Irradiation damage in semiconductors studied by positron annihilation

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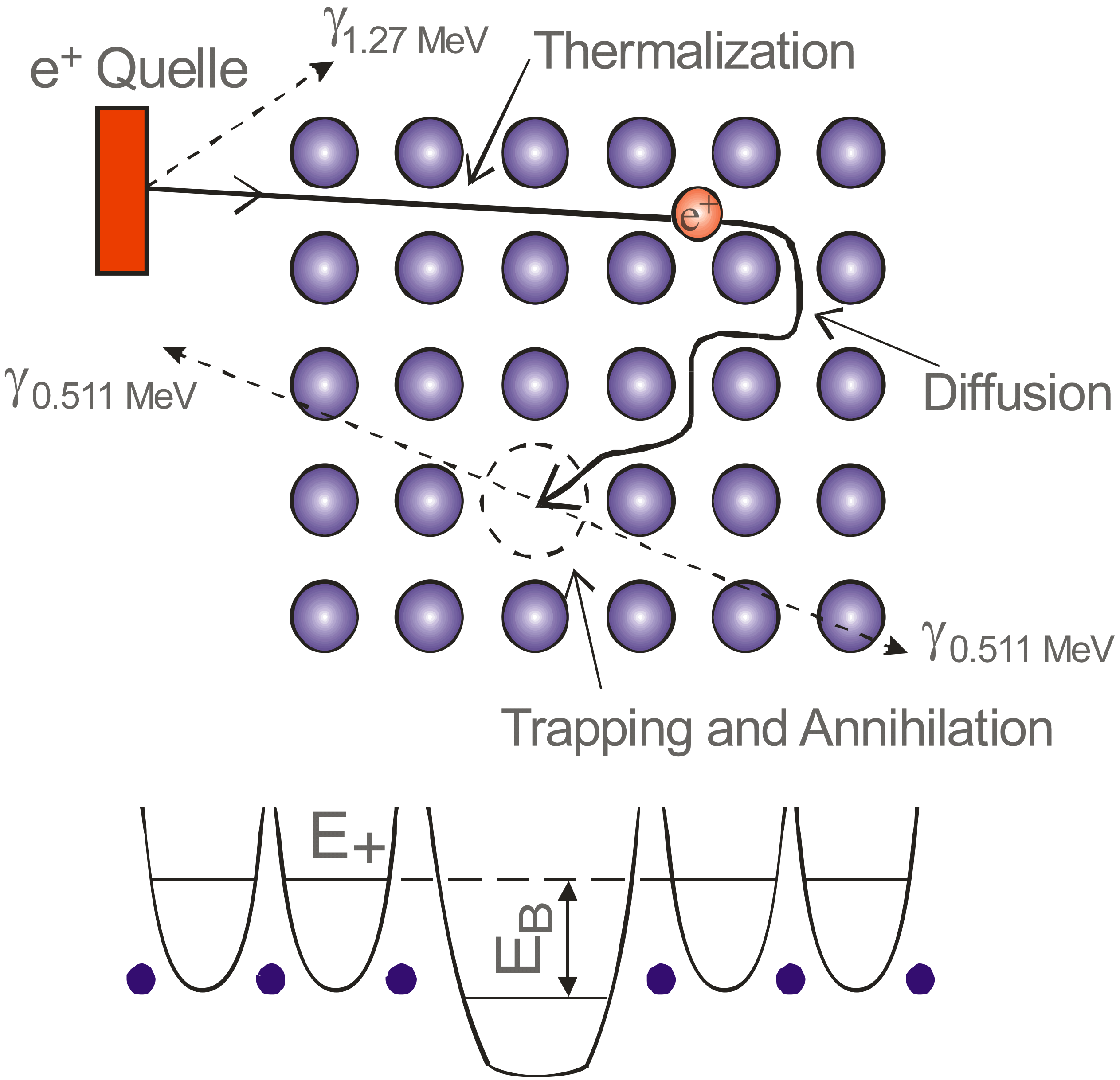
R. Krause-Rehberg, A. Polity, V. Bondarenko

