Investigation of the Rp/2-effect in Si by means of Positron Annihilation

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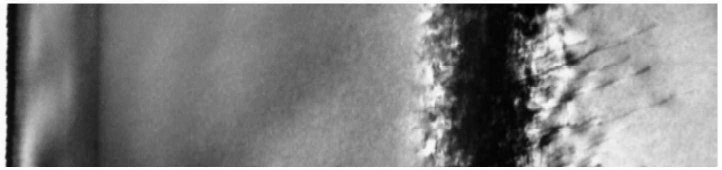
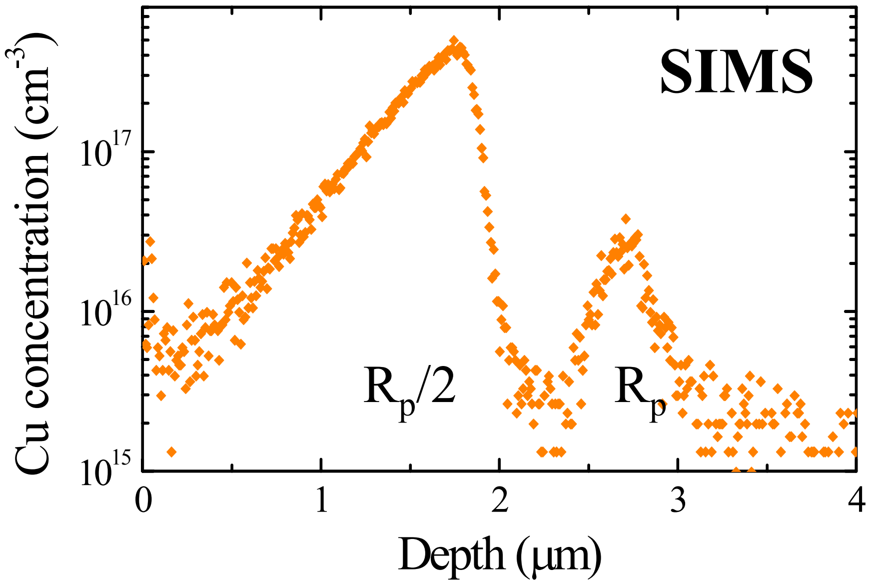
- The $R_p/2$ effect: formation of additional gettering zones
- Vacancy detection by positrons
- Investigation of the $R_p/2$-effect using the Munich Positron Scanning Microscope
- Outlook

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

Cross section TEM image by P. Werner, MPI Halle





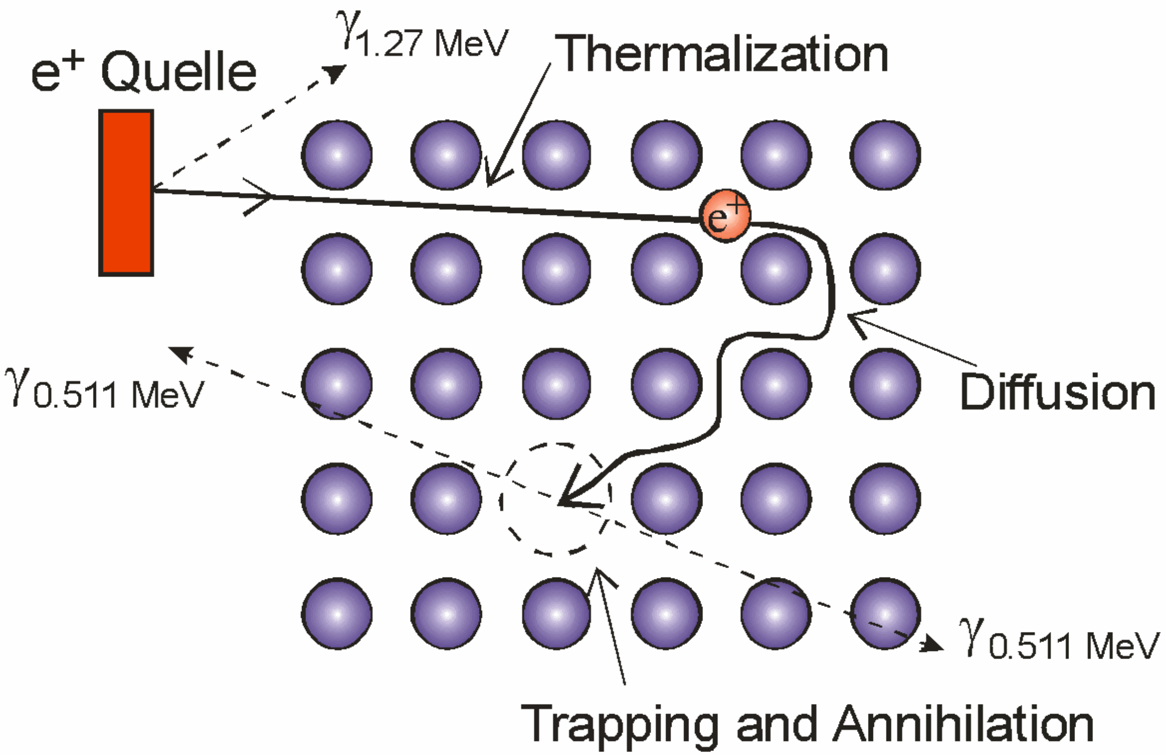
- at R_p: gettering by interstitial-type dislocation loops (formed by excess interstitials during RTA)
- no defects visible by TEM at $R_p/2$
- **What type are these defects?**

