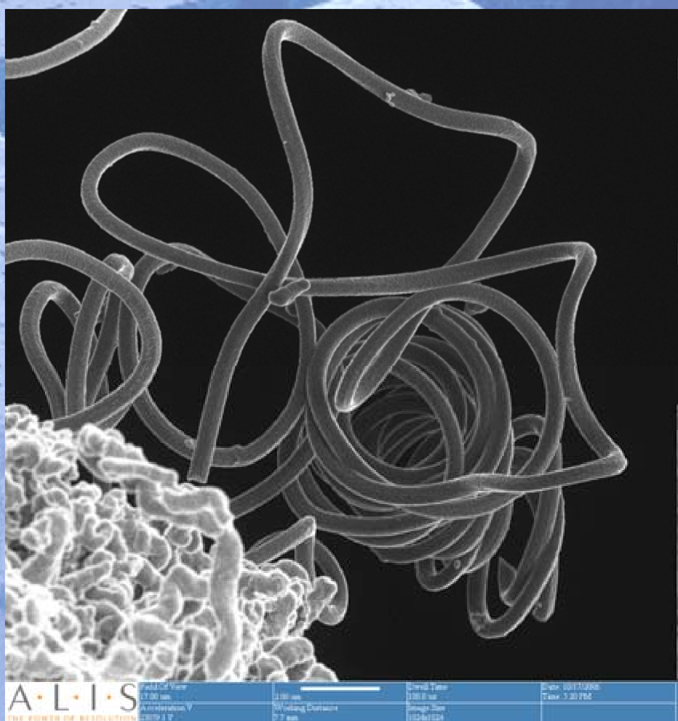

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Carbon Nanotubes
(Provided by Prof. Brendan Griffin Univ. W. Australia)

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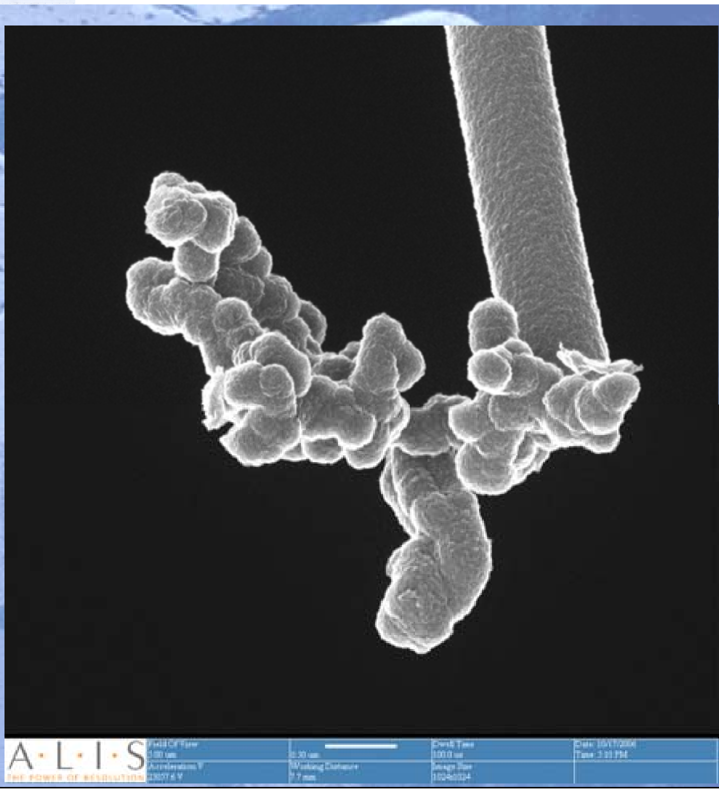

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Carbon Nanotubes
(Provided by Prof. Brendan Griffin Univ. W. Australia)

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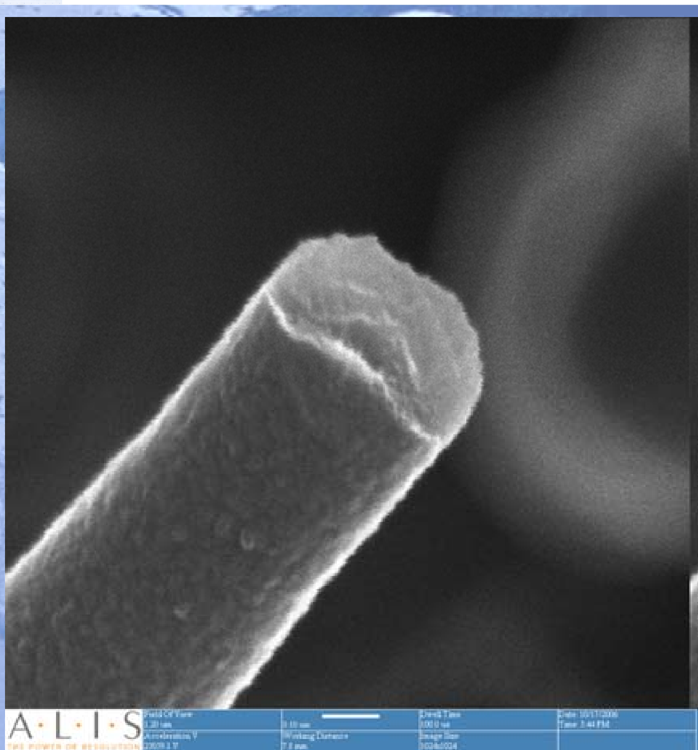

