Study of semiconductors with positrons

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Outlook:

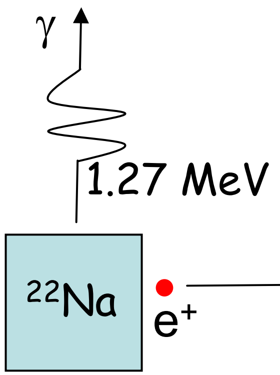
- Introduction
- Positron trapping into defects
- Methods of positron annihilation
  - Positron lifetime spectroscopy
  - Doppler broadening spectroscopy
  - Coincidence Doppler broadening spectroscopy

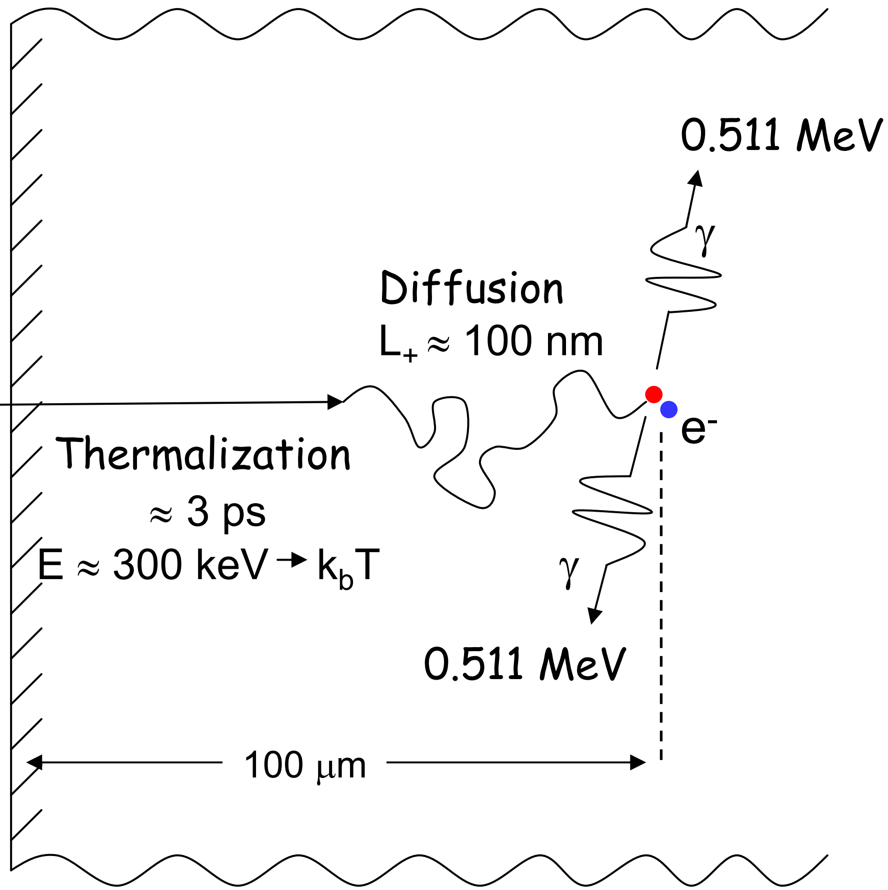
Introduction

- Questions of semiconductor industry
  - Defect types?
  - Defect charge states?
  - Defect concentrations?

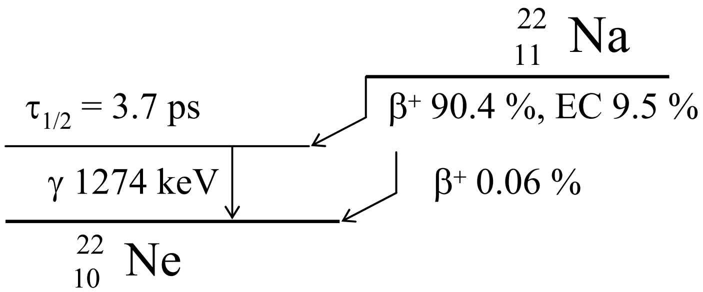
- Answers of positron annihilation
  - Vacancy-like defects and defect complexes
    Size of a vacancy (mono-, di-, vacancy cluster)
  - Neutral or negatively charged vacancy-complexes
    Positively charged defects are invisible
  - Sensitivity limits 10^{14}-10^{19} cm^{-3}

