Study of radiation Defects in Semiconductors by Means of Positron Annihilation

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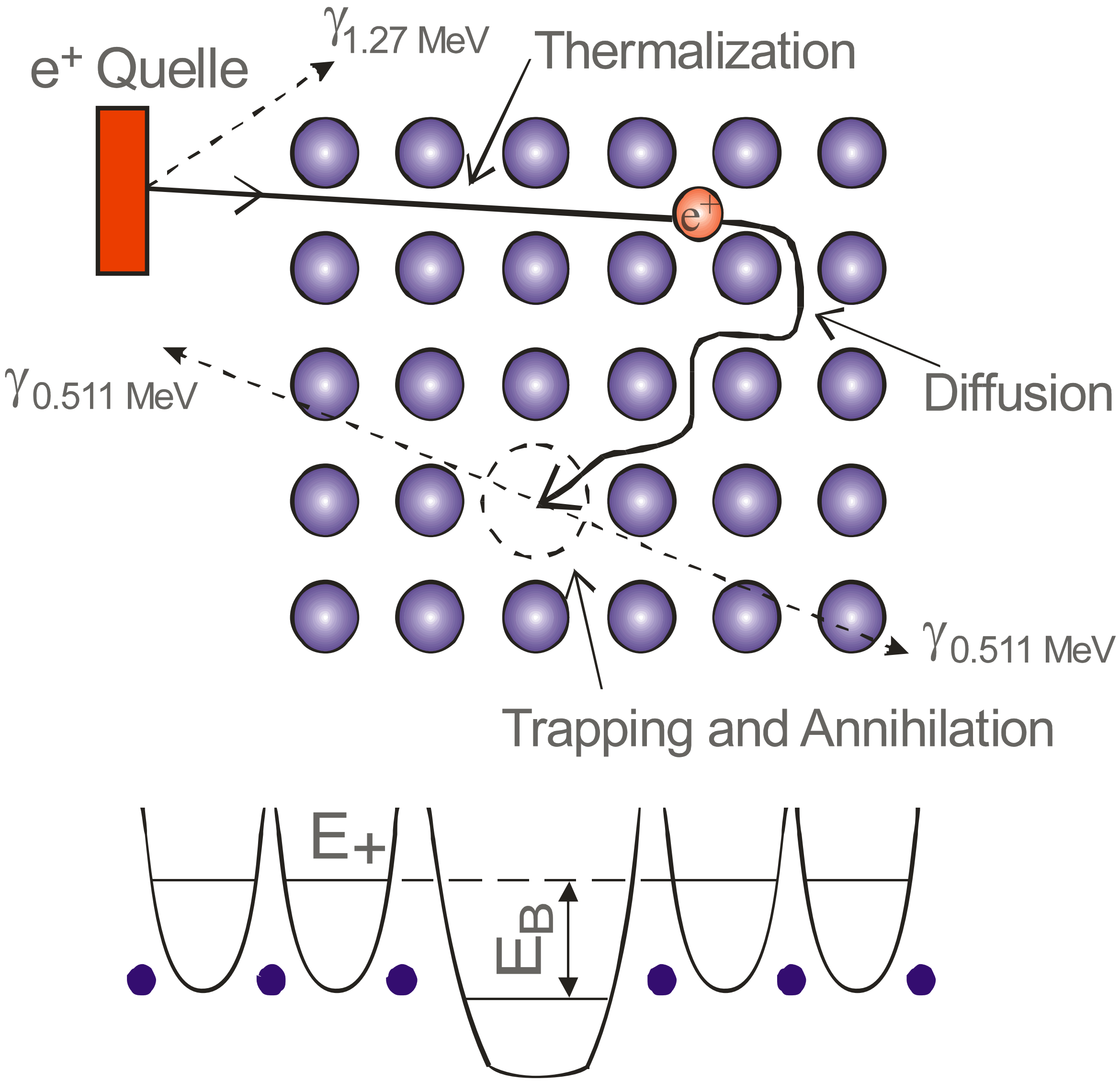
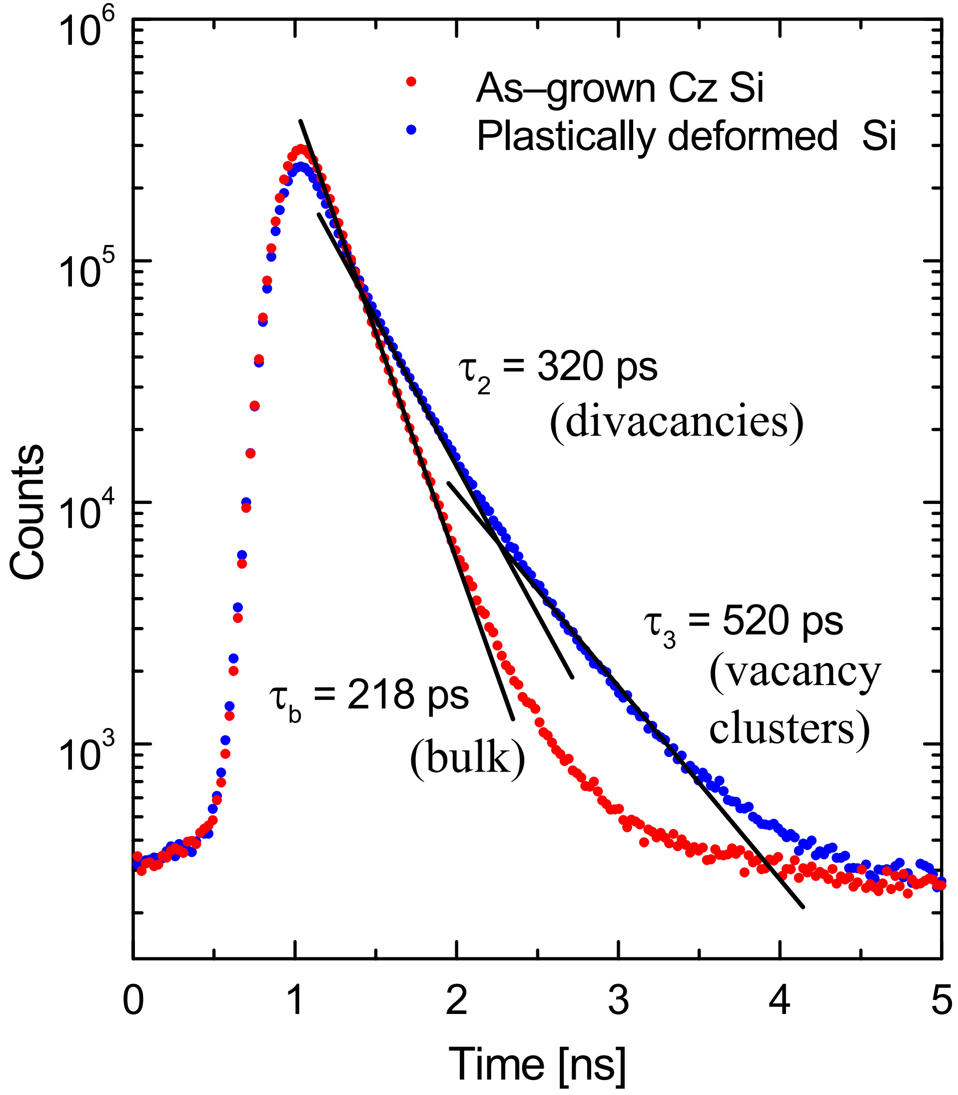
- Introduction: Positrons detect lattice defects
- Examples:
  - electron-irradiated Ge
  - neutron-irradiated Si
  - new getter centers in Si after high-energy self-implantation ($R_p/2$ effect)
- Conclusions

