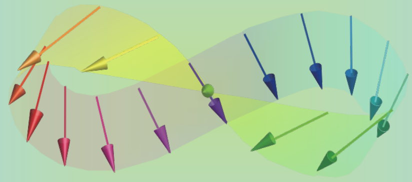
Nanoelectronics
09



Atsufumi Hirohata

Department of Electronic Engineering

THE UNIVERSITY *of York*

09:00 Wednersday, 22/February/2023 (P/L 005)

Quick Review over the Last Lecture

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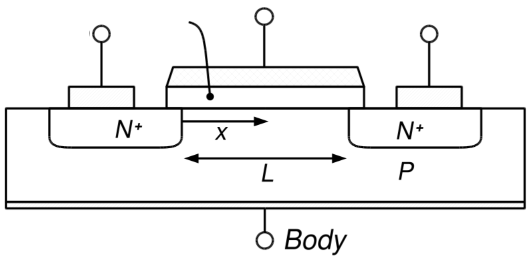
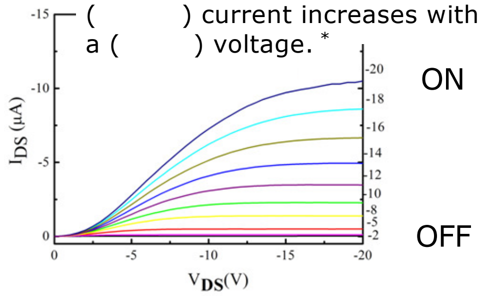


( ) current increases with increasing a ( ) voltage. *



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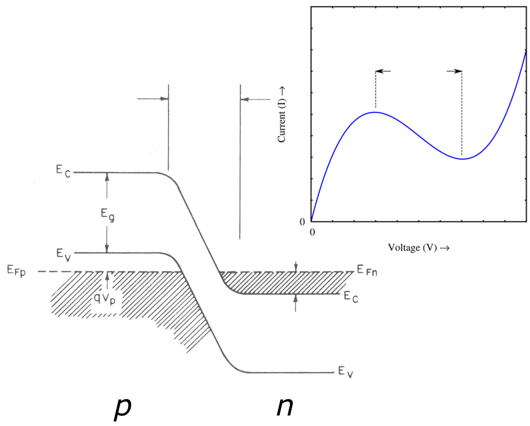

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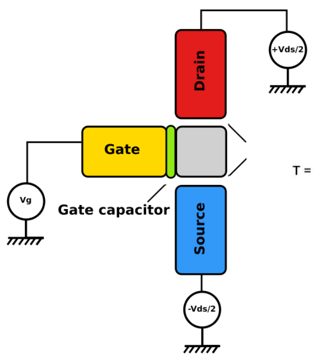
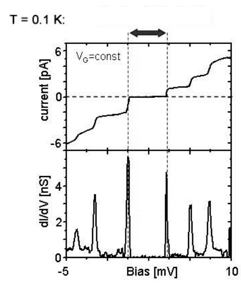




* http://stc-mditr.org/research/lsoe/highlights/highlight4.cfm

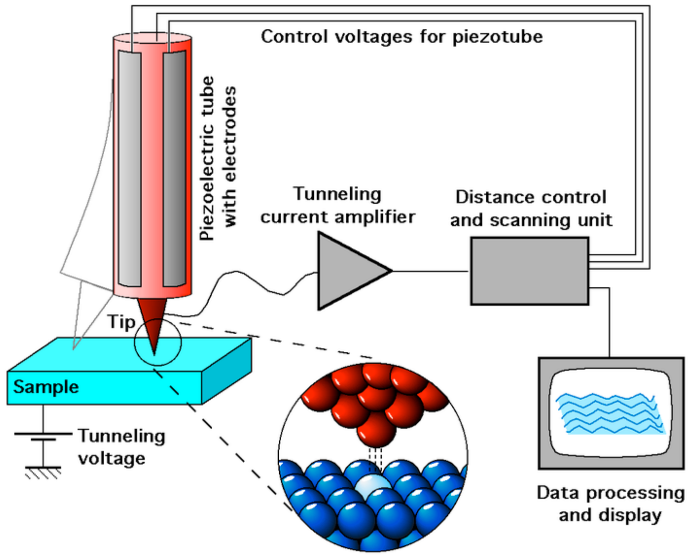
Contents of Nanoelectonics

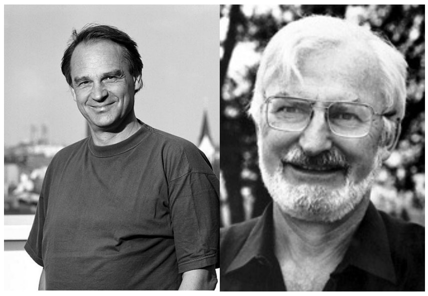
09 Nanomeasurements

- Scanning tunnelling microscope
- Scanning tunnelling spectroscopy
- Atom manipulation
- Atomic force microscope
- Transmission electron microscope
- Scanning electron microscope
- Surface analysis

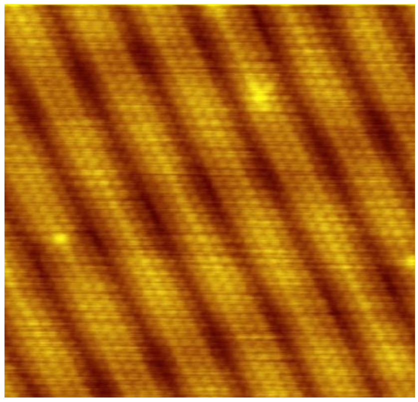
Scanning Tunnelling Microscope (STM)

In 1982, Gerd Binnig and Heinrich Rohrer invented scanning tunnelling microscopy :





Au (001) surface :

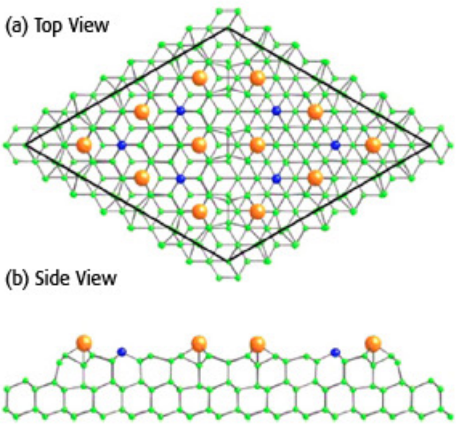


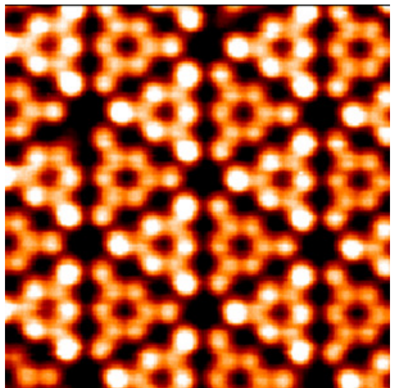
* http://www.wikipedia.org/
** http://nobelprize.org/

