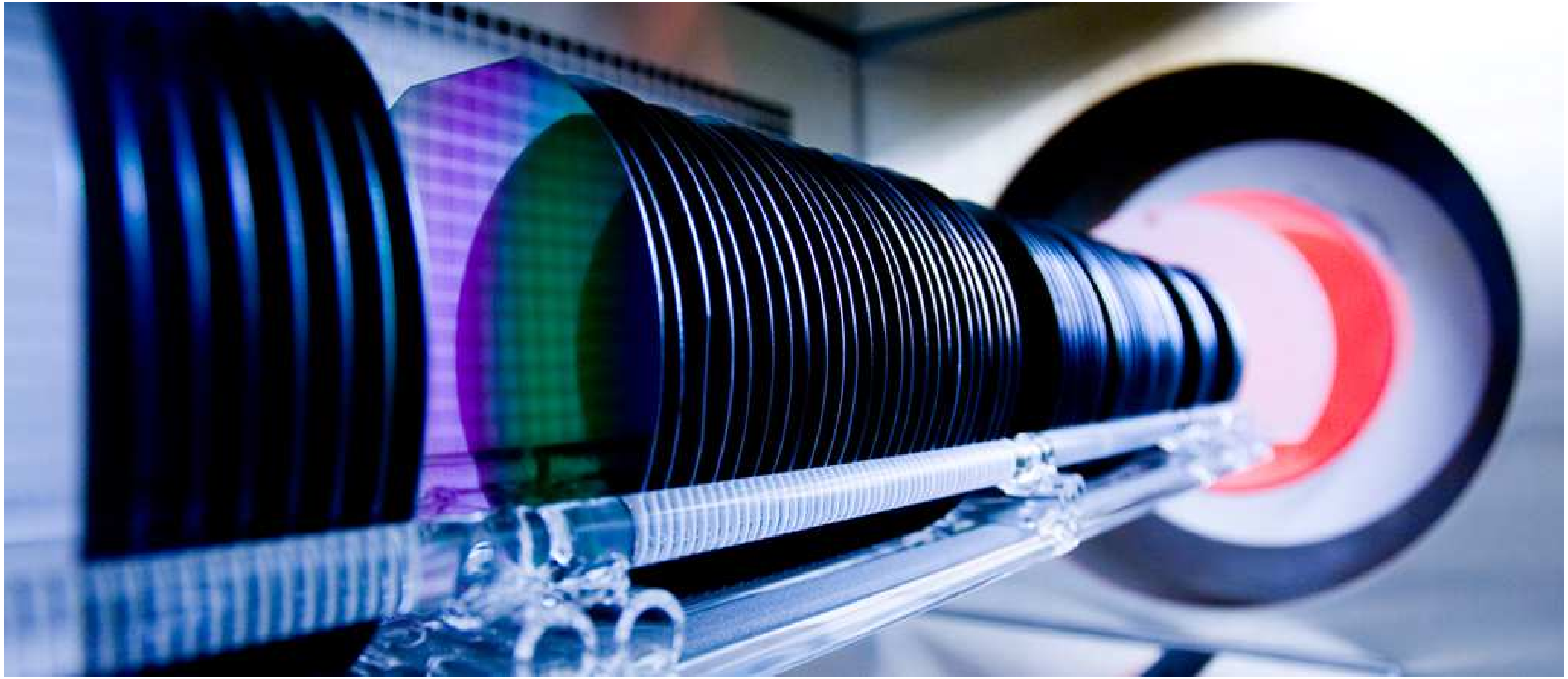


A_{Si}-Si_i defect as possible origin of electronically activated degradation of boron and indium doped silicon

Kevin Lauer, Christian Möller, Tobias Wittig, Ralf Röder

RD50 Meeting, 11.-13.6.14, Bucharest

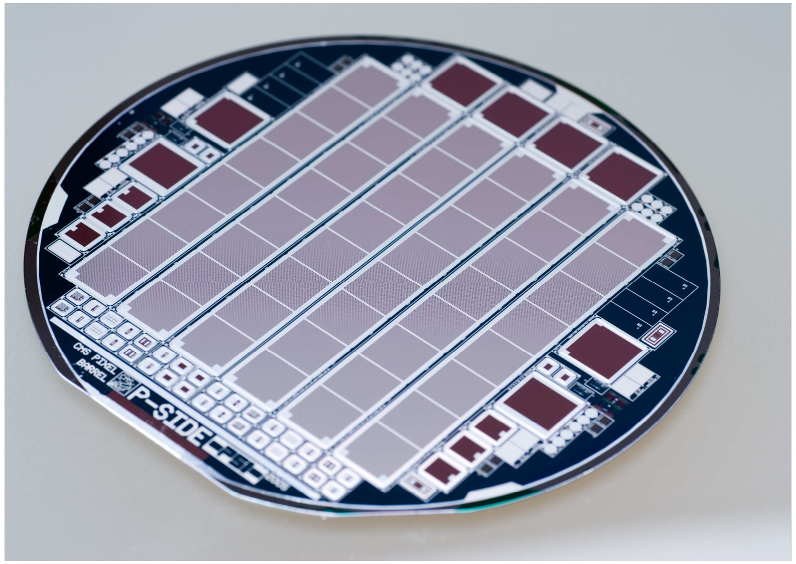
CiS Forschungsinstitut für **Mikrosensorik** und **Photovoltaik** GmbH

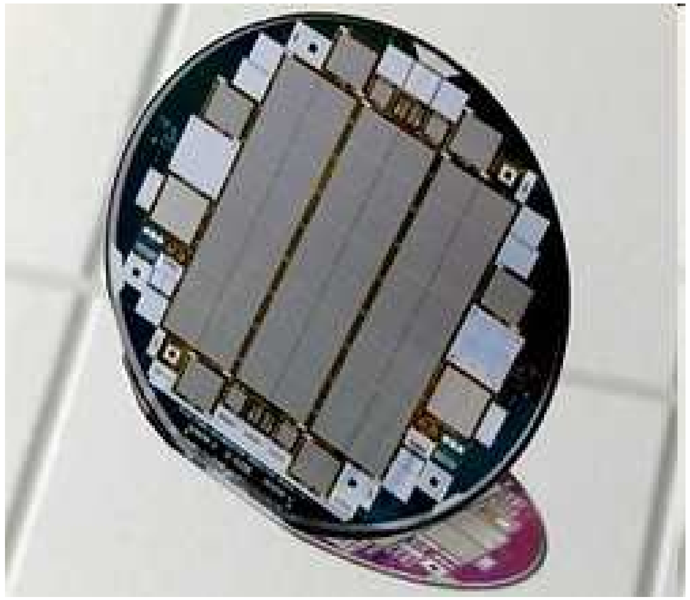
Overview

- Recent developments and possibilities at CiS
- Electronically stimulated degradation in boron and indium doped silicon
- A_{Si}-Si_i defect model

Motivation

- CiS has significantly contributed to sensor productions of various HEP experiments in past and present
    - ATLAS pixel, strips, IBL
    - CMS pixel, strips, CMS upgrade
    - ALICE
    - ...