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

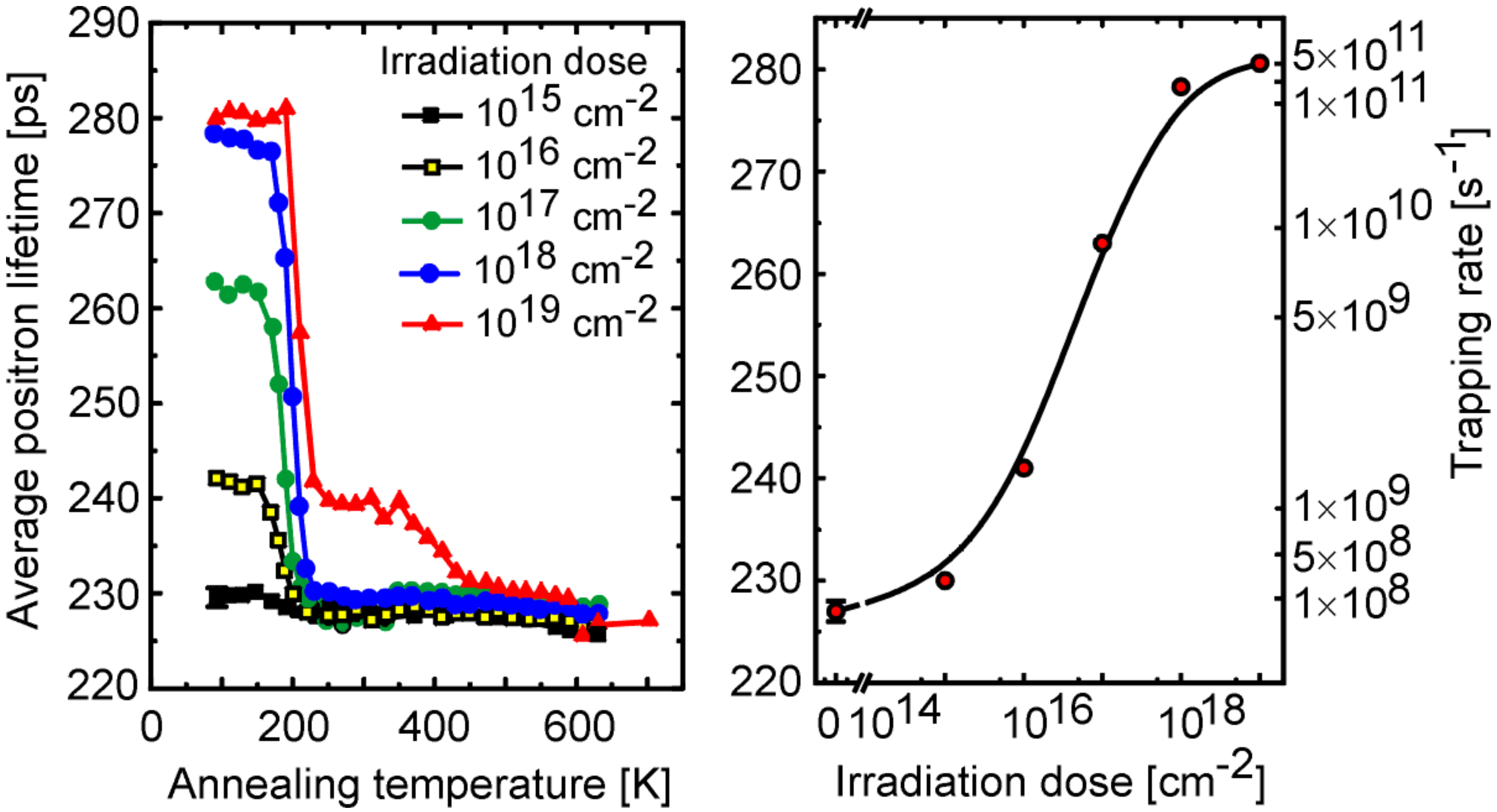
Positron lifetime spectroscopy



- 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 τ_i and intensities I_i
- positron lifetime spectrum: $$N(t) = \sum_{i=1}^{k+1} \frac{I_i}{\tau_i} \exp\left(-\frac{t}{\tau_i}\right)$$
- trapping coefficient
  $$\boxed{\kappa_d = \mu C_d} = \frac{I_2}{I_1}\left(\frac{1}{\tau_b} - \frac{1}{\tau_d}\right)$$
  trapping rate defect concentration

Electron-irradiated Ge

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



(A. Polity and F. Rudolf, Phys. Rev. B **59** (1999) 10025)