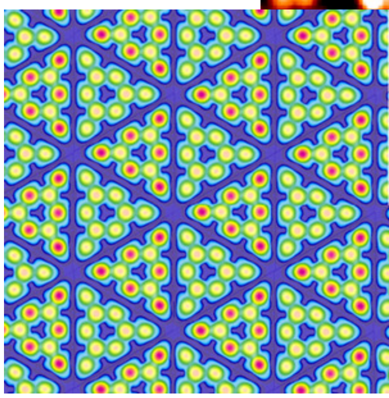
Si Surface Reconstruction

Atomic resolution by STM was clearly proved by Si surface observation in 1983 :

Si (111) 7 × 7 surface reconstruction was proposed in 1959 :

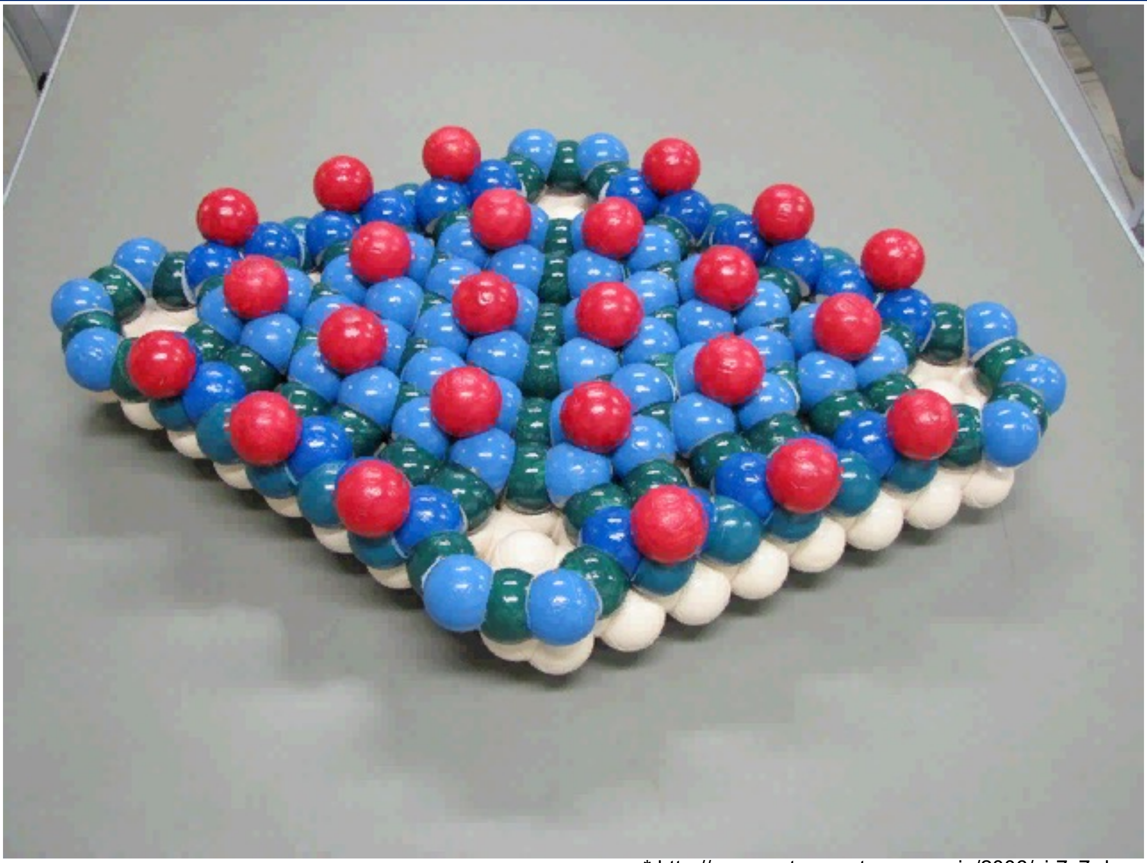






* http://www.omicron.de/

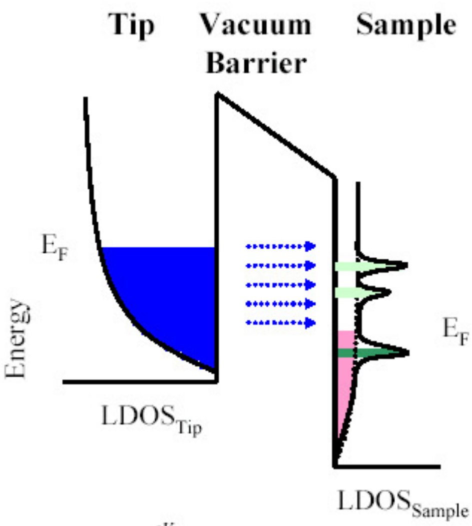
Si (111) 7 × 7 Surface Reconstruction



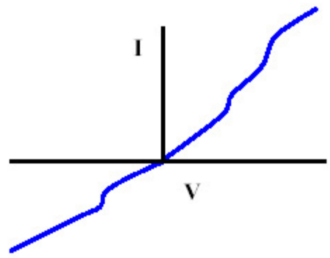
* http://www.ss.teen.setsunan.ac.jp/2006/si-7x7-das-vr.html

Scanning Tunnelling Spectroscopy (STS)

