Study of radiation Defects in Semiconductors by Means of Positron Annihilation

R. Krause-Rehberg, V. Bondarenko, F. Redmann, F. Börner

Martin-Luther-Universität Halle-Wittenberg, Germany

- Introduction: Positrons detect lattice defects
- Examples:
  - electron-irradiated Ge
  - neutron-irradiated Si
  - new getter centers in Si after high-energy self-implantation ($R_p/2$ effect)
- Conclusions
The positron lifetime spectroscopy

- positron wave-function can be localized in the attractive potential of a defect
- annihilation parameters change in the localized state
- e.g. positron lifetime increases in a vacancy
- lifetime is measured as time difference between 1.27 and 0.51 MeV quanta
- defect identification and quantification possible
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 $I_i$

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

- trapping rate
- defect concentration

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

- electron irradiation (2 MeV @ 4 K) generates Frenkel pairs
- vacancy annealing and defect reactions may be studied by positrons

n-irradiated Si

- Radiation defects limit lifetime of detectors in high-luminosity collider experiments (ATLAS, TESLA)
- Neutron irradiation generates vacancy-type defects
- In as-irradiated state at RT:
  - Positron trapping rate: $\kappa = 9.7 \times 10^9$ s$^{-1}$
  - Defect concentration: $C_{\text{def}} = 2.5 \times 10^{17}$ cm$^{-3}$
- Therefore: $C_{\text{def}} \gg [O]$
- Probably isolated divacancies and larger vacancy clusters
  (Monovacancies anneal at about 170 K; divacancies stable up to 450...500 K)

Bondarenko et al., unpublished, 2001
two different vacancy-type defects are detected: divacancies and $V_3$

Defect-related positron lifetimes

- $\tau_{d1} = 290$ ps
- $\tau_{d2} \approx 320$ ps
n-irradiated Si

• vacancy clusters were studied by a self-consistent-charge density-functional based tight-binding method

• especially stable clusters: \( \text{n} = 6, 10 \) and 14

• vacancy clusters with \( \text{n} = 3 \) are energetically not favored, but 6 or 10 vacancies are not found in n-irradiated Si

**n-irradiated Si**

- after annealing of divacancies (673 K annealing step)
  - positron trapping rate: \( \kappa = 2 \times 10^9 \text{ s}^{-1} \)
  - assuming \( V_3 \Rightarrow \)
  - defect concentration: \( C_{V3} \approx 3 \times 10^{16} \text{ cm}^{-3} \)

- annealing stages at 300...600K and at 800 K

Bondarenko et al., unpublished, 2001
Defects in high-energy self-implanted Si — The $R_p/2$ effect

- after high-energy (3.5 MeV) self-implantation of Si ($5 \times 10^{15}$ cm$^{-2}$) and RTA annealing (900°C, 30s): two new gettering zones appear at $R_p$ and $R_p/2$ ($R_p$ = projected range of Si$^+$)
- visible by SIMS profiling after intentional Cu contamination

- at $R_p$: gettering by interstitial-type dislocation loops (formed by excess interstitials during RTA)
- no defects visible by TEM at $R_p/2$
- What type are these defects?

![TEM image by P. Werner, MPI Halle](image)

<table>
<thead>
<tr>
<th>Depth (µm)</th>
<th>Cu concentration (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rp</td>
<td>$10^{17}$</td>
</tr>
<tr>
<td>Rp/2</td>
<td>$10^{16}$</td>
</tr>
<tr>
<td></td>
<td>$10^{15}$</td>
</tr>
</tbody>
</table>

Enhanced depth resolution by using the Munich Scanning Positron Microscope

- sample is wedge-shaped polished (0.5...2°)
- layer of polishing defects must be thin compared to e⁺ implantation depth
- best: chemo-mechanical polishing
First defect depth profile using Positron Microscopy

- 45 lifetime spectra: scan along wedge
- separation of 11 µm between two measurements corresponds to depth difference of 155 nm (α = 0.81°)
- beam energy of 8 keV ⇒ mean penetration depth is about 400 nm; represents optimum depth resolution
- no further improvement possible due to positron diffusion: L*(Si @ 300K) ≈ 230 nm
- both regions well visible:
  - vacancy clusters with increasing density down to 2 µm (R_p/2 region)
  - in R_p region: lifetime τ_2 = 330 ps; corresponds to open volume of a divacancy; must be stabilized or being part of interstitial-type dislocation loops

Silicon self-implantation
- 3.5 MeV, 5×10^{15} cm^{-2}
- annealed 30s 900°C
- Cu contaminated
SIMS profile of Cu
Conclusions

- radiation-induced vacancy-type defects can be detected in solids by means of positron annihilation
- lower sensitivity limit for monovacancies $C_v \approx 1 \times 10^{15}$ cm$^{-3}$
- method very sensitive for early stage of vacancy agglomeration
- tools for thin layers (mono-energetic positron beams)
- scanning positron microbeams available
- defect depth scans by beveled samples (wedge angle 1°)

This presentation can be found as pdf-files on our Website: http://www.ep3.uni-halle.de/positrons

contact: mail@PositronAnnihilation.net