Ion Beam Methods – Introduction

© C.Jeynes, 5th April 2012

University of Surrey Ion Beam Centre, Guildford GU2 7XH, England

The introductory article for the ION BEAM METHODS Chapter of the
Wiley *Characterisation of Materials* (2nd edition) on-line book

Published on-line 12th October 2012; <http://dx.doi.org/10.1002/0471266965.com091.pub2>

Abstract

Ion beam techniques are used with ion energies from eV to many MeV and a very wide range of ion species to characterise materials at length scales from sub-nm to sub-mm and in a wide variety of different ways. Many of these techniques are non-destructive.

Atomic concentration can be determined from matrix elements (the stoichiometry) to minor and trace elements (at ng/g sensitivity and better), in one dimension (depth profiles), two dimensions (elemental maps), and three dimensions with full tomography being feasible. There is sensitivity to the whole Periodic Table one way or another, with nuclear techniques for isotopic sensitivity, and high resolution mass spectrometry for obtaining isotopic ratios at ultra-high sensitivities of 10^{14} and better.

Other techniques include ultra-high resolution microscopy, characterisation of semiconductor device defects at high spacial resolution, and the investigation of damage processes in the nuclear irradiation of materials.

ION BEAM METHODS for thin film materials have major application areas from archaeology to zoology (including materials science, geology, cultural heritage, electronics and many others).

Summary

First we list the articles in the Chapter, briefly sketching the contents of each. The Chapter is very wide-ranging, including depth profiling methods, some rather specialised types of microscopy, and methods relating to radiation damage studies. Many acronyms and other terms are used in this Chapter, and full alphabetical Glossaries are given in **Appendix A** (ion beam techniques and terms) and **Appendix B** (other techniques and terms). Simply expanding the acronyms is often less than helpful, and these Glossaries are given in an expanded form intended to help the reader to appreciate both the term and its relation with others.

Microscopy methods are compared with each other and with other methods in this book in **Table 1**.

Ion Beam Analysis (IBA) methods are compared with each other for various types of primary ion beam in terms of the ratio of nuclear and electronic stopping power of the ion in silicon (**Figure 1**). More pragmatically, they are also compared in terms of their sensitivity and the applicable thin film thicknesses (**Figure 2**). Too much should not be read into these Figures: they are intended only as rough sketches to give some perspective to the discussion.

IBA and other surface sensitive analytical methods in this book are compared in **Table 2**. IBA and other analytical methods applicable to thin film depth profiling are compared in **Table 3**.

Some articles are really in a class of their own and are in this Chapter only because they involve ion beams. Radio-carbon dating is one example of the use of AMS, detailed information about photon and particle detector materials can be obtained by IBIC, and the characterisation of neutron damage in nuclear fusion and fission reactor structural materials can be conveniently done on well-controlled test samples made without being activated by using ion implantation. It should also be pointed out that the FIB is a widely-used tool for *making* samples (with ultra-high spacial resolution), not directly *characterising* them.

Finally, **Table 4** compares the physical installation (footprint) of the various techniques. We should point out that the Total-IBA methods (unlike SIMS) is today largely implemented in academic laboratories; they do not have a significant industrial presence as yet. This may change if the new ideas presented here (*q.v.* the TOTAL-IBA article) are fruitful, and if a small-footprint Total-IBA tool based on a superconducting cyclotron proves feasible. Focussing MeV ion beams at present requires long beamlines with the simple (cheap) ion optics currently in use. Were there a demand the footprint of MeV microbeams could be dramatically reduced.

We anticipate far-reaching changes in the next few years that will further improve the powerful analytical tools already available.

