NanoCourses 2004, Section 4

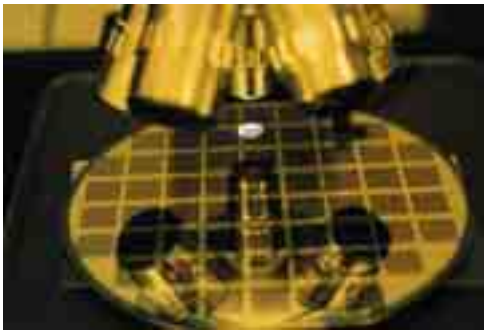
Practical Thin Film Analysis
What is It?

Introduction
by
Lynn Rathbun

Presented by the
***CNF* Technical Staff**
for the education of CNF Users,
Potential Users, and Industrial Sponsors

Why ?

- **Process Development**
- **In Process Monitoring**
- **Process Characterization / Maintenance**
- **Failure Analysis**



What Do We Need / Want to Know

- **Electrical**
  - Resistivity
  - Contact Resistance
  - Barrier Height
- **Chemical/Elemental**
  - Composition
  - Bonding
  - Valence
- **Physical**
  - Crystal Structure
  - Grain Size
  - Orientation
  - Texture
- **Mechanical**
  - Stress
  - Adhesion
  - Optical
- **Index of Refraction**
  - Reflectivity
  - Adsorption

Measurements and Techniques

- **Specialized Measurements**
- **Specialized Techniques**
- **Specialized Instruments**

- **Many Many Available**

Planning

- Design and Plan for Analysis and Characterization
- Don't analyze unless you expect to learn something
- Variety of Tools Available
  - Cornell
  - Outside

Microanalysis

- Analysis of small volumes
  - High spatial resolution in at least one dimension
- Not necessarily the same as, or compatible with trace element analysis

Particle in / Particle out

- "Excite" sample
  - Generally a localized small volume
- "Look" at stuff that comes out

- Ions (high or low E, various kinds)
- Electrons (high or low E)
- Photons (various energies)

- Reflected, scattered, re-emitted, etc.

Lots of Acronyms

- SEM
- EMPA
- AES
- SAM
- RBS
- SIMS
- ISS
- …..
- ……

The Process

- Measure something
- Calculate what we want from the something we measure
  - Model
    - Assumptions
    - Limitations

Cautions

- What you want to know *vs.* what you really measure
- What you measure *vs*. what you think you are measuring
- The authoritative "power" of computer generated / analyzed data
- Important that you understand SOMETHING about the analytical measurement

Rathbun's Laws of Analysis

If you ask the wrong question,
you will get the wrong answer.

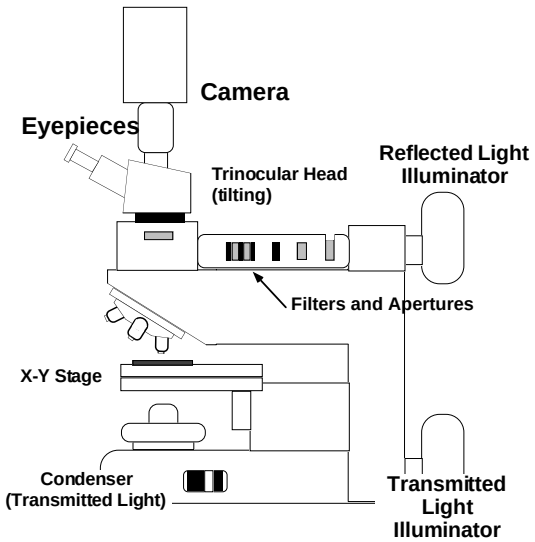
If you try to answer the right question
with the wrong technique,
you will also get the wrong answer.

Optical Microscopy

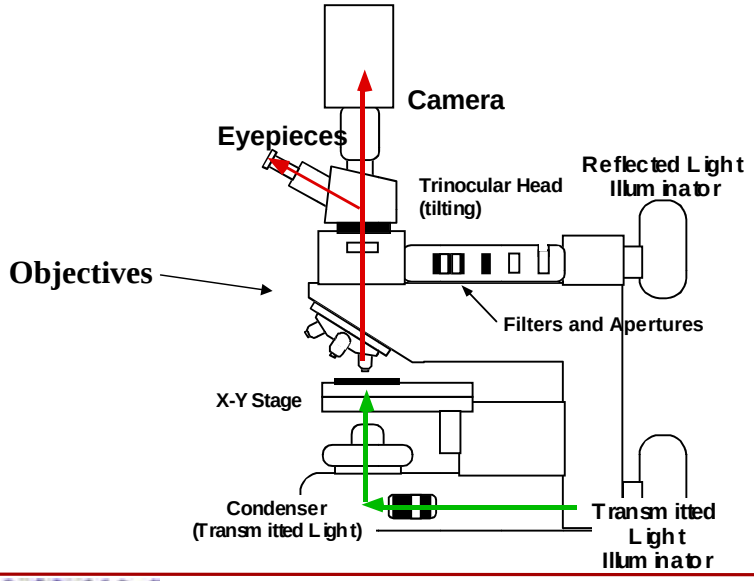
The Semiconductor Inspection Microscope

- It bears some relationship to the thing you used in high school biology…but not much
- Sophisticated optical / mechanical instrument
- Simple to use badly
- Somewhat more difficult to use correctly
- Few people in CNF ever use all its features

Inspection Microscope-Parts

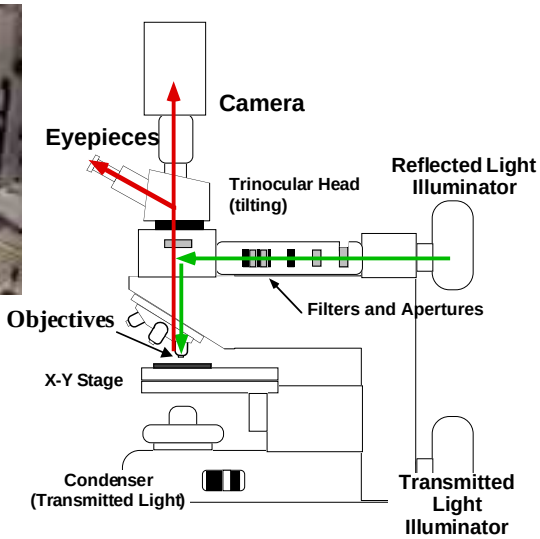


Transmitted Light



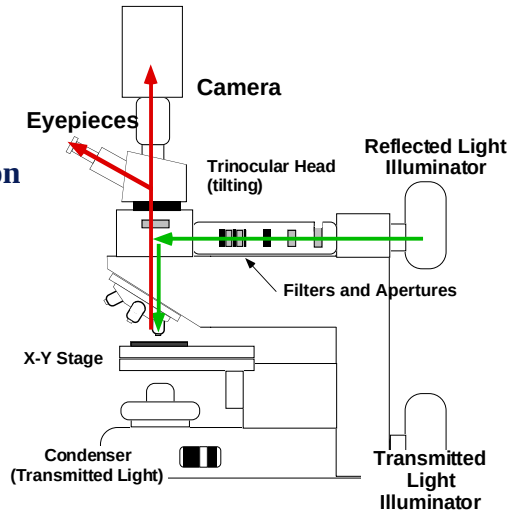
Reflected Light

Most Common



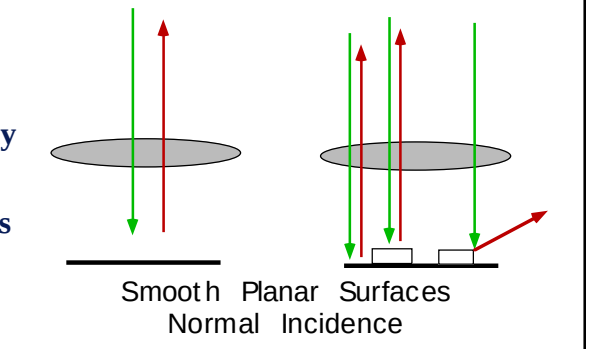
Magnification

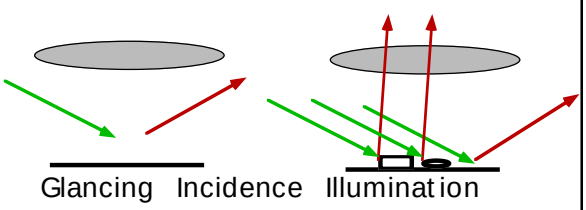
- Total Magnification Product of:
  - Objective (5x - 250 x)
  - Body (1x - 2x)
  - Eyepiece (10 x- 15 x)
    - Camera
- Magnification vs. Resolution
  - Useful magnification
  - Empty magnification
- Good Microscope
  - 1000X
- Great Microscope
  - 2500X



Light Scattering at Surface

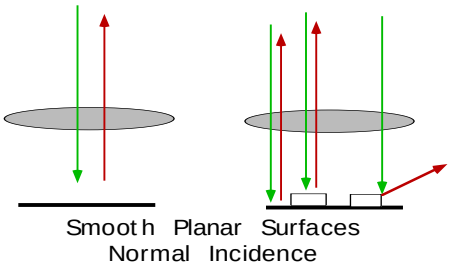
- Plane surface
  - Angle in = Angle out
- Edges reflect differently
- For glancing illumination, only edges will reflect up, perpendicular to the surface



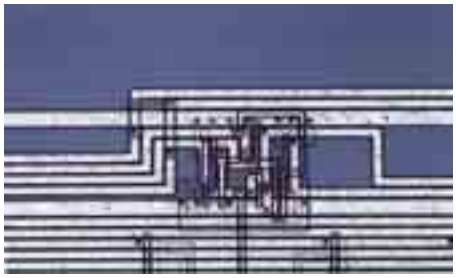


Bright Field

- Light incident more or less perpendicular
- Flat planar surfaces reflect well
  - Appear bright
- Edges and slopes reflect to the side and appear dark
- Most common mode for general use

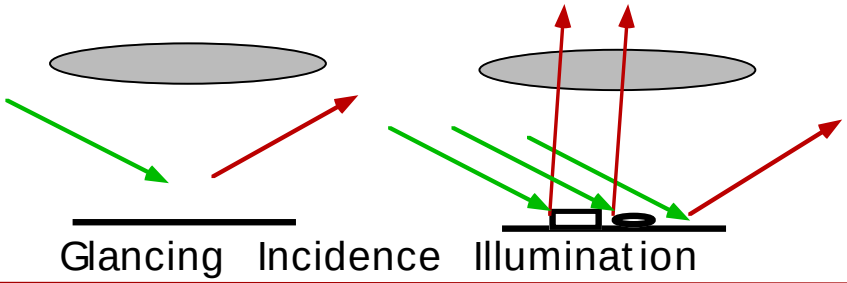


Bright Field, reflected light is the most common arrangement



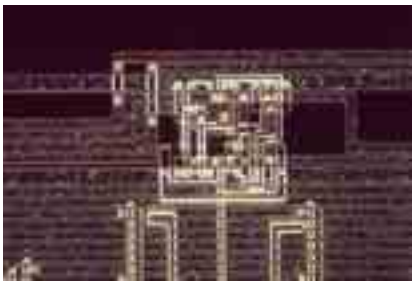
Dark Field

- Angular illumination
- Plane surface reflect away from lens
  - Most of sample is DARK
- Sharp edges will scatter some light into lens
  - Edges and dirt sparkles
  - Starry night

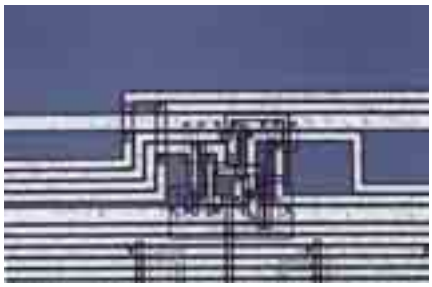


Dark Field vs. Bright Field

Dark Field



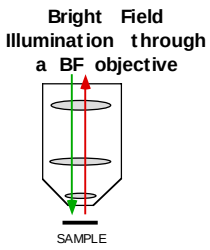
Bright Field

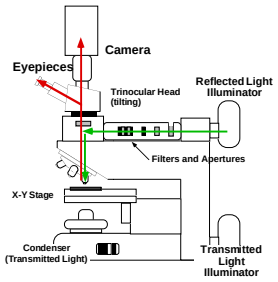


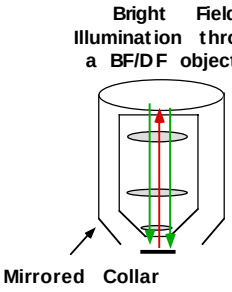
Dark Field-Defect Detection

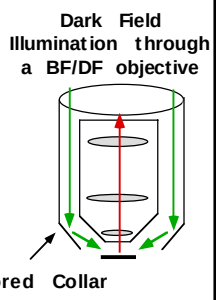
BF/DF Objectives

- How do we get the oblique illumination required for DF
- Combination BF/DF objective
  - Coaxial light paths
- A simple slider in the optical path directs light to the outside, oblique path



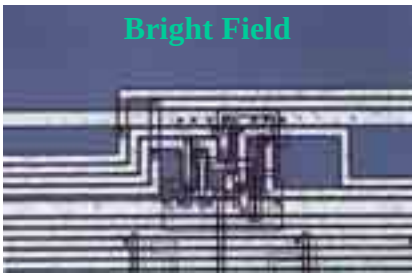


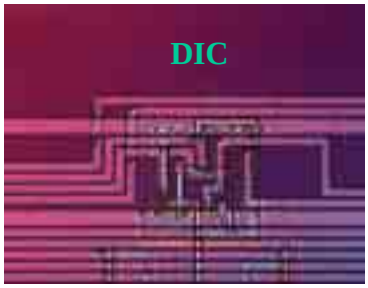




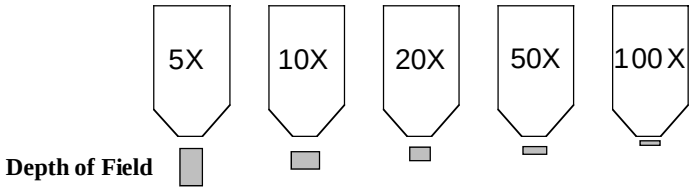
Other Imaging / Illumination Modes

- Polarized light
  - Optical index contrast
- Differential interference contrast
  - A false "depth" contrast achieved by interference
  - aka Nomarski
- About half of CNF scopes are set up for DIC / Polarized light

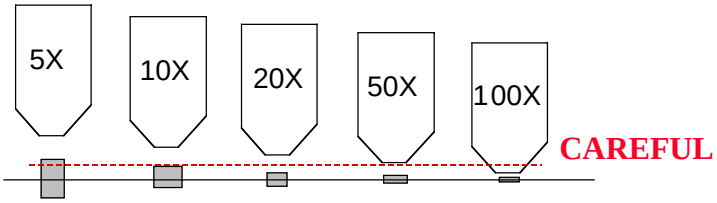




Depth of Field / Working Distance / Par-Focality



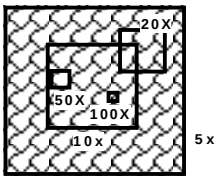
- High magnification objectives have small depth of field
- High magnification objectives have short working distance
- CNF microscopes are Par-focal

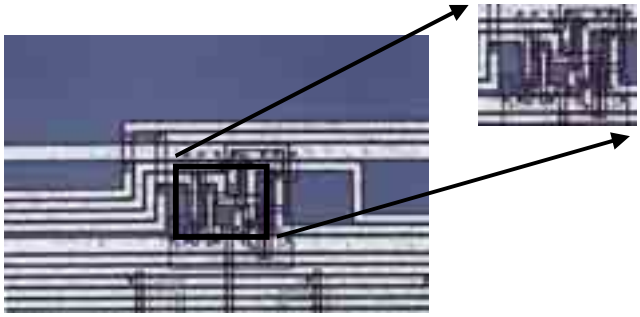


Par-Centricity

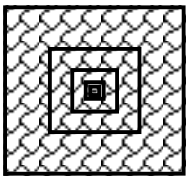
- You would like your sample image not to "move" as you zoom in
- Precision mechanical / optical adjustment
- Most CNF microscopes are par-centric

Non-Parcentric





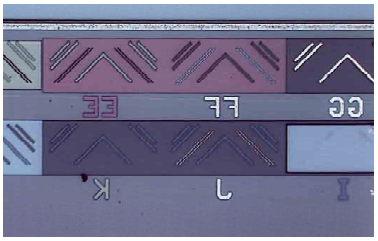
Par-centric



Upright and Bilaterally Correct

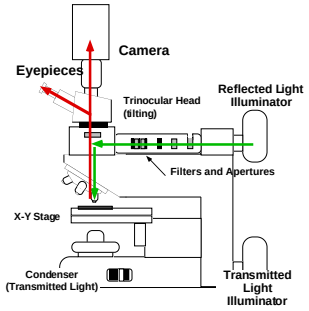
- Left is left
- Right is right
- Top is top
- Bottom is bottom
- Text is legible

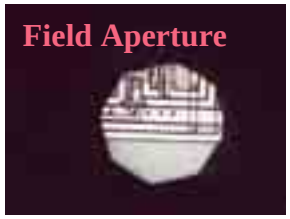
- All CNF microscopes give upright/erect images (I think)



Hints

- Use both eyes!!!!
  - Binocular eyepieces
- Eye is part of the optical instrument
  - Wear your glasses
  - High point eyepieces
  - Proper brightness/contrast
- Illumination aperture
  - Amount of light
- Field Aperture
  - Illuminated area



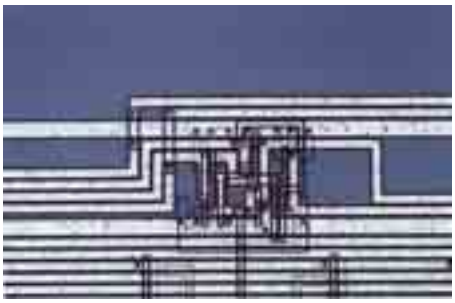


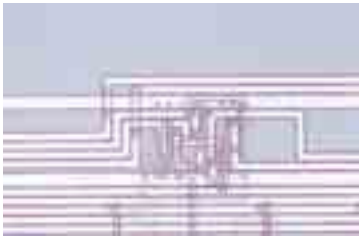
Confocal Microscopy

- Confocal microscopy uses optical "tricks" to create a very shallow depth of focus
  - Only features at a specific depth are imaged clearly
- Olympus BX50
  - High intensity light source required

The Good, the Bad and the Ugly

- Micrograph Options (SEM or Optical)
  - Film
  - Thermal Prints
    - Not publication quality
  - Digital files
- Most pictures I see:
  - Too Dark
  - Too Close
  - Bad contrast





Summary

- CNF has a very good stock of optical microscopes
  - Leitz Ergoluxs
  - Older Olympus scopes
  - Olympus MX50
  - Olympus BX series
    - confocal
- They are precision instruments
- They are expensive
  - $20,000 - $100,000
- Variety of imaging modes
  - Learn how to use

NanoCourses 2004, Section 4

Practical Thin Film Analysis
What is It?

