FROM RESEARCH TO INDUSTRY

CHARACTERIZATION OF OXYGEN-RELATED DEFECTS IN CZOCHRALSKI SILICON WAFERS

CHEETAH Characterization Workshop 14-01-2015

J. Veirman, B. Martel, G. Raymond, N. Enjalbert, S. Dubois

SUMMARY

- **Context – moving towards more stringent material requirements**
- **Oxygen-related defects in silicon - a reservoir of lifetime killers**
- **Introduction to OxyMap**
- **Examples of applications**
- **Conclusion and outlook**

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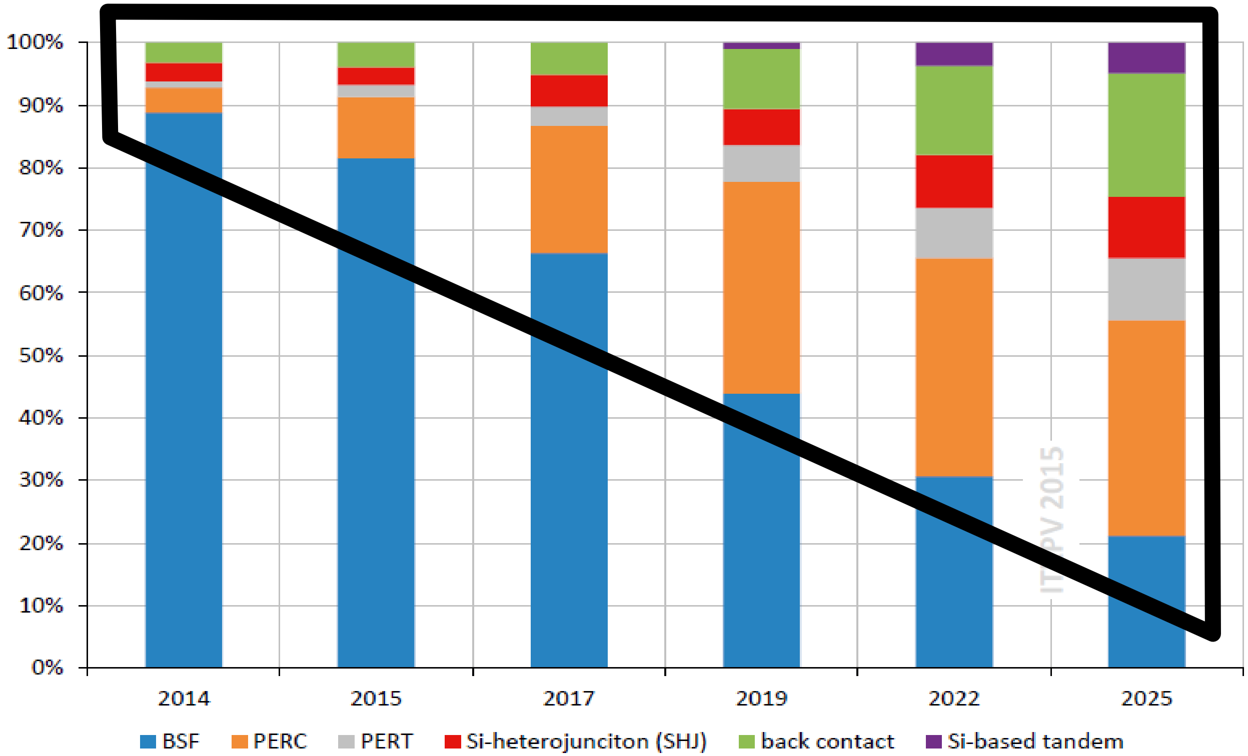
CONTEXT (1/2)

- **Higher efficiency cell technologies are entering the market**
  - Mostly on monocrystalline Czochralski wafers



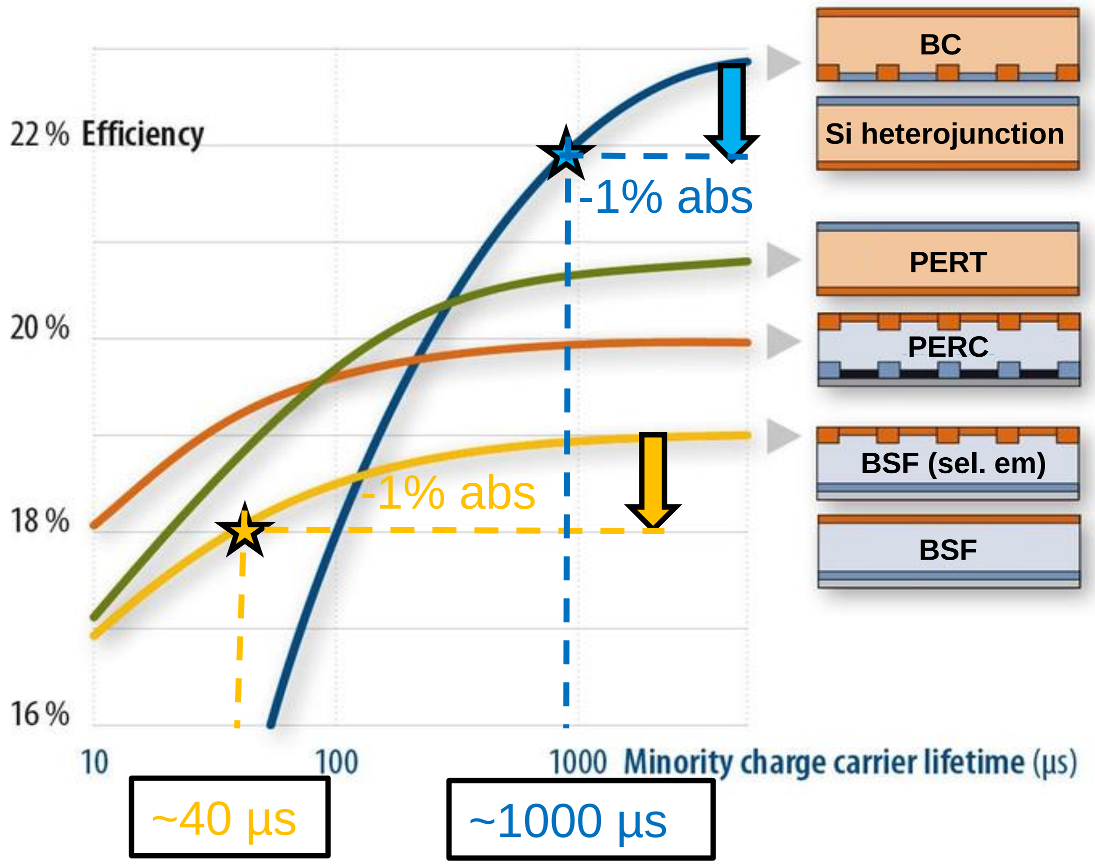
22% 22% NA 25% 26% NA

ITRPV expected mass production efficiency by 2025

Cz ingot

CONTEXT (2/2)

- **Require very high carrier lifetimes (τ) + less tolerance to medium/low quality wafers**

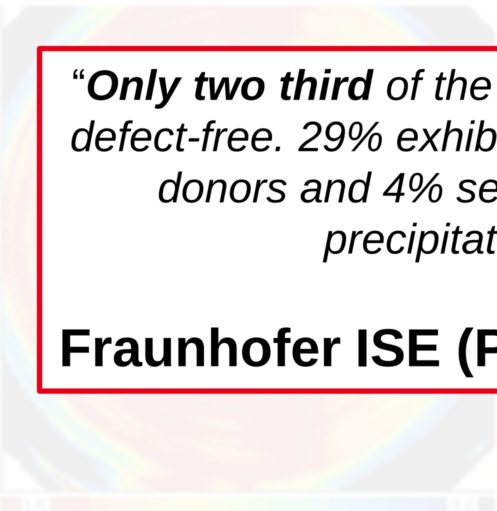


From R. Kopecek and J. Libal, *“Switch from p to n”*, *PV magazine*, **2012**.

OXYGEN-RELATED DEFECTS IN SILICON

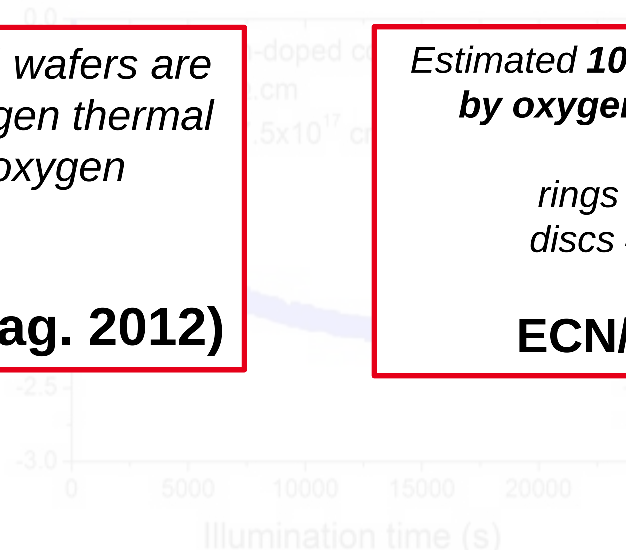
- Large oxygen (O) incorporation from crucible in Cz-Si ($1\text{-}15\times10^{17}$ cm^{-3})
- Interstitial oxygen (O_i) precursor of critical species for the industry

Oxide precipitates | **BO complexes** | **Thermal Donors**

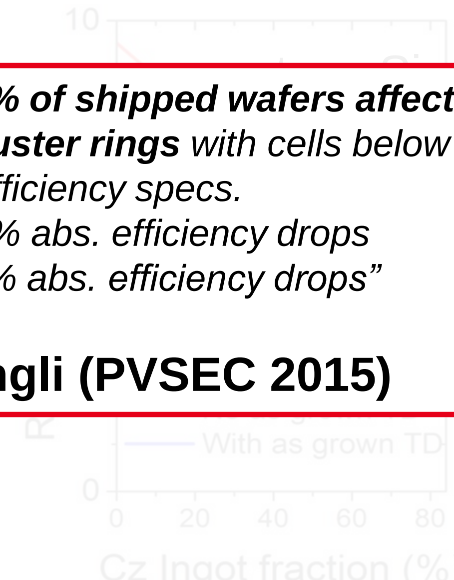


τ_{eff} center = 1 – 3,6 µs

Lifetime killers (black core)



Lifetime killers (LID)



resistivity shifters +lifetime killers

> "***Only two third*** *of the Cz-Si wafers are defect-free. 29% exhibit oxygen thermal donors and 4% severe oxygen precipitation*"
>
> **Fraunhofer ISE (PV Mag. 2012)**

> *Estimated* ***10-20% of shipped wafers affected by oxygen cluster rings*** *with cells below efficiency specs.*
> *rings 1-2% abs. efficiency drops*
> *discs 4-6% abs. efficiency drops"*
>
> **ECN/Yingli (PVSEC 2015)**

Other defects also concerned (Vacancy-O complexes, Nitrogen-O complexes)

