

# **EE6601 Advanced Wafer Processing**

## **Metrology and Analytical Techniques**

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# Metrology and Analytical Techniques

- Optical Characterization
- Charge-Based Characterization
- Electron Beam Characterization
- Ion Beam Characterization



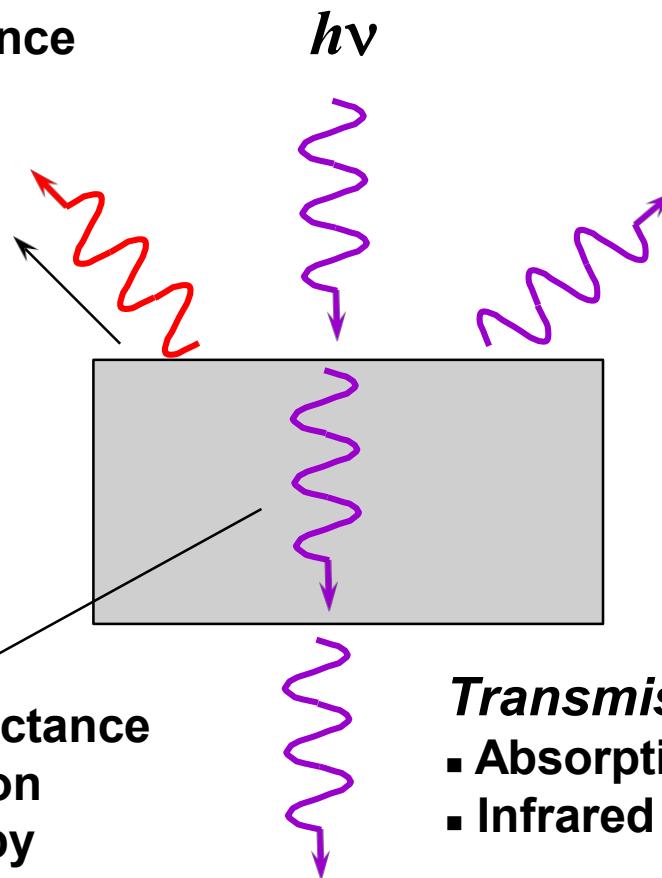
# Optical Characterization

- Optical Microscopy
- Ellipsometry
- Transmission
- Photoluminescence

# Optical Excitation

## Emission

- Photoluminescence
- Raman Spectroscopy
- UV Photoelectron Spectroscopy



## Reflection

- Optical Microscopy
- Ellipsometry
- Reflection Spectroscopy

## Absorption

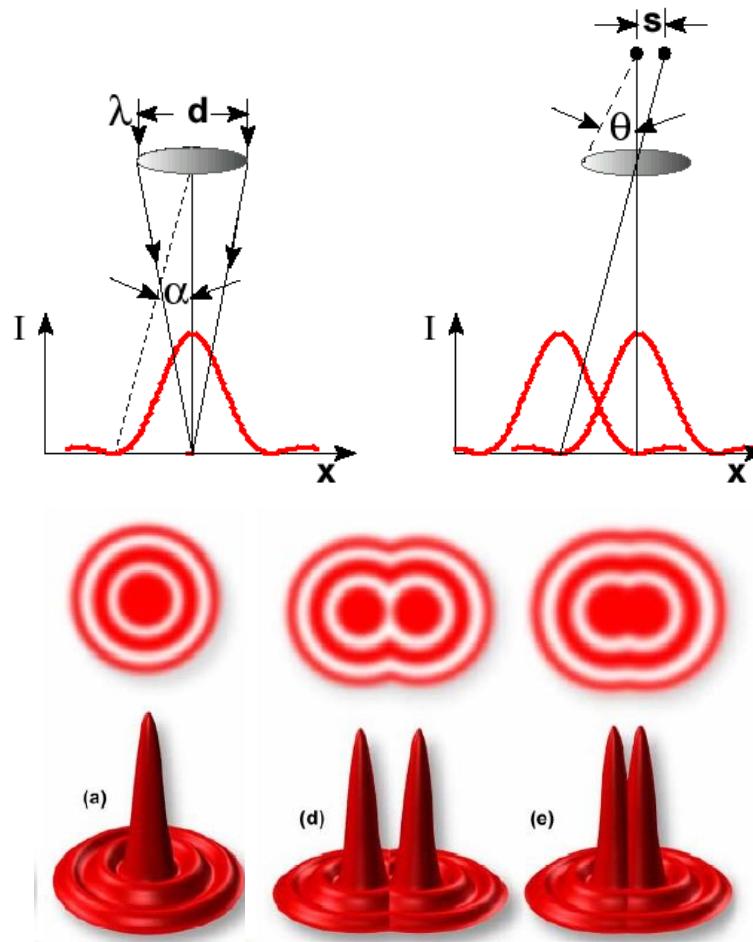
- Photoconductance
- Photoelectron Spectroscopy

## Transmission

- Absorption Coefficient
- Infrared Spectroscopy

# Optical Microscopy

- Light cannot be focused to an infinitesimally small spot due to the wave nature of light

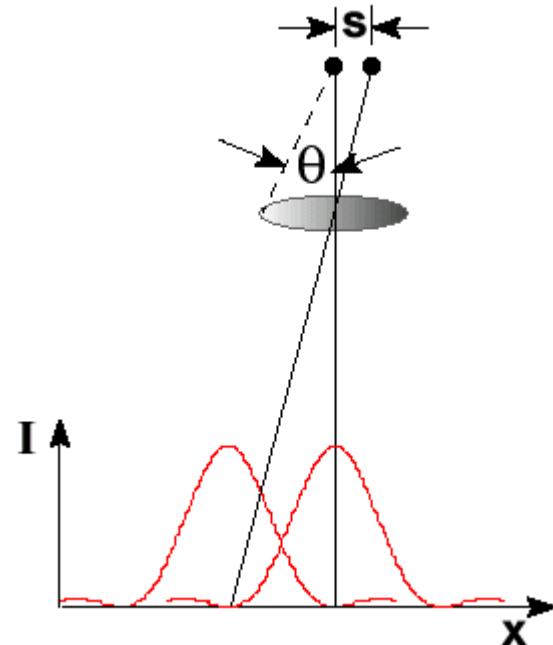


# Optical Microscopy

- There is no lower limit to the size of an *isolated* object that can be detected
- The minimum separation,  $s$ , of two point objects occurs when the first maximum of the diffraction pattern of one object falls on the first minimum of the second object

$$s = \frac{0.61\lambda}{n \sin \theta} = \frac{0.61\lambda}{NA}$$

- $\lambda$  = free space wavelength,  
 $n$  = refractive index of immersion medium,  $\theta$  = half the angle subtended by the lens at the object,  $NA$  = numerical aperture

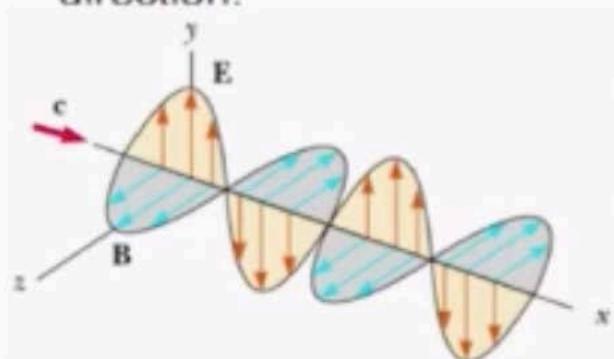


*Best resolution about  $0.25 \mu m$   
for  $\lambda \approx 0.4 \mu m$ ,  $NA \approx 1$*

## Polarization of Light Waves

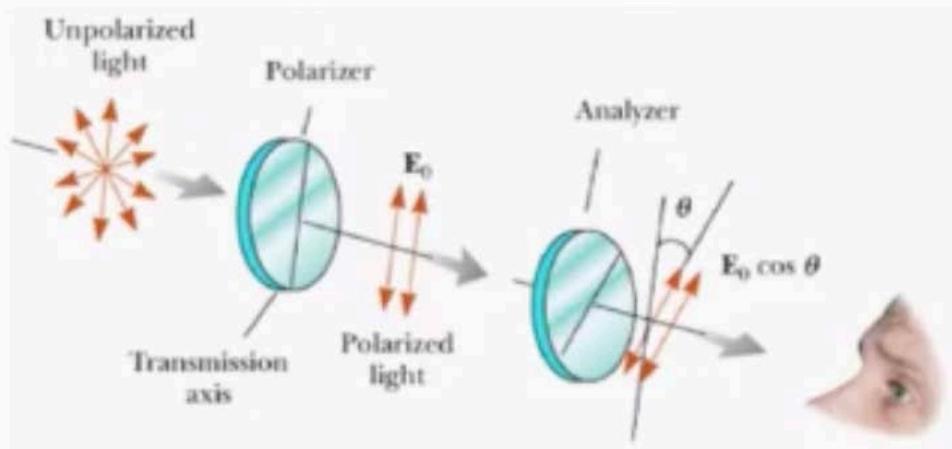
- \* Light is not just a wave but it is a **transverse wave**.
- \* Distinguishing characteristic of transverse wave is that their oscillating motion occurs in planes perpendicular to the propagation direction.

*Maxwell*



The **direction of polarization** of each individual wave is defined to be the **direction in which the electric field is vibrating**.

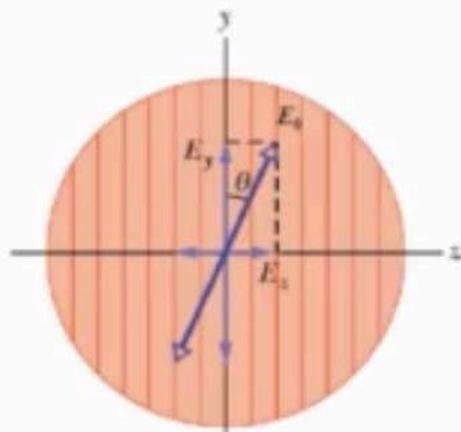
## Polarization by Selective Absorption (Polarizer)



$$E_y = E_0 \cos \theta$$

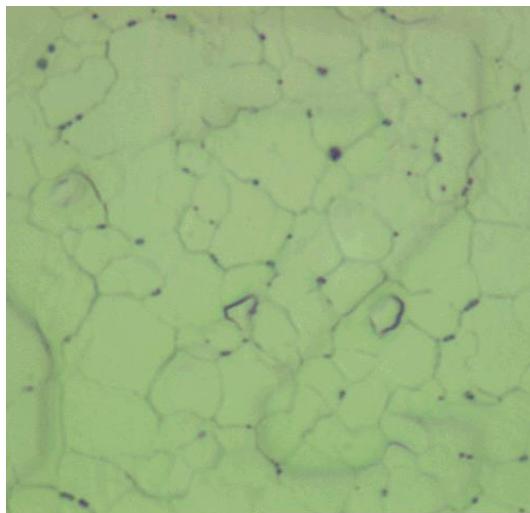
- \* Intensity of electromagnetic wave is proportional to the square of the electric field's magnitude.

$$I = (E_y)^2 = E_0^2 \cos^2 \theta = I_0 \cos^2 \theta$$

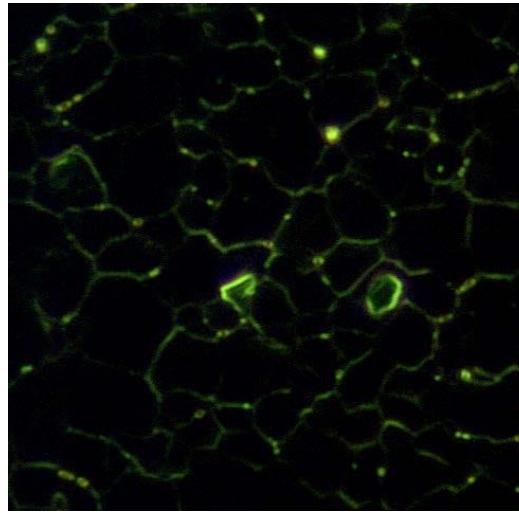


# Optical Microscopy

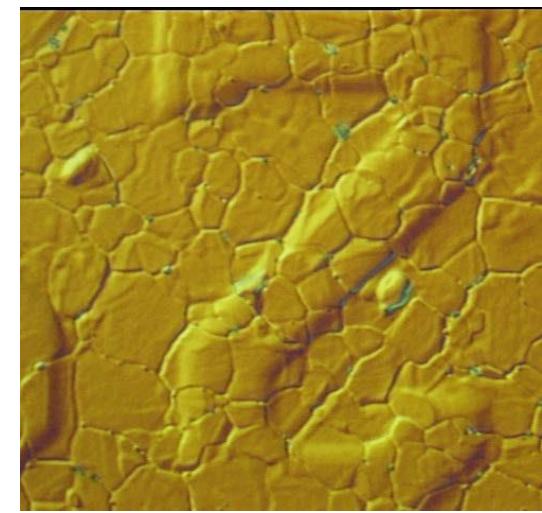
- Different approaches to optical microscopy bring out different features