Scanning Electron Microscopes (SEMs)
by
Daron Westly

Presented by the
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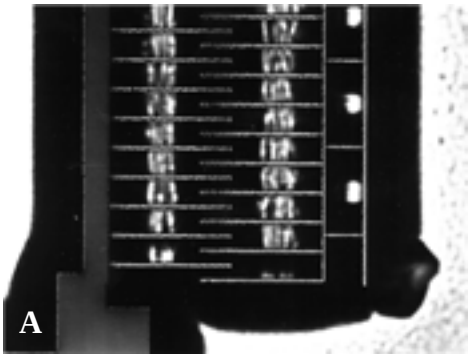
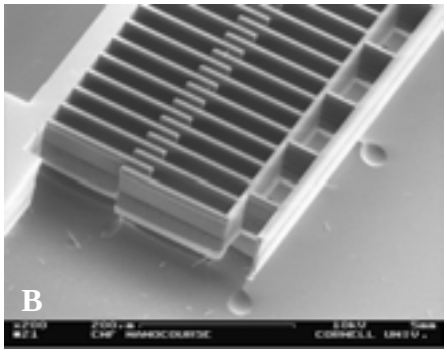
SEM vs. Light Optical Imaging

Superior Depth of Focus

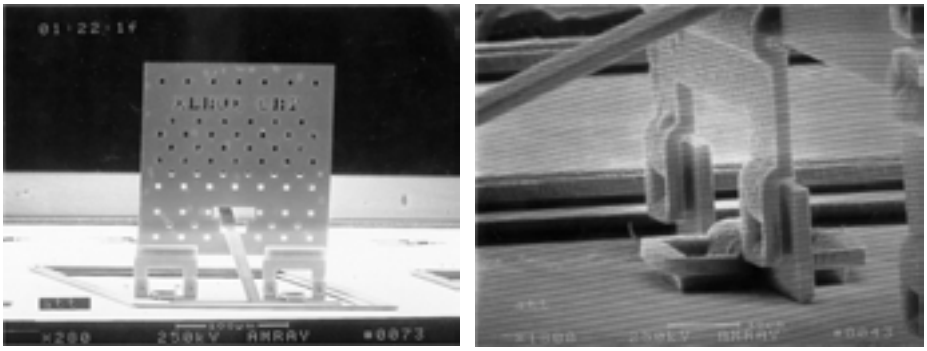




MEMS Comb Drive

Figure A: Optical **Figure B: SEM**

SEM: Superior Depth of Field



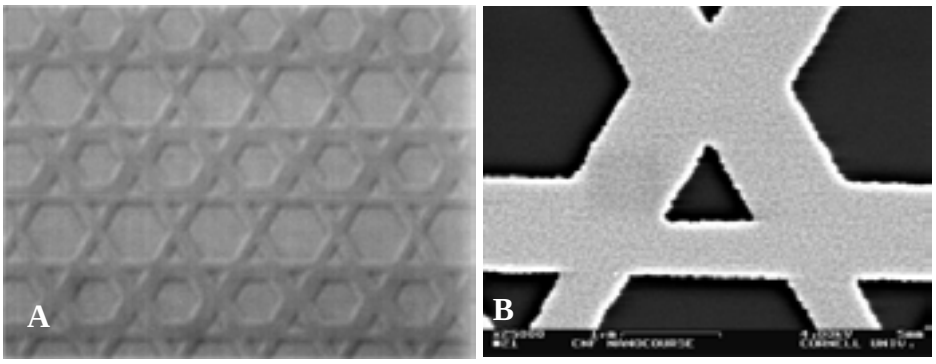
MEMs Mirror

by Alex Tran

Corporate Research & Technology, Xerox Corporation

SEM vs. Light Optical Imaging

Superior Resolution

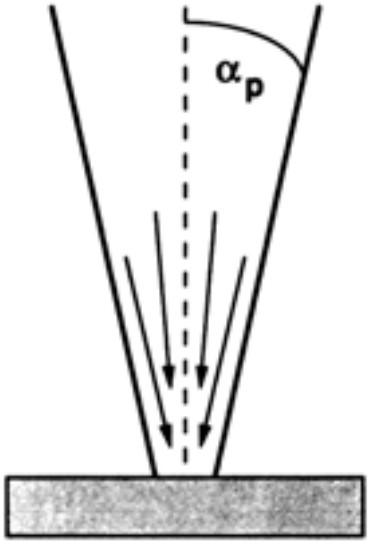


Kagome Superconductivity Structure

Figure A: Optical - 4600x **Figure B: SEM - 25,000x**

Depth of Field & Resolution

- Depth of field is dependent on the probe convergence angle:
  - SEM depth of field 1000X Light
- Resolving power scales with the of the illuminating radiation:
  - Light
    - λ = 433-633 nm
  - Electrons
    - λ = 0.009 nm (20keV)
- SEM Mags to 400,000X



Hitachi S-4700

LEO 982 SEM

SEM Imaging

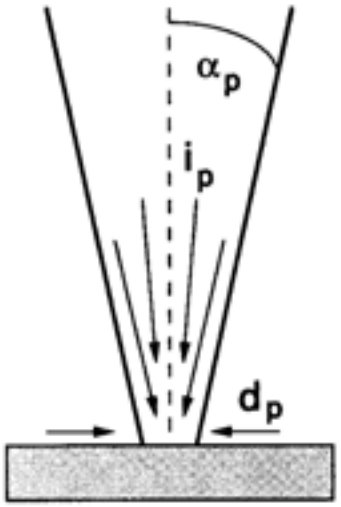
The goal of the instrument is to place a focused beam of primary electrons onto a sample, and to collect secondary electrons from the sample to form an image

Modes of Operation:

- **High Resolution:**
  - Small Probe Diameter → Low Probe Current (I_p) → Poor Signal / Noise (S/N) Ratio
  - Short Working Distance → Less Lens Aberrations
- **High Depth of Field:**
  - Long Working Distance → More Lens Aberrations
  - Small Aperture → Low I_p → Poor S/N
- **Microanalysis:**
  - High Probe Current → High I_p → Good S/N → Large Beam Diameter

Why Learn about Electron Optics?

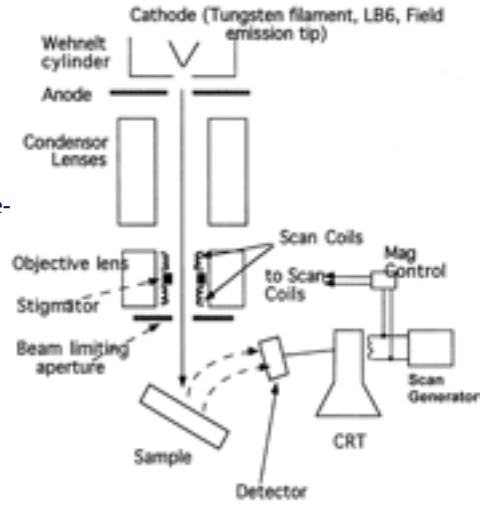
- Three electron beam parameters determine sharpness, contrast, and depth of field of SEM images:
  - Probe diameter – dp
  - Probe Current – Ip
  - Probe Convergence Angle – p
- You must balance these three depending on your goals:
  - High Resolution
  - Best Depth of Field
  - Best Image Quality and X-Ray Analysis



(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Electron Optics: Simplified SEM Schematic

- Gun
  - Source of electrons & accelerates electrons to 1-40keV
- Lenses
  - 1, 2, or more lenses to focus and de-magnify electron beam
- Stigmator
  - Corrects lens errors
- Beam Limiting Aperture
  - Affects depth of field and I_p



Column: Electron Gun

Thermionic Electron Gun

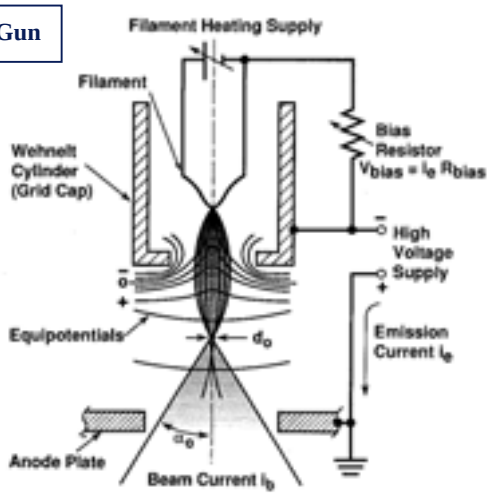
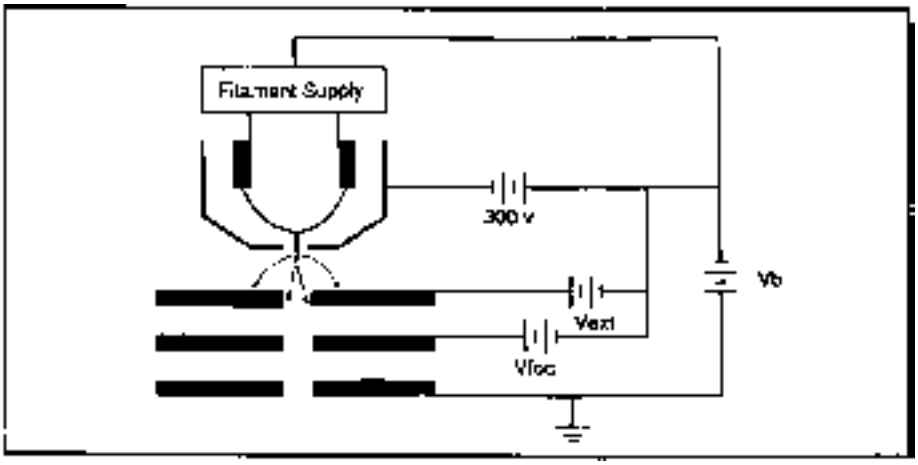


Figure 2.4. Schematic diagram of the conventional self-biased thermionic (triode) electron gun (adapted from Hall, 1966).

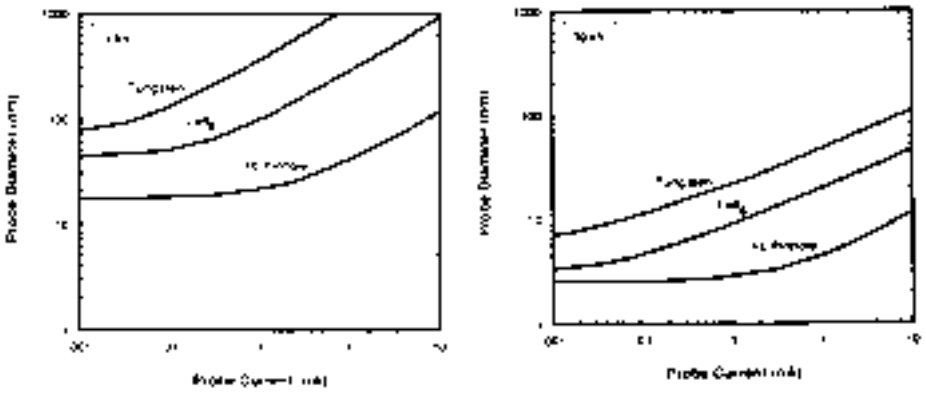
(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Column: Electron Gun



Thermal field emission source and electrostatic gun lens

Electron Sources



Probe Diameter vs. Probe Current

(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Column: Electron Gun

Comparison of Electron Sources at 20 kV

Source	Brightness	Lifetime	Source size	Energy spread ΔE	Beam current Stability	References
Tungsten hairpin	10^5 A/cm^{2}sr	40–100 h	30–100 μm	1–3 eV	1%	[a,b]
LaB_6	10^6	200–1000	5–50 μm	1–2	1%	[b,c]
Field Emission						
Cold	10^8	>1000	<5 nm	0.3	5%	[d,e]
Thermal	10^8	>1000	<5 nm	1	5%	[e]
Schottky	10^8	>1000	15–30 nm	0.3–1.0	2%	[e]

[a] Haine and Cosslett (1961).
[b] Troyon (1987).
[c] Broers (1974).
[d] Crewe *et al.* (1971).
[e] Tuggle *et al.* (1985).

(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Column: Electron Lenses Produce a Small Spot

- Beam diameter at crossover (d_0) in the e-gun too large to generate a sharp image:
  - Thermionic source size: 5 – 100µm
  - Field emission source size: 5 – 30nm
- Lenses reduce diameter (de-magnify) of source of electrons and place small focused beam (1nm - 1µm) on specimen:
  - Demagnification:
    - Thermionic source ≤ 10000
    - Field emission source 10 – 100

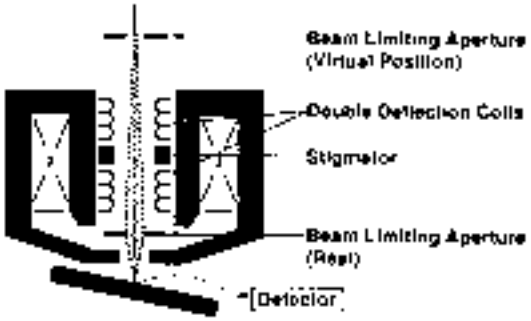
Column: Electron Lenses

- Condenser Lens: 1 or more Lenses
  - Determines the I_p that impinges on the sample
  - Higher I_p – larger spot size – lower resolution – better S/N
  - Knob labeled spot size, condenser, C1, or resolution
- Objective Lens: Final Lens
  - Focuses the beam by controlling the movement of the probe crossover along the optic-axis (Z-axis) of the column
  - Knob labeled focus or objective
  - Pseudo working distance (WD) meter
  - The design of the lens incorporates space for the scanning coils, the stigmator, and the beam-limiting aperture

Lens aberrations that enlarge the final probe size increase rapidly with focal length (WD). So for high-resolution work keep the WD short.

Column: Objective Lens

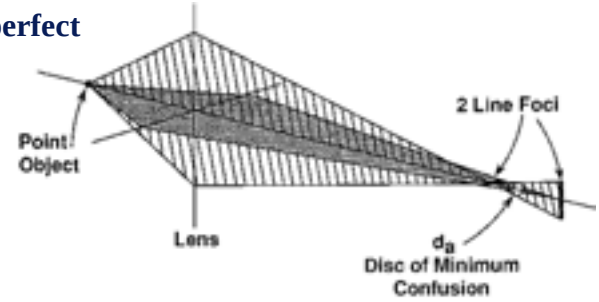
- Stigmator: A device that applies a weak supplemental field to make the lens appear symmetrical to the electron beam
- Method: Try to choose a "round" object
  - Adjust objective lens to best focus
  - Adjust x-stigmator
  - Focus
  - Adjust y-stigmator
  - etc



(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Column: Stigmator

- Lenses do not have perfect rotational symmetry
- Causes:
  - Machining errors
  - Inhomogeneities in the iron of the lens
  - Asymmetry in its windings
  - Dirty apertures

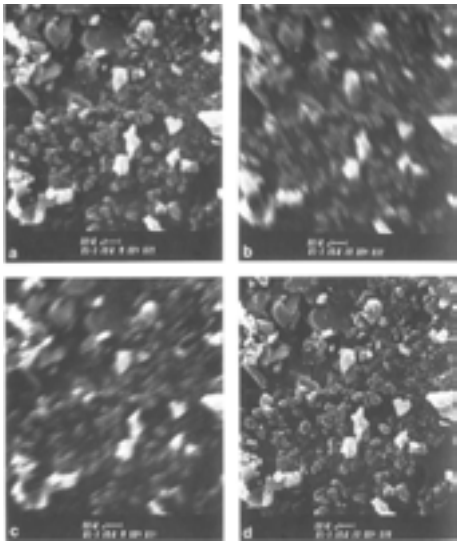


(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

- For example, if a lens has elliptical rather that circular symmetry, electron focuses at 2 separate points at right angles to each other, thus enlarging beam diameter

Astigmatism: IMPORTANT!

