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Formation of dislocation pile-ups and subgrain boundaries in multicrystalline silicon

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SolarWorld — Mit uns wird Sonne Strom.

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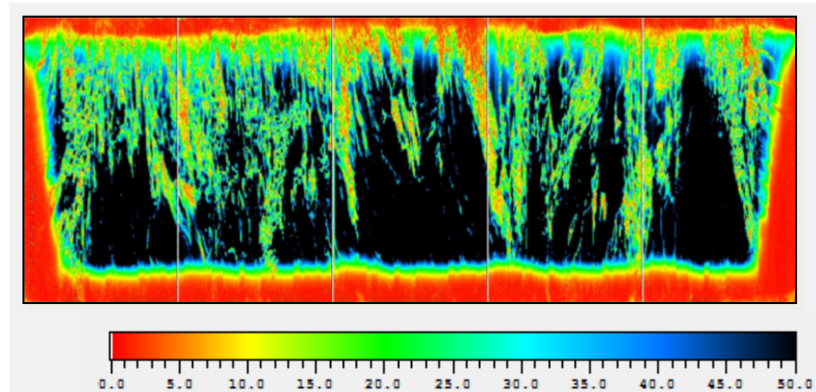
Introduction

Multicrystalline Silicon grown by directional solidification is the mainstream in PV industry due to low cost of ownership and high throughput.

Microwave-detected photoconductivity

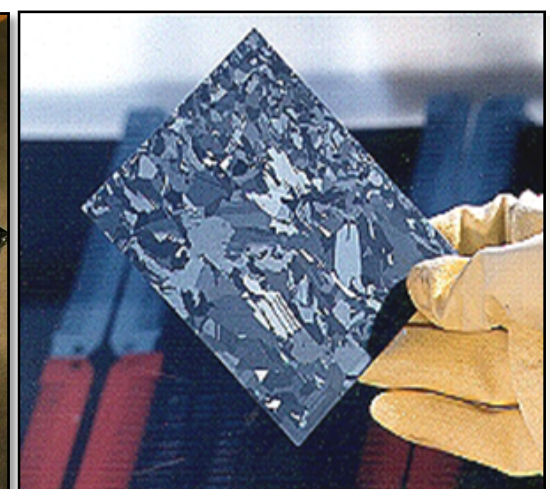


Minority carrier lifetime (µs)

Ingot

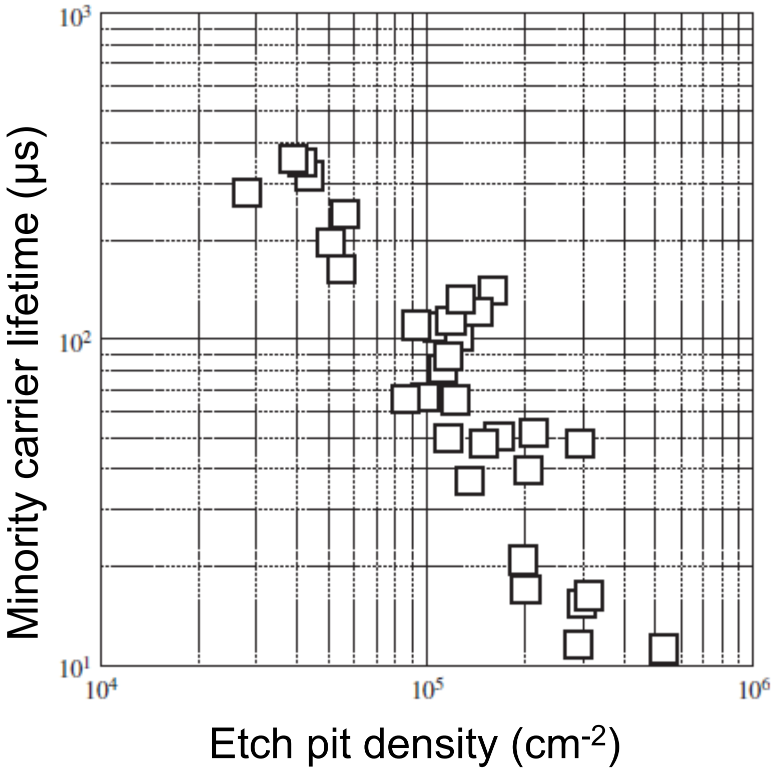
Bricks

Wafers



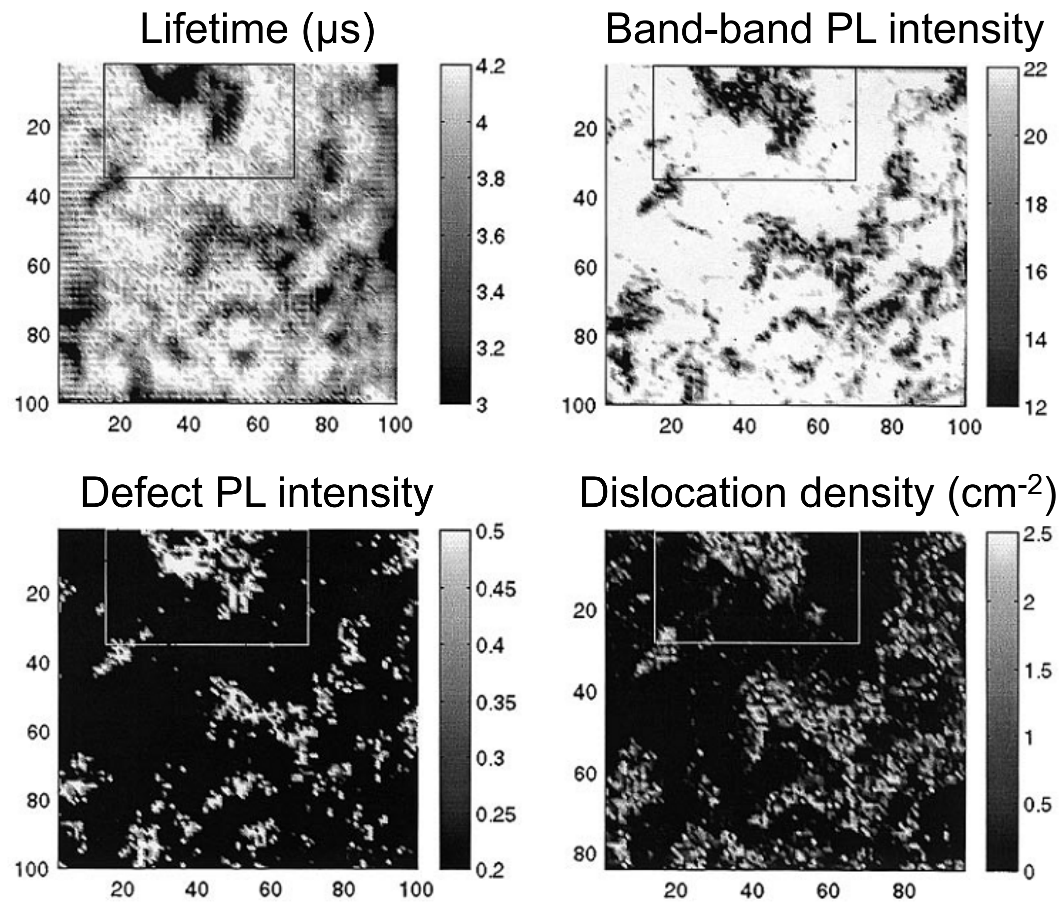
Dislocation issues in mc Si

Minority carrier lifetime *vs* etch pit density



[Arafune 2006]

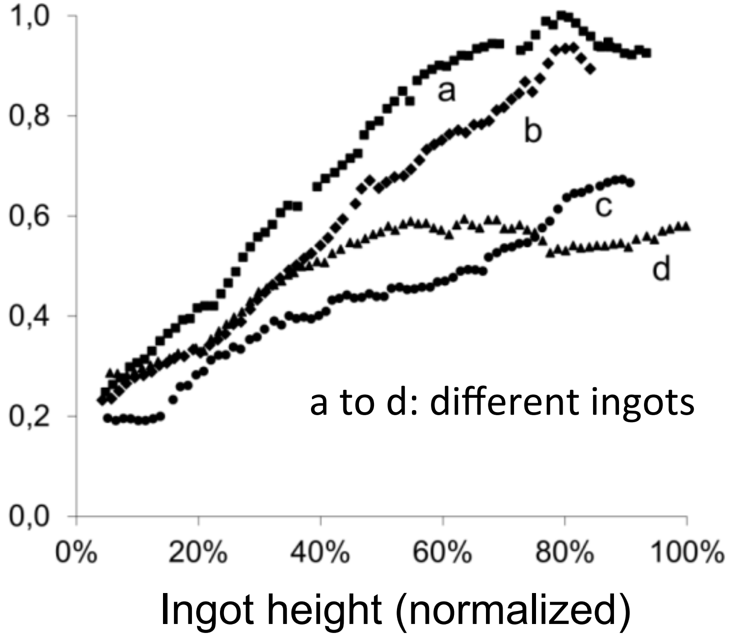
Carrier lifetime, BB PL, defect PL and dislocation density



