Unleashing the Actual Potential of FZ Si and its Application for Defect Studies

Some results from our Research on FZ Silicon

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University of New South Wales
Sydney, Australia
November 21st 2018

AGENDA

- Fraunhofer ISE and the University of Freiburg

- Studies on Float Zone Silicon
  - Limitation-free Reference Material?
  - Improvement of FZ Silicon
  - Surface Passivation Layers
  - Defect Investigation: LeTID

Fraunhofer ISE
At a Glance

Institute Directors:
Prof. Dr. Hans-Martin Henning
Dr. Andreas Bett

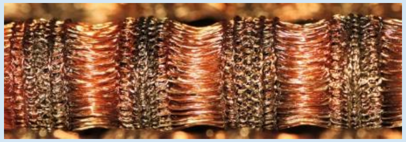
Staff: ca. 1200

Budget 2017: €89.2 million

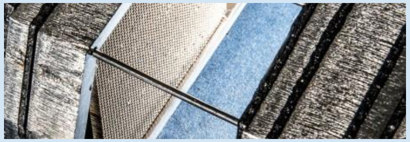
Established: 1981

Photovoltaics

Solar Thermal Technology



Building Energy Technology



Hydrogen Technologies

Energy System Technology

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Silicon Crystal Growth

Material Characterisation

Solar Cell Development

Module Implementation

Albert Ludwig University of Freiburg
At a Glance

11	Faculties
100	Institutes & Departments
~200	Fields of Study
19	Research Centers

Freiburg Materials Research Center

Albert Ludwig University Freiburg

UNI FREIBURG

Students:	>25.000
University Staff:	ca. 7.000 (~4800 academia)
Budget 2016:	~€340 million
Established:	1457

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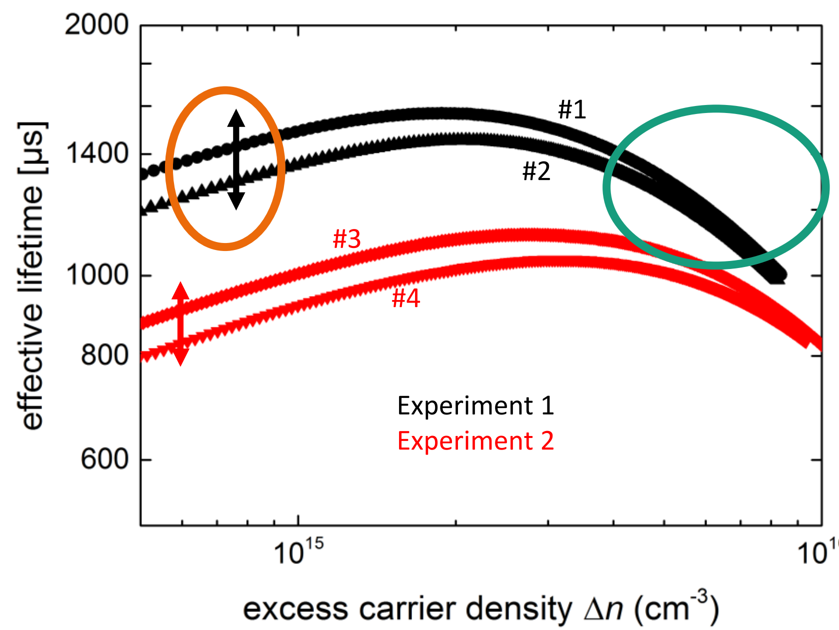
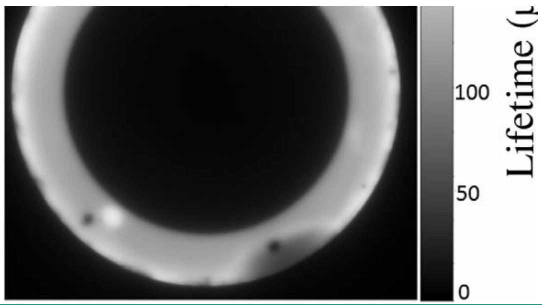
Float-Zone Silicon
Limitation-free Reference Material?

- FZ is often not a great reference
  - High purity
  - Stable quality
    - High bulk lifetime
    - No process interactions