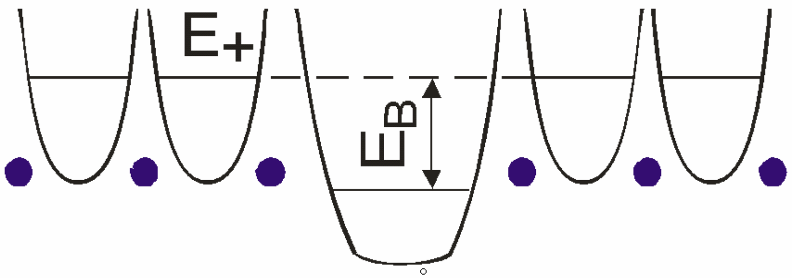
Interstitial type [3,4]

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

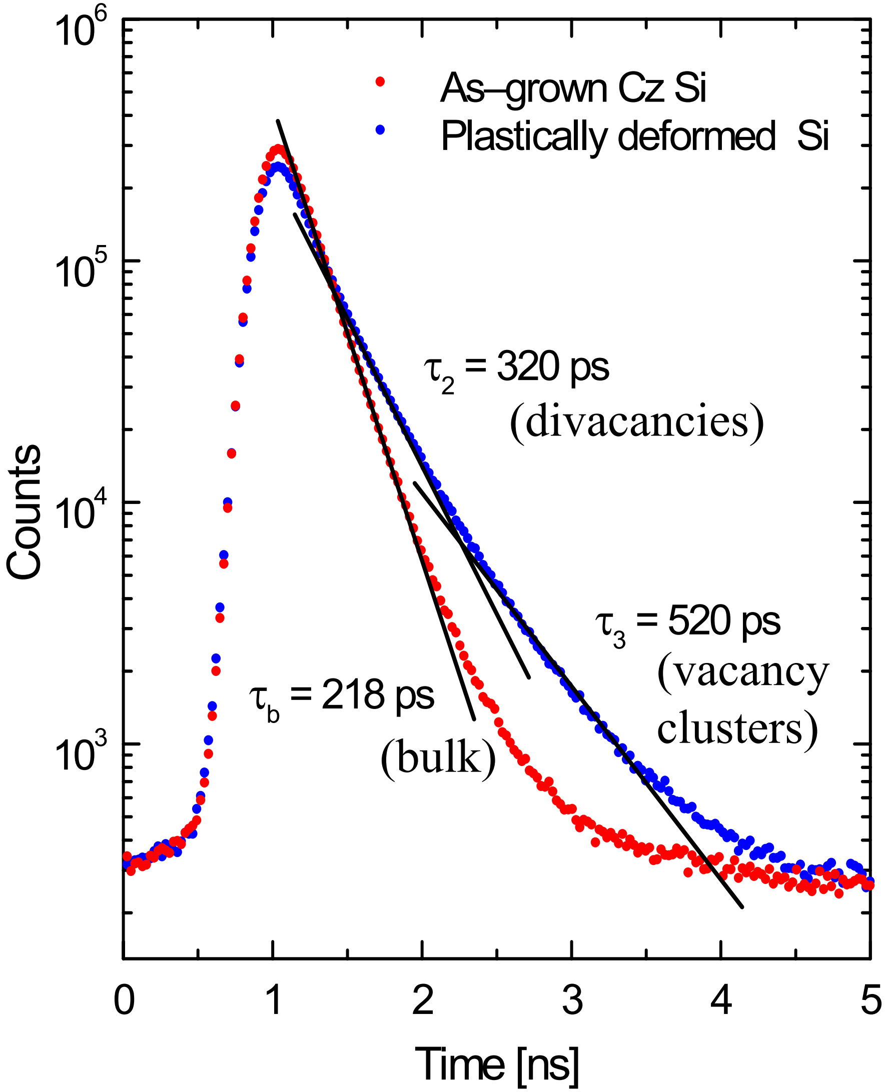
The positron lifetime spectroscopy





- 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

positron lifetime spectrum:

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

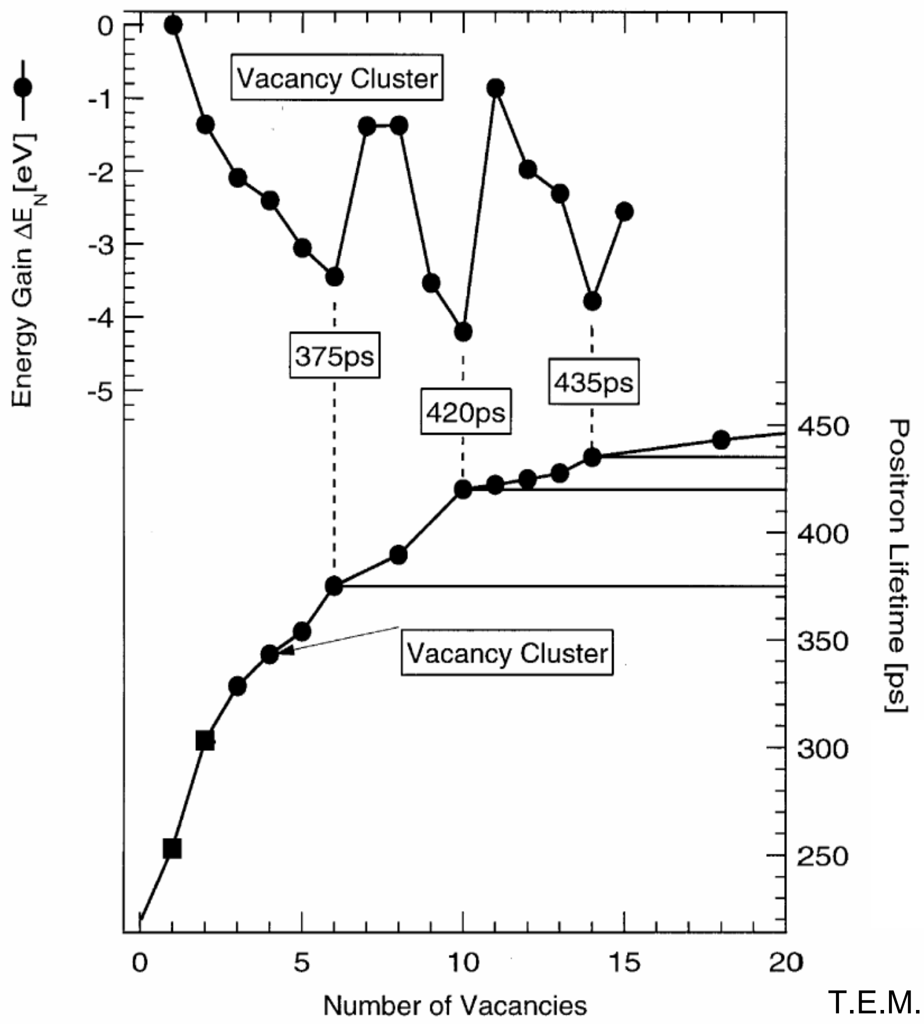
trapping coefficient

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

trapping rate

defect concentration

Theoretical calculation of vacancy clusters in Si



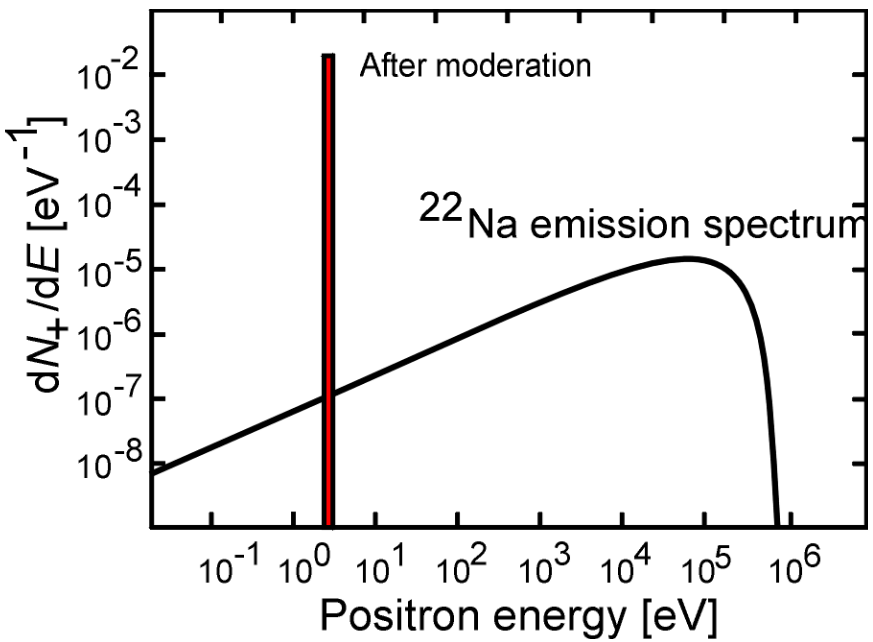
- there are cluster configurations with a large energy gain
- „Magic Numbers" with 6, 10 und 14 vacancies
- positron lifetime increases distinctly with cluster size
- for n > 10 saturation effect, i.e. size cannot be determined