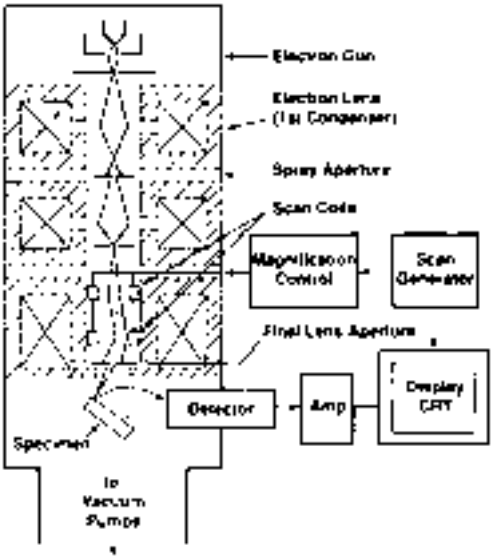
- Effect can be recognized by stretching of the image in two perpendicular directions, when the objective lens is underfocused and then overfocused
- At exact focus — stretching vanishes



(From *Scanning Electron Microscopy and X -Ray Microanalysis* , Joseph I. Goldstein et al., Plenum Press)

Scan System: Image Formation

- CRT & e-beam scanned by single scan generator
- Scan Coils
  - 2 Pairs
  - 1st bends beam off optical axis
  - 2nd bends beam back onto optical axis



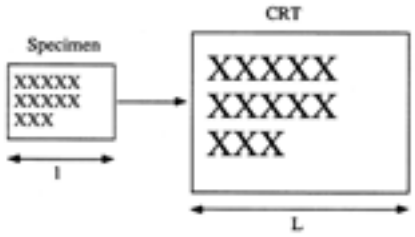
(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Scan System: Image Formation

The number of electrons detected from the specimen determine the intensity changes on the CRT

Beam rasters from left to right on the sample and the CRT screen rasters from left to right at the same rate. The intensity on the CRT is determined by the detected electron intensity at each similar point on the sample.

Magnification is the ratio of the size of viewing CRT to the area scanned on specimen



The CRT image is the same as that on the sample. The magnification is then M= L/l.

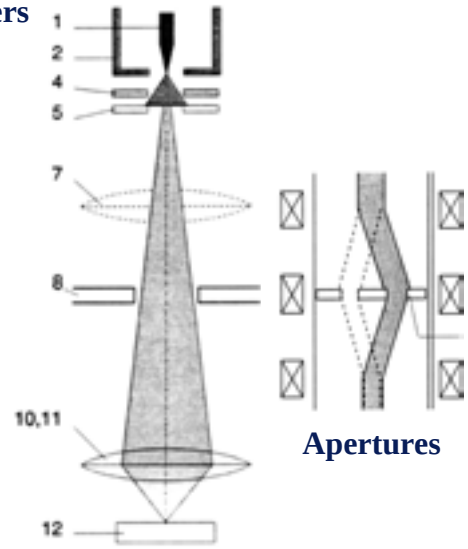
Thermal Field Emitter SEM Column: LEO 982

Simpler Column with no crossovers

- **Schottky Field Emitter**
- **Suppressor**
- **Extraction Voltage**
- **Aperture**
- **Condenser lens**
- **Aperture**

10,11) Objective Lens

12) Specimen



Apertures

Column: Final (Beam Limiting) Aperture

Affects all beam parameters:

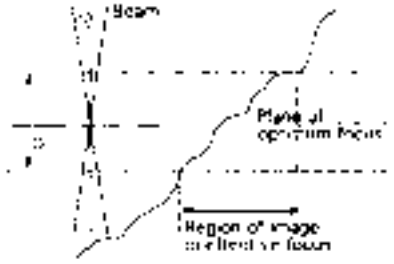
- **Large Aperture:**
  - **Large I_p - Good S/N and microanalysis**
  - **Large α_p - Poor depth of focus**
  - **Large d_p - Poor resolution**
- **Small Aperture:**
  - **Small I_p - Poor S/N and microanalysis**
  - **Small α_p - Good depth of focus**
  - **Small d_p - High resolution**

IMPORTANT! Aperture Must Be Centered

- **For optimum resolution the beam limiting aperture must be centered on the electron optical axis**
- **If your image is shifting while focusing the aperture is not centered**
- **<u>While "wobbling" center the aperture –</u> when properly adjusted the image will show no side to side movement when properly centered**
  - **It will only go in and out of focus**
- **Check whenever the accelerating voltage or aperture is changed, or when you just cannot get good resolution**

Depth of Focus at 10 mm WD

- Depth of focus is a measure of the z (vertical) distance over which two objects will still be in focus
- The depth of focus will depend on the working distance and the aperture
- Long working distances, and small objective apertures yield the best depth of field



Depth of Focus at 10 mm working distance

Mag	100μm aperture	50 μm aperture	20μm aperture
x100	80μm	160μm	400μm
x1000	40μm	80μm	200μm
x10,000	4μm	8μm	20μm
x100,000	0.4μm	0.8μm	2μm

*At 1μm (550 nm) in a light microscope (0.5 mm WD)

(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Depth of Field: Effect of Aperture Size

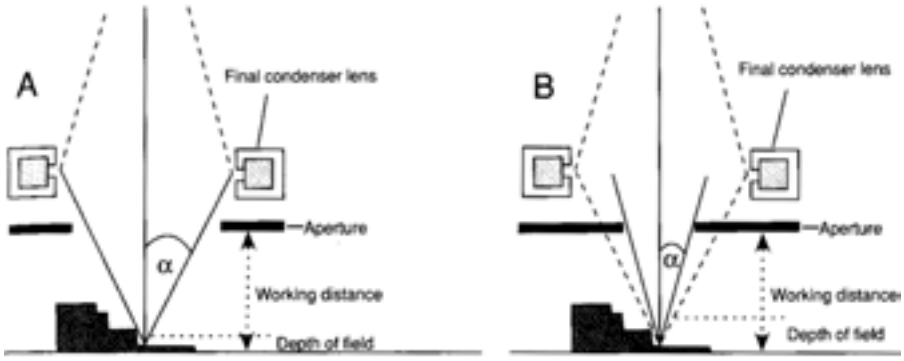


Figure 7-6. Depth of field (the depth that is in focus in the specimen) is increased by using smaller apertures as shown on right.

(Redrawn from Postek et al., 1980)

Depth of Field: Effect of Working Distance

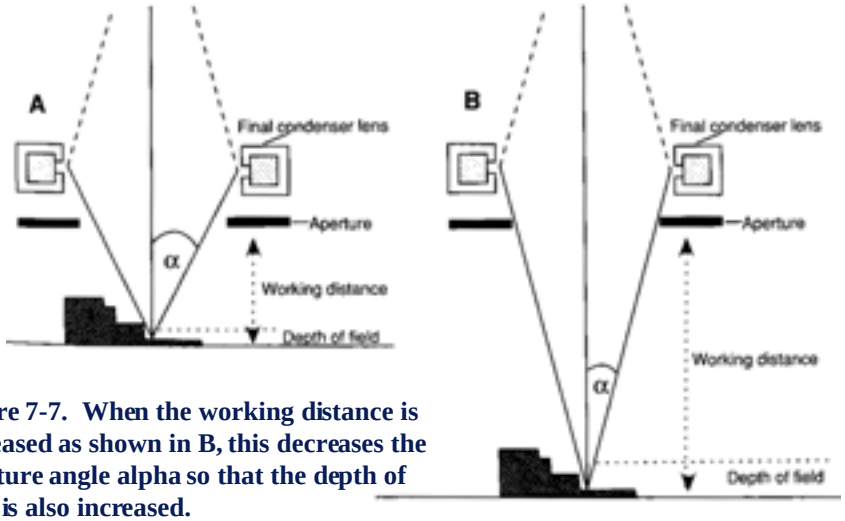
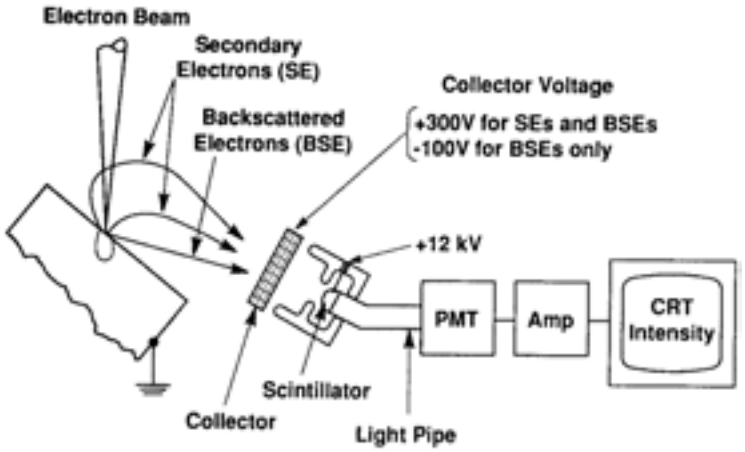


Figure 7-7. When the working distance is increased as shown in B, this decreases the aperture angle alpha so that the depth of field is also increased.

(Redrawn from Postek et al., 1980)

Electron Detectors: Collect Signals

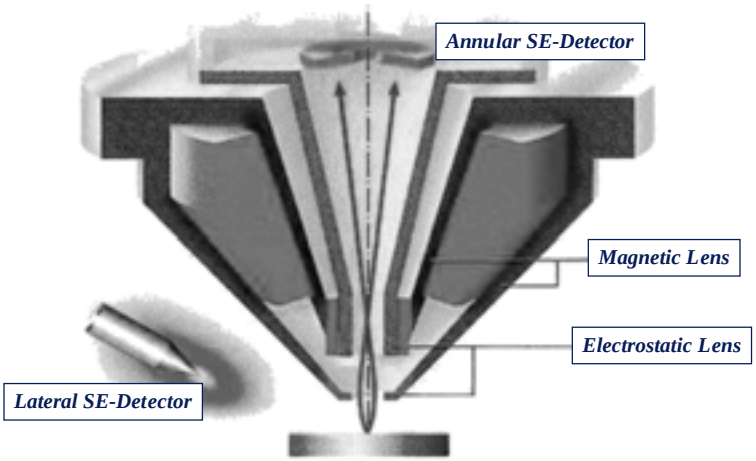
- **Secondary (SE) and backscattered electron (BSE) detectors for imaging**



(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

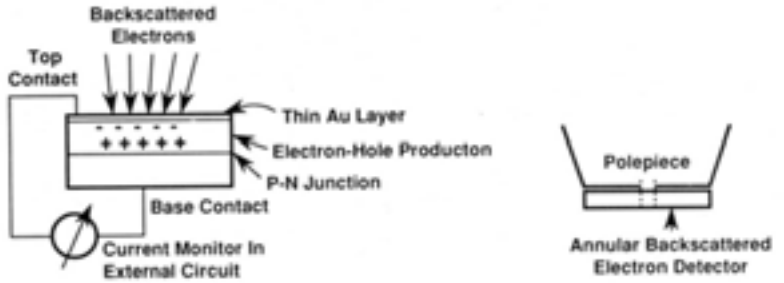
Dual Secondary Detectors: LEO 982 SEM

Principle of Secondary Electron Signal Detection



Solid-State BSE Detector

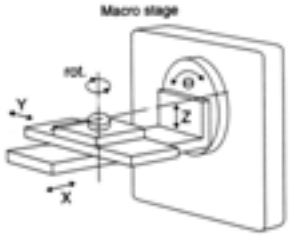
- Single annular detector or smaller discrete detectors placed on pole piece of objective lens
- Size permits close proximity to specimen – provides large solid angle for high geometric efficiency
- Sensitive to high energy BSEs only, not SEs

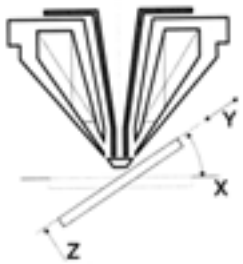


(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Specimen Stage

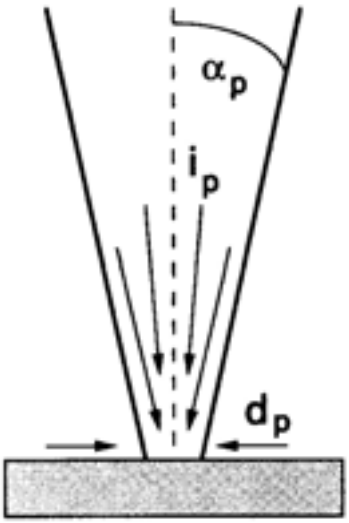
- 5 Axis of Movement:
  - X, Y, Z, Tilt, Rotate
- Manipulation of specimen under beam:
  - To locate areas of interest, e.g., to tilt to look at edges
  - To improve collection geometry relative to detectors
  - To change Z-height to effect depth of field
- Some are motorized





Electron-Specimen Interactions

- We have great control of the beam electrons before they reach the specimen, however, once they enter the specimen, the scattering processes control subsequent behavior
- Are signals generated confined to the area of the beam impact on the specimen's surface?
  - If yes – This would result in images of the highest possible resolution
  - Answer is NO! Electron scattering degrades spatial resolution

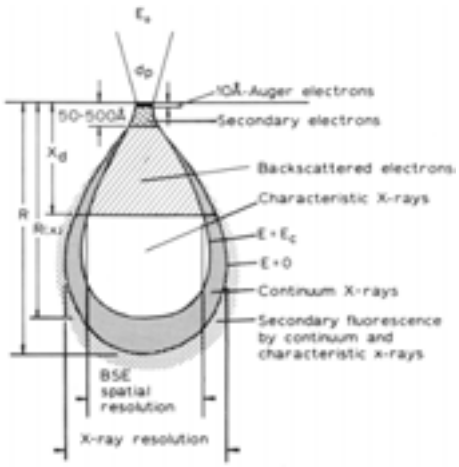


Electron-Specimen Interactions

Rich variety of interactions that can reveal information on a specimen's:

- **Composition**
- **Topography**
- **Crystallography**
- **Electrical potential**
- **Local magnetic field**
- **Etc.**

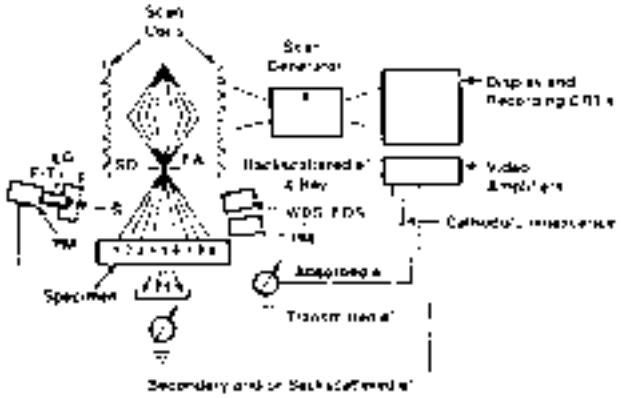
- **E_o=Voltage of e-beam**
- **E_c=Critical excitation energy**
- **R=Range**



Signal Detection

- **With the proper detector or with specialized instruments you can take advantage of the multitude of signals:**

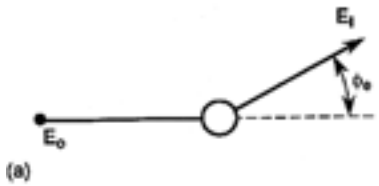
TEM
EELS
SAM
AES
EPMA
WDS & EDS
Etc…



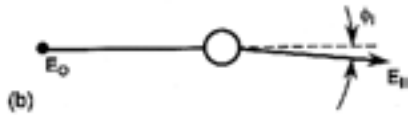
(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Electron–Specimen Interactions

- (a) Elastic Scattering
  - BSEs
  - Electron scattered by interaction with atomic nucleus
  - Direction of beam electron changed, but velocity essentially the same
    - Φ_e = 0 - 180°

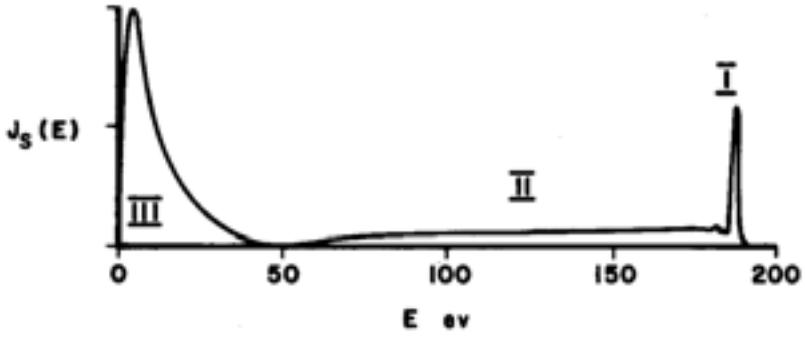


- (b) Inelastic Scattering
  - SEs, x-rays, etc
  - Energy transferred to tightly bound inner shell electrons or loosely bound outer-shell electrons
  - Kinetic energy of beam electron decreases
    - $\Phi_I \leq 0.1°$



(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Energy Distribution of Emitted Electrons



Energy distribution of secondary electrons. $J_s(E)$ is the intensity of secondary electrons. Note that the beam energy E_0 is 180 eV. (From Hachenberg and Brauer.[19])

I = Backscattered Electrons

III = Secondary Electrons

(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Comparison of Coefficients

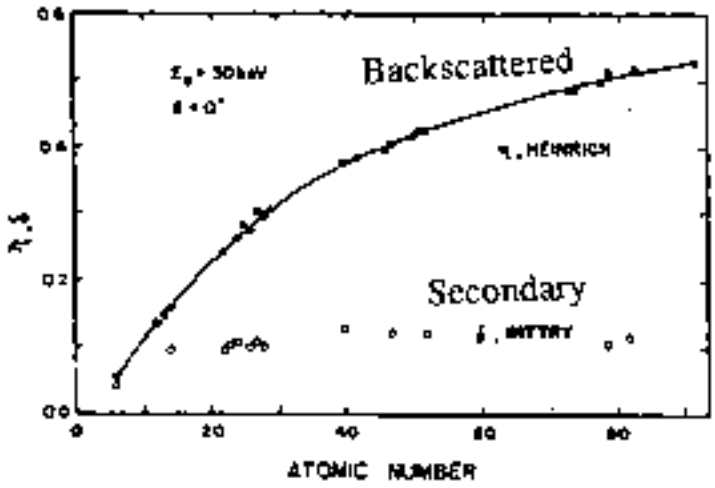
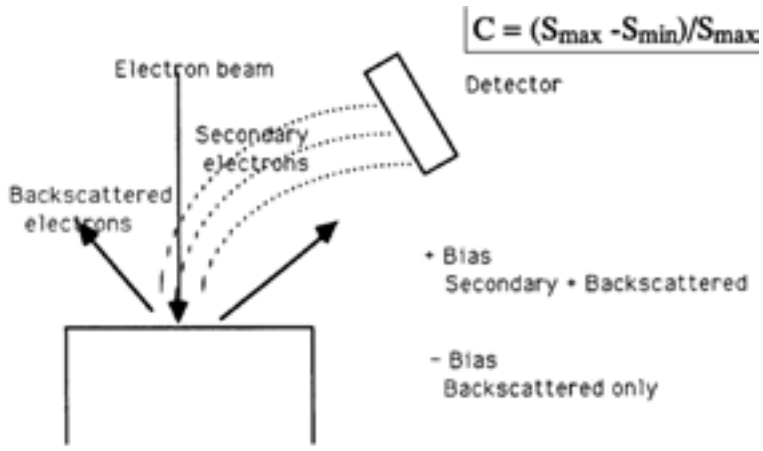


Figure 3.29. Comparison of backscattered electron coefficients and secondary-electron coefficients as a function of atomic number (Wittry, 1966; Heinrich, 1966).