Martin-Luther-Universität Halle-Wittenberg, Germany

Martin-Luther-Universität
Halle-Wittenberg

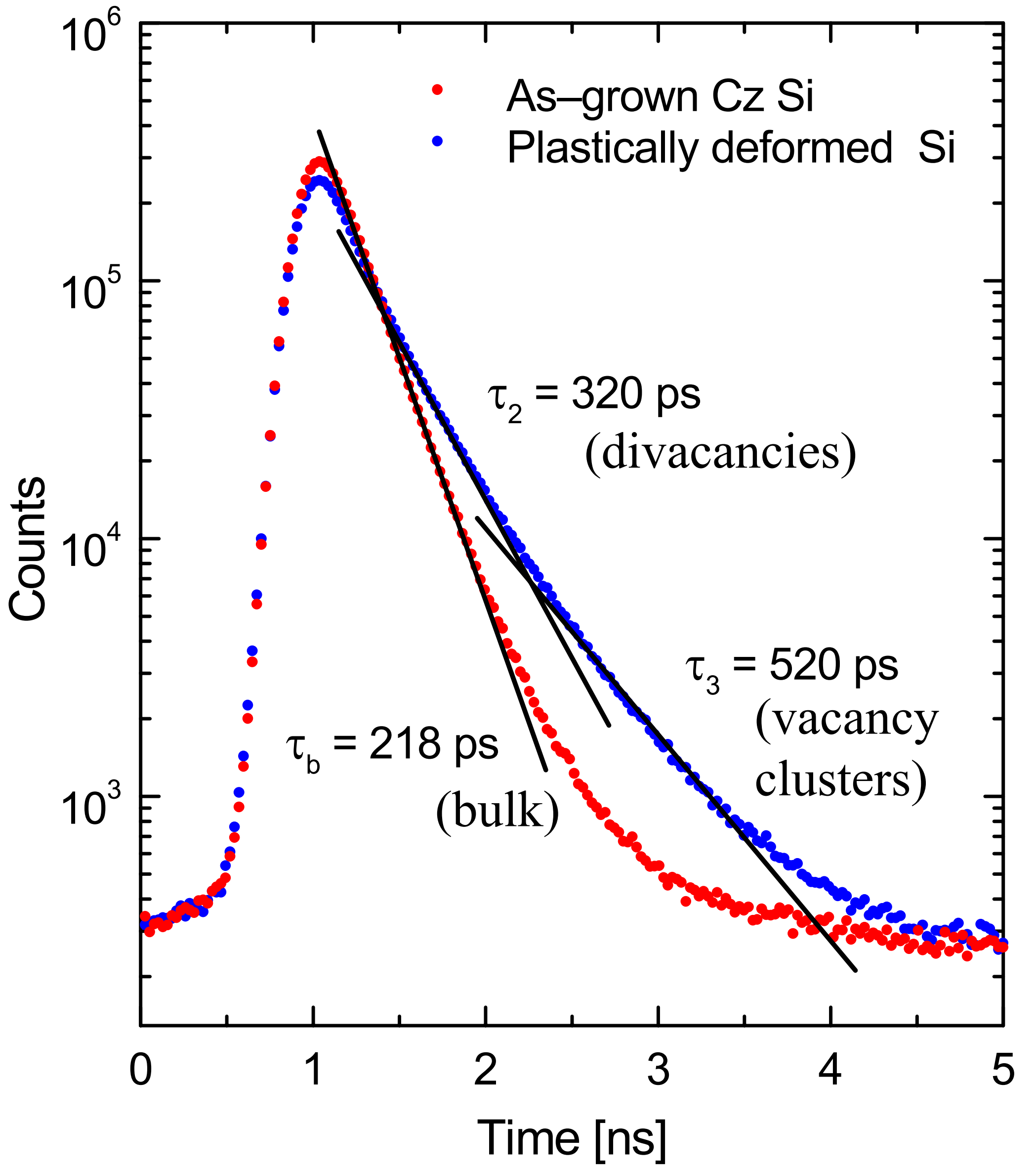
- Introduction: Positrons detect lattice defects
- Examples:
  - electron irradiated Ge
  - neutron-irradiated Si
  - more results
- Conclusions

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

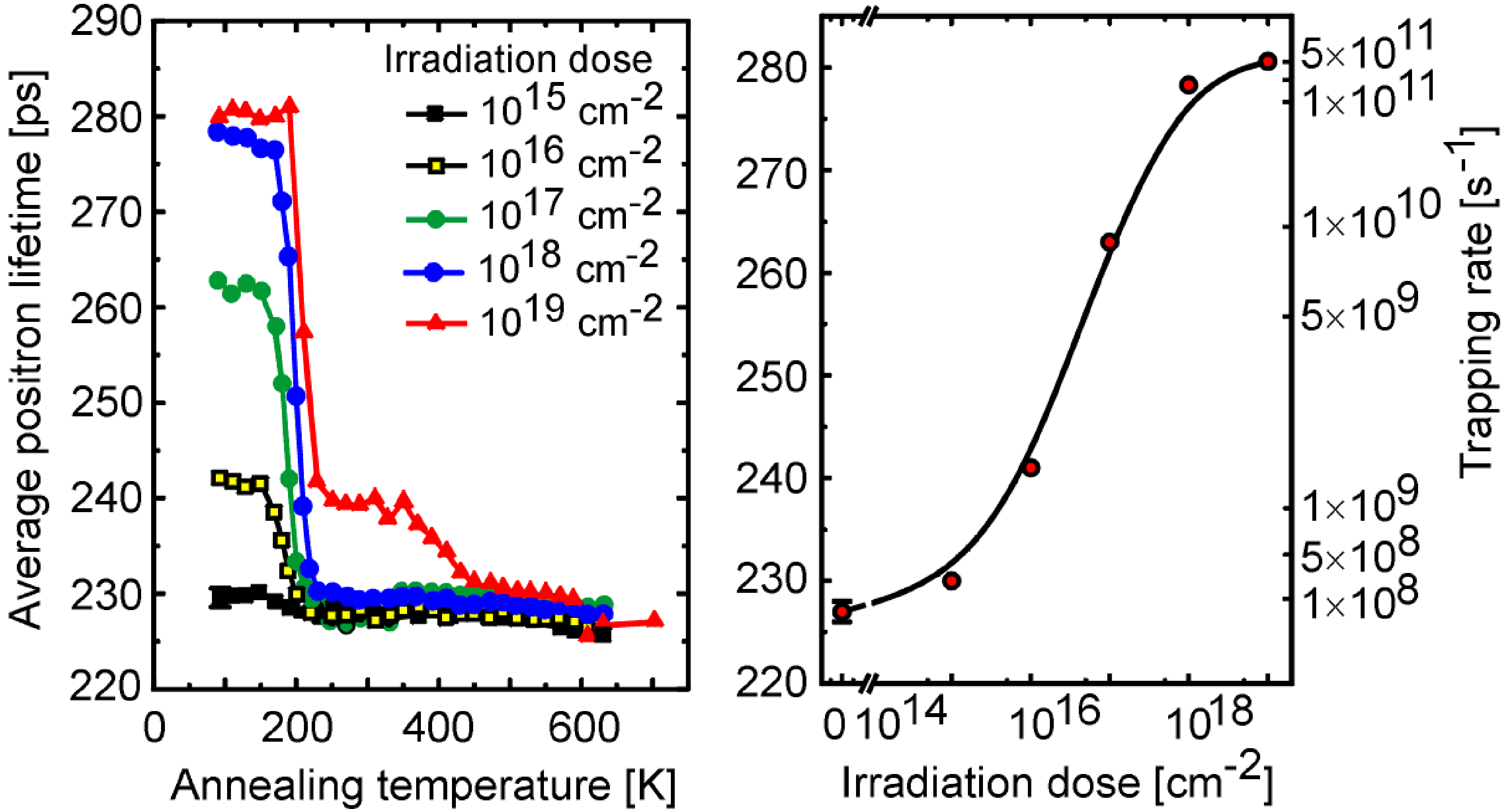


- positron lifetime spectra consist of exponential decay components
- positron trapping in open-volume defects leads to long-lived components
- longer lifetime due to lower electron density
- analysis by non-linear fitting: lifetimes τ_i and intensities I_i
- positron lifetime spectrum: $$N(t) = \sum_{i=1}^{k+1} \frac{I_i}{\tau_i} \exp\left(-\frac{t}{\tau_i}\right)$$
- trapping coefficient $$\kappa_d = \mu C_d = \frac{I_2}{I_1}\left(\frac{1}{\tau_b} - \frac{1}{\tau_d}\right)$$

