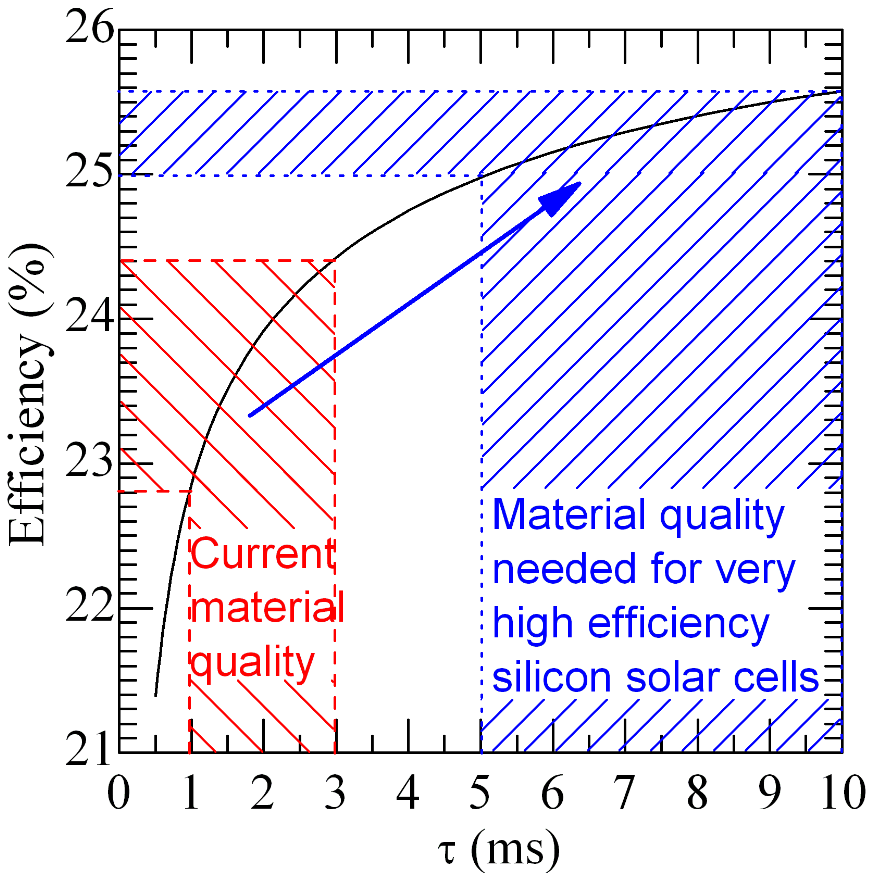
Materials related challenges en route to very high efficiency n-type silicon solar cells

F.E. Rougieux

Research School of Engineering,The Australian National University

What are the lifetime requirement for high efficiency devices?



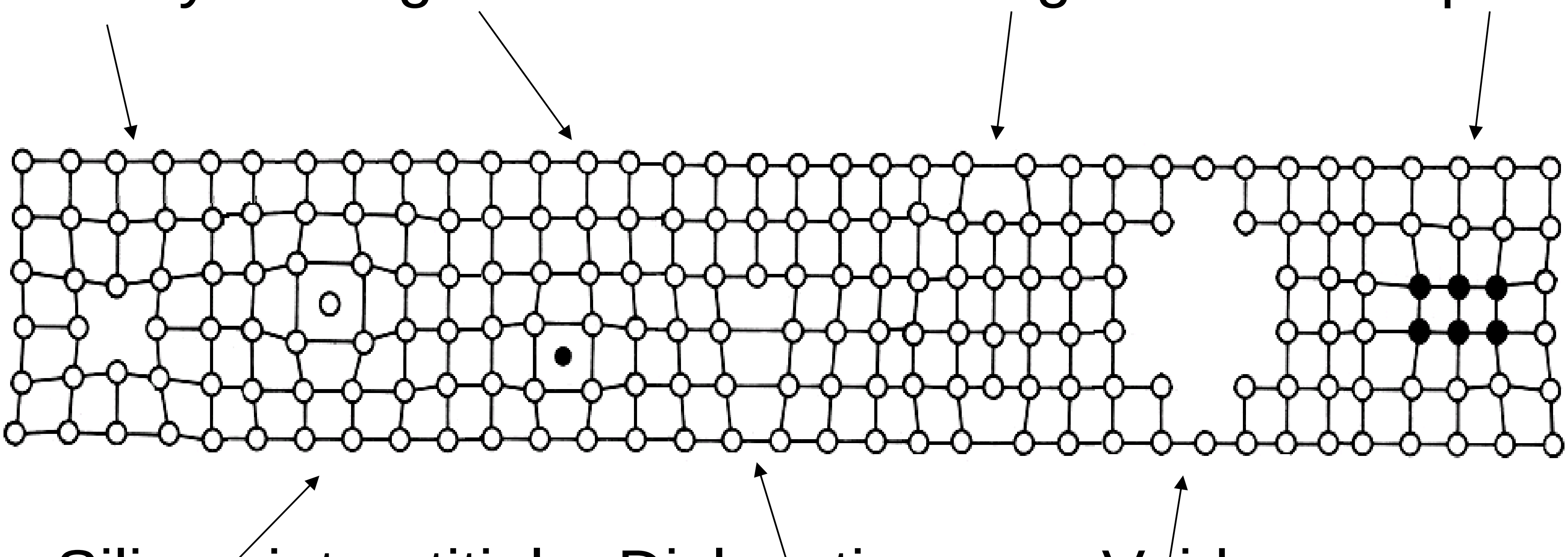
Modified from P. J. Cousins et al. *35th IEEE PVSC,* (2010)

- Multi milliseconds lifetime for very high efficiency silicon solar cells
- What are the material related challenges to achieve high lifetime?

Outline

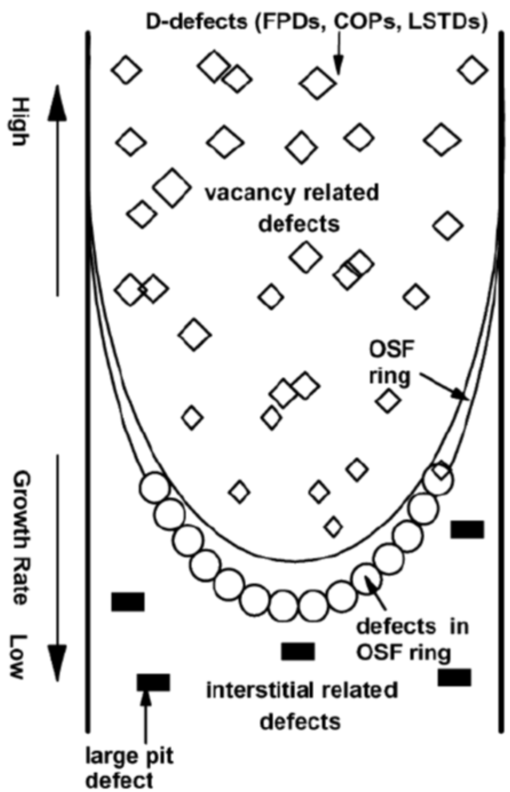
- Grown-in extended defects
- Characterizing as-grown defects
- Grown-in point defects in n-type CZ
- Grown-in point defects in n-type FZ

What grown-in defects are we looking at?

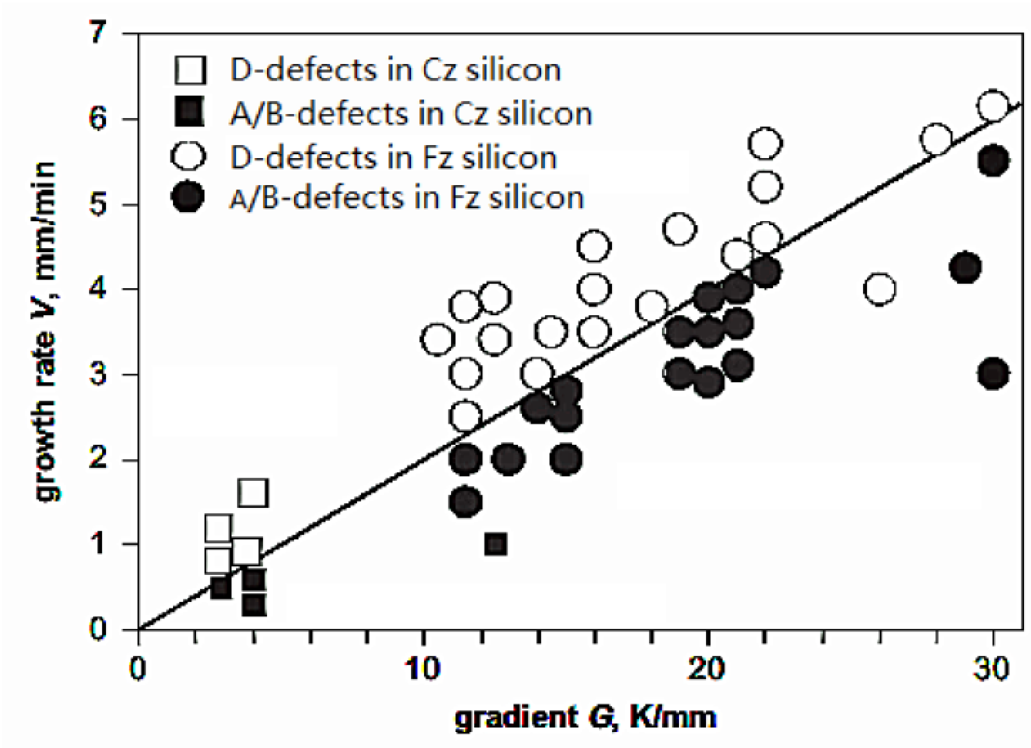


Modified from F. Shimura, "Semiconductor silicon crystal technology" (1989)

Effect of growth rate on defect types
Voronkov criteria v/G

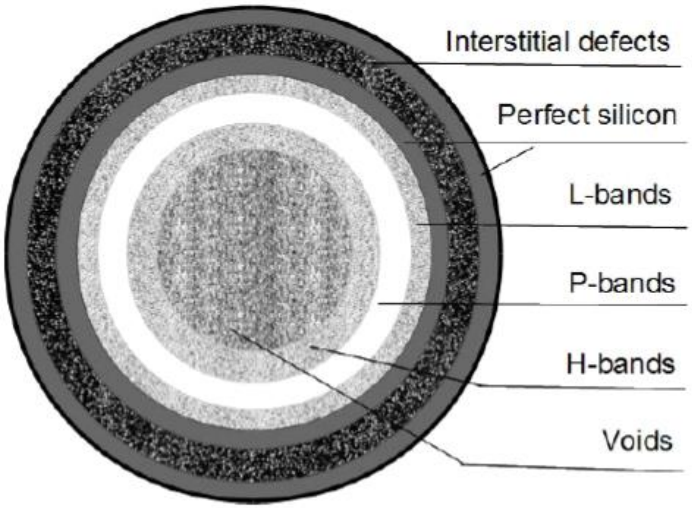


Dornberger et al. J. Cryst. Gr. (2001)



Voronkov et al. J. Cryst. Gr. (2008)

