Positron Studies of Defects in irradiated and ion-implanted n-type SiC

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- The method - some basics
- Combination of positron annihilation and DLTS
- Results about bulk and epilayer SiC measurements
- Future plan
The positron annihilation spectroscopy

$e^+$

- Positron lifetime spectroscopy
- Doppler broadening spectroscopy
- Angular correlated positron spectroscopy

Coincidence doppler broadening Spectroscopy (chemical sensitivity)
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 measurements

Sample-source arrangement

- Photomultiplier
- Scintillator (Start)
- Slice 1
- Slice 2
- Scintillator (Stop)
- Photomultiplier

Photon 1.27 MeV

Positron: $e^+ + e^- = 511$ keV

Aluminium foil

Na-Source

Photon 511 keV
Trapping-centers

• Several trapping centers exist
• Shallow traps visible in combination with vacancies in low temperature region
• Charge state defines the trapping rate
Trapping model

\[
\frac{dn_{\text{bulk}}(t)}{dt} = -\lambda_{\text{bulk}} \cdot n_{\text{bulk}} - \kappa_v \cdot n_{\text{bulk}}
\]

\[
\frac{dn_v(t)}{dt} = \kappa_v \cdot n_{\text{bulk}} - \lambda_v \cdot n_v
\]

\[
N(t) = \sum_i \frac{I_i}{\tau_i} \exp \left( -\frac{t}{\tau_i} \right)
\]

\[
\tau_1 = \frac{1}{\lambda_{\text{bulk}} + \kappa_v}
\]

\[
\tau_2 = \frac{1}{\lambda_v}
\]

\[
I_1 + I_2 = 1
\]

\[
I_2 = \frac{\kappa_v}{\lambda_{\text{bulk}} - \lambda_v + \kappa_v}
\]

\[
\kappa_v = \mu \cdot C = I_2 \left( \frac{1}{\tau_1} - \frac{1}{\tau_2} \right)
\]
Electron density and annihilation probability

SiC 6H bulk
143 ps

SiC 6H $V_C$
148 ps

SiC 6H $V_{Si}$
187-215 ps

ATSUP calculation, after Puska
The slow positron beam

- semiconductor technology: thin layers (epitaxy, ion implantation)
- broad energy distribution due to $\beta^+$ decay
- some surfaces: negative workfunction $\Rightarrow$ moderation

Energy distribution after $\beta^+$ decay

Effect of moderation

- $^{22}\text{Na}$ emission spectrum
- Positron energy [eV]

- $dN_+/dE$ [eV$^{-1}$]

- $2\mu$m

- $^{111}$In (positive workfunction)
- $^{22}\text{Na}$ (negative workfunction)

- $\approx 0.05\%$
- $\approx 13\%$
- $\approx 87\%$

- monoenergetic positrons
- fast positrons
- annihilation
- thermalization
- diffusion
- fast positrons

- up to several 100 keV
Conventional positron beam technique

- positron beam can be made from monoenergetic positrons
- often: magnetically guided for simplicity

- disadvantage: no simple lifetime measurements
- defect studies by Doppler-broadening spectroscopy
- characterization of defects only by line-shape parameters or positron diffusion length
Information from Doppler-broadening spectroscopy

- **S** parameter does not contain all information
- **W** parameter determined by annihilation with core electrons $\Rightarrow$ chemical sensitivity
- **S-W-plot** characterize different trapping centers

L. Liszkay et al., Appl. Phys. Lett. 64 (1994) 1380
Electron-irradiated 6H and 4H SiC

Positron lifetime spectrum

Doppler broadening Spectrum

- Unirradiated 6H (n)
- 2MeV electron-irradiated 6H (n)
- Unirradiated 6H (p)
- 2MeV electron-irradiated 6H (p)

Counting rate (arb. units)

Time (12.3 ps/ch)

γ-ray ENERGY (keV)

Counting Rate (arb. units)
Vacancy depth profile - electron irradiation

- Nearly homogenous damage and increasing of the S-parameter in the complete layer
• Similar annealing behavior of the Silicon Vacancy IN 3C SiC electron spin resonance (ESR)
• Formation of vacancy-type complex in the temperature region of 1000°C involved with a Si-vacancy
He-implantation

Mean implantation depth (µm)

S-parameter

Incident positron energy (keV)

Total

S_{D} = 1.056

S_{B} = 1.000
PAS and DLTS annealing behavior

![DLTS signal vs Temperature](Image)

<table>
<thead>
<tr>
<th>Annealing temperature (°C)</th>
<th>Concentration (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>$10^{17}$</td>
</tr>
<tr>
<td>1400</td>
<td>$10^{16}$</td>
</tr>
<tr>
<td>1400</td>
<td>$10^{15}$</td>
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<tr>
<td>1400</td>
<td>$10^{14}$</td>
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<tr>
<td>1400</td>
<td>$10^{13}$</td>
</tr>
</tbody>
</table>

- 6H Z1/Z2
- 4H RD1/2
- 6H E1/E2
- 4H Z1/Z2

**S-parameter**

- 4H e+$^+$
Electron irradiated 6H SiC bulk material

- After illumination with white light a decrease of the average positron lifetime appears below 110 K.

