Materials Synthesis & Characterization: the role of positron annihilation
Input Materials

Known Material Properties

Synthesis (Equilibrium/non equilibrium Methods)

Modify Structure, Microstructure, Composition

Characterization/Property Evaluation

Suitable?

YES

Products/Components/Applications

Physical and chemical Properties

Application-oriented Properties

- Optical
- Magnetic
- Electrical
- Mechanical
Materials characterization involves 3 questions

- What is the elemental composition?
  Chemistry

- What is the crystal/local structure?
  Structure

- What are the defects?
  Microstructure

Probes for Materials characterization - Photons, Electrons, Protons, Neutrons, Ions, Positrons
How Do We Characterise?

- **General Analytical Technique** - Average Information from Bulk material, generally destructive
- **Microscopy Techniques** - Solid State, Non destructive, Probe Based Techniques, Position sensitive
Classification of Materials Characterization

**Structural Characterisation**
- Crystal structure
- Microstructure
- Defect structure

**Chemical Characterisation**
- Chemical nature
- Macro chemical analysis
- Micro chemical analysis
- Major element (>10%)
- Minor element (0.1 - 10%)
- Trace element (1-1000ppm)
- Ultra trace (< 1 ppm)
### A big canvas of characterization techniques – Microstructural, Structural and Chemical aspects

<table>
<thead>
<tr>
<th>Structural and Microstructural Characterization</th>
<th>Chemical Characterization</th>
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<tbody>
<tr>
<td><strong>Bulk structure</strong> – XRD, TEM, HRTEM, Neutron scattering</td>
<td><strong>Bulk composition</strong> – Spectrophotometry, Mass spectroscopy</td>
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<tr>
<td><strong>Surface structure</strong> – GIXRD, FIM, LEED, Ion Channeling, STM</td>
<td><strong>Surface composition</strong> – AES, XPS, SIMS, EPMA, RBS</td>
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<tr>
<td><strong>Surface topography</strong> – Optical Microscopy, SEM, AFM, Ellipsometry</td>
<td><strong>Impurities &amp; local chemical environment</strong> – Mass Spectroscopy, ESR, NMR, Mass spectroscopy, EPMA, AES, XPS, SIMS, PIXE, Raman, PL, FTIR, PAC, PAS, XRF, EXAFS</td>
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<tr>
<td><strong>Microstructure</strong> <em>(Impurity states, Interstitials, Vacancies, Color centres, dislocations, Grain boundaries)</em> – HRTEM, UVVIS, Raman, PL, FTIR, MS, PAC, PAS</td>
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<tr>
<td><strong>Microstructure</strong> <em>(Cracks, Voids, Precipitates, Exclusions)</em> – NDT, TEM, SAXS, SANS</td>
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<td><strong>Magnetic Structure</strong> – Neutron scattering, MS, PAC</td>
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Abbreviations for the experimental techniques

AES - Auger electron spectroscopy
AFM – Atomic force microscopy
EPMA – Electron probe microanalysis
ESR – Electron spin resonance spectroscopy
EXAFS – Extended X-ray absorption fluorescence spectroscopy
FIM – Field ion microscopy
FTIR – Fourier transform infrared spectroscopy
GIXRD – Glancing incident X-ray diffraction
HRTEM – High resolution electron microscopy
EXAFS – Extended X-Ray Absorption Fine Structure
LEED – Low energy electron diffraction
MS – Mossbauer spectroscopy
NDT – Non-destructive techniques
NMR – Nuclear magnetic resonance spectroscopy
PAC – Perturbed angular correlation spectroscopy
PAS – Positron annihilation spectroscopy
PL – Photoluminescence Spectroscopy
RBS – Rutherford backscattering Spectroscopy
SANS - Small angle neutron scattering
SAXS - Small angle X-ray scattering
SEM – Secondary electron microscopy
SIMS - Secondary ion mass spectroscopy
STM - Scanning tunneling microscopy
TEM – Transmission electron microscopy
UVVIS - UV-VIS absorption spectroscopy
XPS – X-ray photoelectron spectroscopy
XRD – X-ray diffraction
XRF – X-ray resonance fluorescence
Defects - Atomistic Imperfections

Macroscopic consequences – Changes in mechanical (Cracks, Fracture, Swelling), Optical, electrical & magnetic properties
Point Defect Production

- **Crystal Growth**
- **Quenching**, i.e. *rapid cooling*
- **Plastic deformation**
- **Irradiation** with electrons, ions, neutrons
- **Oxidation, Nitridation, Silicidation**
- **Reactive Interfaces**
- **Precipitation**
### Experimental techniques for defect studies

#### Metals & alloys
- Resistivity
- Dilatometry
- Non-destructive techniques (NDT)
- X-ray diffraction (XRD), SAXS
- Electron Microscopy (SEM, TEM)
- Small Angle Neutron Scattering (SANS)
- **Positron Annihilation spectroscopy**
- Perturbed angular correlation

#### Semiconductors
- Resistivity
- Dilatometry
- NDT
- XRD, SAXS
- Electron Microscopy
- SANS
- RBS, Ion Channeling
- EPR, NMR
- Mossbauer spectroscopy
- Electron microscopy
- Perturbed angular correlation
- **Positron Annihilation spectroscopy**
- Raman scattering
- Infrared & Optical absorption
- Ellipsometry
D.A.M. Dirac
- predicted the existence of a positron in 1928 as an explanation of negative energy solutions of his equation: \( E = \pm \sqrt{p^2c^2 + m^2c^4} \)

C.D. Anderson
- 1932 discovers positrons in a cosmic ray event in a Wilson cloud-chamber
- 1933 evidence of \( e^+ - e^- \) pair formation by registration of **annihilation** Gamma quanta

V. Bondarenko, Martin-Luther-University, Halle, Germany
Comparison of various experimental techniques

Each technique has sensitivity over certain size and concentration ranges and only by judicious combination of many, one can attempt to unravel complete information.

Positron lifetime spectroscopy can resolve size, concentration and distribution of free volume holes and depth or sampling volume.
Applicability of positrons in various branches of science

**POSITRONS**

- **Materials Science**
  - Fast $e^+$ (Depth averaged)
    - Lifetime ($\tau$)
    - Doppler Broadening
    - $e^-$ density
    - Defects
  - ACAR
    - 1-D, $\rho(p_z)$
    - Defects at Surfaces/Interfaces
    - 2-D
    - $\rho(p_x,p_y)$

- **Particle & Astrophysics**
  - Slow $e^+$ (Depth resolved)
    - Doppler/$\tau$
    - LEPD
    - Defects at Surfaces/Interfaces
    - PAES
    - Microprobe / Microscope

- **Medical Science**
  - PET

- **Antimatter**