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



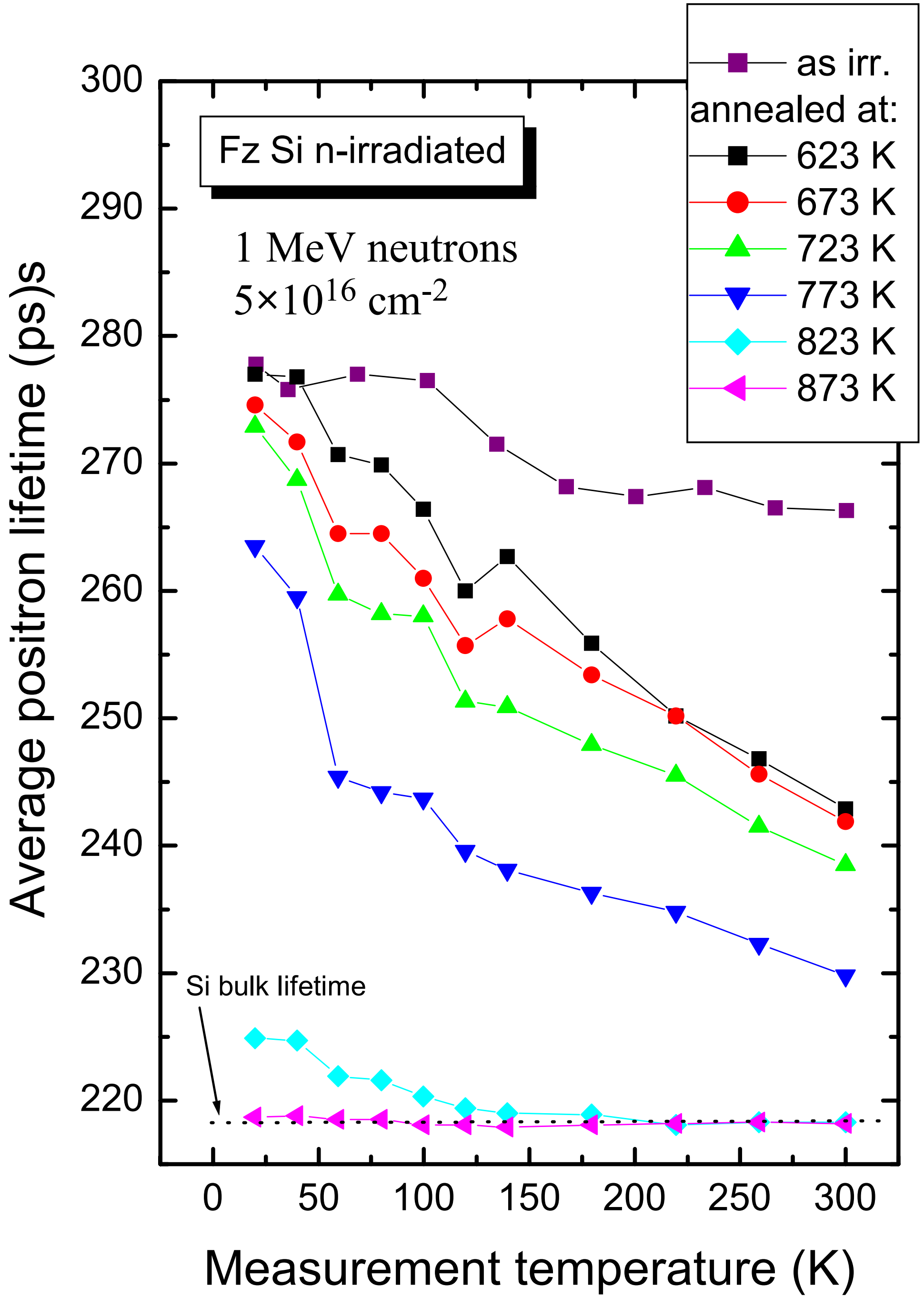
(A. Polity and F. Rudolf, Phys. Rev. B **59** (1999) 10025)

n-irradiated Si

- 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

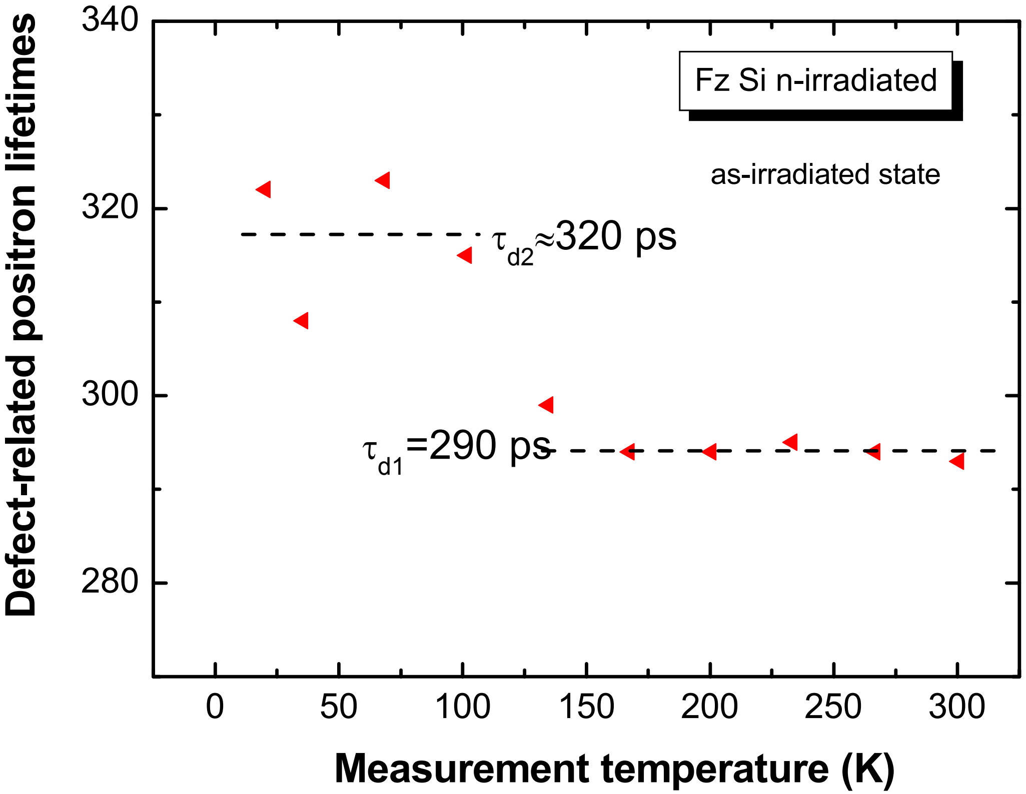
  (monovacancies anneal at about 170 K; divacancies stable up to 450…500 K)