Positron in condensed matter



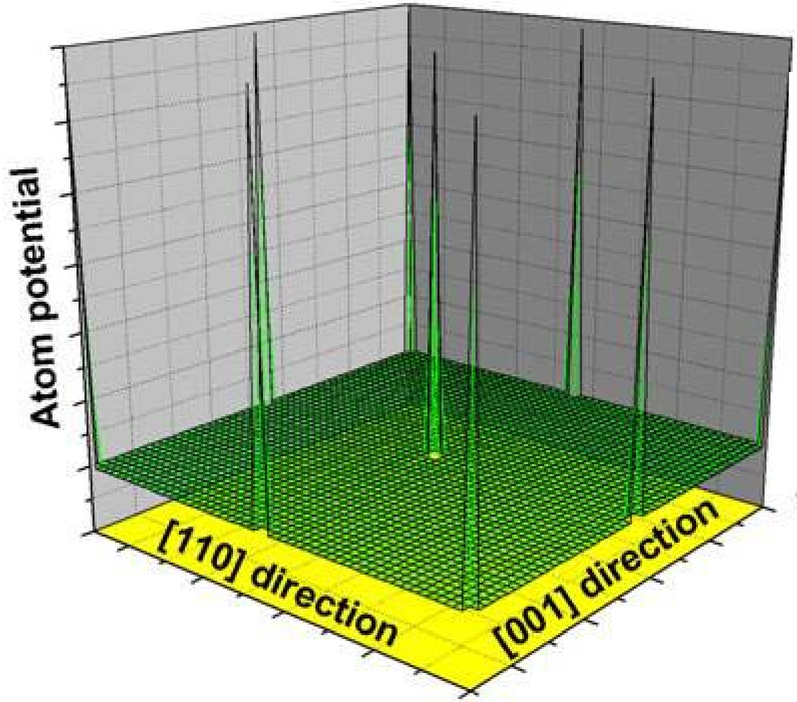


$$^{22}_{11}\mathrm{Na} \rightarrow ^{22}_{10}\mathrm{Ne} + e^{+} + \upsilon$$

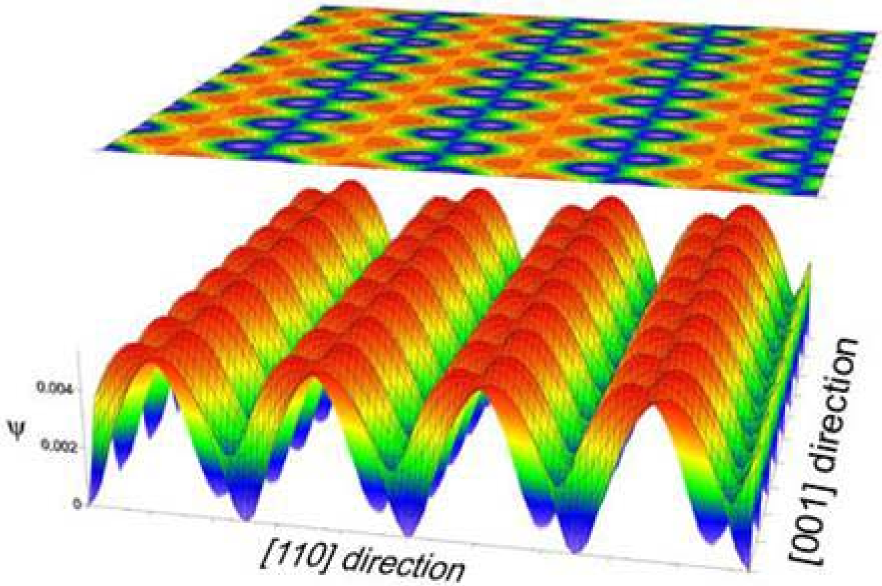


Positron trapping - Vacancy

- Perfect lattice



Atom potential in GaAs (110) plane

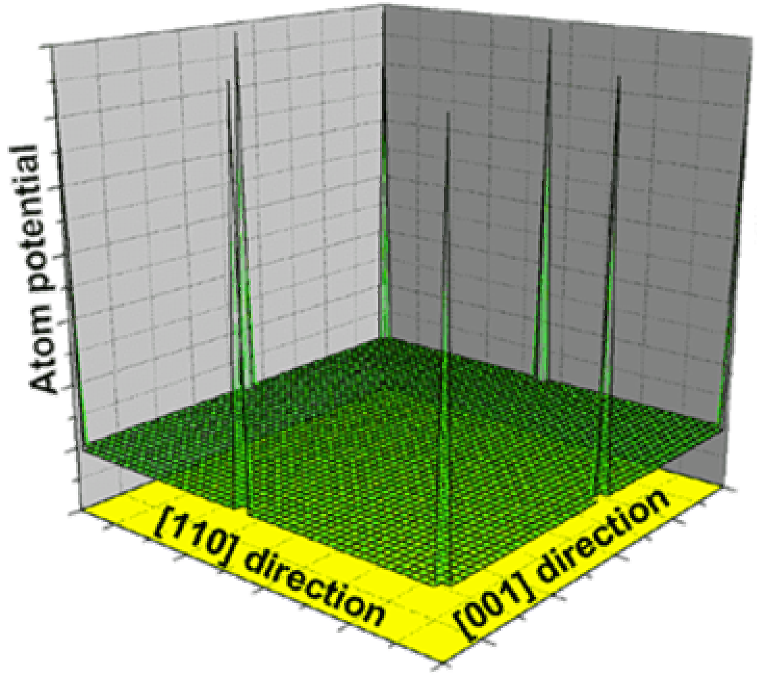


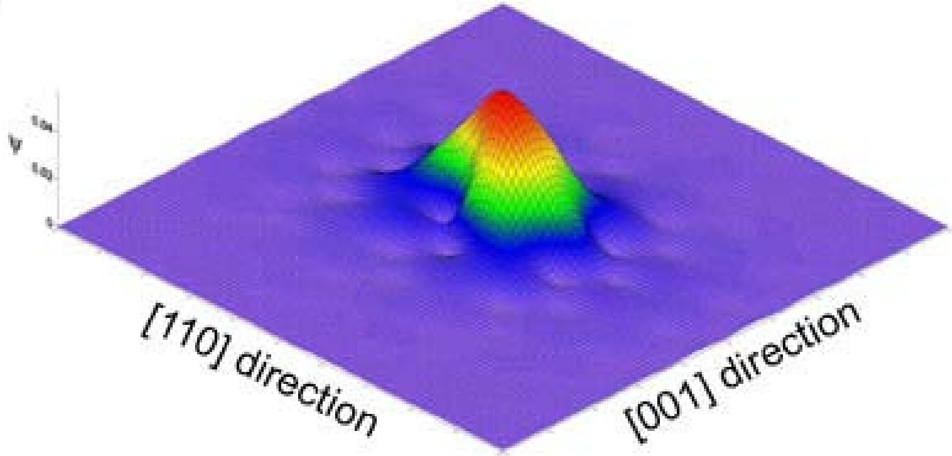
Positron wave function in GaAs (110) plane

- Positrons are repelled by positive atom cores

Positron trapping - Vacancy

- Mono-vacancy





- Vacancy represents a positron trap due to the missing nuclei (potential well for a positron)

Methods of positron annihilation

- Sensitive to electron density distribution
  - Positron Annihilation Lifetime Spectroscopy (PALS)

$$L_+ = \sqrt{D_+ \tau_b} \qquad \lambda = 1/\tau_b = \pi \cdot r_0 \cdot c \int \psi_+(\mathbf{r}) \psi_-(\mathbf{r}) \gamma \, d\mathbf{r}$$

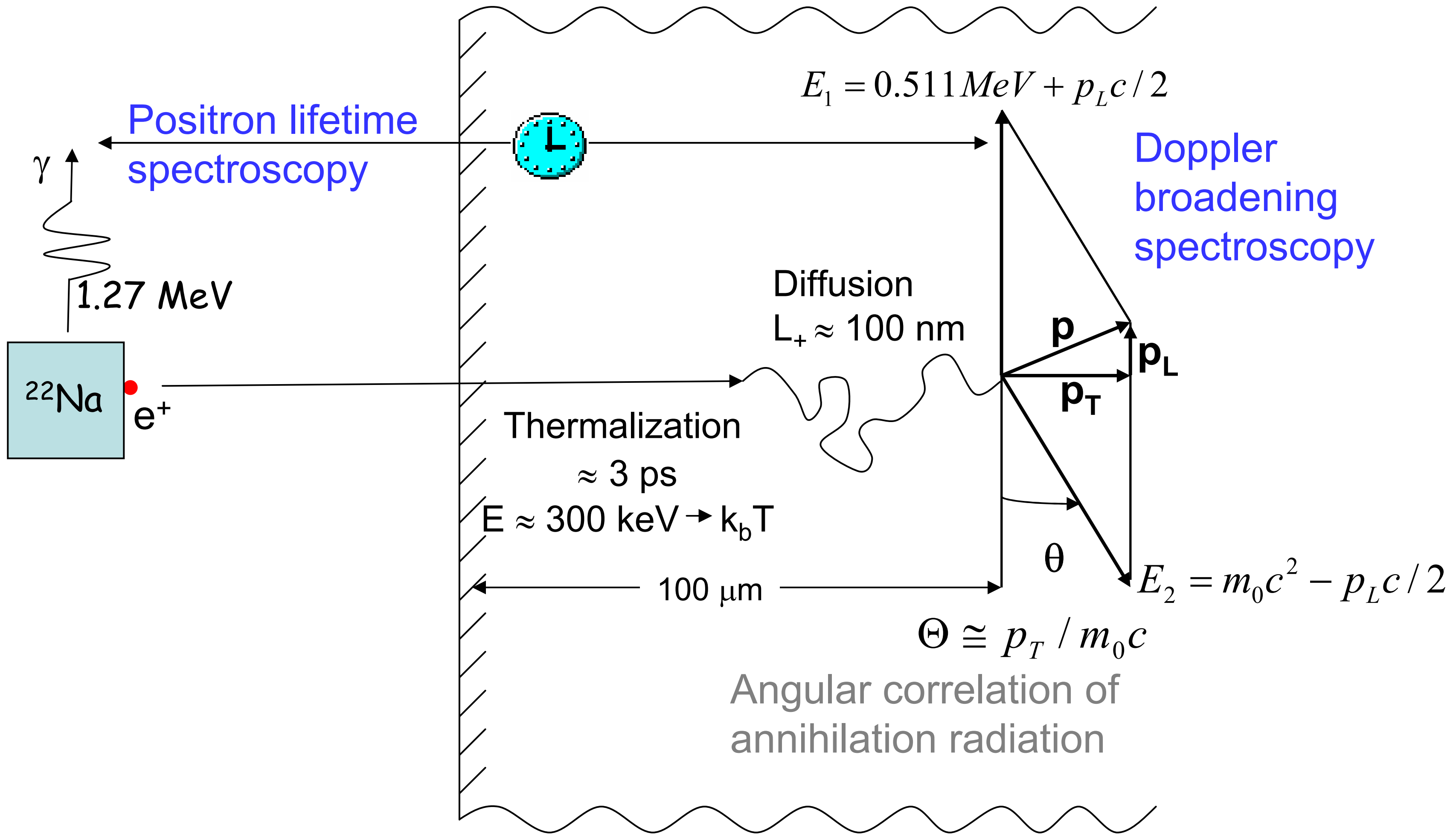
τ_b – positron bulk lifetime λ - positron annihilation rate