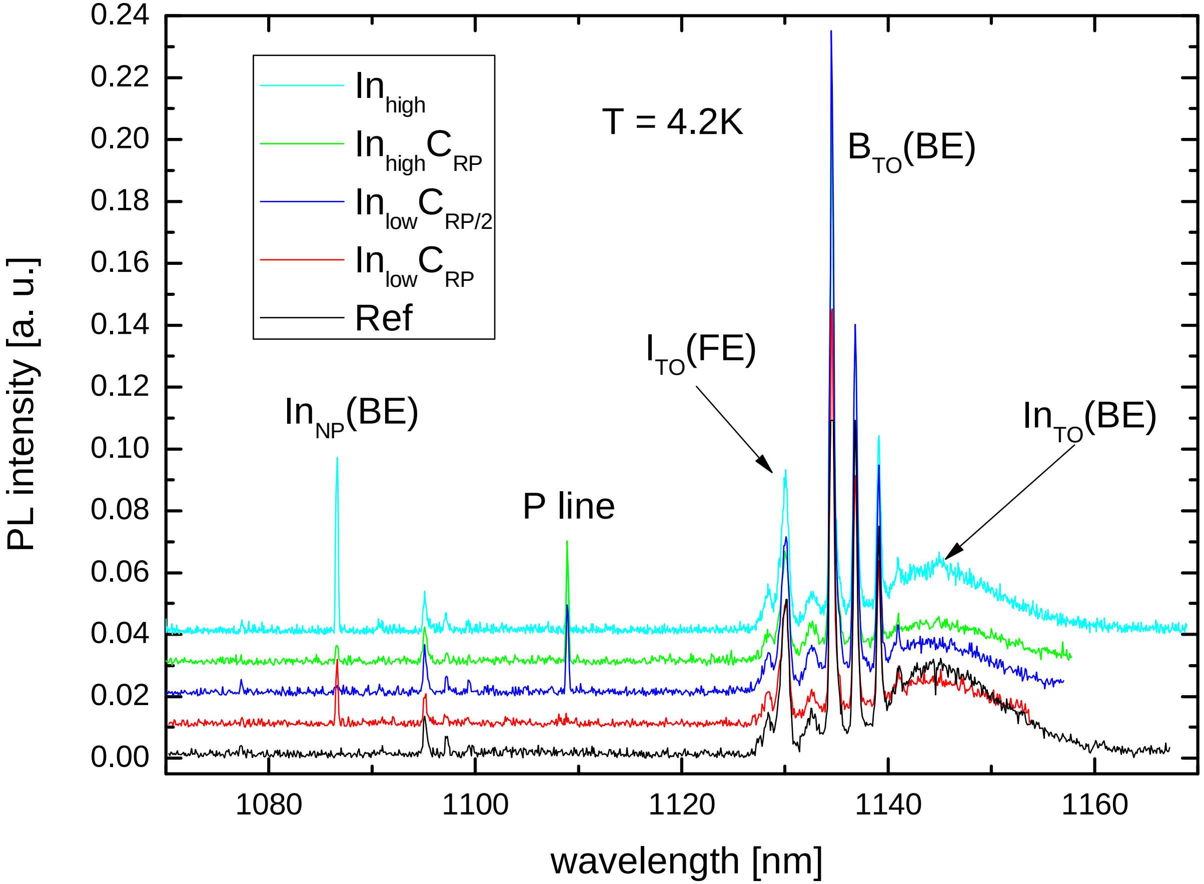


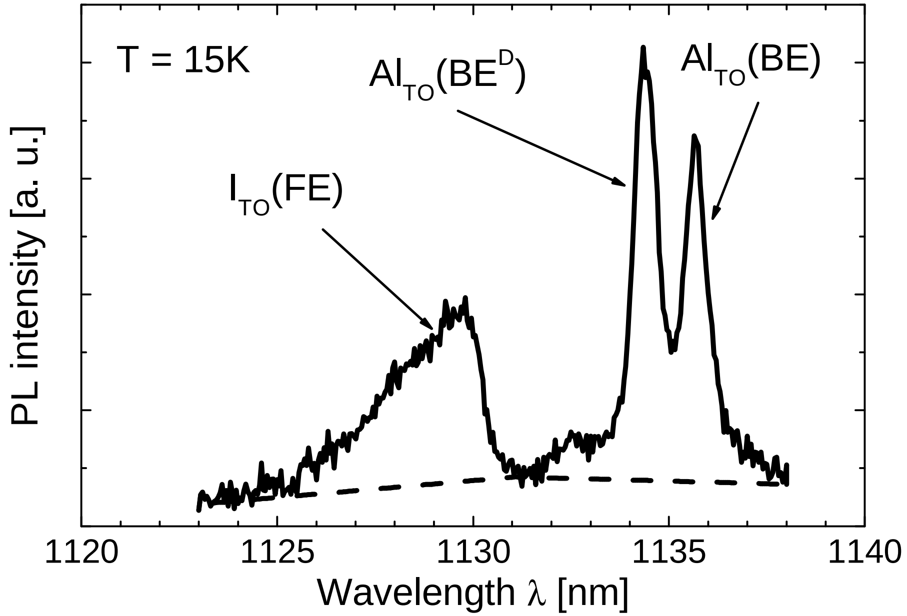


Future plans at CiS

- Foundation of new department “silicon detectors” at CiS
- Synergies from research focused on n-in-p silicon solar cells
- Investigation of defects in silicon radiation detectors
- Methods: Low-temperature PL spectroscopy, low-temperature FTIR, Charge carrier lifetime measurements
- Impact and optimization of defects and defect configurations during detector processing