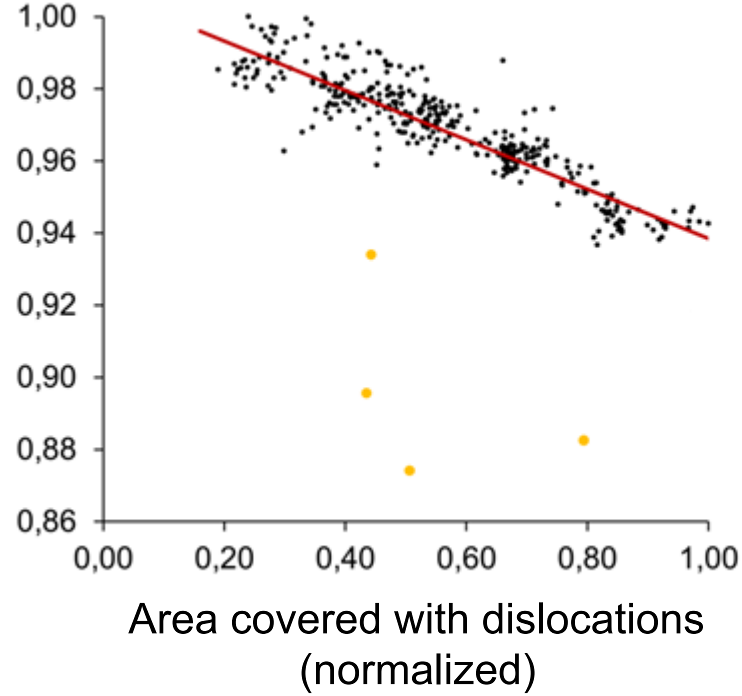
[Tarasov 1999]