Contrast

- **BSE Yield:**
  - Atomic number dependent
    - Higher atomic number → Higher BSE yield → Brighter image
  - Contrast in BEI is a combination of:
    - Surface topography
    - Composition - Z contrast
- **SE Yield:**
  - Less dependent on Z
  - More dependent on accelerating voltage
  - Contrast in SEI dependent on:
    - Sample orientation (emission contrast)
    - Detector position (collector contrast)
    - Surface topography – sharp edges emit more SE's

Contrast



Note: While backscattered electron yield is larger than the secondary electron yield, secondary electrons are collected from a larger area and will contribute from 2-5 x backscattered electron signal. So SEI will give more contrast for the same beam current.

Contrast: Sharp Edges

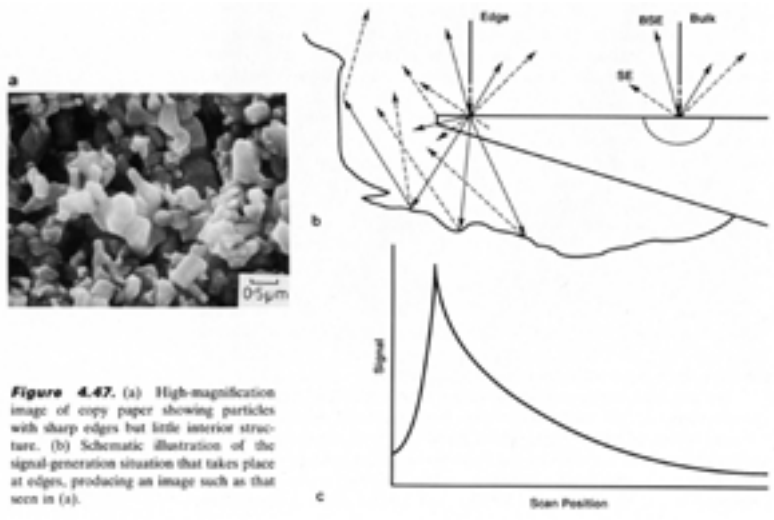


***Figure* 4.47.** (a) High-magnification image of copy paper showing particles with sharp edges but little interior structure. (b) Schematic illustration of the signal-generation situation that takes place at edges, producing an image such as that seen in (a).

(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

SEI Mode

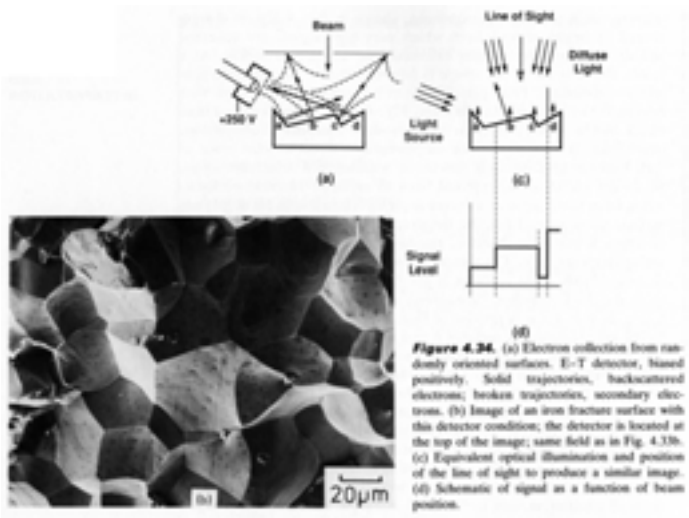


Figure 4.34. (a) Electron collection from randomly oriented surfaces. E–T detector, biased positively. Solid trajectories, backscattered electrons; broken trajectories, secondary electrons. (b) Image of an iron fracture surface with this detector condition; the detector is located at the top of the image; same field as in Fig. 4.33b. (c) Equivalent optical illumination and position of the line of sight to produce a similar image. (d) Schematic of signal as a function of beam position.

(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Light Optical Analogies: SEI Mode

- With the detector positively biased, secondary electrons are attracted to it
- These electrons are detected as well as the backscattered electrons
- However there are usually many more secondary electrons than backscattered electrons
- Also some of the surfaces that are not directly facing the detector will contribute electrons to the signal
- The light optical analogy is a single light source from the side combined with diffuse lighting from the top

BEI Mode

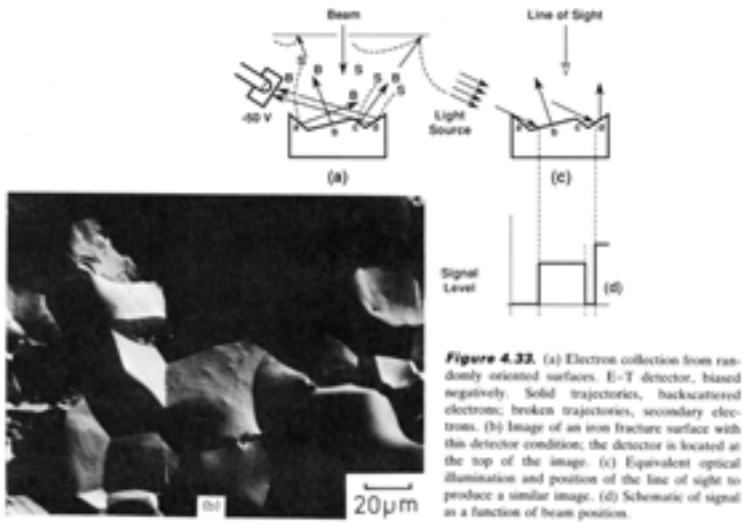


Figure 4.33. (a) Electron collection from randomly oriented surfaces. E–T detector, biased negatively. Solid trajectories, backscattered electrons; broken trajectories, secondary electrons. (b) Image of an iron fracture surface with this detector condition; the detector is located at the top of the image. (c) Equivalent optical illumination and position of the line of sight to produce a similar image. (d) Schematic of signal as a function of beam position.

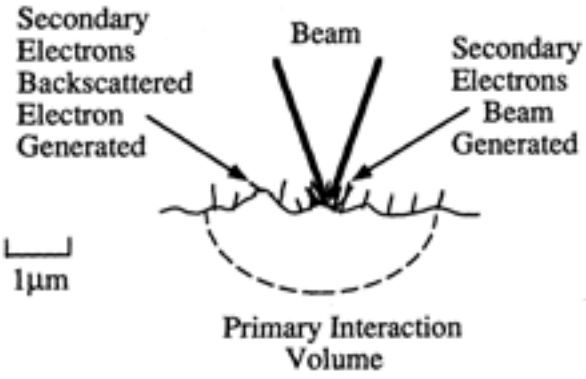
(From *Scanning Electron Microscopy and X-Ray Microanalysis*, Joseph I. Goldstein et al. Plenum Press)

Light Optical Analogies: BEI Mode

- When the detector has a negative bias, only the backscattered electrons are detected
- The path of these electrons is generally line of sight
- The light optical analogy is a single light source from the side with the eye looking down along the beam path
- This mode gives strong topological contrast

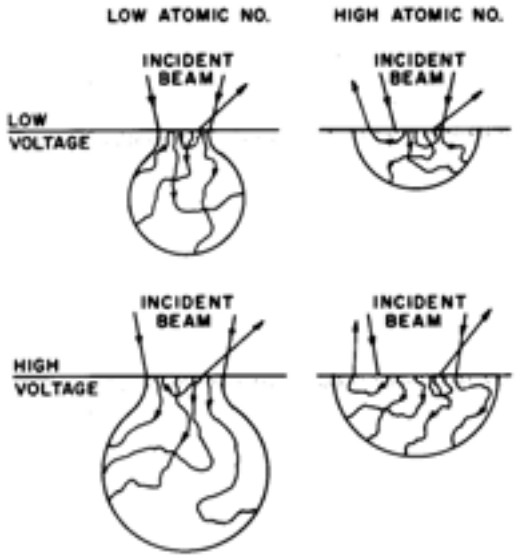
Sample Volume Effects: Image Degradation

- SEI is most susceptible to this effect:
  - The backscattered electrons originating deep in the sample create secondary electrons when they emerge from the surface
  - The distance that the back-scattered electron emerges from the sample can be far from the beam spot (several beam spot diameters)



Interaction Volume

- Interaction volume dependence on accelerating voltage and atomic number:
  - Section through specimen surface illustrating the variation of electron scattering with voltage and atomic number *(from Duncumb and Shields)*



Sample Preparation

- Advantage of SEM - little preparation needed!
- Mount on appropriate stub making electrical contact
  - Use conductive adhesive or clips to secure sample
- Various mounts:
  - Whole wafer mounts
  - Small piece mounts
- Cleave to look at cross-section
- Non-conducting samples will charge causing sample drift, image distortion, and dark or bright image
  - Sputter coat with metal, e.g., Au-Pd
  - Evaporate C for x-ray analysis
  - Use low voltage
- Mark specimen with a "Sharpie" if area of interest difficult to locate

Cheat Sheet

To increase depth of field:
- Long working distances
- Small Aperture

Surface Sensitivity:
- Lower accelerating voltage

High Resolution:
- Higher accelerating voltage
- Reduce spot size
  - smaller aperture
  - or condenser lens
- Short working distance
- Slower scan rate

Charging or insulating sample:
- Low accelerating voltage - ≥ 1.5 kV
- Sputter coat with Au-Pd

Better S/N:
- Larger Aperture
- Slower scan rate

In-lens Detector - LEO 982:
- Sample normal to beam
- ≤ 4 mm WD from pole piece

Focus and stigmation:
- Adjust focus and stigmation at higher mags than working mag
- Adjust to best focus
- Adjust 1 or both stigmator controls
- Iterate between focus and stigmation (roundish structures helpful in adjusting stigmation)
- Center apertures after changes in accelerating voltage or aperture

Equipment Available in CNF

- **LEO 982 SEM's (2)**
  - Thermal Field Emission
  - 4.0 nm @ 1kV
  - 2.0 nm @ 30kV
  - For Low Resolution Work

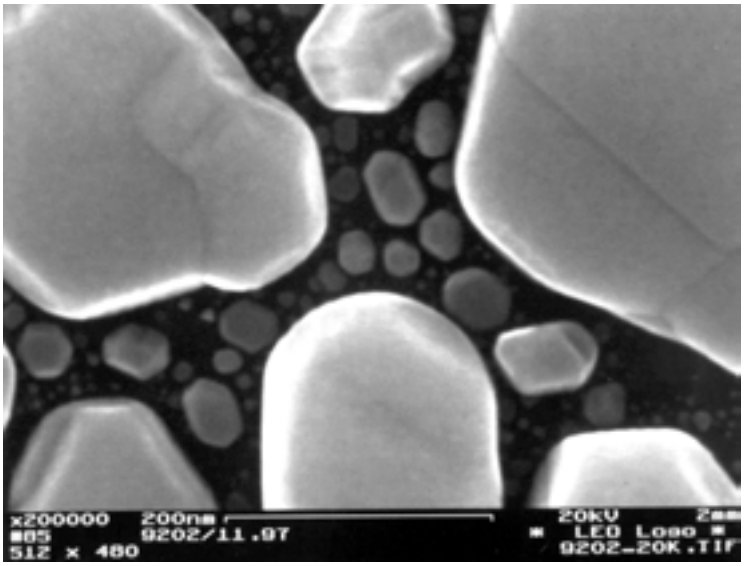
Hitachi S-4700
- Cold Field Emission
- 2.1 nm @ 1kV
- 1.5 nm @ 15kV
- For High Resolution Work

Beware!!!

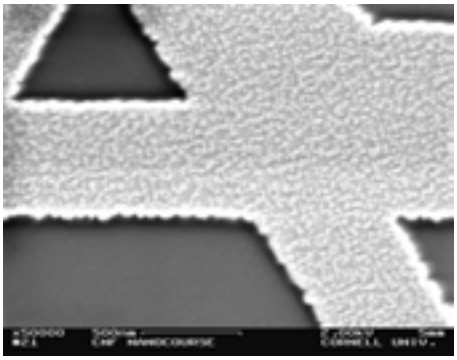
Ultimate Resolution is Often
Sample Limited
NOT
Instrument Limited

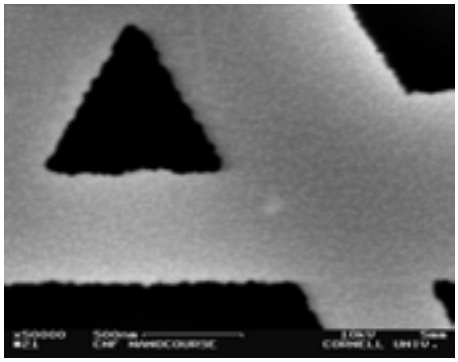
- **Ultimate resolution on an SEM tested with an ideal sample:**
  - Au islands on Carbon
  - High Z material on low Z material
  - Few SEs created by BSEs
  - Strong contrast
- **Your sample is not likely to be as ideal**

Gold on Carbon Resolution Standard



Low vs. High Accelerating Voltage

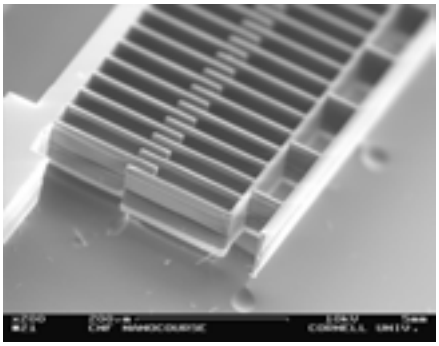


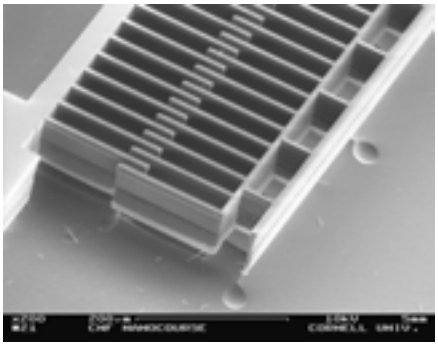


2 KeV **10 KeV**

Kagome Superconductivity Structure

Depth of Field: Effect of Aperture Size



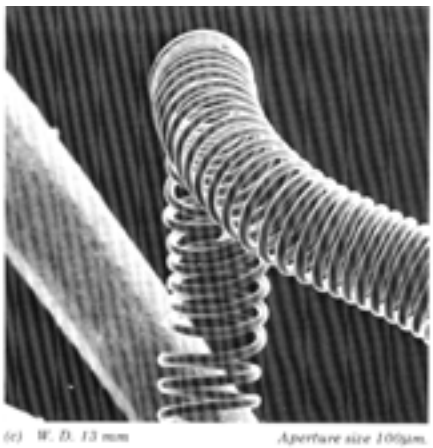


WD - 5mm, Aperture size 120 µm

WD - 5mm, Aperture size 20 µm

MEMS Comb Drive

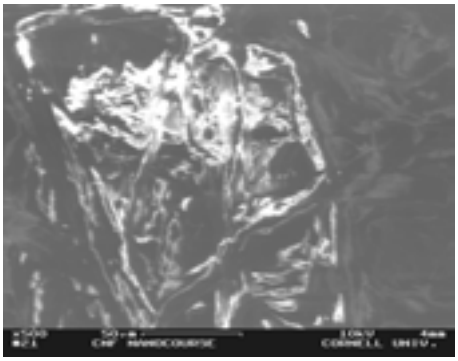
Depth of Field: Effect of Working Distance

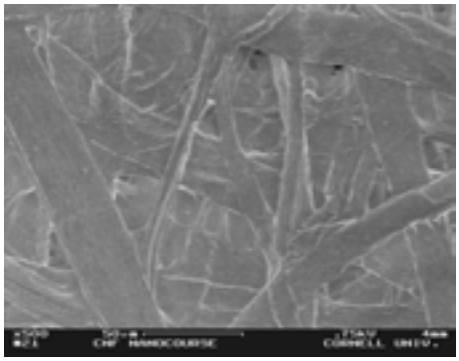


(c) W. D. 13 mm Aperture size 100µm.