- The spectra decomposition shows a defect-related lifetime of 185 ps (VSi) [Bra96] either in darkness or under illumination. The intensity decreases from 45% to 17% under illumination.

- The illumination effect appears also in as-grown material. The irradiation with 2 MeV was done to introduce additional Frenkel pairs.

- In the inset the difference of positron lifetime under illumination and darkness is presented. (the fitted Energy barrier: 32meV)

\[ \Delta \tau = \tau_{\text{dark}} - \tau_{\text{illum}} \]
Electron irradiated 6H SiC bulk material

- Two annealing steps appear.
- The illumination effect and the vacancies disappear approximately at the same temperature.
- The E1/E2 defect also disappears at that temperature region [Zha89]
Electron irradiated 6H SiC bulk material

- The data were fitted to the Lucowsky model [Luc65] which gives the cross section for electron transition from a localized state to a parabolic and isotropic band. The threshold energy is determined to be $E=0.47\,\text{eV}$.

- Illumination effect disappears above 3eV due to direct transition of electrons from the valence band to the conduction band.

- Above 0.4 eV electrons are probably excited from localized levels to the conduction band. Thus, the charge state will change from negative to neutral.
Persistency effect of illumination

- Illumination effect disappears after 10 min
- Small energy barrier between the excited state and the ground state
2MeV Electron irradiation (dose: 3E17 cm$^{-2}$)

- Four step annealing was observed
- First step: annealing of Frenkel pairs
- Second step: carbon vacancies become mobile
- Third step: silicon vacancies become mobile and form complexes
- Fourth step: annealing of most defects introduced by electron irradiation
Decomposition of lifetime spectra $T_{\text{anneal}}=800^\circ\text{C}$

![Graph showing the decomposition of lifetime spectra with measurement temperature (K) on the x-axis and $I_2$, $\tau_2$, and $\tau_{\text{ave}}$ on the y-axis. The graphs also show the ratio $S/S_{\text{bulk}}$ and $W/W_{\text{bulk}}$ with temperature labels and symbols for light and dark conditions.](image-url)
N-type 6H SiC different N-concentration

![Graph showing the average positron lifetime (ps) vs. measurement temperature (K) for different N-concentrations: [n]=2.2E18 cm⁻³, [n]=2.0E18 cm⁻³, [n]=1.0E18 cm⁻³, [n]=4.5E17 cm⁻³, [n]=5.0E17 cm⁻³.](image)
N-type 4H SiC different N-concentration

![Graph showing average positron lifetime (ps) vs. Measurement temperature (K) for different N-concentrations of N-type 4H SiC.]

- [N]=1.19 E18 cm\(^{-3}\)
- [N]=9.65 E18 cm\(^{-3}\)
- [N]=1.89 E19 cm\(^{-3}\)
- [N]=2.58 E19 cm\(^{-3}\)
- [N]=2.63 E19 cm\(^{-3}\)
- [N]=3.30 E19 cm\(^{-3}\)
- Ref Start 4H p-type (cree)
- Ref Stopp
Low N-concentration comparison SiC 4H

[N] = 1.19 E18 cm⁻³

[N] = 9.65 E18 cm⁻³
• Positron annihilation spectroscopy detect vacancy type defect in SiC after crystal growth, electron irradiation or He-implantation
• Main trapping center is the silicon vacancy or complexes with silicon vacancies
• The obtained defects E1/E2 (6H, DLTS) should be decorated with silicon vacancies
• Introduced defects can change their charge state through white light illumination→ vacancies are neutral or single negatively charged (change of trapping rate)
• The increasing N-concentration during the crystal growth reduces the vacancy concentration
• Origin of shallow traps in 6H and 4H is still unclear
Thanks

- A. Kawasuso, R. Krause-Rehberg, K. Petters for their fruitful discussion und lab-facility
- Michael Weidner and Thomas Frank for their sample treatment (Group: G. Pensl, Erlangen)
- DFG Deutsche Froschungs Gesellschaft
- IKZ :bulk crystals

This talk can be downloaded from: www.ep3.uni-halle.de/positrons
Coincidence system

Detektor 1

γ₁

γ₂

Detektor 2

Amp
Ortec
672

Probe

OUT

Digitale Busbox
Koinzidenz (0,3 µs)

ADC
Fast 7070

Out

In

Amp
Ortec
672

OUT

PC mit MPA-WIN System
2dim coincidence spectrum

Normalized intensity

\[
\begin{array}{c|c|c|c|c}
 & 1 & 6.9 \times 10^{-2} & 5.0 \times 10^{-3} & 2.8 \times 10^{-4} & 6.9 \times 10^{-5} \\
\hline
525 & & & & & \\
520 & & & & & \\
515 & & & & & \\
510 & & & & & \\
505 & & & & & \\
500 & & & & & \\
\end{array}
\]

\[E_1 + E_2 = 2 \, m_0 \, c^2 = 1022 \, \text{keV}\]
Background reduction

Keine Koinzidenz

Einfache Koinzidenz

Koinzidenz mit

\[ E_1 + E_2 = 2 m_0 c^2 \]
Theoretical high impuls contribution

T. Staab et al.
(to be published in Mater. Sci. Forum)
As-irrad. + 1000°C anneal

Ratio to SiC

\( V_{Si} \)

Momentum

\( x 0.346 \)

Martin-Luther-Universität Halle