Study of lattice defects in solids by positron annihilation

R. Krause-Rehberg
Universität Halle, FB Physik

- Introduction: How positrons “see” lattice defects
- Techniques of Positron Annihilation
- Examples:
  - electron-irradiation-induced defects in Ge
  - ion implantation in Si
  - non-destructive testing of steel
Positron trapping at crystal lattice defects

\[ e^+ \text{ source} \]

\[ \gamma \text{ quantum due to } \beta^+ \text{ decay (1.27 MeV)} \]

\[ \text{annihilation } \gamma \text{ quantum (} m_0c^2 = 511 \text{ keV)} \]

- positron wave-function can be localized in the attractive potential of a defect
- annihilation parameters change in the localized state (e.g. positron lifetime)
- defects can be detected (identification and quantification)
Positron lifetime spectroscopy

- positron lifetime spectra consist of exponential decay components
- positron trapping in open-volume defects leads to long-lived components
- longer lifetime due to lower electron density
- analysis by non-linear fitting: lifetimes $\tau_i$ and intensities $I_i$

\[ N(t) = \sum_{i=1}^{k+1} \frac{I_i}{\tau_i} \exp \left( -\frac{t}{\tau_i} \right) \]

\[ \kappa_d = \mu C_d = \frac{I_2}{I_1} \left( \frac{1}{\tau_b} - \frac{1}{\tau_d} \right) \]

\[ \tau_2 = 320 \text{ ps (divacancies)} \]
\[ \tau_3 = 520 \text{ ps (vacancy clusters)} \]
\[ \tau_b = 218 \text{ ps (bulk)} \]
Doppler broadening of the annihilation line

1. Positron lifetime

Birth $\gamma$-ray
1.27 MeV

$\Delta t$

$\Theta$

100 $\mu$m
diffusion (100 nm)

Sample

positron source
22-Na

Thermalization
(1 ps)

3. Doppler broadening
$0.511 \text{ MeV} \pm \Delta E, \quad \Delta E = p_z c / 2$

- broadening of 511-keV annihilation $\gamma$-line due to electron momentum
- core electrons cause stronger broadening due to high momenta
- in vacancies: fraction of annihilating core electrons is reduced

Normalized intensity

$\gamma$-ray energy [keV]

FWHM = 2.6 keV

FWHM = 1.4 keV

$\gamma$-ray energy $[\text{keV}]$

$\gamma$-ray energy $[\text{keV}]$

$^85\text{Sr}$

defect-rich

defect-free

$\delta^+$ annihilation
in GaAs

Normalized intensity

$\gamma$-ray energy $[\text{keV}]$

$\gamma$-ray energy $[\text{keV}]$

$\delta^+$ annihilation
in GaAs
Monoenergetic positron beam for defect profiling near surfaces

- monoenergetic positrons created by moderation ($E_+ = 3$ eV)
- energy can be tuned by acceleration stage: defect profiling
Electron-irradiated Ge

- electron irradiation generates Frenkel pairs
- vacancy annealing and defect reactions may be studied by positrons

(Polity et al., 1997)
Ion implantation in Si

- Ion implantation is most important doping technique in planar technology
- Problem: generation of defects \( \Rightarrow \) positron beam measurements

(Eichler et al., 1997)
**Getter centers after high-energy self-implantation in Si**

- **High-energy silicon self-implantation** creates additional gettering zones at \( R_p/2 \) and \( R_p \) (projected range of silicon ions).
- \( E_{Si^+}=3.5 \text{ MeV} \); sample annealed 30 sec at 900°C.
- At \( R_p \): network of interstitial-type dislocation loops captures diffusing impurities.
- At \( R_p/2 \): no indication of extended defects by TEM.
- Positrons show: open-volume defects (small vacancy clusters).
- After intentionally Cu contamination: positron traps are decorated by Cu.
we performed an extended study of defects in iron alloys and different steels.

positrons are very sensitive for fatigue damage and may detect damage during high-temperature creep aging.

positron annihilation is a suitable tool for non-destructive testing in many cases.

(Somieski et al., 1996)
• Positrons are suitable probes to observe lattice defects
• objects: vacancies, vacancy cluster, dislocations, grain boundaries in very fine-grained materials, precipitates
• sensitivity limit, e.g. for vacancies in Si: $5 \times 10^{14}$ cm$^{-3}$

This presentation can be found as pdf-file at our Webpage:

http://www.ep3.uni-halle.de/positrons