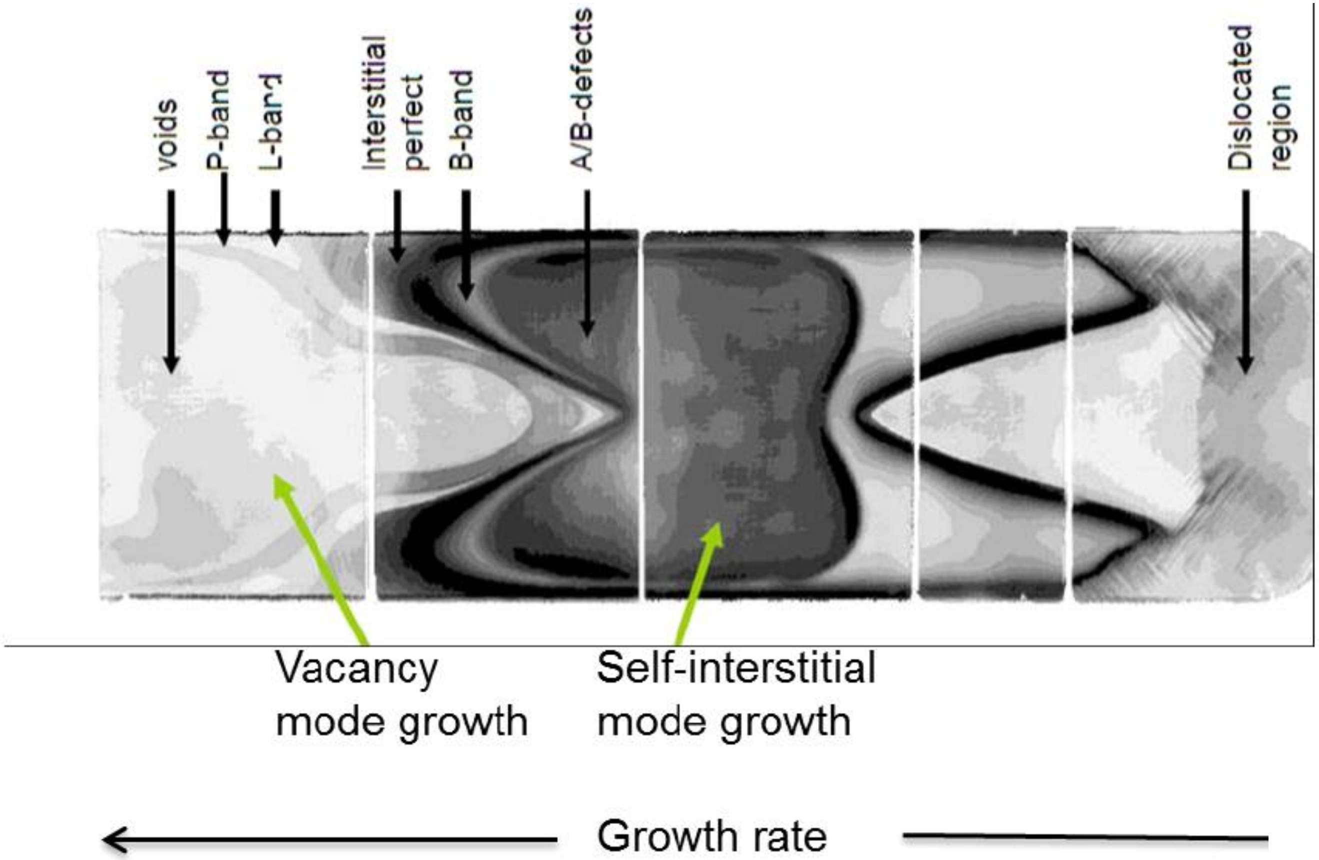
Cross section of a wafer with vacancy rich and interstitial rich silicon



Y. Hu et al 26 EUPVSEC (2011)

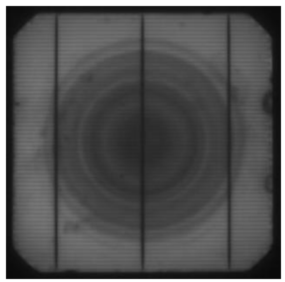
- V: growth rate
- G: axial temperature gradient
- High V/G (fast pulling rate): Vacancy mode
- Low V/G (slow pulling rate): Interstitial mode
- Intermediate V/G: P (Particle) band, H (High vacancy) band, L (low vacancy) band

Effect of growth rate on defect distribution

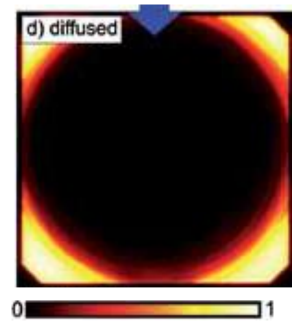


R. Falster Phys. Stat. Solidi (2000)

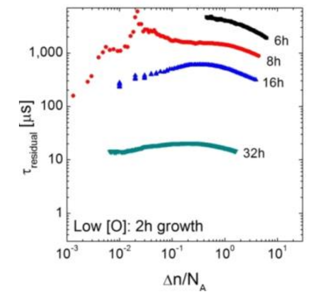
Oxygen precipitates



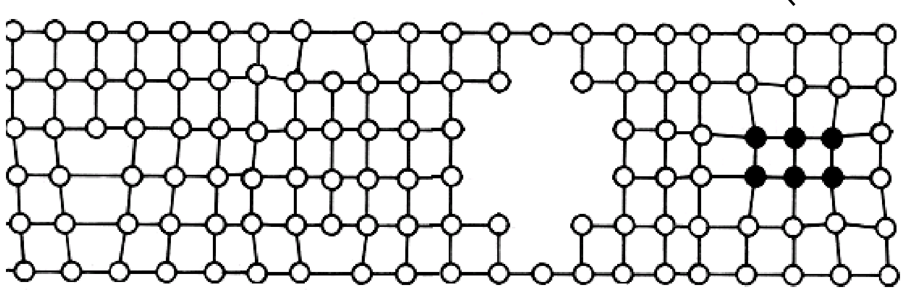
M. Forster et al. N-PV workshop (2014).



J. Haunschild et al. *phys. stat. sol. RRL* (2011)



J. D. Murphy et al. J. Appl. Phys. (2012).

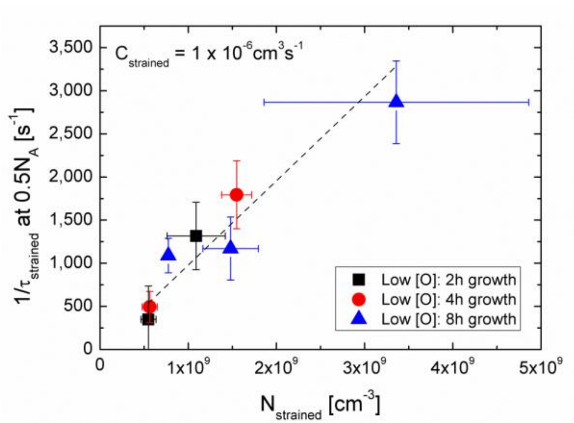


Modified from F. Shimura, "Semiconductor silicon crystal technology" (1989)

Oxygen precipitates and high temperature processing

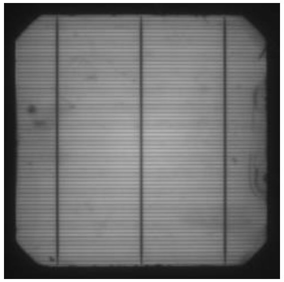
Increased precipitate density

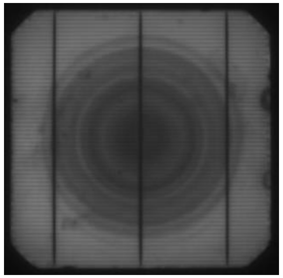
Strained precipitates



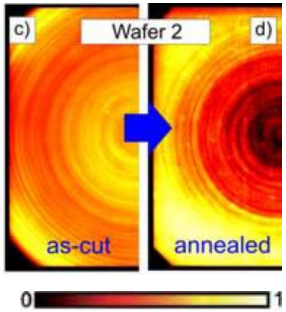
J. D. Murphy et al. J. Appl. Phys. (2011).

Metallic decoration


Clean cell process

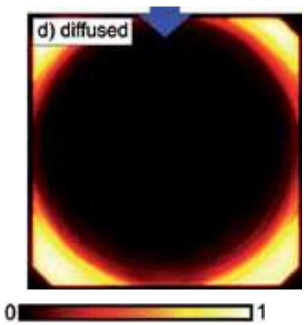

Non-clean cell process

M. Forster et al. N-PV workshop (2014).



J. Haunschild et al. *phys. stat. sol. RRL* (2011)

Oxygen precipitates



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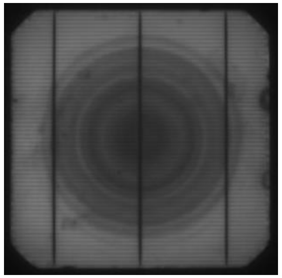
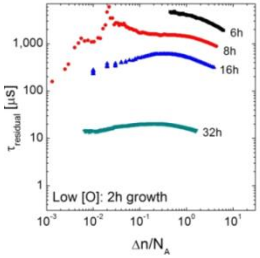


M. Forster et al. N-PV workshop (2014).



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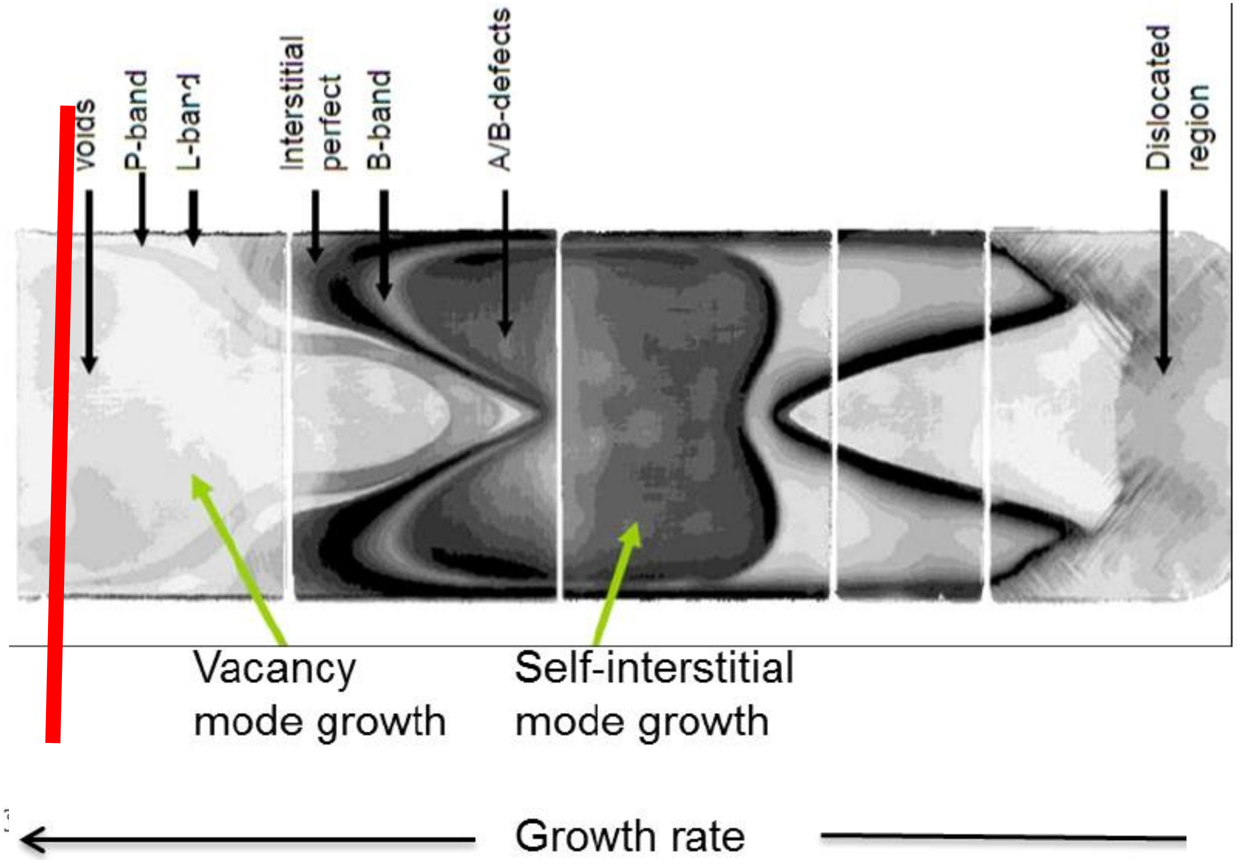
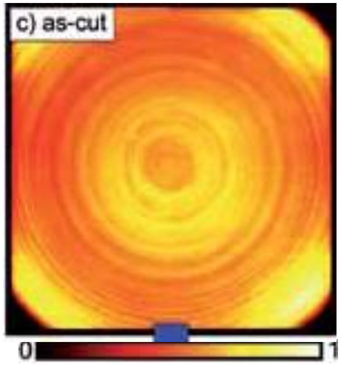
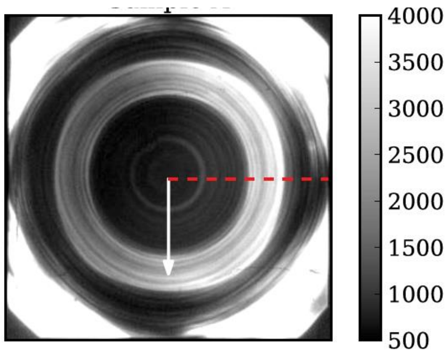