- Characteristic pattern
- Defects not present after high T step

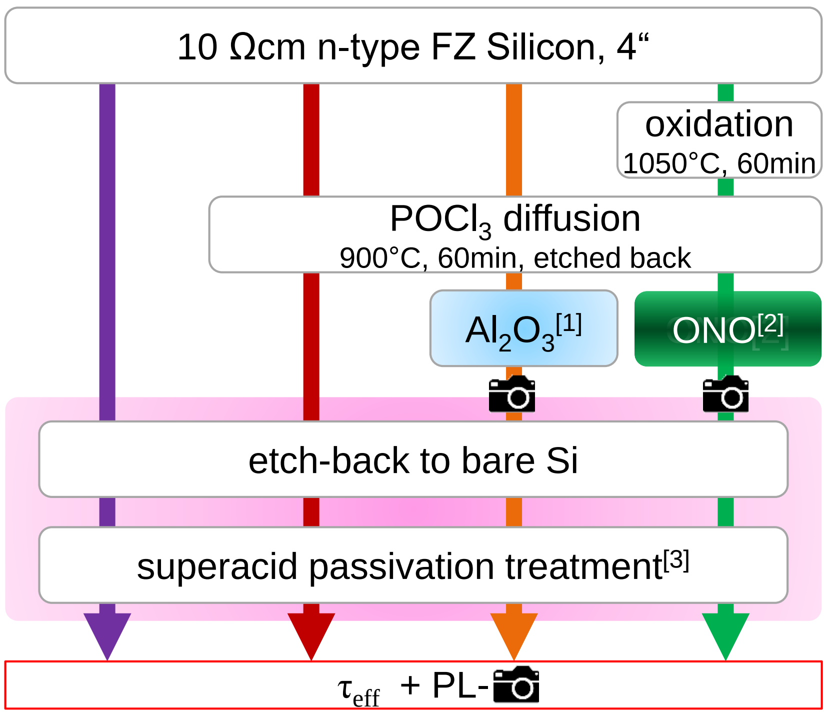


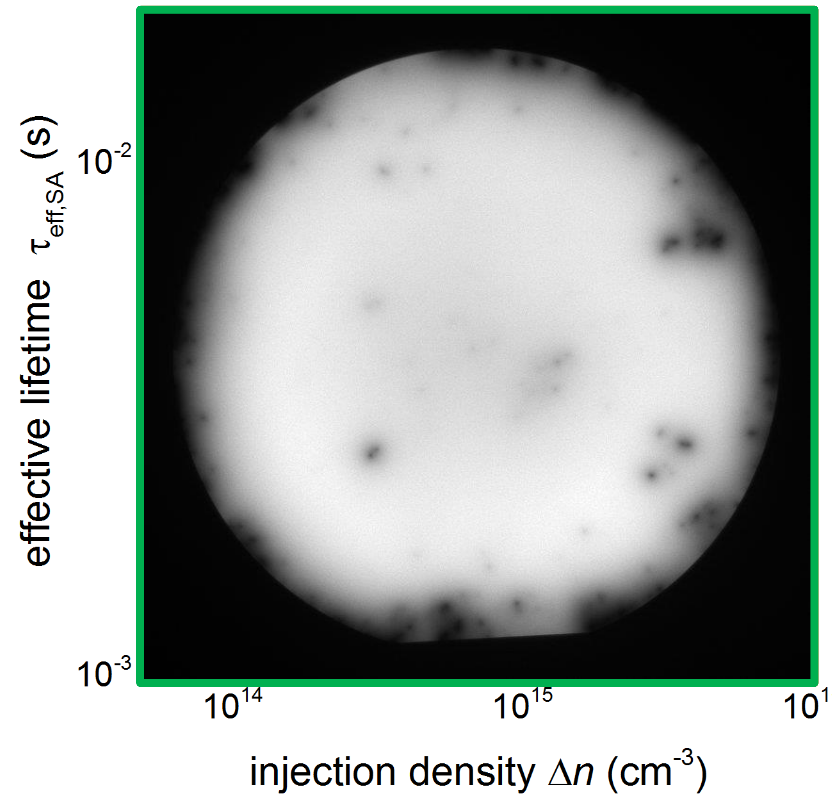
[1]: N.E. Grant et al., pss RRL **10** (2016)

In cooperation with:

Float-Zone Silicon

Improvement of FZ Silicon





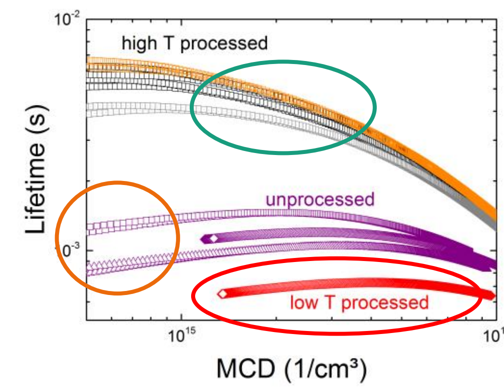
[1]: Richter et al., IEEE JPV **3** (2013)
[2]: Kho et al., SolMat (online 2018)

Float-Zone Silicon

Improvement of FZ Silicon

<u>Findings on bulk improvement:</u>

- Defects can be present in as-grown wafers
- Typical processing affects the defects
- Defects can be deactivated with pre-treatment
- Only stabilised FZ wafers are good references



FZ wafers → pre-treatment → experiment

any oxidation >1000°C
etch-back oxide

short route

60min oxidation @1050°C
etch-back oxide
60min $POCl_3$ diffusion @900°C
etch-back diffused region

recommended

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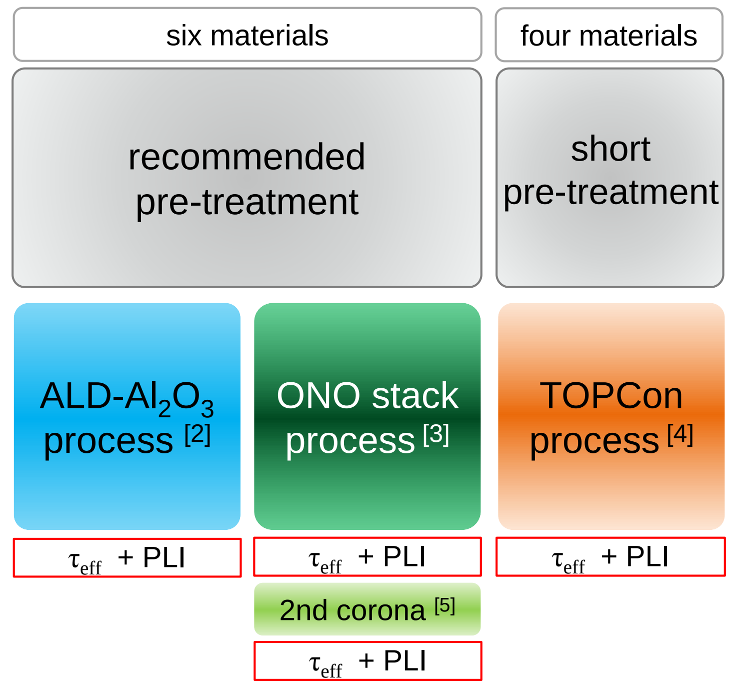
In cooperation with: Australian National University, University of Oxford

Float-Zone Silicon
Surface Passivation

Demonstration study (see paper for details[1])