List of Articles

1. **Total-IBA:** MeV ion beam analysis (IBA) techniques used synergistically for the non-destructive analysis of thin films ranging from sub-nm to many microns thickness. These techniques are especially powerful for multilayer and complex intermixed samples in application areas from archaeology to zoology, and give results unaffected by matrix and interface effects. More information on nuclear scattering is in the PARTICLE SCATTERING article in the COMMON CONCEPTS chapter. TOTAL IBA uses the fact that the same primary ion beam generates many resulting signals all of which can be detected and used for analysis. These signals include:
 - a. **STIM:** (Scanning Transmission Ion Microscopy). Images the energy loss of a scanned primary ion microbeam passing through thin samples. Equivalent to X-ray radiography, with the equivalent computed tomography 3D images equally available. Ultra-low beam currents are required since ~100% of the primary beam is detected.
 - b. **PIXE:** (see the PARTICLE-INDUCED X-RAY EMISSION article). Similar to XRF (see X-RAY METHODS chapter). Excellent elemental discrimination and sensitivity, but poor depth resolution. Comparisons with related techniques in the ATOMIC EXCITATIONS article in the COMMON CONCEPTS chapter.
 - c. **MeV-SIMS:** Secondary Ion Mass Spectrometry with an MeV primary beam (see the SIMS article)
 - d. **RBS & EBS:** Rutherford and non-Rutherford (elastic) backscattering (see ELASTIC BACKSCATTERING article). Excellent accuracy and depth sensitivity, but rather poor sensitivity and mass resolution.
 - e. **ERD:** (see the ELASTIC RECOIL DETECTION article). Excellent mass resolution and depth sensitivity, but rather poor sensitivity and accuracy.
 - f. **NRA & PIGE:** see the NUCLEAR REACTION ANALYSIS AND PARTICLE-INDUCED GAMMA EMISSION article. Gives sensitivity to specific isotopes and is important for light elements that are otherwise hard to analyse.
 - g. **Microbeam:** Lateral resolution using focussed microbeam facility. 1 mm spot size is common, with spot sizes of 100 nm for PIXE and 30 nm for STIM considered feasible. Scanned area (with mapping) can be 3 mm or more.
 - h. **Channelling:** (see the MEIS article) allows damage depth profiles and the lattice location of impurities to be obtained. Ion beams used for IBA are usually collimated well enough for channelling, and suitable goniometers are common.
 - i. **External beam:** allows mapping microbeam Total-IBA in air (or He atmosphere). Good for large, or delicate, or valuable, or wet samples.
2. **LEIS:** (see LOW ENERGY ION SCATTERING article). Ion beams of a few keV are used (in UHV) for sensitivity to the outer atomic layer. (Note that XPS/AES are sensitive to the first few nm, and cannot discriminate the outer atomic layer.) Valuable in catalysis, corrosion and similar studies.
3. **MEIS:** (see MEDIUM ENERGY ION SCATTERING article). Uses ion beams of ~100 keV (in UHV) for RBS with channelling. Gives ultra-high depth resolution and sensitivity to atomic positions of the first few atomic layers. Valuable for surface reconstruction studies.
4. **SIMS:** (see SECONDARY ION MASS SPECTROMETRY article). SIMS is a cluster of techniques of major importance involving stripping the sample layer by layer,

ionising the stripped layer and doing mass spectrometry on it. Thus, even where the ionisation efficiency is low the signal can be very large and therefore the sensitivity is great. The SIMS signal always involves huge matrix effects due to the ionisation efficiency varying by many orders of magnitude, although in many cases protocols can be devised by which these matrix effects can be controlled. **Dynamic SIMS** is a general-purpose destructive depth profiling (sputtering) technique using a keV primary beam (also see AMS). **Static SIMS** is a surface sensitive technique which aims to extract information from the sample before the analysed area is noticeably damaged. It specialises in gentle sputtering methods which preserves the molecular structure of the sample. **MeV-SIMS** is a static SIMS method using an MeV primary ion beam where the sputtering process is due to an electronic (not nuclear) energy loss in the material which emphasises the production of high atomic weight molecular ions. With MeV-SIMS a PIXE signal is also generated which can be used to eliminate matrix effects.