R. Falster Phys. Stat. Solidi (2000)

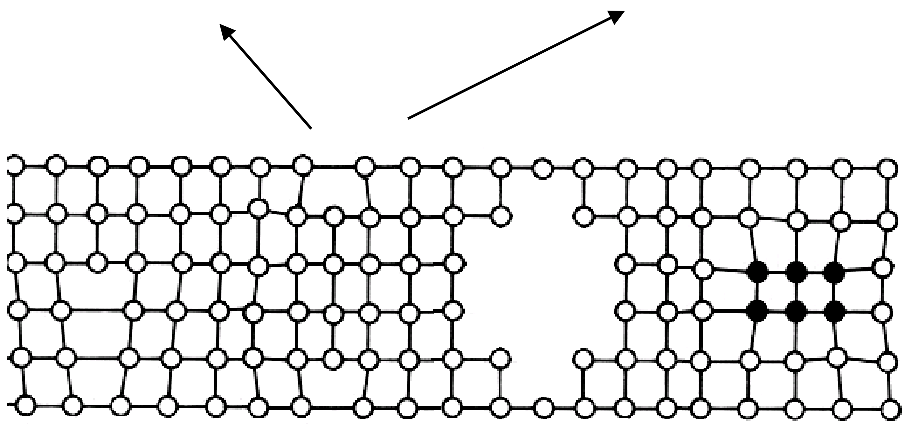
Stacking faults



J. Haunschild et al. *phys. stat. sol. RRL* (2011)



Angelskar et al. Energy Procedia (2012)



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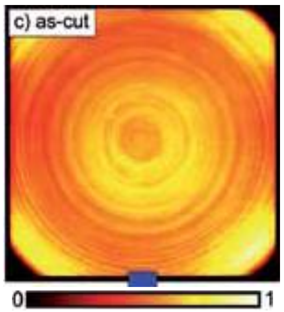

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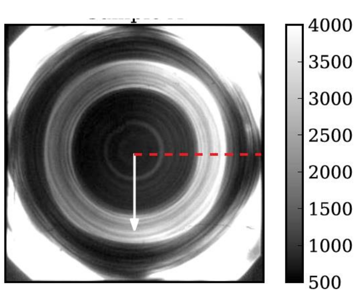

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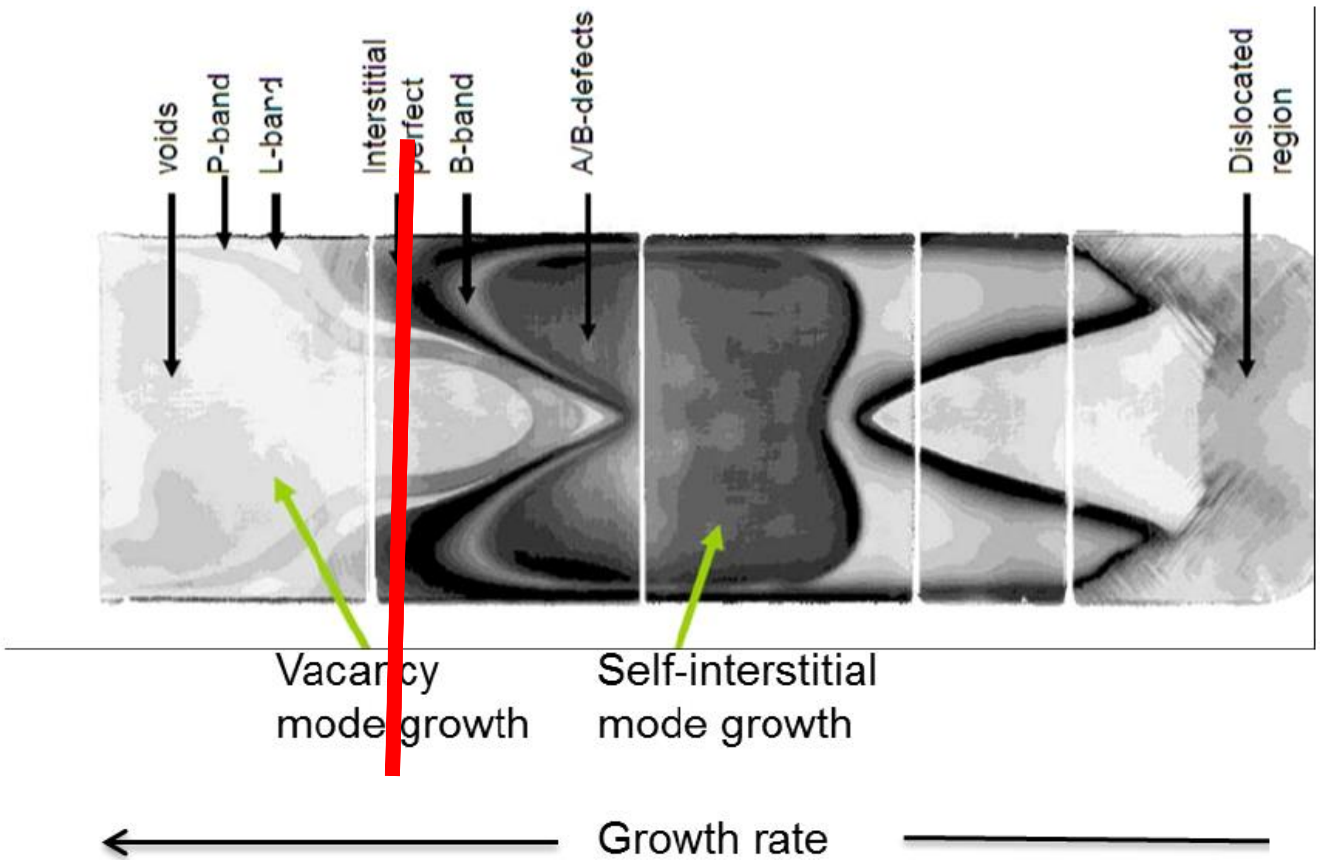

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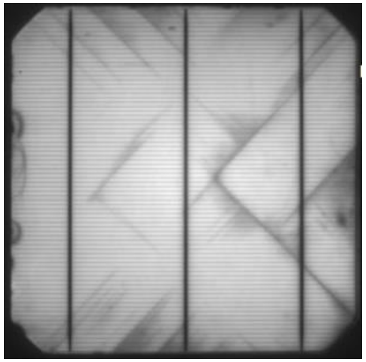
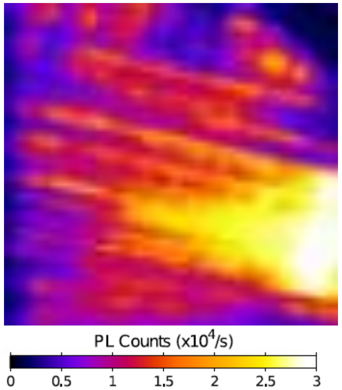
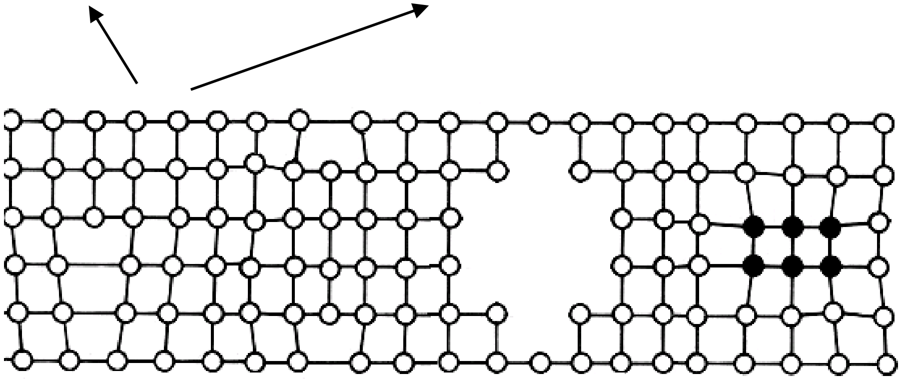
Dislocations





M. Forster et al. N-PV workshop (2014).

B. Hallam et al. IEEE JPV (2014)



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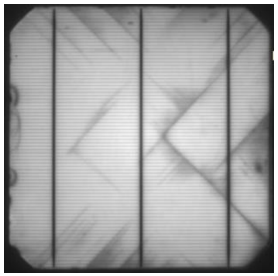

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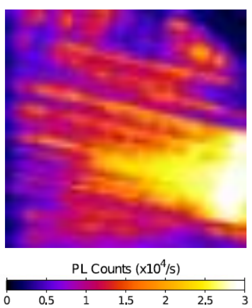

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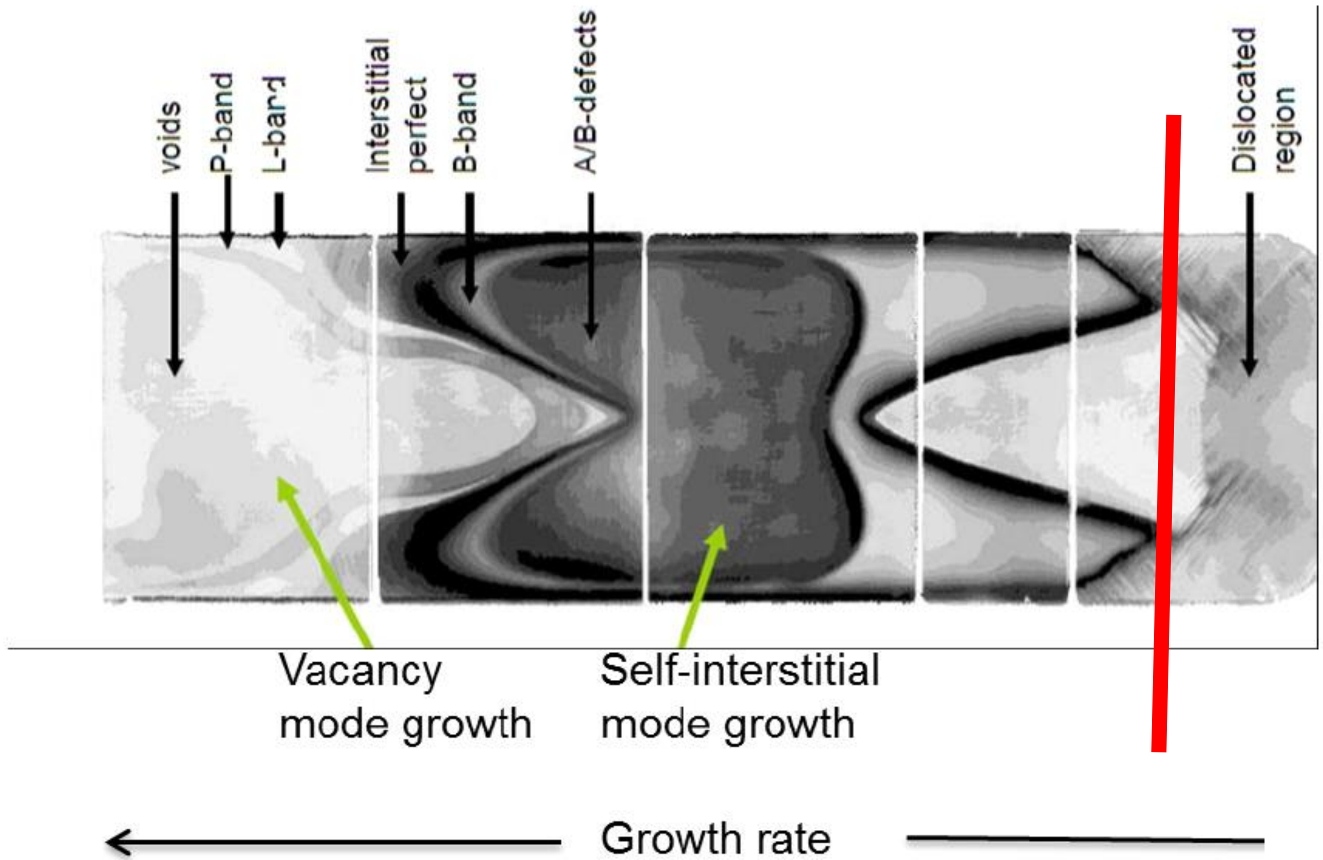
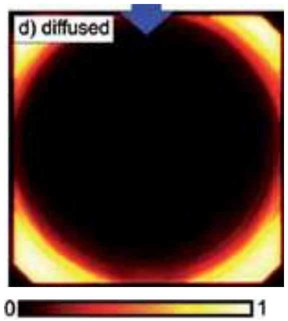


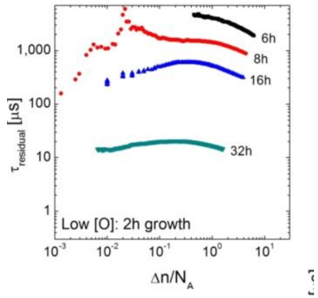
R. Falster Phys. Stat. Solidi (2000)

Australian National University

Grown-in and process-induced **extended** defects

Oxygen precipitates





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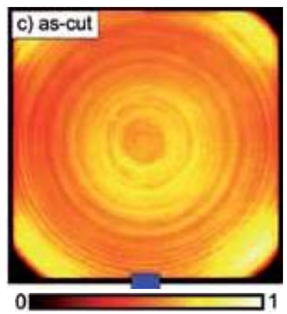