- Commercial p- & n-type FZ materials
  - 3x p-type: 0.5, 1, 100 Ωcm
  - 5x n-type: 1, 1.5, 5, 10, 100 Ωcm
  - Stabilisation pre-treatment
- 3 state-of-the-art passivation schemes
  - ALD Al_2O_3 layers[2]
  - ONO stack[3] +
  - TOPCon passivation[4]
- QSSPC & PL-Imaging



[1]: Niewelt et al., SolMat **185** (2018)
[2]: Richter et al., IEEE JPV **3** (2013)
[3]: Kho et al., SolMat (online 2018)
[4]: Steinhauser et al., solarRRL **142** (2018)
[5]: Bonilla et al., J.Appl.Phys. **121** (2017)

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Float-Zone Silicon
Surface Passivation

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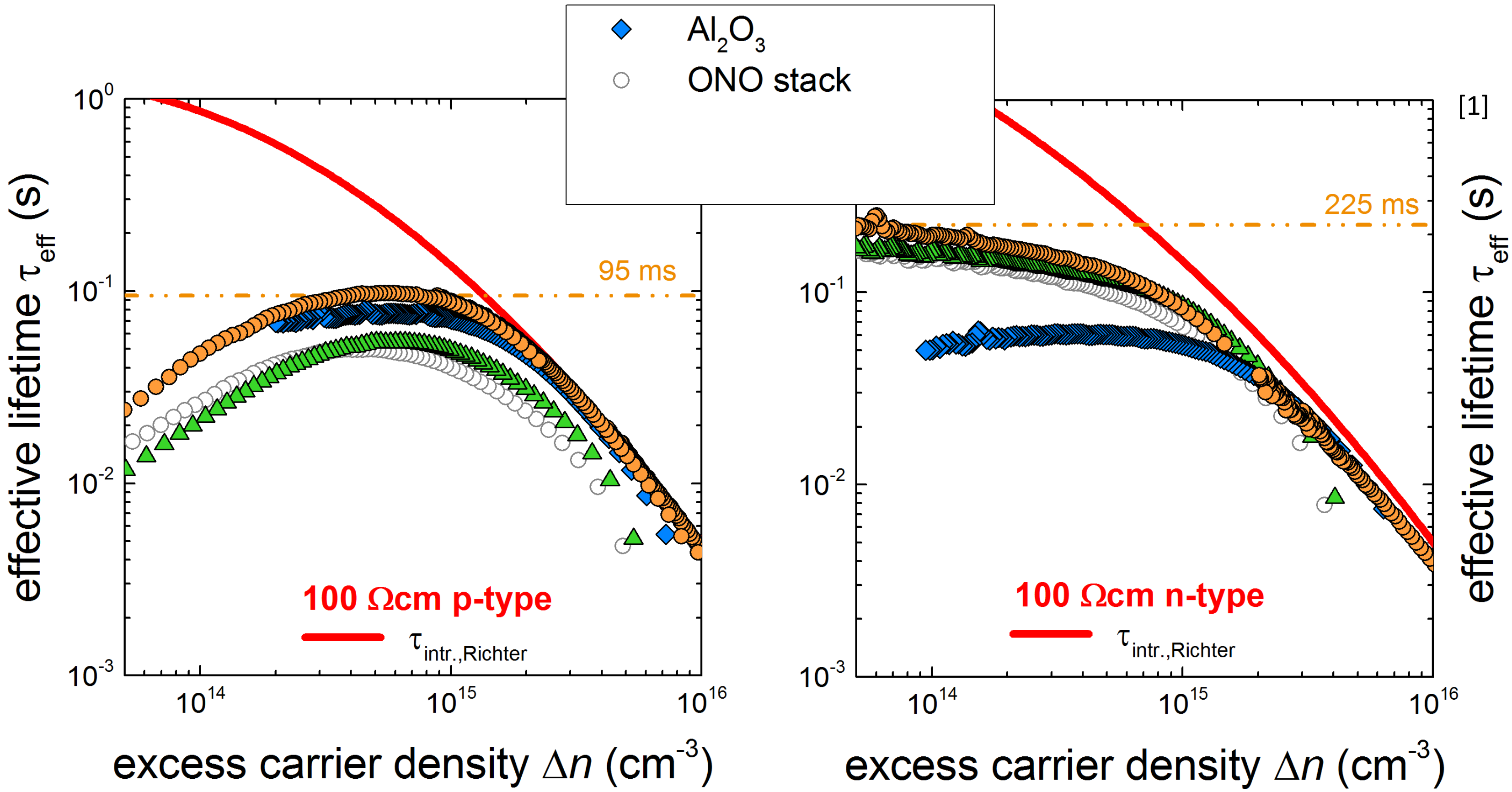
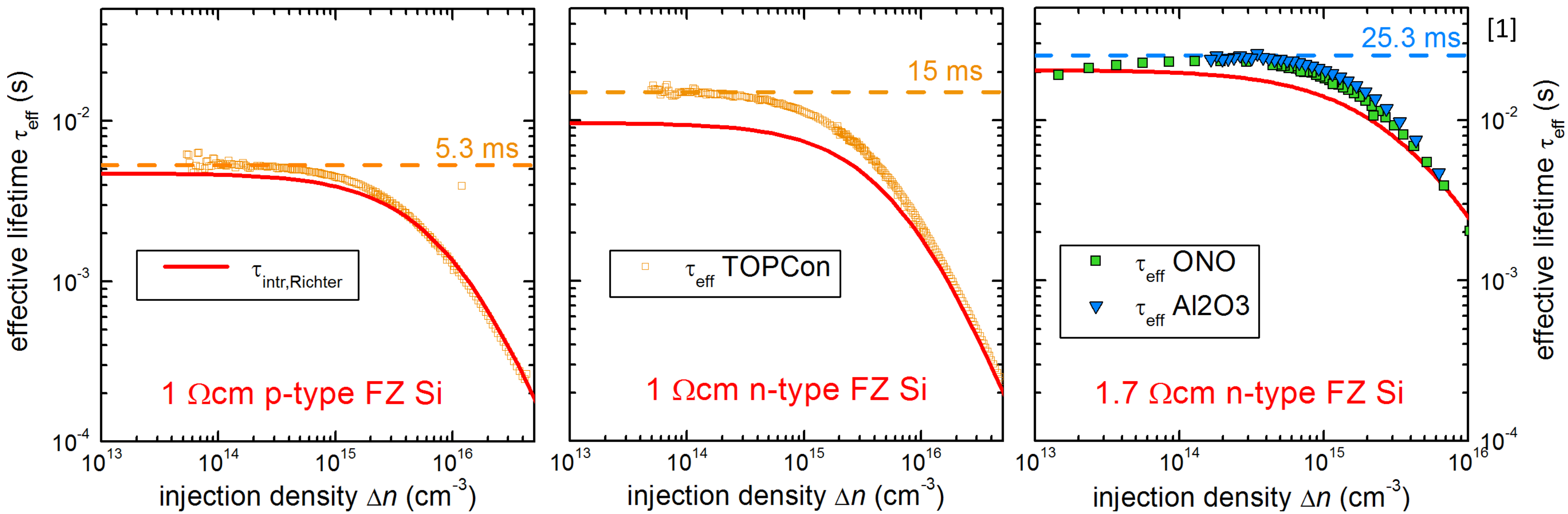