Low-temperature PL spectroscopy

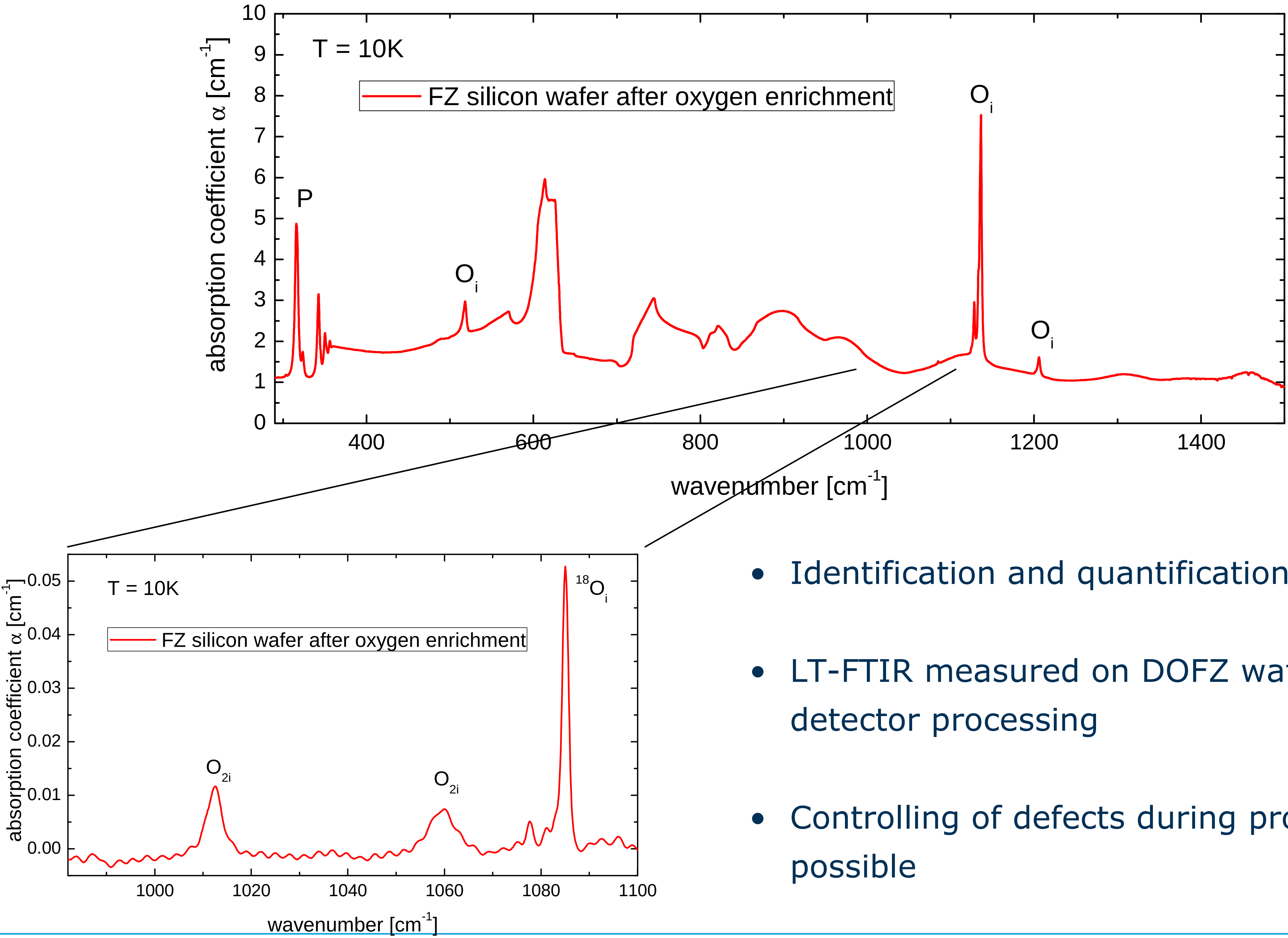




K. Lauer, C. Möller, D. Schulze, T. Bartel, and F. Kirscht, phys. stat. sol. RRL **7**, 265 (2013)

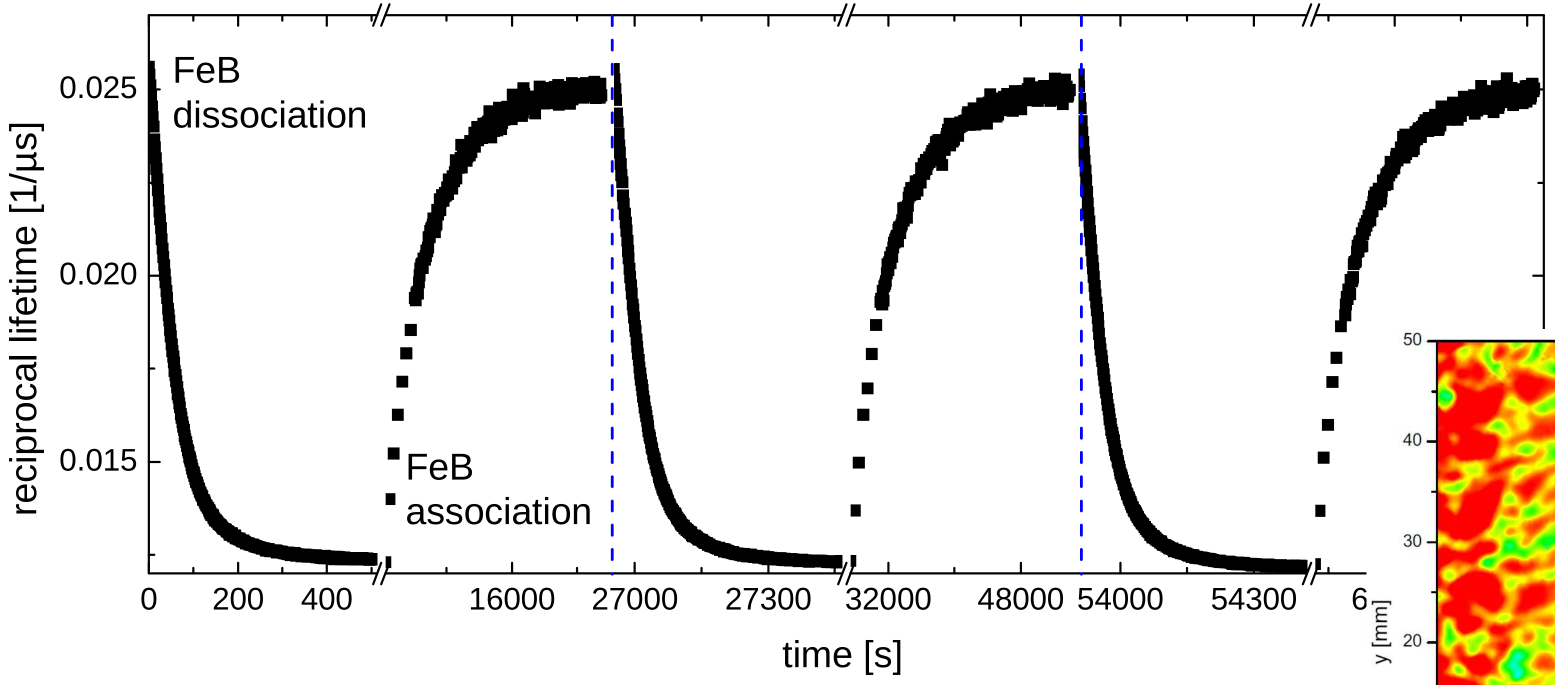
- Defect analysis by LTPL in indium and carbon co-implanted silicon
- Quantification of shallow dopants

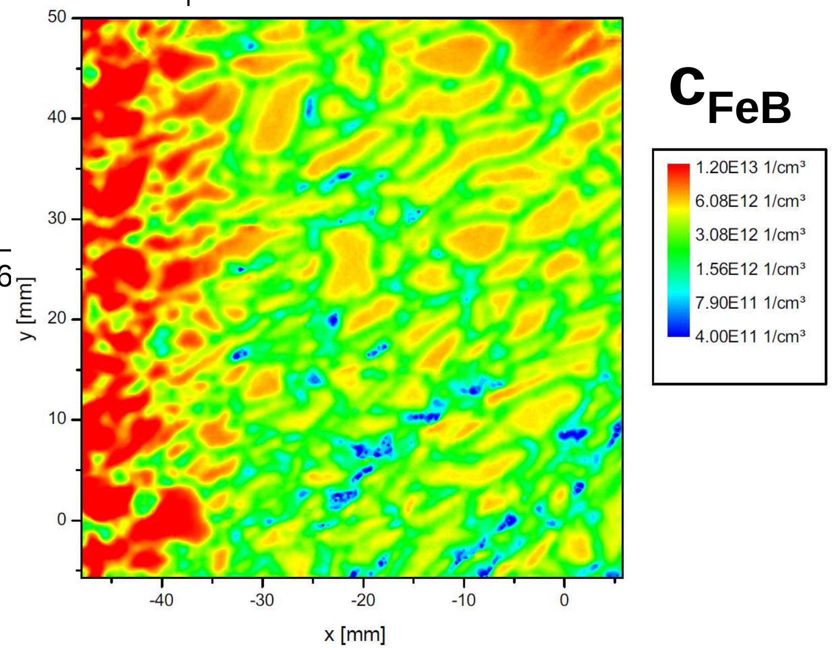
Low-temperature FTIR



- Identification and quantification of defects
- LT-FTIR measured on DOFZ wafers prior to detector processing
- Controlling of defects during processing possible