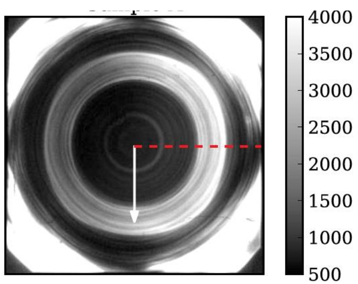

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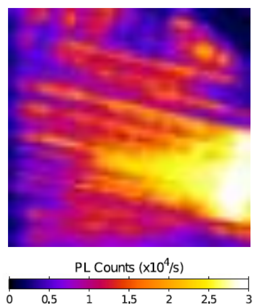

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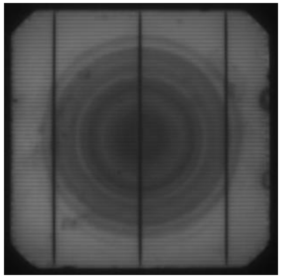

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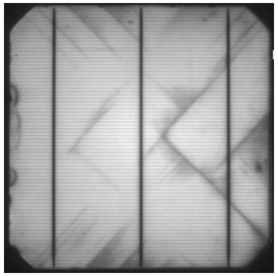

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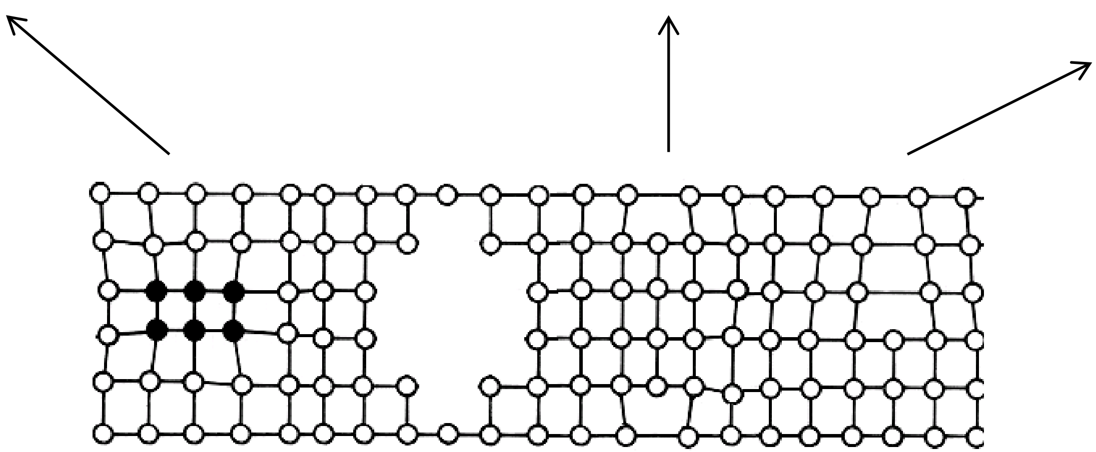

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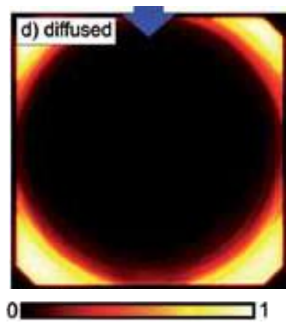
Grown-in and process-induced **extended** defects

Oxygen precipitates



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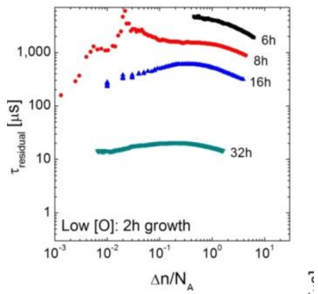

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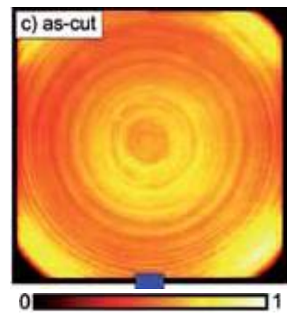

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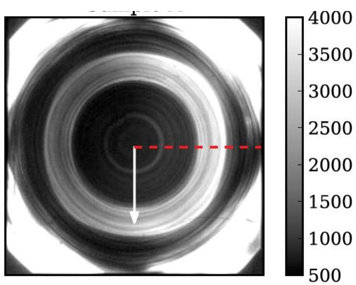

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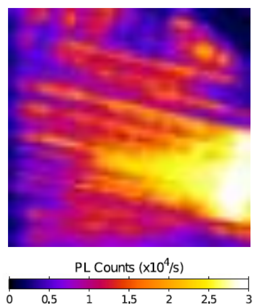

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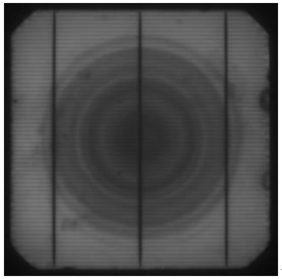
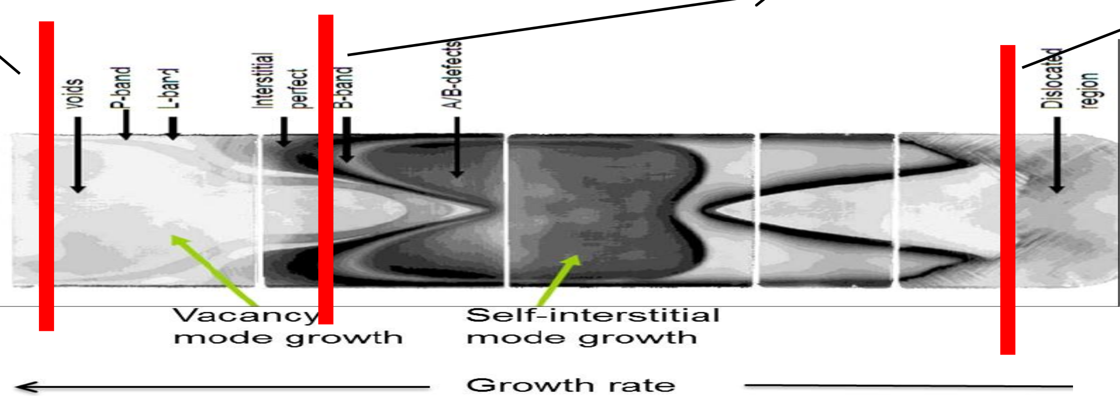


M. Forster et al. N-PV workshop (2014).



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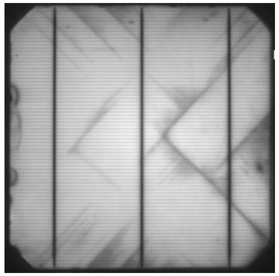

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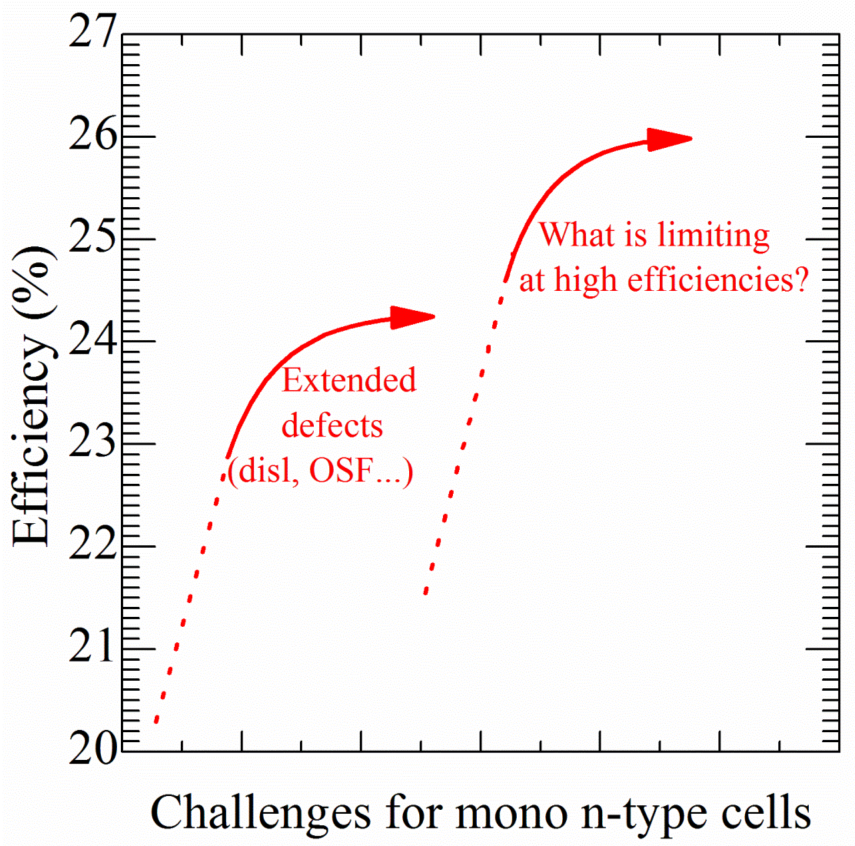
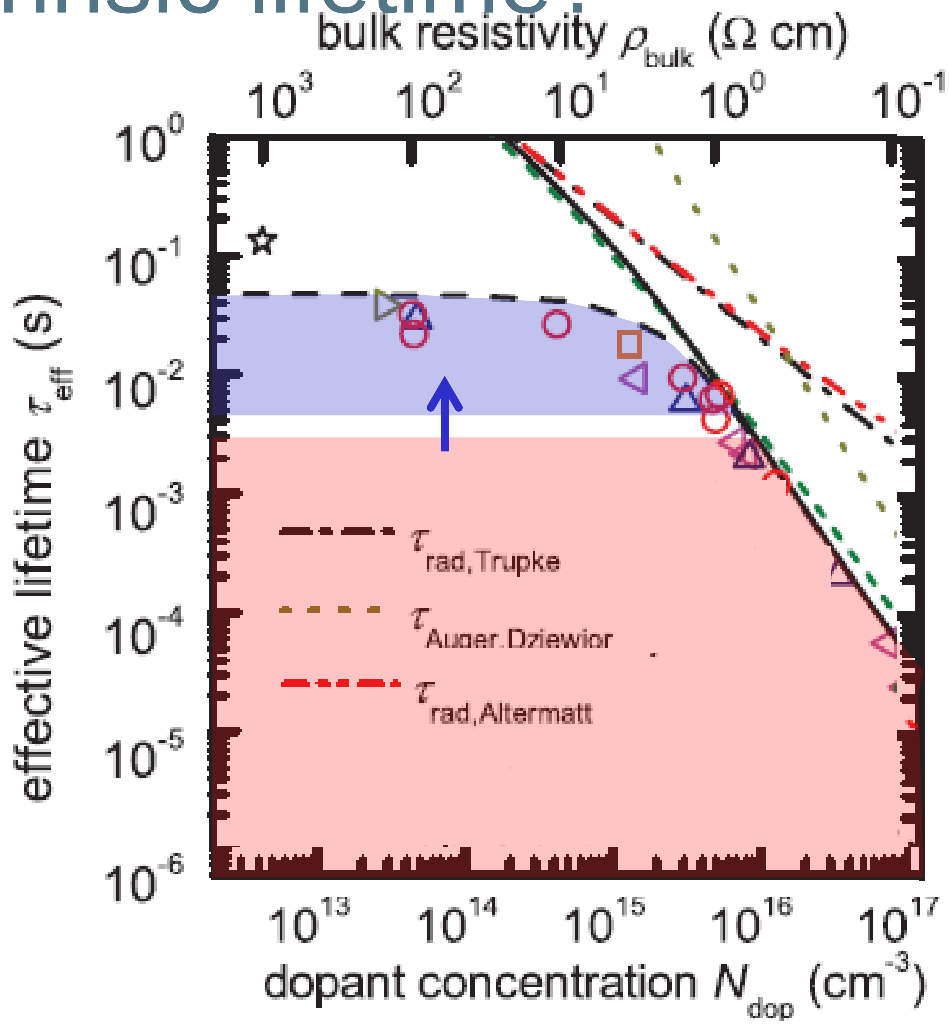
Material-related challenges en route to high efficiency n-type solar cells