**Bright Field**



**Dark Field**



**Interference  
Contrast**

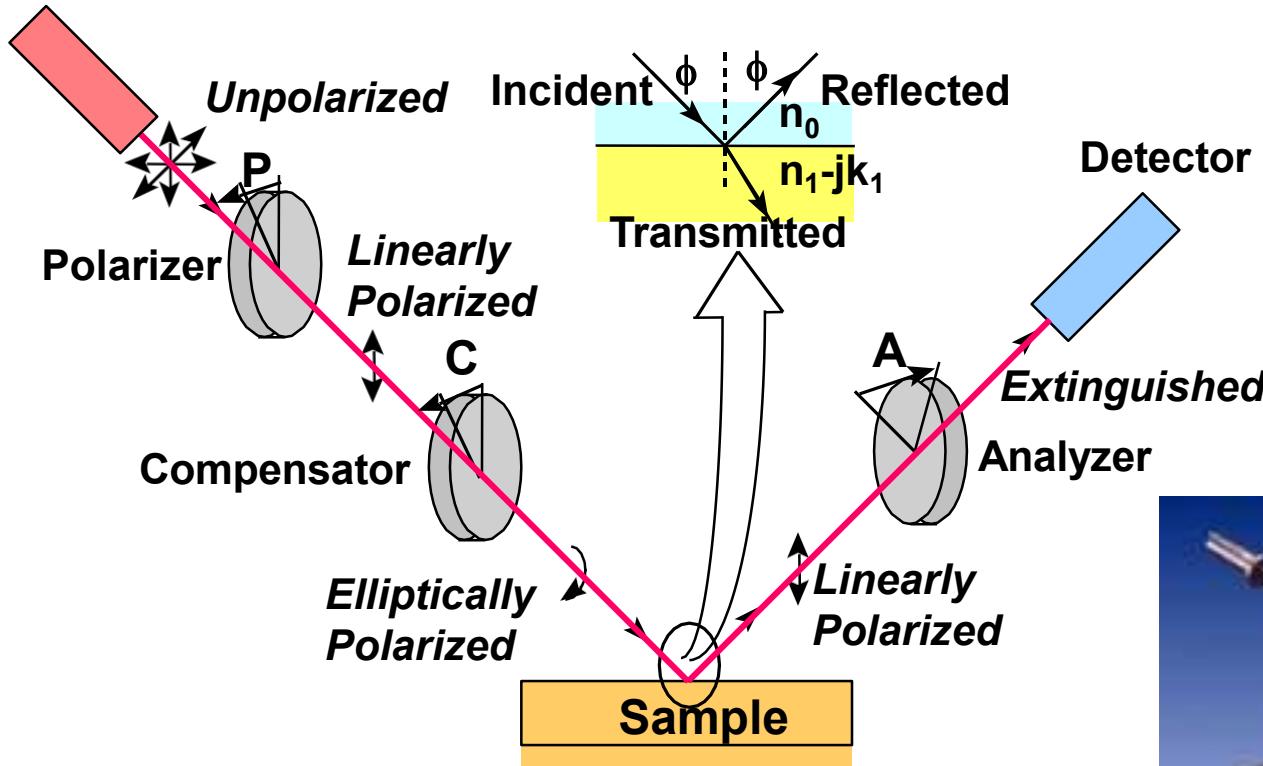
# Ellipsometer

- ◆ Angles P, C, and A lead to ellipsometer quantities  $\rho$ ,  $\Psi$  and  $\Delta$

$$\rho = \tan \Psi e^{j\Delta}$$

The ellipsometry equation!

Laser



# Ellipsometry

- Nondestructive technique
- Film thickness measurement; can measure film thicknesses down to 1 nm
- Refractive index determination; can measure refractive index of thin films of unknown thickness
- Azimuth angles can be measured with great accuracy
- Measures a ratio of two values
  - ◆ Highly accurate and reproducible (even in low light levels)
  - ◆ No reference sample necessary
  - ◆ Not as susceptible to scatter, lamp or purge fluctuations
- Surface uniformity assessment
- Composition determinations
- Can be used for *in situ* analysis

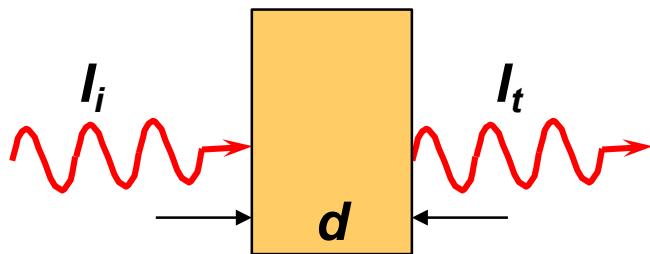
# Transmission / Absorption

## Definition

- Absorption - the loss of a photon from an incident flux by the process of exciting an electron from a lower- to a higher-energy state

## General Scheme

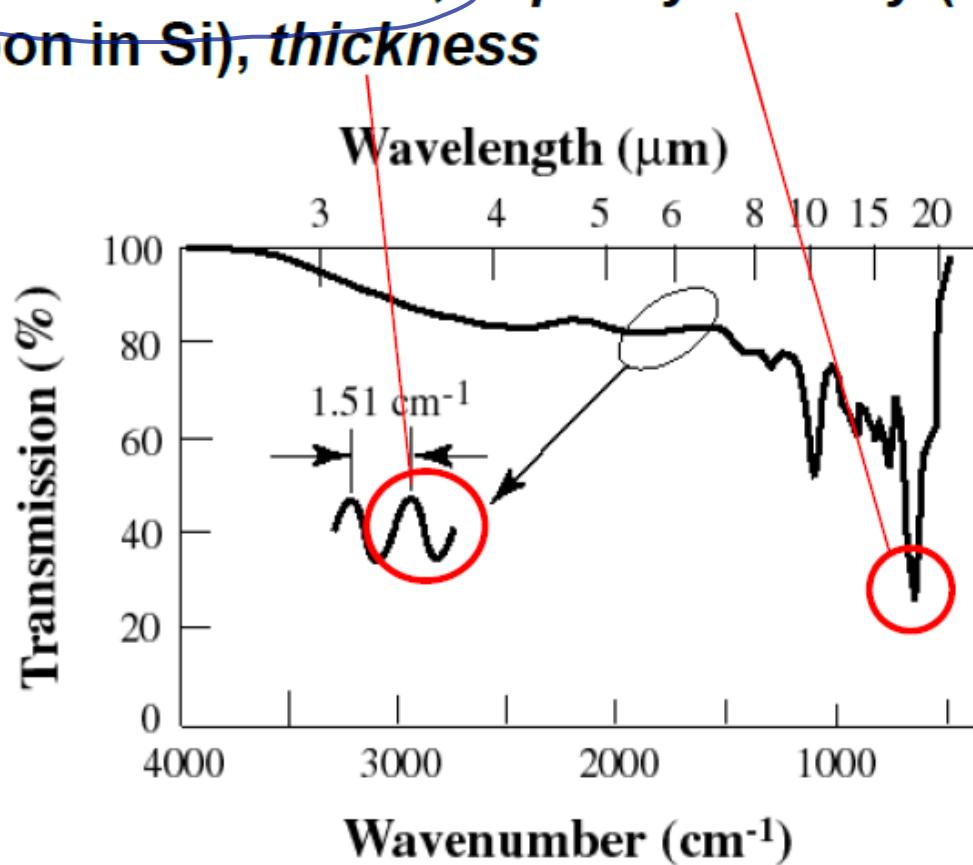
- Light is incident on a thin sample part of the light is reflected and the remainder is absorbed or transmitted; a measurement is made of the transmitted intensity
- The experiment can be carried out as a function of temperature, externally applied fields, sample thickness, etc.



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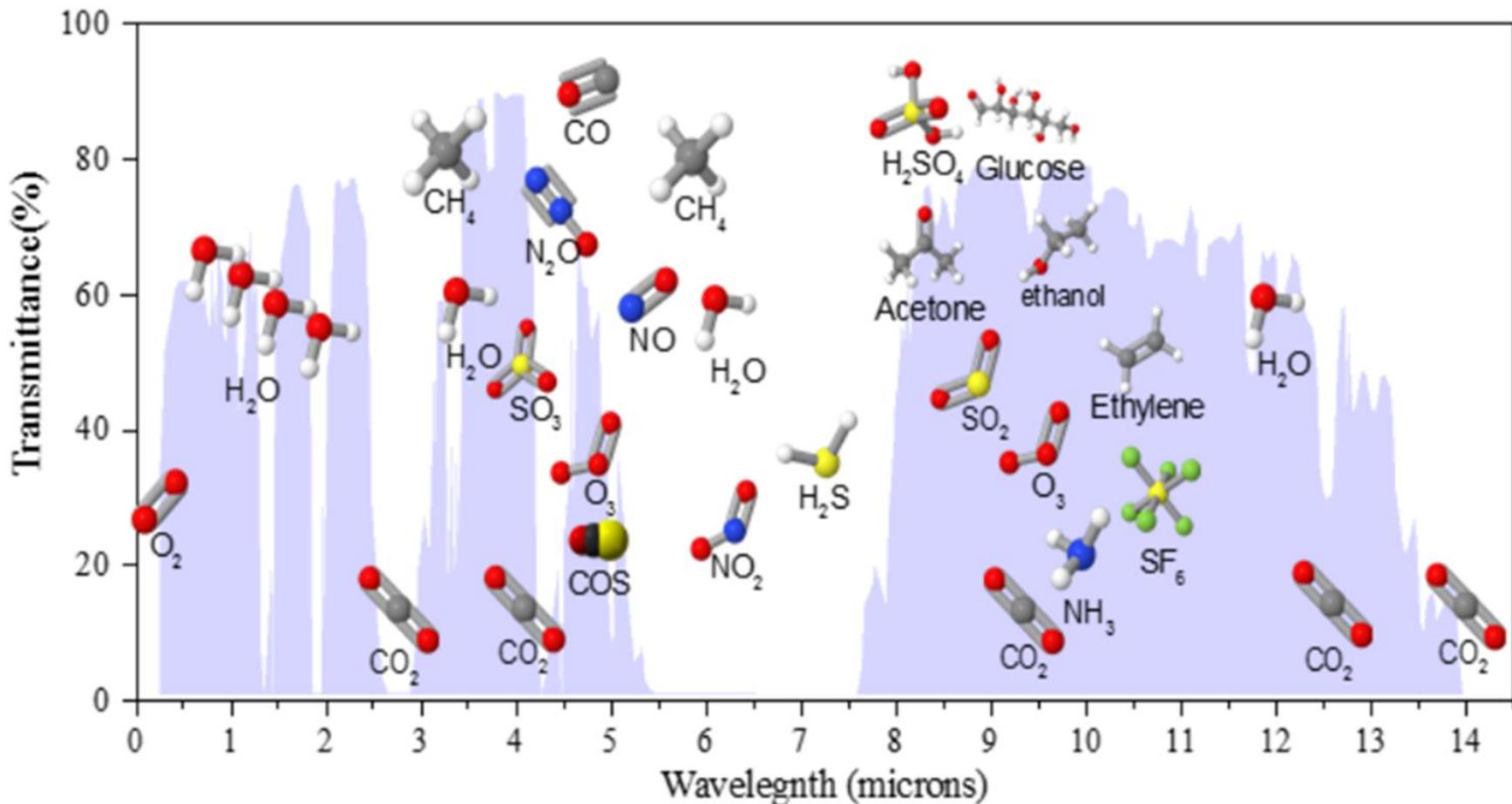
## Transmission

- Gives **absorption coefficient, impurity density (e.g., oxygen, carbon in Si), thickness**



# Absorption

*α. L*



*IR*

发光

# Luminescence

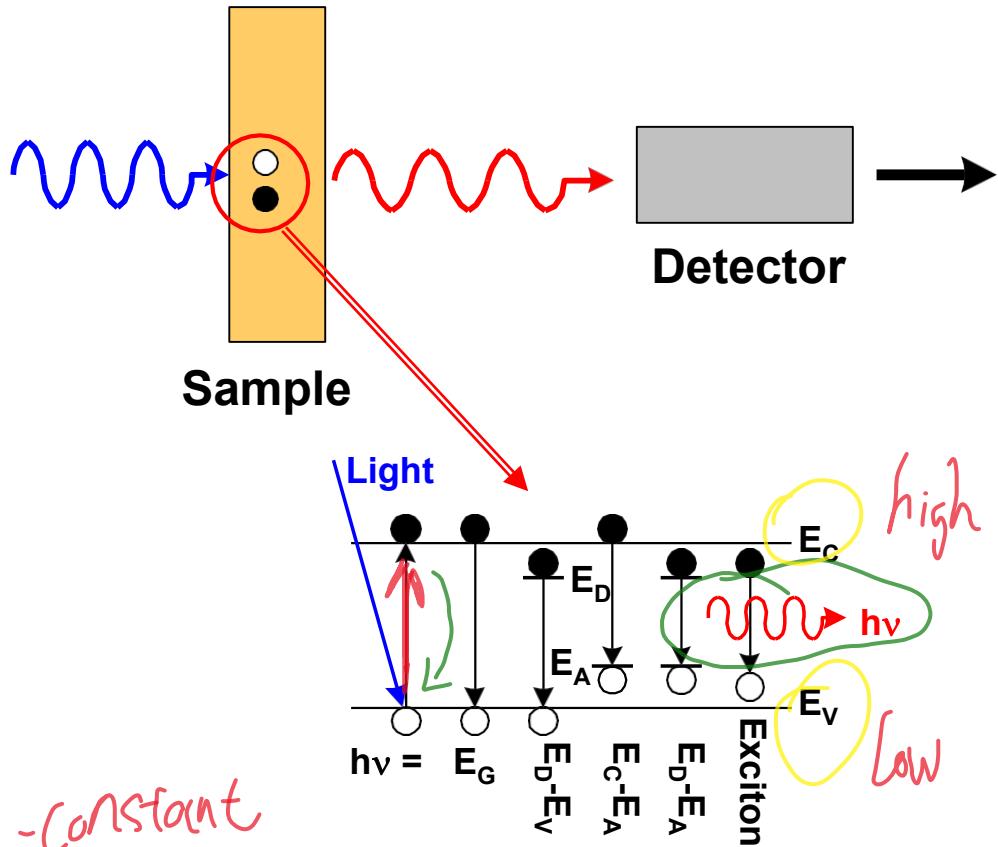
$$E = h \cdot V$$

Luminescence is the emission of light due to:

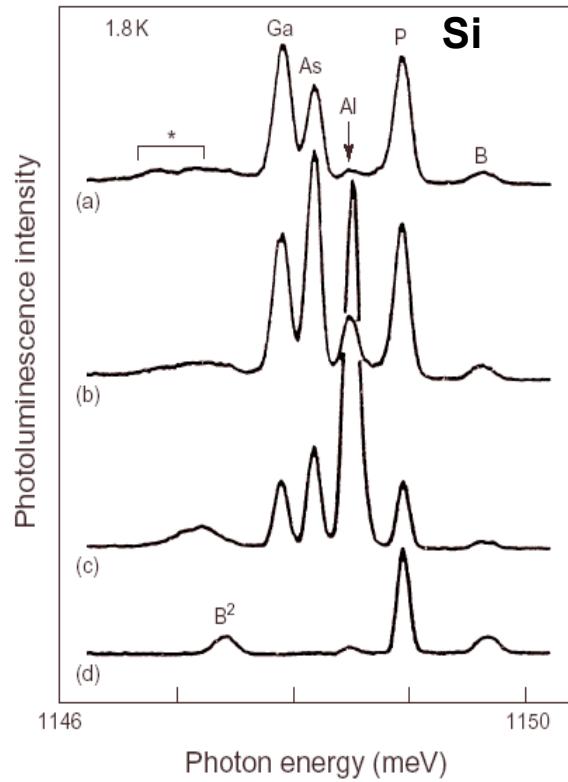
- Incandescence: energy supplied by heat
- Photoluminescence: energy supplied by light
- Fluorescence: energy supplied by ultraviolet light
- Chemiluminescence: energy supplied by chemical reactions
- Bioluminescence: energy supplied by chemical reactions in living beings
- Electroluminescence: energy supplied by electric current/voltage
- Cathodoluminescence: energy supplied by electron beams.
- Radioluminescence: energy supplied by nuclear radiation
- Phosphorescence: delayed luminescence or "afterglow"
- Triboluminescence: energy supplied by mechanical action
- Thermoluminescence: energy supplied by heat

# Photoluminescence

- Incident laser creates electron-hole pairs (ehp)
- When the ehp recombine, they emit light



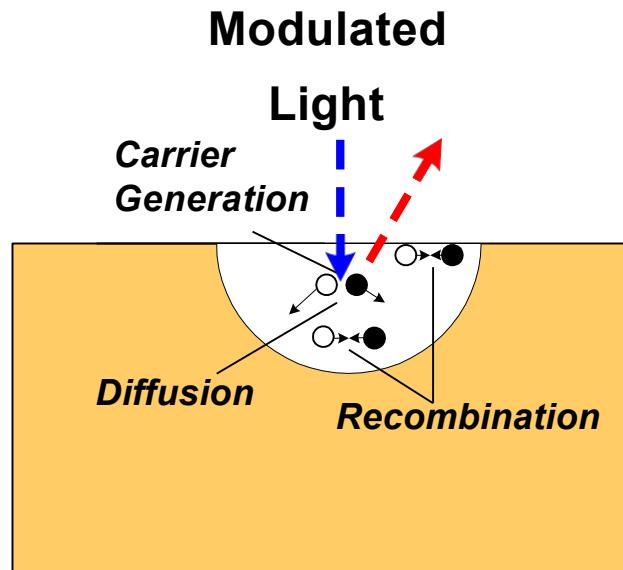
$h$ -constant  
 $\nu$ : frequency



# How Does PL Work And How Can It Be Used?

- Carrier generation depth
  - Wavelength  $\Rightarrow$  **depth information**
- Recombination
  - Shockley-Read-Hall (impurities)  $\Rightarrow$  **impurity information**
  - Auger (high carrier densities)  $\Rightarrow$  **doping density information**
  - Surface (surface states, impurities)  $\Rightarrow$  **surface information**
  - Radiative (light emission)  $\Rightarrow$  **detection mechanism**

*This is what we want!*



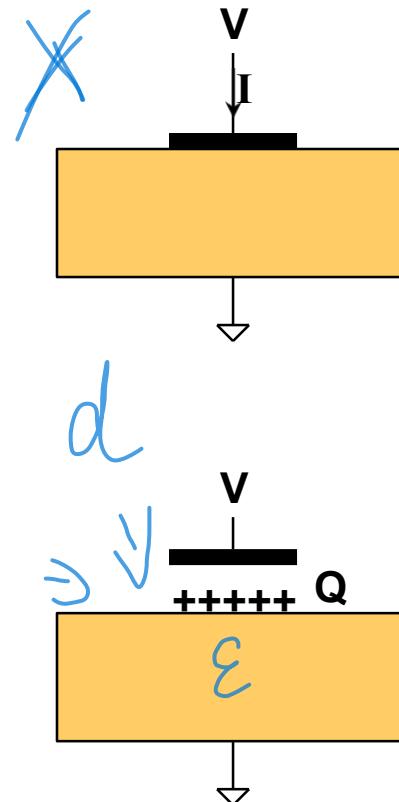
# Charge-Based Measurements Probe Characterization

on surface

- Scanning Tunnelling Microscopy
- Atomic Force Microscopy

# Charge-Based Measurements

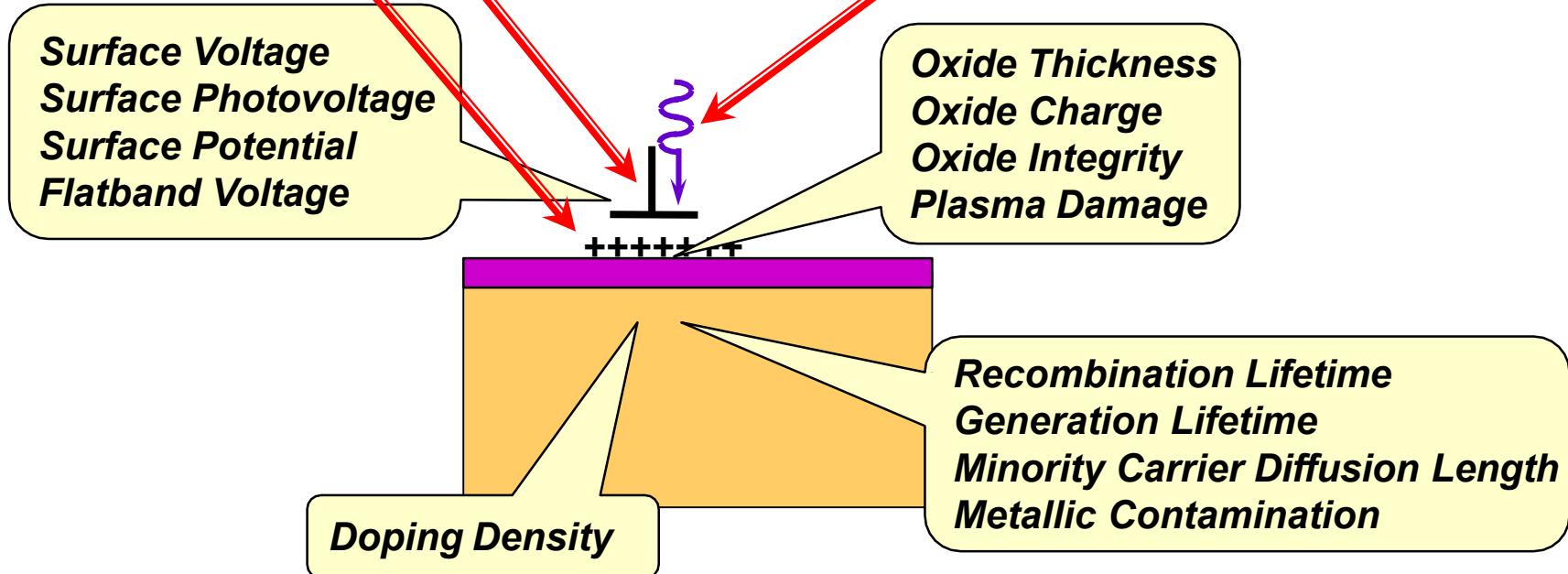
- **Traditional**
  - Current – voltage
  - Capacitance – voltage
  - Current, voltage, capacitance – time
  - Usually need test structure with contacts
- **New**
  - Deposit charge
  - Measure surface voltage, surface photovoltage
  - Use charge, light
  - Usually contactless



# Charge-Based Measurements

- Charge is deposited on the wafer *chemically* or by *corona charge*
- Contactless surface voltage/surface photovoltage is measured
- Measurement can be enhanced with *light*

ionization of a fluid



# Probe Microscopy

- Probe microscopy was invented in 1980 By Binnig and Rohrer at IBM Labs. in Zürich, Switzerland
- They devised a clever way of bringing a sharp metal tip very close (within 1-2 nm) to a conducting sample, applied a voltage and measured the current
- This technique is known a scanning tunneling microscopy
- For this work they were awarded the Nobel prize in 1986



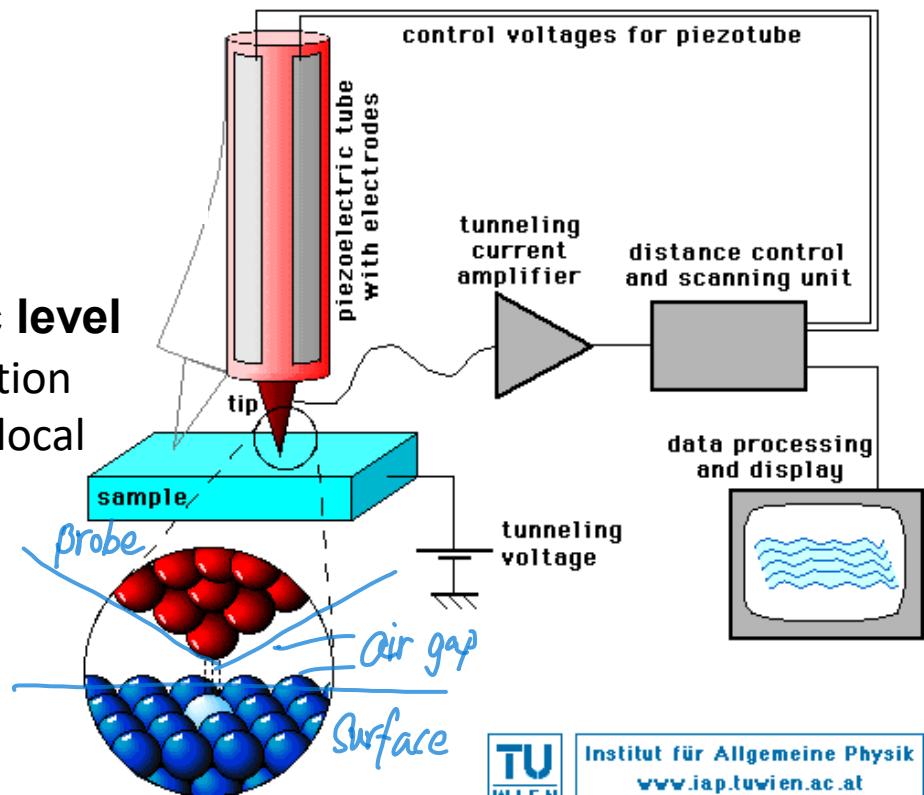
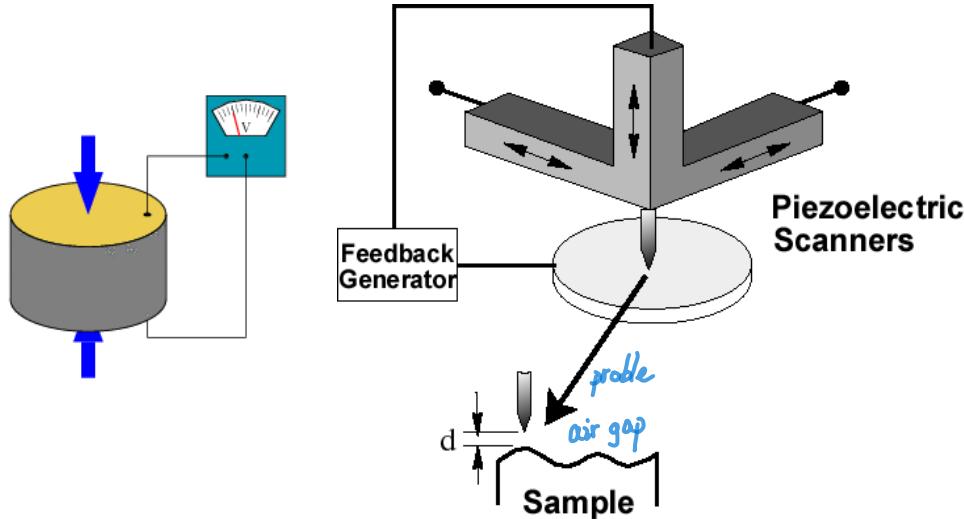
G. Binnig