T.E.M. Staab et al.,
Physica B 273-274 (1999) 501-504

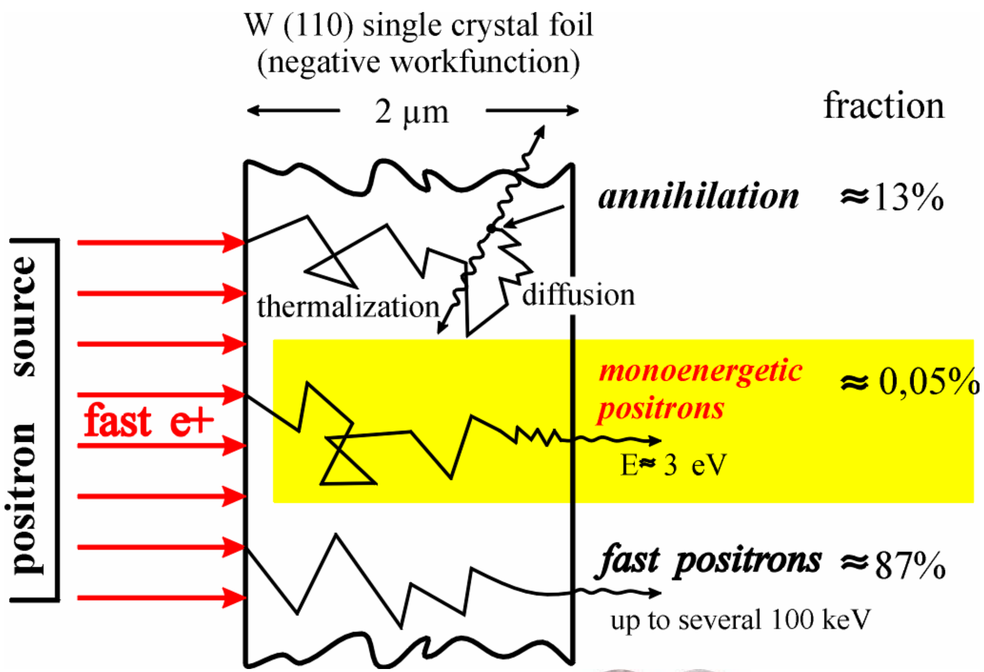
Monoenergetic positrons obtained by moderation

- positron annihilation was very successful in defect identification in last decades
- semiconductor technology: thin layers (epitaxy, ion implantation)
- broad energy distribution due to β^+ decay
- some surfaces: negative workfunction ⇒ moderation (but rather inefficient)