- **Need to monitor [O_i] and O-related defects!**

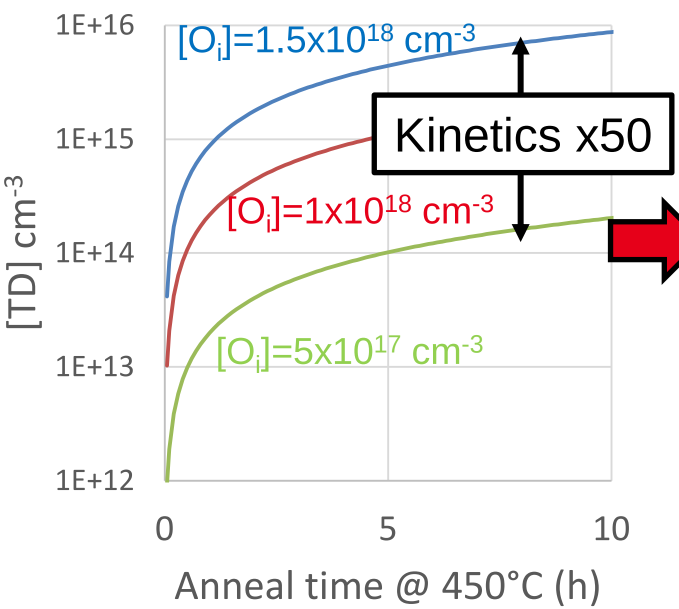
SUMMARY

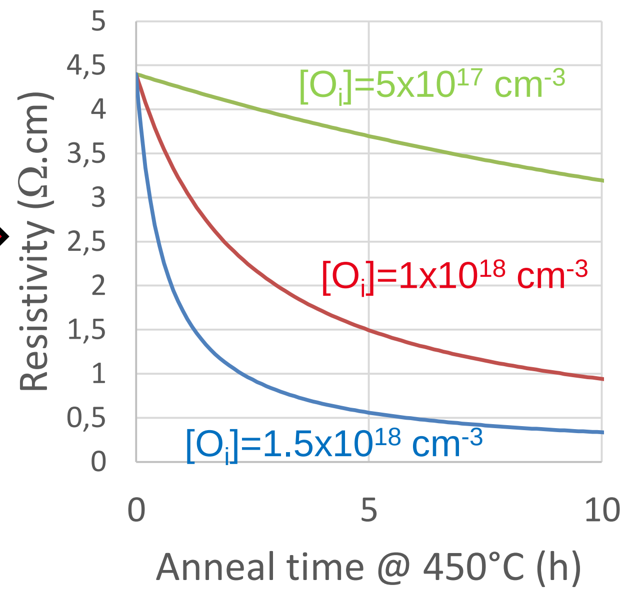
- Context – moving towards more stringent material requirements
- Oxygen-related defects in silicon - a reservoir of lifetime killers
- **Introduction to OxyMap**
- Examples of applications
- Conclusion and outlook

OXYMAP OVERVIEW

- **OxyMap relies on the change in resistivity (ρ) during an intentional formation of Thermal Donors**
  - Small O-related clusters formed at around 450°C
  - Double donors ➔ ρ shift
  - Unwanted ➔ Can be annihilated above 600°C

- **TD generation rate at 450°C highly dependent on $[O_i]$**

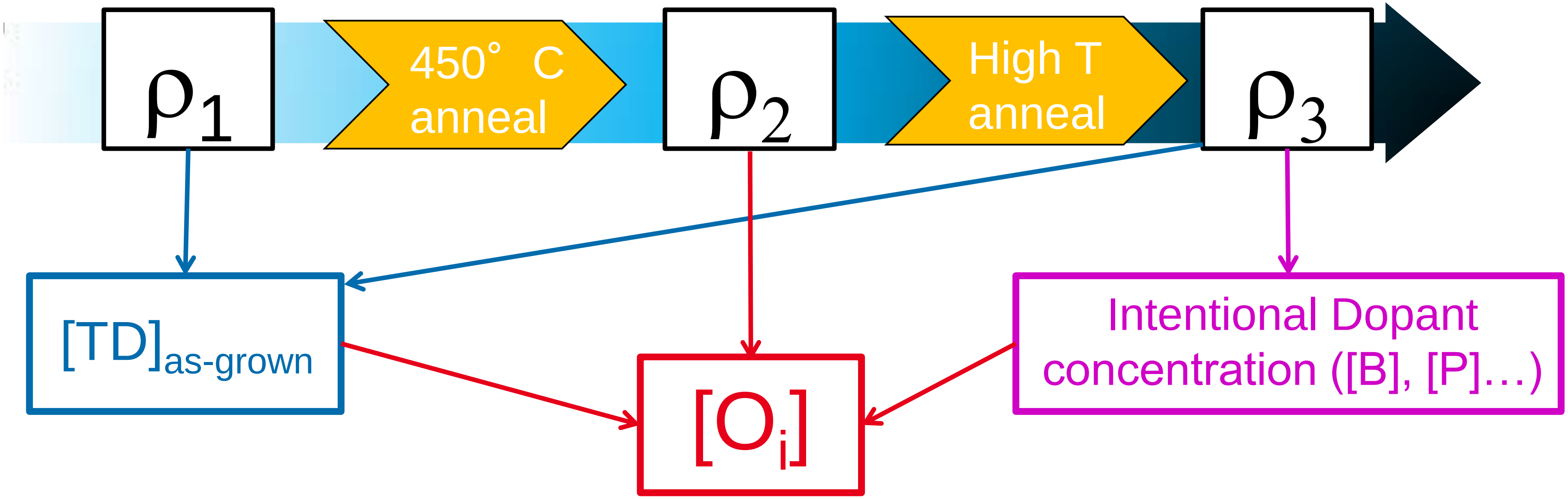




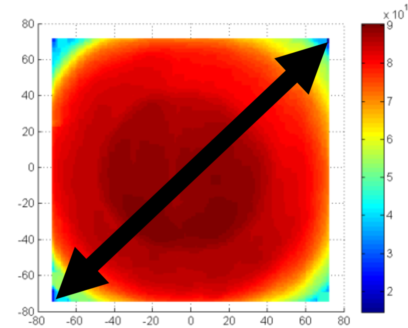
High sensitivity of the ρ shift on $[O_i]$ ➔ ground principle of OxyMap

OXYMAP OVERVIEW

All resistivity (ρ) measurements performed using non-contact Eddy currents
→ OxyMap is **non-destructive** and **independent of wafer morphology** (thickness or surface state)

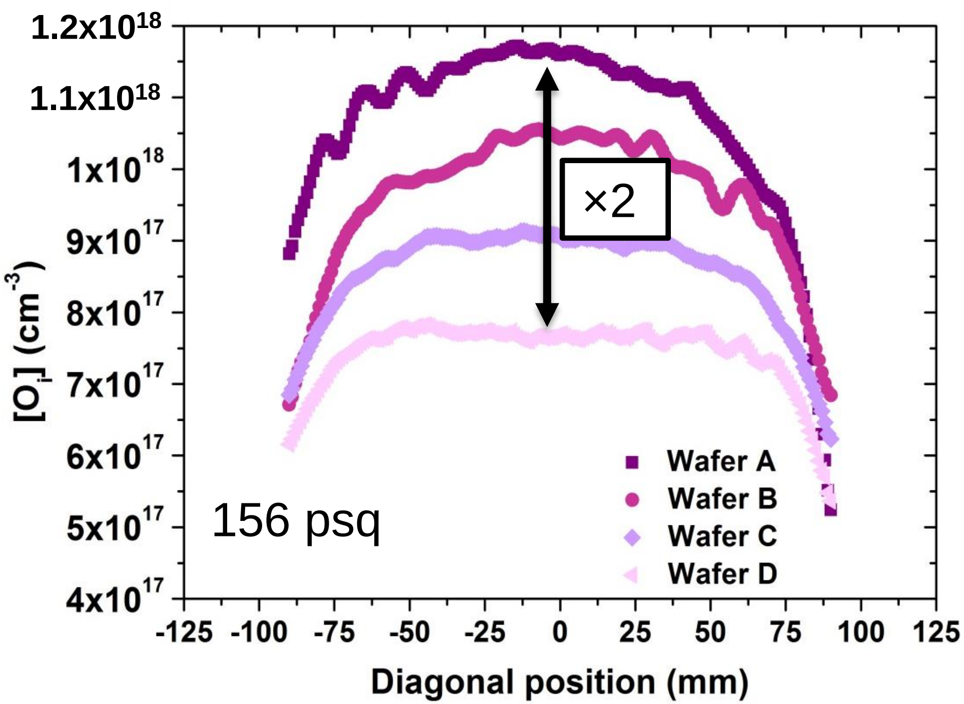


[OI] VARIATIONS MEASUREMENTS

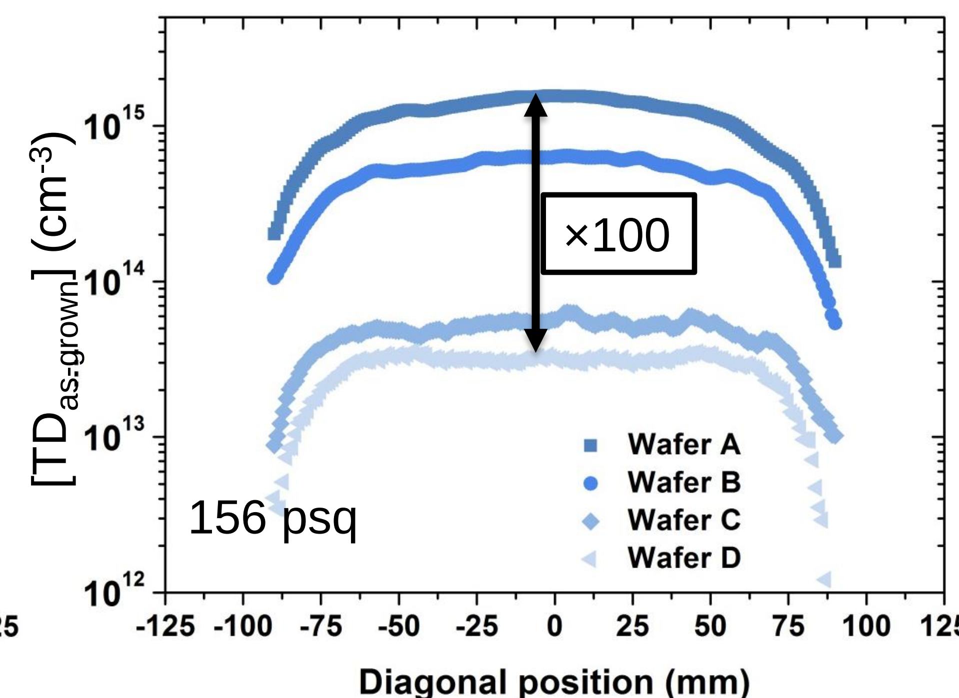


- **Linescans performed on the diagonal of the solar wafer**
  - *Due to the radial symmetry of the O-related defects distribution, linescans along the wafer diagonal are enough to thoroughly characterize a wafer*