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ALIS Imaging Mode - BSI

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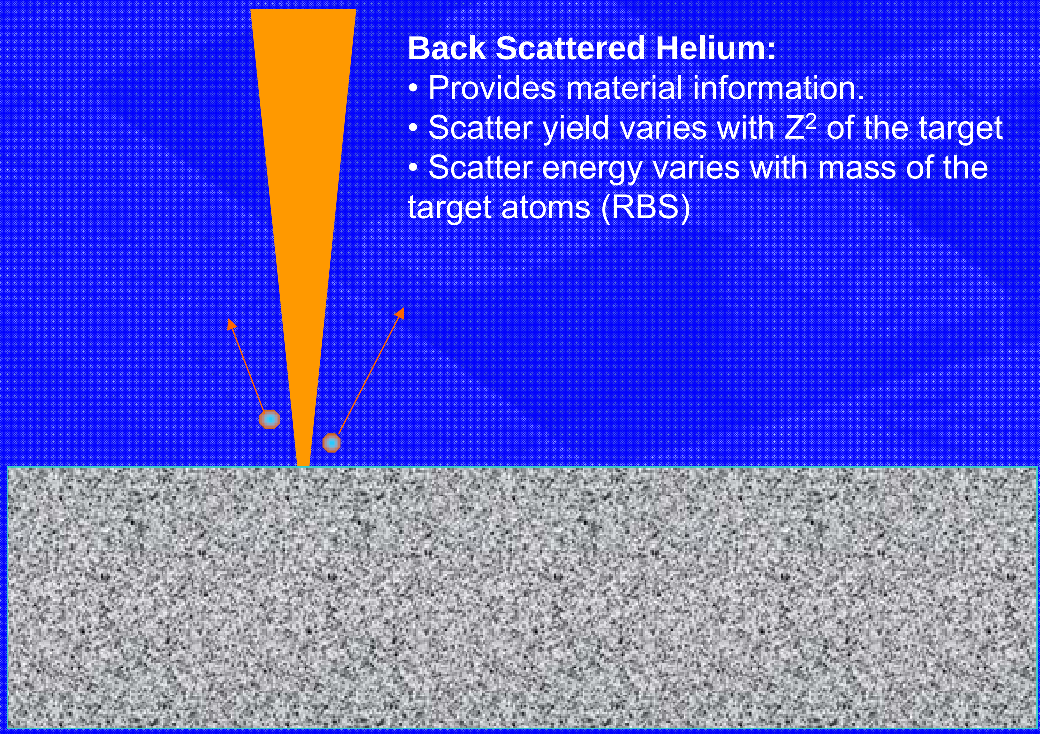
Back Scattered Helium:
- Provides material information.
- Scatter yield varies with Z^2 of the target
- Scatter energy varies with mass of the target atoms (RBS)



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RBS Geometry:

Recall Rutherford's Experiment, Alphas (He+) on Gold Film

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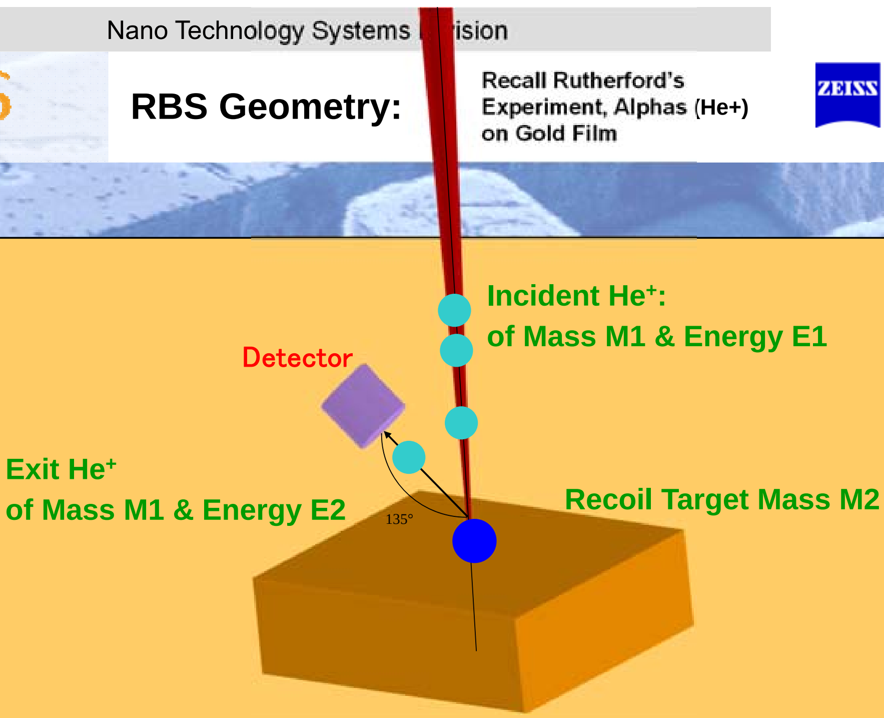

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An RBS Image Gray Level is Material Dependent

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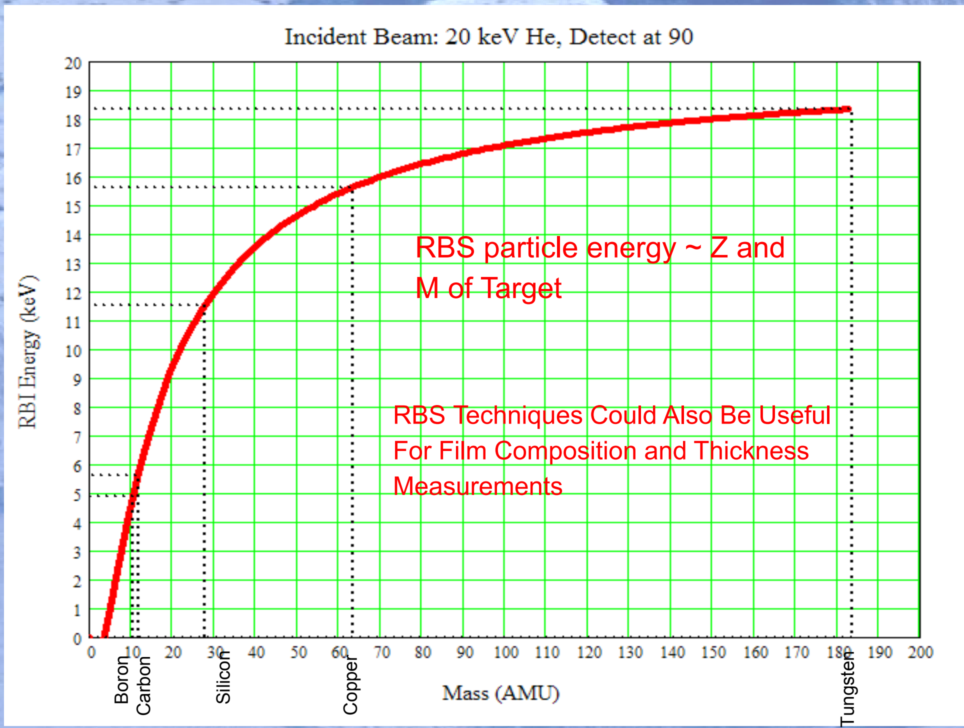