H. Rohrer

# Scanning Tunneling Microscopy (STM)

- STM relies on electron tunneling through an air gap



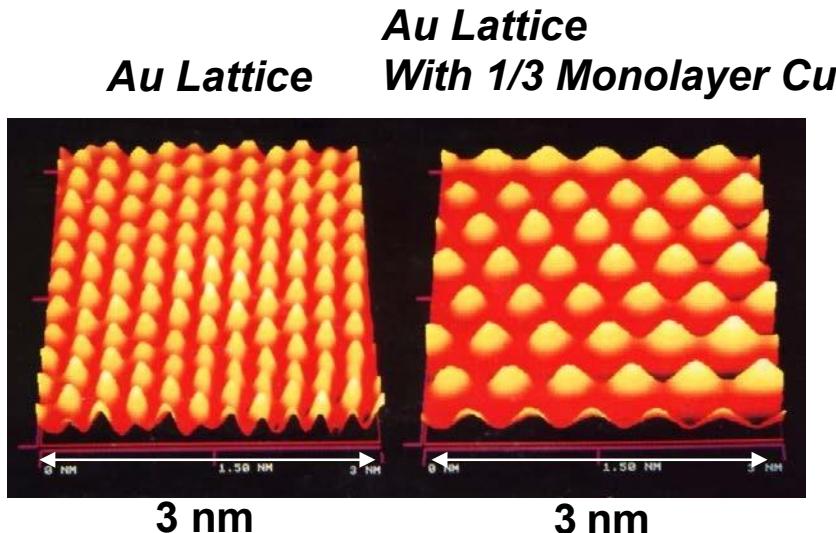
For imaging surfaces at the atomic level

The resulting tunneling current is a function of tip position, applied voltage, and the local density of states (LDOS) of the sample.

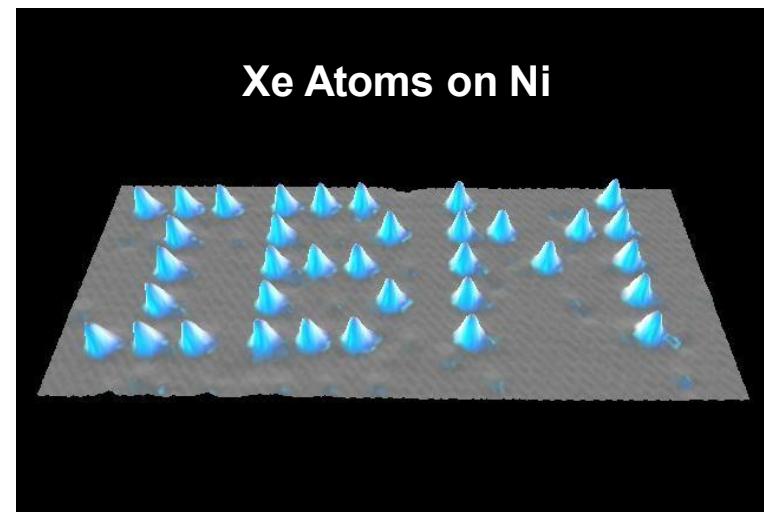
It requires extremely clean and stable surfaces, sharp tips, excellent vibration control, and sophisticated electronics.

# STM Images

- STM images can have atomic resolution



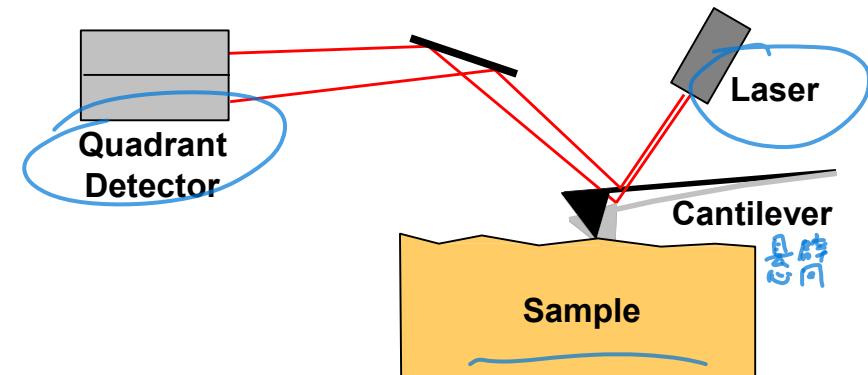
Courtesy of Topometrix



Scanning speed (aw).

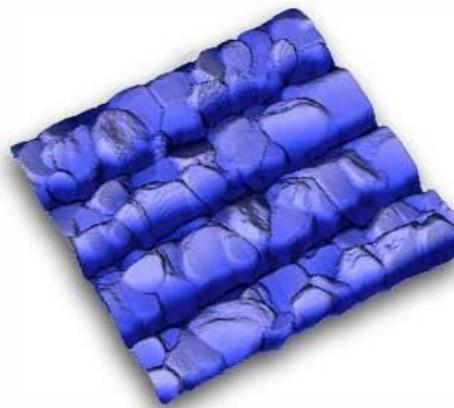
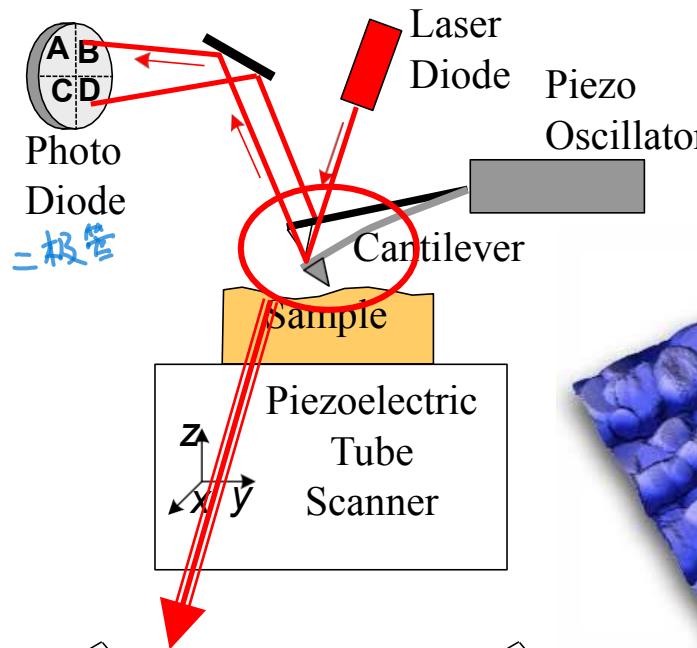
# Atomic Force Microscopy (AFM)

- A sharp tip is scanned over a surface with feedback
- Piezo-electric scanners maintain the tip at
- **Constant force**
  - Height information
- **Constant height**
  - Force information

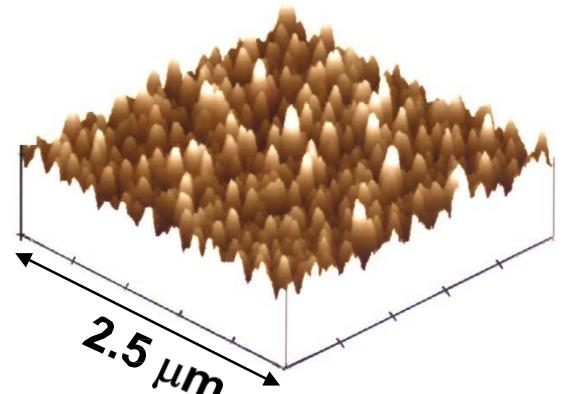


- Tips are typically made from  $\text{Si}_3\text{N}_4$  or Si
- The detector measures the difference in light intensities between the upper and lower photodetectors
- Feedback from the photodiode difference signal enables the tip to maintain either a **constant force** or **constant height**

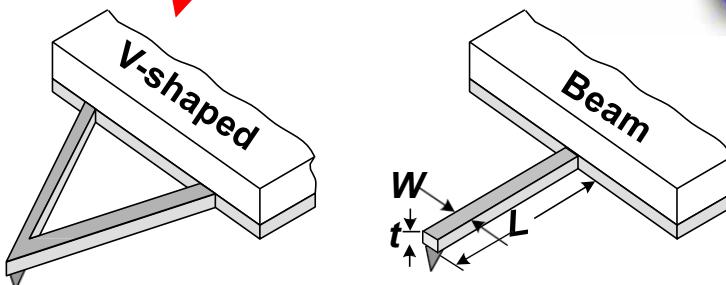
# Atomic Force Microscopy



Epi Si; rms  $\sim 0.7 \text{ \AA}$



Poly Si; rms  $\sim 60 \text{ \AA}$



# Atomic Force Microscopy

## ■ Contact mode High resolution

- ◆ Tip scans the sample in close contact with the surface
- ◆ The repulsive force on the tip is around  $10^{-8}$  N
- ◆ This force is set by pushing the sample against the cantilever with a piezoelectric element
- ◆ The piezo voltage is proportional to sample height

## ■ Non-contact mode Low resolution

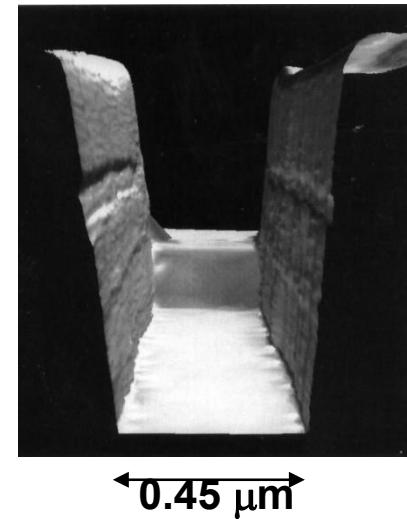
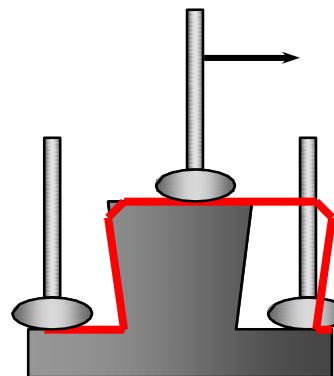
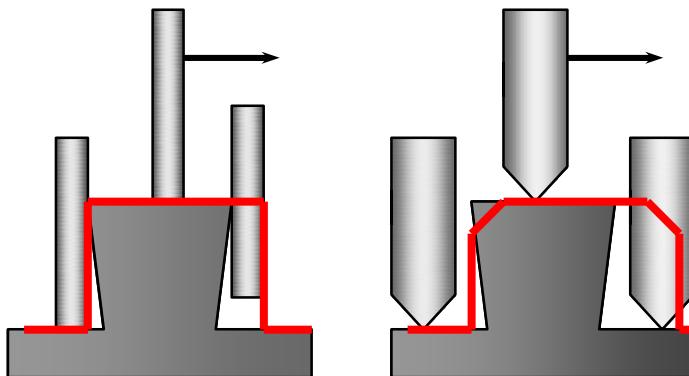
- ◆ Tip is 5-15 nm above the sample surface. Attractive Van der Waals forces acting between the tip and the sample are detected, and topographic images are constructed by scanning the tip above the surface

## ■ Tapping mode

- ◆ Cantilever oscillates at its resonant frequency (50-500 kHz)
- ◆ The cantilever oscillates with a high amplitude (around 20nm) when the tip is not in contact with the surface
- ◆ The oscillating tip is then moved toward the surface until it begins to lightly touch, or tap the surface
- ◆ Oscillation amplitude is reduced
- ◆ The reduction in oscillation amplitude is used to measure surface features

# Atomic Force Microscopy

- Measured line width is probe shape dependent
  - ◆ Tip shape obtained from profiling standard samples
  - ◆ True profile is obtained from known probe tip shape
- Probe shape, flexing stability
- Piezoelectric scan linearity
- Low throughput