the lower the electron density is, the higher is the positron lifetime

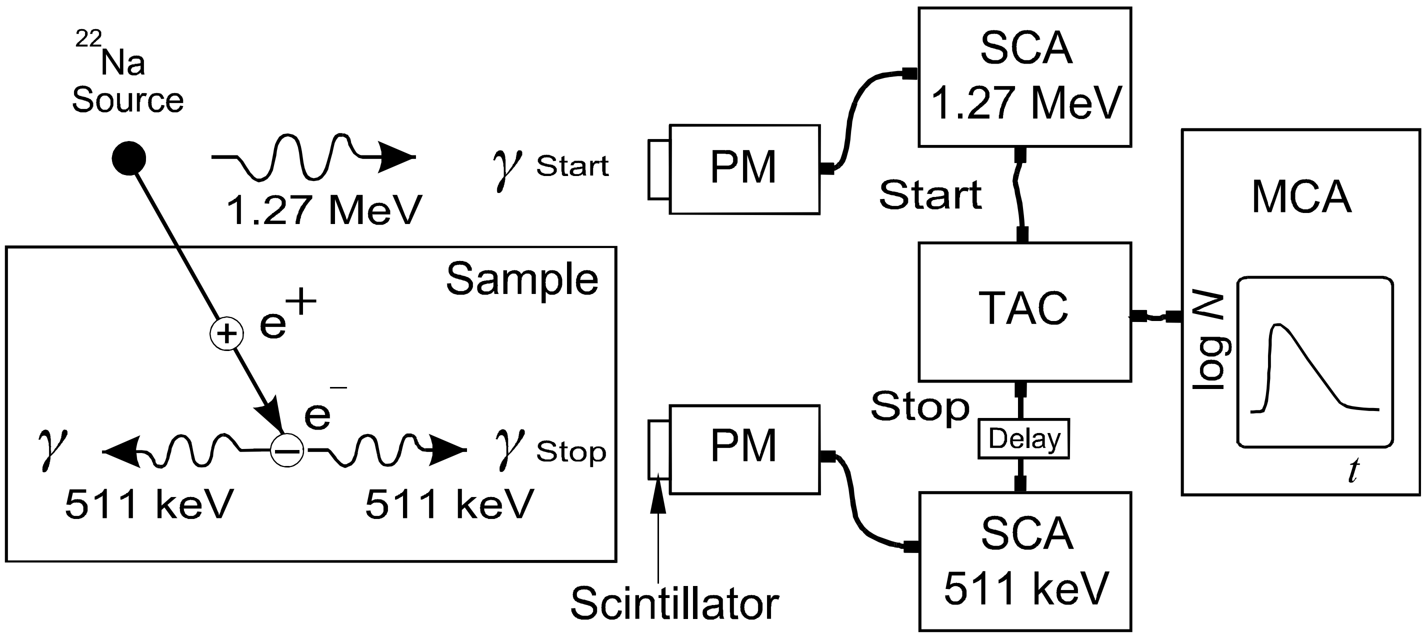
- Sensitive to electron momentum distribution

  energy and momentum conservation leads to
  - Angular Correlation of Annihilation Radiation (ACAR)
  - Doppler Broadening of annihilation line Spectroscopy (DOBS)
    - Coincidence Doppler Broadening

Methods of Positron Annihilation



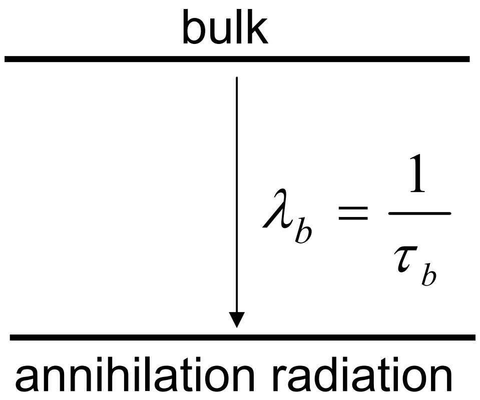
Technique of positron lifetime spectroscopy



- PM – photomultiplier
- SCA – Single Channel Analyzer
- TAC – Time to Amplitude Converter
- MCA – Multichannel Analyzer

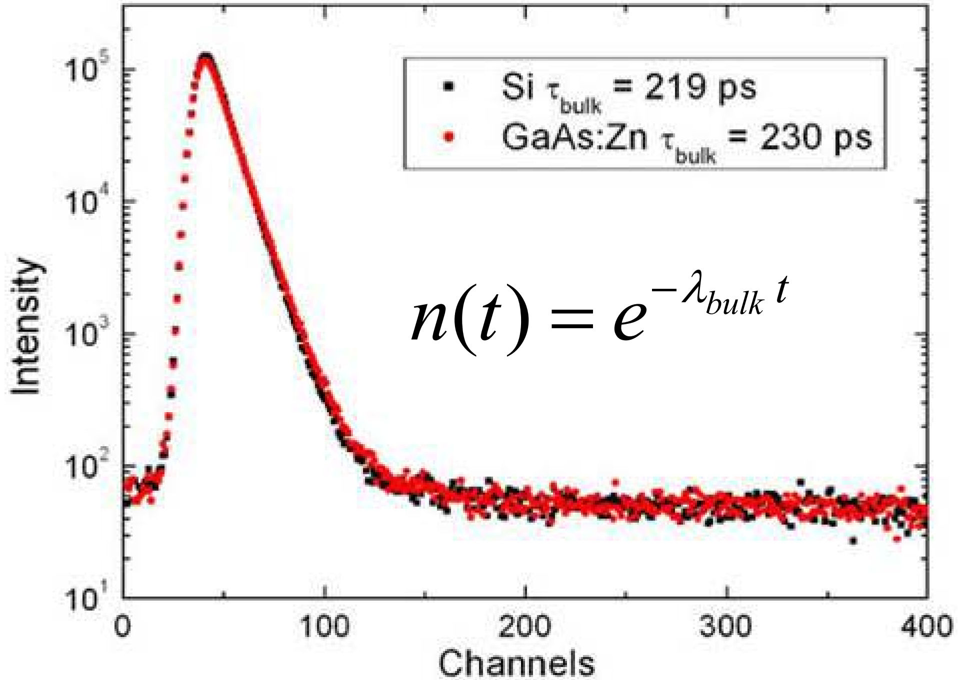
Positron Annihilation Lifetime Spectroscopy (PALS)

- probability **n(t)** that e^+ is alive at time **t**: $$\frac{\mathrm{d}n(t)}{\mathrm{d}t} = -\lambda\, n(t) \qquad n(0) = 1$$
  λ - positron annihilation rate
- Positron lifetime spectrum in bulk:
  (no trapping of positrons)



$$\lambda_b = \frac{1}{\tau_b}$$

λ - slope of the exponential decay



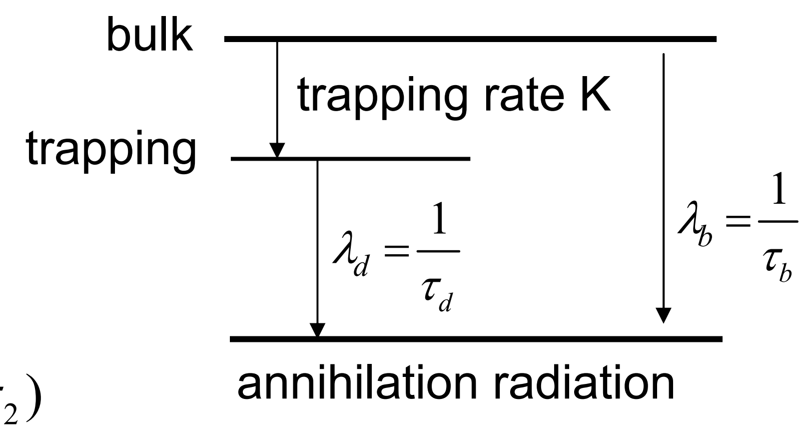
$$n(t) = e^{-\lambda_{bulk}\, t}$$

Positron Annihilation Lifetime Spectroscopy

- model of trapping into a defect
  - annihilation from bulk with $\lambda_b = 1/\tau_b$ s^{-1}
  - trapping to vacancy-defect with **K** s^{-1}
  - annihilation from the defect with $\lambda_d = 1/\tau_d$
  - two-component lifetime spectrum