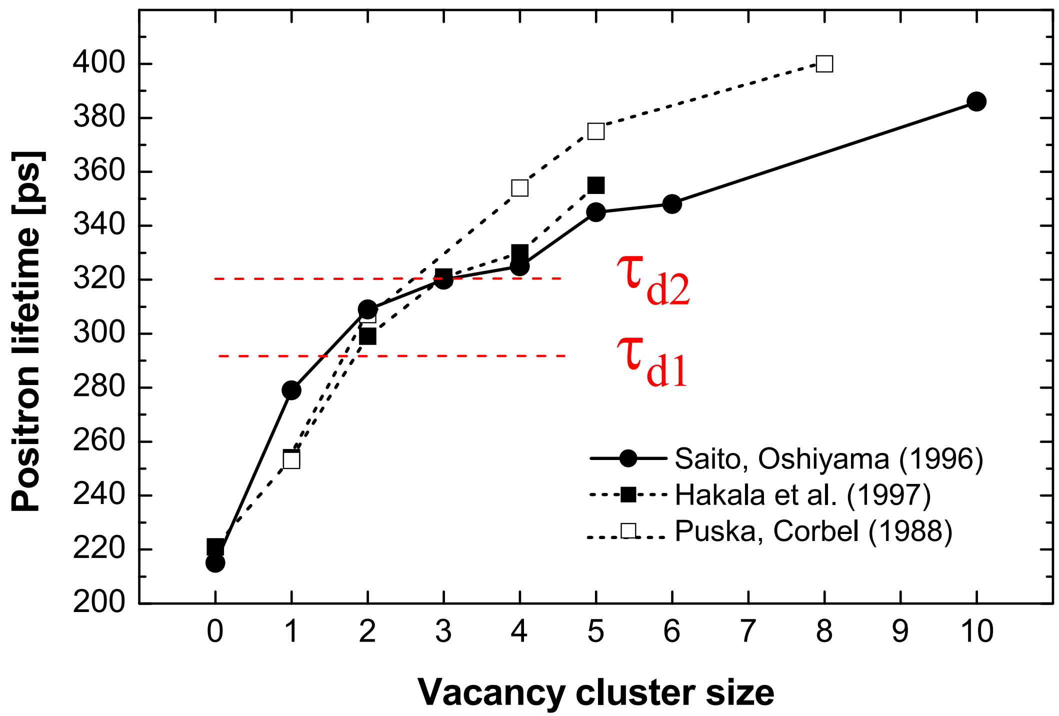
Bondarenko et al., unpublished, 2001

n-irradiated Si

- two different vacancy-type defects are detected: divacancies and $V_3 \ldots V_6$



Bondarenko et al., unpublished, 2001



Computer simulations of vacancy clusters in Si

n-irradiated Si

- after annealing of divacancies (673 K annealing step)

  positron trapping rate:

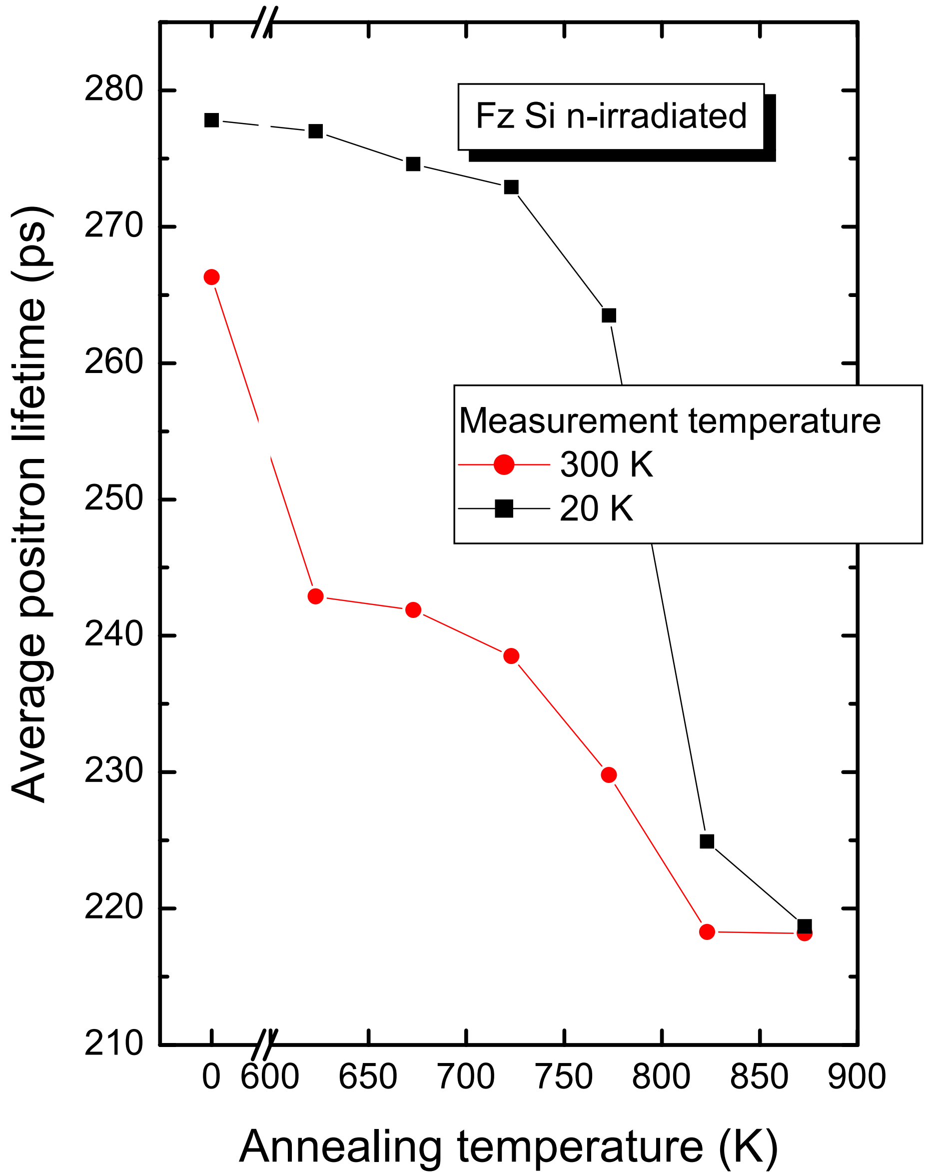
  $\kappa = 2\times10^{9}\ s^{-1}$

  assuming V_4 $\Rightarrow$

  defect concentration:

  $C_{V4} \approx 2.5\times10^{16}\ cm^{-3}$

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

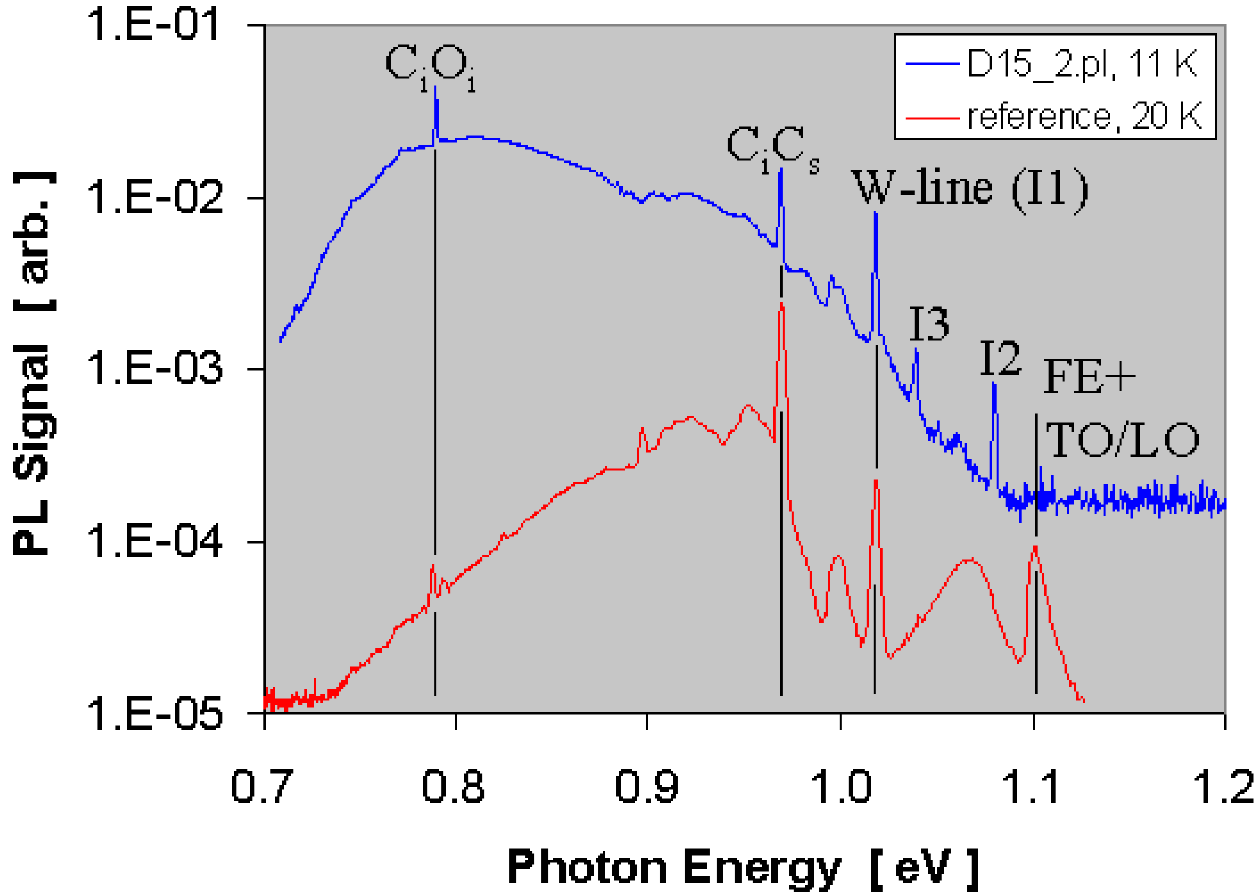


Bondarenko et al., unpublished, 2001

n-irradiated Si

- Photoluminescence spectra of similar sample after irradiation show appearance of I2 and I3 lines
- I3 was earlier correlated to small vacancy clusters
- this is in accordance to positron results
- I2 was attributed before to B-B pair defect after B-implantation (impossible explanation here)