5. **AMS:** (see TRACE ELEMENT ACCELERATOR MASS SPECTROMETRY article). Used in radio-carbon dating and similar measurements which require the isotopic ratio of elements to be determined at ultra-high sensitivity (10^{15} is normal!). Uses the same type of accelerator as for Total-IBA, but the sample is inserted into the ion source. The technique is destructive, requiring samples of order mg mass. Depth profiling is also possible, in which case AMS is a variety of SIMS (*q.v.*).
6. **FIM & FIB:** (see ATOM PROBE TOMOGRAPHY AND FIELD ION MICROSCOPY article). The field-ion microscope destructively images a material which is formed into an ultra-sharp tip which develops a very high electric field on the application of a small electric potential. Ions are stripped from the target by the strong electric field, and can be individually imaged with very high spacial fidelity. In tomography, the imaging process is continued for many layers of the initial tip. The **Focussed Ion Beam** (FIB) uses the same field-emission mechanism to generate a very bright ion beam (in the same way as a bright electron beam is produced for electron microscopes using a field-emission electron gun). A bright ion beam can be focussed to a very small spot, giving a very high sputter rate. The FIB is used routinely today to machine materials with very high spacial resolution for a wide variety of purposes.
7. **SHIM:** (see SCANNING HELIUM-ION MICROSCOPY article). This is a variant on the FIB in construction and a variant on the SEM in function. A field-emission He-ion source is used in the same way that a field-emission electron source is used in the SEM. The de Broglie wavelength of 30 keV He ions is significantly smaller than for electrons, which means that higher spacial resolution is possible.
8. **IBIC:** Radiation Effects Microscopy (see ION BEAM INDUCED CHARGE article). The semiconductor device to be characterised is placed in an ultra-low intensity scanned primary microbeam. Each incident energetic particle is registered by the semiconductor device, and conductivity and mobility maps can be obtained.
9. **Radiation Damage:** (see CHARGED-PARTICLE IRRADIATION FOR NEUTRON RADIATION DAMAGE STUDIES article). The characterisation of neutron damage in nuclear fusion and fission reactor structural materials can be conveniently done on well-controlled test samples made by ion implantation. The neutron damage can thus be modelled off-line and without problems radiation protection due to the activation of the sample by neutron irradiation.

Table 1: Microscopy Methods**** denotes an Ion Beam Method**

Method	Lateral Resolution	Measurand
**Total IBA	200 nm	Elemental composition (major, minor, trace); depth profiles per pixel; damage by channelling; quantitative
**dynamic SIMS	50 nm	Elemental composition (major, minor, trace); depth profiles per pixel (by sputtering); qualitative
**static SIMS	50 nm	Elemental composition (major, minor, trace); chemical information from molecular ions; qualitative
**MeV-SIMS	2 μ m	Elemental composition (major, minor, trace); chemical information from molecular ions; quantitative through PIXE
**FIM	0.2 nm	Quantum tomography: atomic reconstruction of sample
**IBIC	5 μ m	Recombination sites and mobility mapping in particle and photon detectors
SEM-EDS	2 μ m	Elemental composition (major, minor); quantitative
SEM-EBD	2 nm	Major elemental composition; qualitative
**SHIM	0.2 nm	Major elemental composition; qualitative
TEM-EELS	5 nm	Elemental composition (major, minor); chemical information also available
SAM	2 nm	Auger electron (surface) signal: surface elemental composition (major, minor); chemical information also available

Table 2: Surface Methods**** denotes an Ion Beam Method**

Method	Sample Size	Lateral resolution	Ambient pressure	Comment
**HR-RBS/PIXE	100 mm	0.1x1 mm	high vacuum	Glancing incidence/exit geometries allow accurate elemental analysis at very high sensitivity
TR-XRF	100 mm	0.5x5 mm	air	
**Static-SIMS	10 mm	50 nm	UHV	Chemical information from gentle sputtering and mass spectrometry (kDalton molecular weight ions)
MALDI	100 mm	0.5 mm	air	
**MeV-SIMS	100 mm	2 μ m	air	ditto, but higher yield of high molecular weight ions, and complementary PIXE
XPS	10 mm	50 μ m	UHV	Electron spectroscopy at high energy resolution gives chemical bonding information
AES	10 mm	1 nm	UHV	
**LEIS	10 mm	1 mm	UHV	Sensitivity to outermost surface powerful for catalysis and similar problems
**MEIS	10 mm	1 mm	UHV	Sophisticated crystallography powerful for surface reconstruction and similar problems