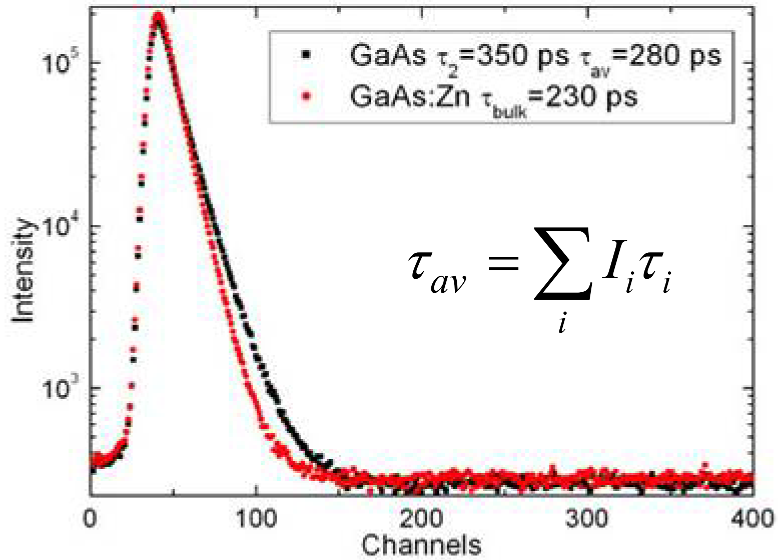
$$N(t) = I_1/\tau_1 \exp(-t/\tau_1) + I_2/\tau_2 \exp(-t/\tau_2)$$

  - analysis by non-linear fitting



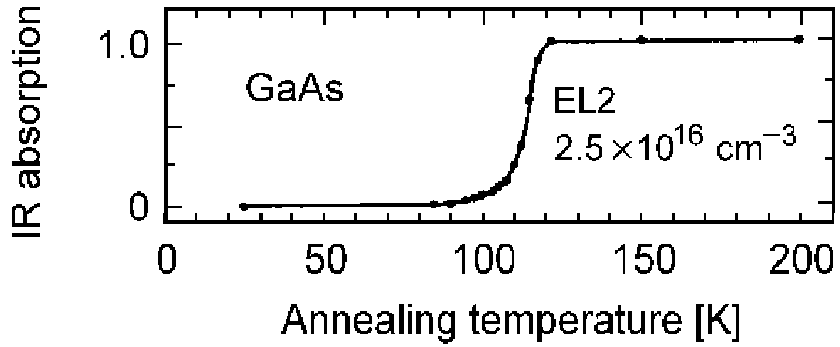
- Information
  - vacancy type (mono-, di-, vacancy cluster)
    τ_2 – reflects the electron density
  - defect concentration C

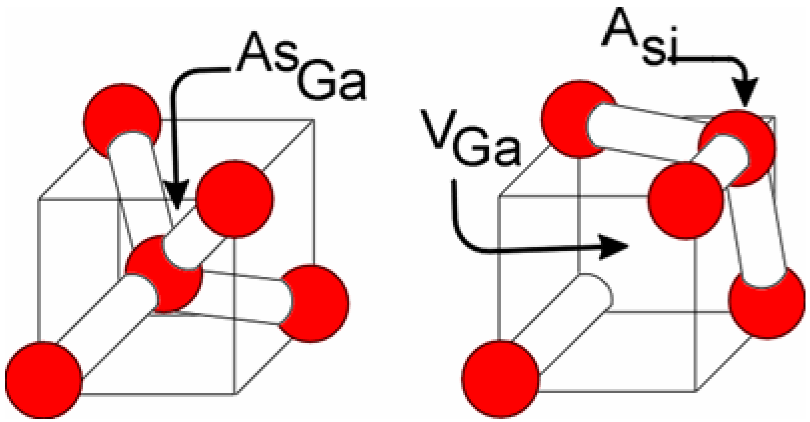
$$K = \frac{I_2}{I_1}\left(\frac{1}{\tau_b} - \frac{1}{\tau_2}\right) \approx C$$



The Nature of EL2 defect in GaAs

- one of the most frequently studied crystal lattice defects at all
- responsible for semi-insulating properties of GaAs: large technological importance
- is deep donor, compensates shallow acceptors, e.g. C^- impurities
- defect shows metastable state after illumination at low temperatures
- IR-absorption of defect disappears during illumination at T < 100 K
- ground state recovers during annealing at about 110 K
- many structural models proposed Dabrowski, Scheffler and Chadi, Chang (1988): simple As_{Ga}-antisite defect responsible
- must show a metastable structural change



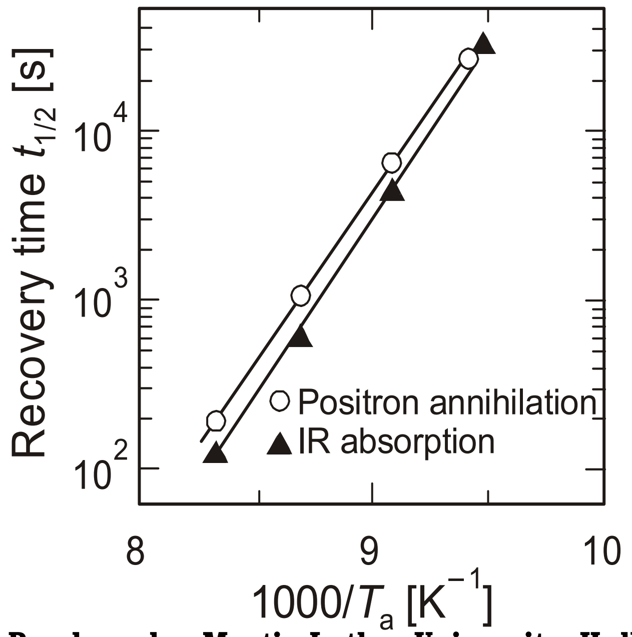


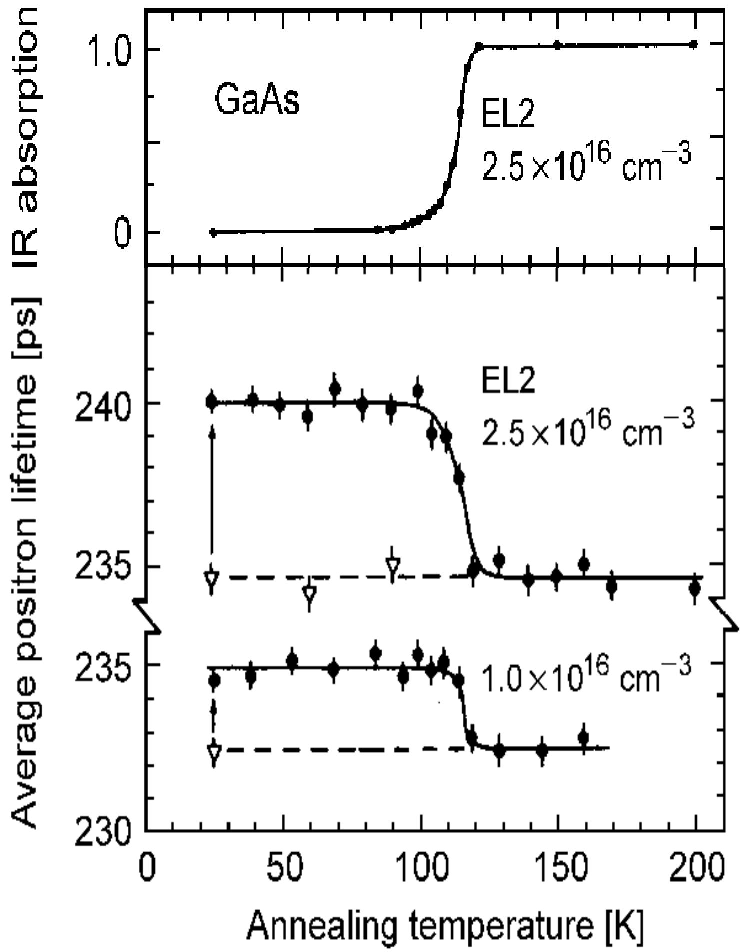
stabil metastabil

(Dabrowski 1988, Chadi 1988)