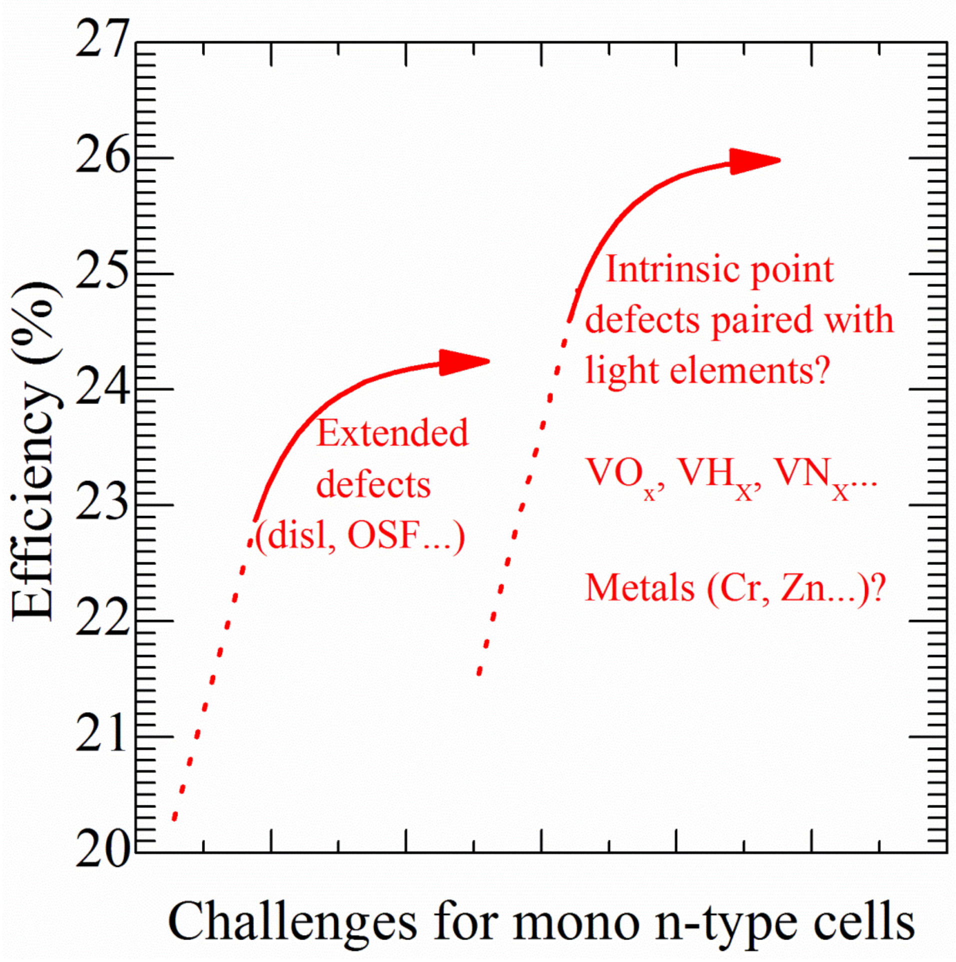


What are the defects between us and the Intrinsic lifetime?



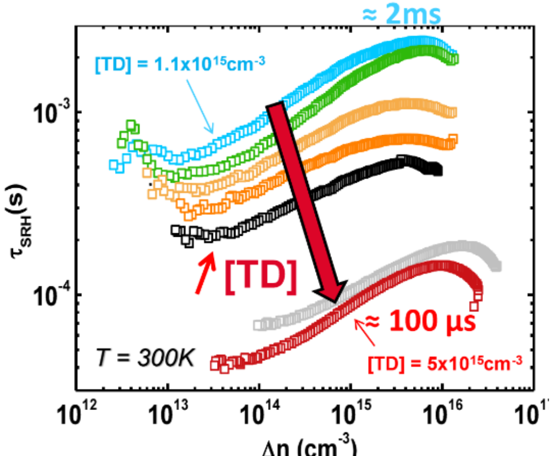
Richter et al. Phys. Rev. B. (2012)

Material-related challenges en route to high efficiency n-type solar cells

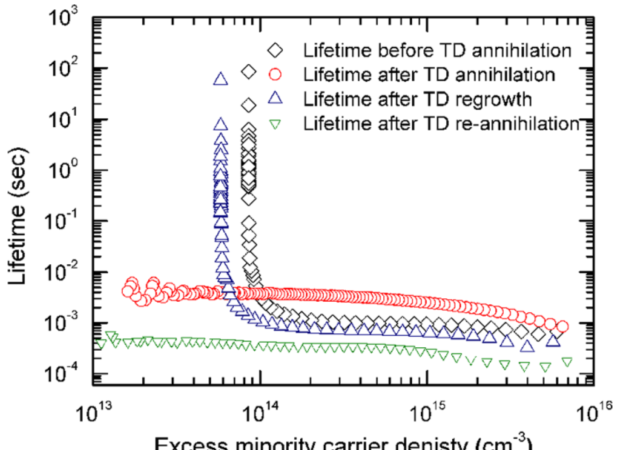


Grown-in and process-induced **point** defects

Thermal donors



N.Najid et al. N-PV workshop (2013)



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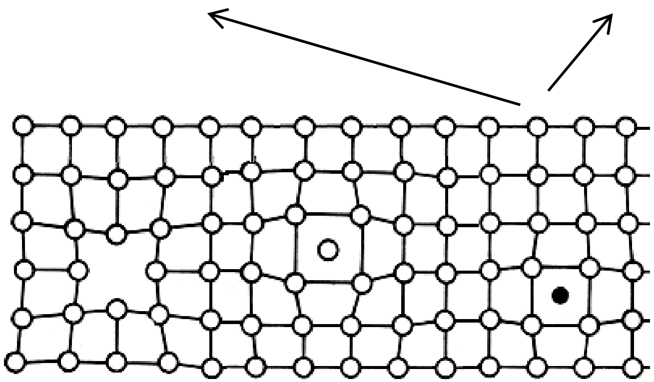


Modified from F. Shimura, "Semiconductor silicon crystal technology" (1989)

Grown-in and process-induced **point** defects

VV?

VO_X?

VH_X?

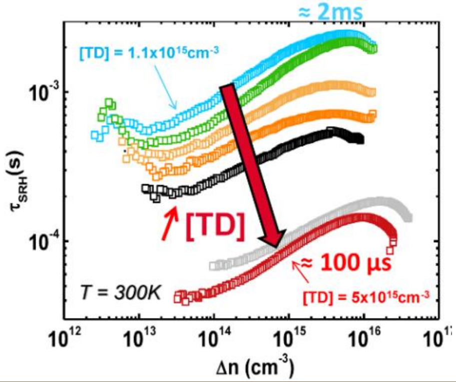
...

C_iC_S?

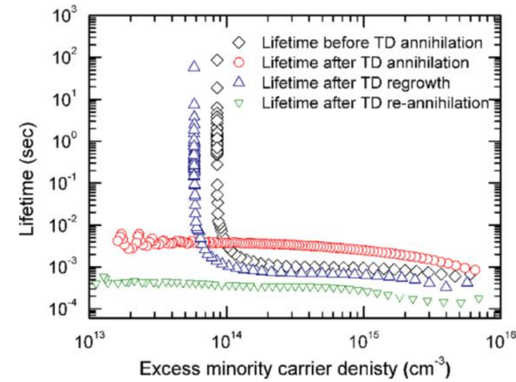
C_i?

Si_iH_X?

…

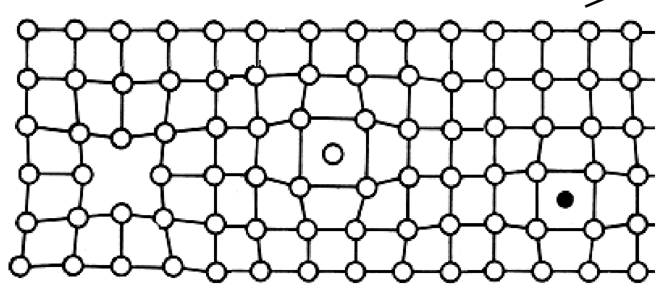


N.Najid et al. N-PV workshop (2013)



Y. Hu et al. J. Appl. Phys. (2012)

Scarce literature on the influence of intrinsic point defects on the lifetime



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Outline

- Grown-in extended defects
- Characterizing as-grown defects
- Grown-in point defects in n-type CZ
- Grown-in point defects in n-type FZ

Lets have a small exercise

- Lifetime of 1ms
- Assume a midgap defect with a standard capture cross section of $\sigma_p = \sigma_n = 1\times10^{-14}$ cm^2

$$\tau_{p0} = \frac{1}{N_t \sigma_p v_{th}}$$

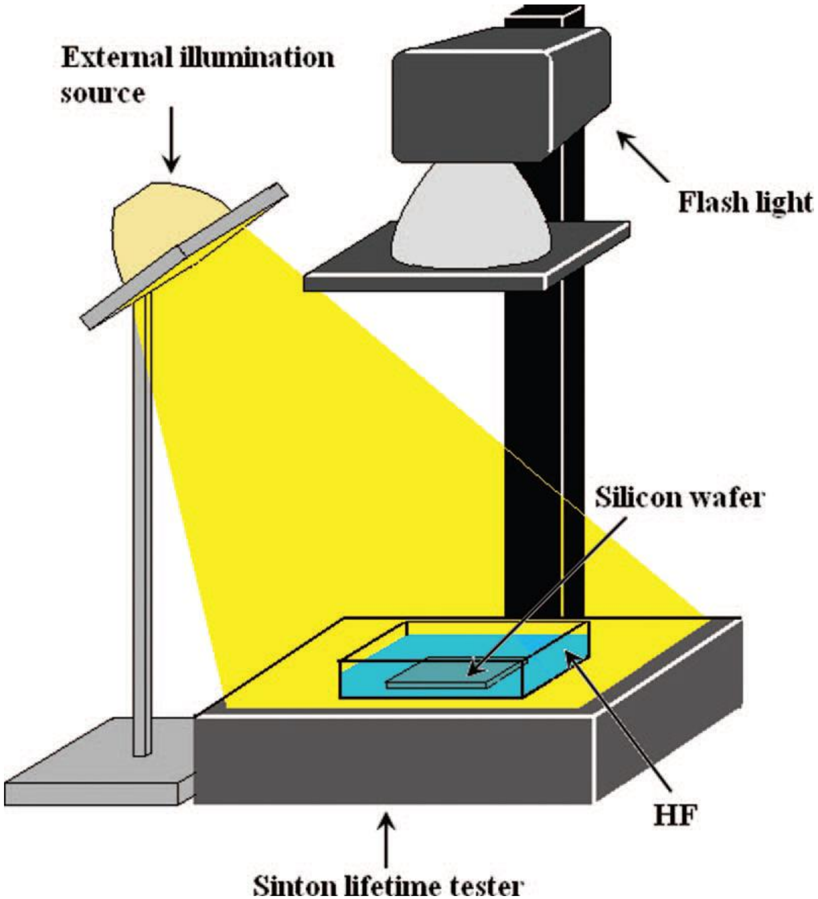
Lets have a small exercise

- Lifetime of 1ms
- Assume a midgap defect with a standard capture cross section of $\sigma_p = \sigma_n = 1\times10^{-14}$ cm^2 $$\tau_{p0} = \frac{1}{N_t \sigma_p v_{th}}$$
- Defect density N = 1× 10^{10} cm^{-3}
- Cannot be identified with DLTS or EPR
- We need lifetime spectroscopy to identify the defect

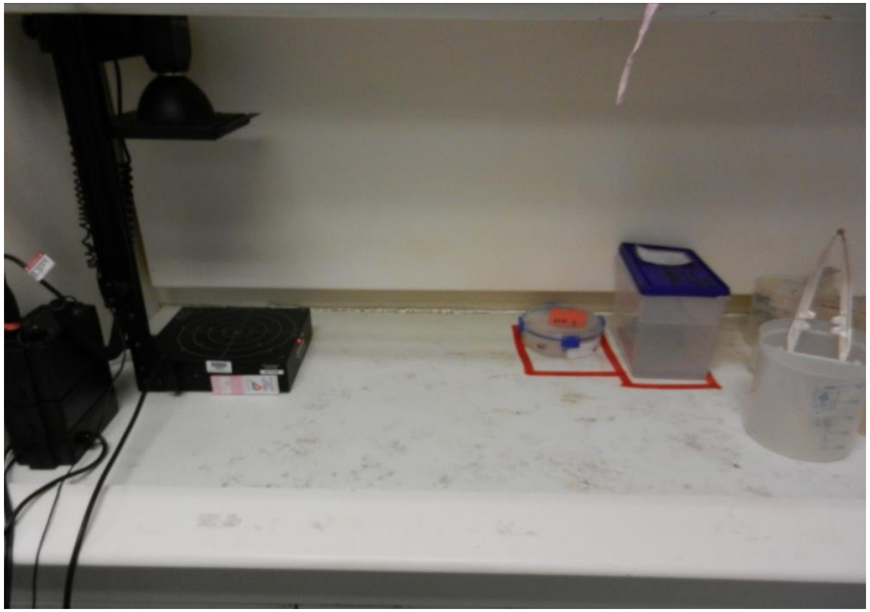
Influence of passivation

- Using SiN_X:H or Al_2O_3:H can potentially anneal or hydrogenate bulk grown-in defects
- We need room temperature passivation
- We use a range of passivation techniques to understand hydrogenation effects