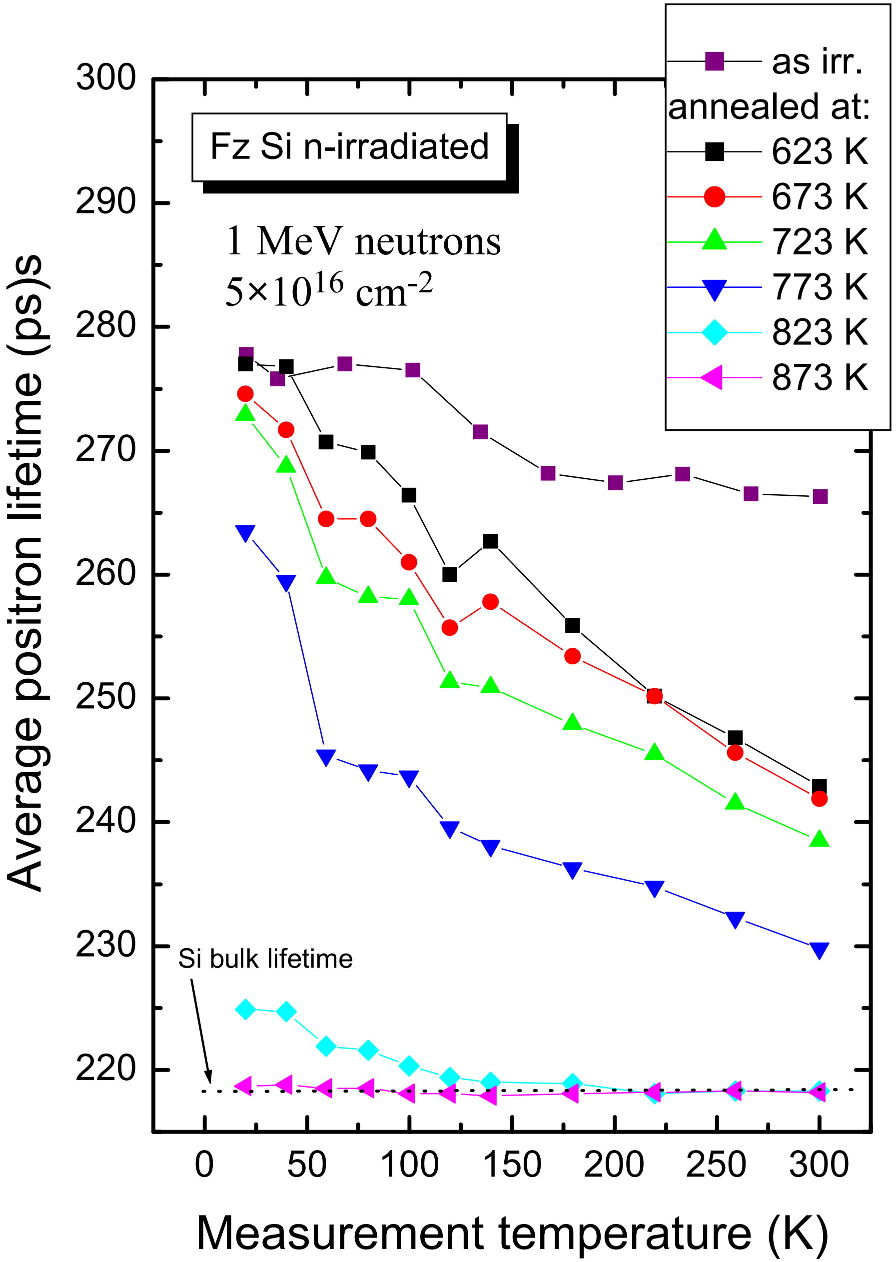
n-irradiated Si

- 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: $\kappa = 9.7\times10^{9}\ s^{-1}$
  defect concentration: $C_{def} = 2.5\times10^{17}\ cm^{-3}$