The Nature of EL2 defect in GaAs

- in metastable state at low temperature: Ga vacancy
- should disappear during annealing at about 110 K
- confirmed by positron lifetime measurements
- kinetics of recovery of ground state is identical for IR- und positron experiment: $E_A = (0.37 \pm 0.02)$ eV
- evidence of the vacancy in metastable state confirms the proposed structural model



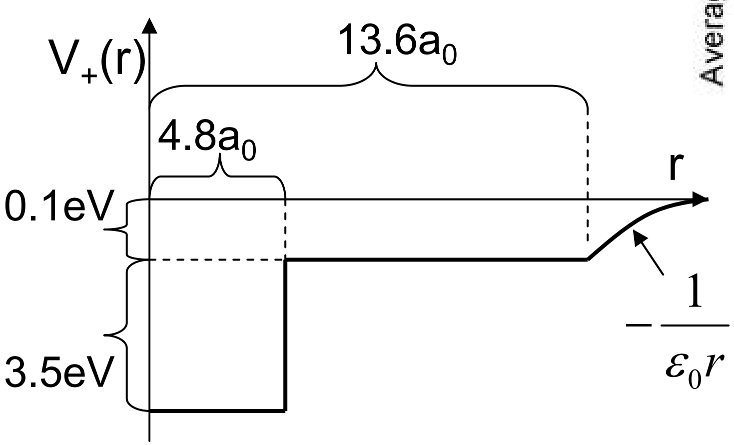


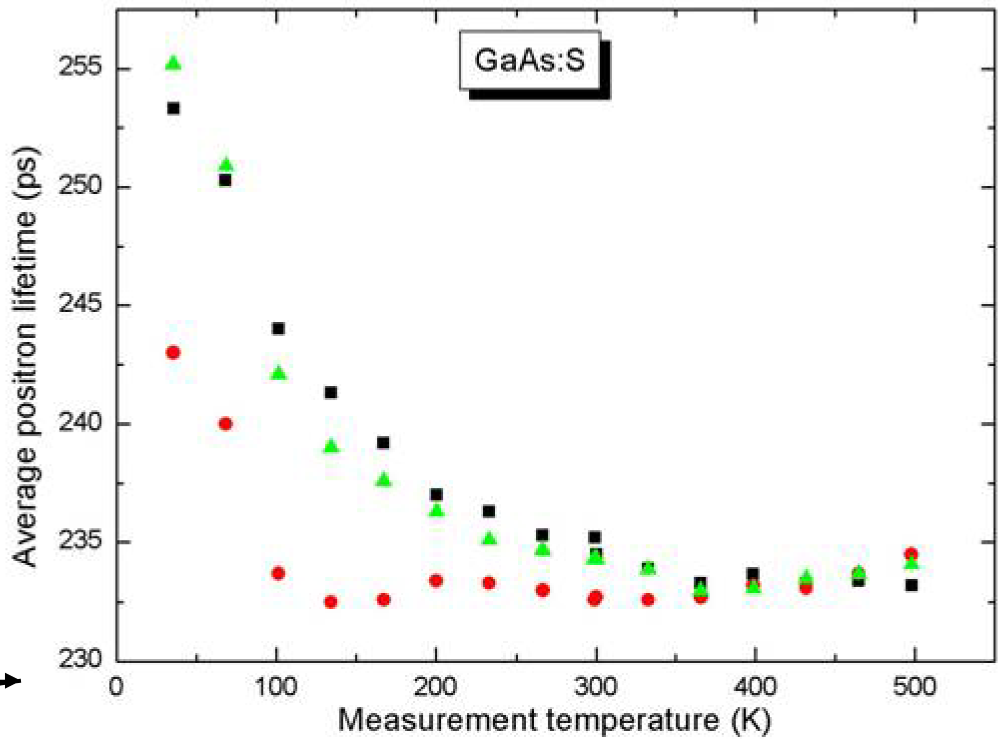
Krause et al., Phys. Rev. Lett. **65** (1990) 3329

Temperature dependence of positron trapping

Compensation in GaAs:S

- formation of S_{As}-V_{Ga} complex
- increase of τ_{av} to low T is due to the trapping into negative shallow Rydberg potential of the defect

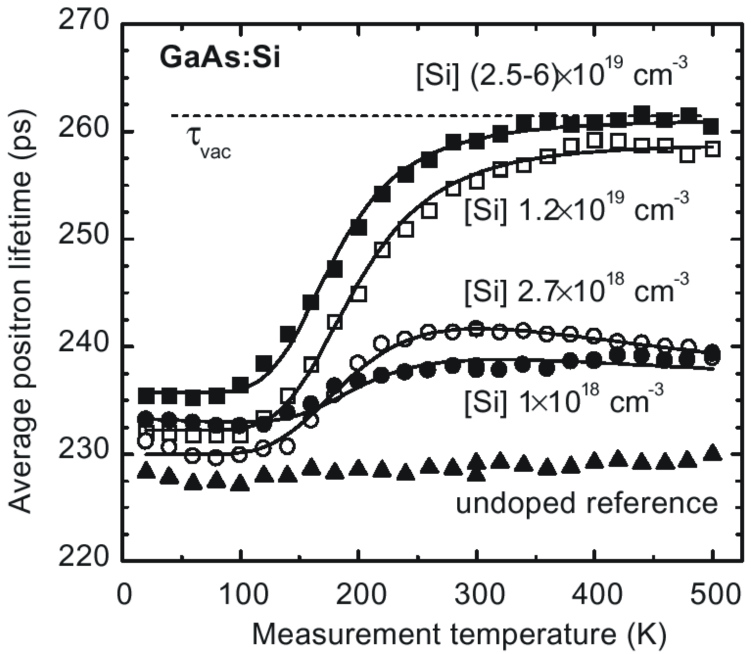




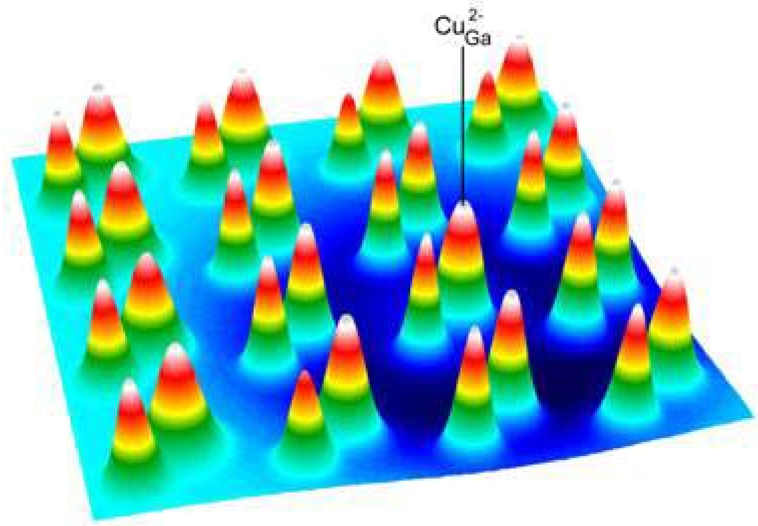
- observed S_{As}-V_{Ga} complex is *negatively* charged

Positron trapping – shallow traps

- negative ions are also positron trapping centers due to small negative Coulomb potential



(J. Gebauer et al. 1997)