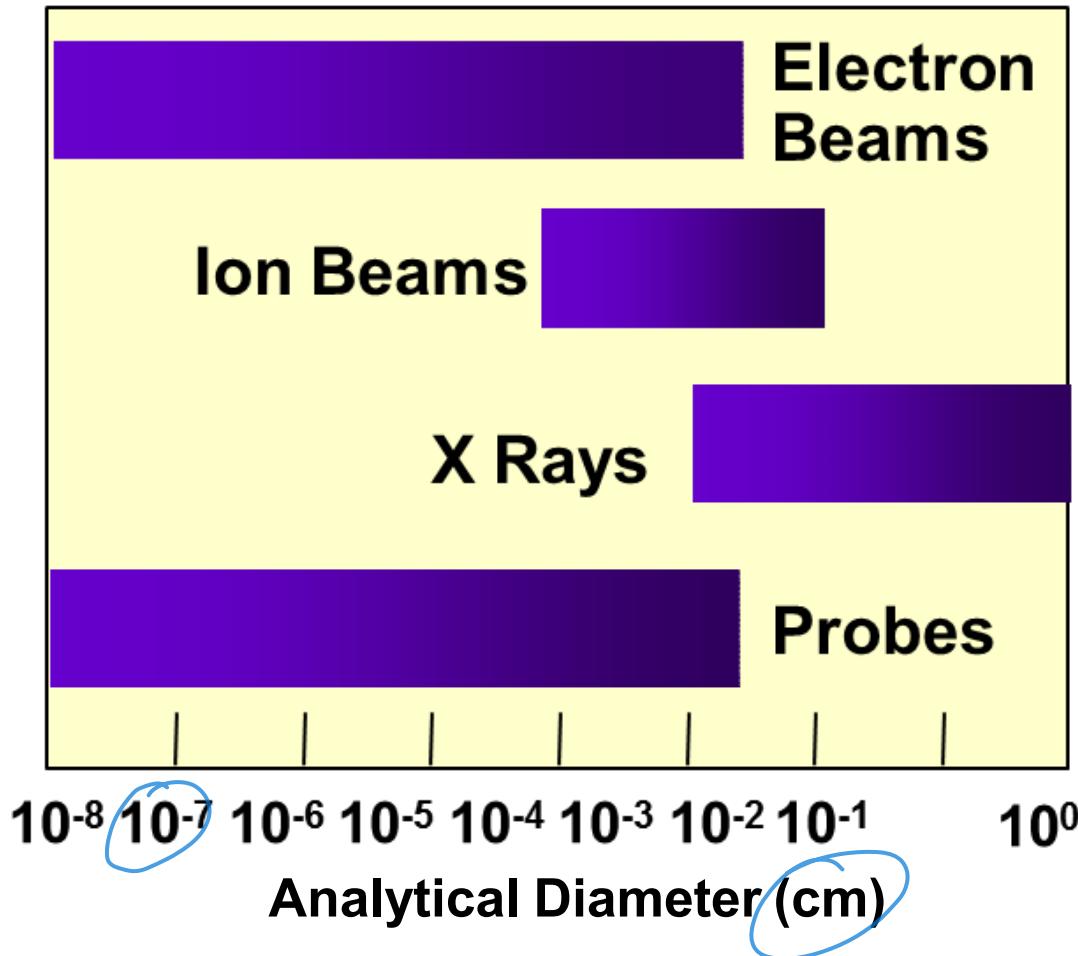


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## Electron Beam Characterization

- Scanning Electron Microscopy
- Transmission Electron Microscopy
- Electron Microprobe

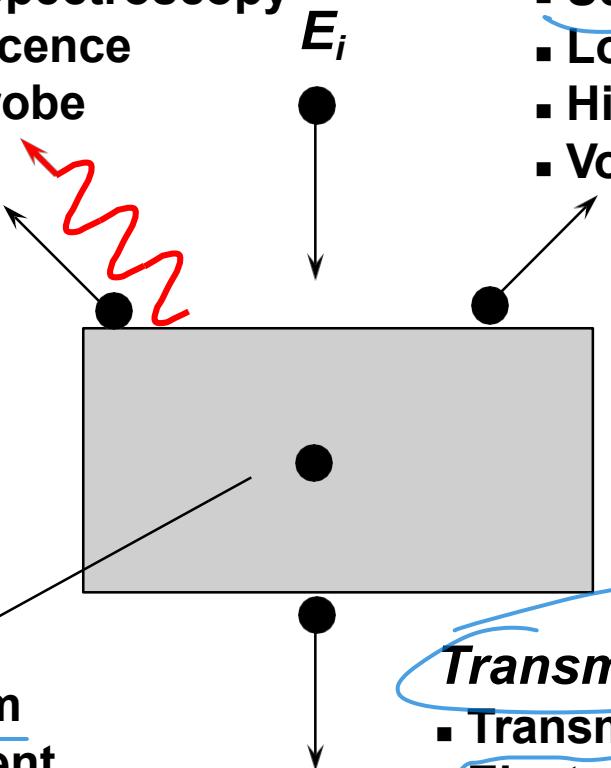
# Sampled Area



# Electron Beam Characterization

## Emission

- Auger Electron Spectroscopy
- Cathodoluminescence
- Electron Microprobe



## Reflection

- Scanning Electron Microscopy
- Low Energy Electron Diffraction
- High Energy Electron Diffraction
- Voltage Contrast

## Absorption

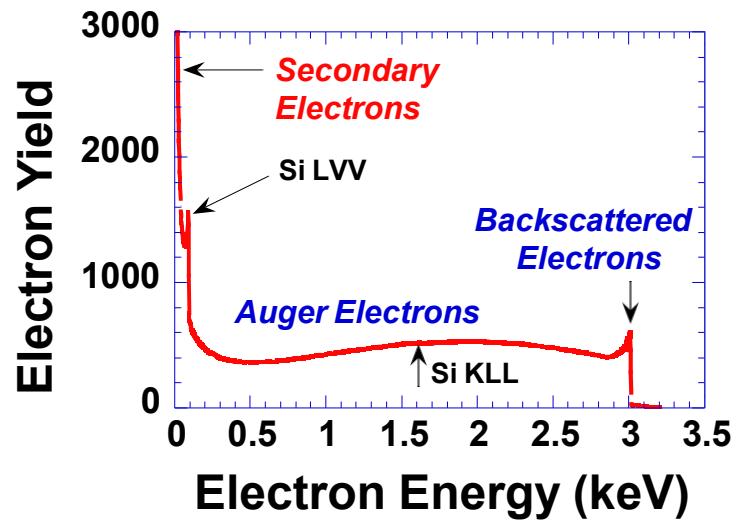
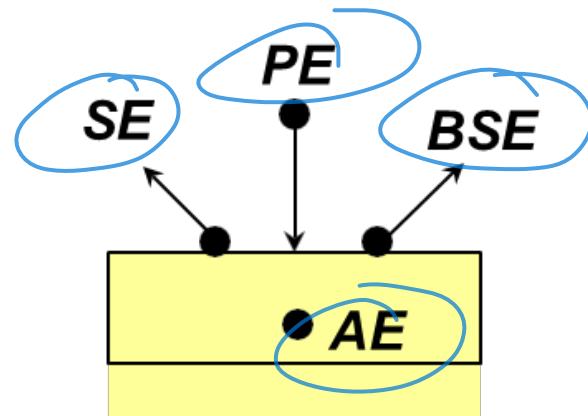
- Electron Beam Induced Current

## Transmission

- Transmission Electron Microscopy
- Electron Energy Loss Spectroscopy

# Electron Yield

- Primary electrons (*PE*) incident on a solid give:
  - ◆ Absorbed electrons (*AE*)
  - ◆ Secondary electrons (*SE*)
  - ◆ Backscattered electrons (*BSE*)
- Secondary electron yield maximum at  $E \approx 1\text{-}3 \text{ eV}$
- *SEs* used in scanning electron microscopy (SEM) and voltage contrast



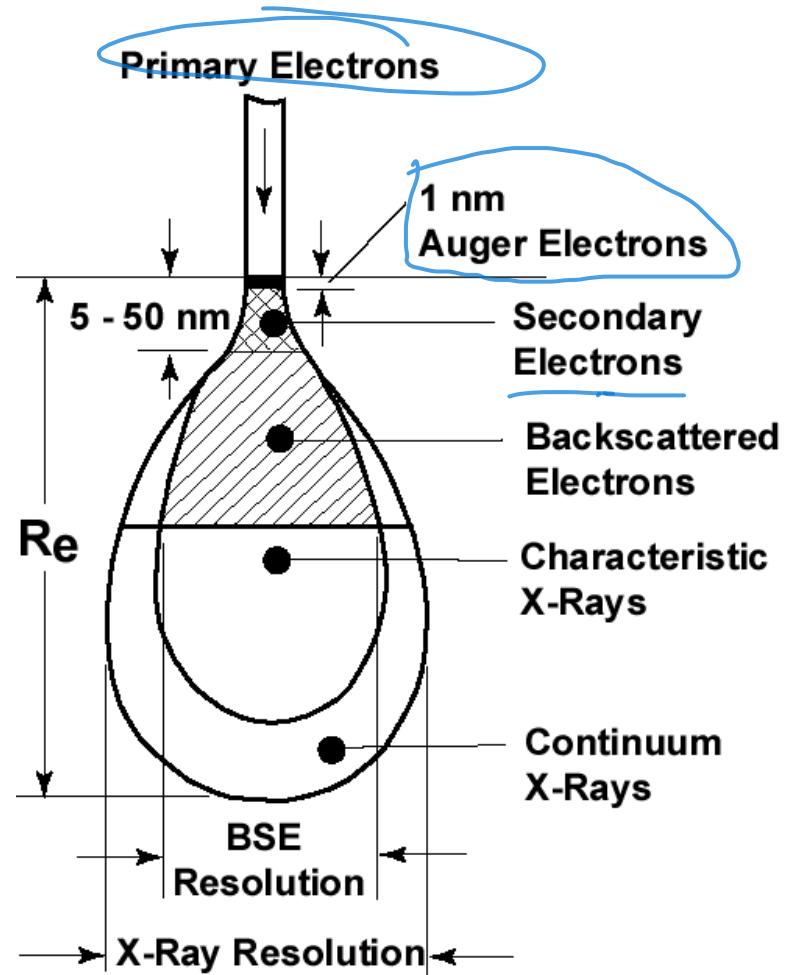
# Electrons in a Solid

- Electrons accelerated to 1 - 30 keV
- Beam can be focused to a few Angstrom diameter
- In the solid the beam “blooms” out to electron range  $R_e$

$$R_e = \frac{4.28 \times 10^{-6} E^{1.75} (\text{keV})}{\rho (\text{density})} \text{ cm}$$

$$R_e = 1.84 \times 10^{-6} E^{1.75} (\text{for Si}) \text{ cm}$$

$$R_e \approx 1 \mu\text{m} \text{ for } E = 10 \text{ keV in Si}$$



- Since secondary's come from liberated core electrons, their energies are low and thus, only near surface electrons escape.

# Scanning Electron Microscopy (SEM)

The electrons interact with atoms in the sample, producing various signals that contain information about the sample's surface topography and composition