(d) W. D. 37 mm Aperture size 100µm.

Sample Charging: Paper



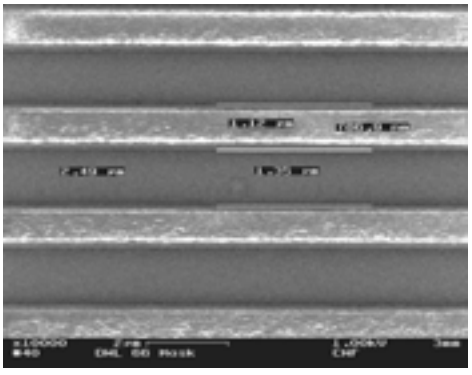


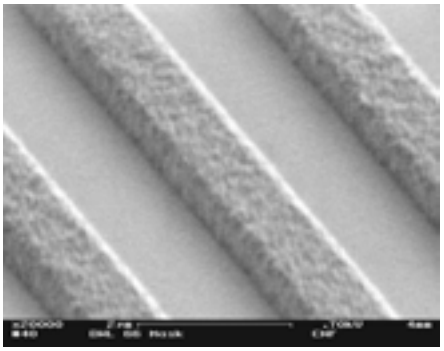
10 KeV Accelerating Voltage

750 eV Accelerating Voltage

Low Voltage Inspection of Resist

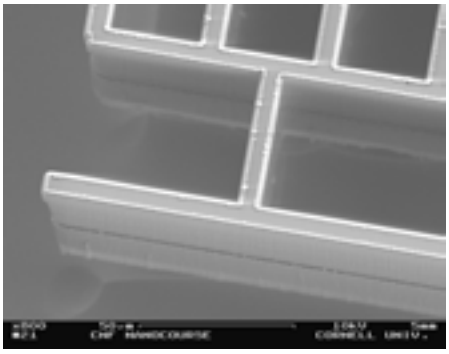
Below: At low accelerating voltages (≤1500V) it is possible to view nonconducting samples uncoated. Note charging at 1kV below – 700V at right no charging.



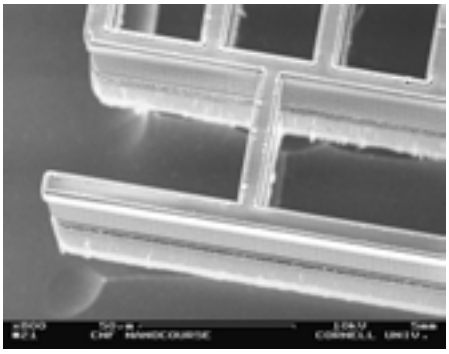


Above: Positive resist on Si wafer – tilted 30° to view sidewall profile above. Normal to beam at left for measuring.

Lateral SE-Detector vs. Annular SE-Detector



"Normal" SE-Detector

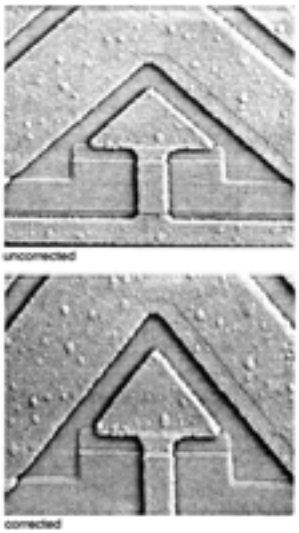


"In-Lens" SE-Detector

MEMs Comb Drive

Tilt Compensation

Set tilt compensation to tilt angle to compensate for foreshortening in Y direction

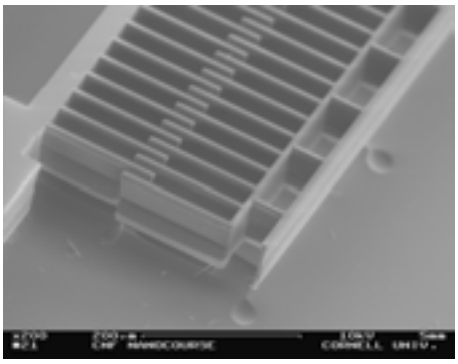


Dynamic Focus

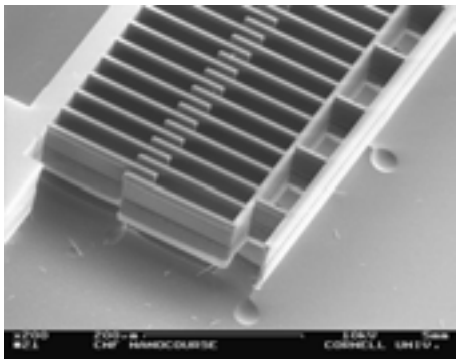
Allows entire sample to be in focus at high tilt angles

- **Dynamic focus ON (45)**
- **Adjust amplitude**
- **Scan rotation (40) must be OFF and the sample aligned in Y direction**

Signal Processing



No Signal Processing



GAMMA 3, Contrast Doubled

MEMS Comb Drive

References

- **SEM:**
  - Scanning Electron Microscopy and X-Ray Microanalysis, Goldstein, Newbury, Echlin, Joy, Romig, Lyman, Fiori, and Lifshin
  - Scanning Electron Microscopy, L. Reimer, Springer Verlag, #45 in the optical sciences series
- **TEM:**
  - Practical Microscopy of Materials Science, J. W. Edington
  - Electron Microscopy of Thin Crystals, Hirsch, Howie, Nicholson, Pashley, and Whelan
  - Introduction to Analytical Electron Microscopy, Hren, Goldstein, and Joy
  - Transmission Electron Microscopy, L. Reimer, Springer Verlag, #36, optical sciences series
  - Electron Microscopy, Bozzola and Russell, 1992
- **EPMA:**
  - Microprobe Analysis, Anderson (ed.), Wiley-Interscience

NanoCourses 2004, Section 4

Practical Thin Film Analysis
What is it?

Electrical & Optical Measurements
by
Phil Infante

Presented by the
CNF **Technical Staff**
for the education of CNF Users,
Potential Users, and Industrial Sponsors

Resistivity Measurement

- **Resistivity (r): A measure of the inability of a layer to support the conduction of electrical carriers (electrons or holes)**

$$\rho = [neu]^{-1} \text{ (units = ohm-cm)}$$

n = carrier concentration

e = electronic charge

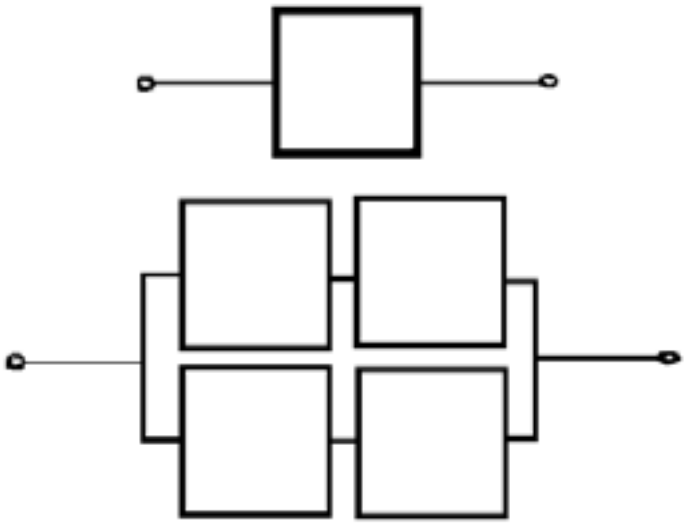
u = carrier mobility

- **For thin layers, it is useful to introduce the concept of resistance per unit area, or Sheet Resistance:**

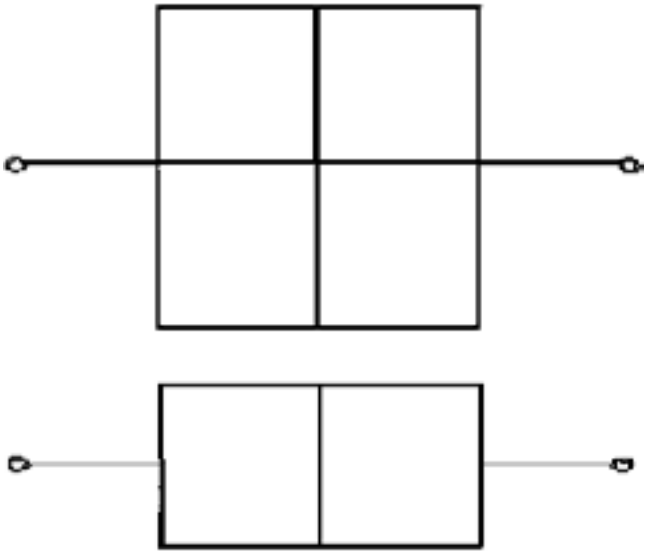
$$R_s = \rho/t \text{ (units = ohm/square)}$$

t = thickness of layer

Sheet Resistance Example



Sheet Resistance Example



Sheet Resistance

- A rectangular sample would have a resistance given by:

$$R = V/I = R_s\,(l/w)$$

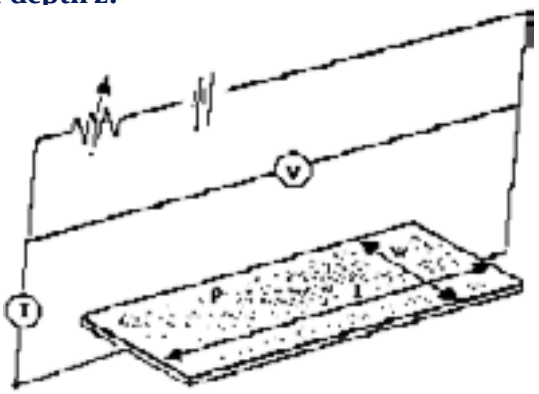
- In most films the carrier concentration, and therefore the resistance will vary with depth z:

$\rho(z) = [n(z)e\,\mu(n)]^{-1}$

(note μ is a function of n)

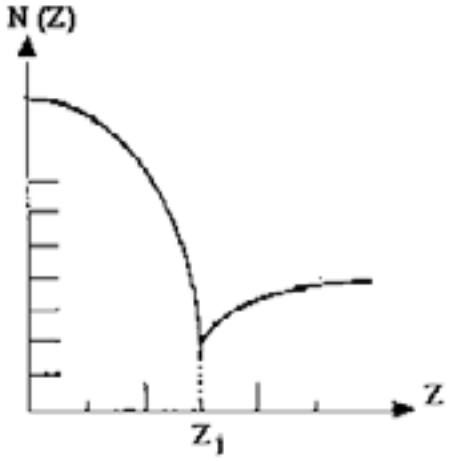
So the sheet rho is:

$R_s = [\int_0^t n(z)e\,\mu(n)\,dz]^{-1}$



Film Thickness

- For a p-n junction, the thickness t equals the junction depth z_j
- Also, the top film is much less resistive than the bulk
- You can assume:
  - t = the film thickness



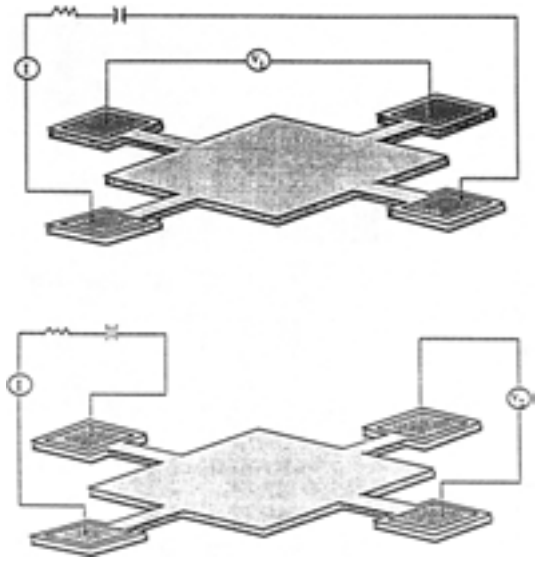
Van der Pauw Structures

- Two methods to measure R_s:
- First Method: Van der Pauw Structure *(See next page)*

$$R_s = (\pi/\ln 2)(R_1 + R_2)/2$$
$$= 4.532(R_1 = R_2)/2$$
$$R_1 = V_1/I \text{ , } R_2 = V_2/I$$

- The measurement is geometry-independent because of the paired resistances, R_1 and R_2
- Problems:
  - Needs to be patterned, may need metallization on pads to carry current to high rho structures

Van der Pauw Structures

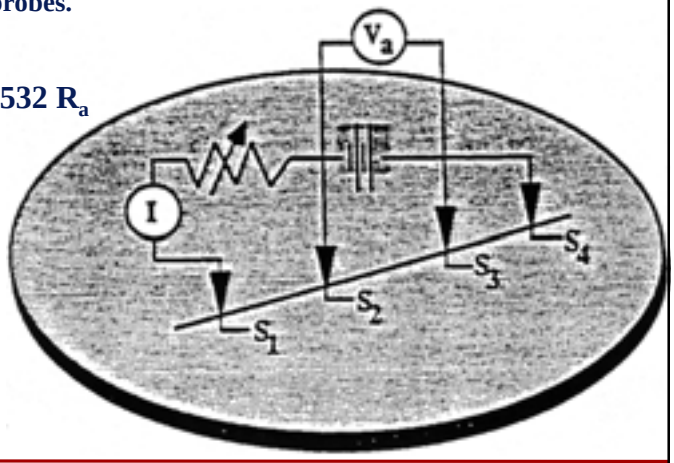


Four Point Probe

- **Second Method: Four Point Probe**
  - **Force a current through two probes, measure the voltage drop across the remaining probes.**

$R_s = (\pi/\ln 2)\, R_a = 4.532\, R_a$

$R_a = V_a/I$



Note: R_a is the average resistance obtained by reversing the polarity of the current supply. This eliminates voltage offsets in the measuring circuit.

Four Point Probe

- **To compensate for geometric effects, do dual configuration measurement, similar to Van der Pauw structure** ***(See next slide)***

$$R_s = k(\zeta)\, R_a$$

$$\zeta = R_a/R_b$$

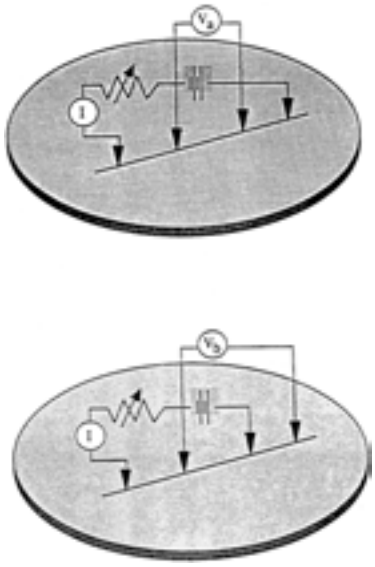
- **For the ideal case of equal probe spacing on an infinite sheet:**

$$\zeta = 1.2619$$

$$k = \pi/\ln 2 = 4.532$$

- **This gives a measurement accuracy of +- 0.5%**

Dual Configurations



Prometrix VersaProbe VP-10

- **At the CNF, we have a Prometrix VersaProbe VP-10, a lovely instrument that does all this for you automatically**
- **Measurement range = 5 microohm/square to 5 megohm/square**
- **Things to remember:**
  1) **Oxide on your film produces a contact resistance. The probes can break through the 10 monolayers present on silicon. If there is much more than this on the film, the oxide should be removed.**
  2) **Whole wafers are the most convenient measurement vehicle. Fragments of wafers can be done, but it isn't as much fun.**
  3) **NO ALUMINUM FILMS MAY BE MEASURED ON THE VP-10. Aluminum lodges in the pits in the probe tips, oxidizes, adds a resistor to the measurement circuit, and screws up future measurements. Aluminum MAY be measured with the manual 4-point probe.**
  4) **Geometry effects come into play when the "infinite film" becomes smaller in area (sic). Make sure your "infinite film" is at least a 1 cm by 1 cm square.**
  5) **Grain boundaries can cause ζ to be too high -- "ratio error." Do single configuration test instead of dual configuration.**

Interferometry (Leitz MPV-SP)

- **A method of measuring film thickness based on the interference analysis of the light reflected from the surface of the object to be measured**
- **Our Leitz SP focuses white light on the sample and analyzes the reflected signal from 400 to 800 nm**
- **Measurement Principal**
- **The Leitz manual gives an excellent explanation of the measurement principal, so here it is:**

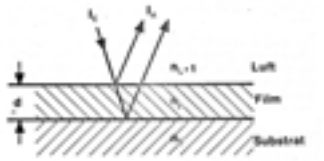
3.3 Measuring

3.3.1 Principle

The measuring principle is based on the interference analysis of the light reflected from the surface of the object to be measured.

A normalized spectral curve is necessary for the determination of film thicknesses, i.e. the intensity measured from the point in question must be divided by that from the substrate. This ensures that substrate- and instrument-specific influences are largely eliminated.