- therefore: $C_{def} \gg [O]$
- probably isolated divacancies and larger vacancy clusters

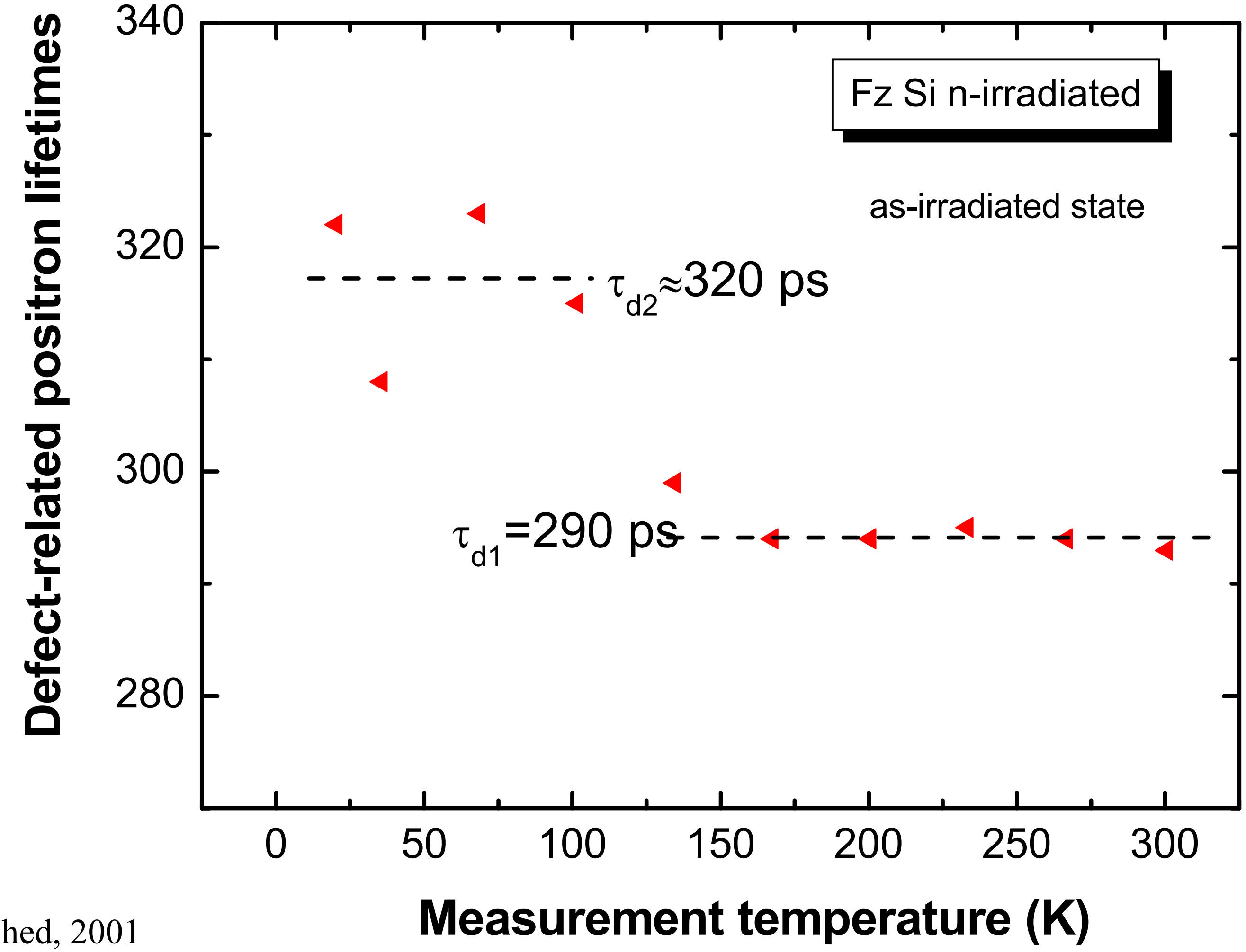
  (monovacancies anneal at about 170 K; divacancies stable up to 450…500 K)