HF passivation to investigate grown-in defects

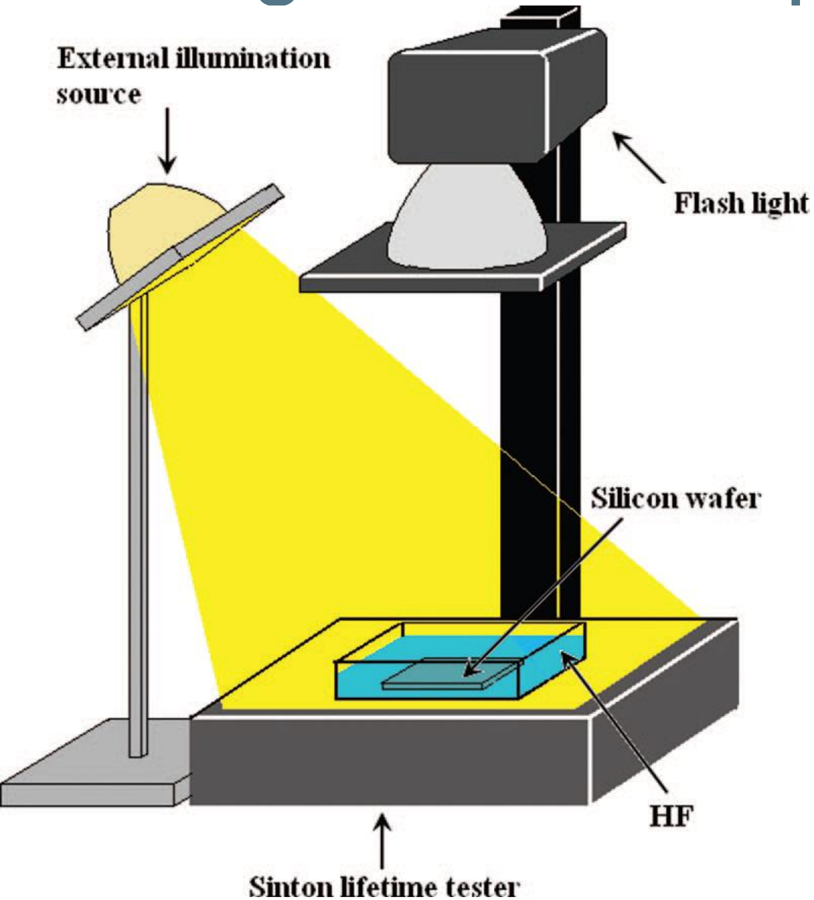


E. N. Grant et al. *ECS J. Sol. St. Sc. Tech.* (2012)



HF passivation provides room temperature passivation

Value in understanding defect in their as-grown or as-processed state



E. N. Grant et al. *ECS J. Sol. St. Sc. Tech.* (2012)

- Represent the "true" growth conditions
  - Using thermal SiO_2, SiN_X:H or Al_2O_3:H can change the state of the defect
  - HF passivation will measure the defect as is
  - $S_{eff} = 1.1 \pm 0.2$ cm.s^{-1}

Outline

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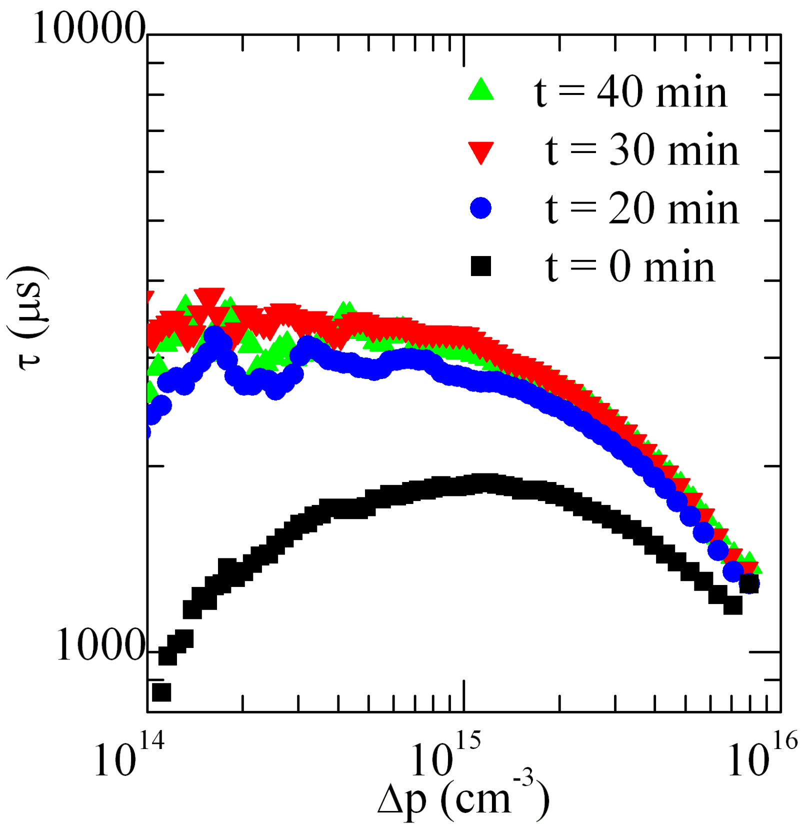
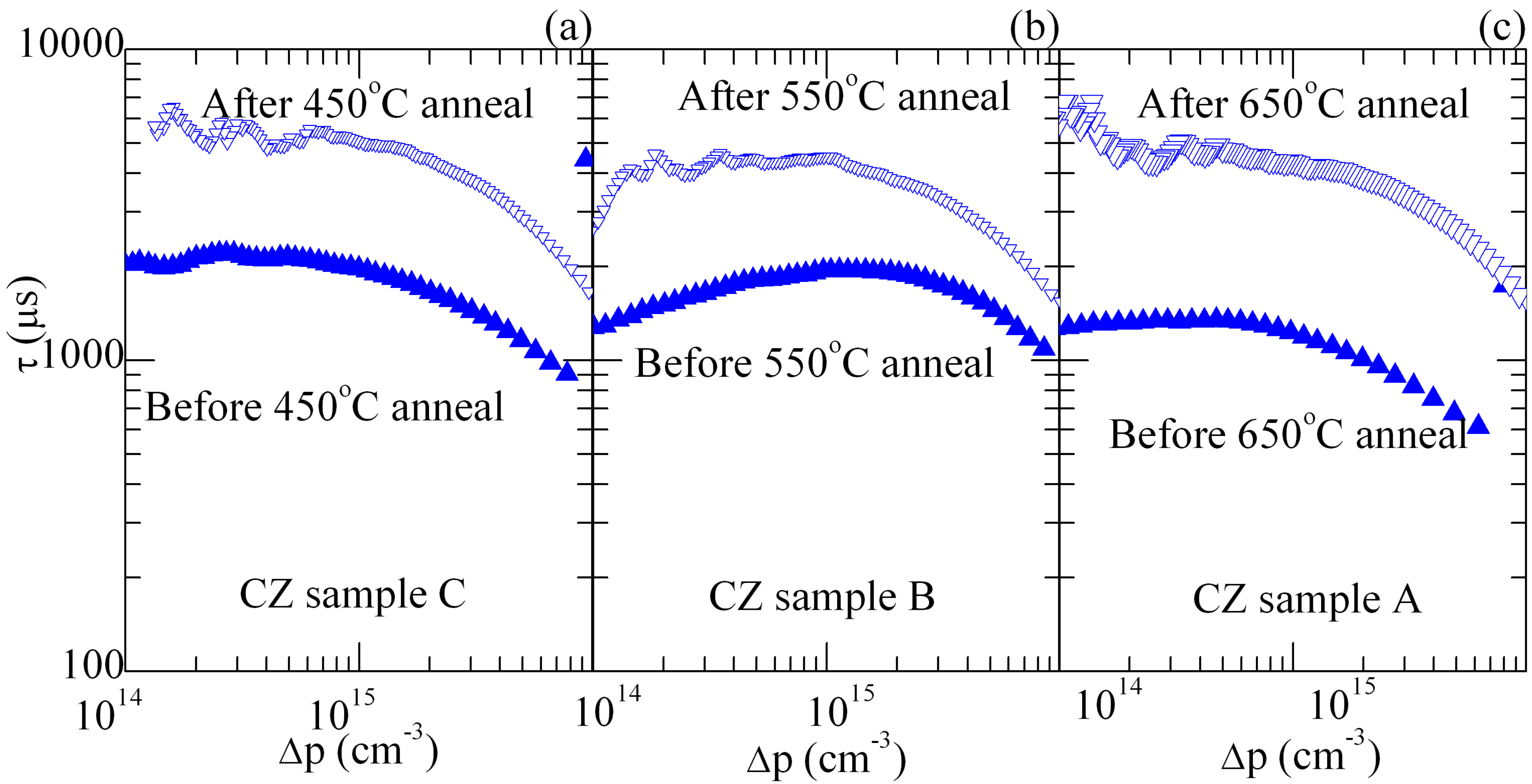
- Grown-in point defects in n-type FZ

Defects in CZ silicon

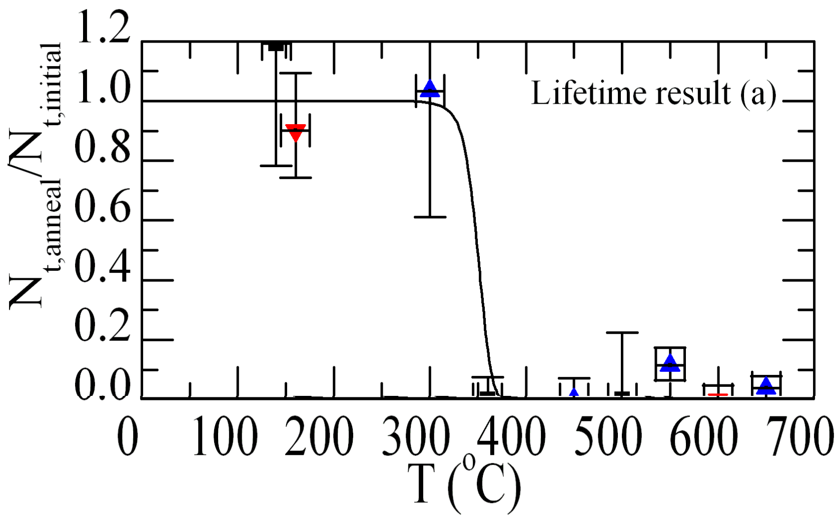


- Anneal at 360°C for different length of time
- The defect is deactivated after 30 min