To make this clear, the following example considers the special case of light incident perpendicularly on thin, transparent, non-absorbent films on a non-absorbent substrate.



$$R = \frac{I_r}{I_e} = \frac{r_{Lf}^2 + r_{fs}^2 + 2\, r_{Lf}\, r_{fs} \cos x}{1 + r_{Lf}^2\, r_{fs}^2 + 2\, r_{Lf}\, r_{fs} \cos x}$$

where $x = 4\pi\, n_f \cdot \frac{d}{\lambda}$,

the reflection coefficient between air and film

$$r_{Lf} = \frac{1 - n_f}{1 + n_f}$$

the reflection coefficient between film and substrate

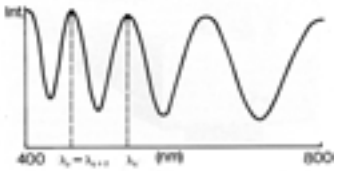
$$\frac{n_f - n_s}{n_f + n_s}$$

(n_f and n_s are the refractive indices of film and substrate, λ is the wavelength, and d is the film thickness)

The film thickness d is determined from the peak positions (at least two peaks in the normalized spectral curve):

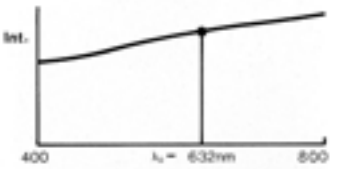
$$d = \frac{q - p}{4 n_f} \cdot \frac{\lambda_q \cdot \lambda_p}{\lambda_p - \lambda_q}$$

where p and q are the ordinal numbers, λ_p and λ_q are the wavelengths of peaks p and q, and n_f is the refractive index of the film.



Normalized spectral curve for a 1100nm thick SiO_2 film on an Si substrate.

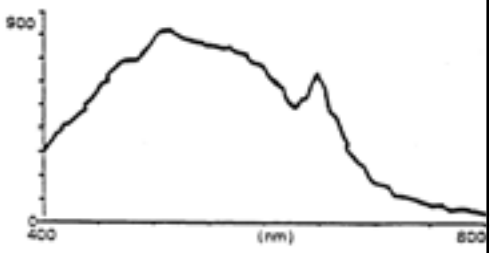
For single-layer films with a thickness of about 10 to 80 nm (ordinal number p = 0), the thickness is determined, according to the first equation given above (for R), from the ratio of the intensity of the light reflected from the film to that of the light reflected from the substrate, at a selected wavelength (that of the He-Ne laser, i.e. λ_e = 632 nm).



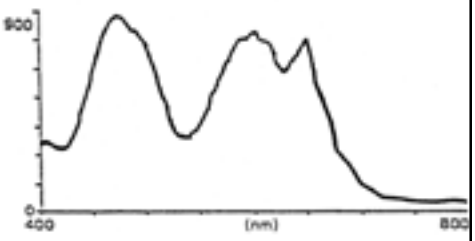
Normalized spectral curve for a 50 nm thick SiO_2 film on a Si substrate.

Measurement Sequence

1) Measure and record the reflectance spectrum for a BARE SUBSTRATE (2 nm native oxide can be ignored)

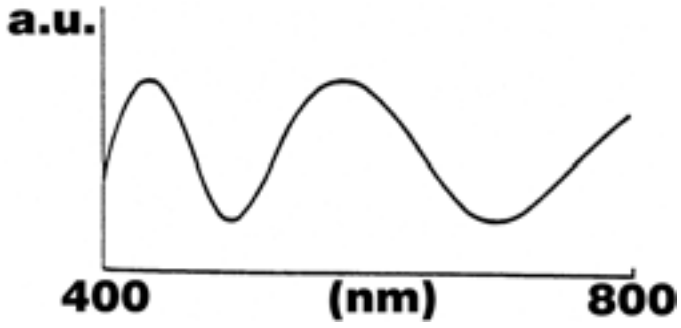


2) Measure and record the reflectance spectrum for the film on the substrate



Measurement Spectrum

3) Normalize the measurement spectrum by dividing by the calibration spectrum



Measurement Spectrum

- The film thickness is calculated from the normalized spectrum
- For films < 80 nm (thin film program)
  - Measure reflected intensity from substrate at 550 nm. measure refl. intensity from film at the same wavelength
  - Calculate thickness from intensity ratio

What can (and can't) the Leitz do?

Minimum measurement area = 2 µm by 2 µm. Yes, this is very small. But the signal to noise ratio, and hence the accuracy, improves as the area gets bigger. So make sure your sample has a nice large area for Leitz measurement.

The Leitz can measure the thickness of the top layer of a film-on-film-on-substrate sample (e.g. polysilicon on SiO_2 on Si). You must know the thickness of the intermediate layer within 10%. Also the intermediate layer should be no thicker than 200 nm. (Empirical observation by yours truly for polysi on $Si0_2$. You are welcome to try other combinations. If you find combinations that work with thicker intermediate films, please tell me.)

If the film and substrate have refractive indices that are very close (like polysilicon on silicon) don't expect good results. It helps to have an intermediate layer of a different refractive index.

What can (and can't) the Leitz do?

Film thickness range = 10 nm to 15 µm.

Accuracy < + /- 2 to 5%

for films > 100 nm depending on material,

< 2 nm for films < 100 nm.

First Thing to Remember:

- **DON'T BELIEVE EVERYTHING YOU READ !!!**
- **While this instrument is quite sophisticated, the principal is such that the software is easily confused**
- **When trying something "unconventional" for the first time (e.g. SiO_2 on PMMA on GaAs), it is a good idea to verify the measurement via some other technique**

Second Thing to Remember:

- **DON'T TRY TO FOOL IT !!!**
- **It is easily fooled.**
  - **For example, if you tell it to measure $Si0_2$ and you really have photoresist, it will give you an answer that it thinks is perfectly logical**
- **Make sure you have an area large enough to measure**
- **If you are measuring film on film make sure you know the thickness of the intermediate layer**

Example 1

Examples of samples that can and cannot be measured:

Oxidize Silicon - Thermal Oxidation

Pad Oxide - 30 nm
P-Type Silicon

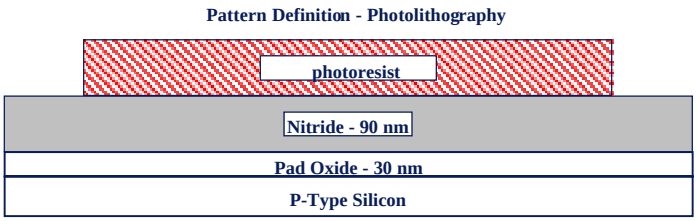
Yes. Use thin film or thick film programs.

Silicon Nitride Deposition - LPCVD

Nitride - 90 nm
Pad Oxide - 30 nm
P-Type Silicon

Yes. Use nitride on oxide program.

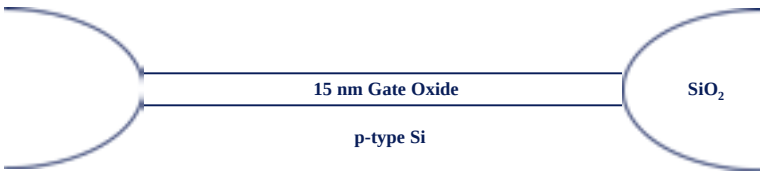
Example 2



No. Cannot measure 3-layer structure. However, you can ignore the 30 nm pad oxide and get good results.

Use resist on nitride program.

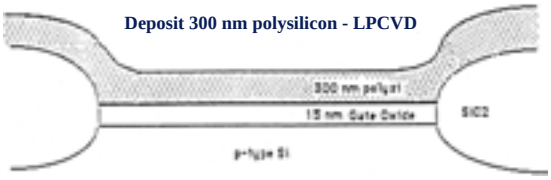
Example 3



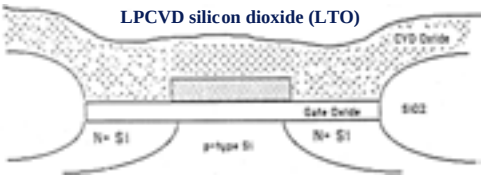
Yes, provided the gate area is at least 2µm x 2µm.

Use the thin film program.

Example 4



Yes. Use polysilicon on oxide program.

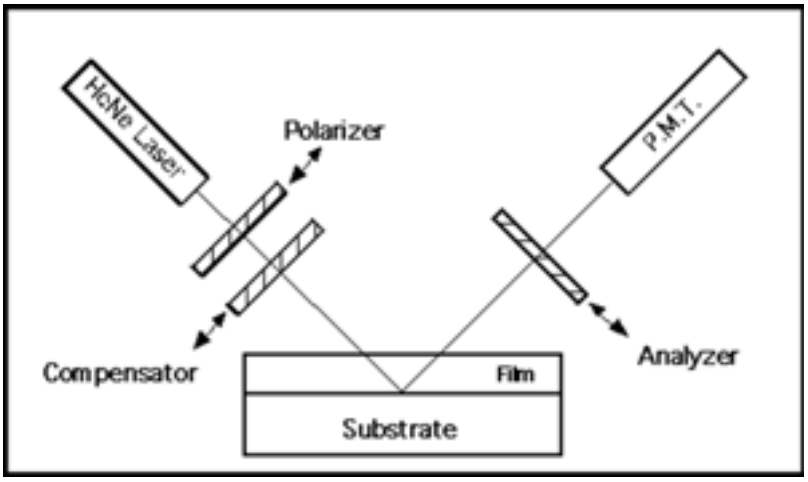


<u>No,</u> in gate area (3 films).

<u>Yes,</u> in source-drain area provided the area is large enough. Use oxide on Si and ignore 15nm gate oxide.

Ellipsometry

Apparatus:



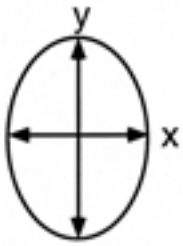
Ellipsometry

- **Principal:**
  - Monochromatic light (633 nm in our case) passes through two polarizing grids.
  - The first is called the "polarizer," the second is the "compensator."
  - This produces light that is elliptically polarized. This light reflects off the sample and experiences a change in the ellipticity of polarization.
  - A third polarizing grid, called the "analyzer," is adjusted along with the polarizer to achieve a reflected signal of minimum intensity.
  - This is called a "null." The positions of the polarizer and analyzer are recorded at this point.

Null Points

- Null points are measured in four "zones," corresponding to the four quadrants of the ellipse. The positions of the analyzer and polarizer for all four zones are fed into a computer which calculates Δ and Ψ. These are angles that describe the shape of the ellipse. From this the program calculates the thickness and refractive index of the film.
- Very accurate and precise (+/- 1 monolayer for some films).
- Can measure films < 10 nm thick -- >
- USE INSTEAD OF LEITZ FOR FILMS < 20 nm.
- Can measure refractive index of bare substrates.
- Maximum film thickness 1 µm.
- Refractive index of very thin films may be different than that of "bulk" material so you may have to assume an index (i.e. fudge it).

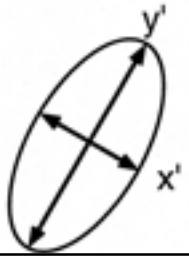
Before passing through film



After passing through film

$\Delta = y^1/x^1$

ψ = Phase shift



Spot Size

- Spot size is large - 1 mm diameter. Measurement area should be 0.5 cm by 0.5 cm. The bigger the better.
- Refractive index of film should be less than 3.0 --> you can't measure polysilicon.

NanoCourses 2004, Section 4

Practical Thin Film Analysis
What is It?

Auger Electron Spectroscopy
by
Lynn Rathbun, Ph.D.

Presented by the
***CNF* Technical Staff**
for the education of CNF Users,
Potential Users, and Industrial Sponsors

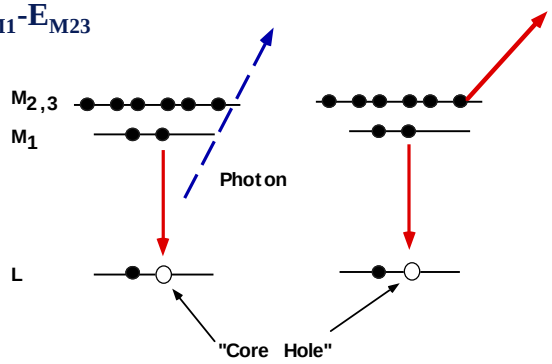
Auger Electron Spectroscopy

- One of several techniques for materials analysis commonly used
  - Surface analysis
  - Thin film analysis
  - Not bulk analysis

    - Auger Electron Spectroscopy
    - Auger
    - Auger Microprobe
    - Scanning Auger Spectroscopy
    - Scanning Auger Microprobe
    - AES
    - SAM

Auger Transition

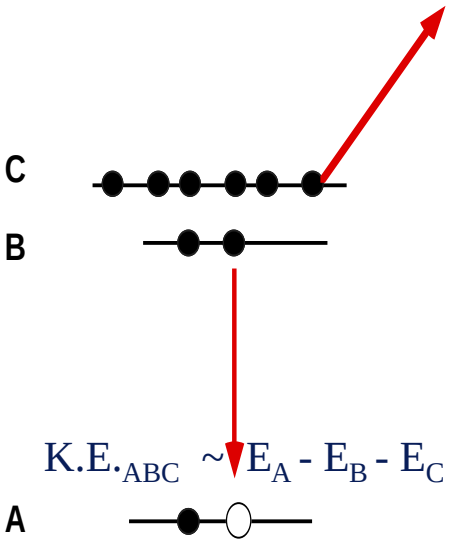
- Radiationless electron transition in an atom
- Fluorescence yield dominates only for transitions > 10KeV, i.e. certain heavy atoms transitions
- Kinetic energy ~ E_L-E_{M1}-E_{M23}



Fluorescence "Auger"

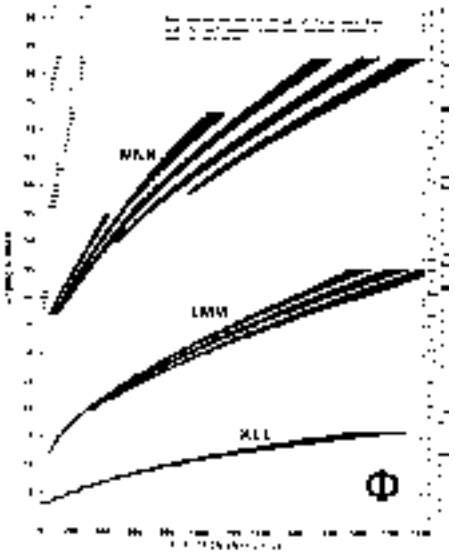
Auger Transition

- Electron of a fixed energy, independent of excitation method
- Characteristic of atom
- Not an energy loss process
- Labeled by the 3 atomic shells involved, i.e KLL, LMM, LVV, etc
- Commonly kinetic energies up to 2500 eV



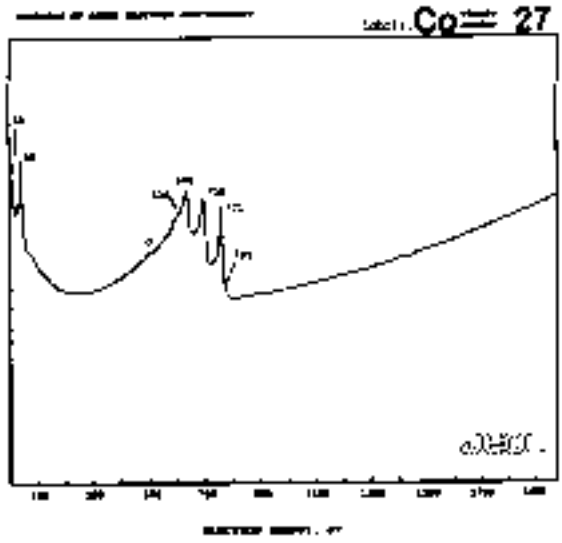
Auger Transition Bands

- A set of energy bands with unique transitions for each element



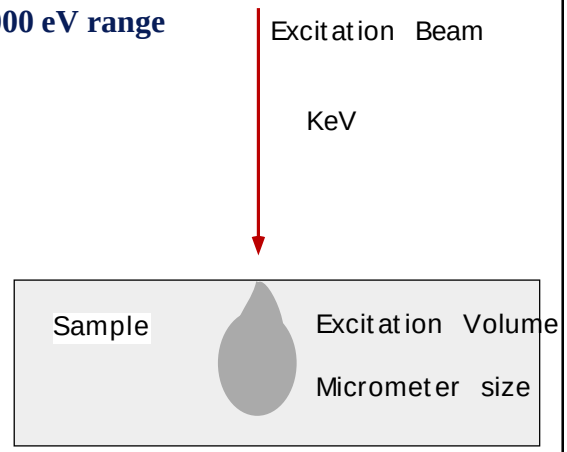
Spectral Example, 1

Spectral Example, 2



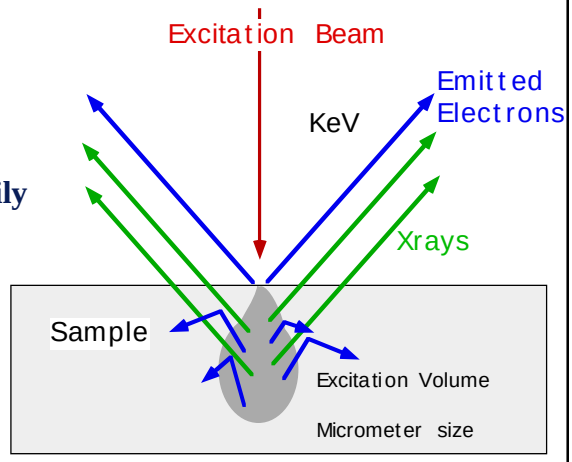
Excitation

- Auger decay presumes a "core hole," i.e. an excitation
- High energy electron beam impacting a solid surface
- Threshold varies 200-2000 eV range