Dislocations and solar-cell efficiency

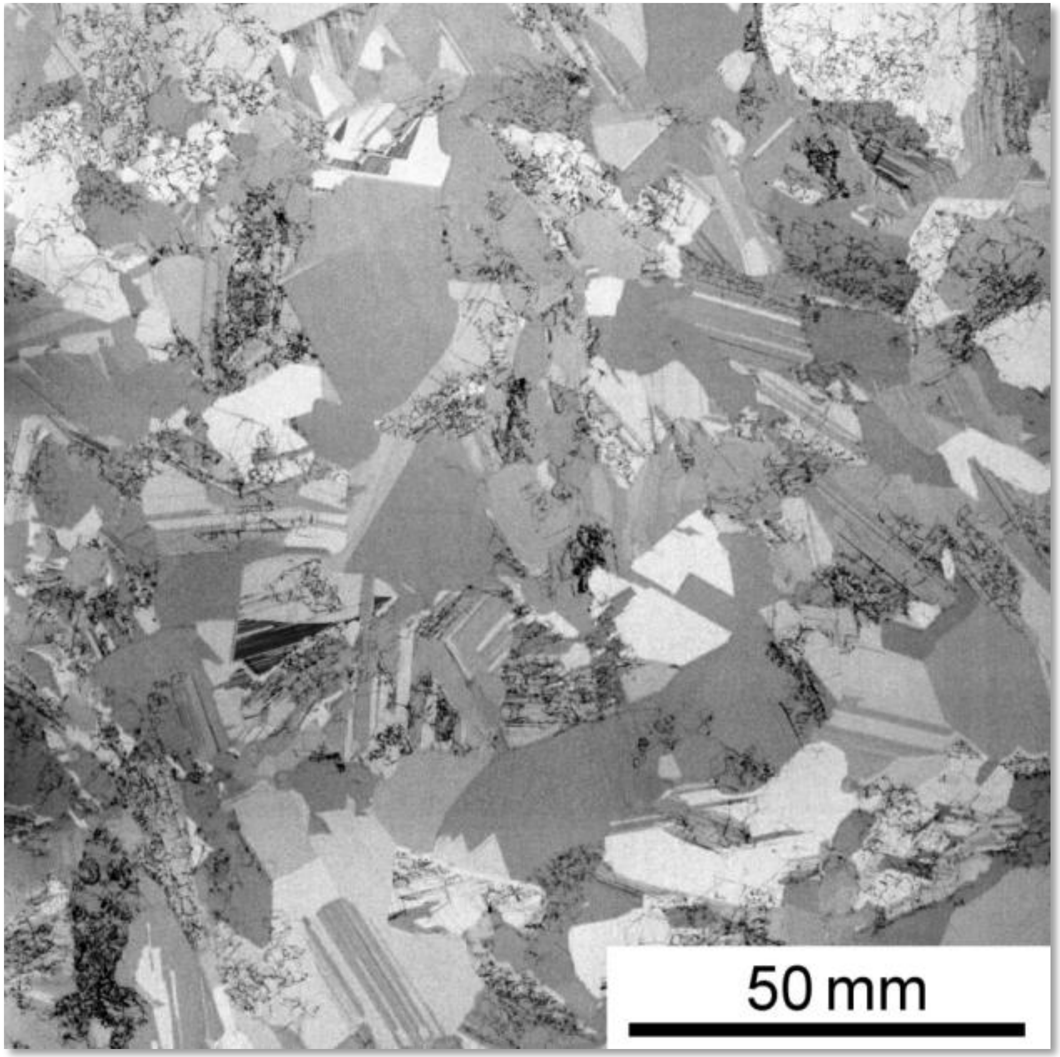
Area covered with dislocations



Solar-cell efficiency η

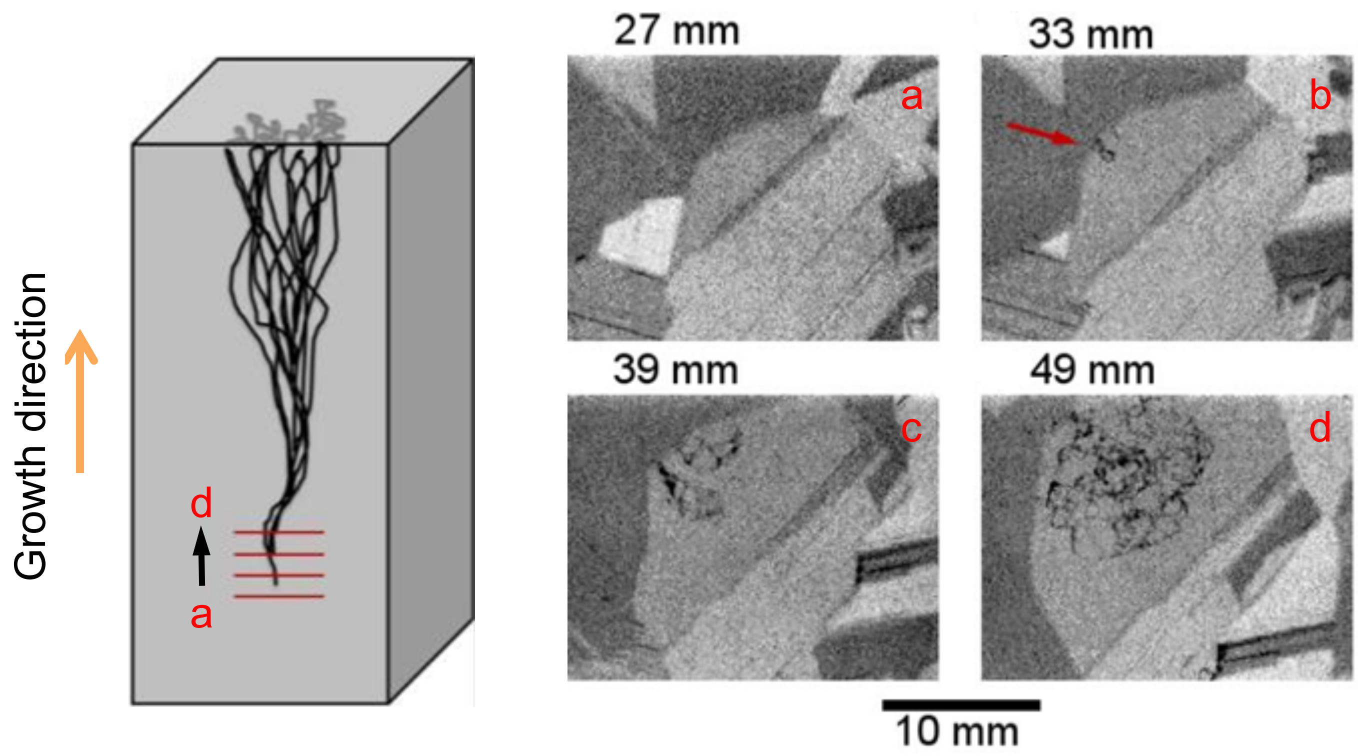


Etched wafer surface



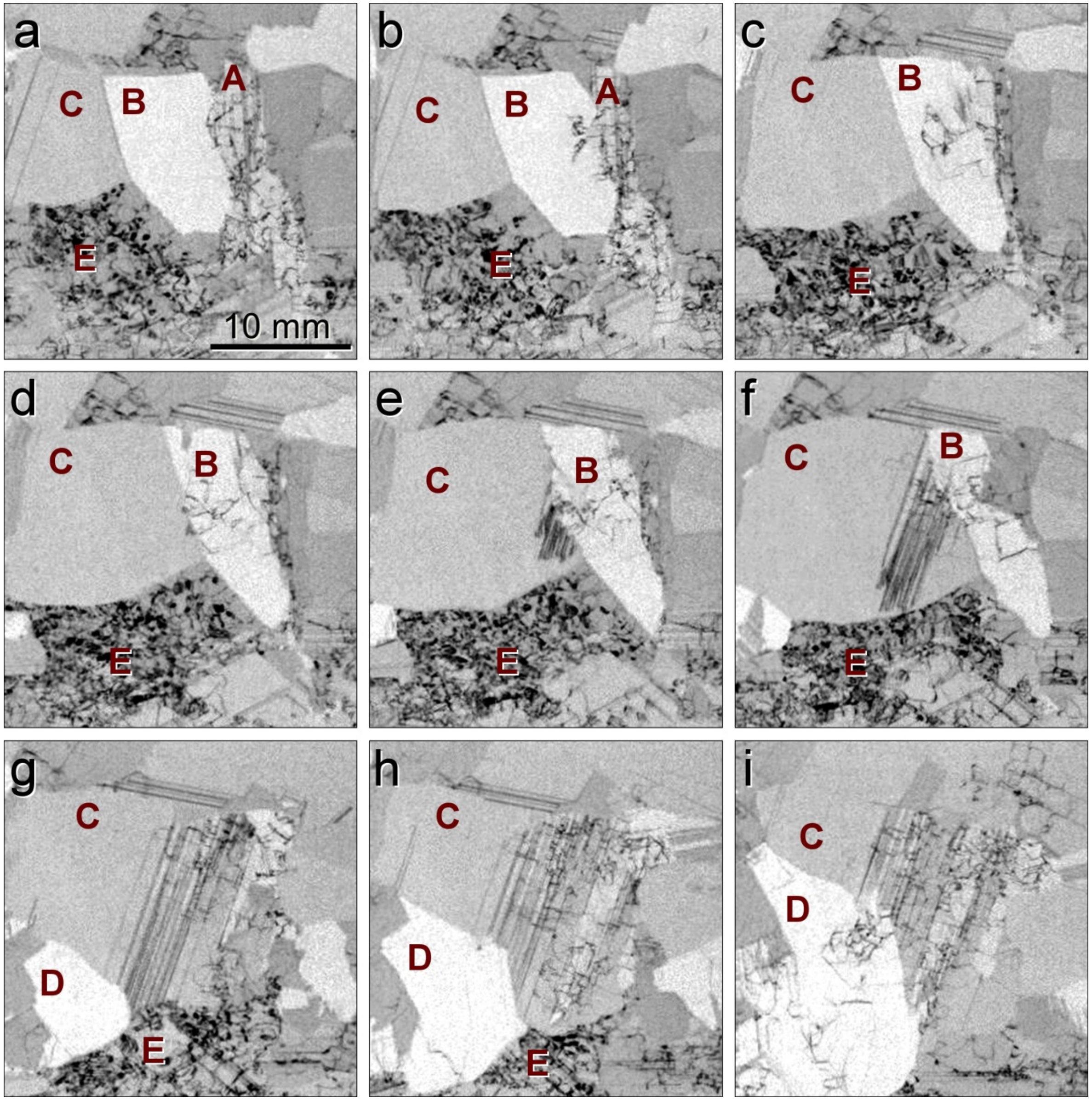
Typical dislocation distribution

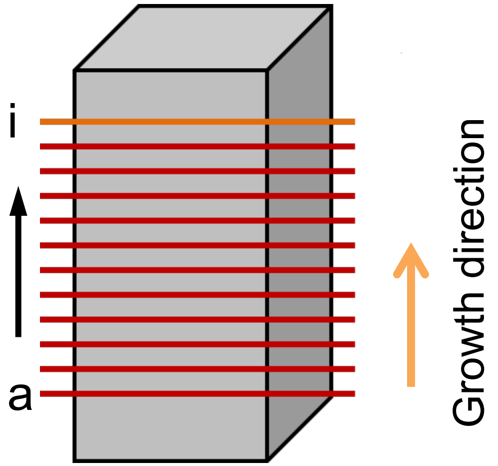