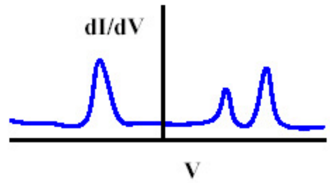
In order to measure a density of states (DOS) with a STM tip,



$$I \sim e^{-\kappa z} \int_0^{eV} dE \cdot LDOS_{Sample}(E_F + E)$$



$$I \sim e^{-\kappa z} \int_0^{eV} dE \cdot LDOS_{Sample}(E_F + E)$$

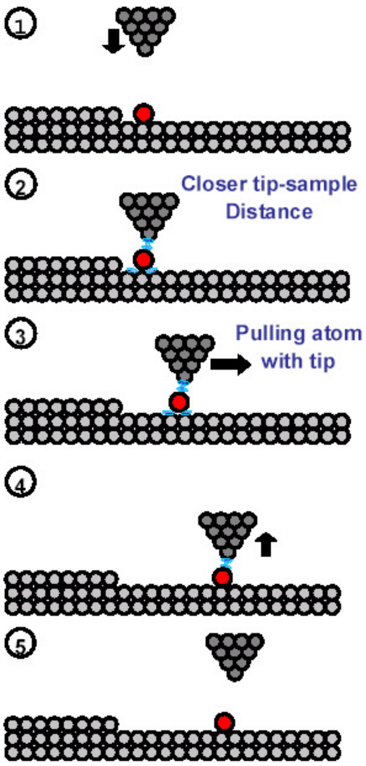


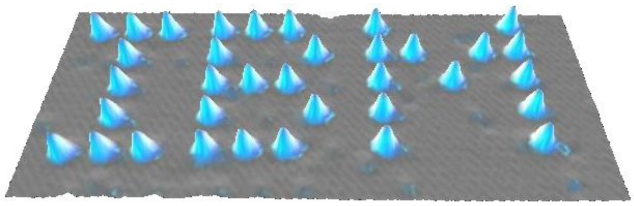
$$\left.\frac{dI}{dV}\right|_V \sim LDOS_{Sample}(E_F + eV)$$

* http://www.physics.berkeley.edu/research/crommie/research_stm.html

Atom Manipulation

An individual atom can be manipulated by a STM tip shown by Donald Eigler in 1989 :





35 Xe atoms

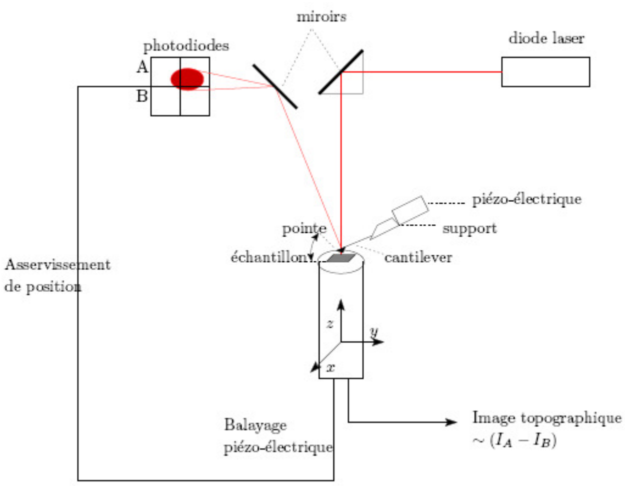
* http://www.wikipedia.org/
** http://www.physics.berkeley.edu/research/crommie/research_stm.html

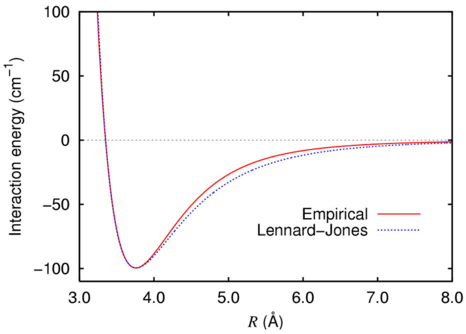
Atom Manipulation by IBM

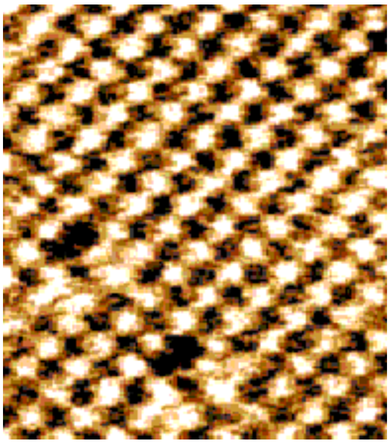
Atom Manipulation by IBM

Atomic Force Microscope (AFM)

In 1985, Gerd Binnig invented atomic force microscopy :





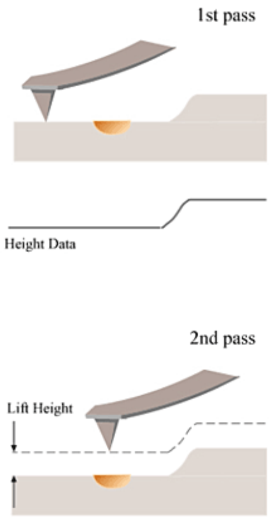


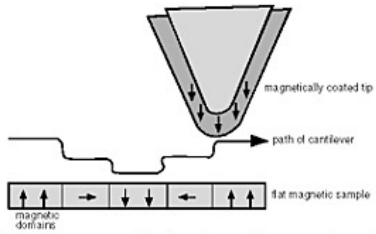
→ can be observed.

* http://www.wikipedia.org/

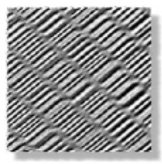
Magnetic Force Microscope (MFM)

In 1987, a magnetic tip was introduced to observe a magnetic stray field : *





MFM maps the magnetic domains of the sample surface.



MFM image showing the bits of a hard disk.
30μm. scan

→ By subtracting surface morphology, are observed.

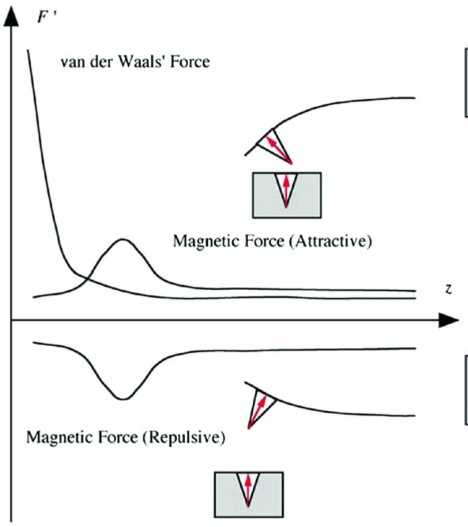
→ Similarly, scanning SQUID † / Hall ‡ microscope were developed.