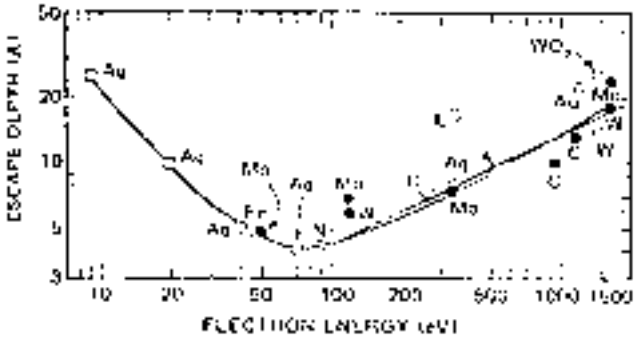


Excitation and Escape

- Atoms within entire bulb are being excited
- Decay by
  - X-ray fluorescence
  - Auger electrons
- X-rays easily escape
- Electrons can only easily escape from surface without energy loss

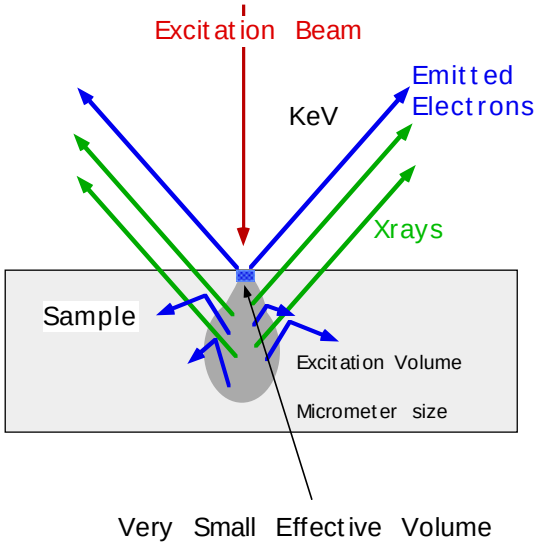


Electron Escape Depth



- Elastic Mean free path for electron in solid is very short
- Unscattered "Auger" electrons only come from the very surface region.
- VERY SURFACE SENSITIVE

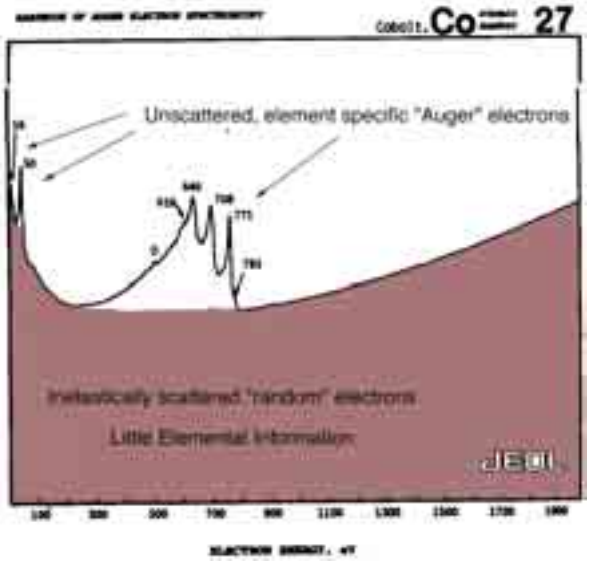
Surface Sensitive !!!



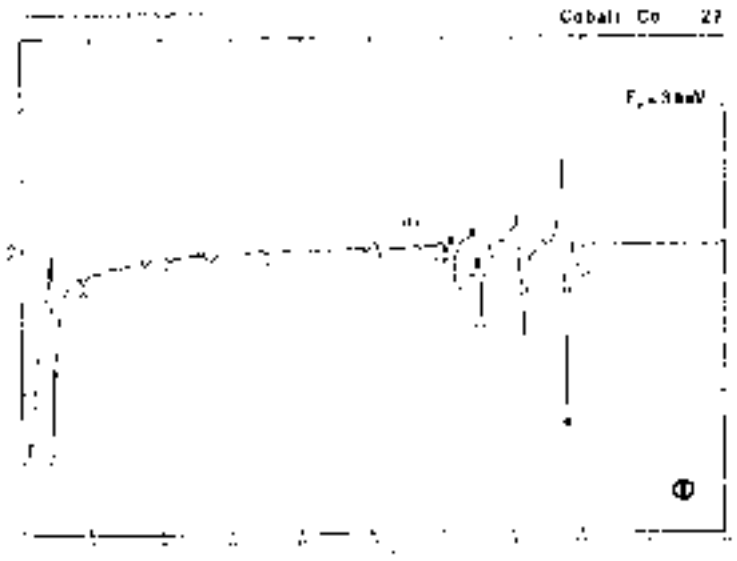
An Auger Spectroscopy Tool

- If we can excite and detect Auger electrons from a solid — we can identify atoms !!!
  - Surface Sensitive
    - Clean Surface
      - UHV
- An Ultra high vacuum, SEM like tool, with an energy analyzer

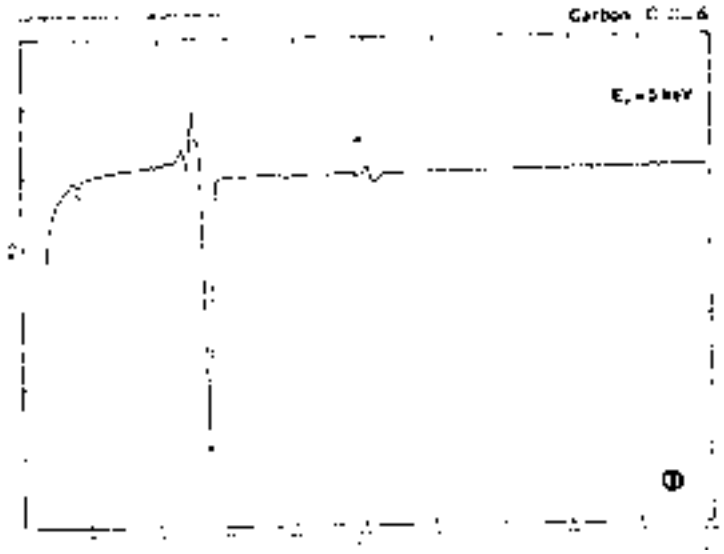
N(E) vs E Spectrum



Derivative N(E) vs. E Spectrum



Carbon Auger Spectrum



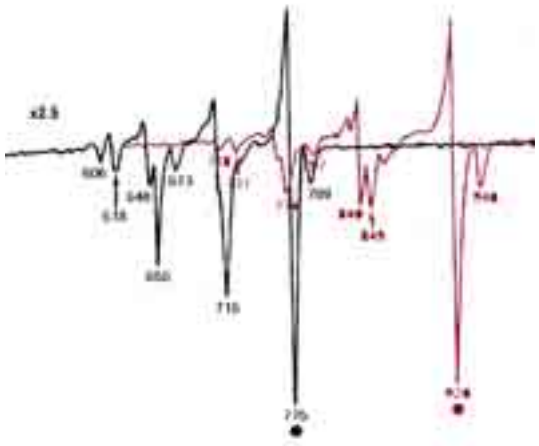
Auger Spectroscopy

- Elemental Analysis Technique
  - What atoms not what molecules
  - Not chemical analysis
- Surface Analysis Technique
  - Not bulk

Limitations

- Insulators
- Electron beam sensitive materials
- Interferences
  - Peak overlap

Cobalt and Copper Superposition



Capabilities

- Sensitivity to approx. 1%
- Quantity Accuracy
  - Limited
  - Empirical "sensitivity factors"
  - 1- 5%
  - Surface not Bulk !!!!
- Resolution
  - Limited by ebeam size and current
  - < 100 nm lateral
  - Bigger beam==> more current ==> more signal

Accuracy limitations

- Surface vs. bulk
- Matrix effects
  - Electron scattering
- Chemical effects
  - Small changes in peaks effect accuracy even if not useful for "chemical" identification

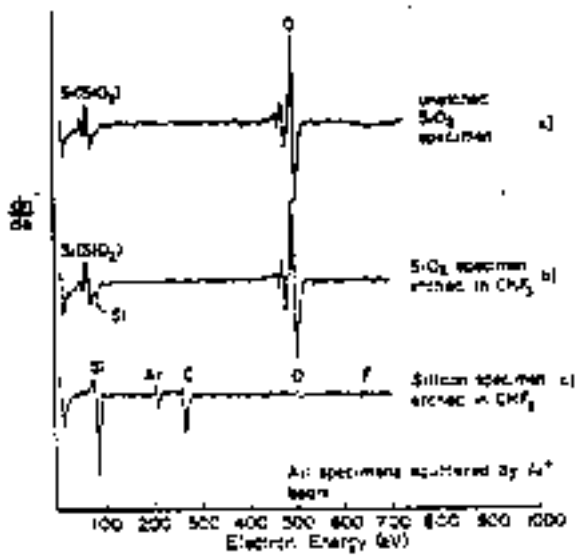
Scanning Auger

- Combination of SEM imaging techniques with Auger depection
  - Point analysis
    - Best S/N
  - Composition var. along a line
  - Compositional "maps"
    - Low S/N
    - Qualitative

Use of Scanning Auger

- Failure Analysis
- Process documentation / characterization

Residue Study: Example

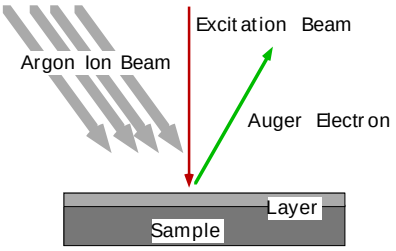


Thin Film Analysis

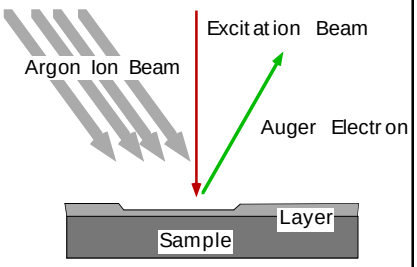
- Auger is fundamentally a surface analysis technique
- What about under the surface
- Slowly erode surface and look at surface vs. time
- Destructive
  - Auger depth profiling
  - Auger sputter profiling

Sputter Depth Profiling

- Ar ions
- 500-5000 ev
- 10 A/min - 1000 A/min
- Depths to ~ 1 µm

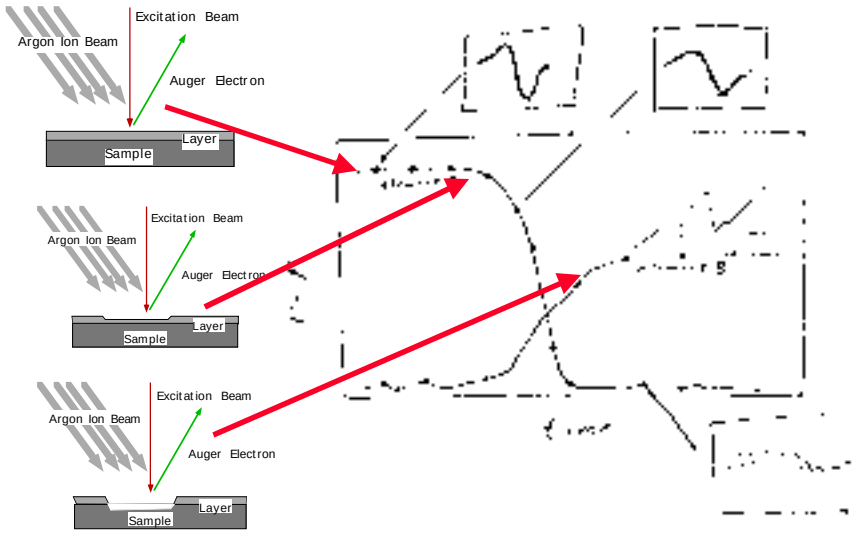


- Erode a crater
- Monitor signal vs time

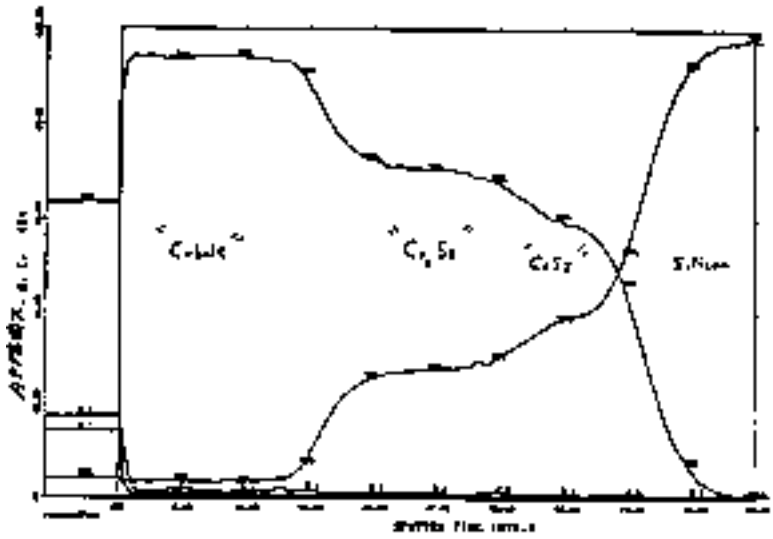


- Destructive!!

Auger Depth Profile



Auger Depth Profile

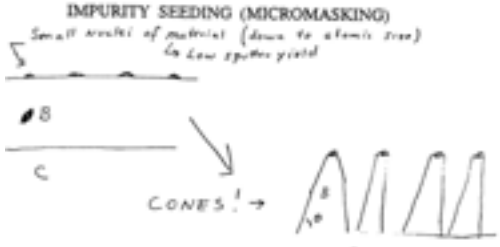


An Auger Depth Profile is NOT ----

- **Composition vs. depth -----NOT NOT NOT!!!**
- **Signal vs. time ---- Yes**
- **Assumptions:**
  - **Composition as a function of signal**
  - **Depth as a function of time**
  - **Uniform**

Micromasking and Roughness

IMPURITY SEEDING (MICROMASKING)



NORMAL ROUGHNESS LIMITS SPUTTERING DEPTH TO 1 MICRON OR SO

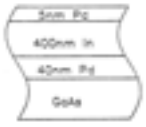
1)initial roughness

2)due to ion irregularities

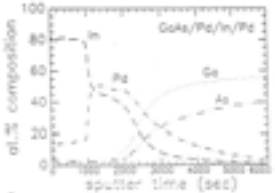
THE AUGER PROFILE GIVES YOU ONLY THE COMPOSITION ON THE CRATER BOTTOM THAT IT SEES.

Depth Profile Artifacts

a) Sample



b) Auger Results

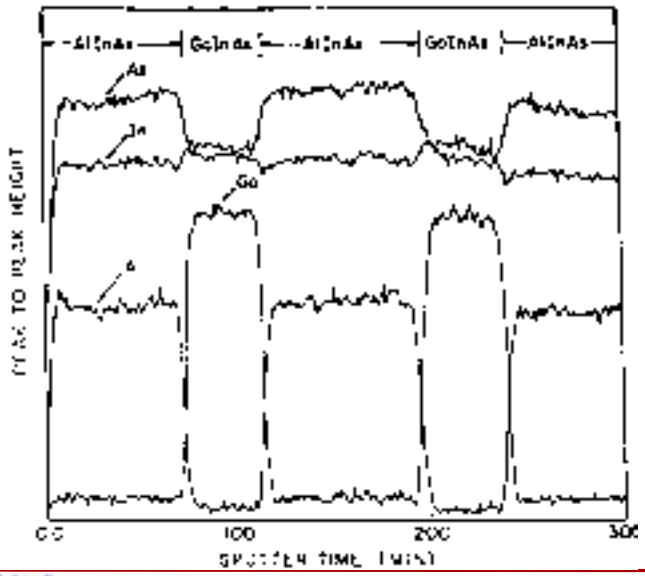


c) Surface

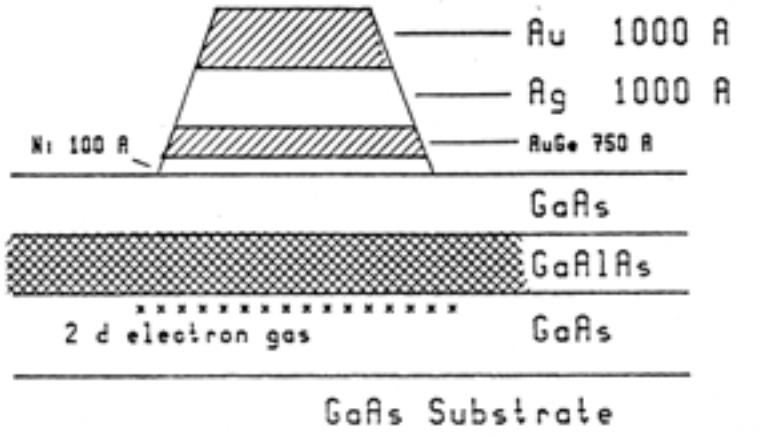
Depth Resolution

- Near surface
  - 3 nm in good case
  - 10 nm common
- Worse the deeper you go
- NOT A TOOL FOR MEASURING DEPTHS

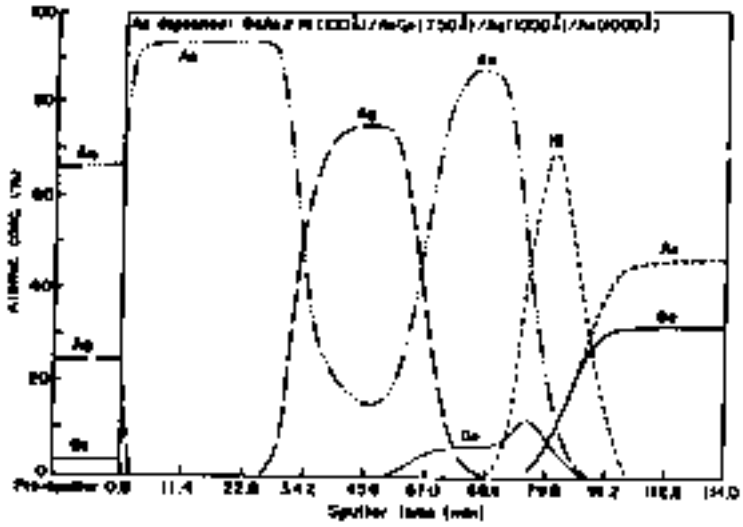
High Quality Depth Profile



Ohmic Contact Example



Ohmic Contact Profile



Summary-Depth Profiles

- Ion Milling allows extension of surface analysis technique into thin film analysis
- Localized high resolution depth profile
- Other methods of thin films analysis

Scanning Auger

- Powerful tool for surface characterization on a submicron scale
- Reasonable sensitivity
- Reasonable accuracy
- Reasonable speed
- High spatial resolution imaging !!