Evolution of dislocations



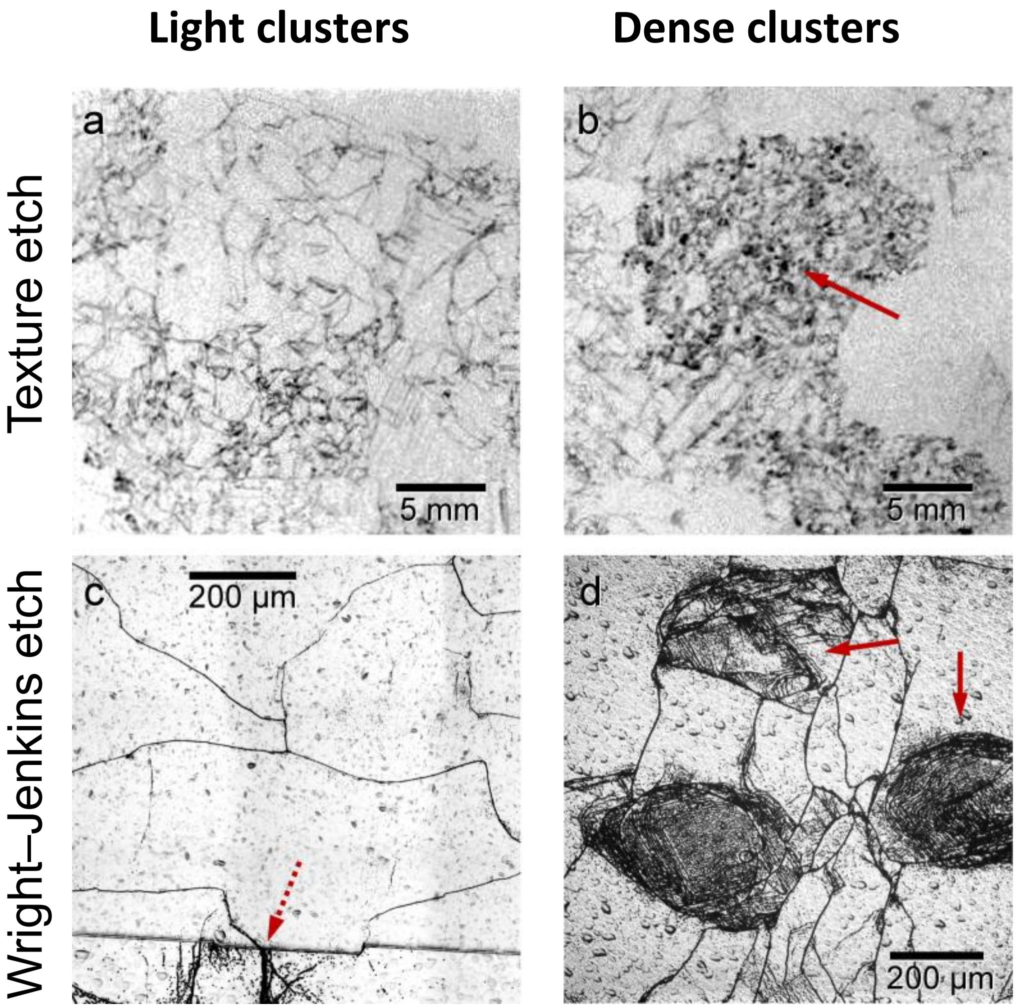
- Dislocation clusters mainly generated at grain boundaries
- Atomistic source of the spontaneous dislocation generation not known

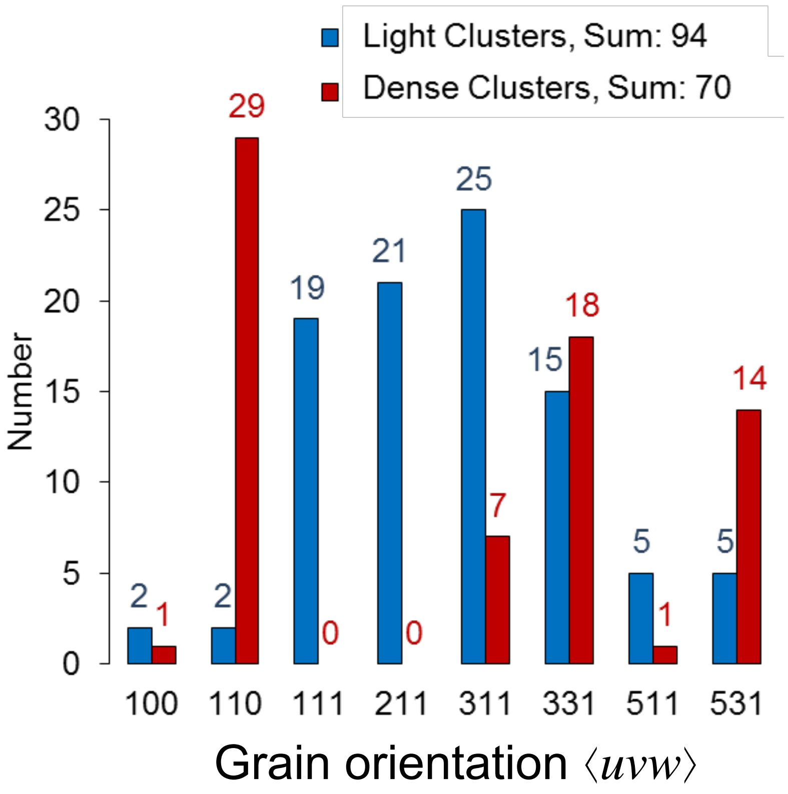
Change of defect distribution in the ingot