Table 3: Thin Film Methods

**** denotes an Ion Beam Method; "na" denotes "not applicable"**

Method	Sample Size	Information Depth	Depth Resolution		Lateral Resolution		Sensitivity	Precision	Accuracy	Ambient Pressure	Comment
**Total IBA	2 m	20 µm	<5 nm	from energy loss	> 100 nm	from spot size	10 ⁻⁶	0.5%	1%	air	see note [1]
**Dynamic-SIMS	50 mm	2 µm	<1 nm	from sputter rate	50 nm	from spot size	10 ⁻⁸	0.5%	(-na-)	High vacuum	
EPMA	50 mm	2 µm	~1 µm	from primary electron energy	~1 µm	from primary electron energy	10 ⁻⁴	0.5%	6%	High vacuum	see note [2]
XRF	2 m	200 µm	5-50 µm	from X-ray energy detected	50 µm	from microfocussed X-ray beam	10 ⁻⁶	0.5%	5%	air	see note [3]
TEM-EELS	3 mm	500 nm	(-na-)	(integrated over sample thickness)	0.5 nm	from spot size	~1%	2%	~10%	High vacuum	
AR-XPS	10 mm	10 nm	0.5 nm	from differential attenuation	50 µm	from microfocussed X-ray beam	~1%	1%	~10%	UHV	
AES with sputtering	10 mm	2 µm	<1 nm	from sputter rate	1 nm	from spot size	~1%	1%	~10%	UHV	
XPS with sputtering	10 mm	2 µm	<1 nm	from sputter rate	50 µm	from microfocussed X-ray beam	~1%	1%	~10%	UHV	
**MEIS	5 mm	250 nm	<1 nm	from energy loss	1 mm	from spot size	~1%	5%	~10%	UHV	
**LEIS	5 mm	25 nm	<0.5 nm	from energy loss	1 mm	from spot size	~1%	5%	~10%	UHV	
**FIM	100 nm	25 nm	<0.5 nm	quantum method: atom counting	<0.5 nm	quantum method: atom counting		(-na-)	(-na-)	UHV	single atom imaging

- Notes:** 1) Example of 1% absolute accuracy by RBS, with Uncertainty Budget, by Jeynes, Barradas & Szilágyi (submitted to *Anal.Chem.* April 2012)
2) Example of EPMA absolute accuracy critically estimated by Bailey *et al.*, (*X-Ray Spectrometry*, **38**, 2009, 343–347)
3) Example of absolute standard-less XRF accuracy estimated by Beckhoff (*J. Anal. At. Spectrom.*, **23**, 2008, 845–853)

Table 4: Analytical Installations

** denotes an Ion Beam Method

Method	Footprint	Dominating feature
**Total-IBA	200 m2	2 or 3 MV accelerator and microbeam lines
**SIMS	tabletop	
**ToF-SIMS	3 m2	Mass spectrometer
MALDI	(tabletop)	Mass spectrometer
EPMA	2 m2	WDS spectrometers
XRF	tabletop	
sy-XRF	2000 m2	Synchrotron light source
TEM	tabletop	
XPS	tabletop	
AES	tabletop	
**MEIS	100 m2	200 kV ion implanter
**LEIS	tabletop	
**AMS	300 m2	2 or 3 MV accelerator, with SIMS injector and mass spectrometry