$[O_i]$ diagonal scan

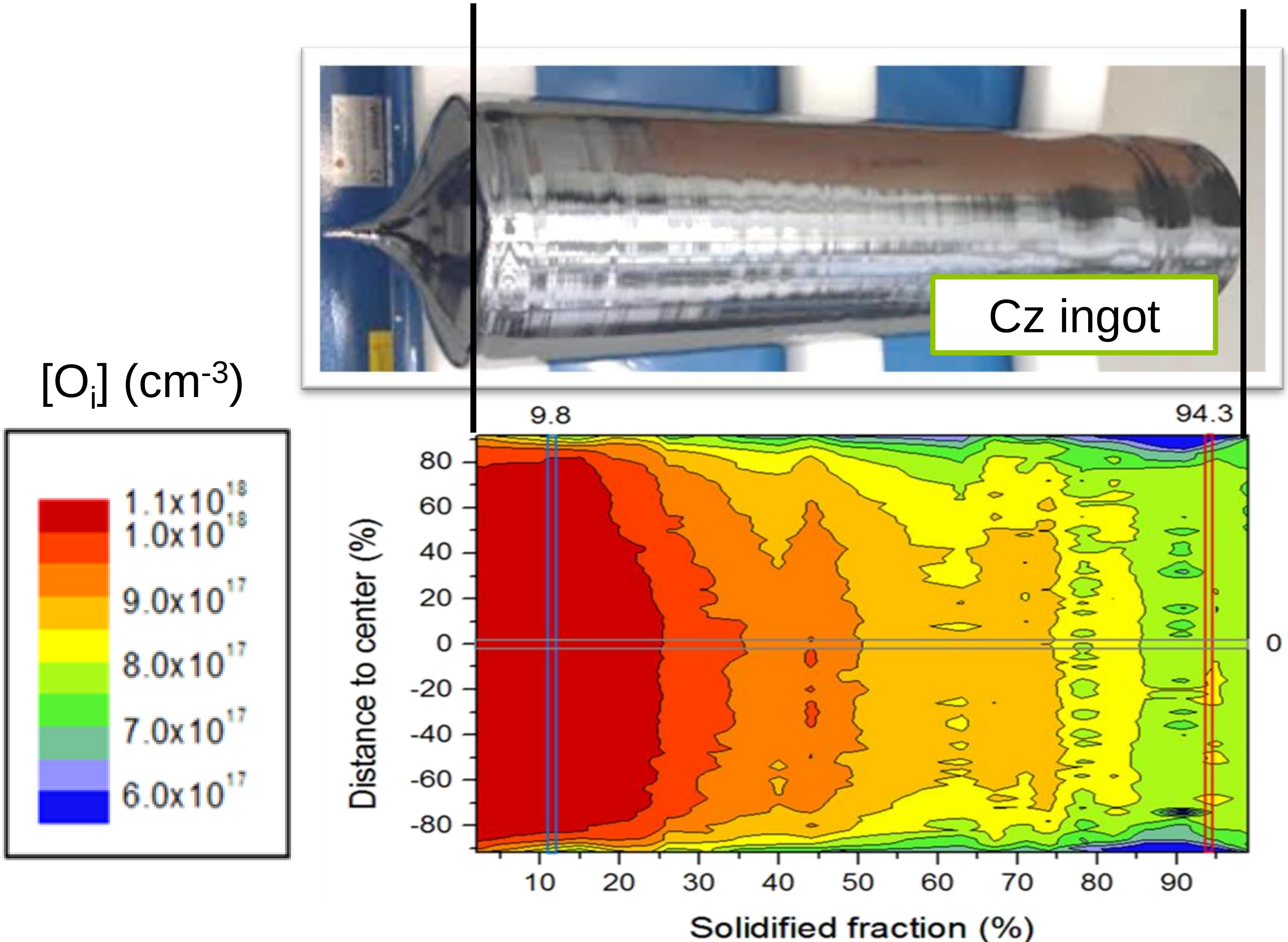


$[TD_{as\text{-}grown}]$ diagonal scan



FULL INGOT CHARACTERIZATION

- **Example : Reconstruction from 25 wafers scanned through an ingot**
  - Process control for routine products
  - Optimized feedback for R&D purposes

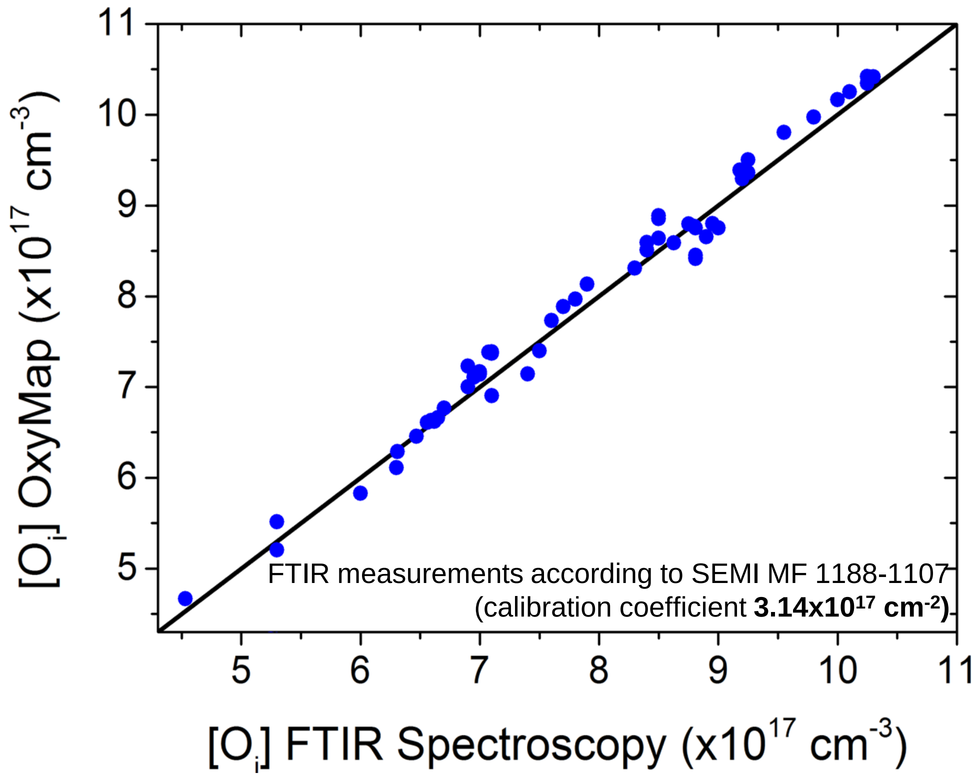


COMPARISON WITH EXISTING TECHNIQUES

- **Fourier Transform InfraRed spectroscopy (FTIR) routinely applied on thick polished slices (application to solar wafers tricky)**

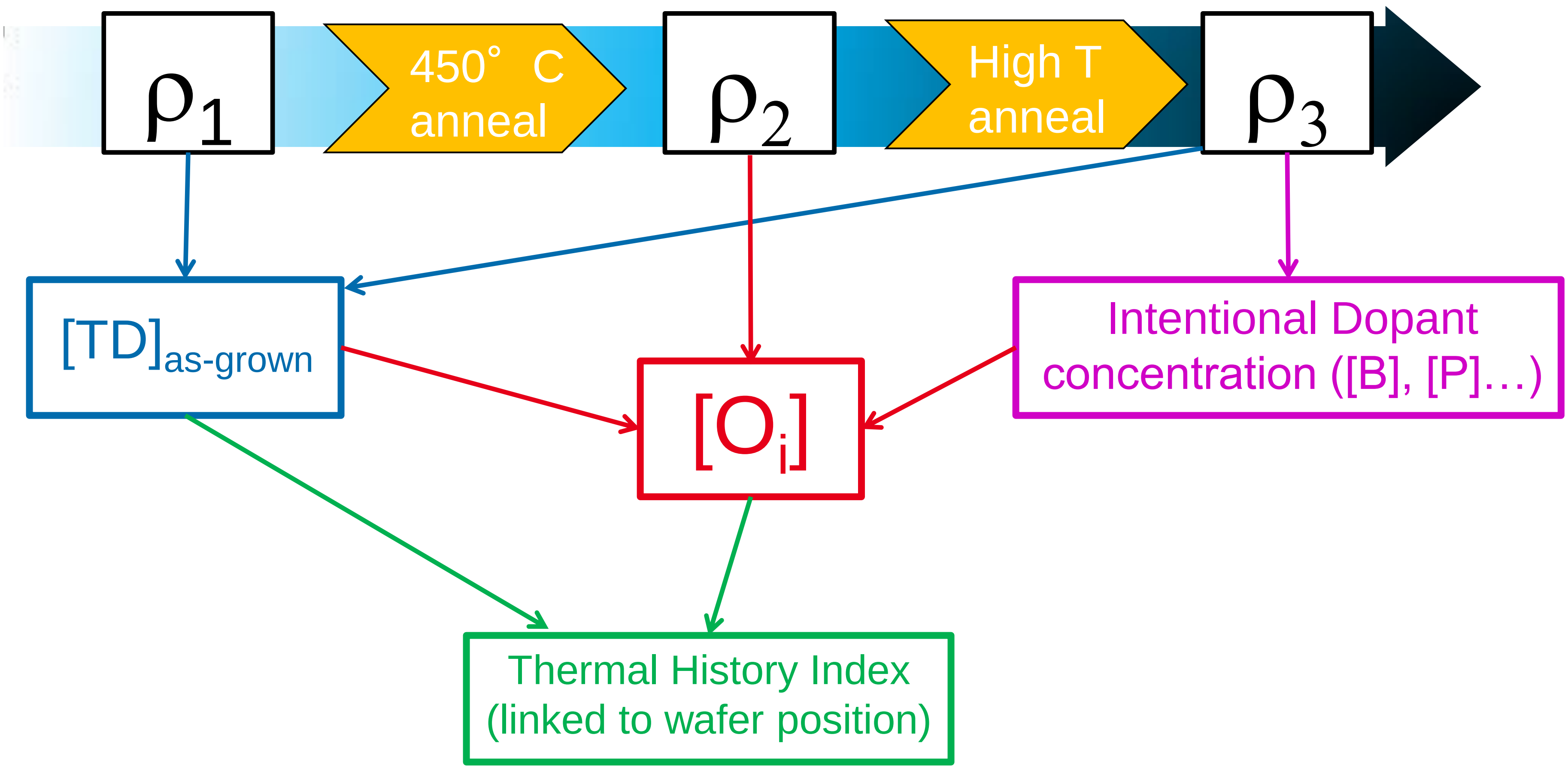
Various samples used for the comparison

- 2 mm thick p and n type samples
- Resistivity 0.5 - 10 Ω.cm
- Top, middle and bottom ingots (different thermal histories)
- Different Cz pulling parameters (seed and crucible rotation speeds, pulling speed)
- $[O_i]$ covering the whole Cz range



Very good agreement between OxyMap and FTIR measurements
Confirmed by tests made for industrial partners