- **Routinely used for semiconductors**

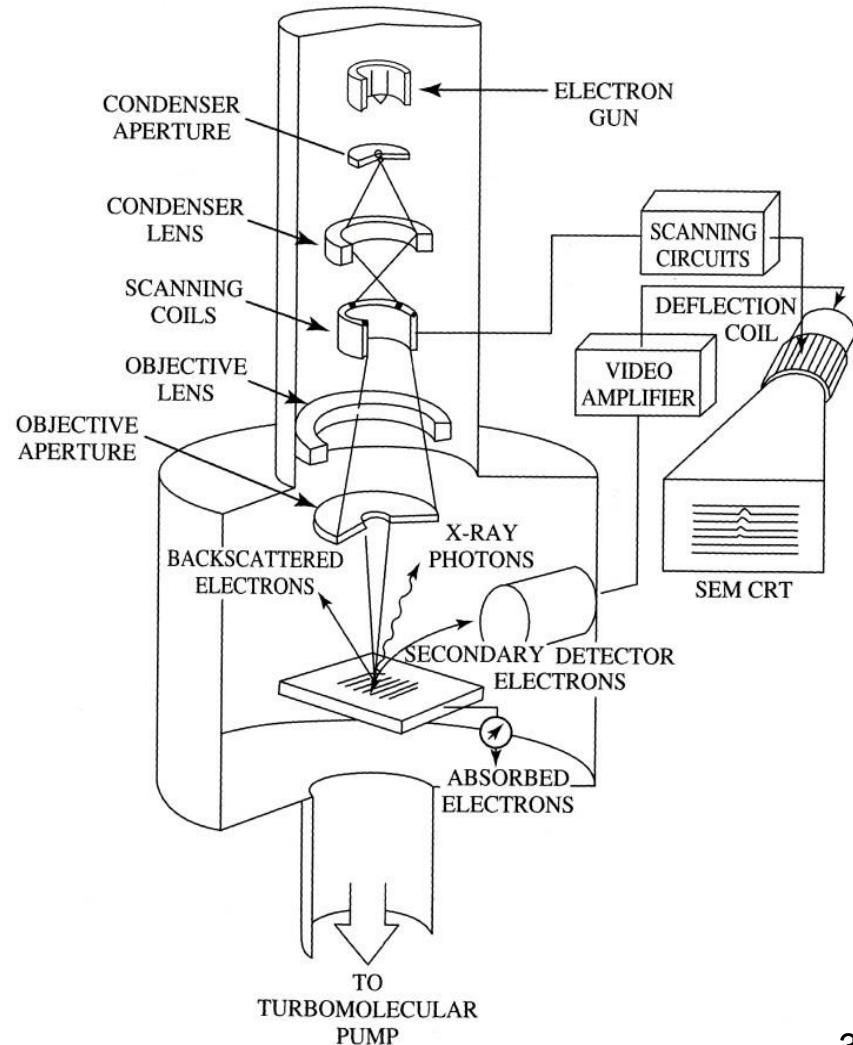
- Line width
- Topology

- **Cathodoluminescence**

- Light emission

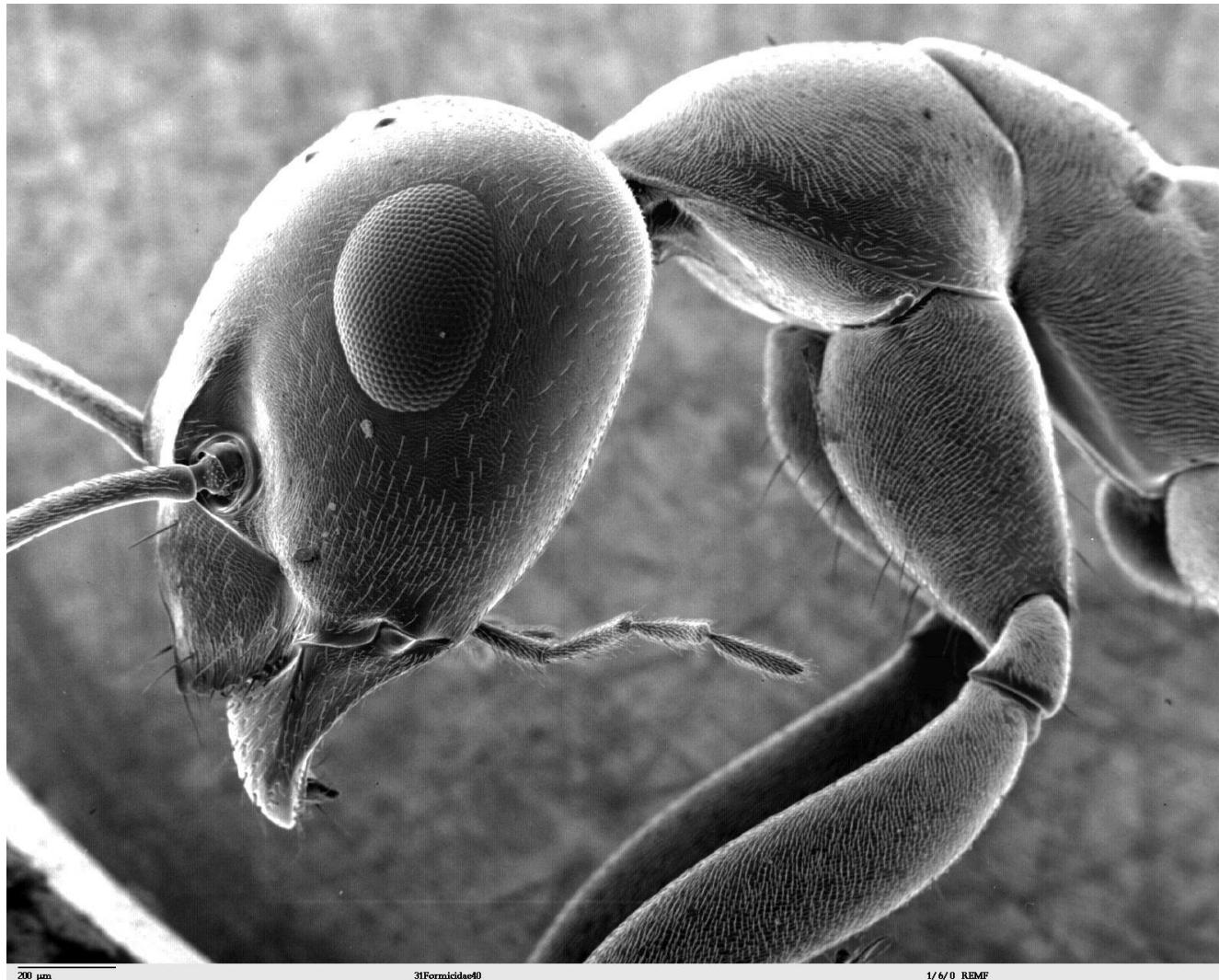
- **Electron microprobe**

- X-ray emission



# Scanning Electron Microscopy (SEM)

- Contrast depends on angle of incidence of electrons



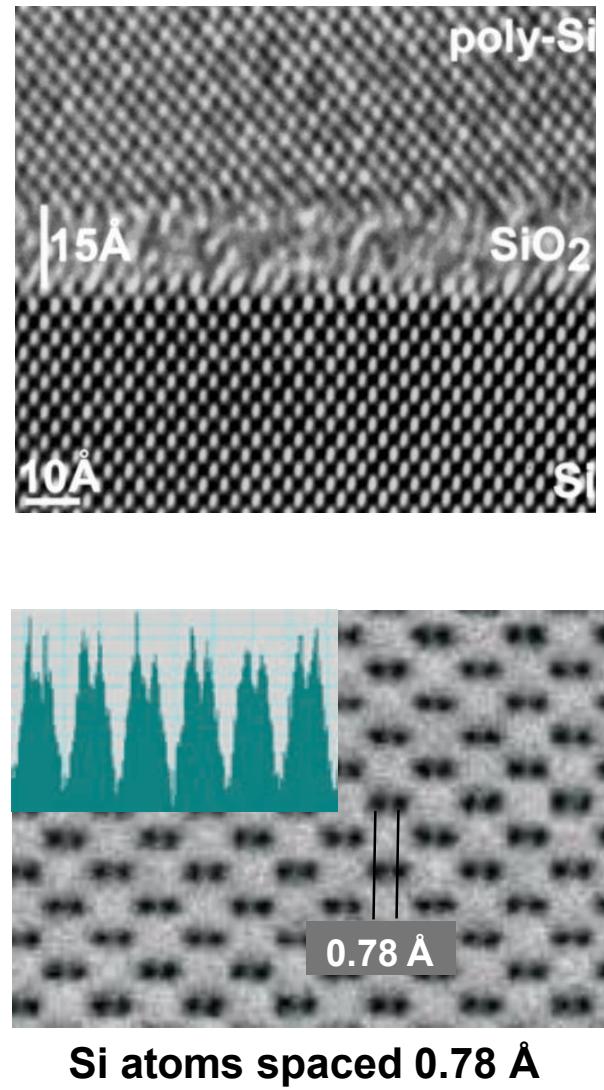
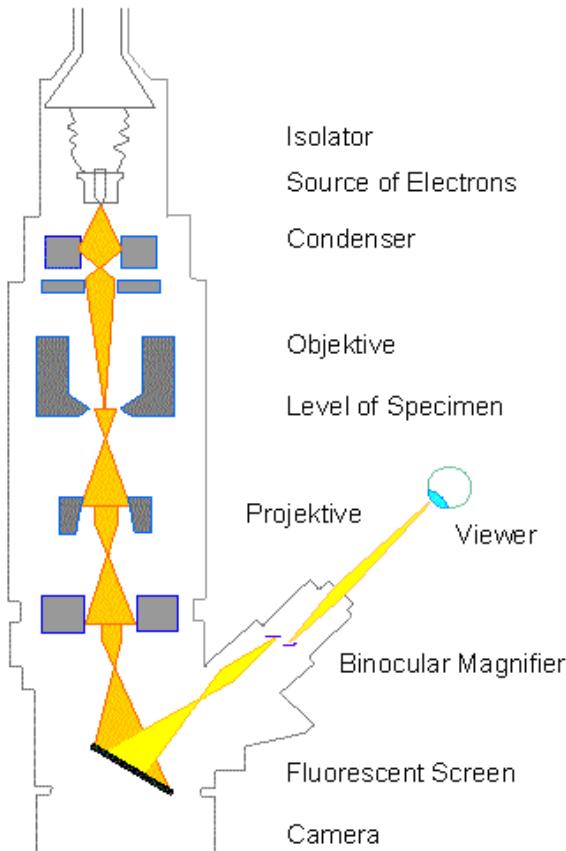
200 μm

31Formicidae40

1/6/0 REMF

# Transmission Electron Microscopy

- Electrons accelerated to  $\sim 100 - 300$  keV
- Sample must be very thin so electron do not spread out

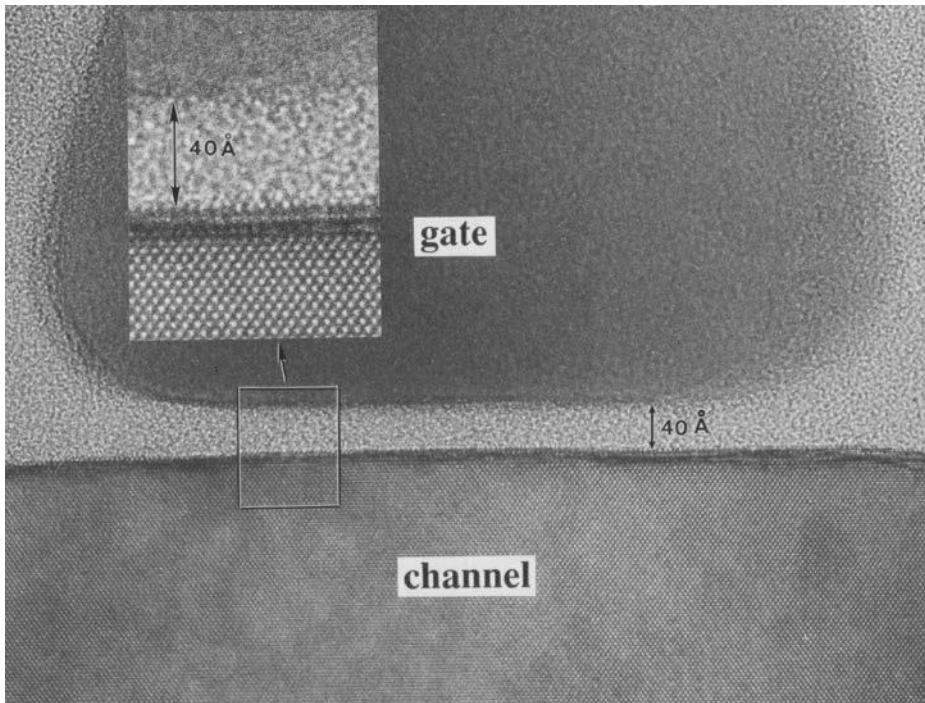


Si atoms spaced  $0.78\text{\AA}$

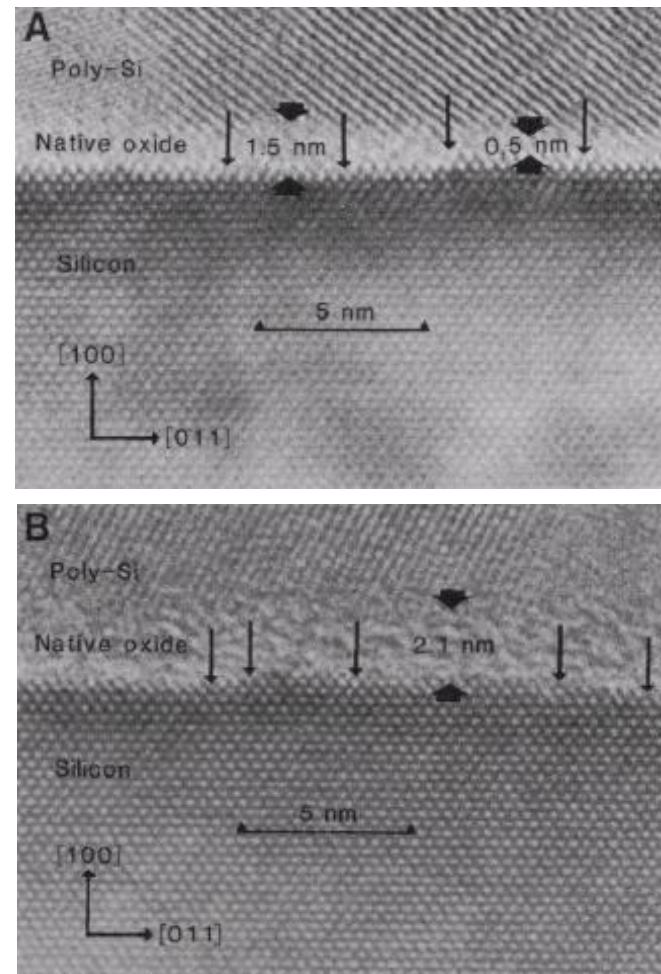
# Transmission Electron Microscopy

## High-resolution TEM images of native oxide on Si

- ◆ A: HF clean
- ◆ B:  $\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2$  clean
- ◆ Arrows indicate interfacial steps



Courtesy of Y.O. Kim, Bell Labs.