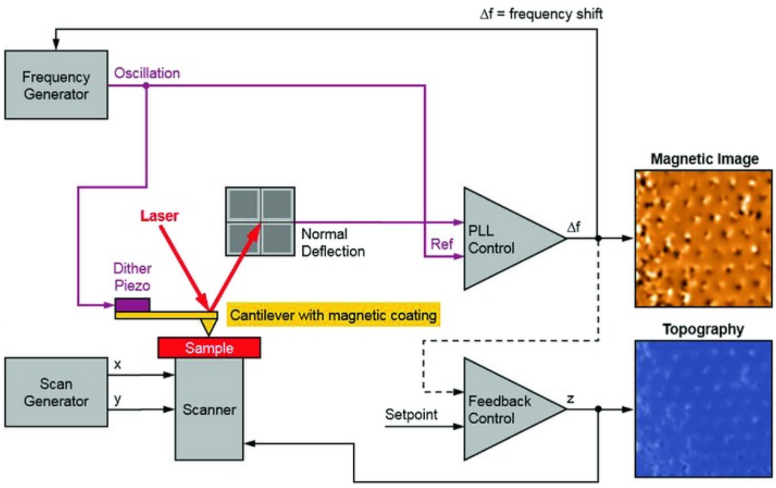
† C. C. Tsuei *et al.*, *Phys. Rev. Lett.* **73**, 593 (1994).
‡ A. Oral *et al.*, *Appl. Phys. Lett.* **69**, 1324 (1996).

* Y. Martin, H. K. Wickramasinghe, *Appl. Phys. Lett.* **50**, 1455 (1987).
** http://www.veeco.com/

AFM / MFM Operation

Different lift height can make a tip to be sensitive to atomic / magnetic forces : *

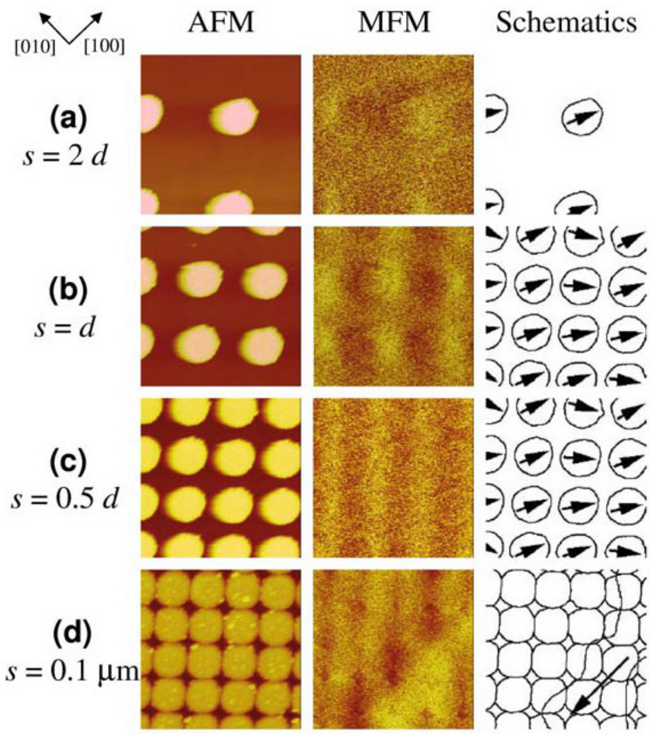




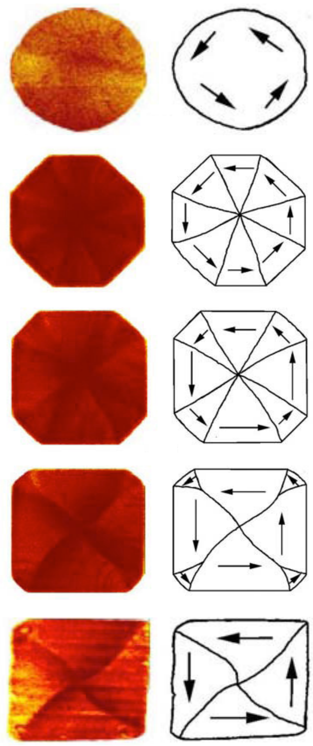
* A. Hirohata, M. Samiepour, M. Corbetta, "Magnetic Force Microscopy for Magnetic Recording and Devices," in "Electrical Atomic Force Microscopy for Nanoelectronics" Umberto Celano (Ed.) (Springer, Berlin, Germany, 2019) p. 231-265.

AFM / MFM Images

MFM images can subtract dots morphology :



20 nm thick Fe dots (1 μm diameter)

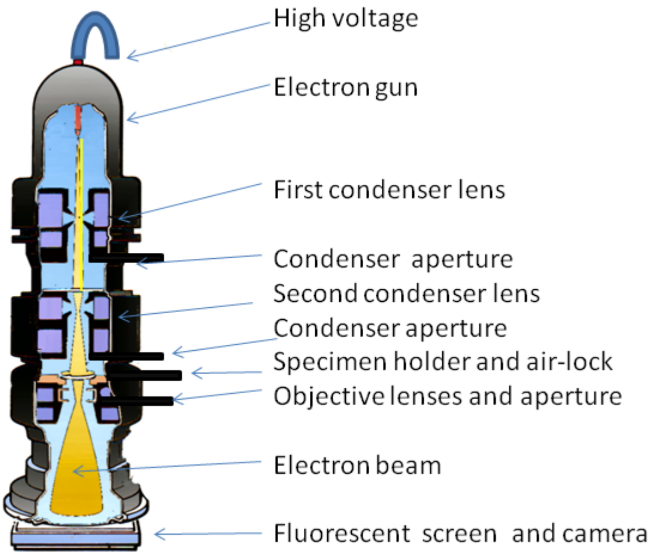


30 nm thick NiFe dots (5 μm)

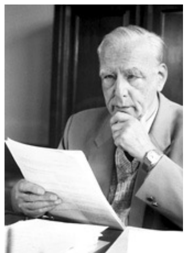
Transmission Electron Microscope (TEM)

In 1933, Ernst A. F. Ruska and Max Knoll built an electron microscope :

- Preliminary electron microscope (×   ) in 1931
- Improved to ×   in 1933
- Commercially available from Siemens in 1938



Transmission Electron Microscope



- Sample thickness :
  200 ~ 300 nm
- Magnetic field acts as a lens to electron-beam :
  Hans W. H. Busch in 1927

* http://nobelprize.org/
** http://www.wikipedia.org/

Early TEM Images

Early oxide replica of etched Al :

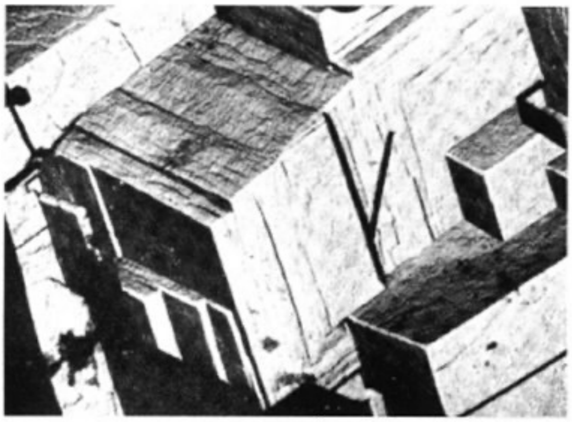


FIG. 1 TEM image of an early oxide replica of etched aluminum (Mahl 1941); horizontal field width = 9 μm.