Energy distribution after β^+ decay

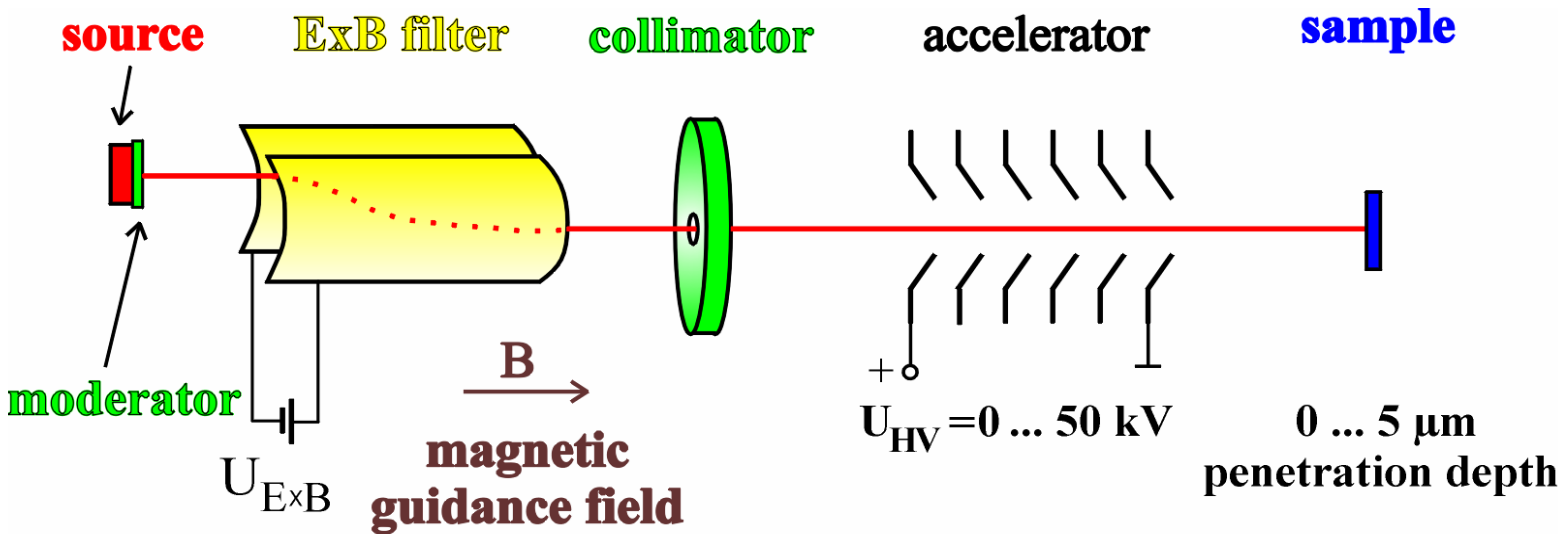


Effect of moderation



Conventional positron beam technique

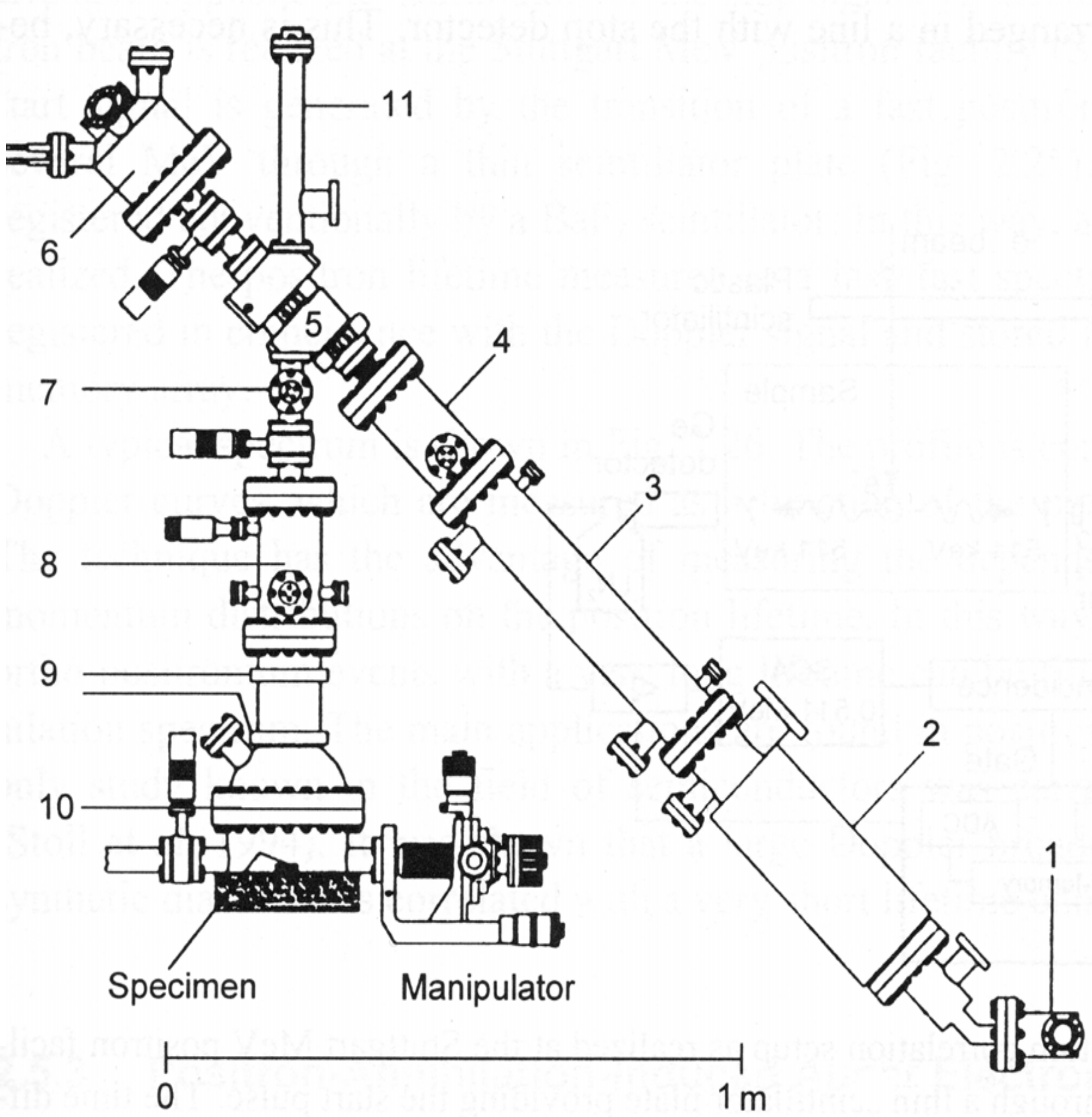
- positron beam can be formed using mono-energetic positrons
- often: magnetically guided for simplicity