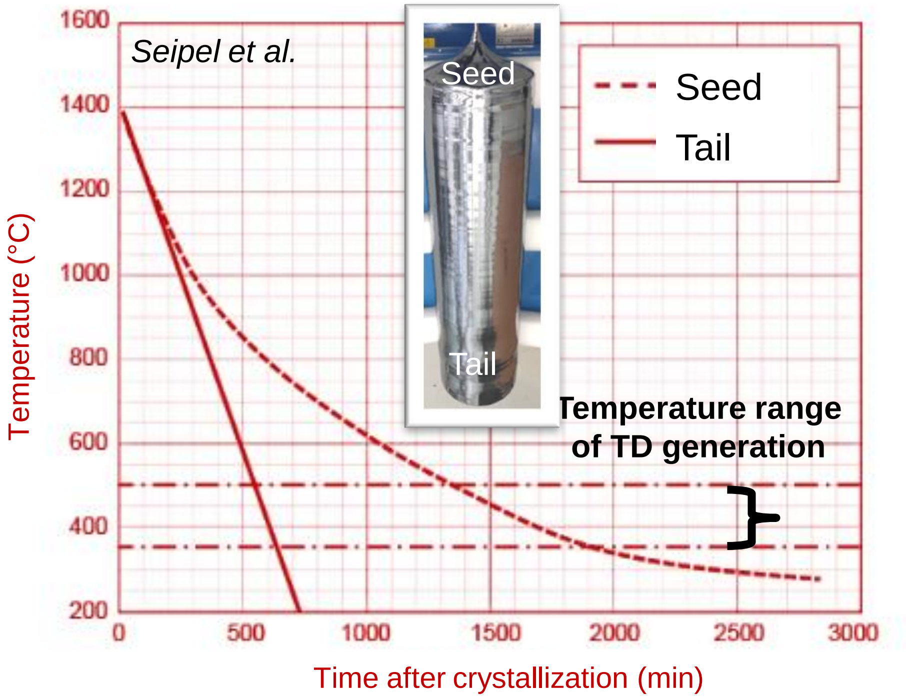
OXYMAP OVERVIEW



THERMAL HISTORY : DEFINITION

- $[O_i]$ = driving force for O-defects formation
- Thermal history : T=f(t), governs the amplitude of formation
  - Larger thermal histories = larger [defects]

Thermal history strong function of height



Thermal History Index (THI)

$$THI \approx \frac{1}{60}\left(\frac{[TD]_{as-grown}}{k_t \times [O_i]^{3.44}}\right)^{\frac{1}{1.02}}$$

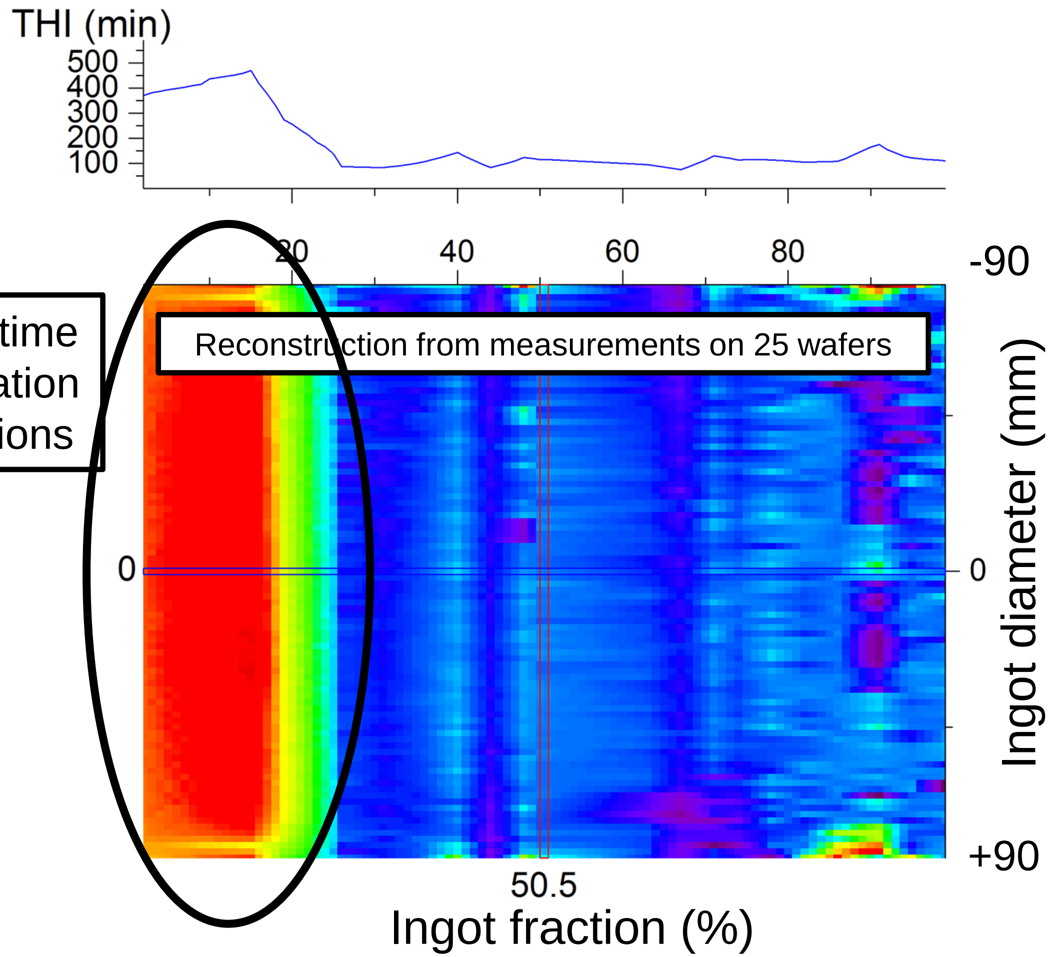
Measured with OxyMap

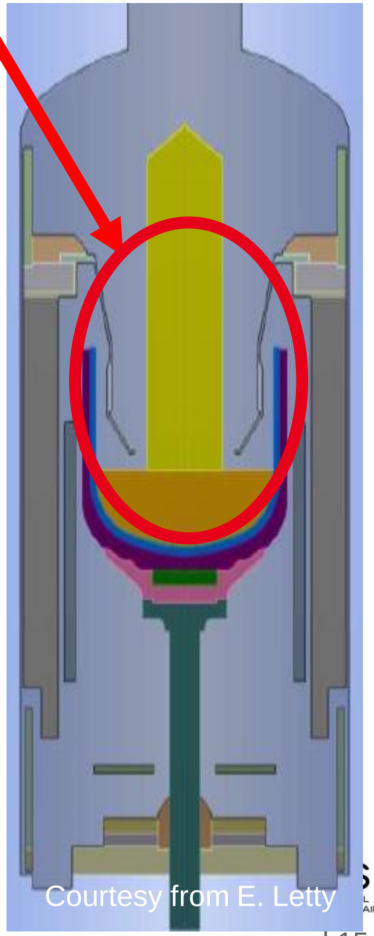
From W. Wijaranakula, Appl. Phys. Lett. 59, 1608-1610 (1991)

RECONSTRUCTION OF THE INGOT THERMAL HISTORY

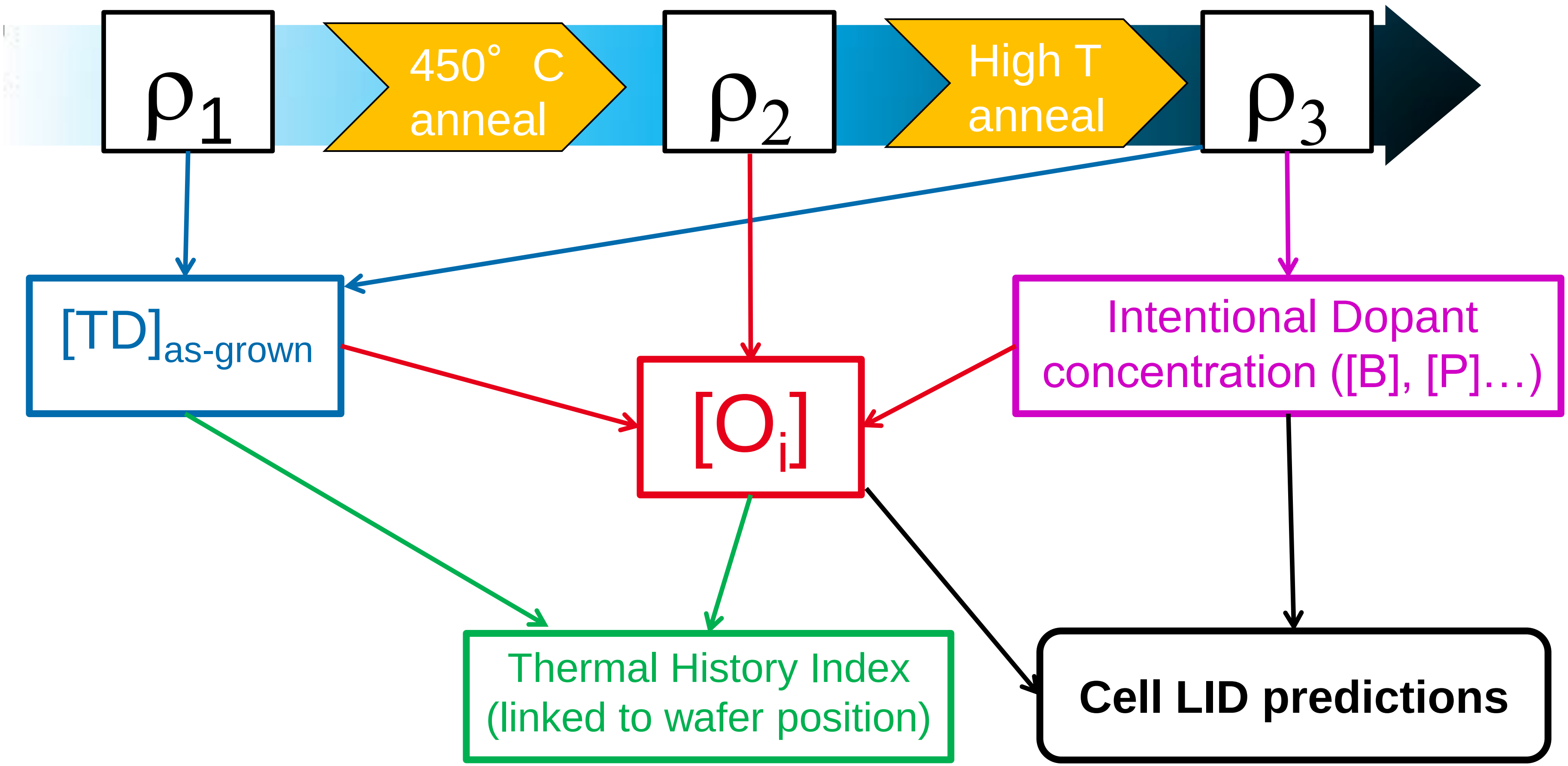
- **Pulling process issues can be quickly identified**
  - valuable feedback for R&D purposes (hotzone optimizations)