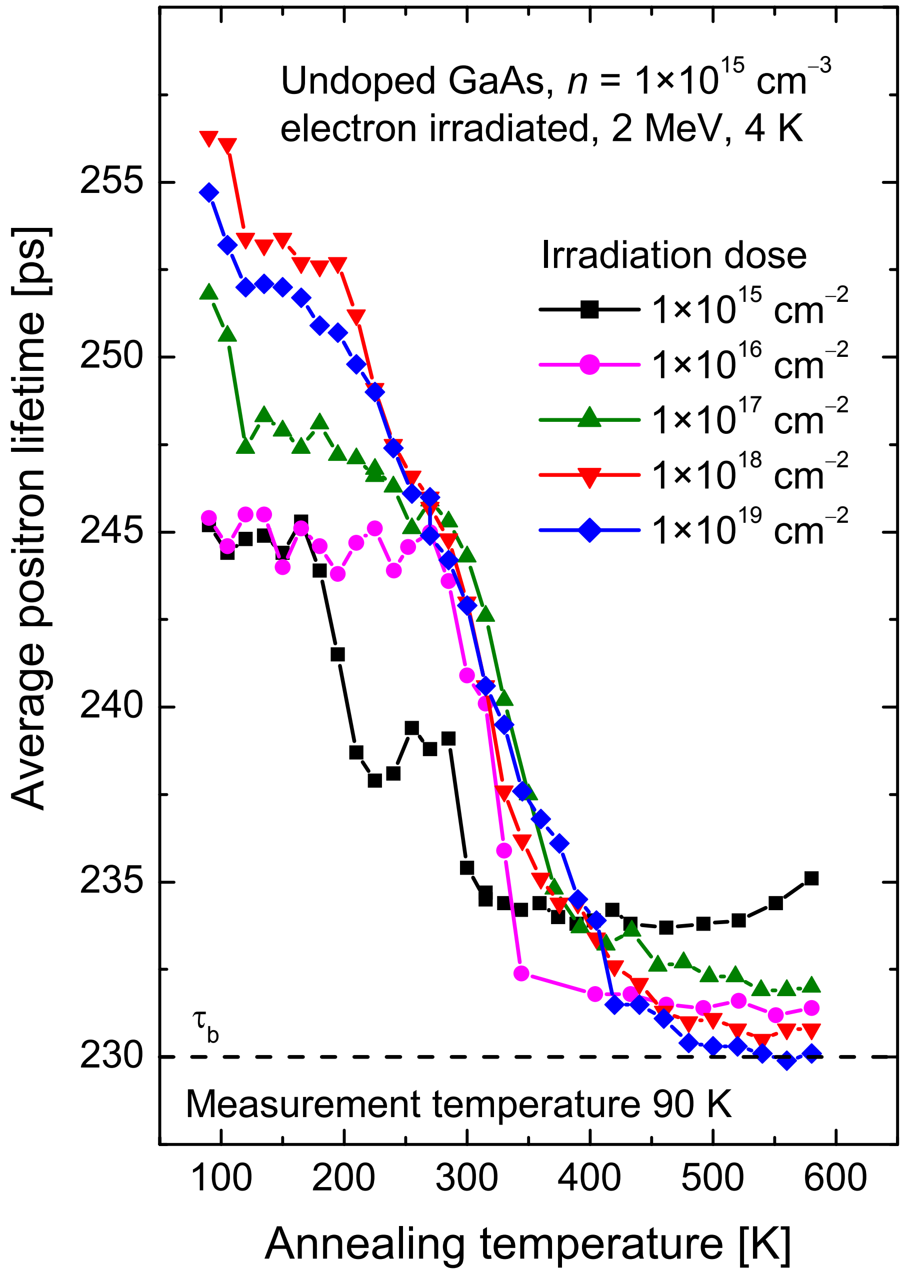
1 MeV neutrons
5×10^{16} cm^{-2}



H. Feick et al., unpublished, 2001

electron-irradiated GaAs

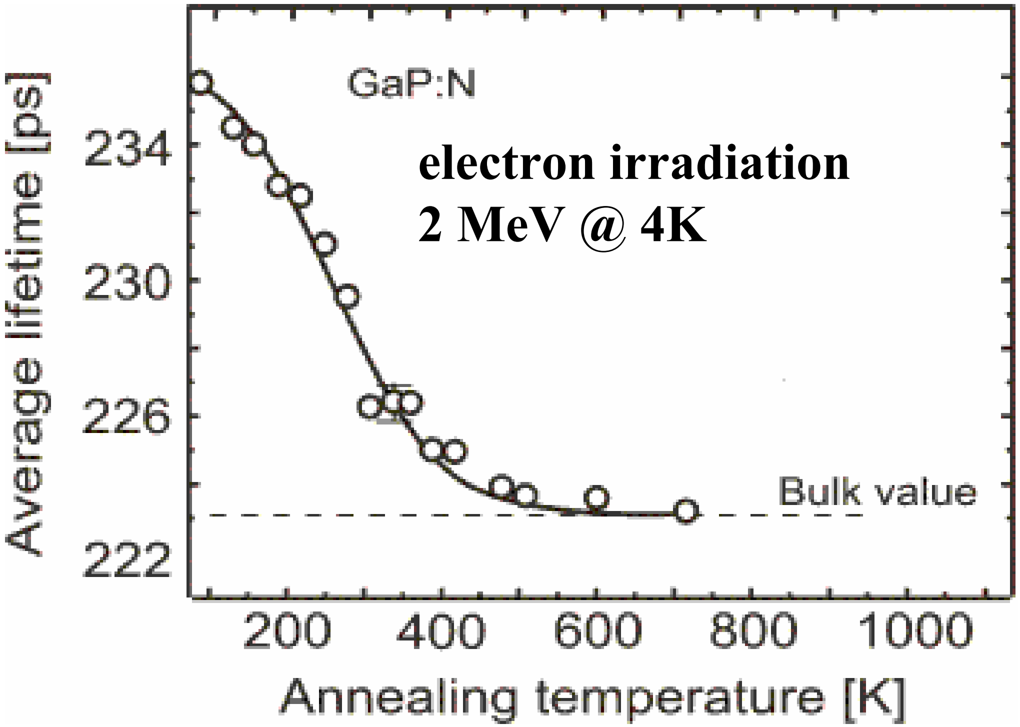
- electron irradiation generates vacancies in both sublattices
- very complex annealing behavior
- main annealing stage at 300 K
- similar annealing stage found for doped GaAs