Appendix A: Glossary of ion beam (mostly IBA) techniques and terms

- AMS** Accelerator mass spectrometry. A form of IBA (the accelerator is the same) where the sample goes in the source. Used routinely for ^{14}C and similar isotopic analyses. In depth profiling mode is a form of dynamic SIMS.
- ANN** Artificial neural networks. Black boxes containing image recognition software (and no physics!) that instantly recognises (without calculation) features of spectra (layer thicknesses etc). The performance of ANNs depends critically on their training.
- BS** (Elastic) backscattering. Can be either RBS or EBS.
- Blocking:** Inverse of channelling. Crystal channels have high transparency to collimated ion beams, major axis strings of atoms block the ion beam.
- CAICISS:** Coaxial impact collision ISS. A variety of LEIS.
- Channelling:** Damage in single crystals is frequently quantified with ion channelling, where the well collimated ion beam is aligned with major crystallographic axes. Can readily be used with STIM, PIXE, BS, NRA. Channelling and blocking patterns are essential to MEIS.
- EBS** Elastic (non-Rutherford) backscattering. Scattering cross-section is given by the the elastic scattering channel of the reaction, and depends on the nuclear structure of the two nuclei. Cross-section can be calculated by R-matrix or other methods which have nuclear data (energy levels etc) as input, but the calculations must be informed by direct cross-section measurements. Measurements and evaluations are on the IBANDL website.
- EDS** Energy dispersive (X-ray) spectrometry. See Appendix B
- ERD** Elastic recoil detection. Follows the recoiled rather than the scattered ion in the elastic collision. He-ERD is valuable for analysing H isotopes. HI-ERD (heavy ion ERD) typically uses primary beams of ~ 1 MeV/amu, and ToF (time of flight) or gas detectors for the heavy recoils.
- ERDA** Elastic recoil detection analysis. Synonym for ERD and preferred in Finland, sounding better in Finnish
- ESS** Elastic scattering spectrometry. Refers to any of RBS, EBS, ERD, or elastic forward scattering (off-axis STIM)
- FIB** Focussed ion beam. See SIMS.
- FIM** Focussed ion microscopy. The sample is made into a field-emission tip and then imaged destructively.
- FRS** Forward recoil spectrometry. Synonym for ERD.
- HEIS** High energy ion scattering. RBS using MeV ion beams.
- HI-ERD** Heavy ion ERD. Gas ionisation, E- ΔE , or ToF detectors are needed today (although Si diodes with range-foils can be used). Energies comparable to 1 MeV/nucleon are usually used.
- HI-RBS** Heavy ion RBS (gas ionisation detectors are ideal). A Li beam is often used for better mass resolution. Because yield goes with Z^2 , HI-RBS can be used to calibrate TR-XRF for very high sensitivity to surface metal contamination.
- HR-PIXE** High energy resolution PIXE (using WDS or HR-EDS)
- IBA** MeV Ion Beam Analysis, including STIM, IBIL, PIXE, BS (RBS or EBS), ERD, NRA, PIGE, MeV-SIMS. MEIS and LEIS are lower energy versions of RBS. Commercial SIMS instruments use keV energy primary beams.
- IBIC** Ion beam induced current. Low fluence technique for non-destructively characterising semiconductor device quality: carrier lifetime, carrier mobility, charge trapping defects etc. Ion analogue of EBIC and XBIC.
- IBIL** Ion beam induced luminescence. The ion analogue of cathodoluminescence (electron-induced) and photoluminescence.
- ISS** Ion scattering spectrometry. Synonym for one of LEIS, MEIS, RBS, depending on the energy regime.
- LEIS** Low energy ion scattering. RBS using keV ion beams. New high sensitivity detectors make this a rapid technique which looks at the outermost layer of the sample. Thus complementary (with higher depth resolution) to XPS.
- MEIS** Medium energy ion scattering. RBS using ~ 100 keV ion beams. Gives information on the crystallography and composition of the near-surface region ($\sim 100\text{nm}$).
- MeV-SIMS** A static SIMS method using an MeV beam with enhanced sensitivity to high molecular weight molecular ions. Can be used in air, similar to MALDI but with high spacial resolution. A PIXE signal is usually also available, enabling standard-less and matrix-independent quantification (unlike MALDI).
- Microbeam** Ion beams can be readily focussed with quadrupole triplets (or multiplets) to a focus of $\sim 1\ \mu\text{m}$. It is thought that 100 nm is feasible for PIXE and 30 nm is feasible for STIM.
- NRA** (Inelastic) nuclear reaction analysis. NRA cross-sections can also be calculated (as well as measured of course) and a few evaluations are on the IBANDL website together with many measured cross-sections.
- PDMS** Plasma desorption mass spectrometry. Forerunner of MALDI
- PESA** Proton elastic scattering analysis. Synonym for proton EBS, except that PESA can also be at forward angles.
- PIGE** Particle induced gamma ray emission. A special case of NRA where a gamma ray results.