Extended cooling time requiring cristallisation process optimizations





OXYMAP OVERVIEW

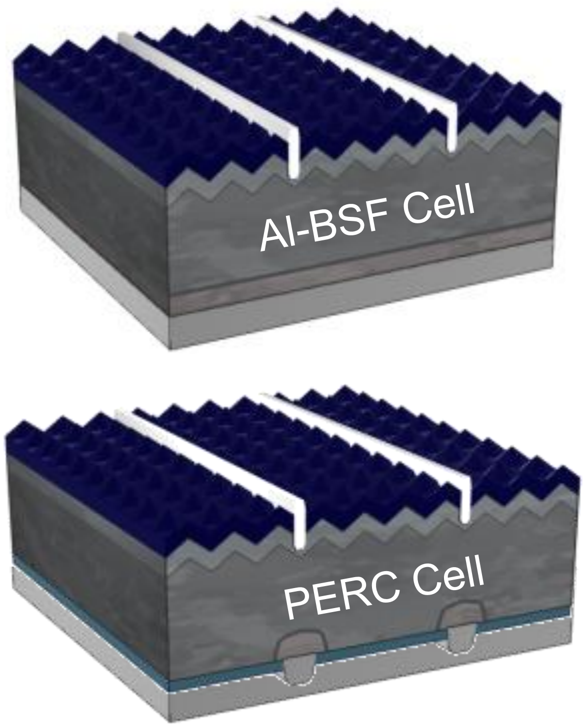


For boron-doped Cz

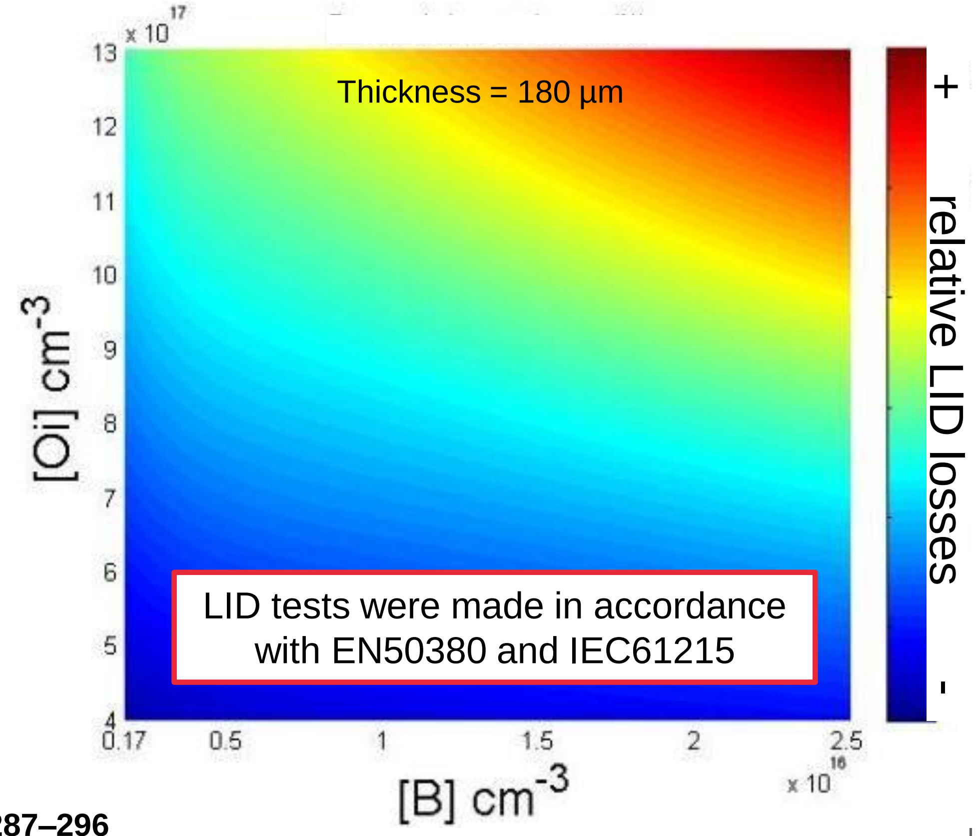
PREDICTION OF LIGHT-INDUCED DEGRATION AT CELL LEVEL DUE TO THE BORON-OXYGEN COMPLEXES

- Degradation amplitude = strong function of [B] and [O_i] [1]
- Induced cell LID losses (ΔV_{oc}, ΔJ_{sc}, ΔFF, ΔEfficiency) modeled with PC1D and adjusted to CEA experimental results obtained on BSF and PERC cells

Models for Al-BSF and PERC architectures



Typical results obtained



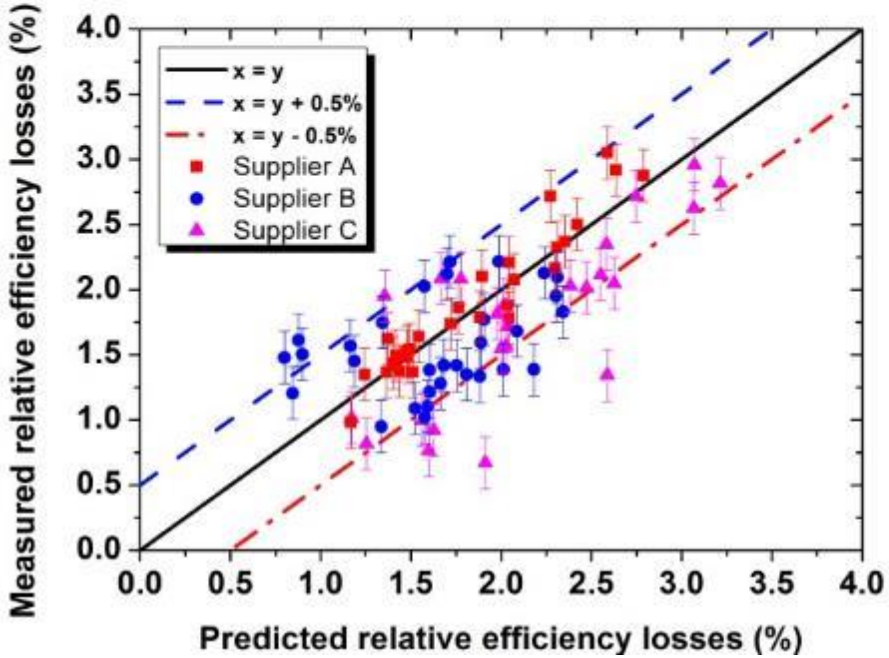
LID tests were made in accordance with EN50380 and IEC61215

[1] K. Bothe et al., Prog. Photovolt: Res. Appl. 2005; 13:287–296

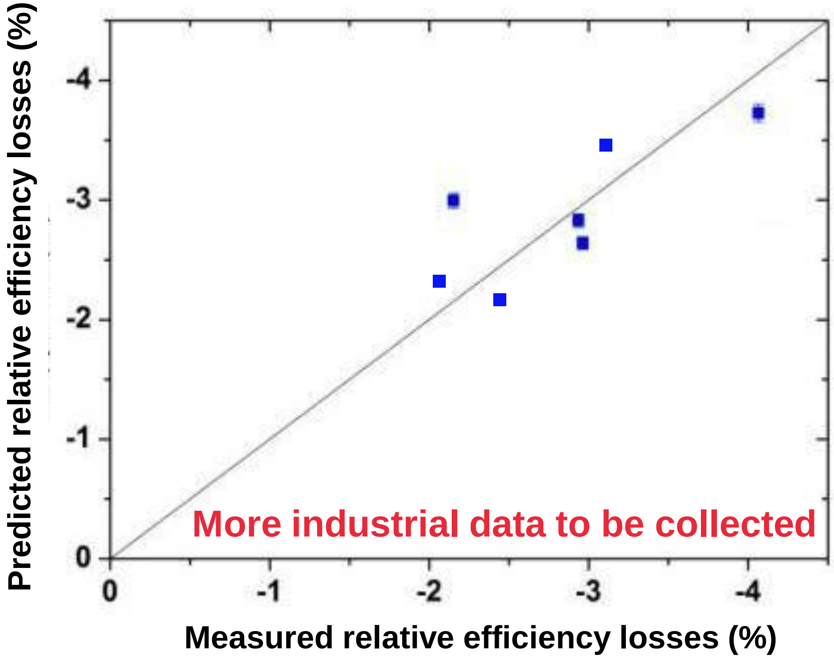
LID PREDICTION – COMPARISON TO INDUSTRIAL DATA

- **OxyMap predictions validated within uncertainty by comparison with industrial LID losses measurements.**