Charge carrier lifetime



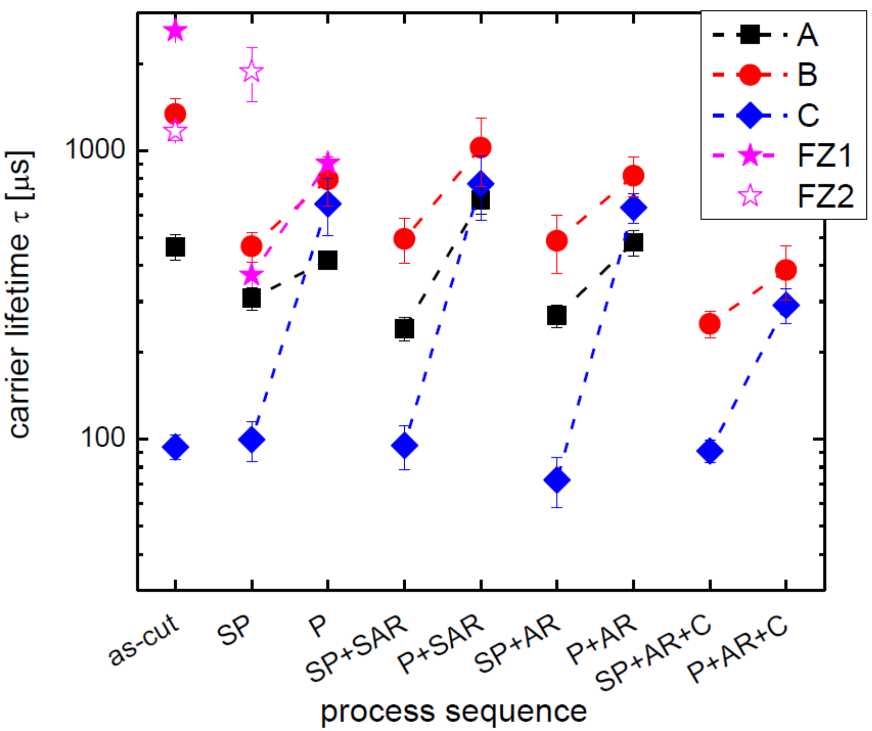


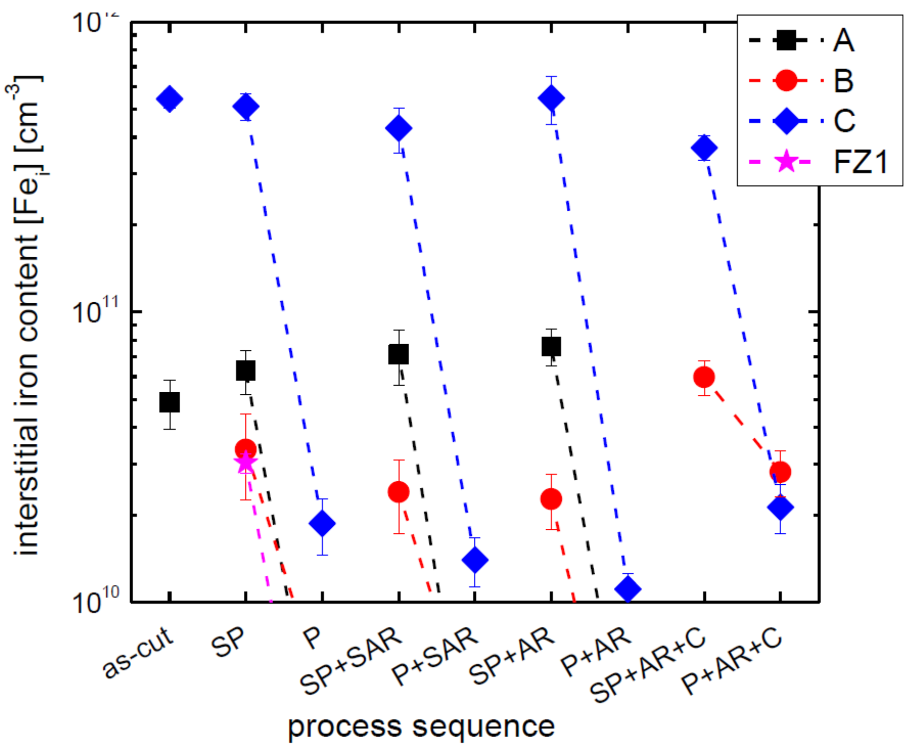
K. Lauer, A. Laades, H. Übensee, H. Metzner, and A. Lawerenz, J. Appl. Phys. **104**, 104503 (2008)

T. Bartel, F. Gibaja, O. Graf, D. Gross, M. Kaes, M. Heuer, F. Kirscht, C. Möller, and K. Lauer, Appl. Phys. Lett. **103**, 202109 (2013)

- Quantification of electrical quality of silicon (spatial and injection resolved)
- Monitoring of defect reactions in silicon
- Iron-acceptor association and dissociation kinetics

n-in-p silicon solar cells





K. Lauer, C. Möller, K. Neckermann, M. Blech, M. Herms, T. Mchedlidze, J. Weber, and S. Meyer, Energy Proc. **38**, 589 (2013)

T. Mchedlidze, L. Scheffler, J. Weber, M. Herms, J. Neusel, V. Osinniy, C. Möller, and K. Lauer, Appl. Phys. Lett. **103**, 013901 (2013)

- Impact of defects on solar cell parameters
- Impact of processing steps on defect properties
- Gettering of impurities by phosphorous diffusion

P … P-diffusion
SP …thermal budget of P
AR …PECVD SiNx
SAR … thermal budget of AR
C …Contacting

A_{Si}-Si_i defect?

Properties

- Defect known since over 40 years
- First observed in n-in-p solar cells for space application after electron irradiation and subsequent photon irradiation
- Defect degrades charge carrier lifetime in boron doped silicon by electron injection (illumination or forward bias)
- Efficiency of n-in-p solar cells reduced by about 10% due to this defect (commercial problem)
- Possible impact on n-in-p radiation detectors by increasing leakage current (meta stable)

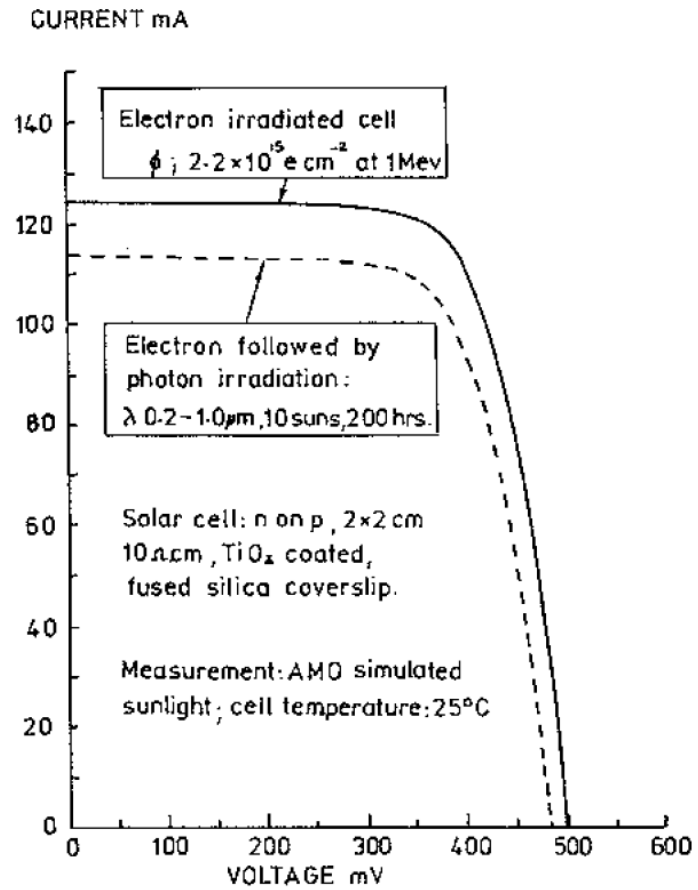
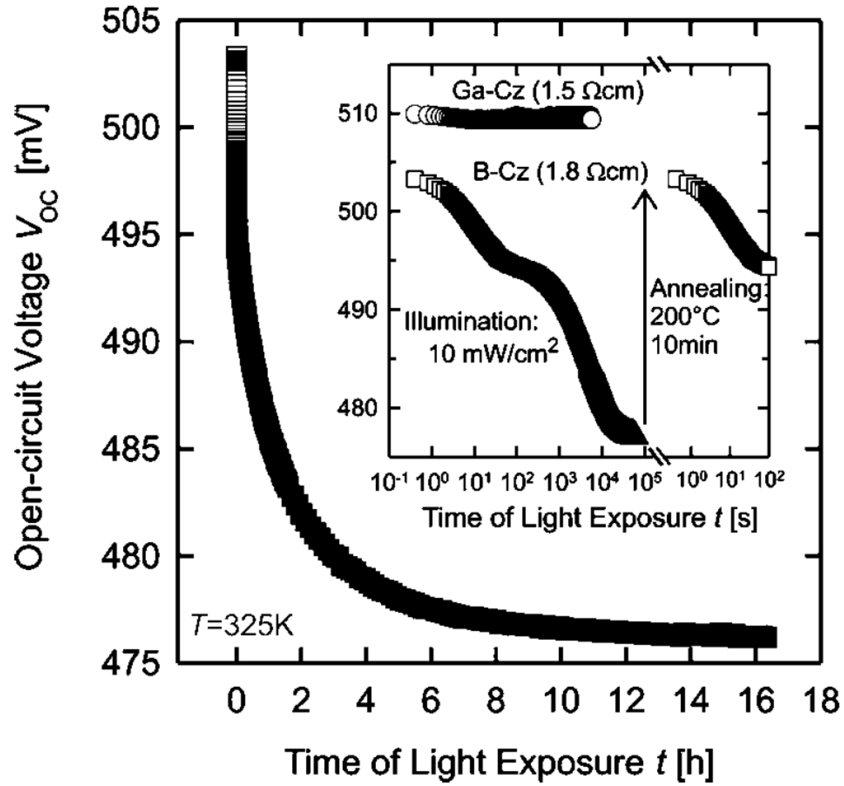