- PIXE Particle induced X-ray emission. The ion analogue of XRF or, since today PIXE is usually used with a scanning microbeam, SEM-EDS or EPMA. Note that EPMA is also PIXE, since electrons are also particles!
- RBS Rutherford backscattering spectrometry. Scattering cross-section is analytical, and given by the Coulomb potential (with screening). Ion analogue of the BSE signal in SEM. Switches to EBS when the Coulomb barrier is increased. Called MEIS for beams near the stopping power maximum (~100 keV), and LEIS for keV beams.
- SIM Scanning ion microscopy. Ion analogue of SEM.
- SIMS Secondary ion mass spectrometry. Another form of IBA using (for example) a 30 keV ion source for sputtering. The secondary (sputtered) ions are mass analysed. One important variant is FIB (focussed ion beam machining) which uses a high intensity (and very bright) nano-focussed liquid metal ion source (usually Ga): another is MeV-SIMS, where the sputtering results from electronic energy loss, not the nuclear collision cascade.
- SHIM Scanning He-ion microscopy. An SEM based on a FIB. RBS detector is a BSE analogue for qualitative Z-contrast.
- STIM Scanning transmission ion microscopy. Typically looks at the energy loss of primary beam particles transmitted through thin samples, so that it is similar to EELS in the TEM (but with much lower energy resolution). Off-axis STIM can be used simultaneously with PIXE since the STIM detector is not in the primary beam.
- ToF Time of flight. ToF-SIMS and ToF-ERD are standard techniques
- WDX Wavelength dispersive X-ray spectrometry (high resolution). See Appendix B.

Appendix B: Glossary of related techniques and terms

- AES Auger electron spectrometry. Also SAM: scanning Auger microscopy. Electrons in, electrons out. Same electron spectrometer as XPS, same EMFP, thus also a true surface technique. AES is really SEM in UHV (ultra-high vacuum), but looking at the (high energy) Auger electrons rather than the number of (low energy) secondary electrons. Chemical shifts are also present in AES, but are more complex than in XPS.
- AFM Atomic force microscopy. One of a number of scanning probe microscopies, including the original STM (scanning tunnelling microscopy).
- BSE Backscattered electron signal available on SEMs. This carries qualitative Z-contrast.
- DESI Desorption electrospray ionisation. Similar to MALDI.
- DART Direct analysis in real time. Similar to MALDI.
- EBIC Electron beam induced current. Analogue of IBIC.
- EDS Energy dispersive X-ray spectrometry ("EDX" is a tradename). Usually used as "SEM-EDS".
- EELS Electron energy loss spectrometry. A TEM technique. See XAS.
- EPMA Electron probe microanalysis: just an SEM specialised for X-ray analysis, generally with one or more WDXs (wavelength dispersive X-ray spectrometers). See also SEM-EDS.
- ESCA Electron spectroscopy for chemical analysis. The photoelectron process can show pronounced chemical shifts for difference valence states. Synonym for XPS.
- EXAFS Extended X-ray absorption fine structure. Incident X-ray energy ~50 eV – ~1000 eV above the absorption edge, giving high energy photoelectrons for which *single* scattering dominates. See NEXAFS and XAS.
- FTIR Fourier transform infra-red spectrometry. One of a large class of emission and absorption spectrometries sensitive, like Raman spectroscopy, to atomic and molecular vibration modes.
- HR-EDS High energy resolution EDS using superconduction transition edge sensor technology microcalorimeter detectors (third generation TES devices expected to have energy resolution ~1 eV – comparable to WDS). For chemical bonding information.
- ICP-MS Inductively coupled plasma mass spectrometry. One of a large class of mass spectrometries sensitive to ng/g (and better) where PIXE is only sensitive to mg/kg (at best). But ICP-MS analyses trace elements in bulk samples whose gross composition is known. Has now largely superseded INAA.
- INAA Instrumental neutron activation analysis. A reactor technique for trace element analysis now largely superseded by ICP-MS.
- LEED Low energy electron diffraction. Often used as a surface monitor in UHV (ultra-high vacuum) deposition systems.
- MALDI Matrix-assisted laser desorption ionization. An in-air spectrometry sensitive to molecules of high molecular weight. SIMS (with keV ions) must be done in vacuum; also gives molecular ions, but is a much more energetic sputtering technique and fragments the sputtered ions more for larger molecules. See also MeV-SIMS, DESI, DART, PDMS.
- NEXAFS Near-edge extended X-ray absorption fine structure. Incident X-ray energy ~10 eV – ~50 eV above the absorption edge, giving low energy photoelectrons for which *multiple* scattering dominates. See EXAFS and XAS.
- NMR Nuclear magnetic resonance or MRI (magnetic resonance imaging) in imaging mode.
- PDMS Plasma-desorption mass spectrometry. Forerunner of MeV-SIMS. See MALDI.