Al-BSF cells

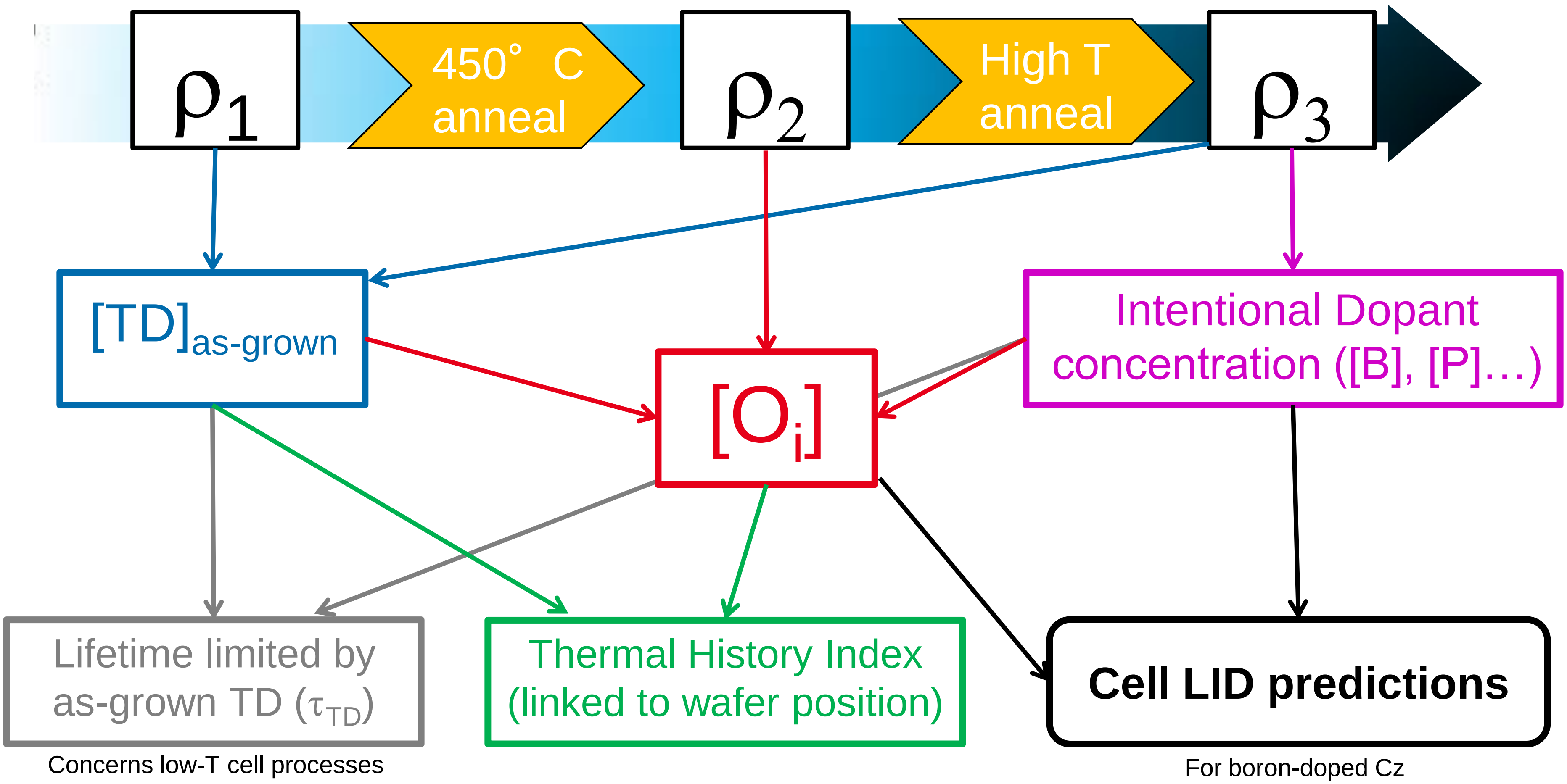


PERC cells



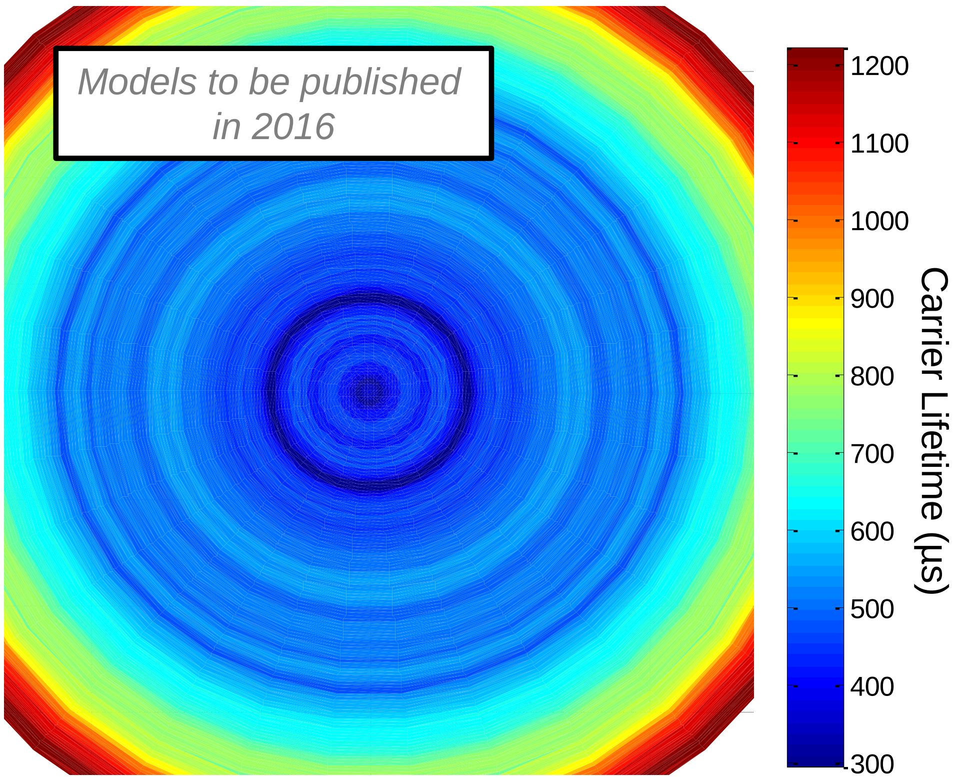
- **Potential interest from:**
  - wafer and cell manufacturers to identify high-LID wafers
  - module manufacturers to improve the cell matching (after cell LID)

OXYMAP OVERVIEW

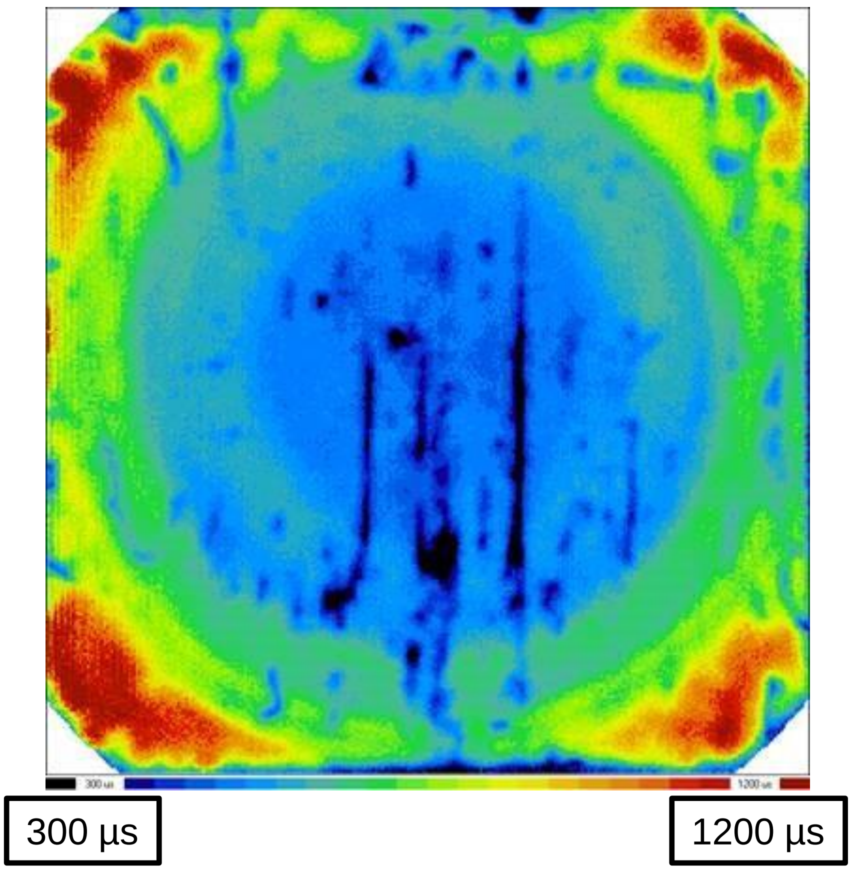


CARRIER LIFETIME LIMITED BY AS-GROWN TD

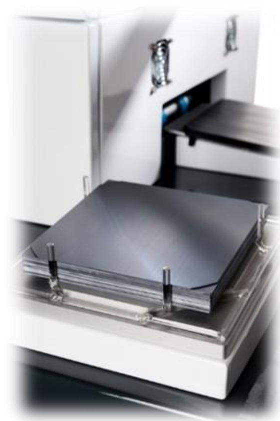
- **High [$TD_{as\text{-}grown}$] is incompatible with high bulk carrier lifetime**
  - Critical for low-T cell processes for which TD are not suppressed



2D reconstruction of the carrier lifetime limited by $TD_{as\text{-}grown}$ from a diagonal OxyMap linescan



Confirmation from 2D carrier lifetime mapping (µW-PCD)



The R&D version now available from AET Solar Tech, France

http://aetsolartech.com/oxymap/

Non destructive ✔	No restriction on wafer thickness ✔	No restriction on wafer surface roughness ✔

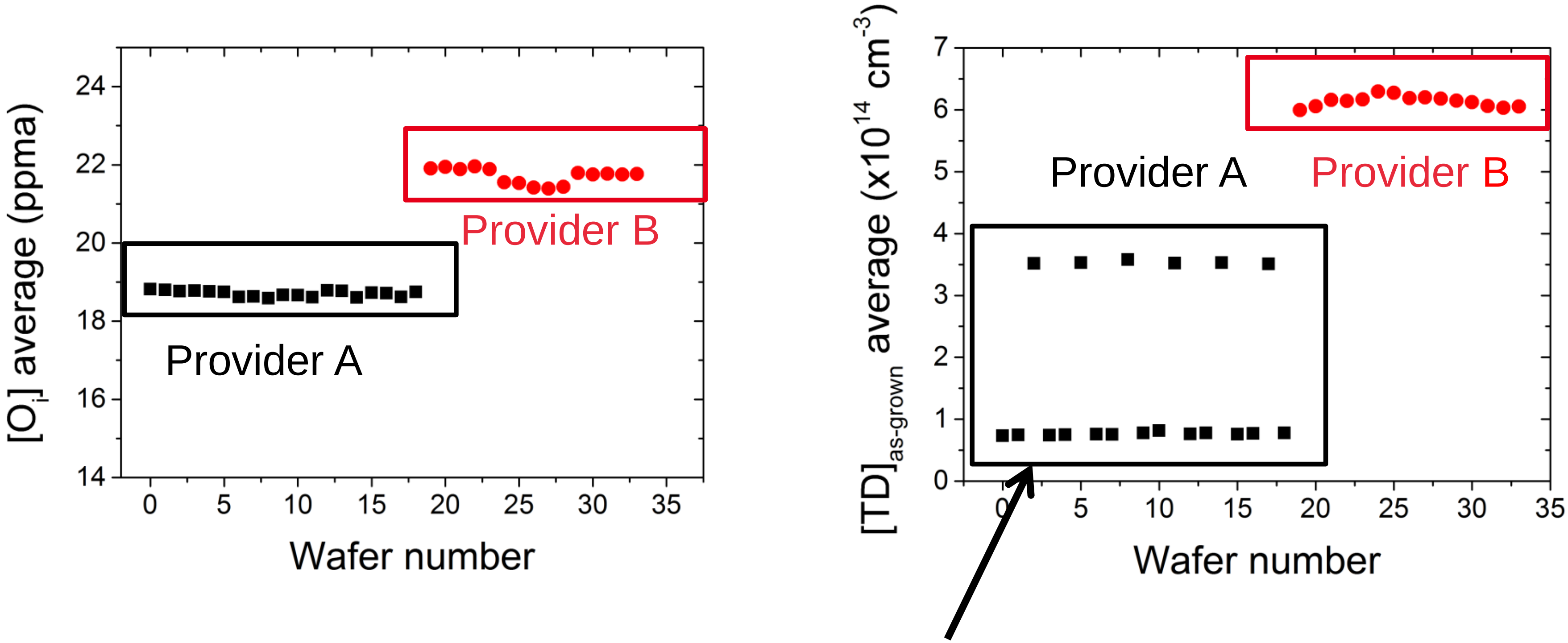
Characterization of O-related defects / Detection of defective wafers / Feedback for ingot and cell R&D dvpts

Thanks for your attention!

Commissariat à l'énergie atomique et aux énergies alternatives
150 avenue du lac Léman | 73375 Le Bourget-du-Lac
www-liten.cea.fr

ANALYSING THE SORTING STRATEGIES OF WAFERS

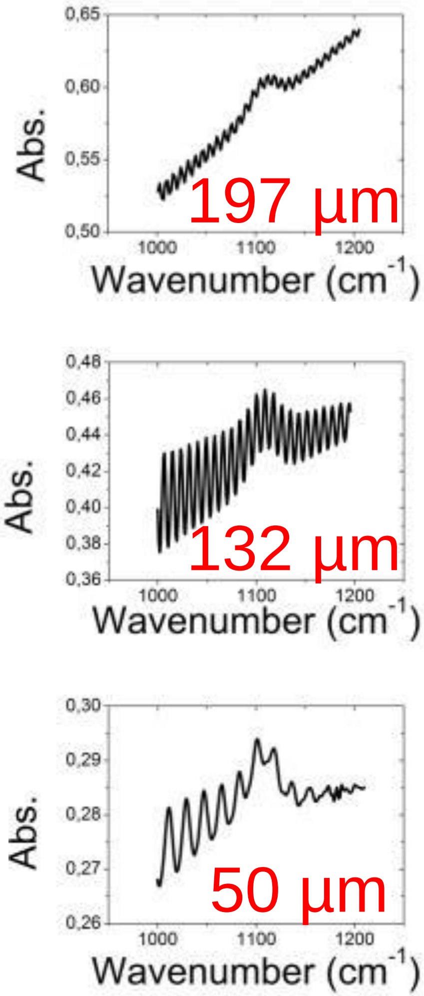
- **Better quality check of incoming wafers that reveals the sorting strategy of wafer providers**