Bondarenko et al., unpublished, 2001



n-irradiated Si

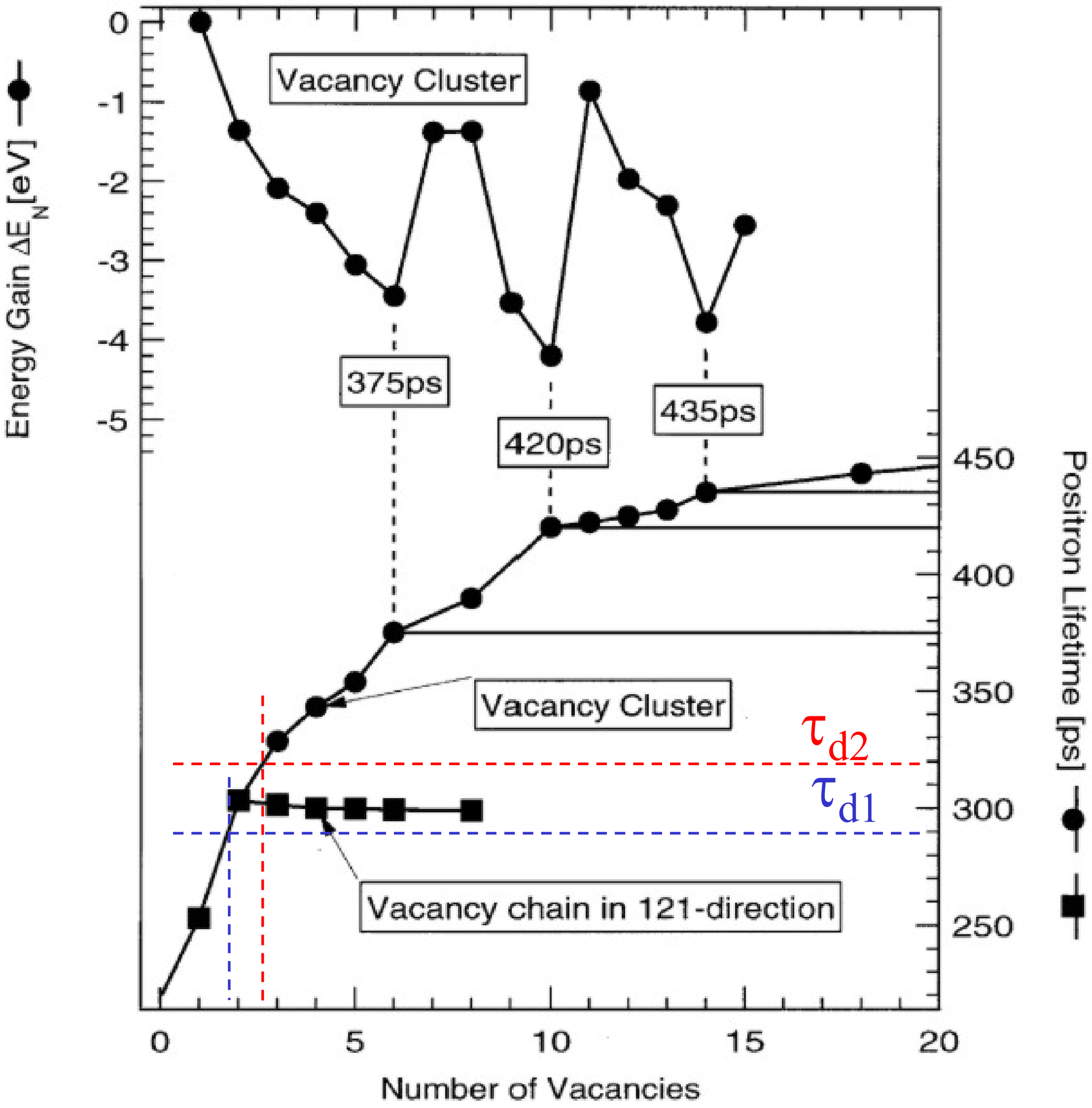
- two different vacancy-type defects are detected: divacancies and V_3



Bondarenko et al., unpublished, 2001

n-irradiated Si

- vacancy clusters were studied by a self-consistent-charge density-functional based tight-binding method
- especially stable clusters: n = 6, 10 and 14
- vacancy clusters with n = 3 are energetically not favored, but 6 or 10 vacancies are not found in n-irradiated Si



T.E.M. Staab et al., Physica B 273-274 (1999) 501

n-irradiated Si

- after annealing of divacancies (673 K annealing step)

  positron trapping rate:

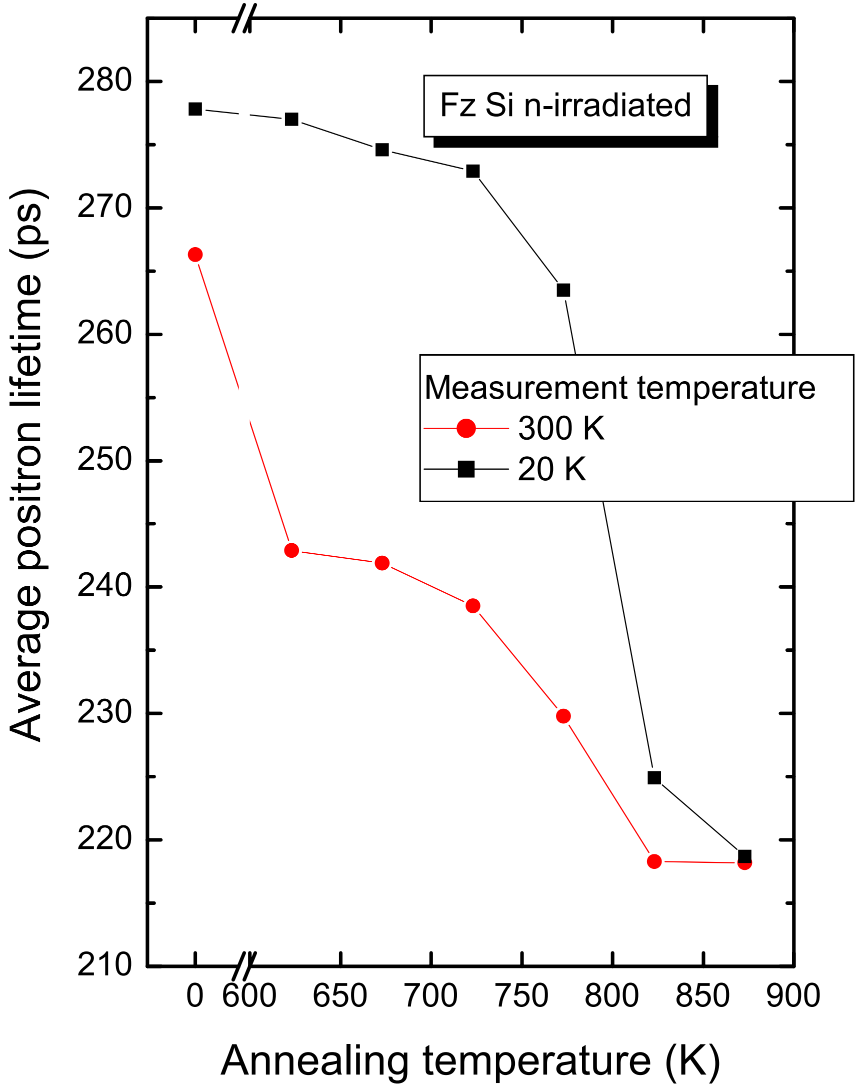
  $\kappa = 2\times10^9\ s^{-1}$

  assuming V_3 ⇒

  defect concentration:

  $C_{V3} \approx 3\times10^{16}\ cm^{-3}$

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

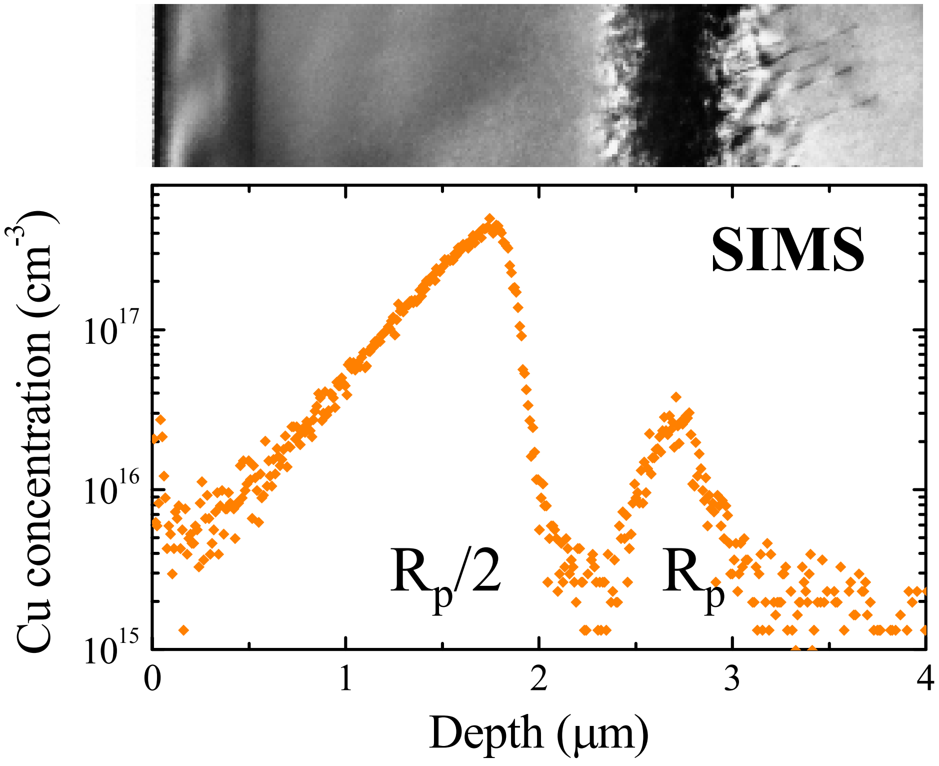


Bondarenko et al., unpublished, 2001

Defects in high-energy self-implanted Si — The $R_p/2$ effect

- after high-energy (3.5 MeV) self-implantation of Si (5×10^{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