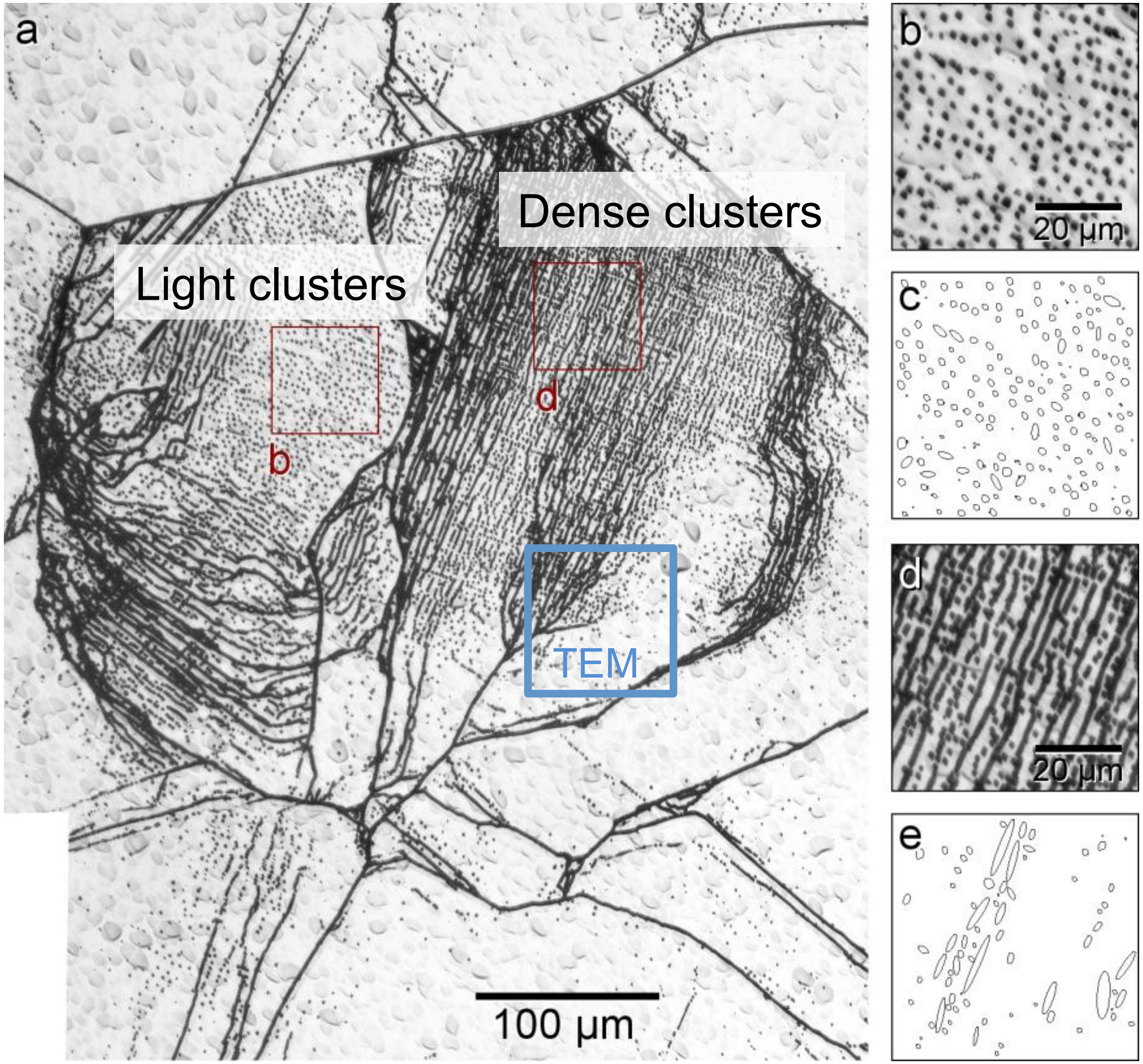


Grain orientation effect





Dislocation arrangements

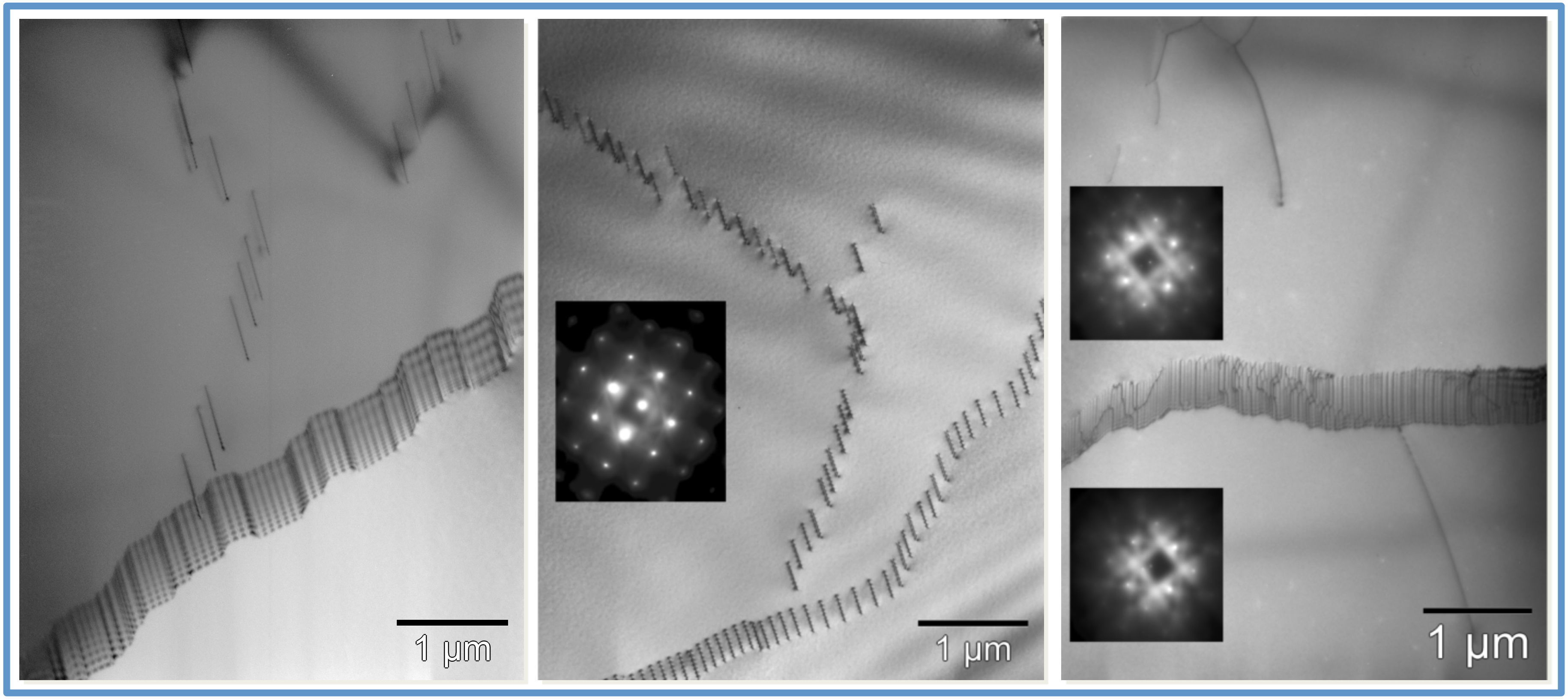


EPD ~ 1×10^5 cm^{-2}

~~EPD 2×10^5 cm^{-2}~~

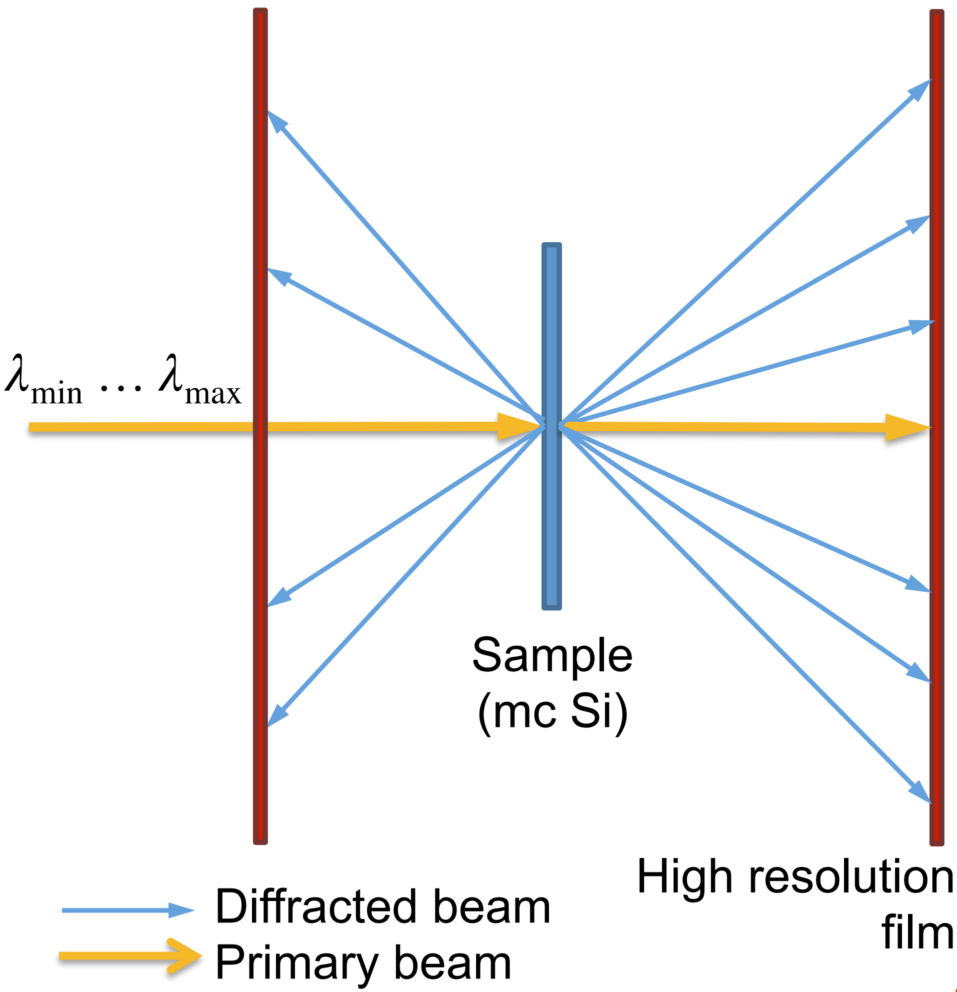
Too low for dislocation pile-ups/subgrain boundaries

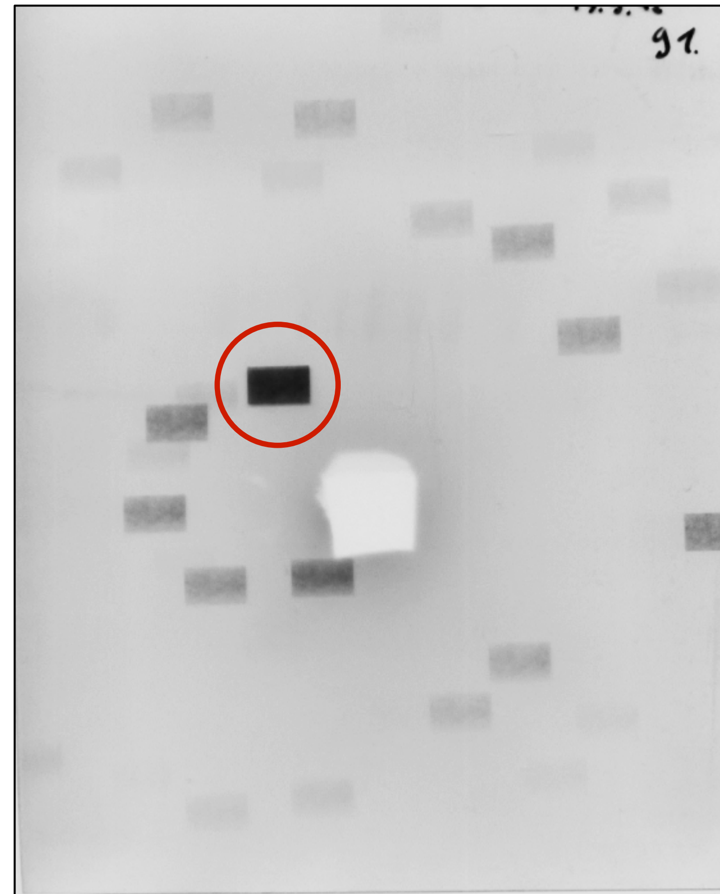
TEM of subgrain boundaries



- Dislocation distance h = 5 … 900 nm
- A preferred alignment dislocation arrangements exist, but not in relation to the orientation of the grains.

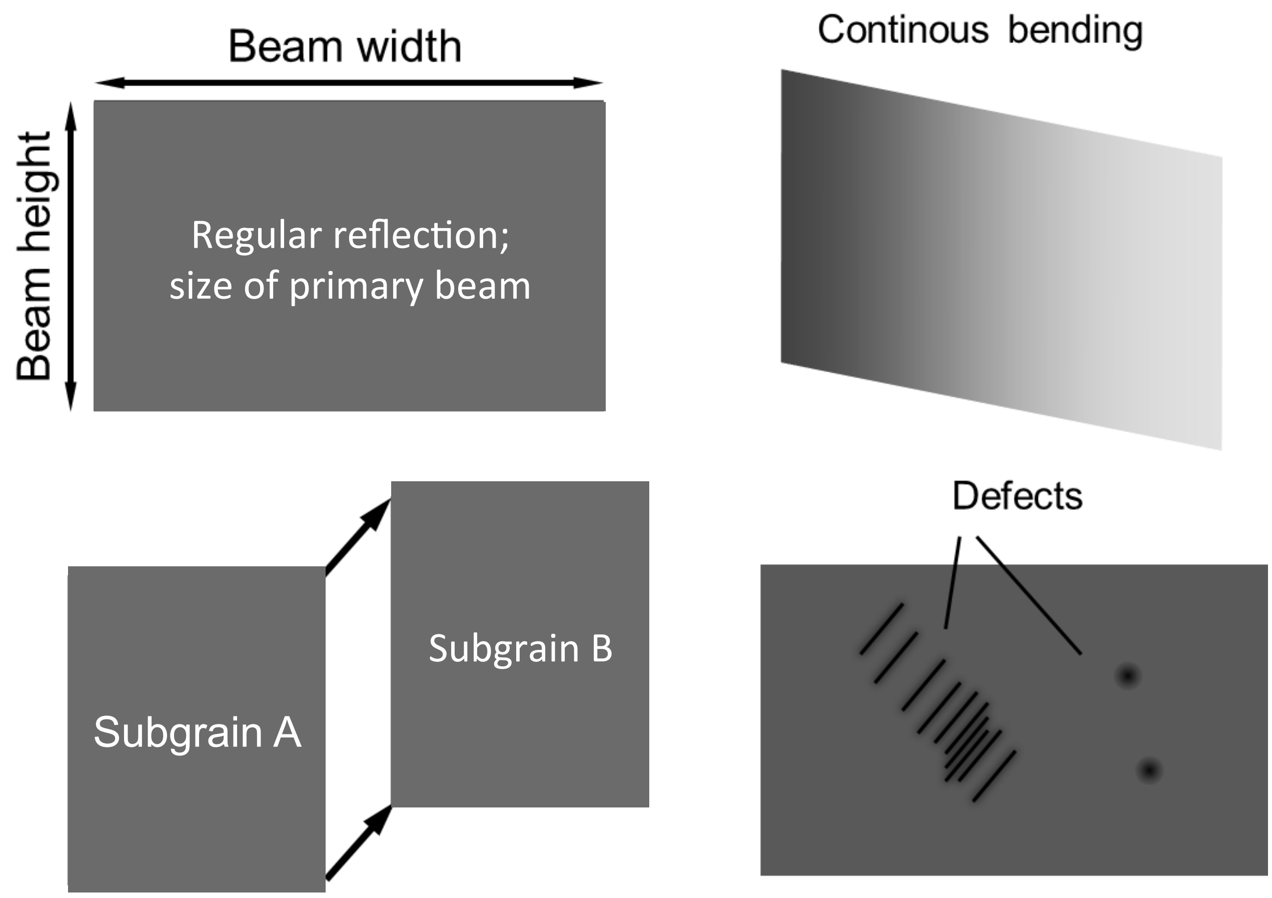
White beam X-ray topography (WB-XRT)