Defects in CZ silicon



Defect thermal de-activation



- Isochronal anneal for 30 min
- The defect is deactivated above 360°C

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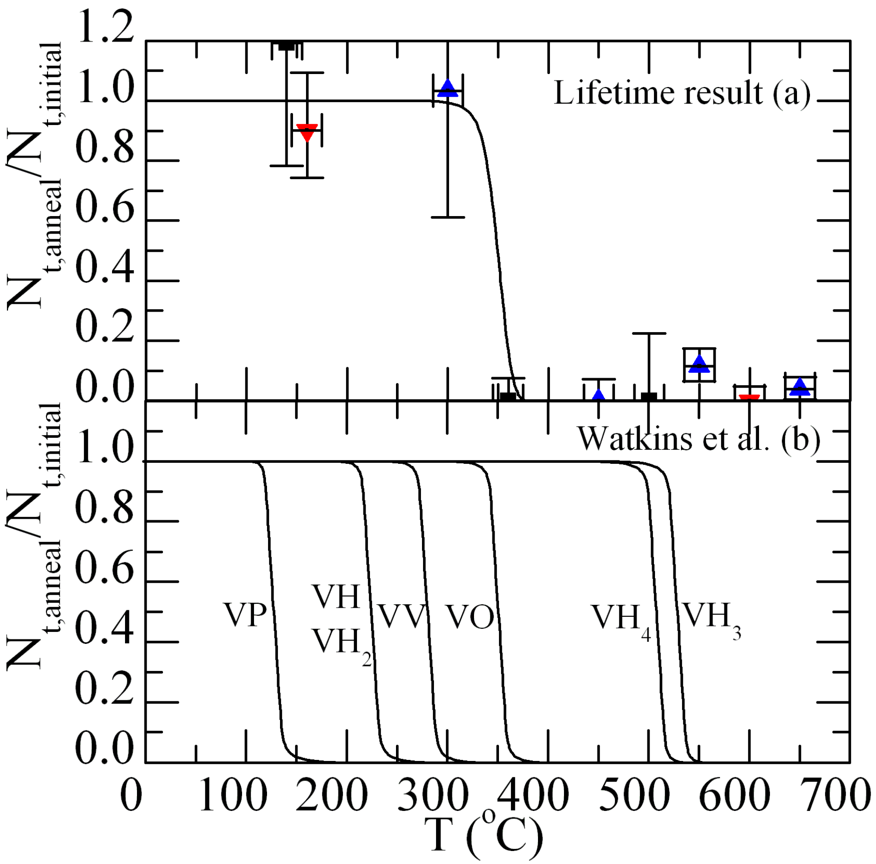
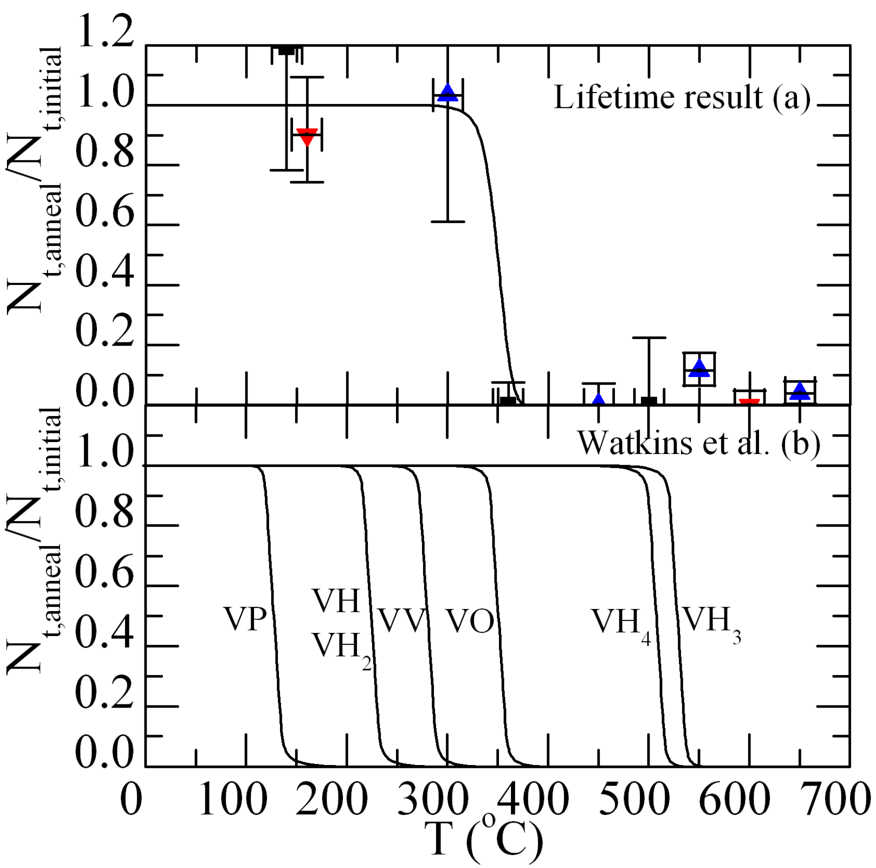
Identification (tentative) of the defect



- The defect is deactivated above 360°C
- The defect could be related to vacancy-oxygen pairs
- Highly influential for heterojunction designs

Defects in CZ silicon



- Oxygen is a problem for precipitates, stacking faults, thermal donors and pairing with vacancies
- Why not use FZ silicon?

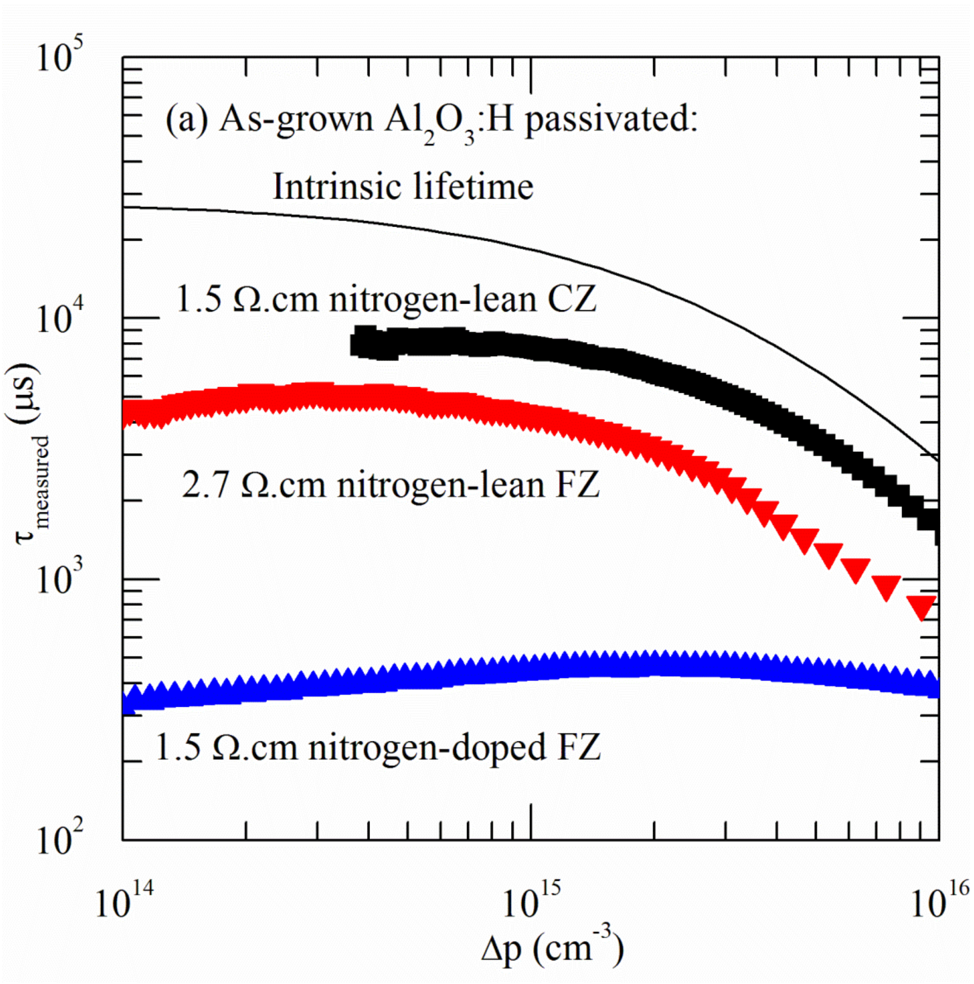
Outline

- Grown-in extended defect
- Characterizing as-grown defect
- Grown-in point defects in n-type CZ
- Grown-in point defects in n-type FZ

Why is there nitrogen in FZ silicon?

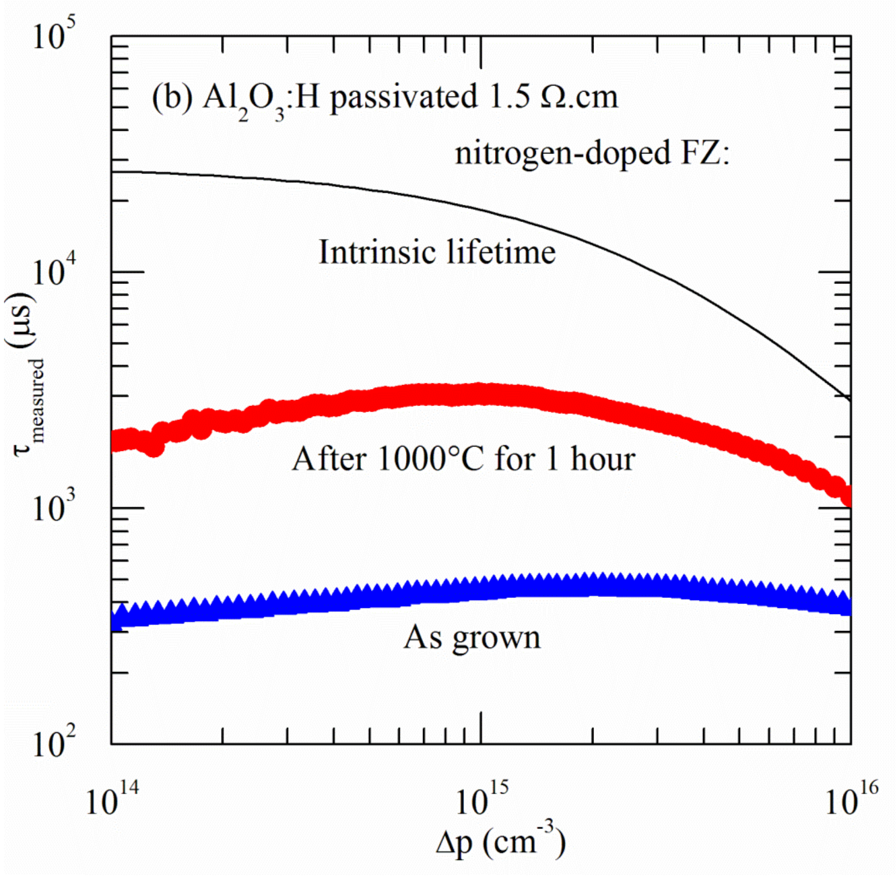
- Mitigates the impact of extended defects.
- Suppresses the formation of vacancy and interstitial aggregates
- $N_2 + V \rightarrow N_2V$
- $N_2V + I \rightarrow N_2$
- Pins dislocations for improved mechanical stability at high temperature

Defects in nitrogen-doped FZ silicon?



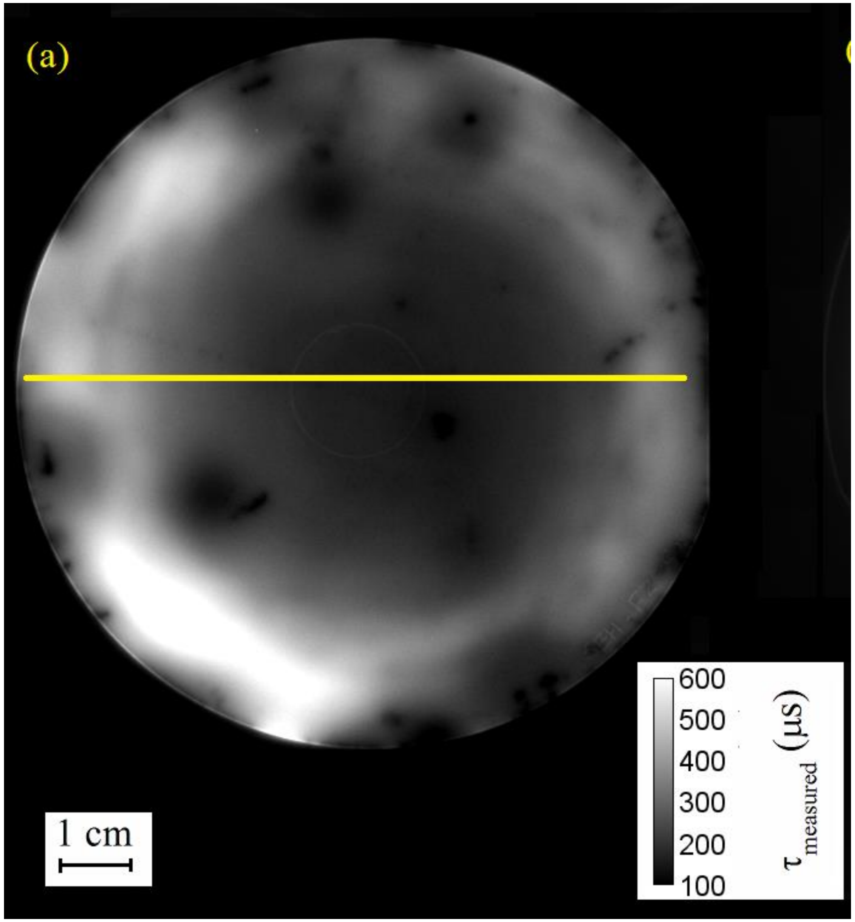
- Nitrogen-doped FZ silicon wafers have lower as-grown lifetime than nitrogen-lean FZ or CZ wafers