Auger Microprobe is----

- Not a tool for chemical analysis
- Not a tool for insulators
- Not a tool for trace elements
- Not a tool to measure film thicknesses
- Not a tool for bulk analysis

- Pick the right tool for the job

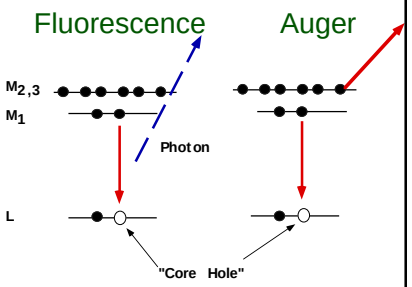
Electron Spectroscopy for Chemical Analysis

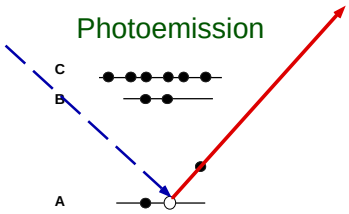
Chemical Information

- Auger
  - Elemental Information Only
  - Peaks are wide
- Chemical Information
  - Bond type
  - Valence
  - Compound identification
    - Graphite vs. diamond vs. CO vs. hydrocarbon..etc

ESCA or XPS

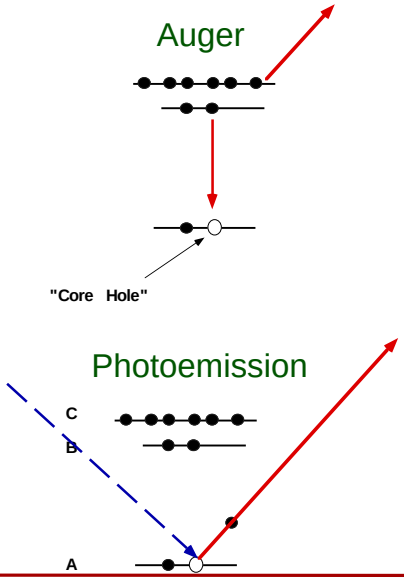
- X ray photo-emission
- Electron spectoscopy for chemical analysis
- A photo-emission process
  - X ray in
  - Electron out
  - A single core electron process





Electron Transitions

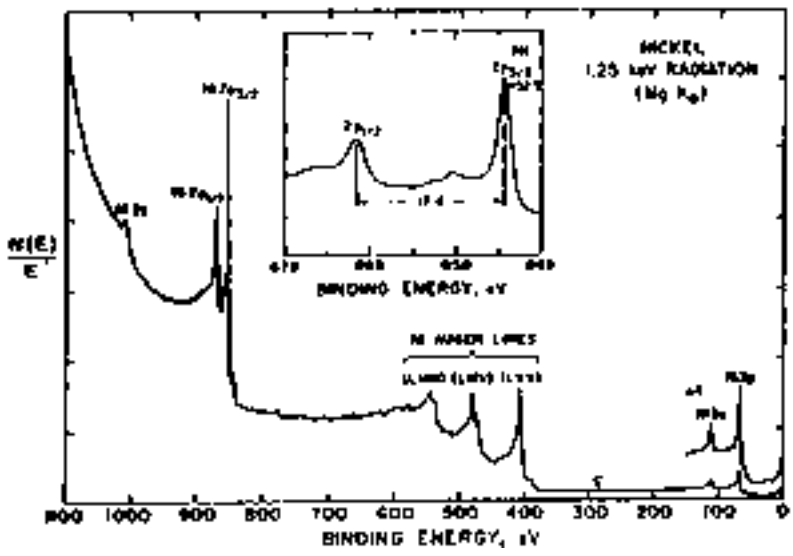
- **Auger**
  - 3 electron process
  - Wide
- **Photoemission**
  - 1 electron process
  - Core electron
    - Sharp narrow level
  - Bonding into valence levels changes core levels slightly by screening
  - Identify type of bonding



XPS

- **KE =hν-E_b**
- **Typically fixed energy x ray source ~ 1 keV**
- **Accurate measurements of absolute peak position**
  - **< 0.1 eV**

XPS Spectrum



XPS as an Analytical Tool

- Tables of peak positions
  - Type of bond or type of bonded species
- X ray source
  - Not focused well
  - Poor spatial resolution
  - 0.1 - 1 mm
- Surface Sensitive
  - UHV
- Can do insulators
  - Not significant charging effects

XPS as an Analytical Tool

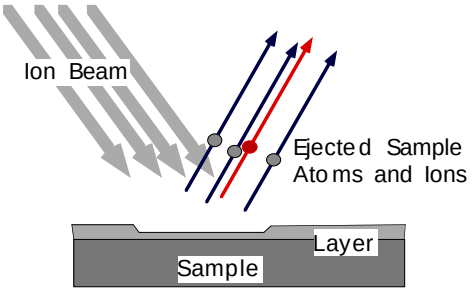
- Quite complementary to Auger
- Sacrifice spatial resolution and scanning for chemical information and insulators

- Common analysis tools in most industrial laboratories
- Research systems at CU but no generally accessible drop it in analytical tool

Secondary Ion Mass Spectroscopy

Secondary Ion Mass Spectroscopy (SIMS)

- **Ion Beam In**
  - Argon
  - Cesium
  - Oxygen
- **Sputtered Sample Out**
  - Inherently destructive
- **Analyze ions not atoms**
  - Major problem
  - Element variations
  - Conductivity variations



SIMS

- **Incredibly Sensitive for some materials**
  - Wide variation in sensitivity and detectibility
    - Between elements and between samples and compounds (conductivity)
  - Sensitivity to 1015/cc for Phosphorus in Si
    - Vs. 1019 or more for Auger/ESCA
- **Quantitation is difficult**

SIMS Applications

- Dopant Profiles
- Commercial services have best characterized instruments

Summary:

Thin Film and Microanalysis

Practical Thin Film Analysis

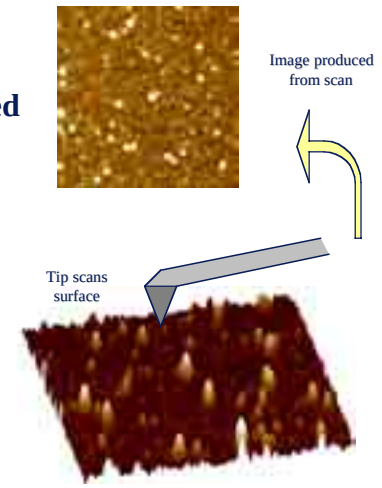
What is It?

Atomic Force Microscopy
(AFM)
by
John Treichler

Presented by the
CNF **Technical Staff**
for the education of CNF Users,
Potential Users, and Industrial Sponsors

Overview of AFM

- Probe scans surface
- Surface interacts with probe
- Surface interaction is interpreted
  - Topography
  - Friction/Adhesion
  - Viscoelasticity
  - Electric/Magnetic fields
- Two modes used at Cornell
  - Contact
  - Tapping



Advantages of AFM

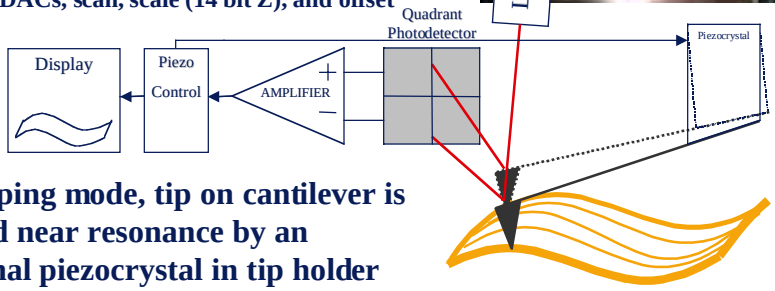
- Nondestructive measurements
- Angstrom to nanometer resolution in x, y, and z
- Material properties
- Can better separate between height and material differences
- Data format offers easy analysis of many surface characteristics
  - Roughness
  - Arbitrary slice angle
  - Data may be filtered

Limitations of AFM

- Surface profile is always convoluted with tip profile
  - Measured side wall angle is limited to tip angle
  - It can be difficult to separate surface and tip profile
- Limited range in x, y and z
- Surfaces with loose particles can not be cleanly imaged
- Tip control is not closed loop on CNF AFM
  - Small slope changes can not be separated from piezocrystal nonlinearities
- High resolution scans can be time consuming

Operation

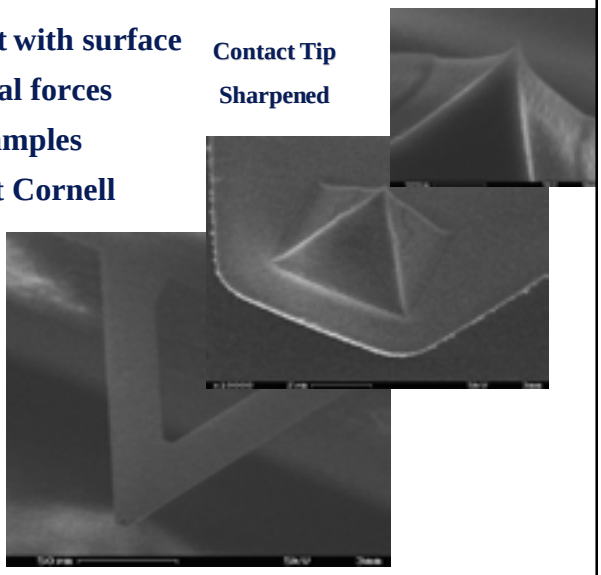
- Tip deflection is sensed by reflected laser spot on photodetector
- Tip is moved in X, Y and Z by piezocrystals
  - Maximum range: 100um X & Y, 5um Z
  - 16 bit DACs, scan, scale (14 bit Z), and offset
- For tapping mode, tip on cantilever is vibrated near resonance by an additional piezocrystal in tip holder



Contact Mode

- Tip maintains contact with surface
- Can measure frictional forces
- Can damage softer samples
- Not in common use at Cornell

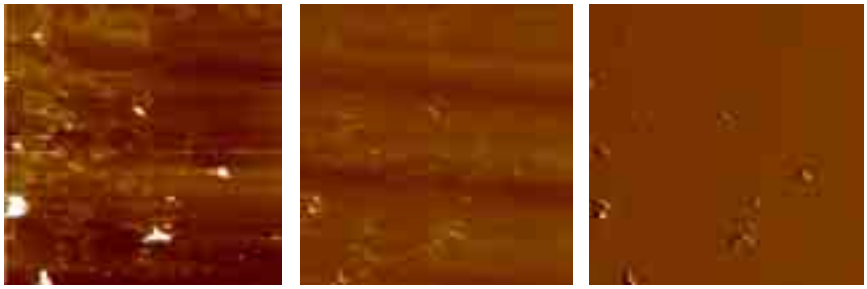
Contact Tip
Sharpened



Contact Mode

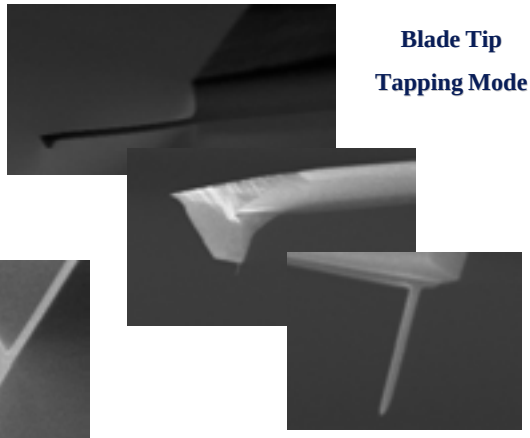
- Same sample
  - Data are: height, friction, and deflection

Height | Friction | Deflection



Tapping Mode

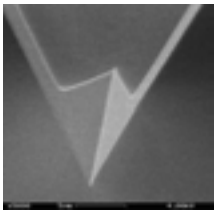
- Tip on resonating cantilever makes intermittent contact with surface
- Amplitude of oscillation decreases as tip strikes surface
- Avoids friction and adhesion to surface fluid layer or trapped charges



Blade Tip

Tapping Mode

X 30,000

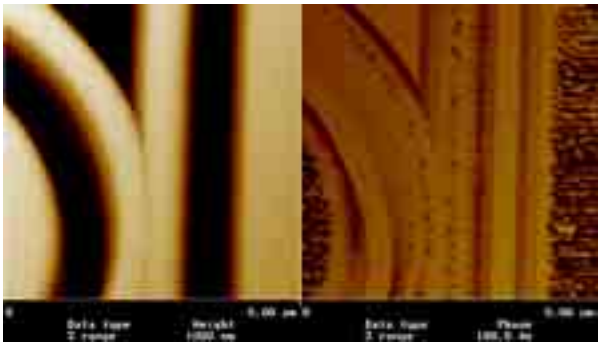


Supplied Tip

Radius is 5 to 10nm

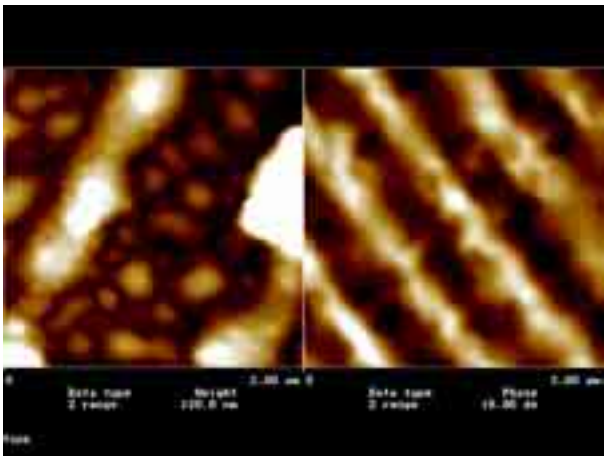
Phase Plots

- Phase of cantilever relative to driving voltage can be plotted
- Phase plots can show variations in composition, adhesion, and viscoelasticity
- Surface can simultaneously be scanned for height and phase

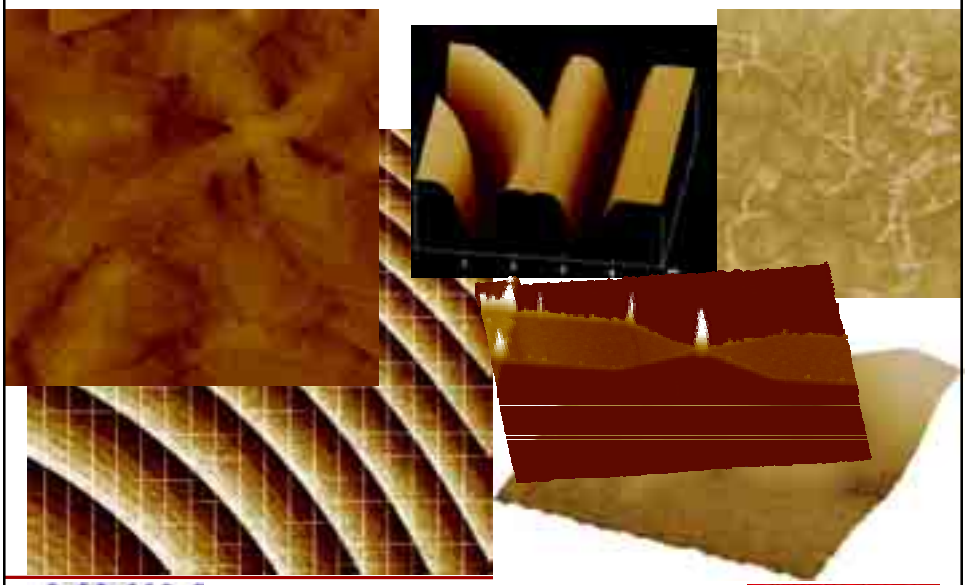


Phase and Interleave Scanning

- Interleave scanning
  - Surface is scanned for height, tip is lifted, and surface is rescanned for phase
  - Used to image electric and magnetic fields



Tapping Mode, Images From Users



Imaging Problems

- Improper scan parameters
- Dirty or worn tip profile is convolved with sample's profile
- Dirty sample
- Vibration
- Sample too flexible