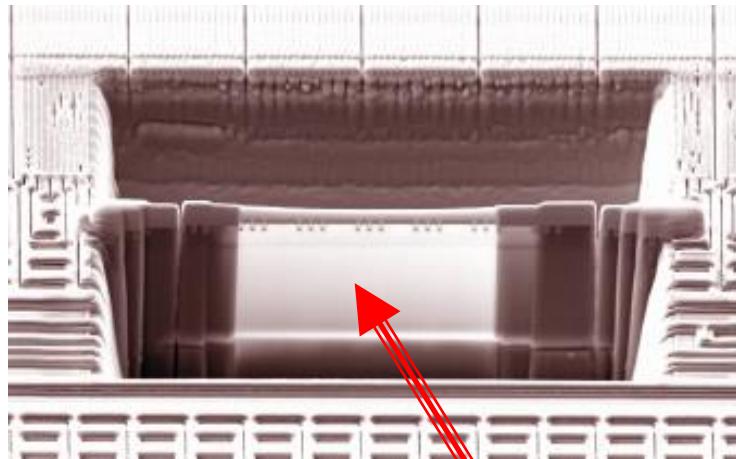
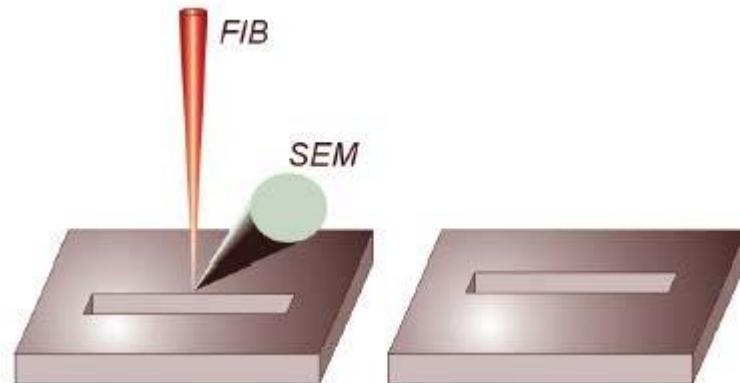


A.C. Carim et al., *Science*, **237**, 630 (1987)

# Sample Preparation: Focused Ion Beam

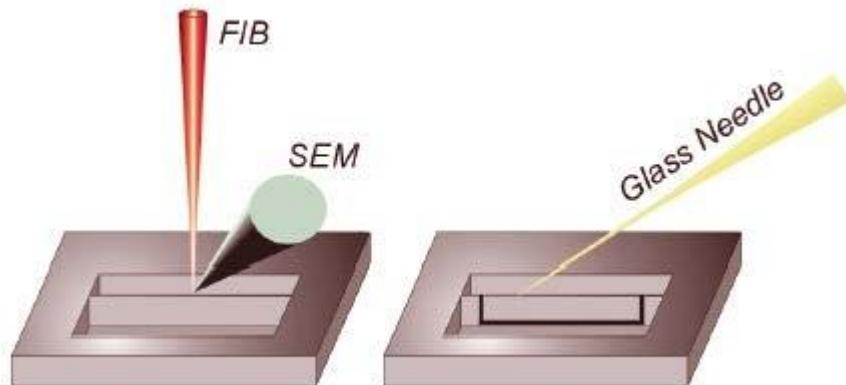
## ■ Focused ion beam (FIB)

- ◆ Ga beam
- ◆ Focused to 5-10 nm
- ◆ Cut holes in a sample
- ◆ Prepare TEM samples
- ◆ Connect metal lines



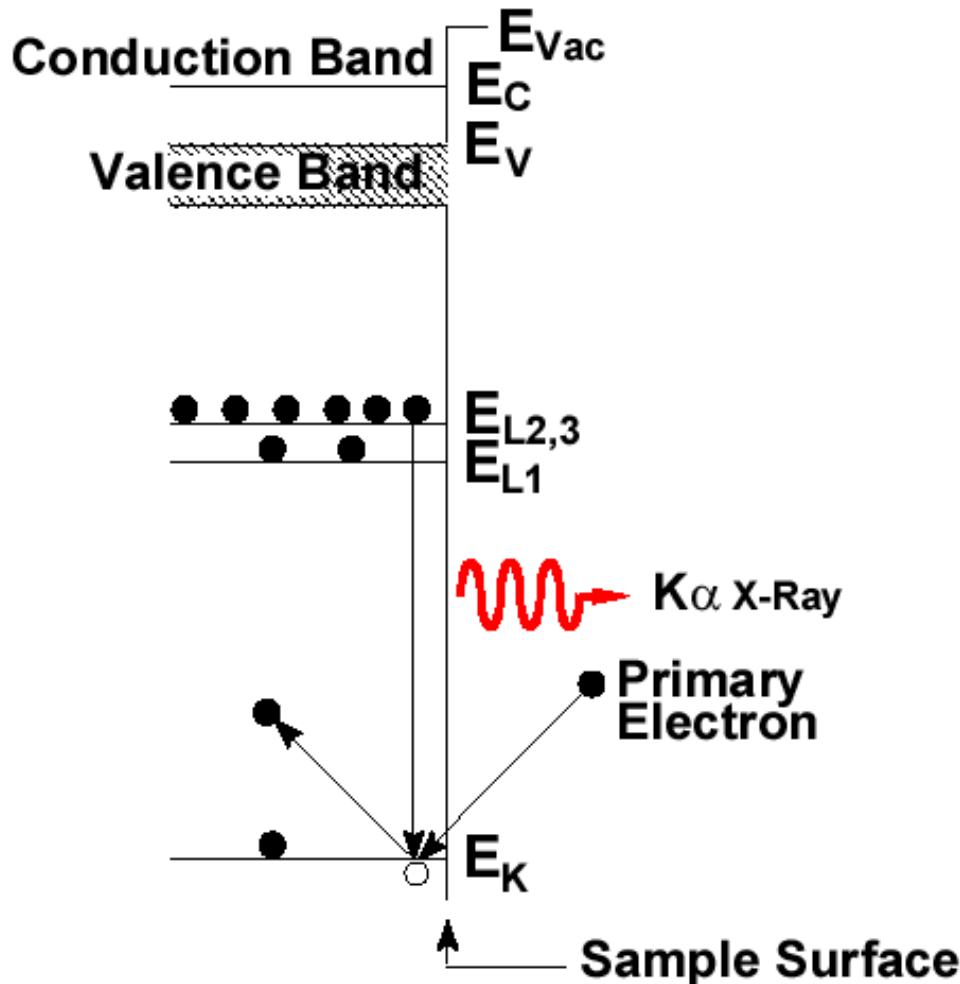
*TEM lift-out sample after milling and polishing. Note the electron transparency of the thin area.*

*thin layer*

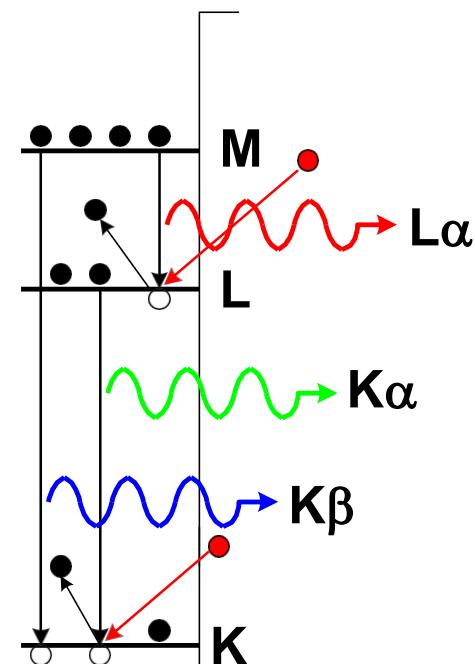


# Electron Microprobe (EMP)

Similar as SEM, but to detect X-ray

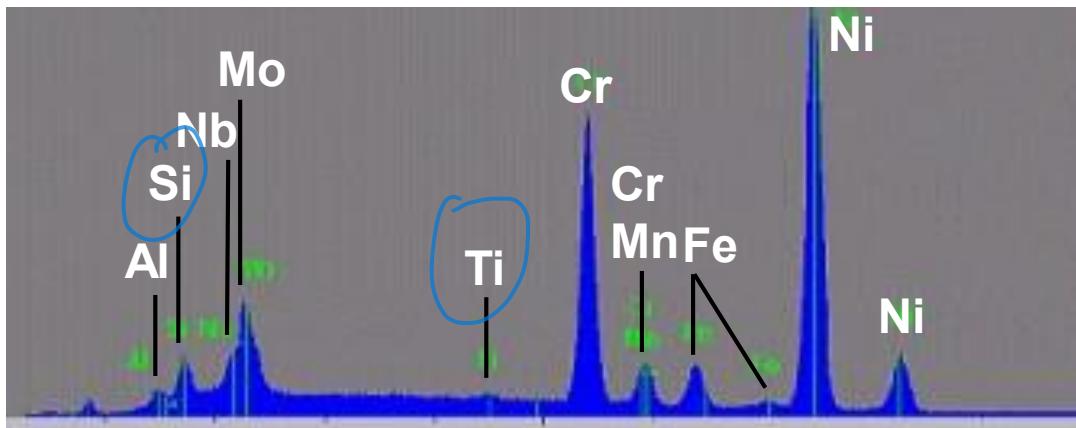


- Incident electron knocks electron out of K shell
- L shell electron falls into vacancy (hole)
- Energy is emitted as an X-ray



# Electron Microprobe

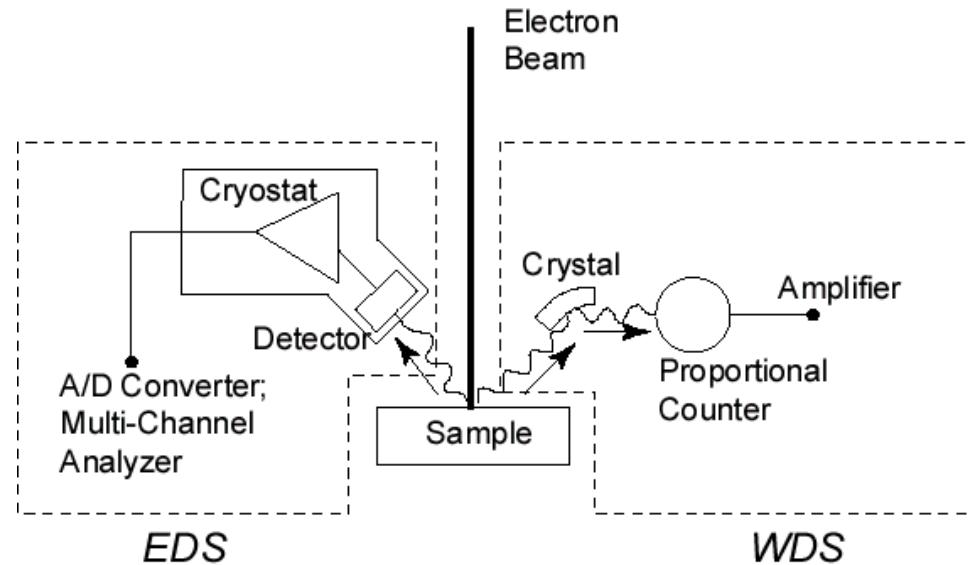
- **Advantages:** Nondestructive technique; trace impurities and major components in a single analysis. Two-dimensional information by scanned beam.
- **Limitations:** Poor sensitivity for elements with  $Z < 10$ . X-ray resolution determined by the electron absorption volume not the e-beam size.
- **Sensitivity:**  $10^{18} - 10^{19} \text{ cm}^{-3}$
- **Volume sampled:**  $\sim 10 \mu\text{m} \times 10 \mu\text{m} \times 10 \mu\text{m} = 10^{-9} \text{ cm}^3$
- **Applications:** Rapid analysis of thin films and bulk samples. Two-dimensional elemental display.