Fig 1 Solar cell V-I performance degradation following sequential electron-photon irradiation

R. L. Crabb, Proceedings of the 9th IEEE Photovoltaic Specialists Conference, New York, 329 (1972)

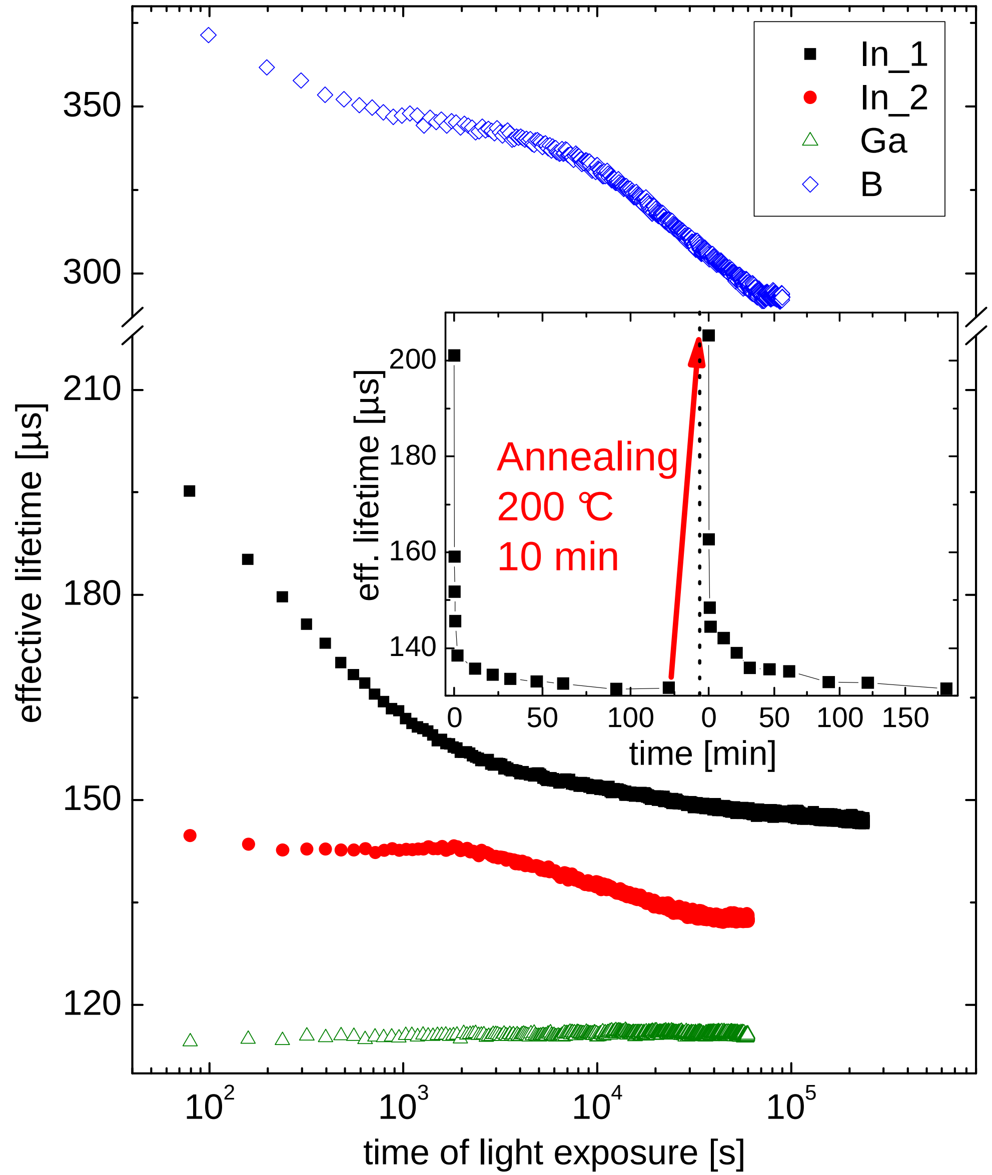
Properties

- Appears in as-grown CZ silicon and is reversible
- Does not appear in gallium and aluminum doped silicon
- Depends on oxygen concentration in CZ silicon
- Has fast and slow component
- Depends on hole concentration
- Permanently deactivated by illuminating at elevated temperatures



K. Bothe and J. Schmidt, J. Appl. Phys. **99**, 13701 (2006)

Degradation in indium doped silicon



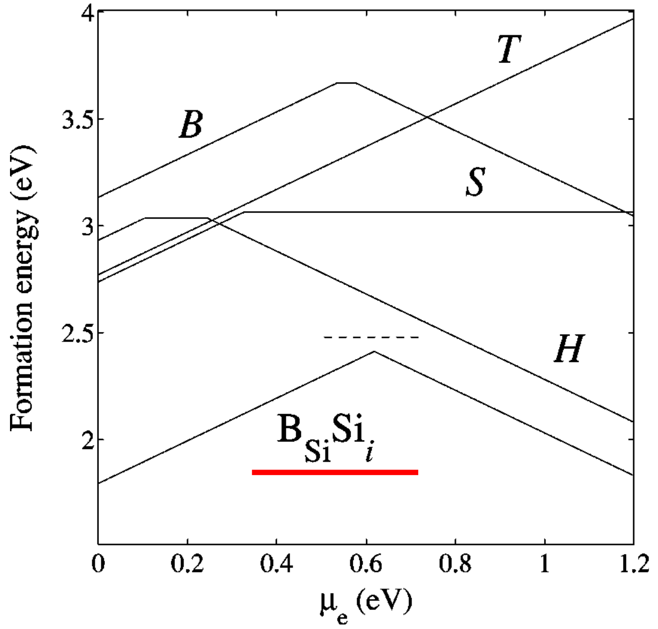
- Defect occurs in indium-doped silicon
- Fast and slow component visible
- Degradation is fully reversible