Thermal deactivation of defect



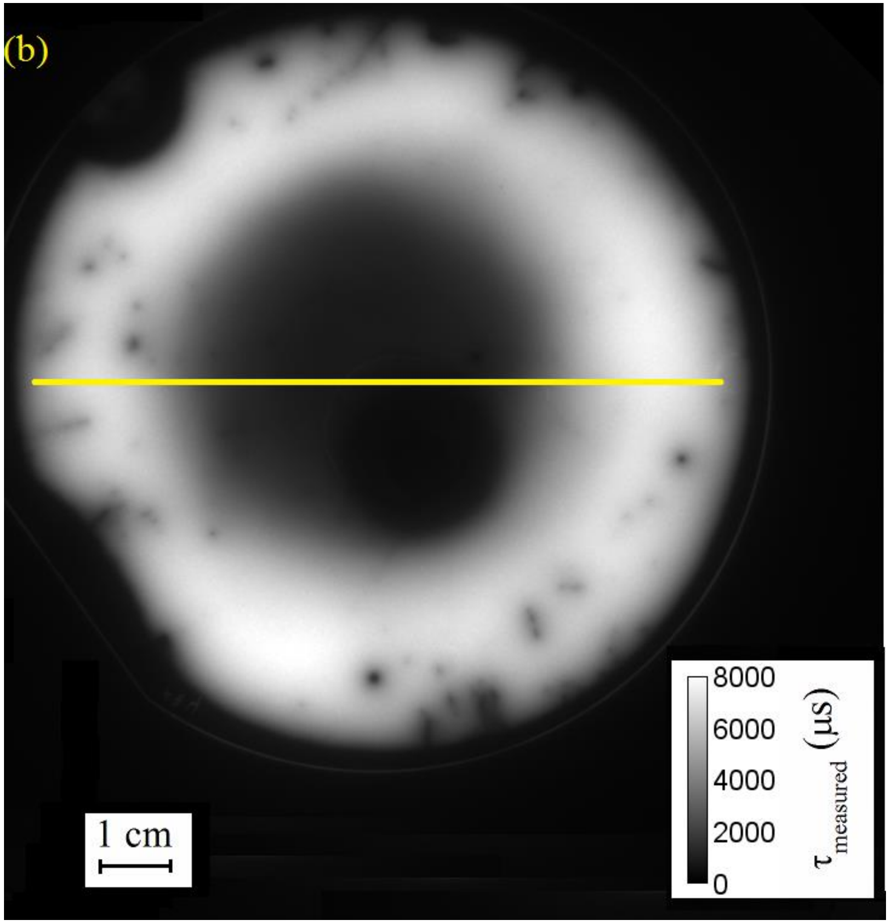
- Lifetime increases significantly after anneal at 1000°C
- Removal or transformation of recombination active defect
- What is the defect?

Spatial distribution of the lifetime Al_2O_3:H



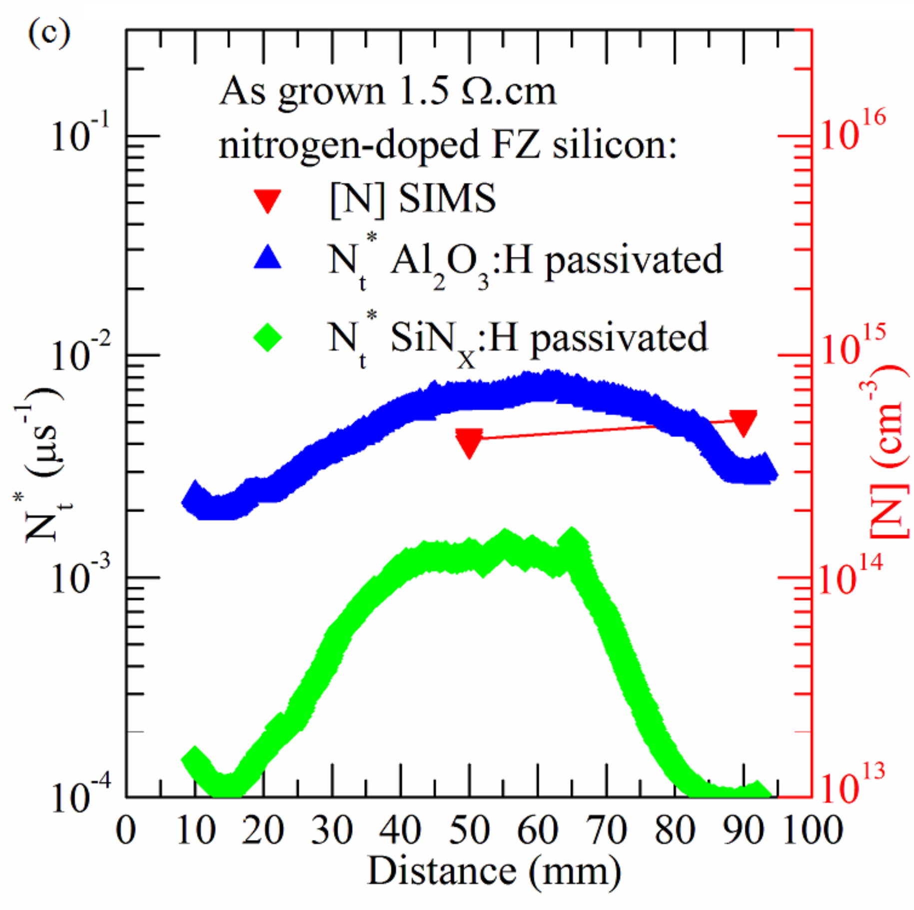
- Higher lifetime around the edges
- Radially symmetric distribution of lifetime

Spatial distribution of the defect lifetime SiN_X:H



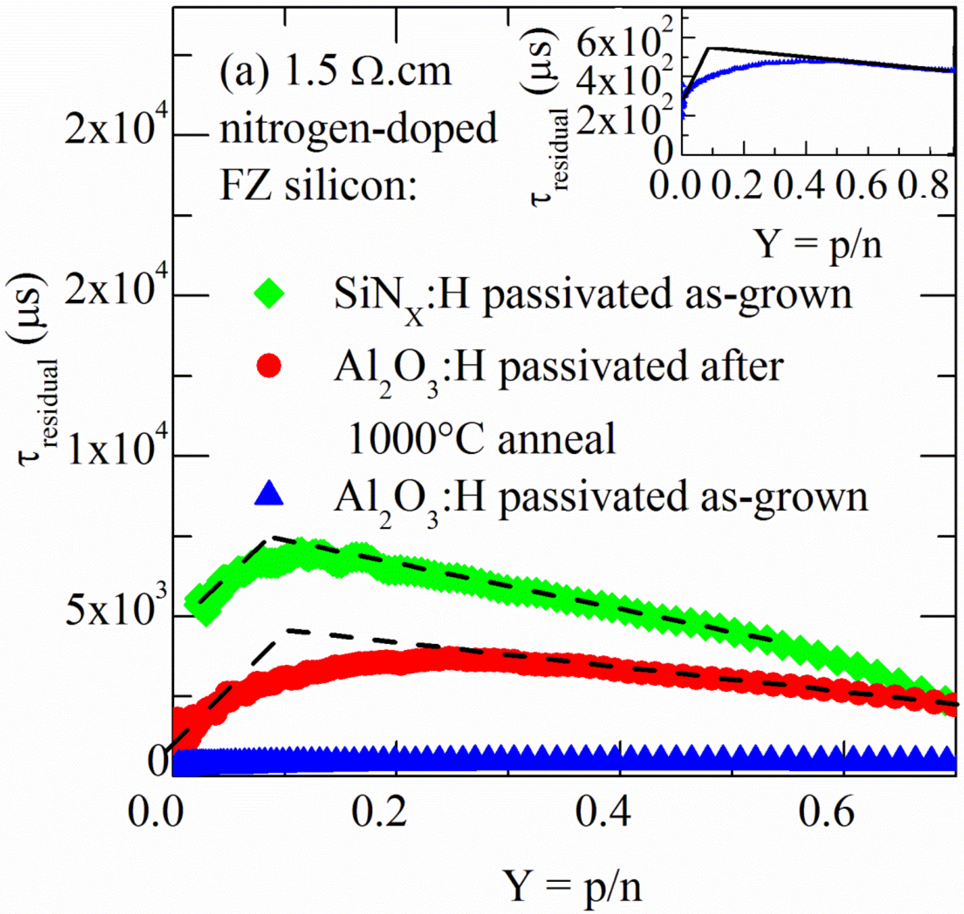
- Higher lifetime around the edges
- Radially symmetric distribution of lifetime
- Higher lifetime than Al_2O_3:H
- What does that imply for the defect structure?

Spatial distribution of the defect



- Defect density higher in the centre
- Nitrogen constant laterally
- Radial distribution suggests nitrogen-vacancy point defect
- Is there one or many different defect species?

One or many defect species?

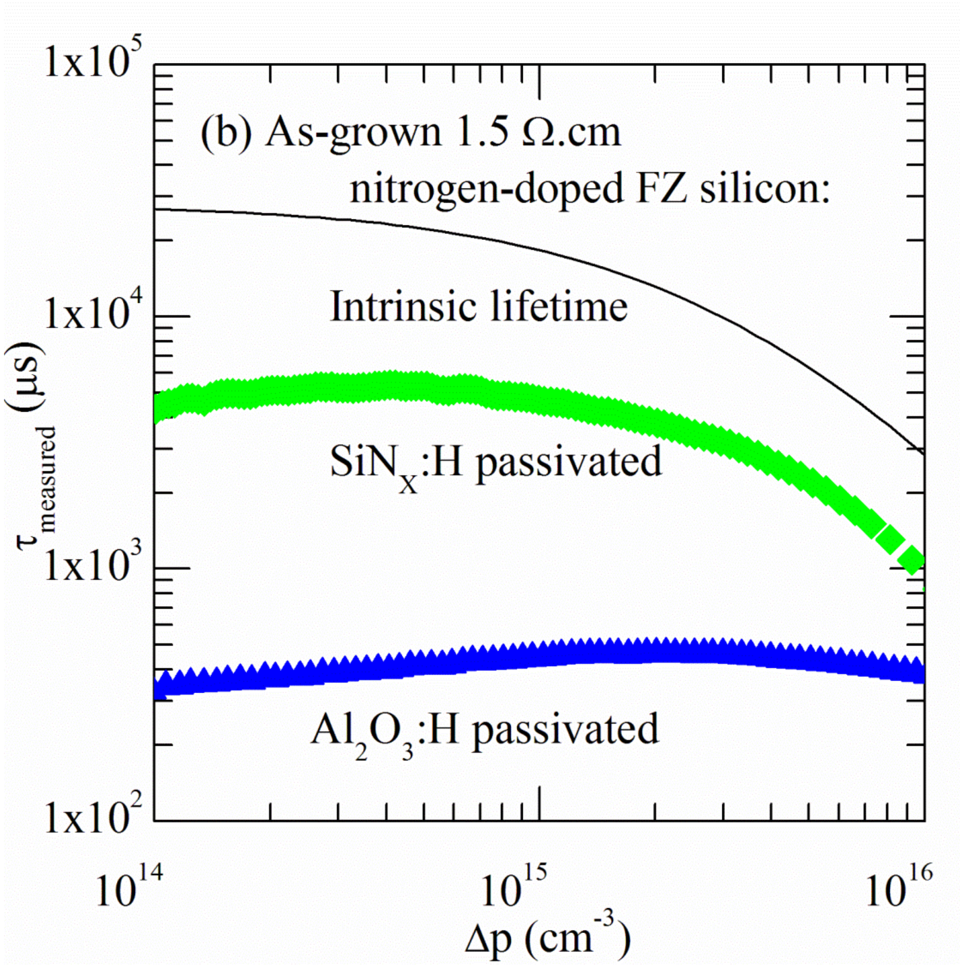


$$\tau_p = \frac{1}{\alpha_p N}\left[1 + \frac{n_1}{n_0} + \frac{p_1}{n_0 Q} + Y\left(\frac{1}{Q} - \frac{n_1}{n_0} - \frac{p_1}{Q n_0}\right)\right]$$

J. D. Murphy et al. J. Appl. Phys. (2012).

- Absence of a single linear trend
- More than one type of defect

Effect of passivating films with different hydrogen contents



- SiN_X:H contains 15%-20% total H (complexed and atomic)
- Al_2O_3 contains less than 5% total H
- Increases the lifetime through bulk hydrogenation

Conclusion: Extended defects

- Stacking faults and oxygen precipitates can severely limit the lifetime of n-type monocrystalline silicon
- High temperature processes can increase the recombination activity by changing the precipitate density, having strained precipitates and through metallic decorations
- Dislocations and slip lines are detrimental but should not occur when using high purity feedstocks

Conclusion: Point defects

- We demonstrate that intrinsic point defects paired with light elements can limit the lifetime of high purity silicon wafers
- V_XO_Y and V_XN_Y complexes are two likely candidate limiting the lifetime of CZ and FZ silicon
- Solutions to increase the lifetime:
    - from 1-2ms to 5ms after annealing above 360°C of CZ silicon
    - from 0.5 ms to 3-5ms after annealing above 1000°C or hydrogenation of FZ silicon

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What is a control wafer?

- Standard high temperature and passivation processes are likely to affect the states or concentrations of defects through hydrogenation or annealing
- There is no such things as a perfect and stable control
- One must use multiple controls in order to rightfully interpret enhanced surface passivation or cell parameters

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Thank you for your attention