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ALIS SE vs. Backscattered Ion Images: Ablated Copper Over SiO2

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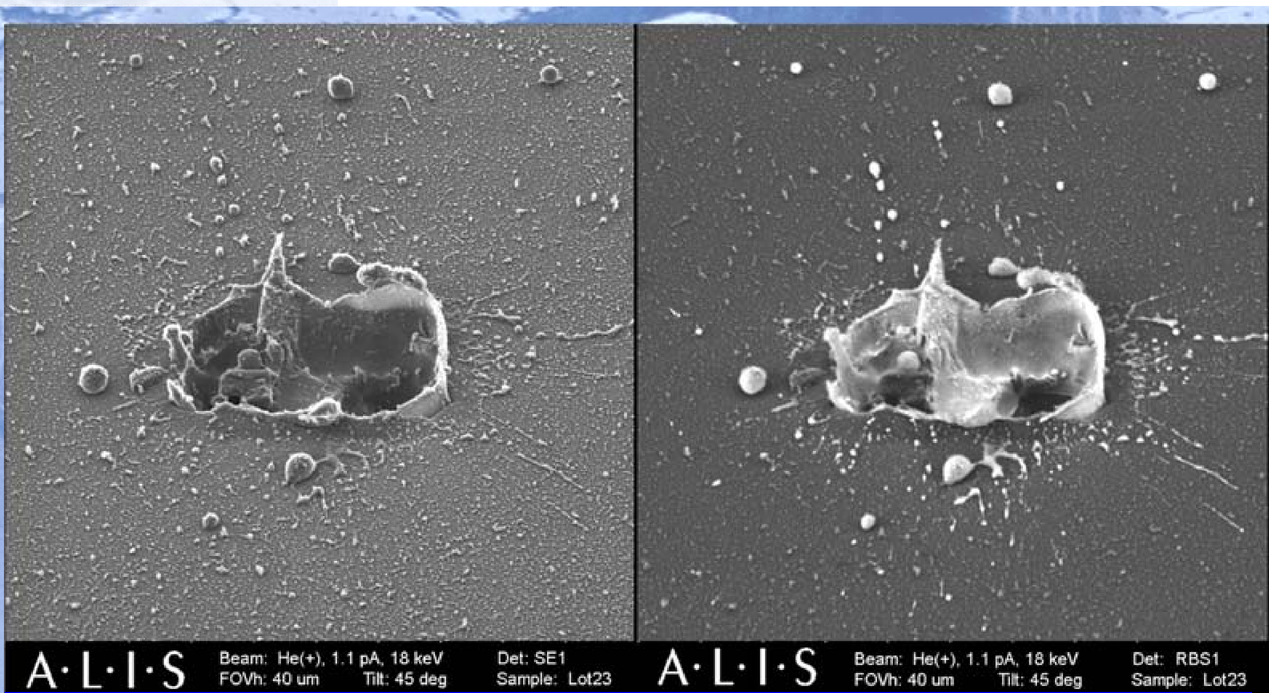

The SE image (left) shows great topographic information. The RBI Image (right) clearly differentiates the two materials.

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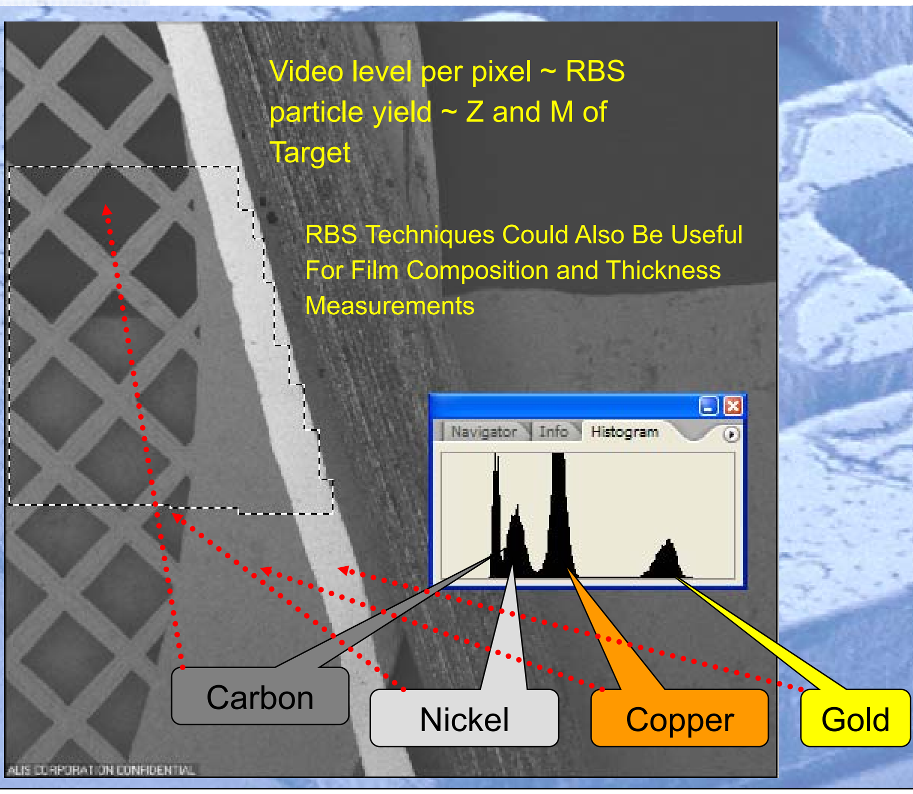
ALIS Back Scattered Ion Images Contain Material Information



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Summary of Important Detected He+ RBS Dependences