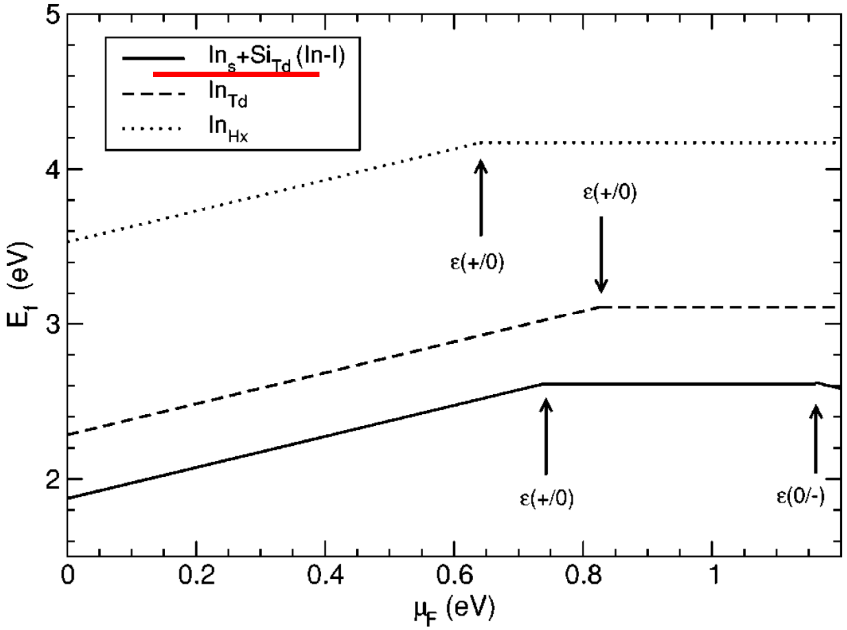
- Why does the defect occur in boron and indium and not in gallium doped silicon?

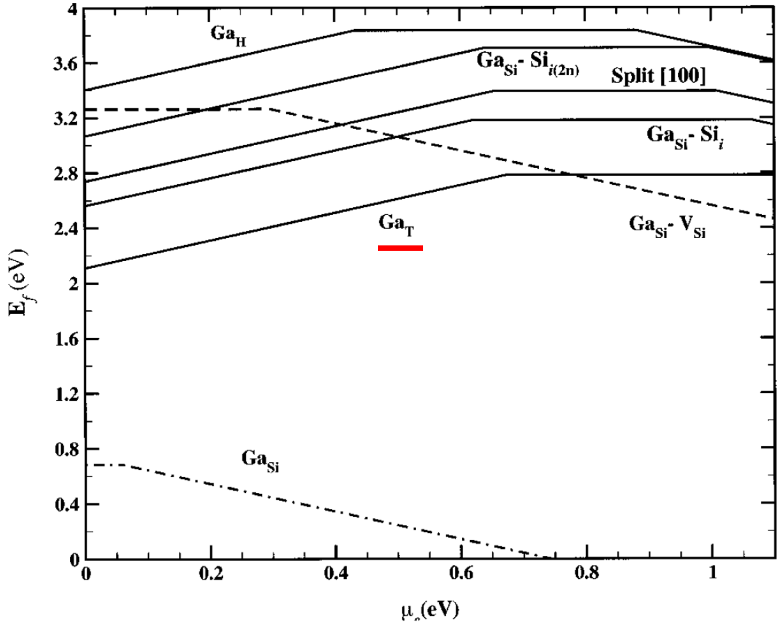
sample	method/ orientation	dopant	ρ (Ω cm)	N_A (10^{15} cm^{-3})	[O_i] (10^{17} cm^{-3})
B	CZ/100	boron	5.80	2.4	9.84
Ga	CZ/100	gallium	3.41	4.1	8.39
In_1	CZ/100	indium	7.82	1.8	17.68
In_2	FZ/111	indium	8.61	1.6	0.11

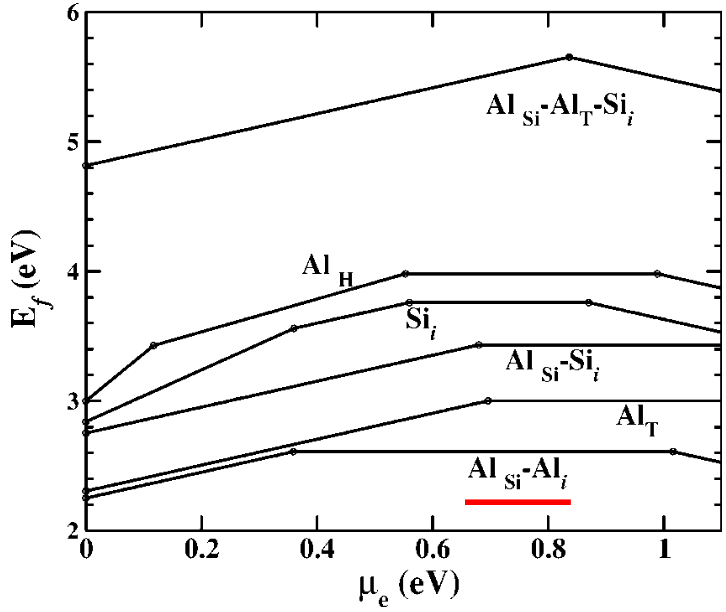
C. Möller and K. Lauer, phys. stat. sol. RRL **7**, 461 (2013)

Formation energies of interstitial acceptor atoms









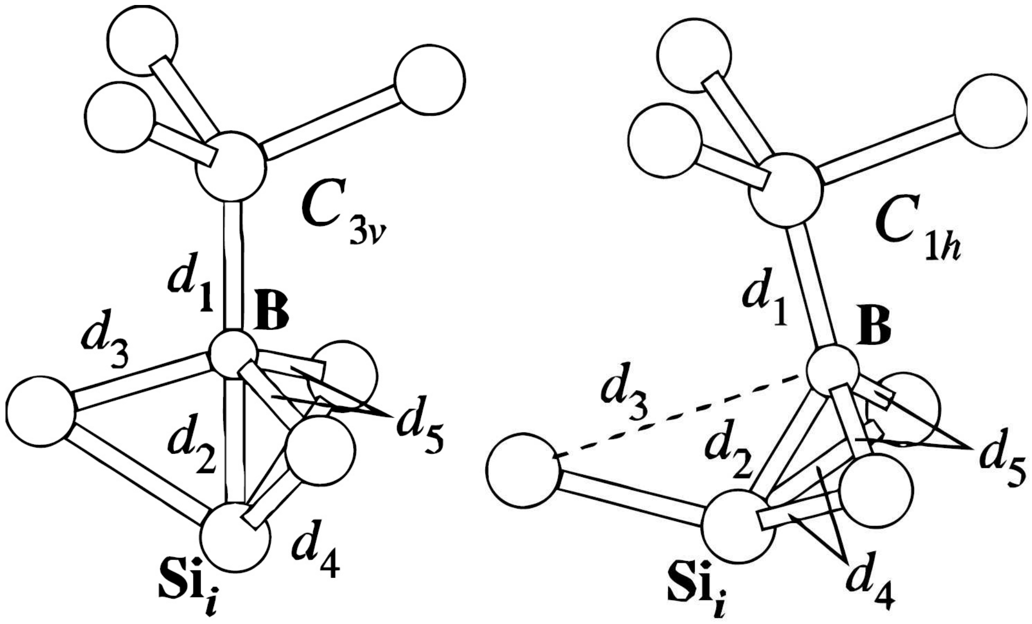
- Configuration of interstitial acceptor atom with lowest formation energy of varies
- Gallium on tetrahedral position
- Aluminum forms pair with another Al atom
- Boron and indium forming an acceptor silicon interstitial pair (A_{Si}-Si_i)

=> A_{Si}-Si_i responsible for observed defect?