Si-Fe :

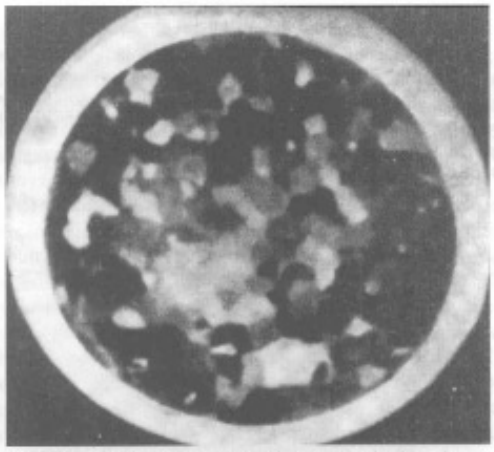
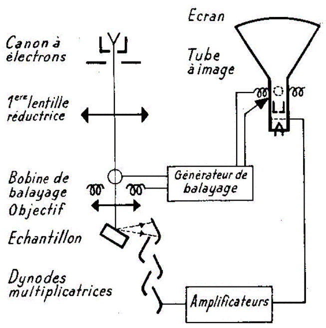


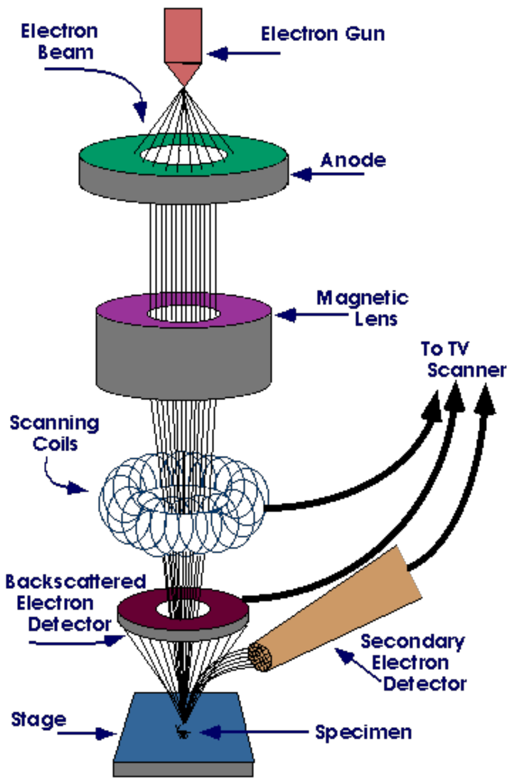
FIG. 3 Electron-beam scanner image of silicon iron showing electron channeling contrast; horizontal field width = 50 mm. (Knoll 1935).

* http://www-g.eng.cam.ac.uk/125/achievements/mcmullan/mcm.htm

Scanning Electron Microscope (SEM)

In 1937, Manfred von Ardenne developed a scanning electron microscope :





* http://www.wikipedia.org/

** http://bluedianni.blogspot.com/2008/05/scanning-electron-microscopy-sem.html

Early SEM Images

SEM image of etched brass :

FIG. 8 Micrograph of etched brass produced by the SEM of Zworykin *et al.* (1942a); horizontal field width = 18 μm.

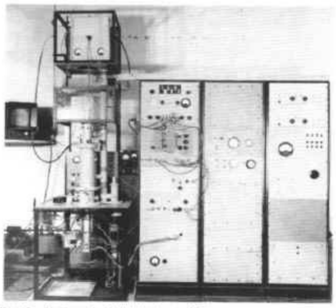


FIG. 12 Photograph of SEM 1 taken in 1953.

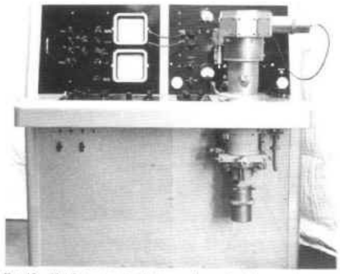


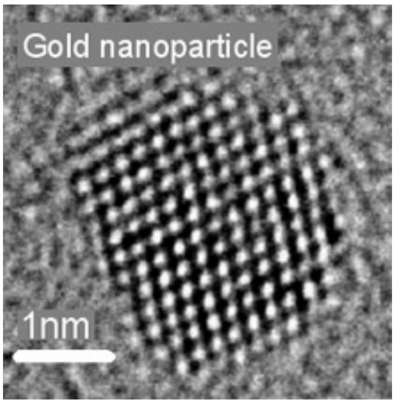
FIG. 13 The first magnetically focussed scanning electron microscope (SEM 3) built by K.C.A. Smith for the Pulp and Paper Research Institute of Canada (Smith 1959, 1961).

* http://www-g.eng.cam.ac.uk/125/achievements/mcmullan/mcm.htm

Scanning Transmission Electron Microscope (STEM)

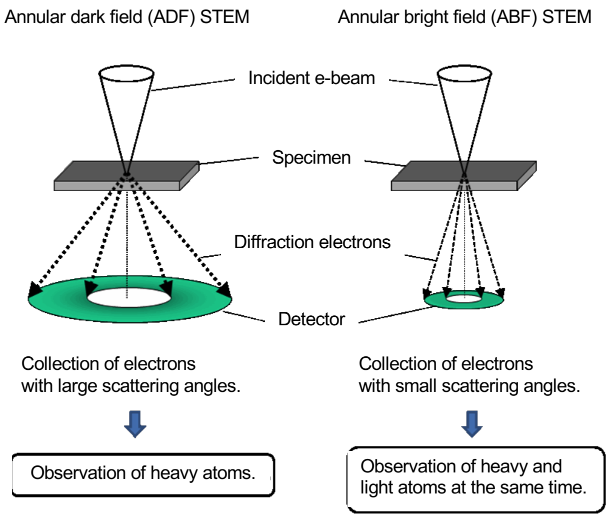
By scanning electron-beam, TEM resolution can be improved significantly :