- Detected Count Rate Generally Increases with Target Atomic Number, Z_2
  - There are some shell closure (Screened Rutherford) effects
- Detected Count Rate Increases with Decreasing Energy, E
- Detected Count Rate Decreases with Increasing Detector Angle, θ
- Detected Particle Energy Increases with Target Mass, M_2
- Detected Count Rate ~ Video Level
- With Secondary Ion Count Rate Information, as well as Energy & Angle Information, Accurate Material Identification of Small Particles Seems Possible

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Orion Advantage – Ion Imaging & RBS Mode Materials Analysis Possible

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– Rutherford Backscattering Permits:
  - Materials analysis from the video gray level
  - RBS energy spectra & angular distributions may be able to uniquely determine small defects composition
  - As well as thin film compositions

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ALIS RBI Images: No Charging Artifacts even on Uncoated Biological Samples

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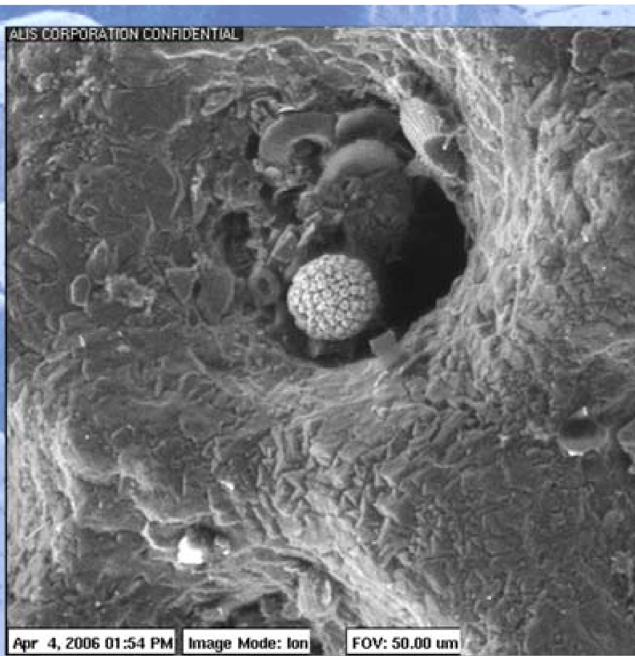

RBI images show no signs of charging on insulating materials. Sample is Uncoated Benthic Foraminifera courtesy of WHOI.

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He+ Image of Photomask: (Impossible by SEM)

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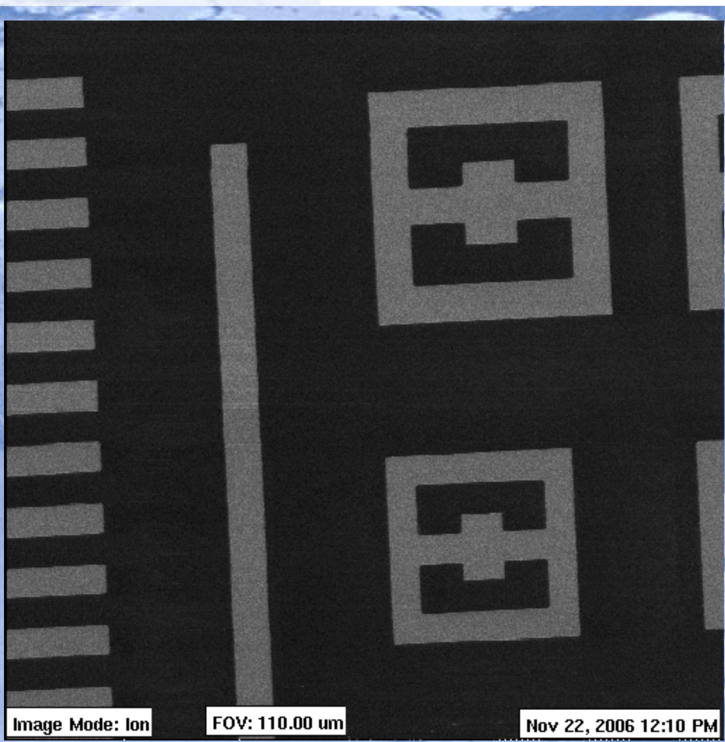

He+

Sample:
Chrome on Quartz Mask
Field of view:
~ 110 μm
Pixels:
512 x 512
Comment:
No charging artifacts are seen between the dark material (quartz) and the light material (chrome). This image could not be obtained using a SEM. Scattered helium was used for generating this image.

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Orion Advantage – In RBI (Ion Mode) Lost SE's & Charging Not as Big a Problem

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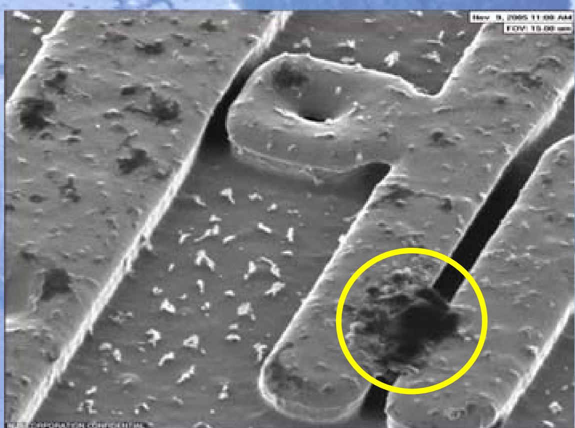
- Because ions escape easily from ++ charged surface:
  - –Less sample charging effects in the RBI images
  - –Flood electron imaging a real option (There are no good ion flood guns and SEM energies must be tuned)

Comparison: ALIS SE vs. SEM

ALIS SE Images: Contain Material Surface and Topography Information

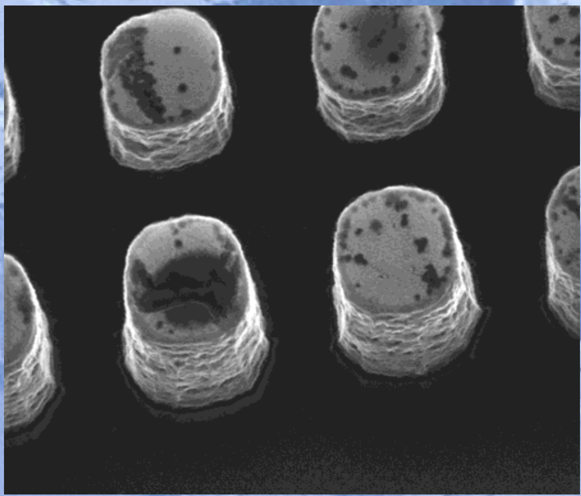


The ALIS SE image (left) shows strong material contrast.