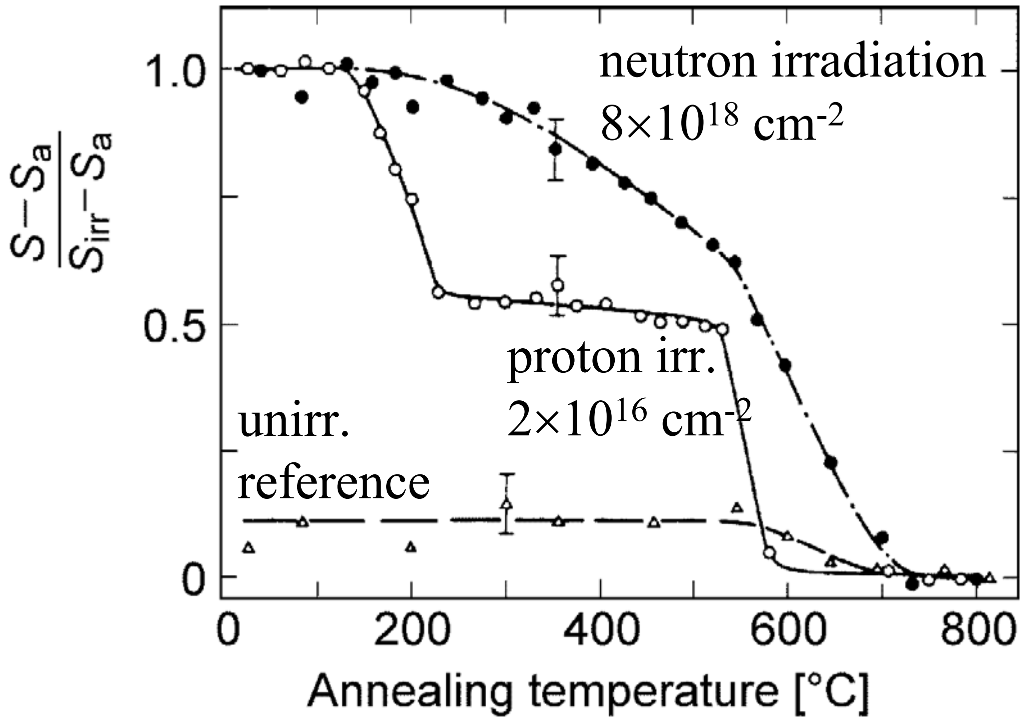


A. Polity et al., Phys. Rev. B **55** (1997) 10467

irradiated GaP

- monovacancy annealing appears around room temperature
- only larger vacancy agglomerates are detectable after neutron irradiation at RT