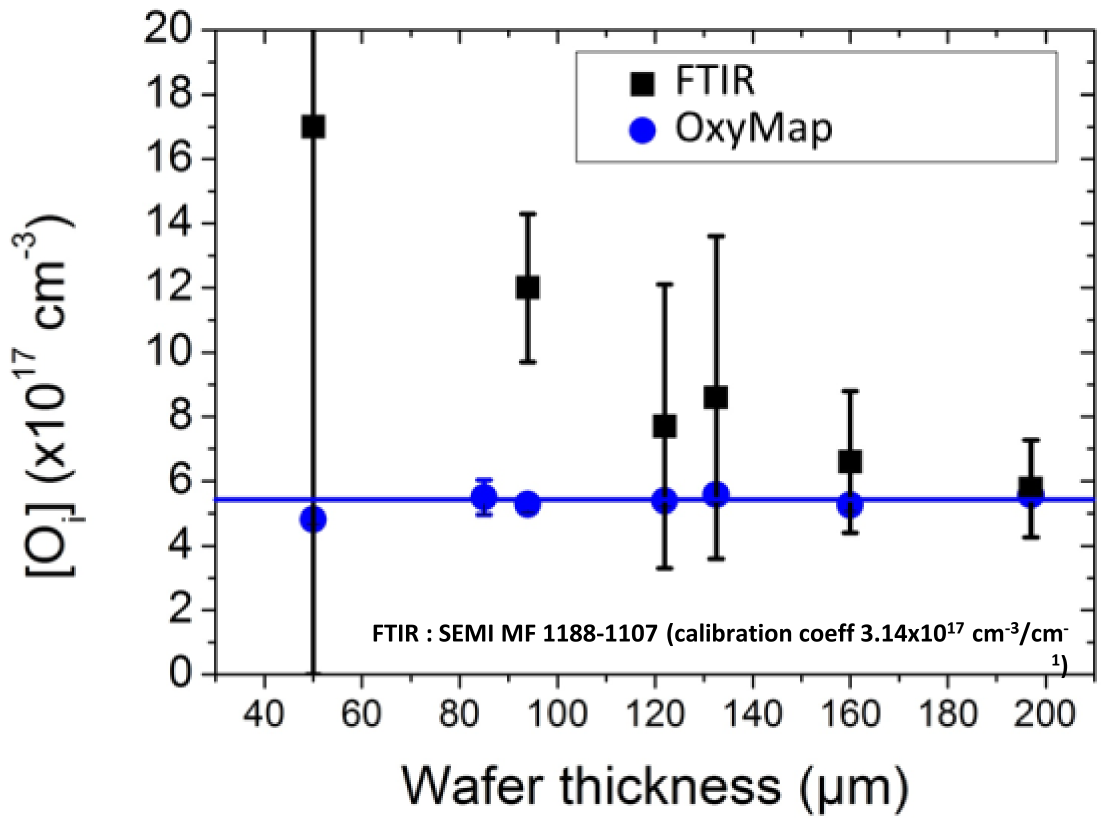


Measurements of the $[TD]_{as\text{-}grown}$ shows that the Cz wafer provider A mixes wafers

Applicable on thin wafers

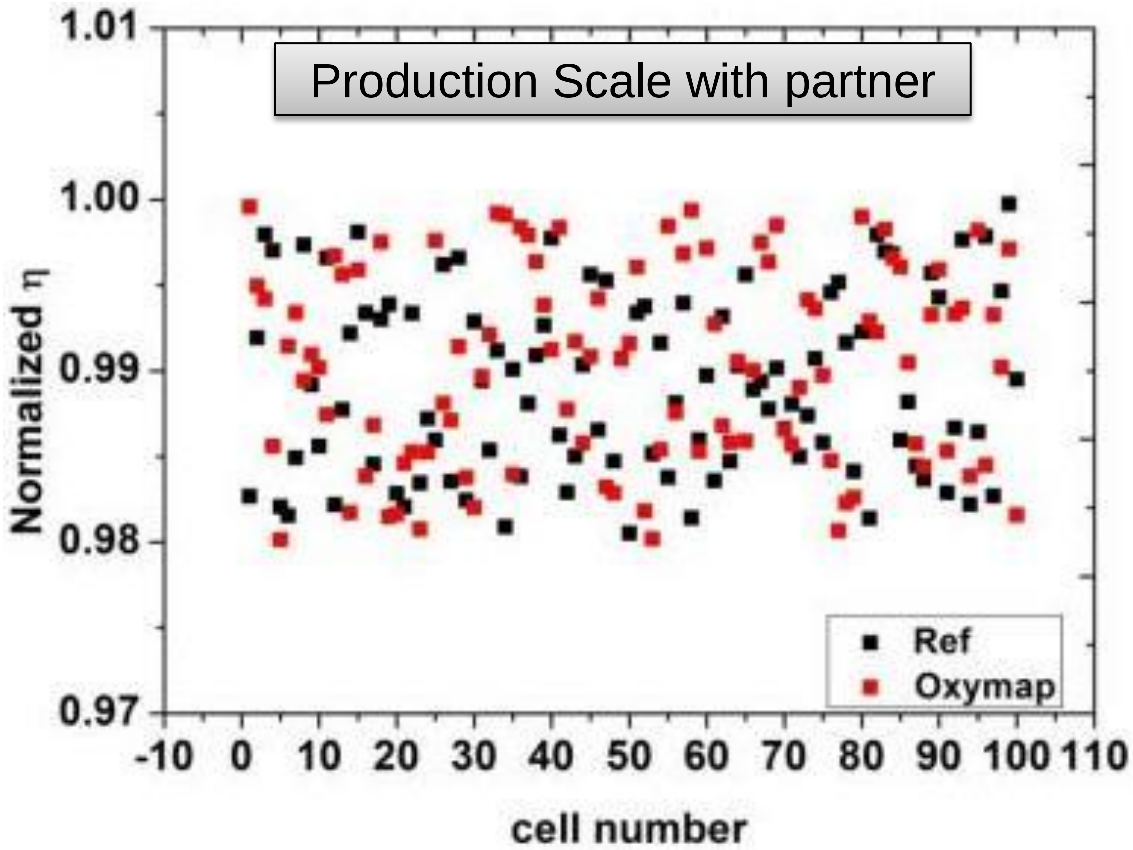
FTIR signal





- ❑ Poor FTIR performance on thin wafers
  (random scattering of IR beam at surfaces and chaotic internal multireflexions)
- ❑ OxyMap performs equally good for whatever the thickness

Can measured wafers be transformed into efficient cells ?



No detectable impact of the measurement **on the final cells efficiencies** noticed for AlBSF process

EFFICIENCY VARIATIONS VS INGOT HEIGHT TODAY

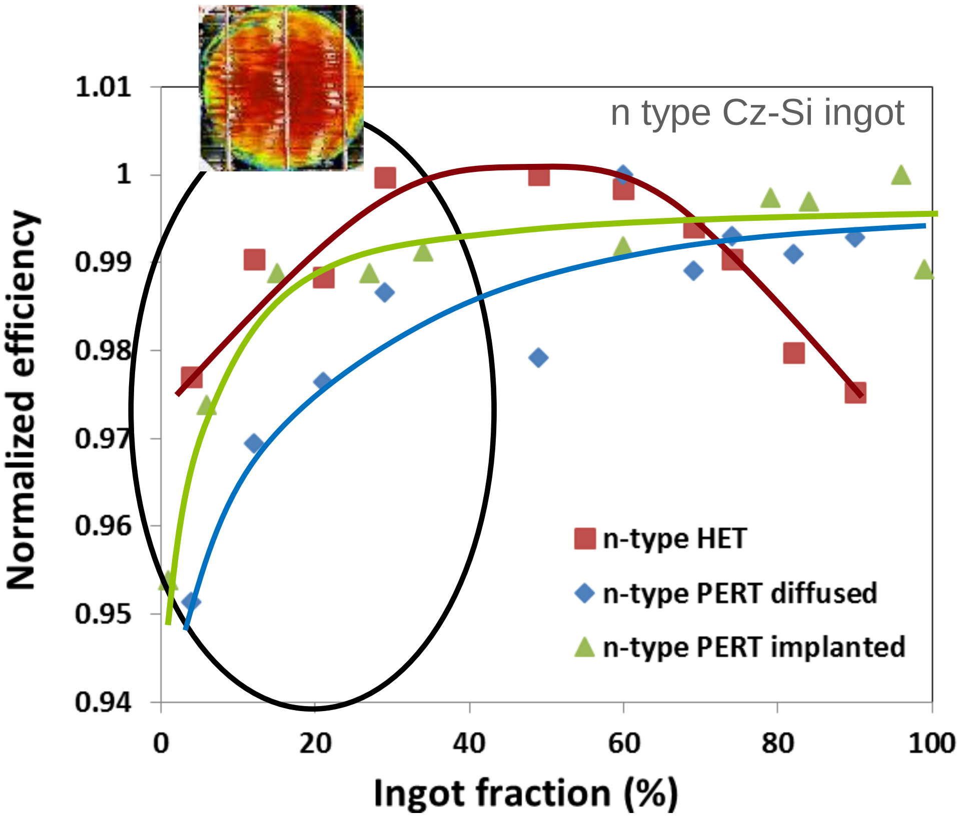
- **Large variations of stabilized η observed along the ingot height (both p and n-type Si)**

"Only two third of the Cz-Si wafers are defect-free. 29% exhibit oxygen thermal donors and 4% severe oxygen precipitation"

Fraunhofer ISE (???)

"Estimated 10-20% of shipped wafers affected by rings -> cells below efficiency specs. "rings" 1-2%, "discs" 4-6% abs. eff"
"Recombination active defects in ring shape related to oxygen cluster formation during ingot growth"

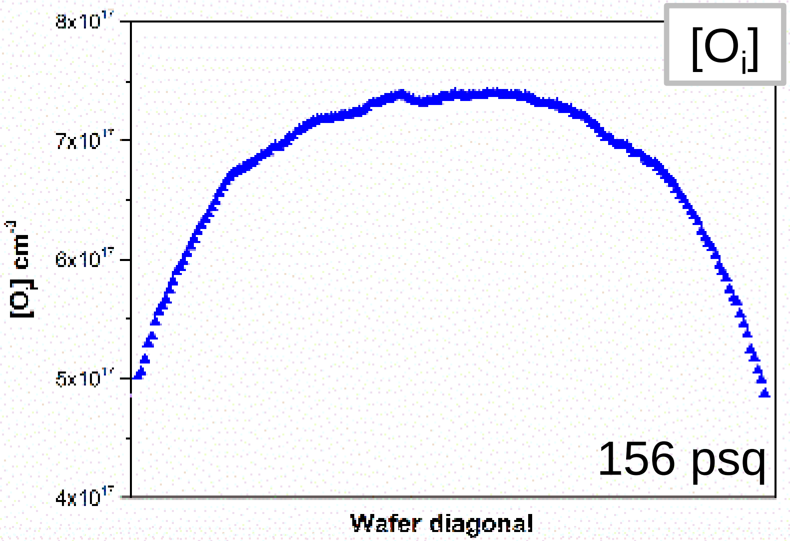
ECN/Yingli (PVSEC 2015)