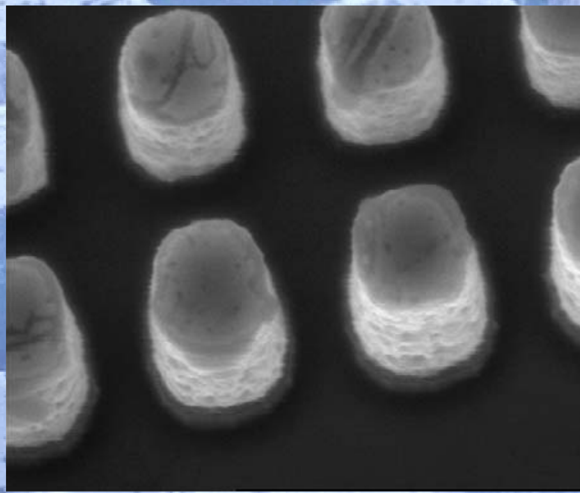
The traditional SEM image (right) appears "washed out", and blurred due to SE2 contribution.

ALIS SE Images: Contain Material Surface and Topography Information

Al posts on Si: 3 um FOV

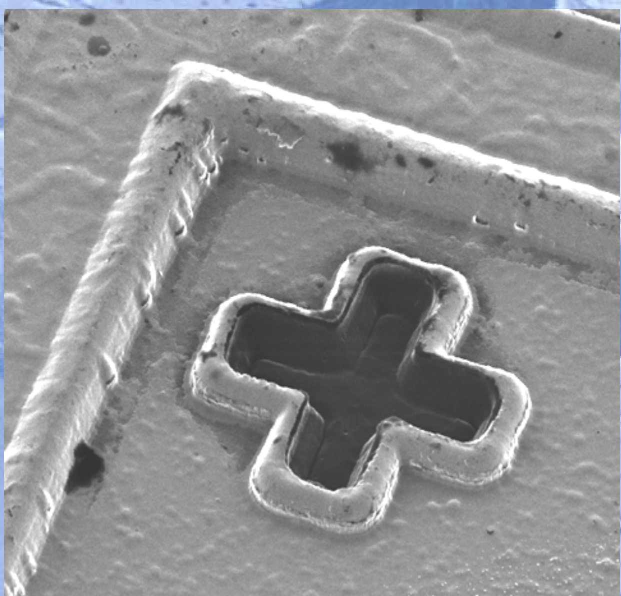


ALIS SE Image

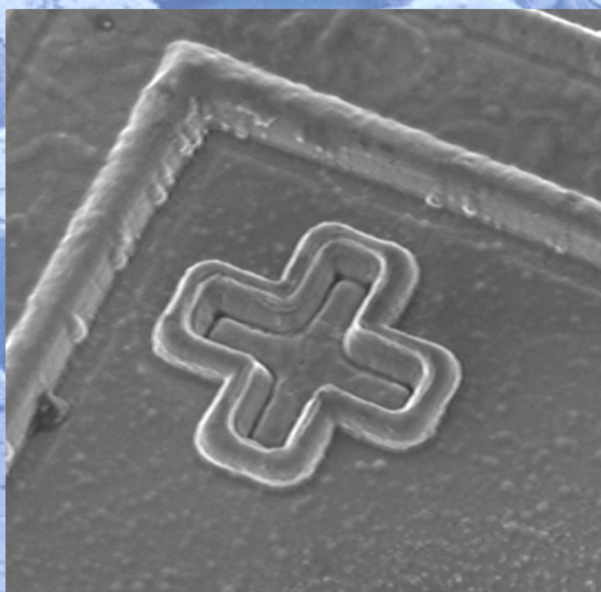


SEM Image

ALIS SE Images: Contain Material Surface and Topography Information



The ALIS SE image (left) shows a wider range of material contrasts.



The image form the traditional SEM shows very limited grey scale range.

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Comparison of He+ microscopy *vs.* SEM: Gold on Carbon

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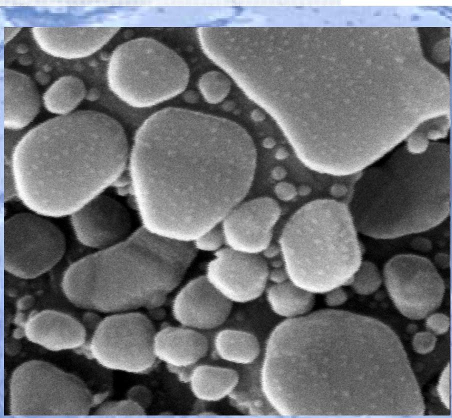
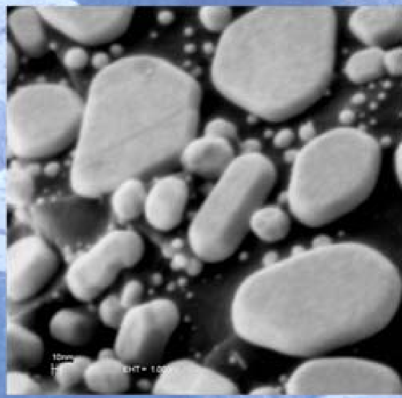


He$^+$

Sample:
Gold on Carbon
Field of view:
1000 nm
Beam current:
He+ 1 pA
Dwell time:
100 µs
Pixels:
512 x 512



SEM

Sample:
Gold on Carbon
Field of view:
1000 nm
Beam:
Electrons, 1 kV

Resolution capability and surface sensitivity:

- High-energy He$^+$ (30 kV) provide more surface information than low-energy electrons (1 - 3 kV), with only the uppermost surface area contributing to the SE signal.