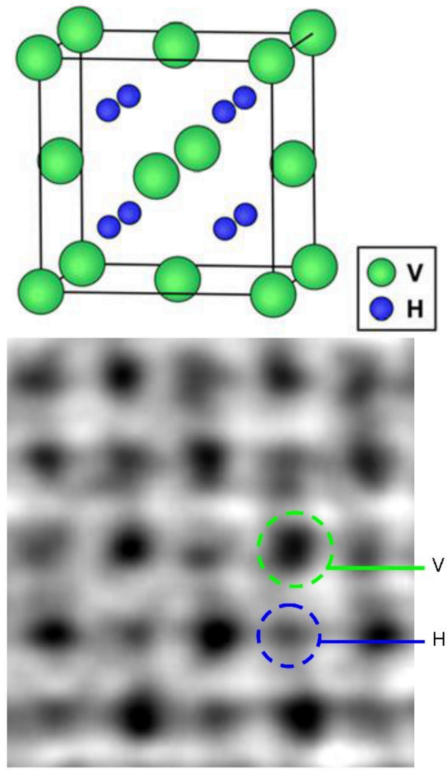
• 0.8 Å resolution



Capability of STEM

By STEM, H atoms were directly observed :

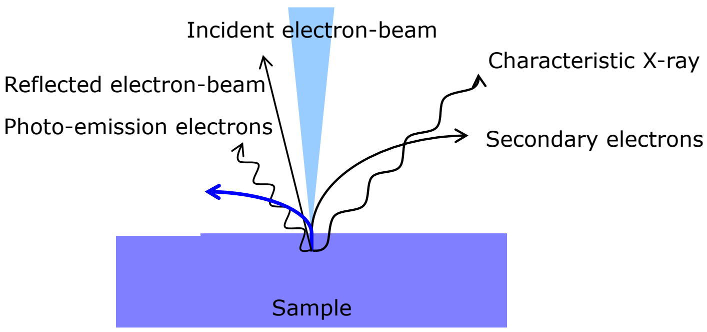


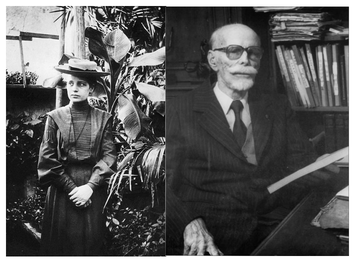


* S. D. Findlay *et al.*, *Appl. Phys. Exp.* **3**, 116603 (2010).

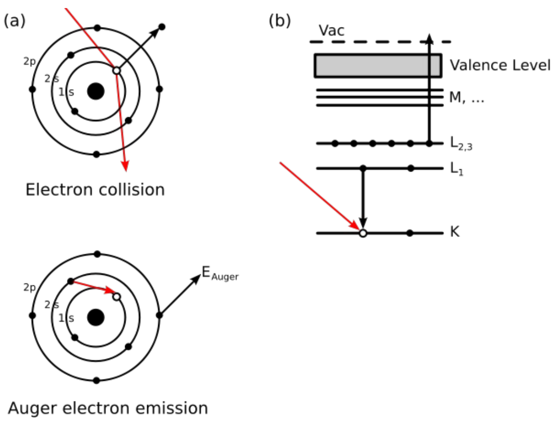
Surface Spectroscopy

By introducing electron-beam onto a sample surface :





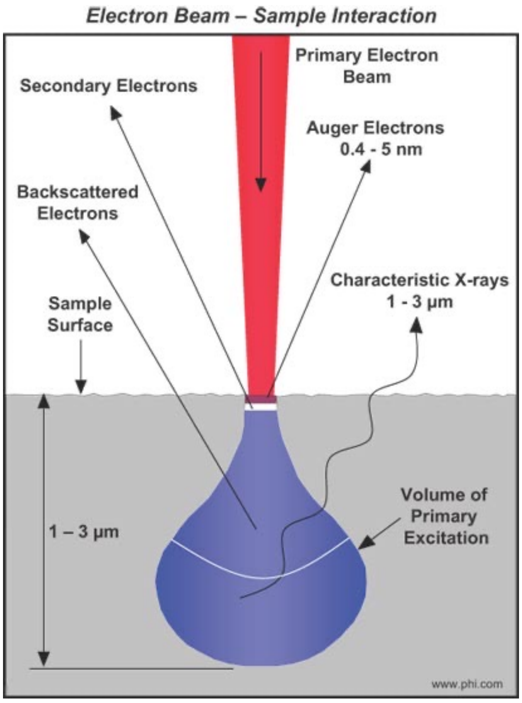
Auger electrons are found by Lise Meitner in 1922 and Pierre V. Auger in 1925 :



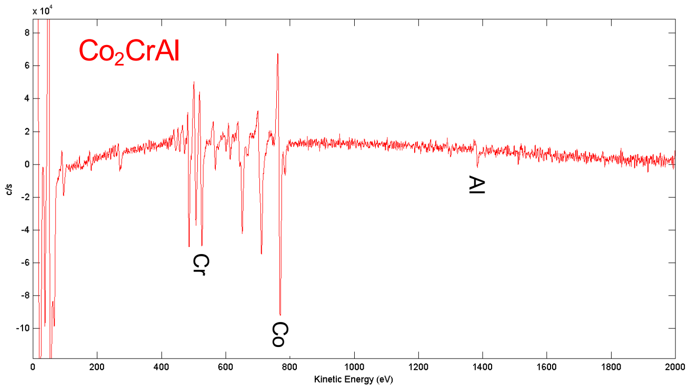
* http://www.wikipedia.org/
** http://auger.ung.si/agn/

Auger Electron Spectroscopy (AES)

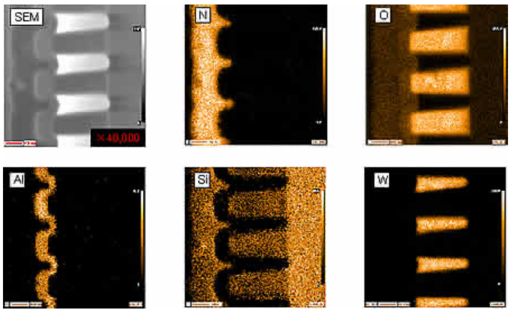
Penetration depth : *



AES signal :