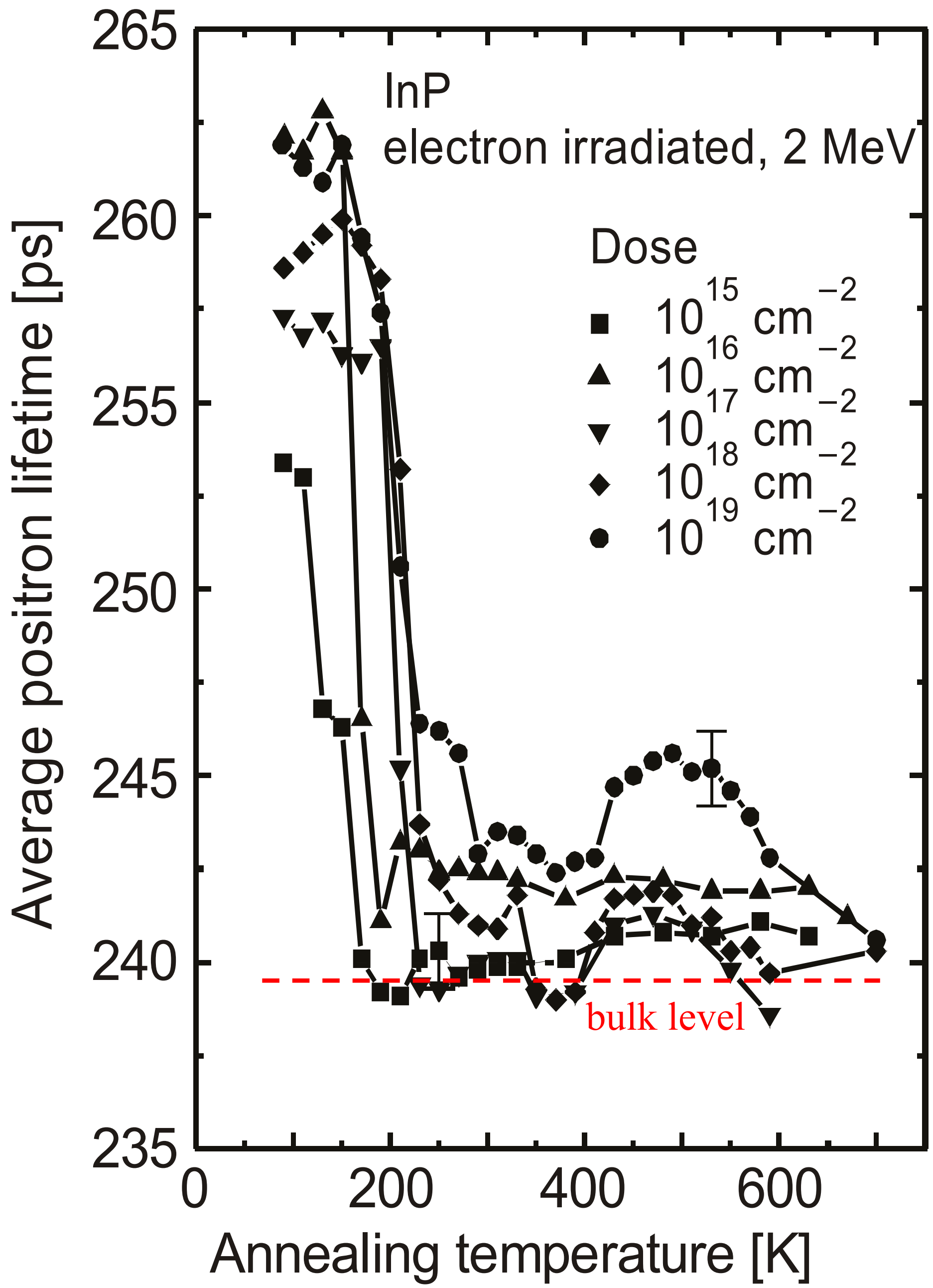


Polity et al., Appl. Phys. A 60 (1995) 541

Dlubek et al., phys. stat. sol (a) **106** (1988) 81

electron-irradiated InP

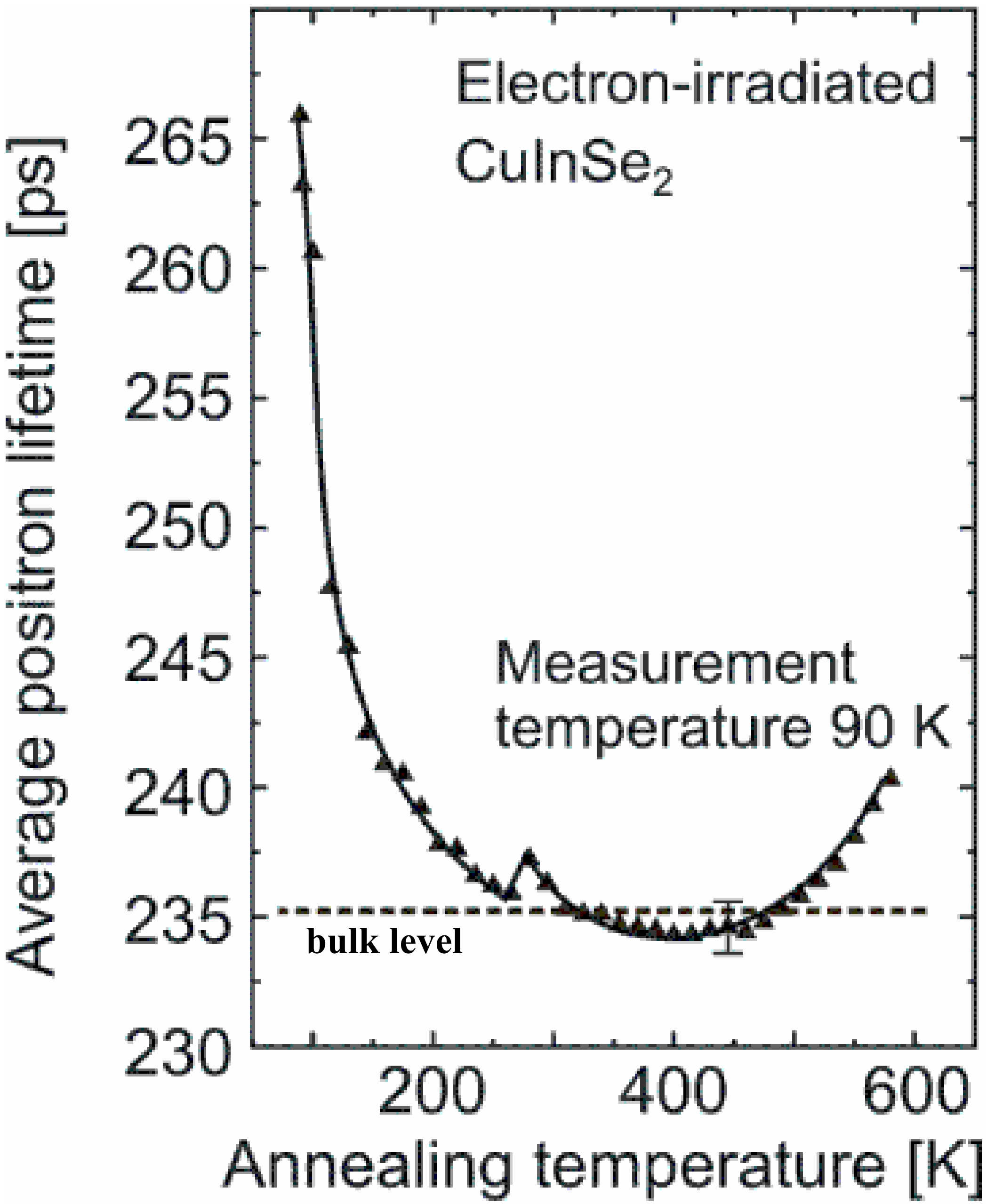
- again: complex annealing behavior
- main annealing stage around 200 K
- annealing temperature is function of dose
- around 500 K: vacancy agglomeration



A. Polity and T. Engelbrecht, Phys. Rev. B 55 (1997) 10480

electron-irradiated $CuInSe_2$

- important solar cell material
- main annealing stage below 150 K
- lowest annealing temperature found in all our experiments
- some defects survive "invisible" up to 550 K
- probably monovacancies in positive charge state (possibly V_{Se})
- divacancies are detected at 600 K with a concentration of about 1×10^{17} cm^{-3}



A. Polity et al., J. Appl. Phys. **83** (1998) 71

Further techniques of positron annihilation

- VEPAS: **V**ariable-**E**nergy **P**ositron **A**nnihilation **S**pectroscopy uses monoenergetic positrons of $E_+ = 0.1 \ldots 50$ keV for near-surface defect depth profiling; important for thin epitaxial layers or after ion implantation
- Doppler-Coincidence Spectroscopy: annihilations with core electrons give chemical information
- Scanning positron microbeams are available: line-scans and pictures of defect distributions; detailed depth scans by using wedge-shaped samples

Conclusions

- vacancy-type defects can be detected in semiconductors by means of positron annihilation
- lower sensitivity limit for monovacancies $C_v \approx 1\times10^{15}$ cm^{-3}
- method very sensitive for early stage of vacancy agglomeration
- tools for thin layers (mono-energetic positron beams)
- scanning positron microbeams available

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

contact: mail@krauserehberg.de