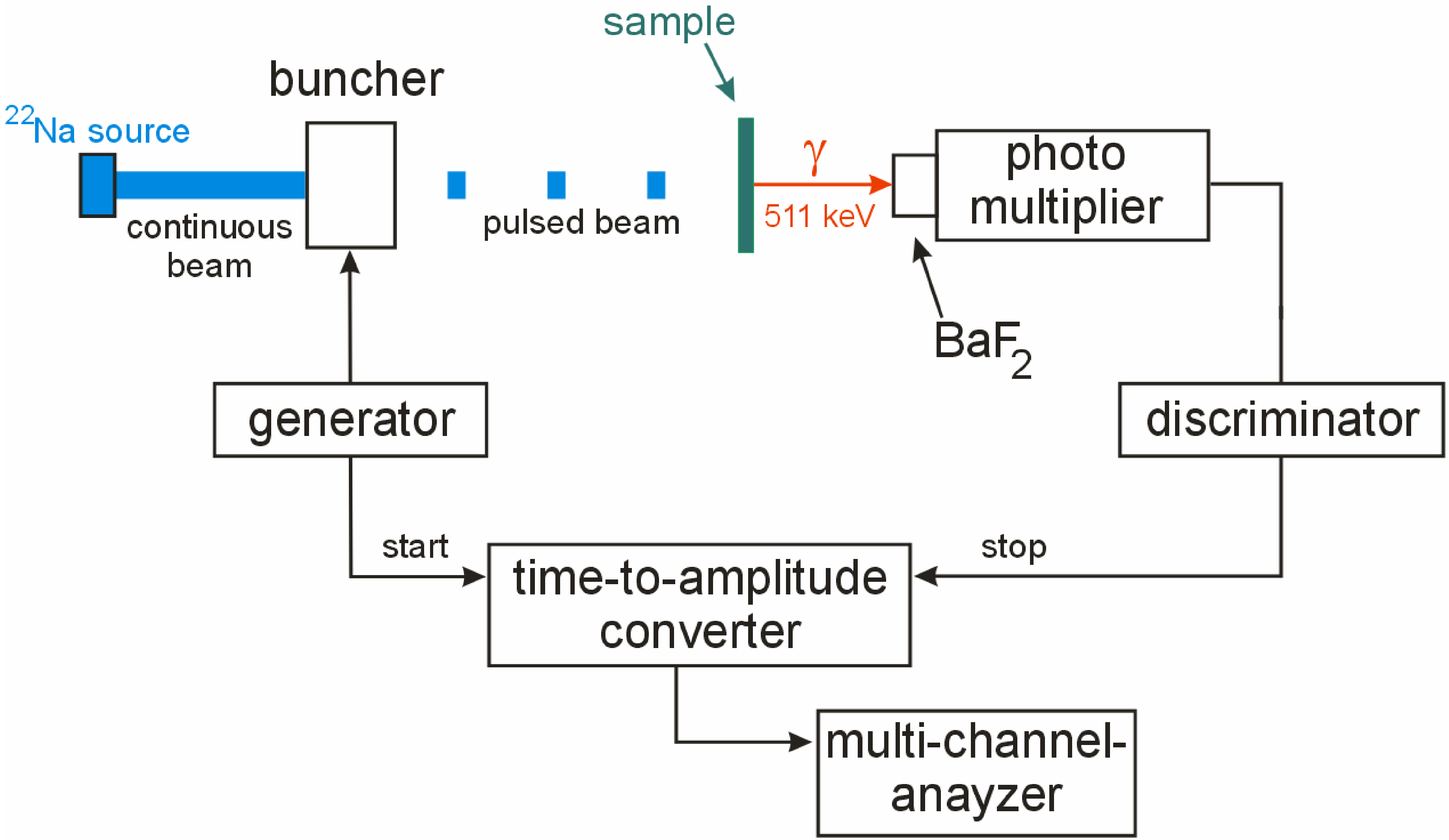
- defect studies by Doppler-broadening spectroscopy
- characterization of defects only by line-shape parameters or positron diffusion length
- for positron lifetime spectroscopy: beam can be bunched