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Enhanced surface/sub-surface imaging

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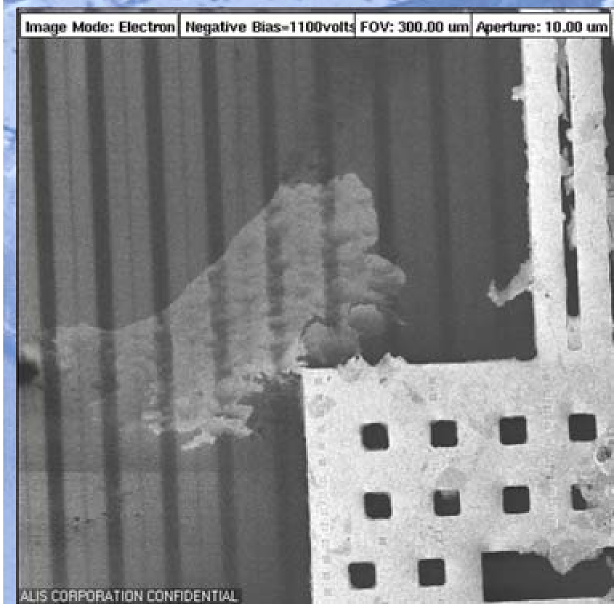
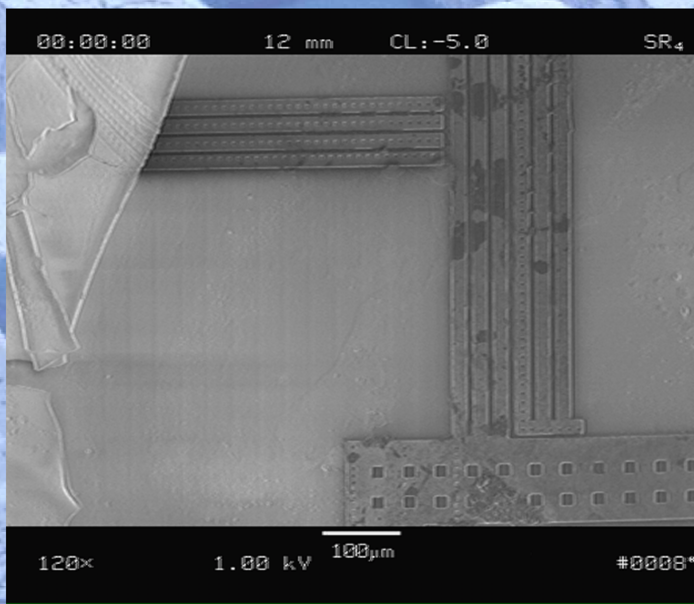
ALIS

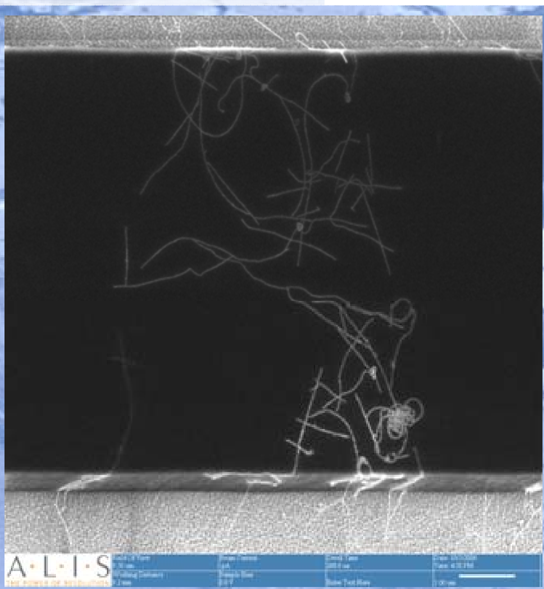


SEM 1keV

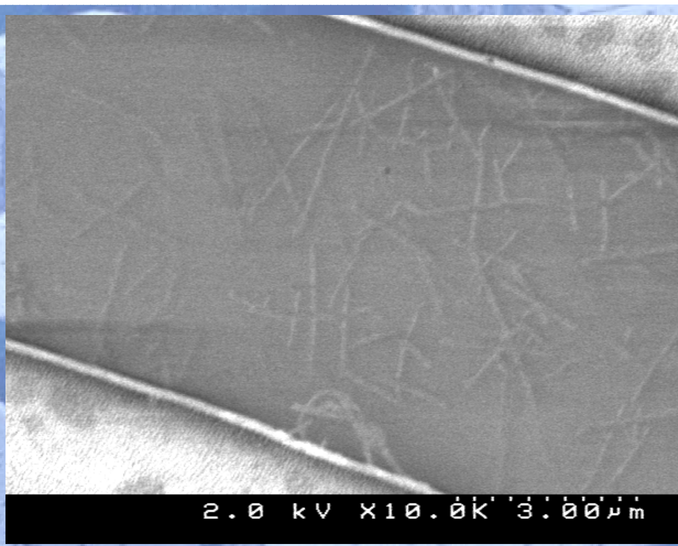


ALIS image reveals surface contamination not even visible in SEM

Comparison of He+ microscopy *vs.* SEM: CNT on Silicon



He+ image of nanotubes on silicon

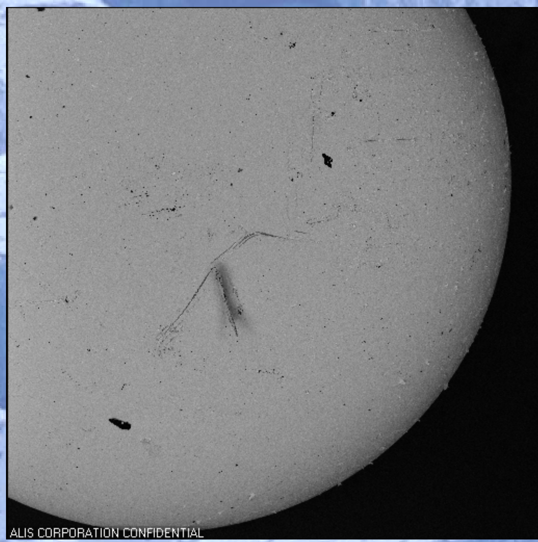


SEM image of nanotubes on silicon

High Contrast: He+ image (left) the carbon nanotubes clear.
Show high contrast.
SEM image (right) the carbon nanotubes are indistinct,
CNT's have little contrast relative to the background silicon.