[1]: data from Niewelt et al., SolMat **185** (2018) 252-259

Float-Zone Silicon
Surface Passivation

- Excellent effective lifetimes achieved after pre-treatment
- $\tau_{intr,Richter}$ exceeded significantly on typical resistivities for solar cells[1]
  - Determination of S_{eff} or J_0 values not meaningful



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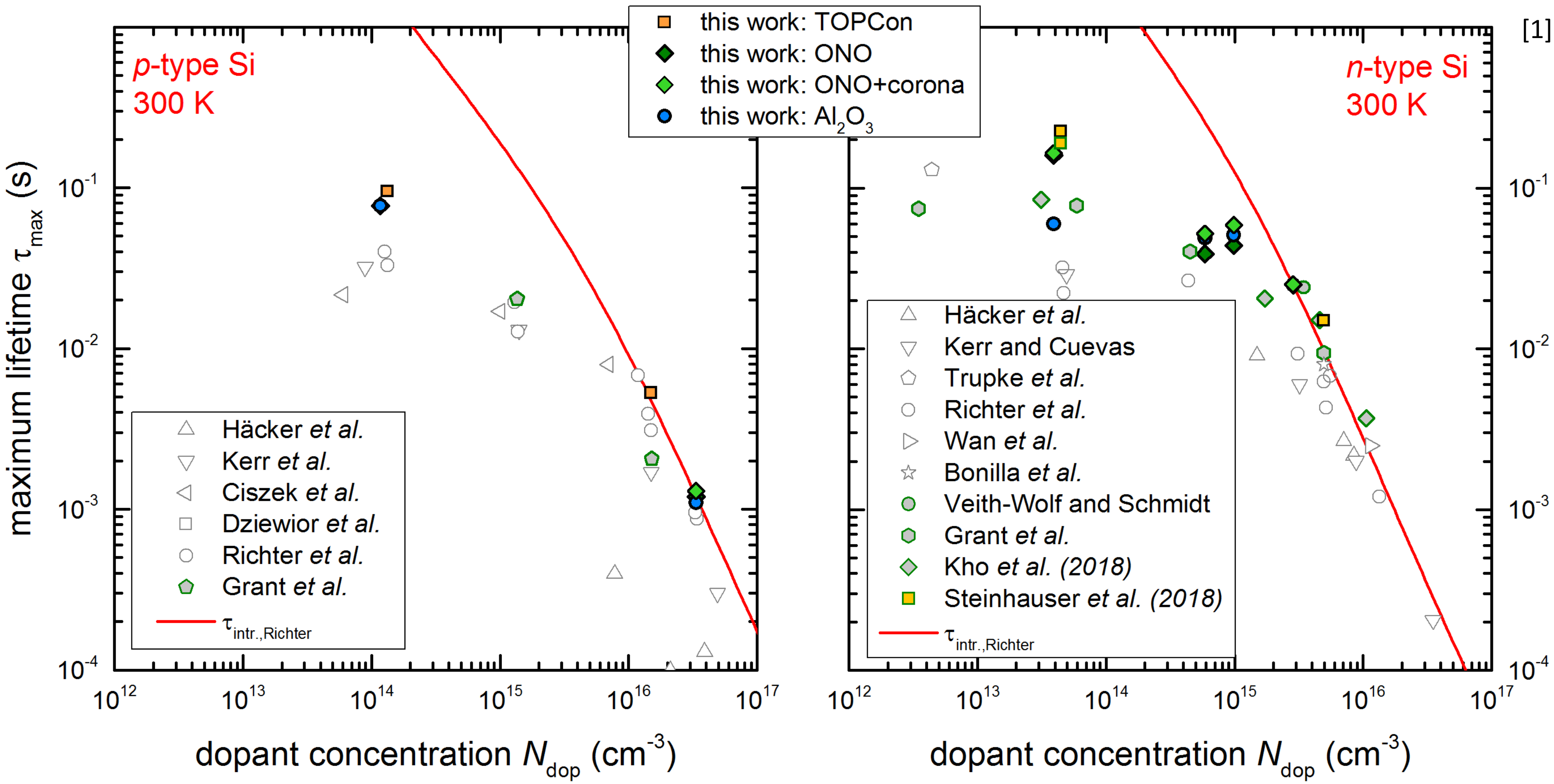
In cooperation with:

Float-Zone Silicon

Surface Passivation



[1]: Niewelt et al., SolMat **185** (2018) 252-259

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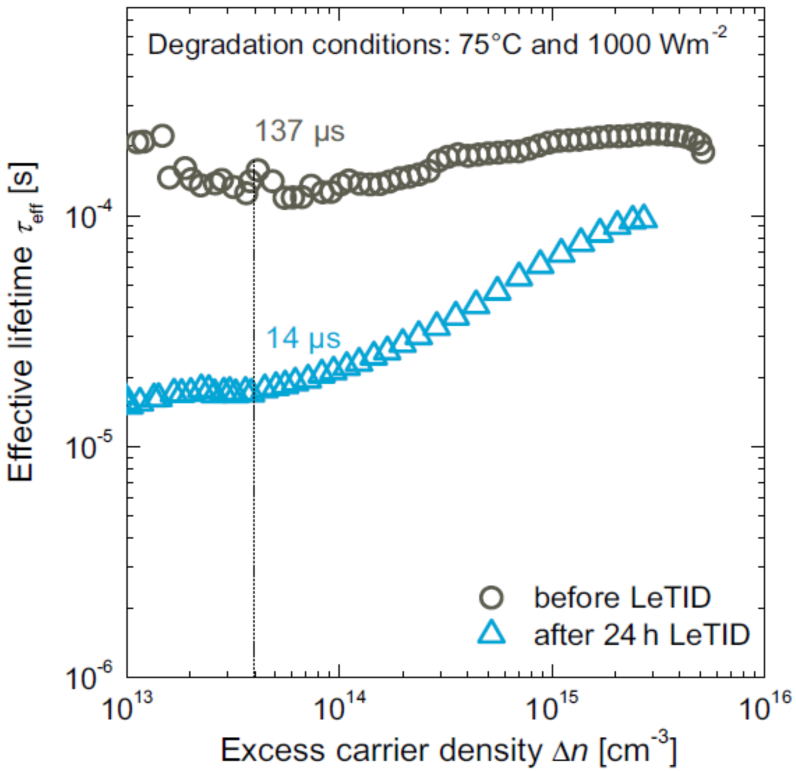
Float-Zone Silicon
Defect Investigations: LeTID

- Severe performance loss in the field on PERC modules processed from multicrystalline silicon
  - Adapted processes help*
  - Followed by recovery

- PERC process:
  etched clean Wafer
  ⇨ Diffusion ⇨ Dielectric Layers
  ⇨ Metalisation ⇨ Contact Firing

- SiN_x layers are important

- T_{peak} is crucial



[2]

[1]: Kersten et al., SiliconPV 2017

Float-Zone Silicon
Defect Investigations: LeTID

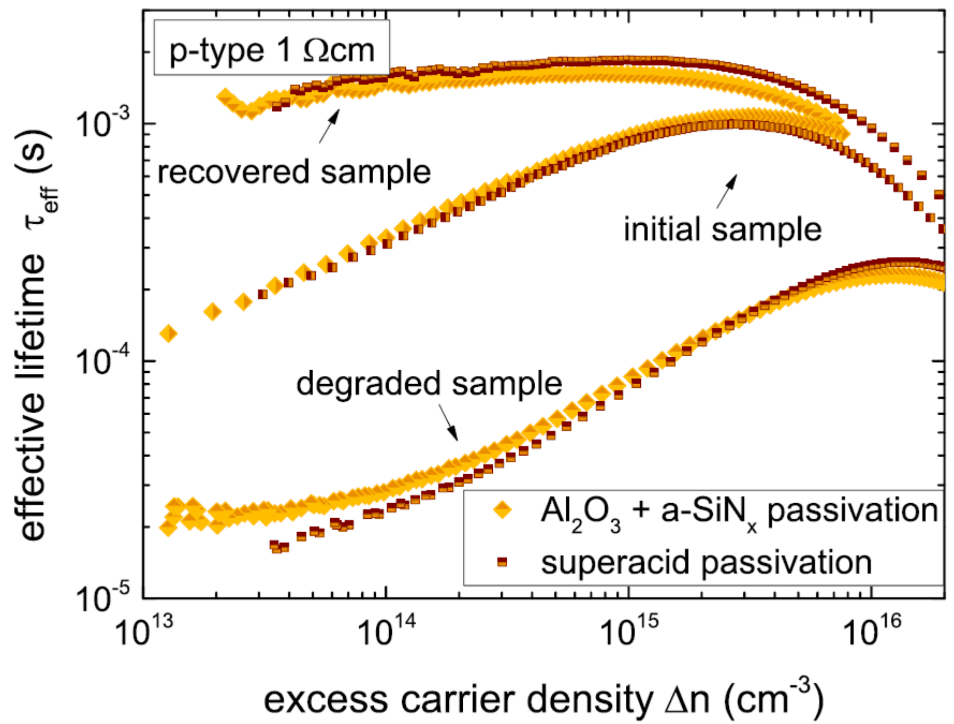
Impact of Bulk Wafer

- Associated with mc Si
  - most studies on mc
- LeTID observed in Cz [1]
  - dark annealing to avoid BO
- LeTID observed in FZ
  - Same characteristics

➡ occurs in all material types

➡ bulk defect caused by the PERC process

data from [2][2]