Laue pattern of the grain

Interpretation of WB-XRT contrasts

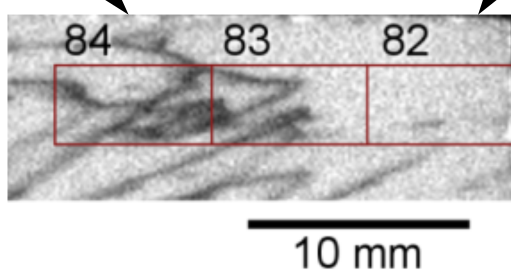


Splitting of the reflection
due to subgrain boundary

Splitting of reflections

Laue patterns acquired by WB-XRT in transmission mode

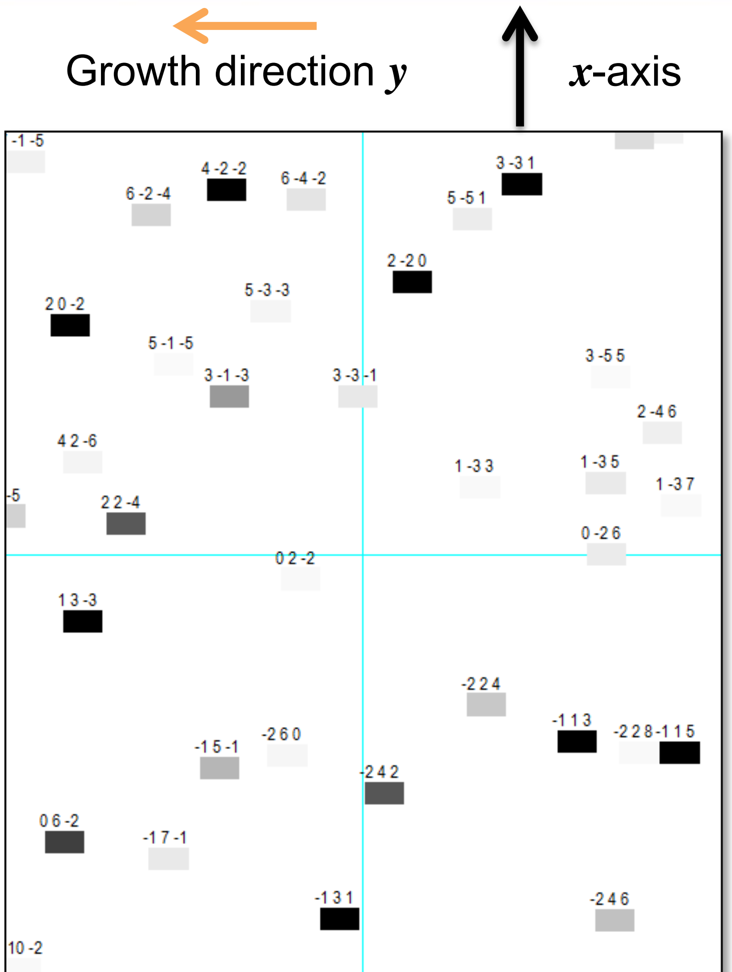
Growth direction



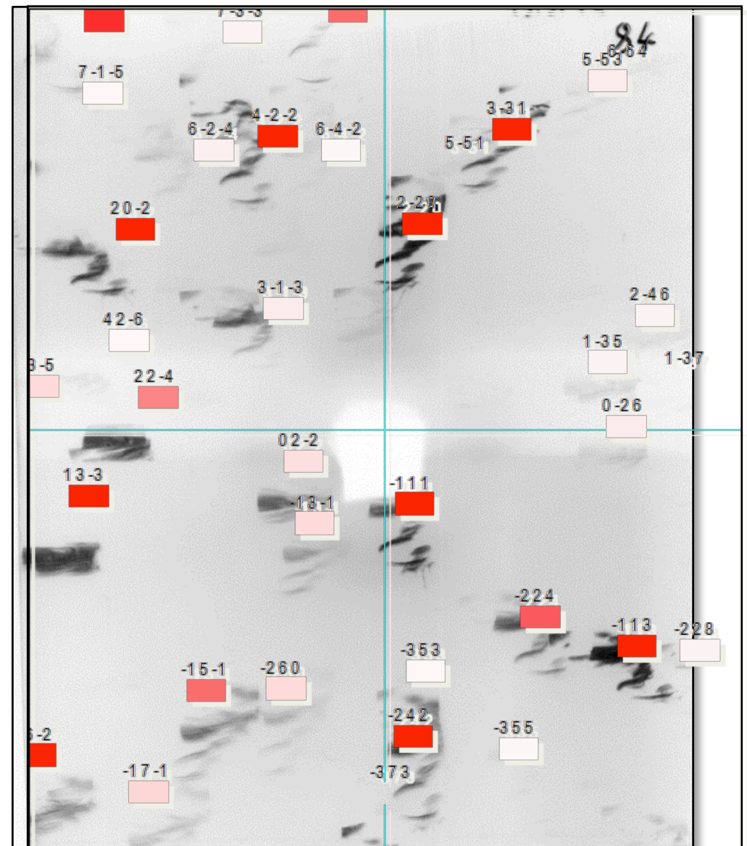
Band-band PL distribution (RT)

D Oriwol *et al*: Acta Mater **61** (2013) 6903.