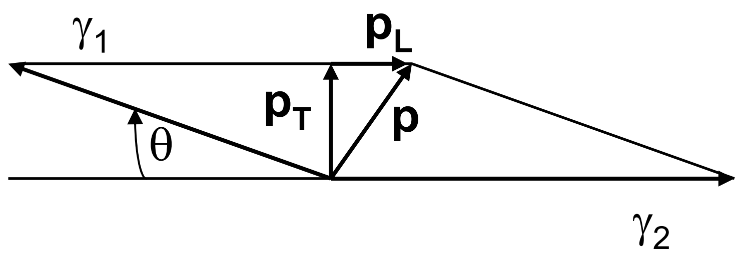


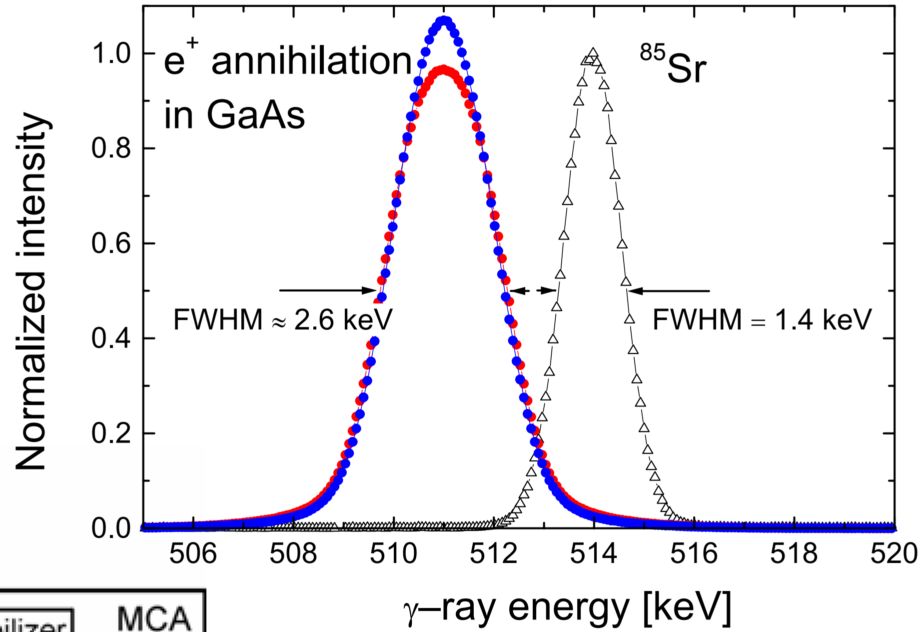
- term "shallow" relates to the positron binding energy (few meV).
- therefore the trapping is significant at low temperatures only
- the electron density is not reduced:

$$\tau_{st} = \tau_b$$

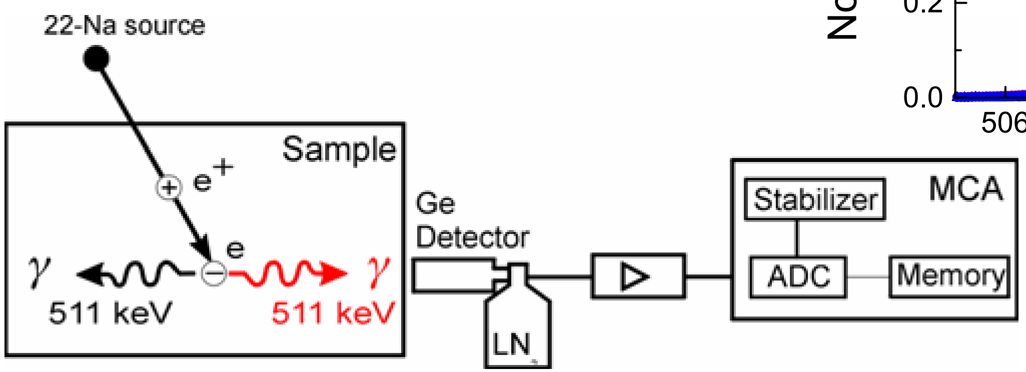
Annihilation-Line Doppler broadening spectroscopy

- Doppler effect
  - electron momentum in propagation direction of 511 keV γ-ray leads to Doppler broadening of annihilation line