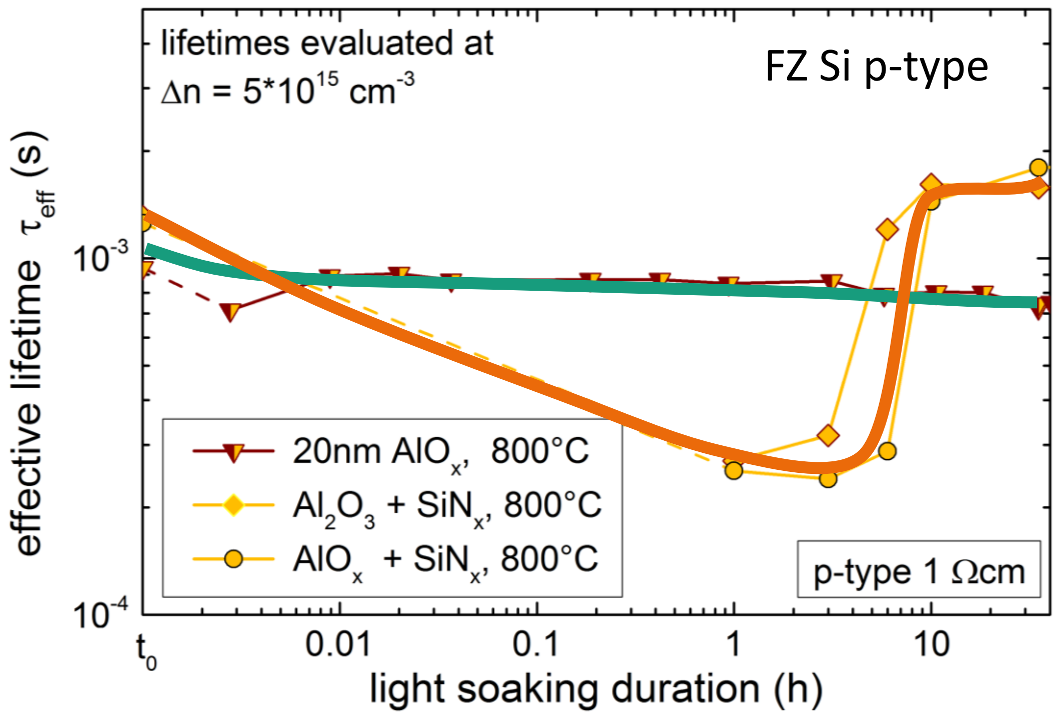


[1]: UNSW, e.g. Chen et al., SolMat **173** (2017) 293-300

Float-Zone Silicon
Defect Investigations: LeTID

Impact of Dielectric Layers

- Stacks including SiN_x degrade and recover (same for only SiN_x[2])
- Al_2O_3 alone shows no strong degradation



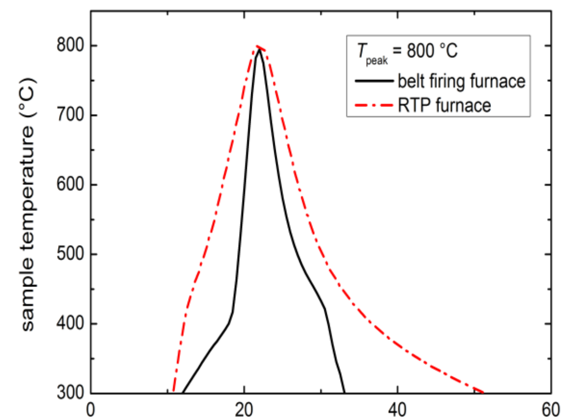
[1]

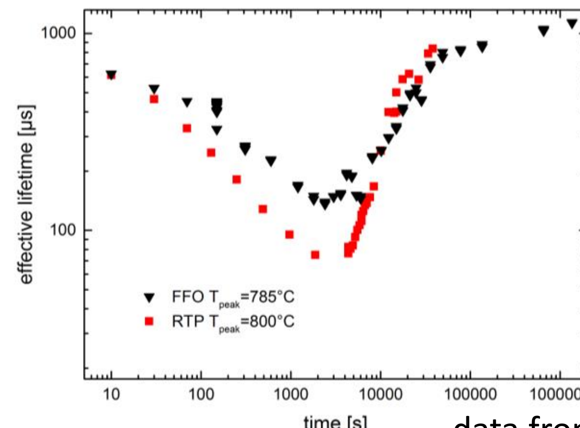
[1]: Niewelt et al., JAP **121** (2017) 185702

Float-Zone Silicon
Defect Investigations: LeTID

Impact of Firing Step

- LeTID depends on T_{peak}, sets in at ~600°C [1]
- Fast firing necessary on mc[2]
  - no LeTID for RTP profile
- LeTID for both profile types on FZ
  - Extent similar (still correlates with T_{peak})





data from [2]

[1]: Chan et al., JPV 6 (2016)

Float-Zone Silicon
Defect Investigations: LeTID

Gathered criteria:

- Can be present in all material types
  - FZ more defined than mc & FZ
- Introduced during firing
  - Fast diffusor (denuded zones, activated by electrons)
  - SiN_x-layers necessary
  - Firing profile important (less so in FZ)

➡ Would all agree with suggested involvement of H [1,2]

➡ Involvement of C or O? [3] →

[1]: Niewelt et al., Prog. Photovolt. Res. Appl. **26** (2017)
[2]: UNSW, e.g. Ciesla et al. WCPEC 2018, Hawaii

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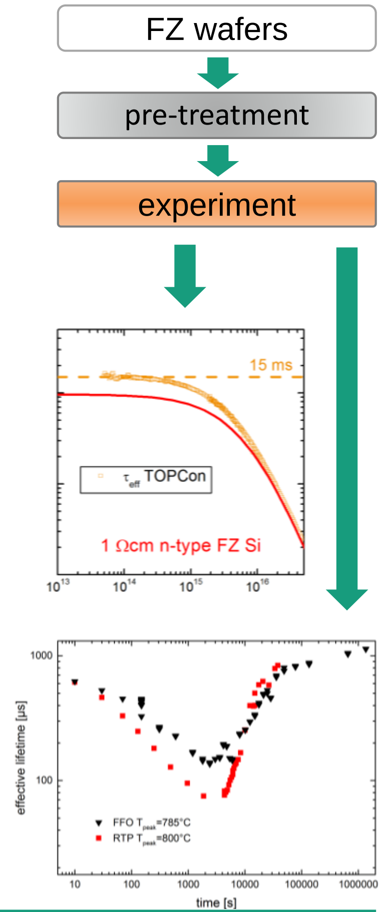
Conclusion