Tilt of subgrains



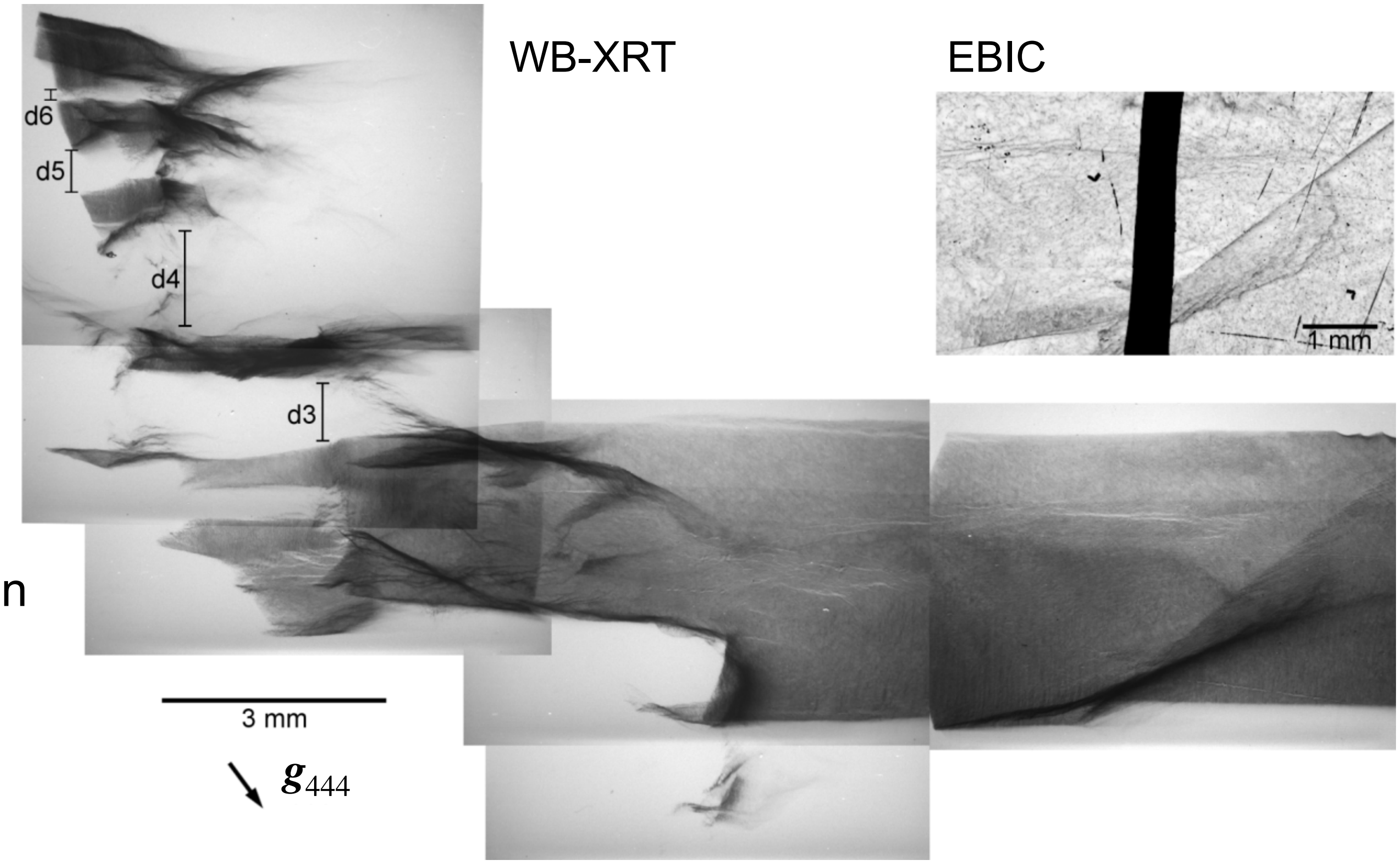
Simulation with **LauePT**



Simulation, rotated by 3° about *y*

Subgrains are tilted about an axis parallel to the growth direction

Relation of tilt and subgrain boundaries

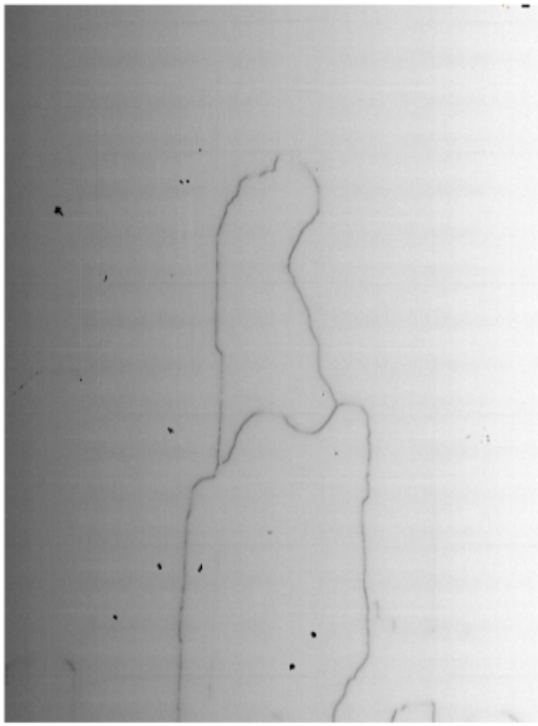


Growth direction

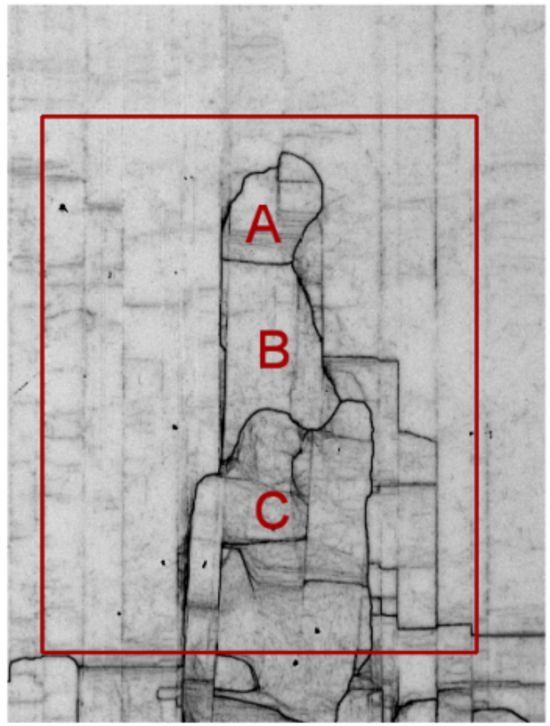
- Tilt = 0.07° (d6) ... 0.3° (d4) → dislocation distance h = 800 ... 30 nm
- The increase in dislocation density as a function of ingot heigth leads to a continuous generation of subgrain boundaries.

EBIC and X-ray topography

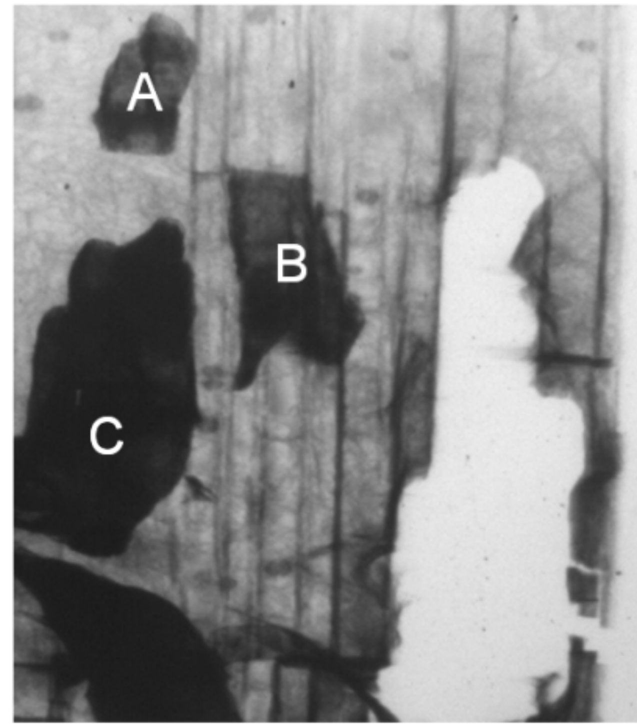
EBIC at RT



EBIC at 77 K



WB-XRT (transmission mode)