- Technique



$E_1 - E_2 = p_L c$

E_1, E_2 – energy of γ quanta

Annihilation-Line Doppler broadening spectroscopy

Data Treatment

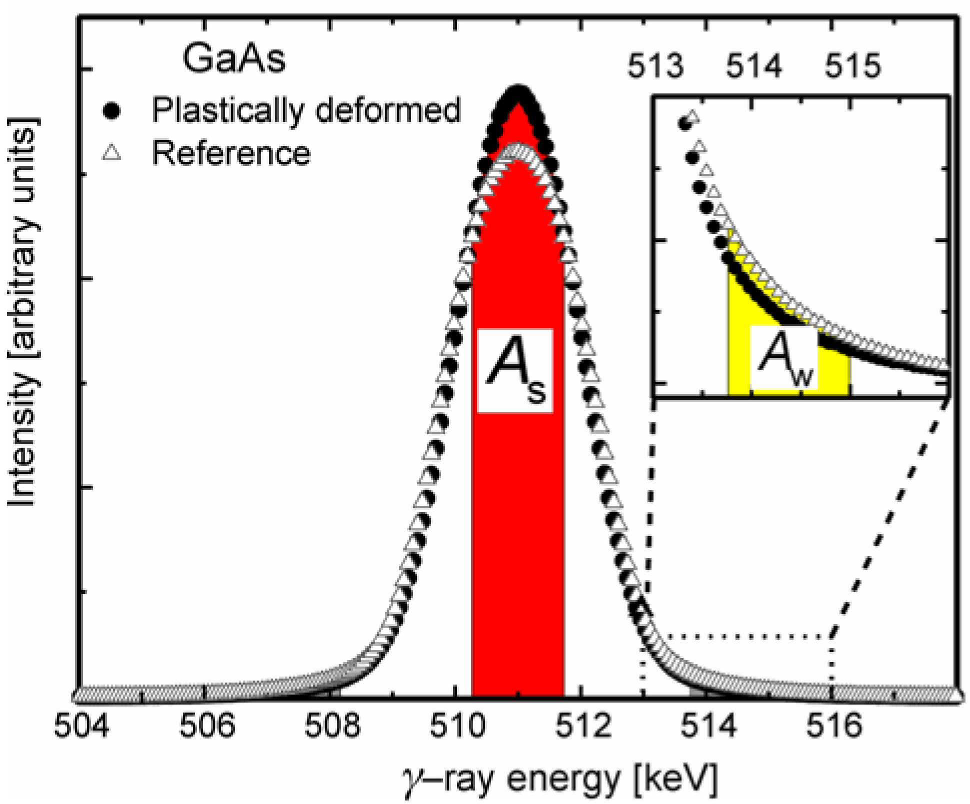
Line Parameters

- “Shape” parameter

$$S = \frac{A_s}{A_0}, \quad A_s = \int_{E_0 - E_s}^{E_0 + E_s} N_D dE$$

- “Wing” parameter

$$W = \frac{A_w}{A_0}, \quad A_w = \int_{E_1}^{E_2} N_D dE$$

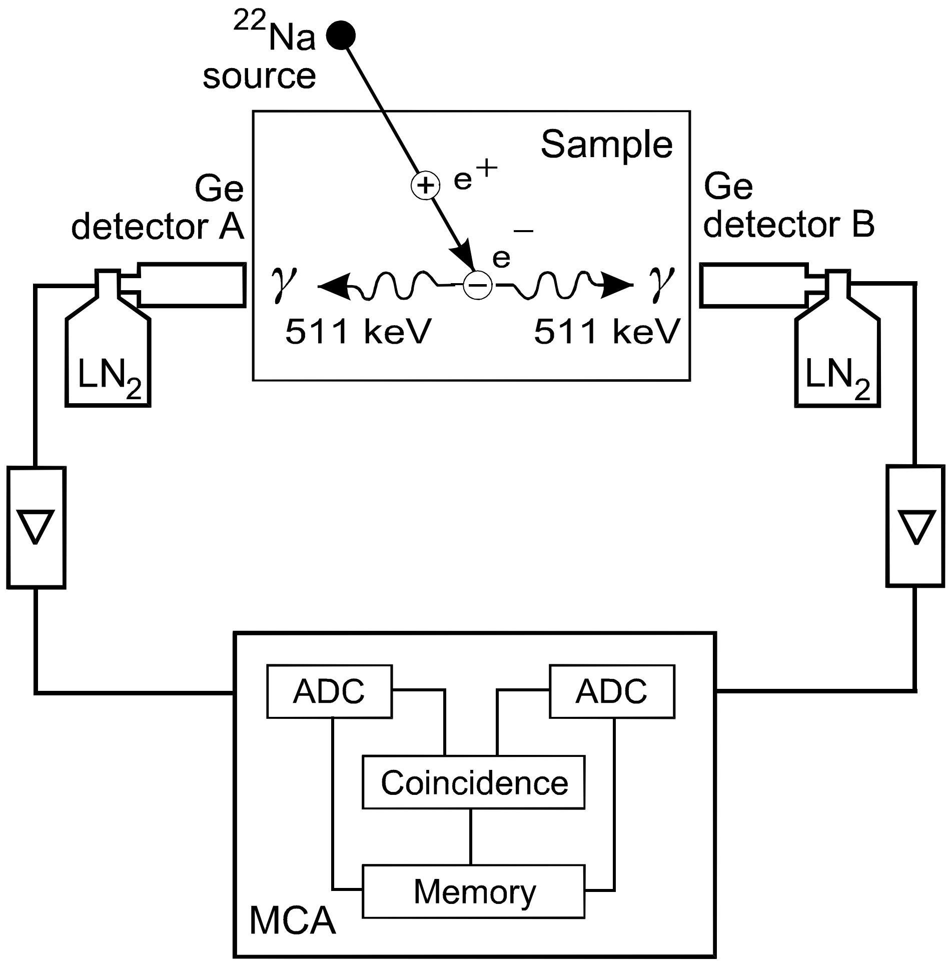


Information

- Both S and W are sensitive to the concentration and defect type
- W is sensitive to chemical surrounding of the annihilation site, due to high momentum of core electrons participating in annihilation

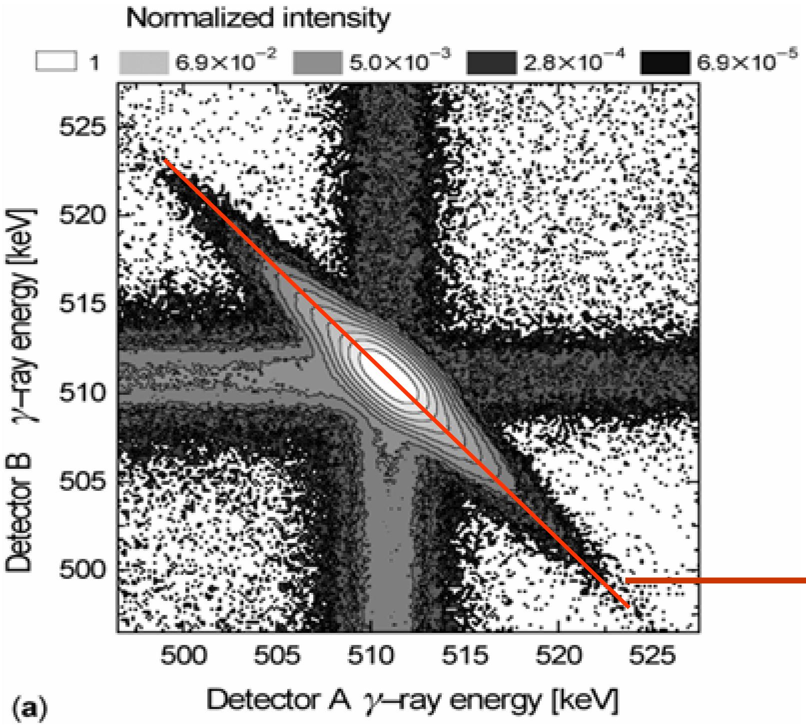
Coincidence Doppler broadening spectroscopy