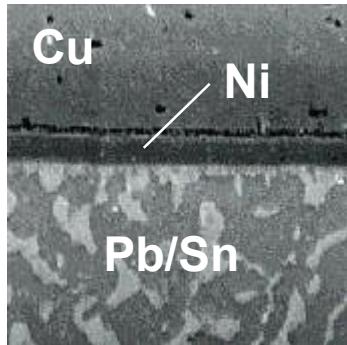
Nickel-based alloy consisting of *nickel, chromium, manganese, titanium, silicon, molybdenum, and aluminum*

# Electron Microprobe

- The X-rays can be detected by
  - ◆ Energy-dispersive spectrometer (EDS)
  - ◆ Wavelength-dispersive spectrometer (WDS)

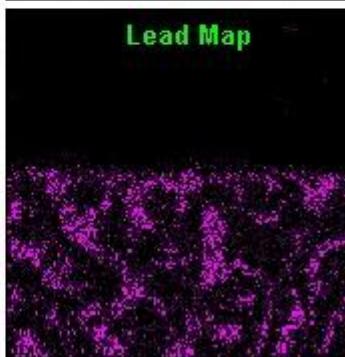
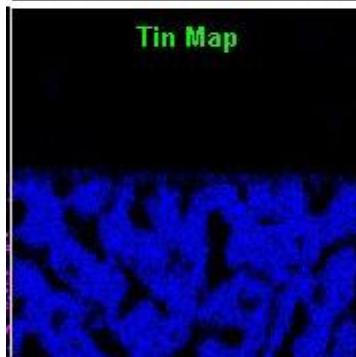
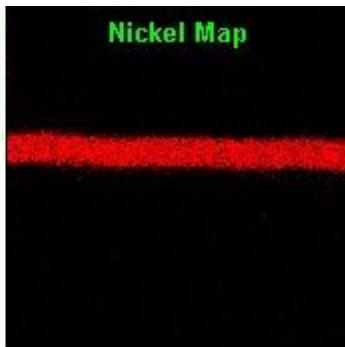
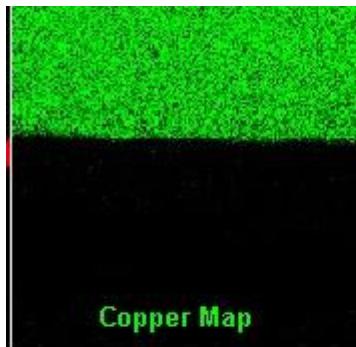


# Electron Microprobe

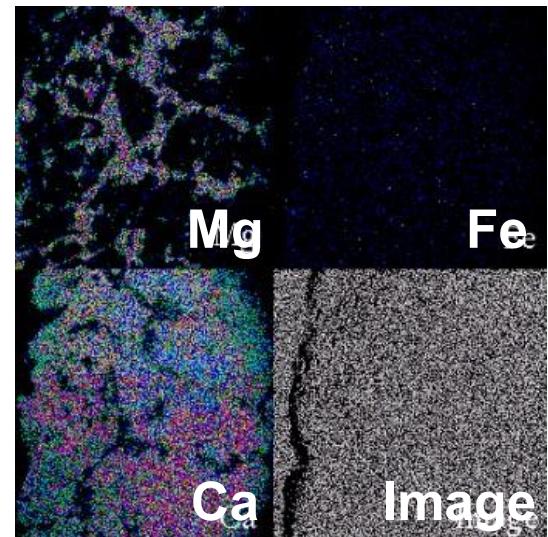


SEM cross-sectional image  
of Pb/Sn solder joint on  
Ni-plated Cu wire

500x Magnification



Kidney stone  
150x Magnification



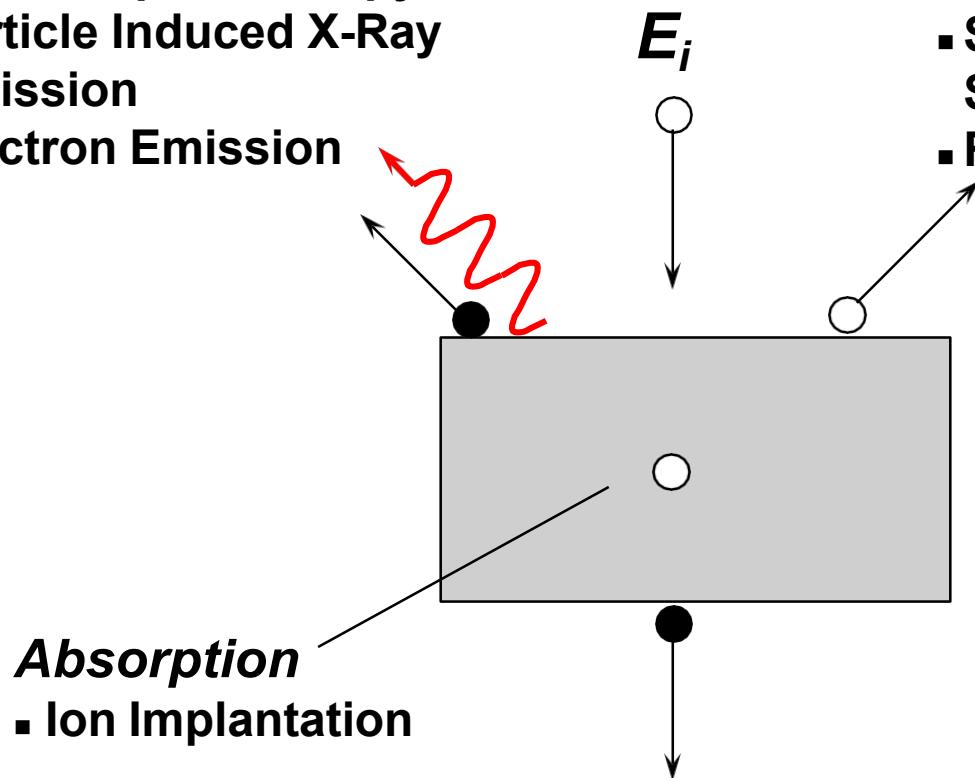
# **Ion Beam Characterization**

- Secondary Ion Mass Spectrometry
- Rutherford Backscattering

# **Ion Beam Characterization**

## **Emission**

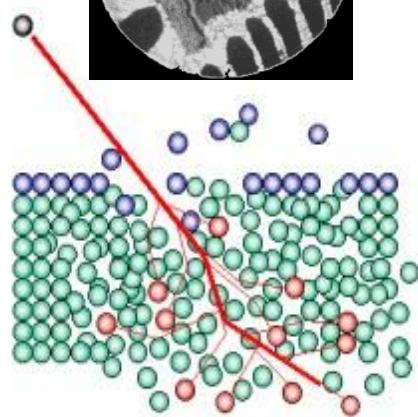
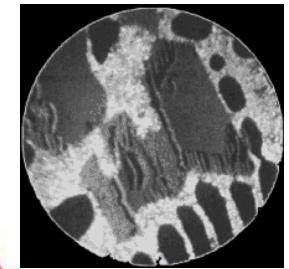
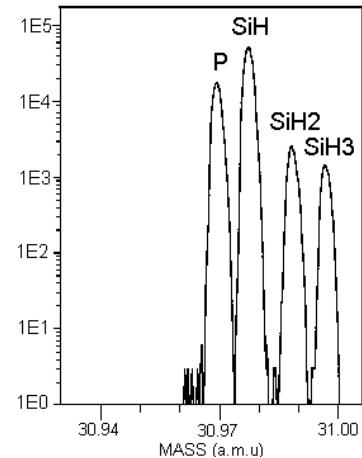
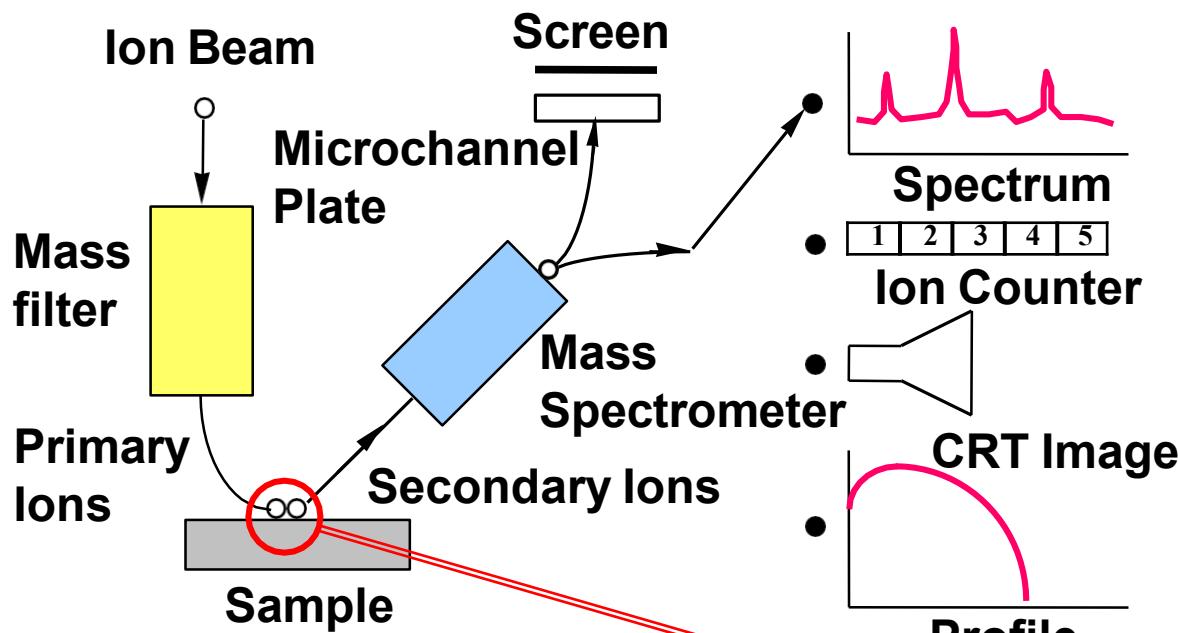
- Photon Spectroscopy
- Particle Induced X-Ray Emission
- Electron Emission



## **Reflection**

- Sputtering
- Secondary Ion Mass Spectrometry
- Rutherford Backscattering

# Secondary Ion Mass Spectrometry

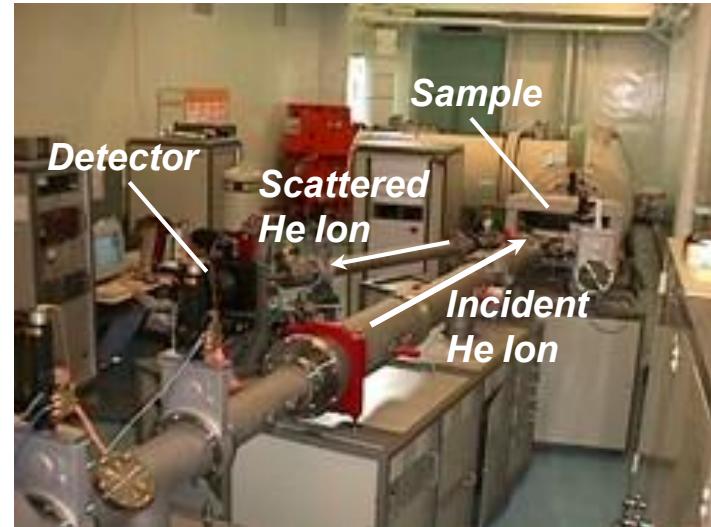
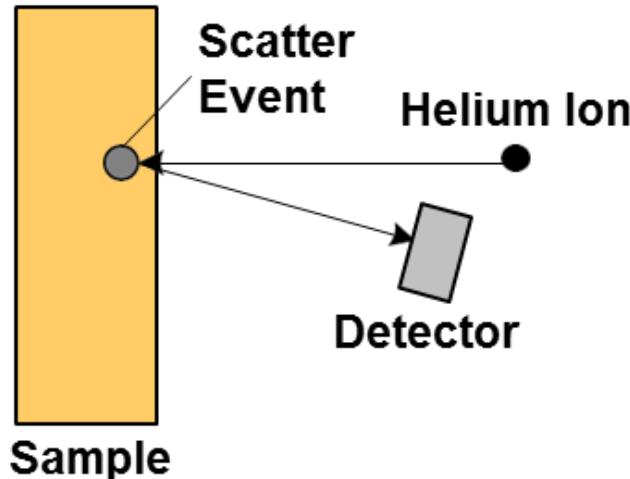


# Secondary Ion Mass Spectrometry

- Secondary ion mass spectrometry (SIMS) is the most common doping profile method
- *Principle:* Atoms sputtered from the sample; mass of the ejected ions analyzed
  - ◆ Ion mass  $\Rightarrow$  element identification; ion intensity  $\Rightarrow$  element density
- *Advantages:* Gives depth profiles. Can analyze all elements; most sensitive of all analytical techniques. Can measure several impurities simultaneously
- *Limitations:* Destructive method. Subject to matrix effect: ion yields influenced by a change in surface composition. Need standards for concentration determination, independent depth measurement
- *Sensitivity:* Depends on impurity. Highest sensitivity is boron in Si at  $\sim 10^{14} \text{ cm}^{-3}$ ; all other elements less sensitive. Sensitivity limited by interference from ions of similar mass/charge

# Rutherford Backscattering

- He ions with several MeV energy are scattered by the sample atoms
- The mass of the sample atom is determined from the energy of the scattered ions



# PYP 2017-2018 Semester 2

## PYP 2017-2018 Semester 2

- (iv) Complete the following table to classify the typical analytical tools based on their working principle as listed below.

Analytical tool	Working principle
Atomic Force Microscopy	
Ellipsometry	
Scanning Tunnelling Microscopy	
Scanning Electron Microscopy	
Photoluminescence	
Rutherford Backscattering	
Transmission Electron Microscopy	
Secondary Ion Mass Spectrometry	

Working principle: Optical Characterization  
Charge-Based Characterization  
Electron Beam Characterization  
Ion Beam Characterization