*Hakala et al., Phys. Rev. B **61**, 8155 (2000)*
*Melis et al., Appl. Phys. Lett. **85**,4902 (2004)*
*Alippi et al., Phys. Rev. B **69**, 085213 (2004)*
*Schirra et al., Phys. Rev. B **70**, 245201 (2005)*

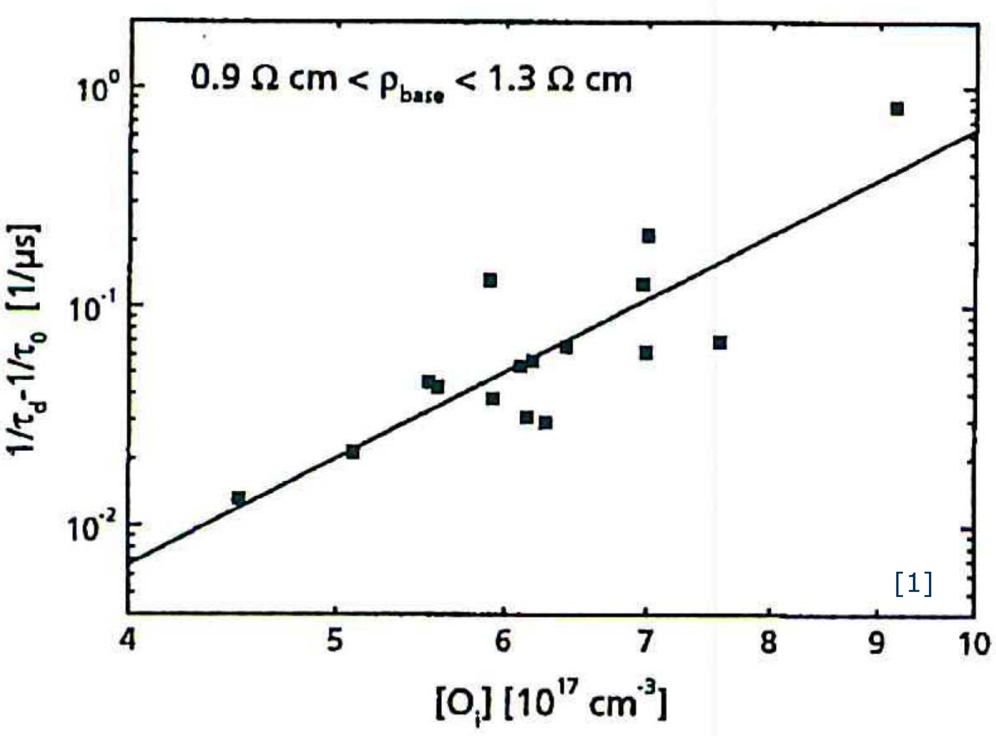
A_{Si}-Si_i-defect model

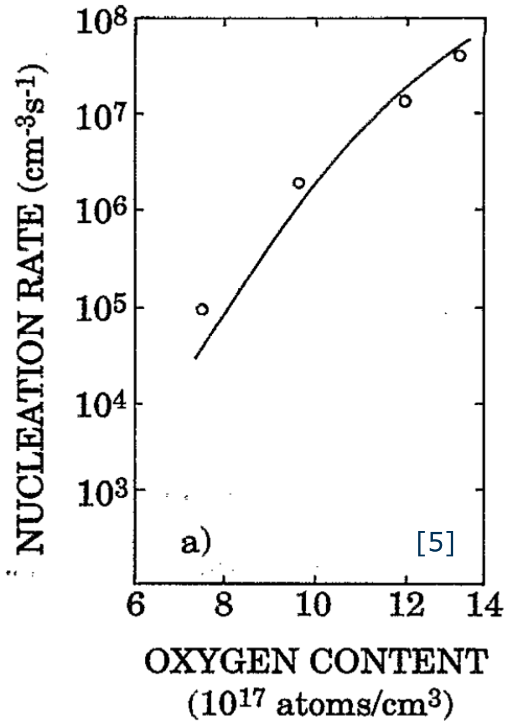
- Configuration in case of boron well investigated by simulation and experiment
- Boron diffusion mediated by this defect
- A_{Si}-Si_i-defect [1] also known as BI defect [2]
- A_{Si}: acceptor atom close to its substitutional position
- Depending on charge state two configurations of defect (C_{3v} and C_{1h}) possible



[1] Hakala et al., Phys. Rev. B **61**, 8155 (2000)
[2] Mirabella et al., J. Appl. Phys. **113**, 031101 (2013)