TEM image by P. Werner, MPI Halle



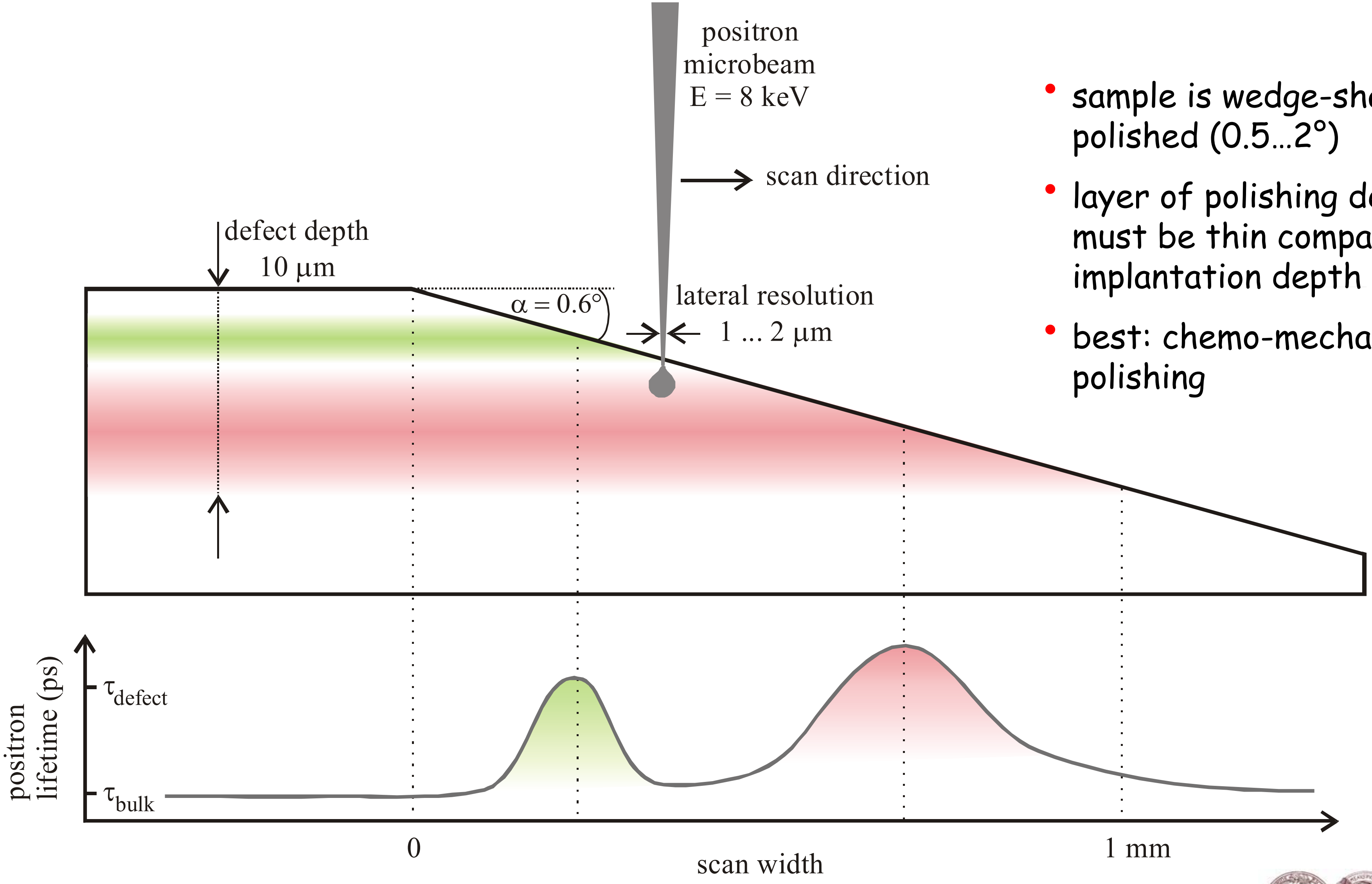
- at R_p: gettering by interstitial-type dislocation loops (formed by excess interstitials during RTA)
- no defects visible by TEM at $R_p/2$
- **What type are these defects?**

Interstitial type
[3,4]

Vacancy type
[1,2]

[1] R. A. Brown, et al., J. Appl. Phys. **84** (1998) 2459
[2] J. Xu, et al., Appl. Phys. Lett. **74** (1999) 997
[3] R. Kögler, et al., Appl. Phys. Lett. **75** (1999) 1279
[4] A. Peeva, et al., NIM B **161** (2000) 1090