RBS Line Scans May Improve Line Width Measurement Information

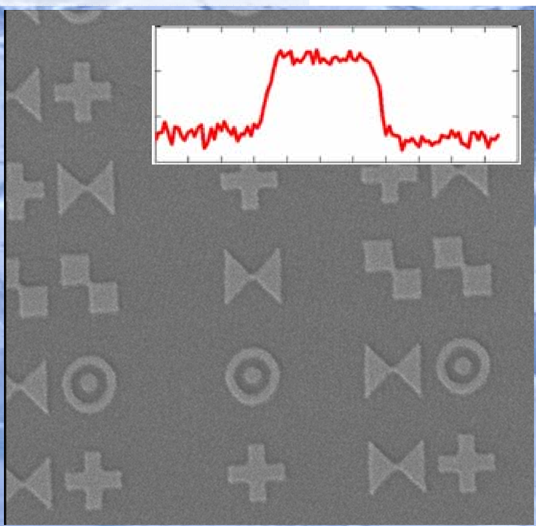
ALIS SE vs.RBI (Backscattered Ion Images) on Small Copper Beads



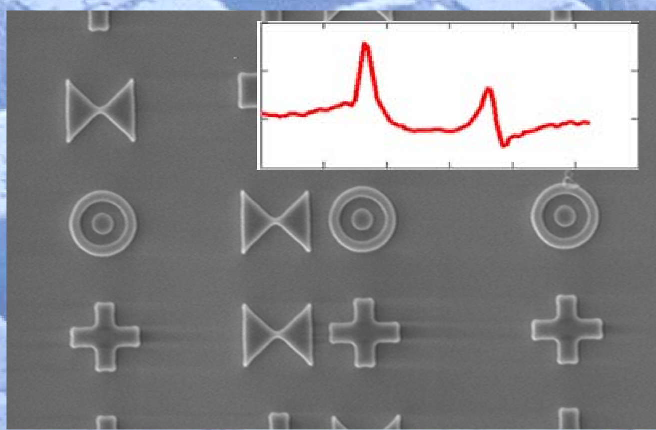
SE image shows topographic information that dominates over the material information.

With a proper selection of detector, the RBI Image shows little if any topographic information, so the material information dominates.

Edge Profile: ALIS vs. SEM



He+ Image



SEM Image

Reduced Edge Blooming:
The helium ion microscope can be configured to image with scattered helium. Under these circumstances, the topography is minimized and the image shows primarily material contrast. Thus edges are distinct transitions (left) without the edge blooming which can saturate the signal and obscure the edge location.

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He Ion Channeling
Another Contrast Mechanism

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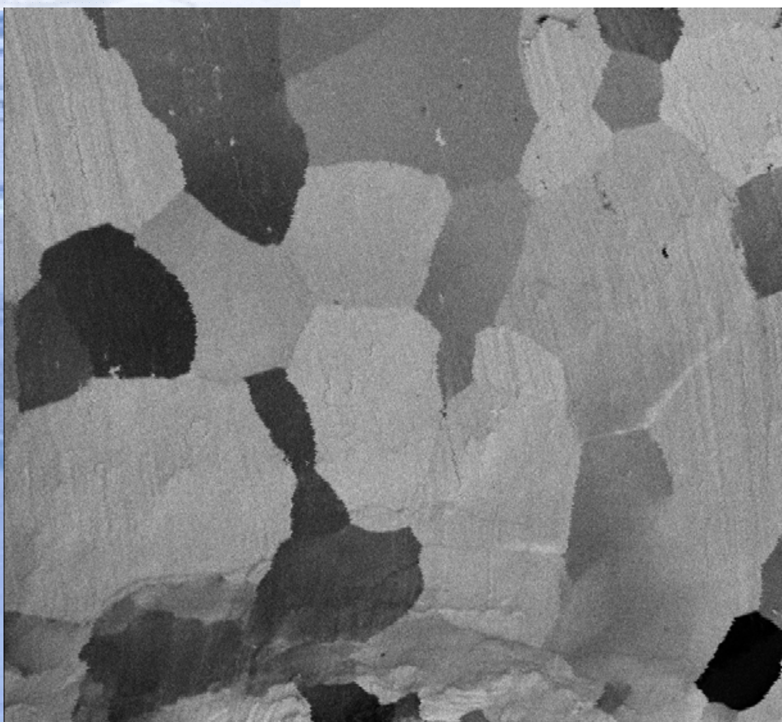
He+ crystallographic Images: Channeling contrast



He+ image of the grain size of a weld

Sample:
Tungsten Weld
Field of view:
~ 100 µm
Pixels:
1024 x 1024
Comment:
In grains where the atoms are aligned parallel to the beam, the grain is dark.
In grains where the atoms are not aligned parallel to the beam, the grain is bright.
Potential: Further crystallographic information, like EBSD Kikuchi patterns may also be possible.

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Orion Advantage – Enhanced Surface & Surface Film Imaging in Secondary Electron (SE) Mode

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– Enhanced sensitivity to surface films because of:

- Large depth of He+ penetration
  – He+ induced SE's launch primarily from the surface
  – No high energy electron backscatter
- Extremely localized SE launch location
  – Vs large primary electron interaction volume in high resolution SEMs

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ALIS Imaging Modes - Photon?