Dependence on oxygen concentration

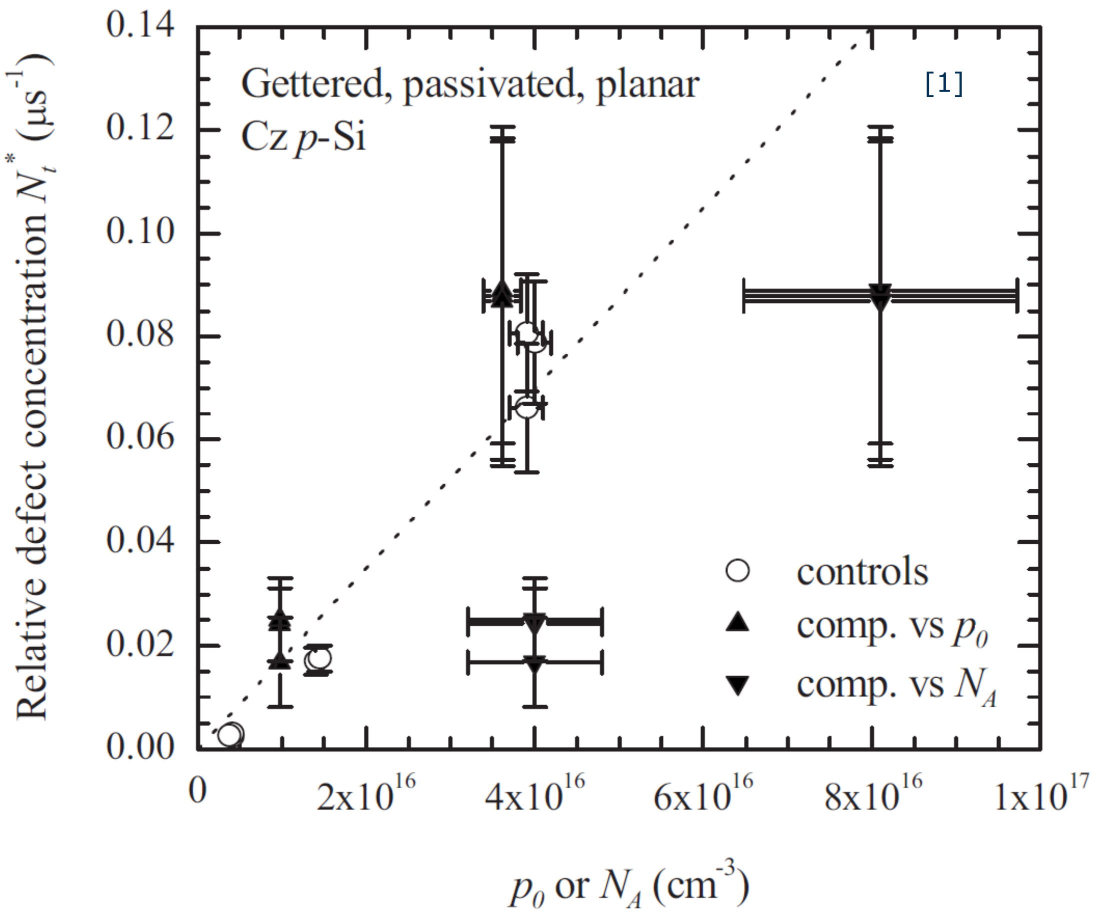


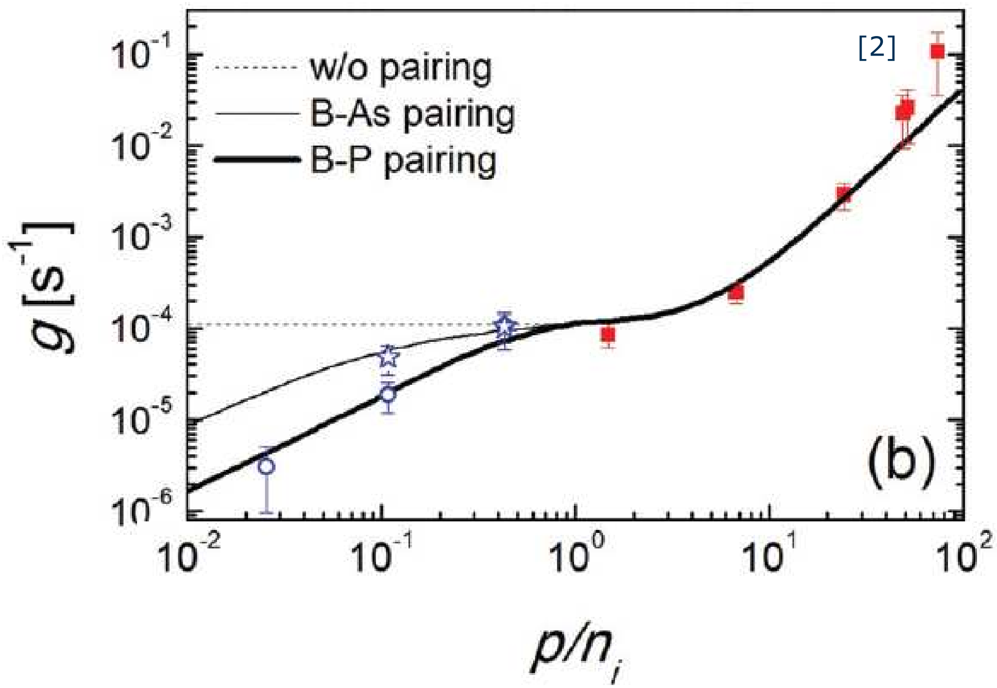


[1] Glunz et al., 2nd WCPVSEC, Vienna, 1343 (1998)
[2] Gösele, Appl. Phys. A **28**, 79–92 (1982)
[3] Akhemetov et al. Phys. Stat. Sol. A **72**, 61 (1982)
[4] Bean et al. J. Phys. C, Solid State Phys. **5**, 379 (1972)
[5] Borghesi et al., J. Appl. Phys. **77**, 4169 (1999)

- Defect density correlates with interstitial oxygen concentration in CZ silicon (large spread for correlation function in literature)
- O_i precipitates during CZ crystal cooling ($2O_i$ -> Si_i [2])
- Defect density and nucleation rate show similar dependence on oxygen concentration [1,5]
- Si_i migrates to substitutional boron and forms B_{Si}-Si_i [3,4]

Dependence on hole-density





- Defect density is proportional to the hole density [1]
- B_{Si}-Si_i generation rate increases with increasing hole density (measured at 700 °C) [2]

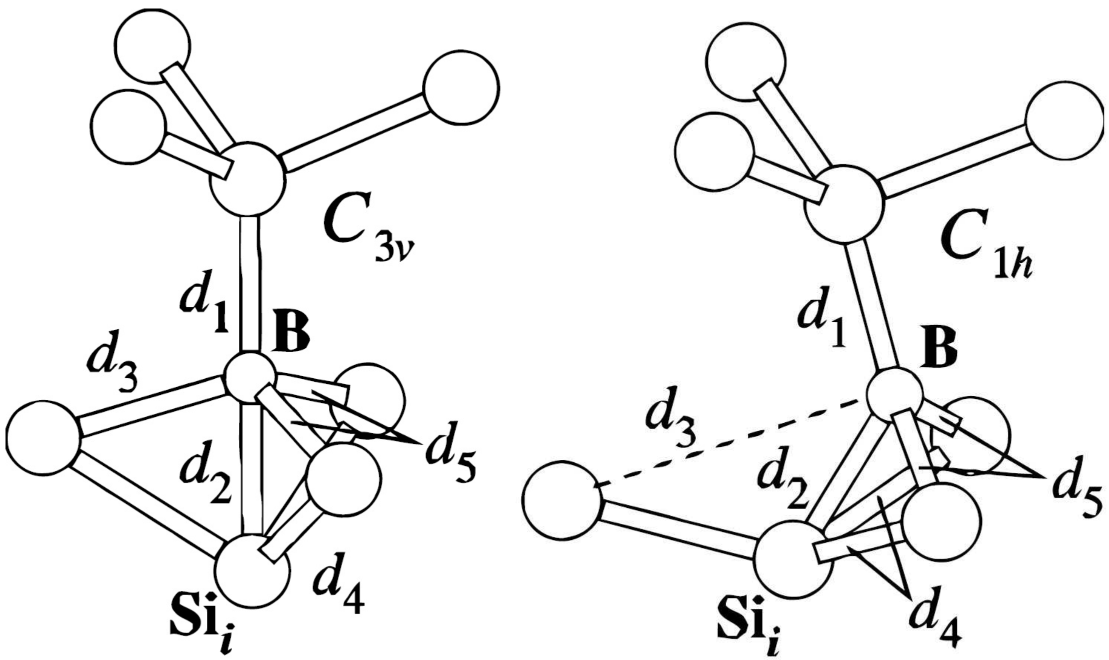
[1] Macdonald et al., J. Appl. Phys. **105**, 093704 (2009)
[2] Mirabella et al., J. Appl. Phys. **113**, 031101 (2013)

Defect kinetic

$$\left(\mathrm{B_{Si}}-\mathrm{Si_i}\right)^{+}+2e^{-}\rightarrow\left(\mathrm{B_{Si}}-\mathrm{Si_i}\right)^{0}+e^{-}\rightarrow\left(\mathrm{B_{Si}}-\mathrm{Si_i}\right)^{-}$$

$$\mathrm{C_{3v}}\rightarrow\mathrm{C_{3v}}\text{ or }\mathrm{C_{1h}}\rightarrow\mathrm{C_{3v}}\text{ or }\mathrm{C_{1h}}$$

- Fast process due to trapping of one electron by $(B_{Si}\text{-}Si_i)^+$
- Slow process due to thermal activated change of configuration from C_{3v} to C_{1h}



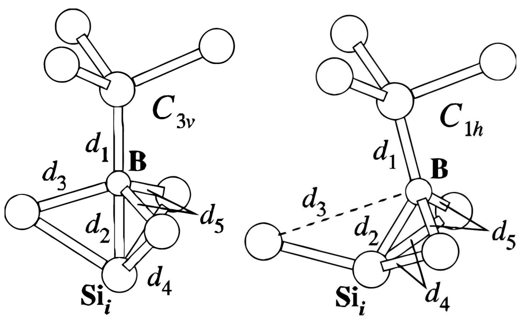
Hakala et al., Phys. Rev. B **61**, 8155 (2000)

Conclusion / outlook

- LTPL, LTFTIR and carrier lifetime measurements used at CiS for defect analysis
- Investigation of defects during detector processing to realize defect engineering planned

- Degradation of carrier lifetime in boron doped silicon by an electronically activated defect
- Similar defect found in indium-doped silicon
- Defect model proposed based on an acceptor silicon interstitial pair (A_{Si}-Si_i)
- Observed properties of defect can be explained by A_{Si}-Si_i-defect model

- Proof of model is missing
- Maybe possibility to generate defect by electron irradiation and look at the defect using state of the art lifetime measurements?
- Investigating effect of defect on n-in-p radiation detectors



Thank you for your kind attention!

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J. Weber
N. Abrosimov (IKZ Berlin)
A. Laades

xµ-Material (03SF0398A)

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