- SAM Scanning AES.
- SEM Scanning electron microscopy for imaging surface topography, primarily looking at the secondary electron signal. Often comes with EDS (or EDX: energy dispersive X-ray spectrometry) and often has a BSE (backscattered electron) signal too. The X-ray detector is the same as usually used for PIXE. The scanning ion microbeam (SIM) is thus an analogue of SEM, EDS and BSE being analogues of PIXE and EBS. And often a secondary electron detector is included in an SIM chamber to see the topography directly.
- TEM Transmission electron microscopy for imaging in both real and reciprocal space: always includes SAD (selected area electron diffraction). Also XTEM for cross-sectional TEM, and HR-TEM for high (atomic) resolution TEM. Often has EDS and EELS.
- TR-XRF Total-reflection XRF. Uses a glancing incidence focussed X-ray beam and special methods of sample preparation to deposit the measurand on an ultra-flat substrate for ultra-high sensitivity to trace contamination.
- WDX Wavelength dispersive X-ray spectrometry. Very high energy resolution is available. See EDS and EPMA.
- XANES X-ray absorption near-edge structure. In the XANES region the energy of the incident beam is ~ 10 eV from the absorption edge, and transitions of core electrons to non-bound levels with close energy occur with high probability. See XAS.
- XAS X-ray absorption spectrometry. See EELS for the low resolution TEM technique. See XANES, NEXAFS and EXAFS for the high resolution synchrotron techniques which need high intensity monochromatic beams.
- XBIC X-ray beam induced charge (synchrotron technique). Analogue of IBIC and EBIC.
- XPS X-ray photoelectron spectrometry. X-rays in, photoelectrons out. Because the EMFP (electron mean free path) is only a few nm this is a true surface technique, but sputtering is frequently used to give depth profiles. Synonym for ESCA.
- XRD X-ray diffraction for observing crystalline structure. A very wide variety of methods are in use including thin-film variants.
- XRF X-ray fluorescence. Like PIXE and EPMA but excited by X-rays. Same physics as XPS & AES but looks at the X-ray resultant, not the Auger or photo-electron one, and is therefore a "bulk", not a surface technique.

Figure 1: Ion Beam Analysis Regimes for Silicon Target and Incident Ions of Energy from 10^0 - 10^9 eV/amu.

Ion Beam Analysis techniques are compared using a coordinate system of projectile atomic number (specifically for H, He, C, Si, Mo and Au), plotted versus ion energy/mass (logarithmic in E/amu) within the framework of a log-log plot of nuclear stopping power $[S(n)]$ versus electronic stopping power $[S(e)]$, where the stopping power units are MeV/(mg/cm²). This plot has been generated for the “favorite son” of IBA—silicon—as the target. (Reproduced from the Wiley Characterisation of Materials 1st Edition "Ion Beam Techniques" chapter Introduction by B.L.Doyle & K.M.Horn)

Figure 2: Characterisation Methods Roughly Compared

The methods fall into three main groups: ultra-high spacial resolution, ultra-high sensitivity, and general purpose. The actual values given are intended only as a qualitative indication.