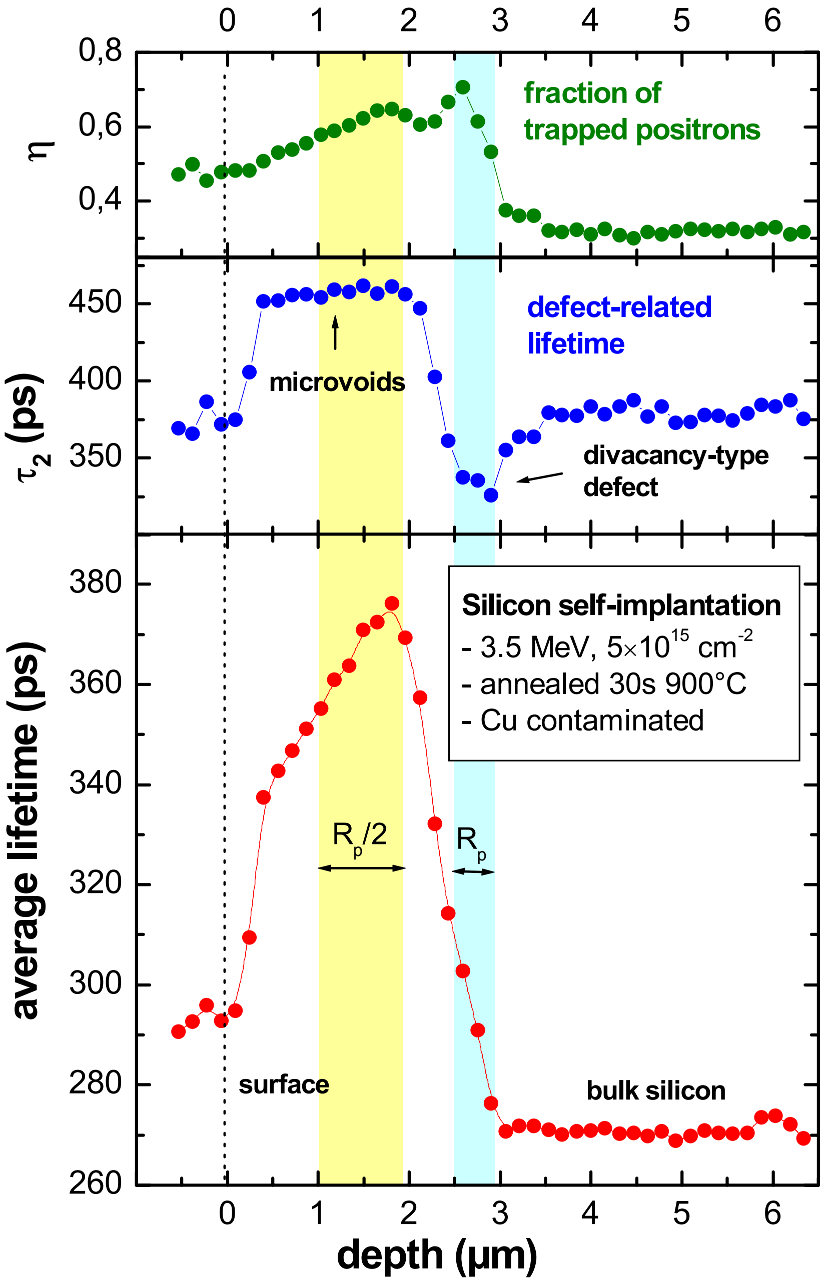
Enhanced depth resolution by using the Munich Scanning Positron Microscope

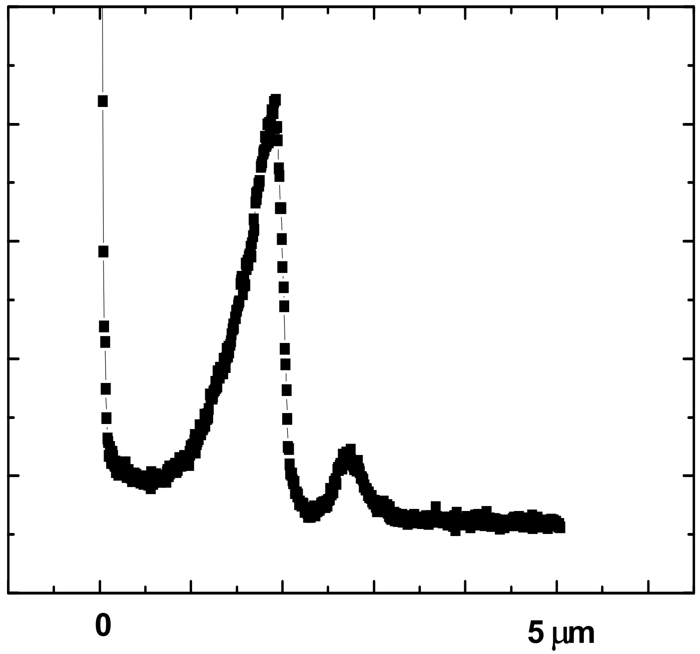


- sample is wedge-shaped polished (0.5…2°)
- layer of polishing defects must be thin compared to e^+ implantation depth
- best: chemo-mechanical polishing

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





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 $C_v \approx 1\times10^{15}\ \mathrm{cm}^{-3}$
- 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

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