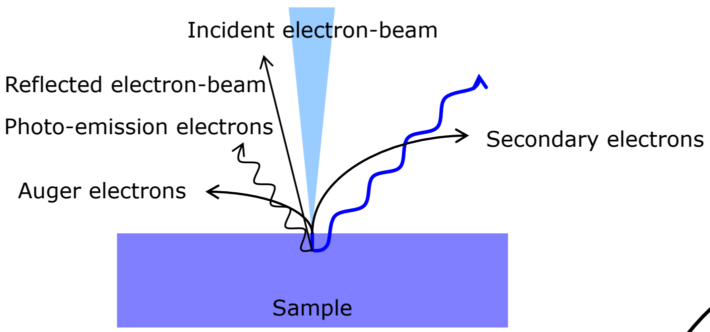
AES mapping : **



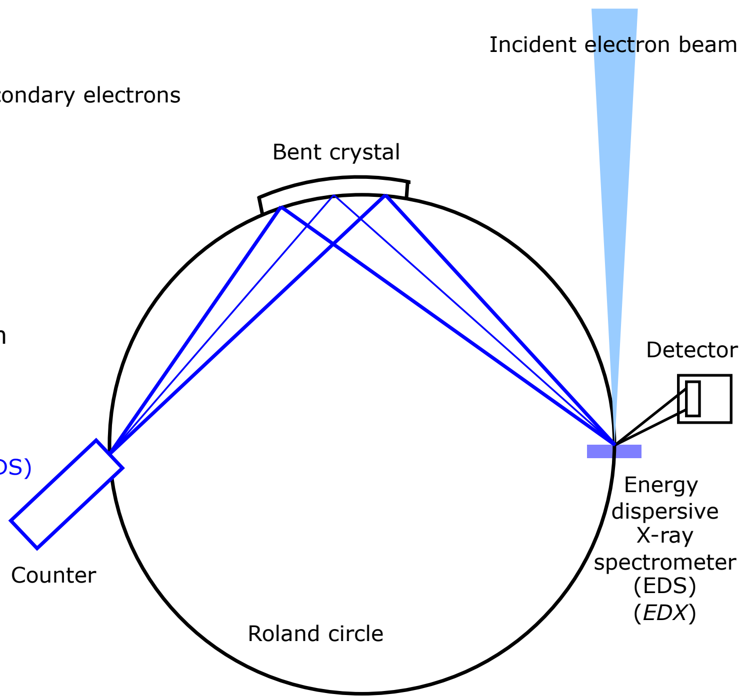
* http://www.phi.com/
** http://www.jeol.com/

Electron Probe Micro-Analyser (EPMA)

Electron Probe Micro-Analyser (EPMA) :