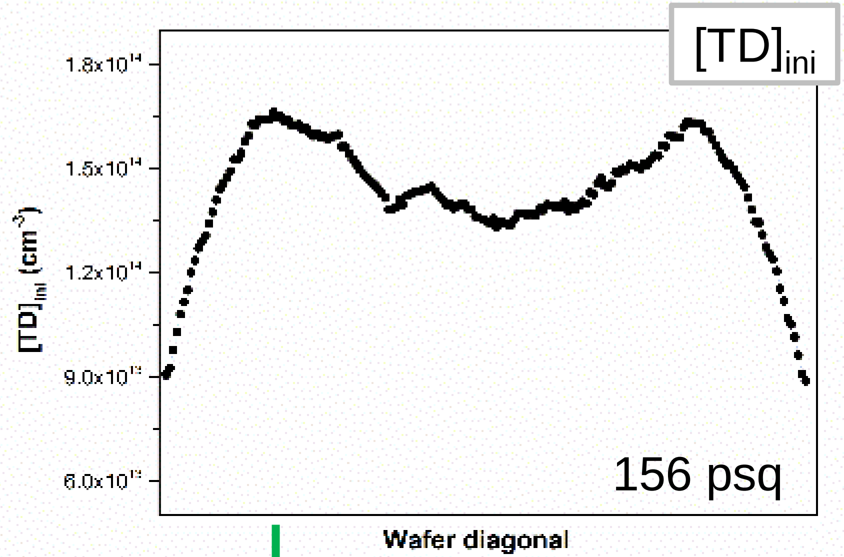


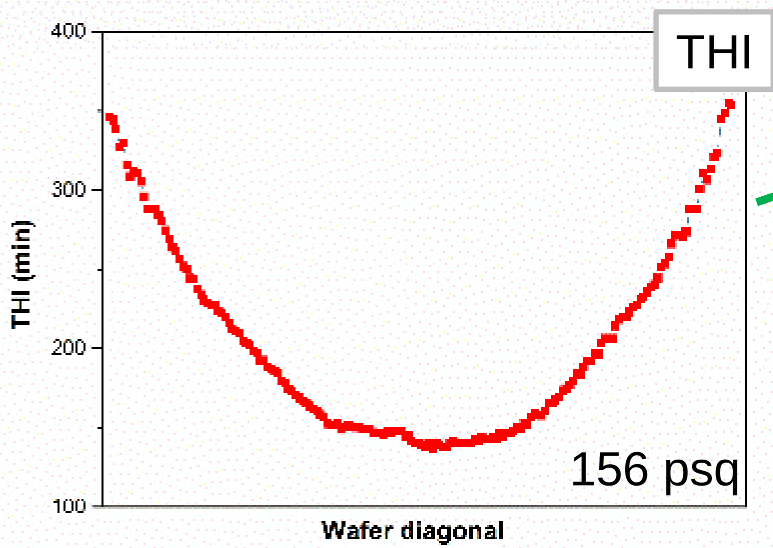
B. Martel et al., NPV Workshop 2015

Already today, O-related defects do not allow to leverage efficiency improvements permitted by high efficiency cell processes ➔ Monitoring is required

HOW TO LEVERAGE LINESCANS







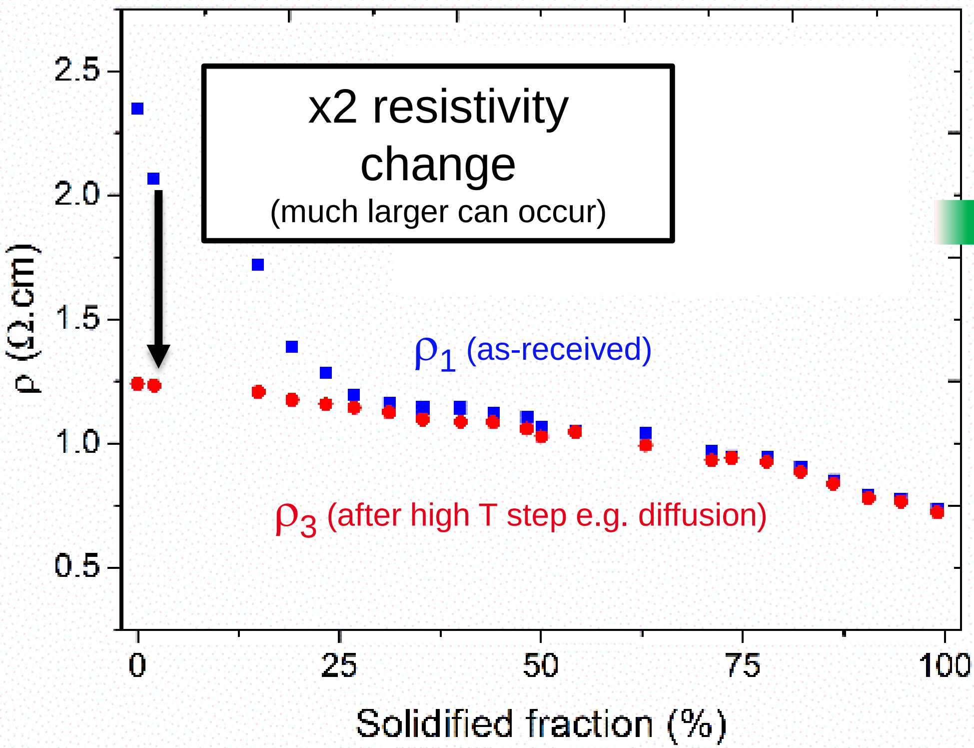
Unusual $[TD]_{ini}$ profile explained by huge lateral variations in thermal history across the wafer

Linescans bring valuable new insight on pulling process issues

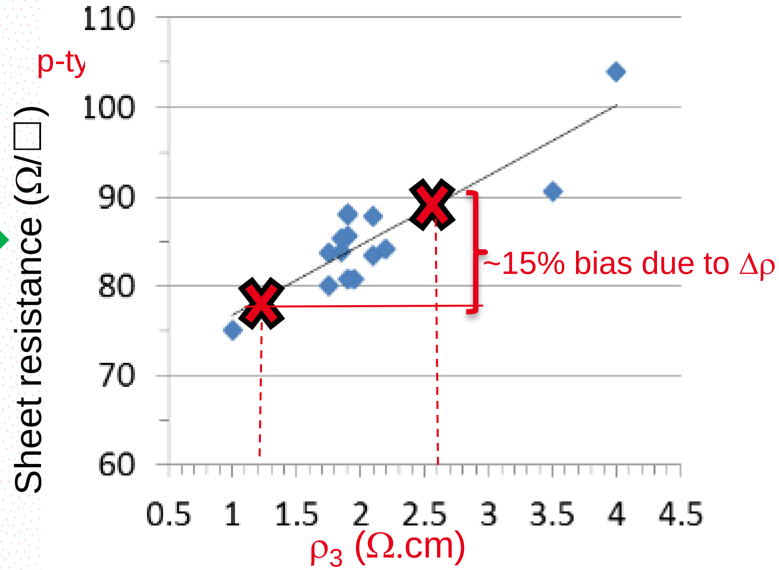
in this case very bended isothermals during ingot cooling suggesting high residual stress within the wafer

SmartER SELECTION OF WAFERS TO BE USED FOR PROCESS OPTIMIZATION

Very large and unexpected resistivity changes after high T steps can occur due to high $[TD]_{ini}$



Phosphorus emitter dvpt



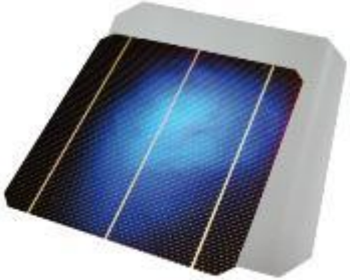
Can strongly complicate interpretation of process development results !

Quick and accurate access to the resistivity before and after high T step (>600°C) is essential for cell process developments

CONCLUSIONS

- A large set of accurate data can be obtained to help material qualification along the value chain

- ***Data over the diagonal of the wafer***
  - **[O_i]** and spatial homogeneity
  - **Initial resistivity and resistivity after high T process steps**
  - **[$TD_{as\text{-}grown}$]** and spatial homogeneity

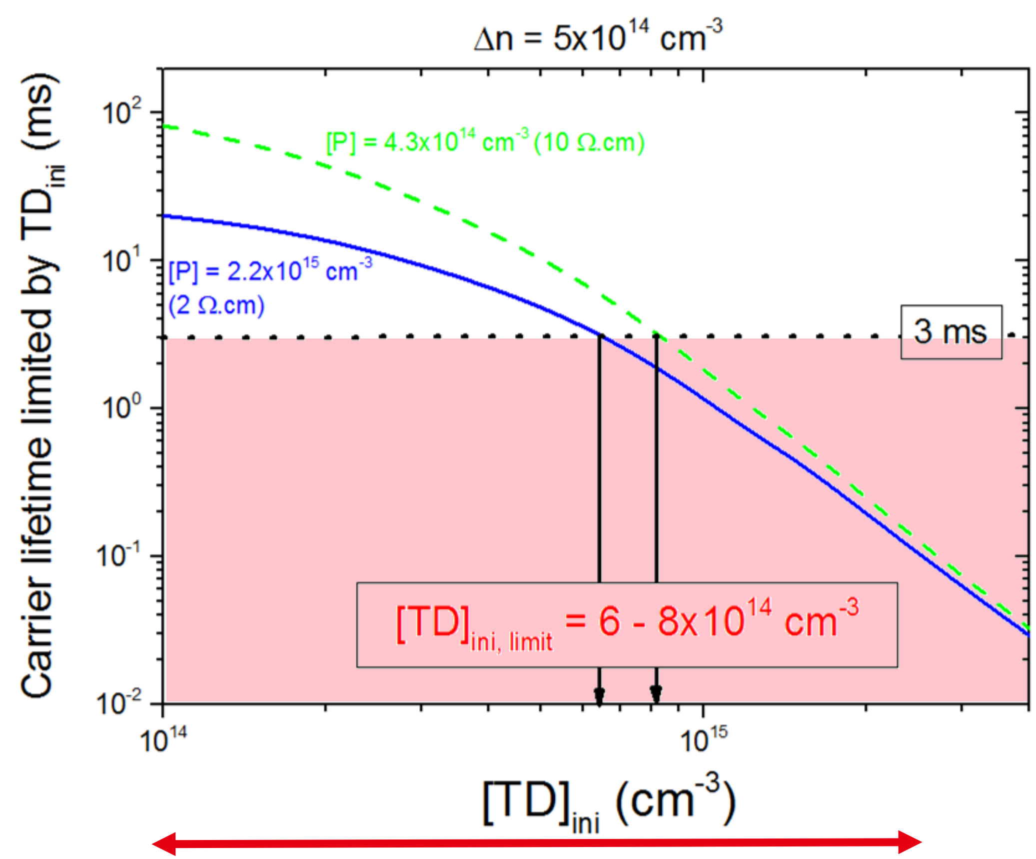


- ***Additional features:***
  - **Position of the wafer** in the original ingot
  - **Detection of low-efficiency wafers**
  - Predictions of the **cell LID** losses
  - Estimation of the **carrier lifetime limited by TD**
  - Feedback on **crystallization issues** for crystal growers

Non destructive ✔	No restriction on wafer thickness ✔	No restriction on wafer surface roughness ✔

CARRIER LIFETIME LIMITED BY AS-GROWN TD

- **High concentrations of as-grown TD is incompatible with high bulk carrier lifetime**
  - From the measured $[TD_{ini}]$, OxyMap predicts the carrier lifetime limited by TD



$\tau_{TD} \sim [TD_{ini}]^{-2.5}$ over the 0.2-3 ms range!

Models to be published in 2016

$[TD]_{ini}$ range in Cz-Si : 10^{13} – $2x10^{15}$ cm^{-3}