- FZ material often limited by grown-in defects
  - Affected by typical process steps ⇨ τ_{bulk} change
  - ➡ Wafers must undergo pre-treatment
- Record lifetimes achieved
  - ➡ 225ms on 200µm 100Ωcm n-type wafer
- $\tau_{intr,Richter}$ can be overcome
  - ➡ New parameterisation necessary
- FZ is a good model system for process-induced defects
  - ➡ LeTID could well be caused by H-related defects
  - Or by H+ intrinsic defects / omnipresent contaminants?



Acknowledgement

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Direct contributions to the presented work:

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University of Warwick: N.E. Grant, J.D. Murphy

University of Oxford: S. Bonilla

Australian National University: T.C. Kho

Thank you for your attention!
I'll be happy to discuss with you

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Fraunhofer Institute for Solar Energy Systems ISE
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Laboratory for Photovoltaic Energy Conversion

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Financial support by:

Federal Ministry of Education and Research

Federal Ministry for Economic Affairs and Energy

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ccpv Australia Germany

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Federal Ministry of Education and Research
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Proof of the FZ Bulk Improvement

Experimental details

Demonstration study (see paper for details [1])

- Commercial p- & n-type FZ materials
  - 3x n-type: 0.5, 1, 100 Ωcm
  - 5x n-type: 1, 1.5, 5, 10, 100 Ωcm
  - Stabilisation pre-treatment
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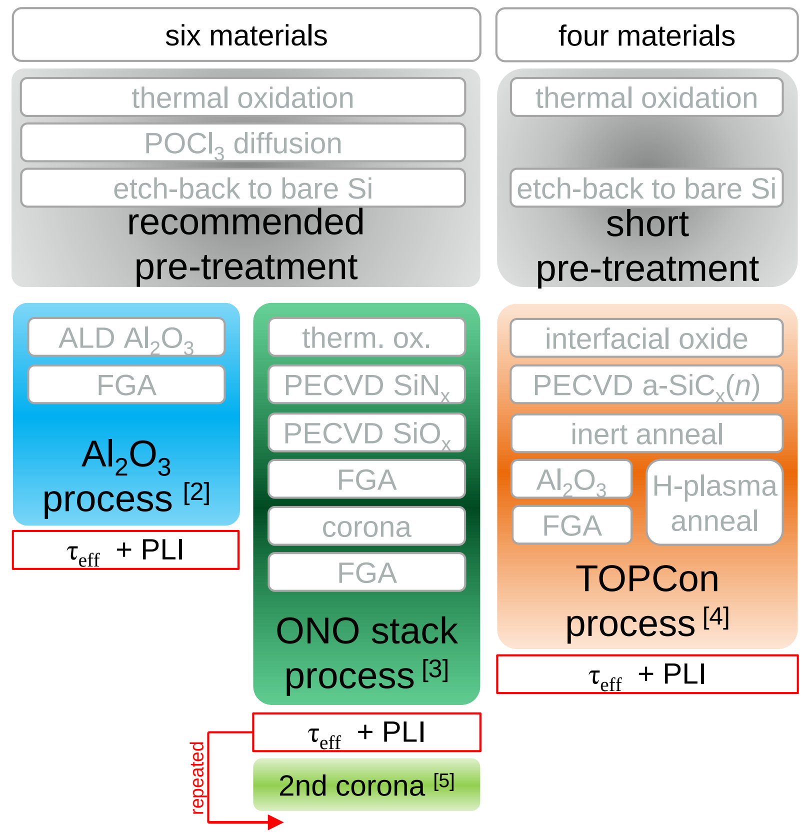

[1]: Niewelt et al., SolMat **185** (2018)
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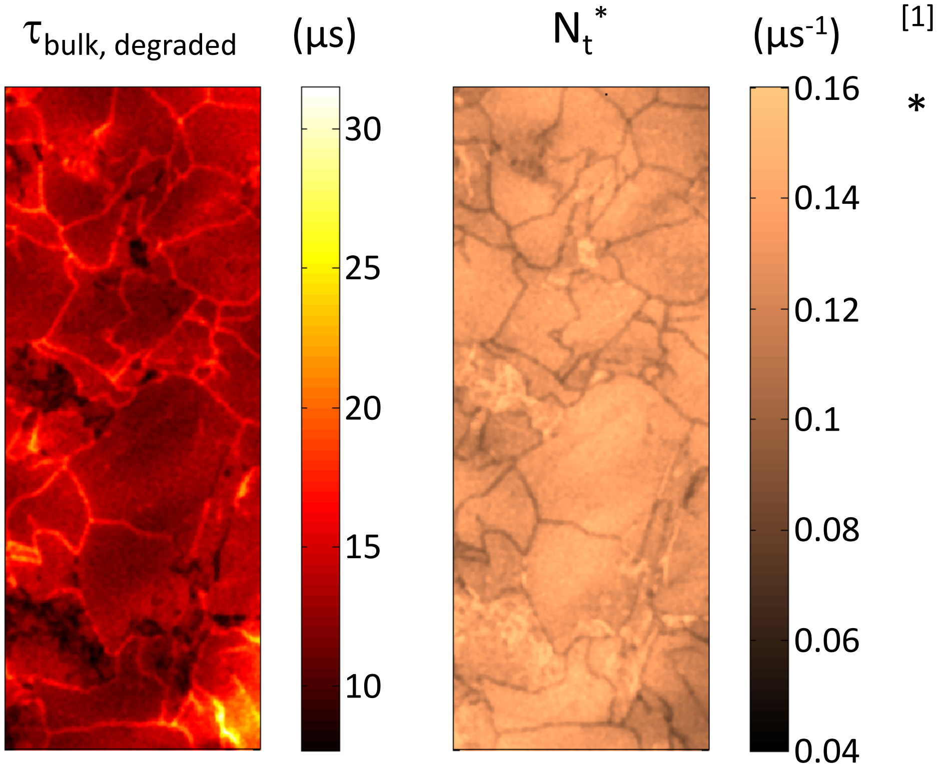
Float-Zone Silicon
Defect Investigations: LeTID