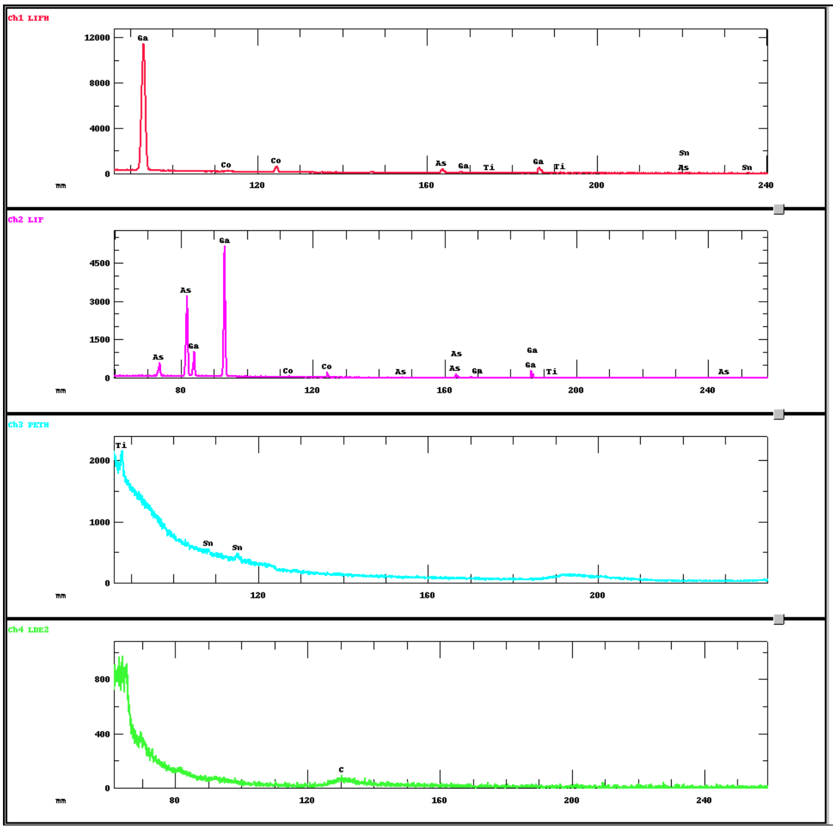


Typical penetration depth : ~ 1 µm



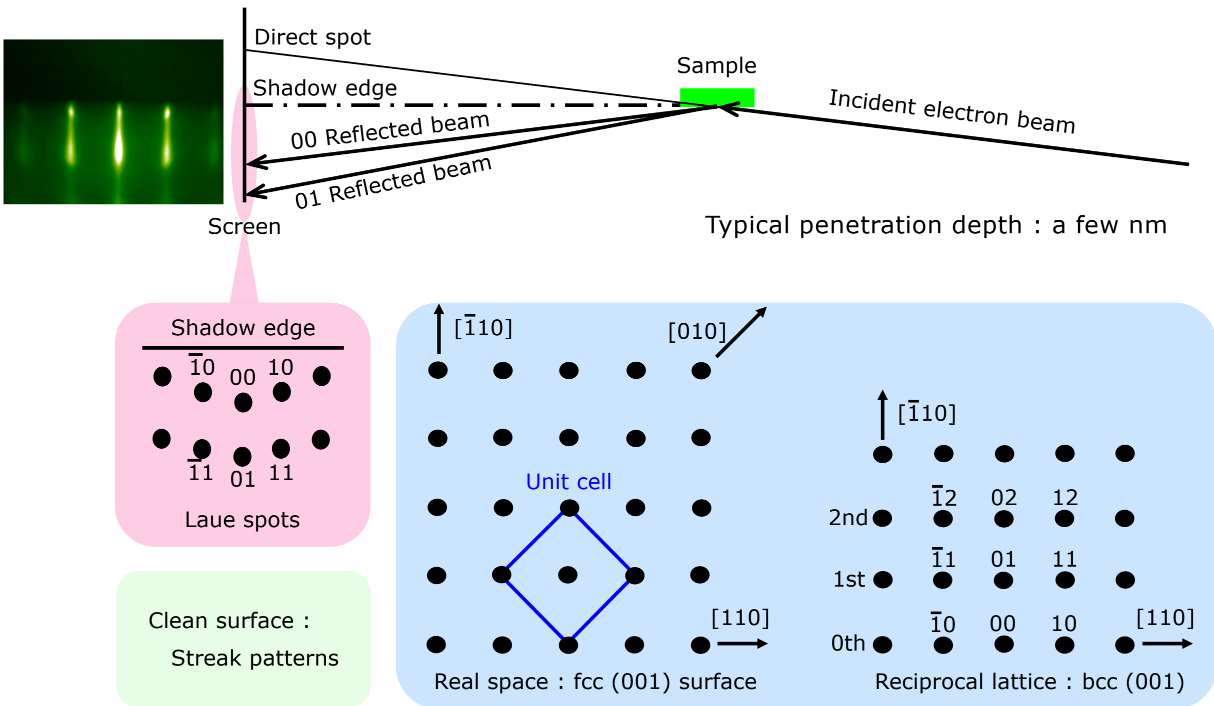
EPMA Signals

Example of Co_2TiSn :



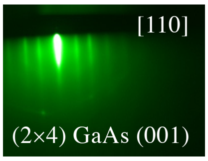
Surface Structural Analysis

Reflection high energy electron diffraction (RHEED) :

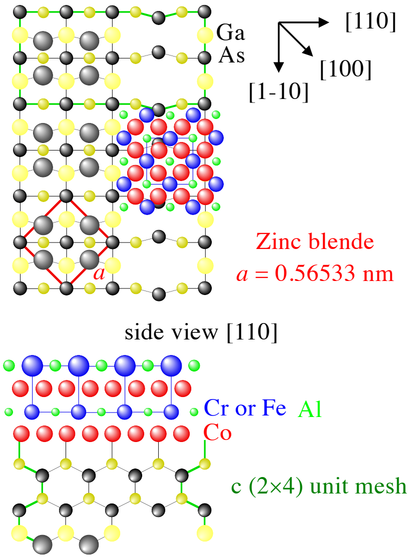


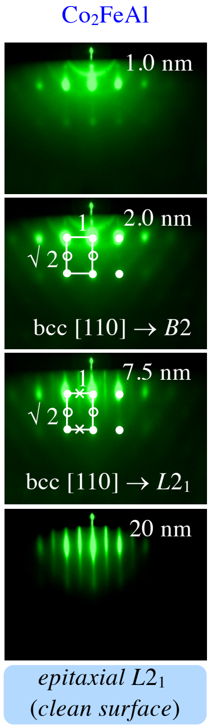
RHEED Observation

RHEED patterns of Co_2FeAl grown on GaAs (001) :



top view (001)





Co_2FeAl (001) <110> || GaAs (001) <110>

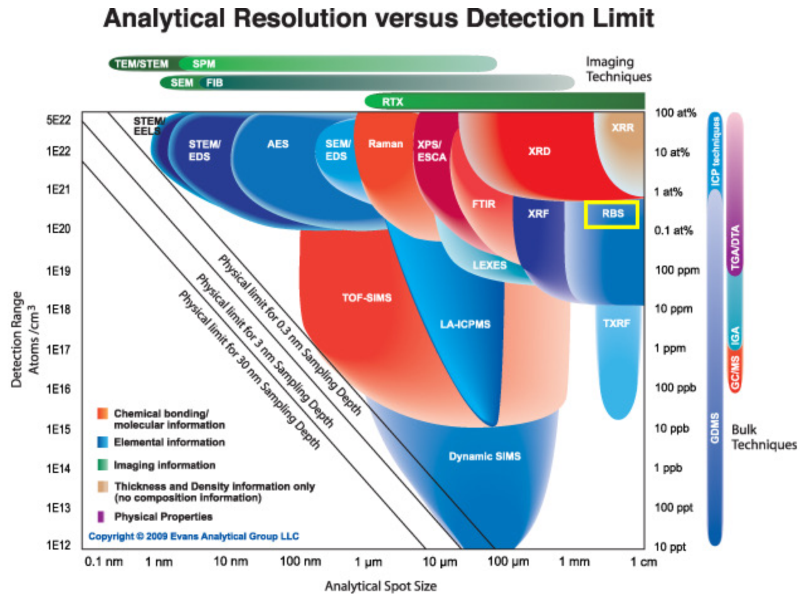
Surface Analysis

Major techniques for surface analysis :

Techniques	Incident beam	Signals	Composition	Structure	Electronic state
Auger electron spectroscopy (AES)	Electron-beam		Qualitative analysis		Auger electron spectra
Auger electron diffraction (AED)	Electron-beam	Auger electrons		Auger diffraction (~ a few atoms)	
Electron probe micro-analyzer (EPMA)	Electron-beam		Qualitative analysis (sensitivity ~ 0.1 %)		X-ray spectra
Energy dispersive X-ray analysis (EDX)	Electron-beam	Characteristic X-ray	Qualitative analysis		X-ray spectra
X-ray photoelectron spectroscopy (XPS)	Electron-beam	Photo-emission electrons	Qualitative analysis		Atomic binding energy
Photoemission electron microscopy (PEEM)	X-ray / photon	Photo-emission electrons	Atom mapping		Atomic binding energy
Secondary ion mass spectroscopy (SIMS)	Electron-beam	Secondary electrons	Qualitative analysis		
Electron energy-loss spectroscopy (EELS)	Electron-beam	Secondary electrons	Surface absorption spectra		
Reflection high energy diffraction (RHEED)	Electron-beam			Reflected diffraction patterns	
Low energy electron diffraction (LEED)	Electron-beam	Reflected electron-beam		Back-scattered diffraction patterns	
X-ray absorption fine structure (XAFS)	X-ray	Photo-emission electrons	Surface absorption spectra		
X-ray diffraction (XRD)	X-ray	Reflected X-ray		X-ray diffraction	
Transmission electron diffraction (TED)	Electron-beam	Transmission electrons		Diffraction patterns (t < 30 nm)	

* D. P. Woodruff and T. A. Delchar, *Modern Techniques of Surface Science* (Cambridge University Press, Cambridge, 1994).

Detection Limits of Surface Analysis



* http://www.nanoscience.co.jp/surface_analysis/technique/RBS-HFS-PIXE-NRA.html