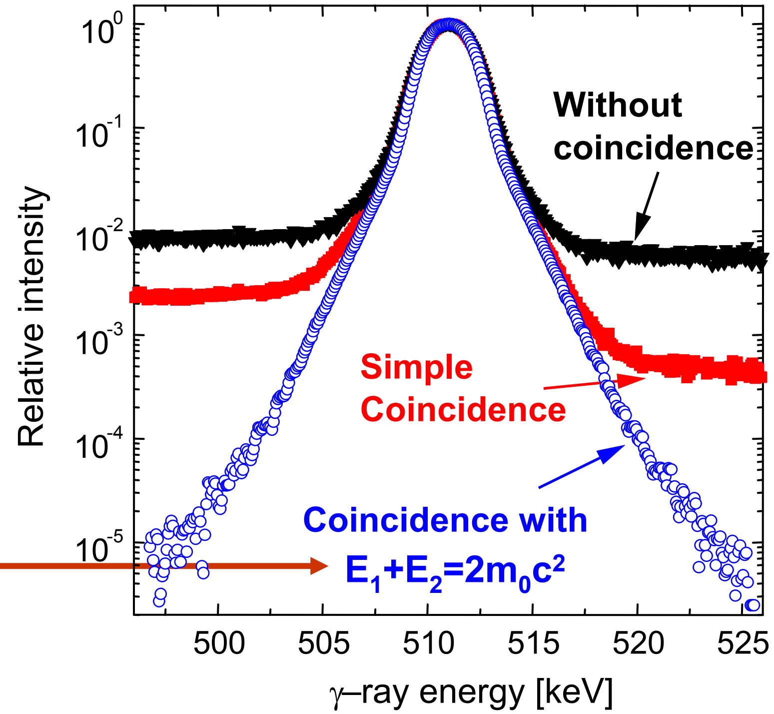
- Technique



- Both γ - quanta are detected
- coincidence time is 0.5 μs

Doppler coincidence spectroscopy

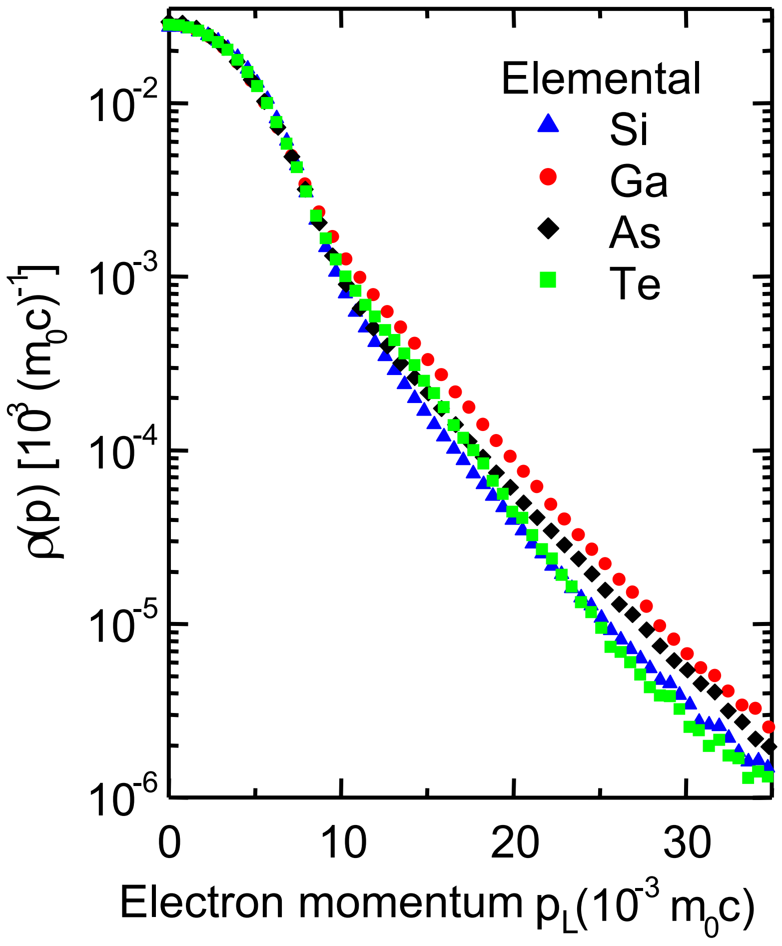


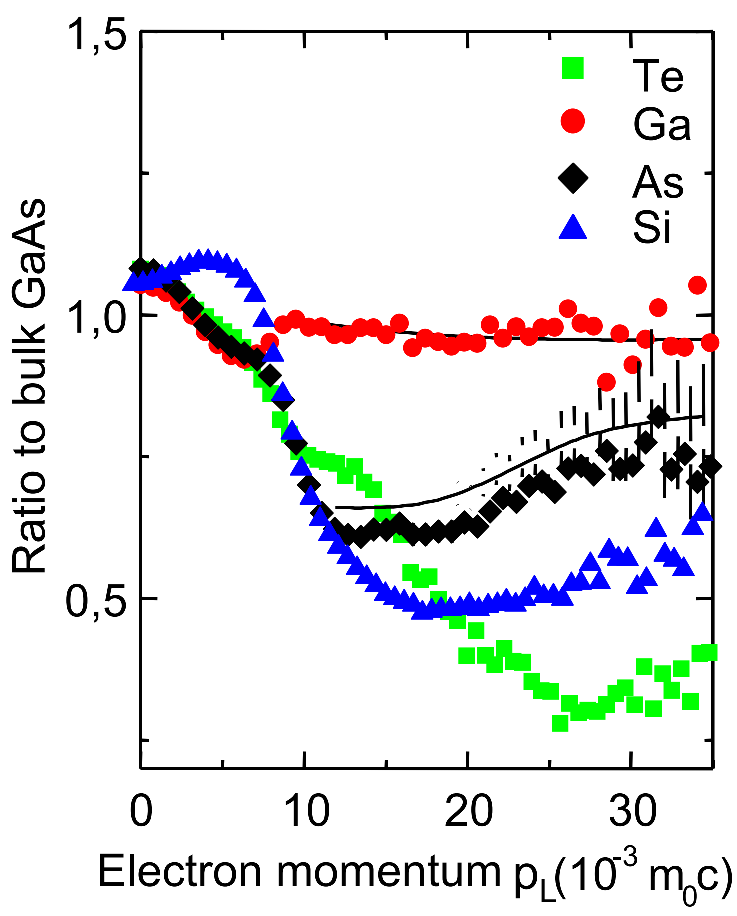


- background is dramatically reduced by coincident detection of second annihilation γ-quantum
- this opens a possibility to investigate the high momentum part of the energy spectrum, i.e. annihilation with core electrons the atoms
- thus the chemical surrounding of a positron trap can be studied

Doppler coincidence spectroscopy

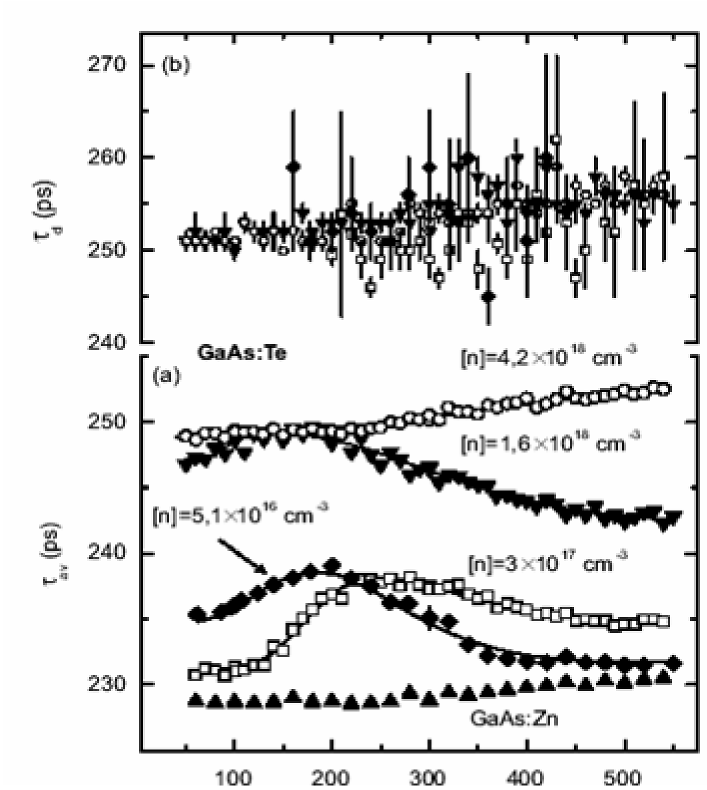
- chemical sensitivity of energy spectra





Nature of vacancy complexes in Si and Te doped GaAs

- positron lifetime spectroscopy

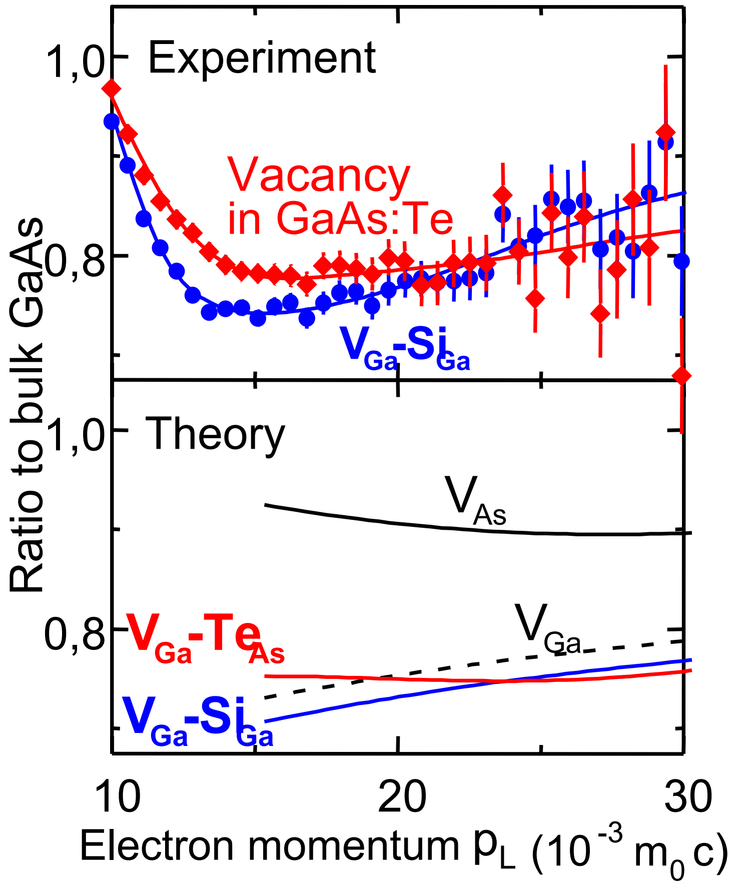


Measurement temperature

V_{Ga}-Si_{Ga} in GaAs:Si τ_2 = 260 ps

V_{Ga}-Te_{As} in GaAs:Te τ_2 = 253 ps

- Doppler coincidence



J. Gebauer et al., Phys. Rev. B ***60****, 1464 (1999)*

Conclusion

- positron annihilation is a sensitive tool for investigation of vacancy-like defects in semiconductors
- information on type and concentration of vacancies can be obtained
- temperature dependence of positron trapping is governed by the charge state of the defects
- chemical surrounding of the annihilation site can be studied with the help of coincidence Doppler broadening technique

- positively charged defects are invisible for positrons

This presentation can be found as a pdf-file on our Websites:

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