Multicrystalline Silicon

- Denuded zones with lower LeTID defect density
  - Determined zone width: 200-400 µm

➡ Indication for diffusivity of LeTID precursor component

➡ fast diffusers
→ Ni, Co, Cu, H, …



mc Si lifetime sample, fired at 900°C

[1]: Niewelt et al., Prog. Photovolt. Res. Appl. **26** (2017)

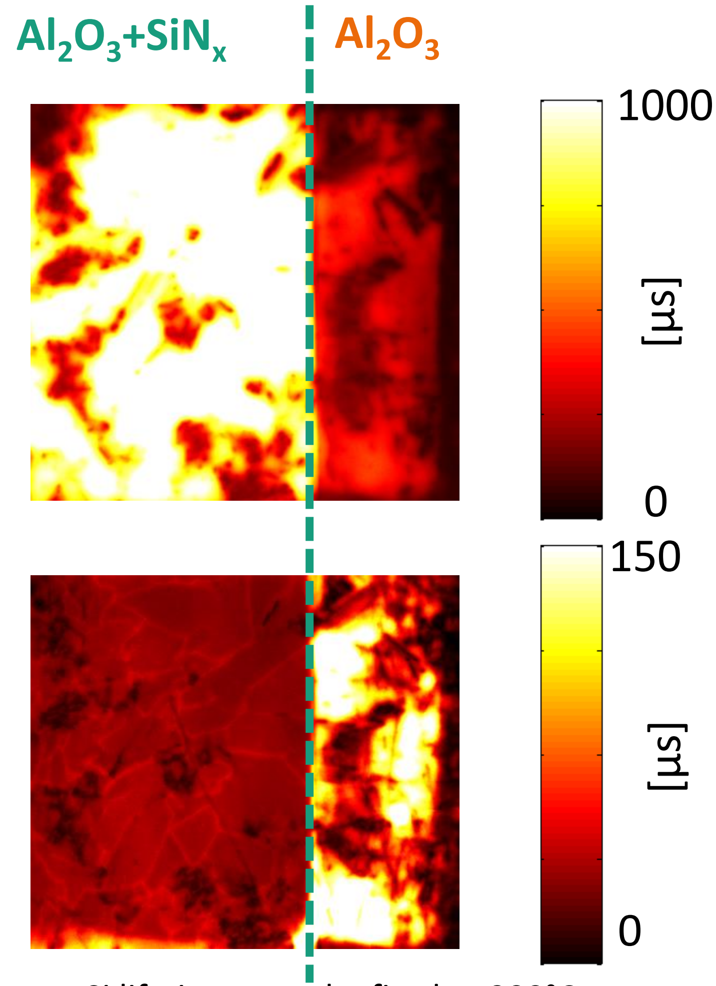
Float-Zone Silicon
Defect Investigations: LeTID

Multicrystalline Silicon

- Stacks including SiN$_x$ degrade and recover
- Al_2O_3 alone shows no strong degradation

initial

degraded



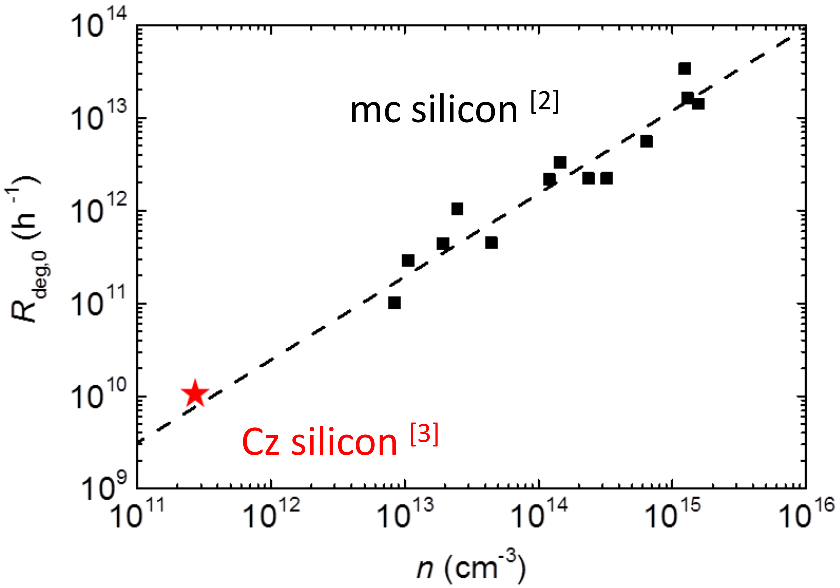
*

mc Si lifetime sample, fired at 900°C

Float-Zone Silicon

Defect Investigations: LeTID

- Influence of illumination intensity on degradation rate observed [1]
- Linear dependence of R_{deg} on Δn
  - mc: from current injection[2]
  - Cz: from dark annealing[3]



➡ Rate-limiting step of degradation involves an electron

➡ One involved species is recharged to allow defect activation

[1]: e.g. Bredemeier et al., SolMat **173** (2017), 80-84
[2]: Kwapil et al., SolMat **173** (2017), 80-84
[3]: Chen et al., SolMat **172** (2017) 293

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