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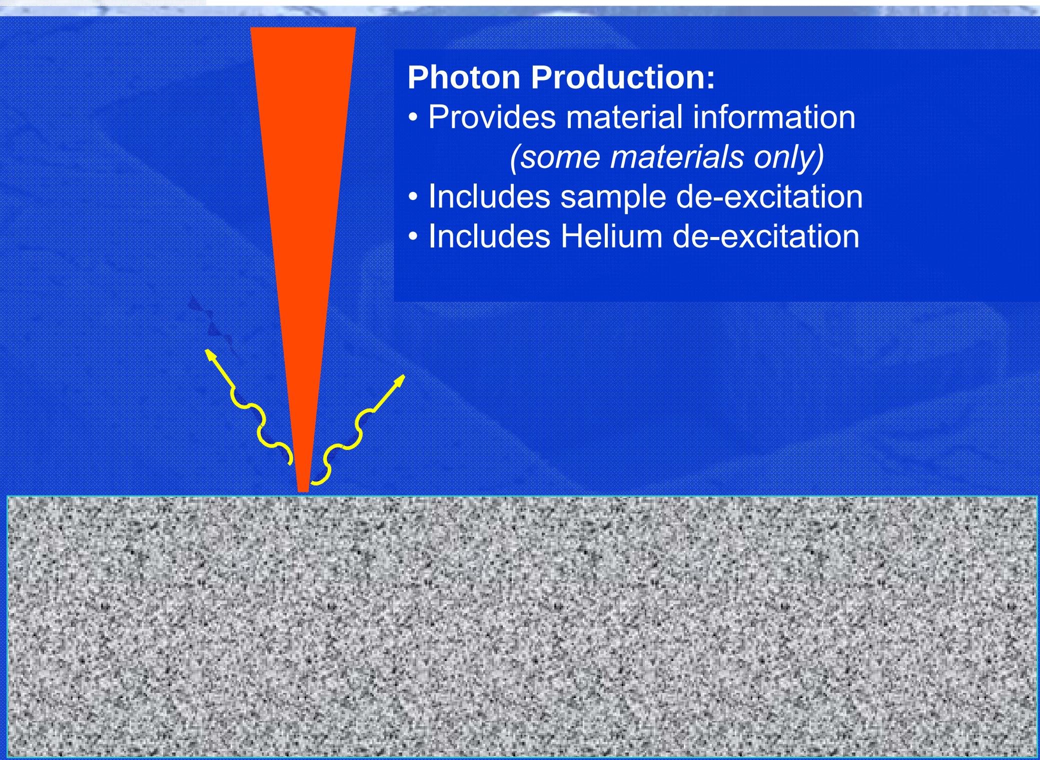

Photon Production:
- Provides material information *(some materials only)*
- Includes sample de-excitation
- Includes Helium de-excitation

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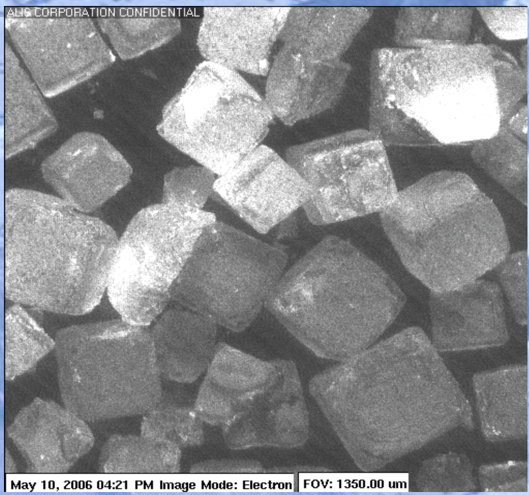
He+ Images from photons: NaCl



He+ photon image of table salt

Sample:
NaCl (table salt)
Field of view:
~ 1300 μm
Detector:
photons only
Comment:
The signal in this case is generated from photons generated from the helium beam. The photons are partly from sample de-excitation, and partly from helium de-excitation.

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The Orion He-Ion Microscope

- **Helium Ion Microscope Advantages**
  - Ultimate Spot size: d_{50} = 1/4 nm
    - High Brightness: > 3.4×10^9 A/(cm^2 sr)
    - Small Virtual Source Size (Sub-Angstrom)
    - Reduced Diffraction Effects compared to SEM
    - Low energy spread (~1/2 eV)
  - Long Source Lifetime and Stability
  - Small sample interaction volume
  - Image Information:
    - Topographic information
    - Material information
    - Voltage Contrast Information
    - Crystallographic information
    - Minimized charging artifacts
    - Good S/N with low beam currents.
    - Long depth of field
    - Images from electrons, ions and photons available
  - Analytical Information:
    - From RBS ions' Yield, Energy, and Angle
  - Many Applications Completely Unexplored

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Product Specifications

Overview

• Application	General Microscopy
• Ultra-High Resolution (Goal)	0.25nm
• Ultra-High Contrast	Material/Chemical/Crystallographic
• Multiple Imaging Modes	SE (Secondary Electron) RBI (Rutherford Backscattered Ions)

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Product Specifications

Resolution: Goal Currently Committed	0.25 nm @ 45 kV @ 4 mm WD 1.0 nm @ 40 kV @ 4 mm WD 3.0 nm @ 10 kV @ 4 mm WD
Magnification	100X – 1,000,000X
Field of View	1 mm – 100 nm
Sample Working Distance	4 mm – 15 mm
Source Type	He ion field emitter
Probe Size	≤1nm @ 1 pA
Accelerating Voltage Goal Committed	500 V – 45 kV 10 kV – 45 kV
Probe Current	1 fA – 25 pA
Charge Neutralization	Yes

Product Specifications

Standard Detector	Everhart-Thornley Detector
Multiple Detector Capable	Yes
Sample Size Range	Up to 50mm x 50mm
5-Axis Motorized Sample Stage	50mm x 50mm X-Y, 12mm Z 360° θ, +45° tilt , – 5° tilt
SIM Image Acquisition	Up to 8196 x 8196 pixels
SIM Image Displayed	Up To 2048 x 2048 pixels (1024 x 1024 viewable)
System Displays	Dual 1680 x 1050 TFT Displays
System CPUs	1 Standard, 2^{nd} Optional
System Control	Windows® XP Operating System Mouse, Keyboard, Control Panel Optional Gamepad Controller

Summary:
Orion He Ion Microscope Advantages

1	High resolution
2	Surface Sensitivity
3	Low Z (carbon) imaging ability
4	Large Depth of Field
5	Room for Future Hardware – New detectors etc.
6	Productivity – Stage can move fast
7	RBI Mode determines materials from video level
8	Particle & Thin Film Analysis in RBI Mode
9	Images n, p, n+ & p+ in Si trenches & cross sections
10	In RBI (ion) mode, less charging & e^- flood OK
11	Crystal grain orientation produces contrast variation
12	In RBI mode better CD measurement tools may be possible w/ He+
Others	No Ga Staining, No Electrical Invasiveness & No Edge Blooming as in SEM

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The End

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The END