Scanning Positron Microscope in Munich

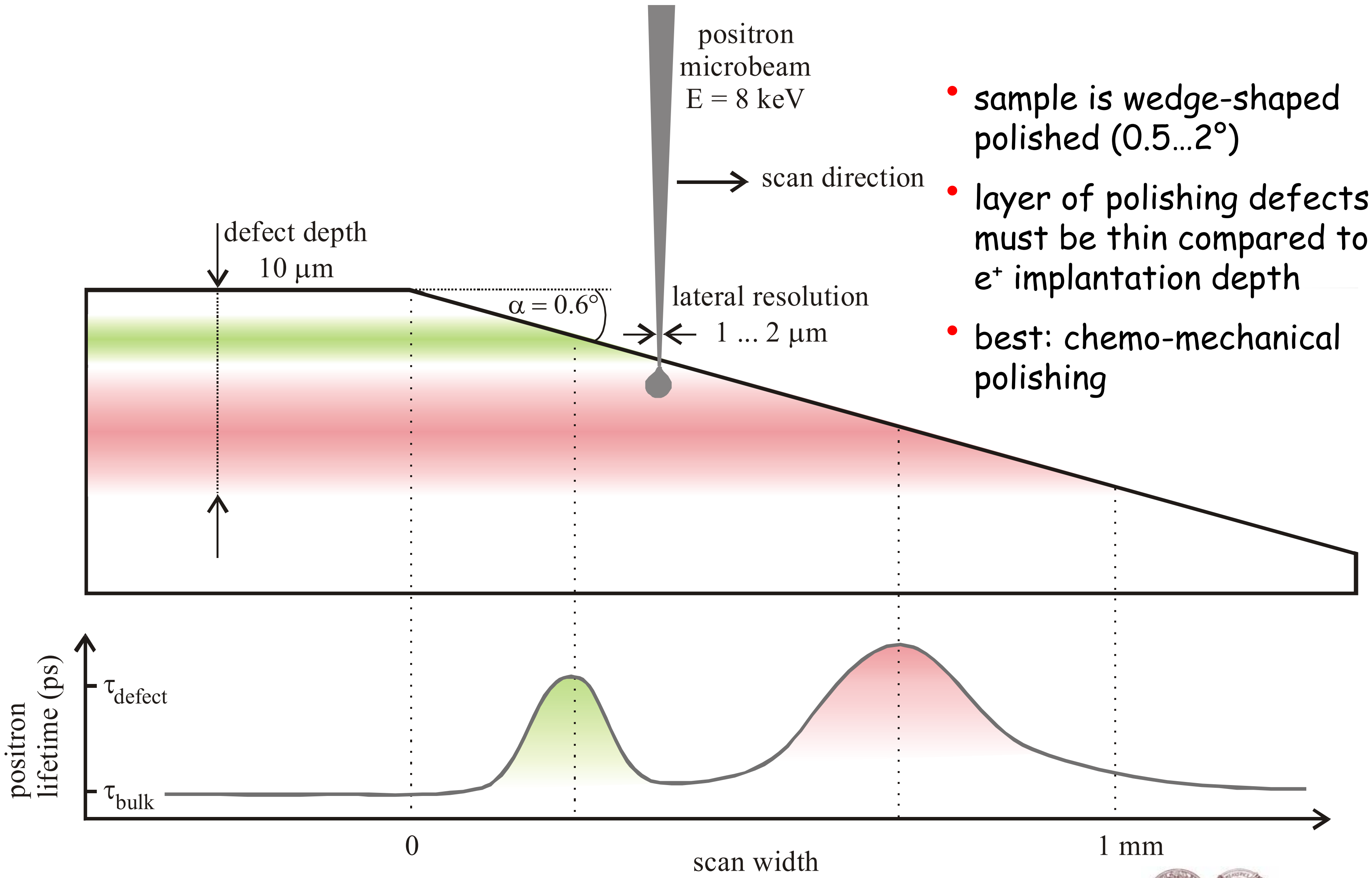
- Semiconductor devices nm-sized ⇒ Positron microprobes required
- However: positron diffusion length is fundamental limit for lateral resolution
- no sense to improve resolution much below 500 nm
- first instrument was realized at Univ. Bonn (20 μm; Doppler spectroscopy)
- first realization of scanning positron microscope for lifetime spectroscopy: in Munich



Positron lifetime at Munich
Positron Scanning Microscope



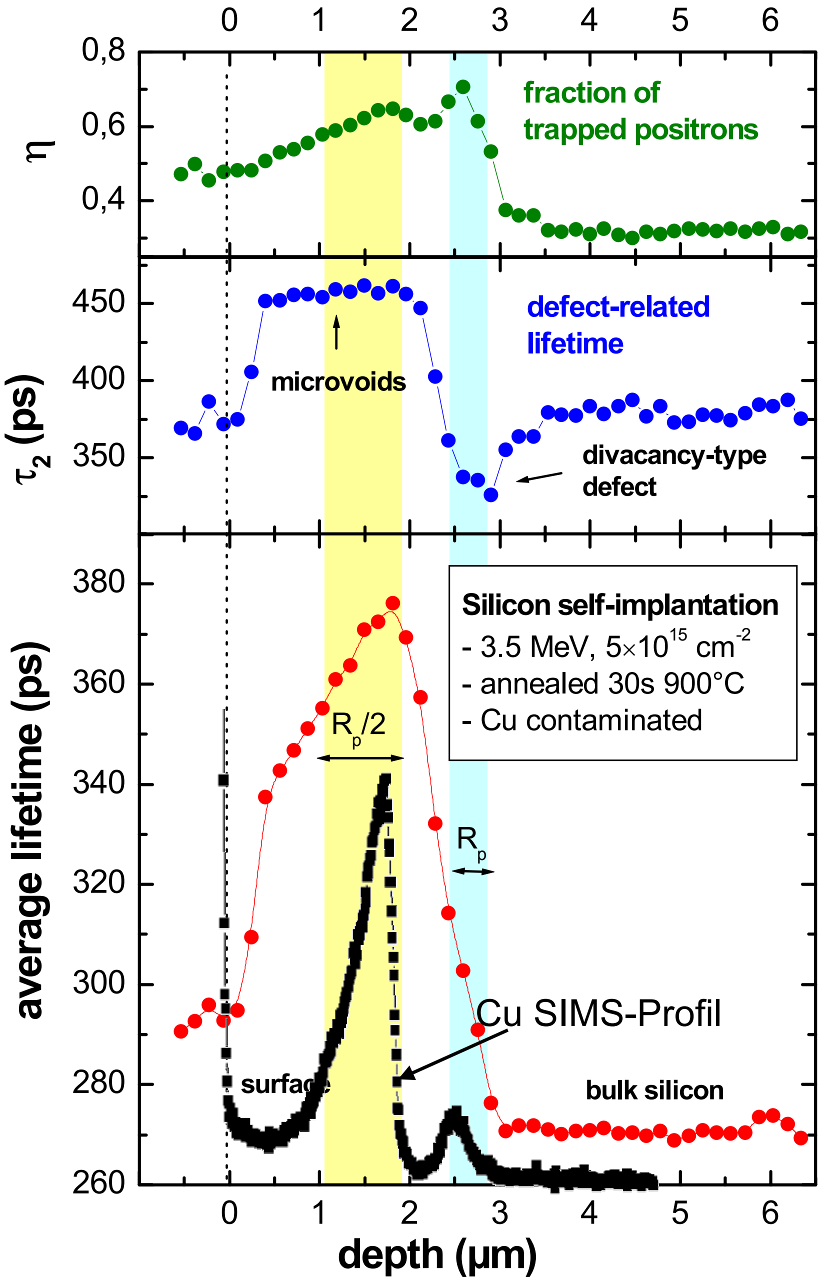
Enhanced depth resolution by using the Munich Scanning Positron Microscope



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

Depth profile of Rp/2 smple measured using the Microscope

- 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
- Problem with Microscope: Intensity



Outlook

- By using positron microbeam: high-quality defect depth profiles
- in future needed: user-dedicated high-intensity positron sources
- planned: FRM-II in Garching and EPOS (= **E**LBE **Po**sitron **S**ource) at Research Center Rossendorf

Talk can be downloaded as PDF-File:

http://positron.physik.uni-halle.de

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