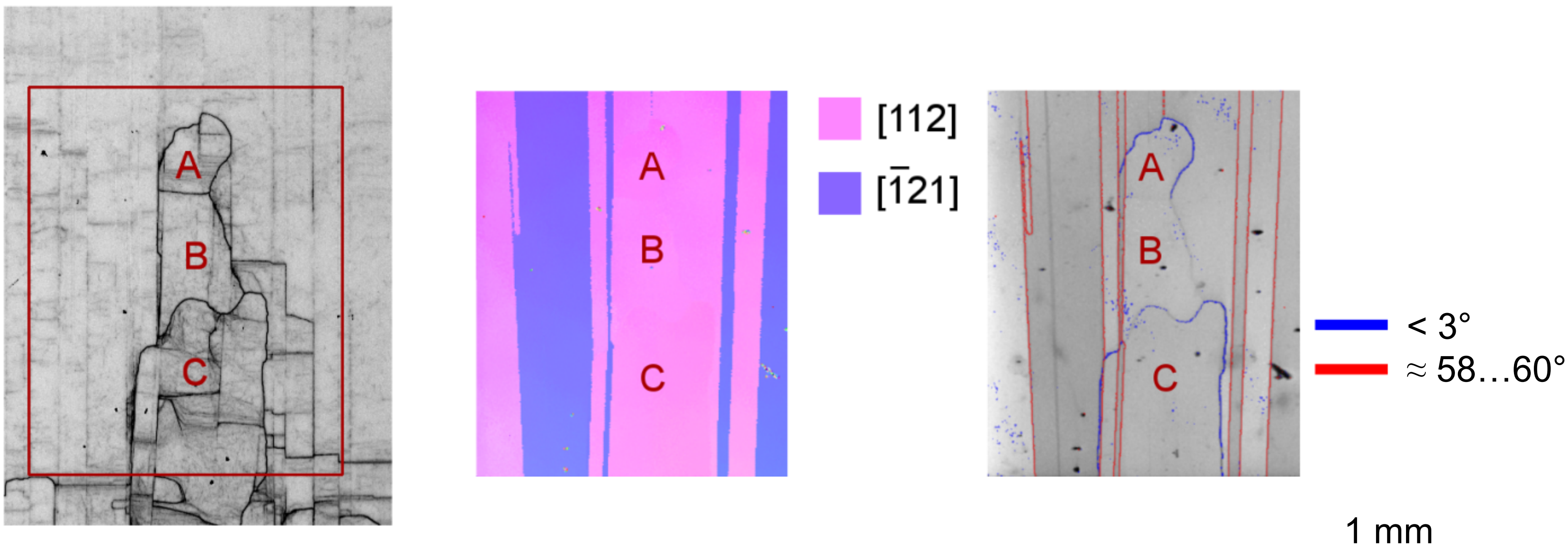


1 mm

EBIC and EBSD

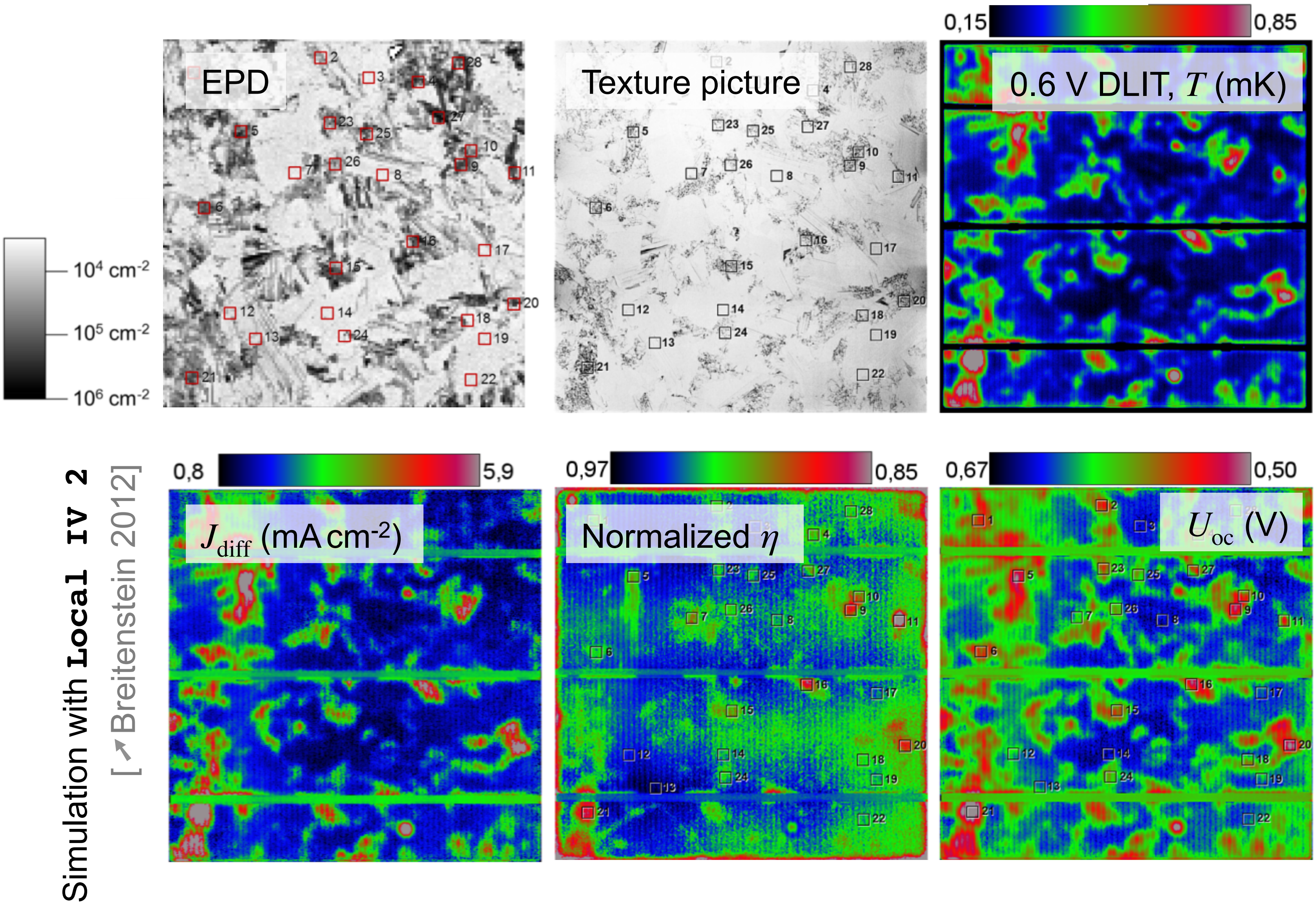
EBIC at 77 K

Electron backscatter difraction

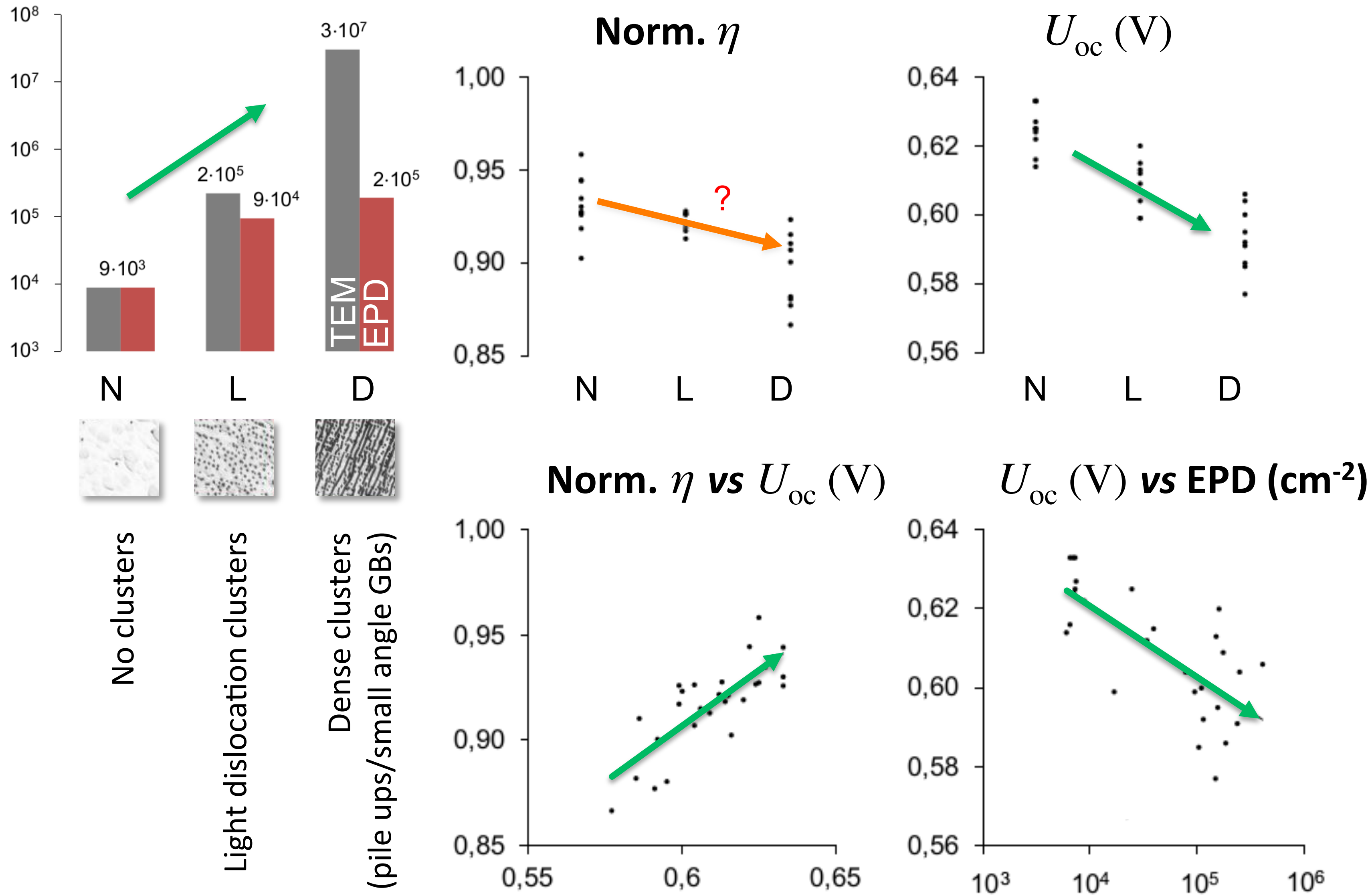


- Subgrain boundaries with tilt angles > 0.4° electrically active
- Large-angle grain boundaries with no EBIC contrast at RT
  → other reasons for electrical activation (no dislocation model)

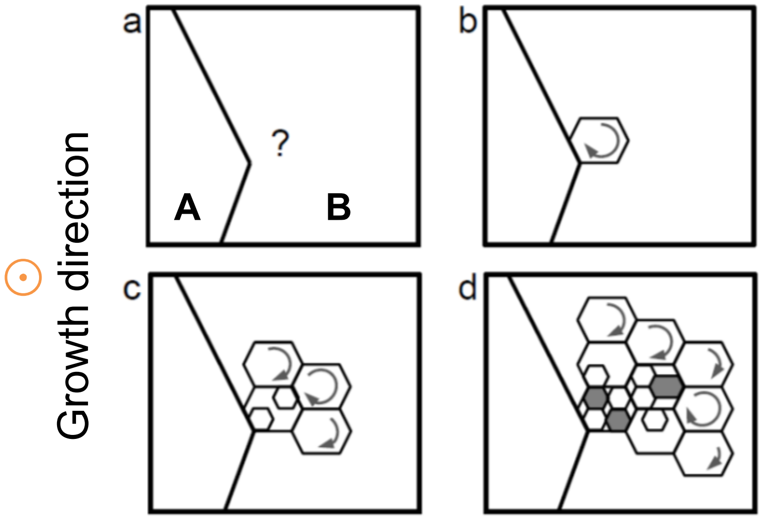
Dark lock-in thermography (DLIT)

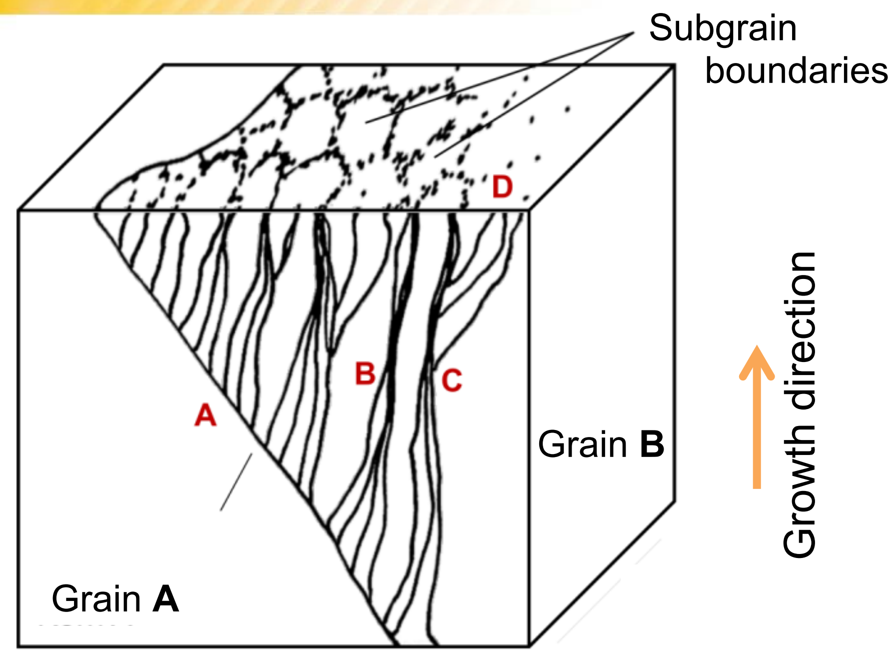


Correlation analysis



Conclusions





Evolution of dislocation pattern

- Initial generation, mostly at grain boundaries
- Inhomogeneous dislocation distribution on different scales
- Multiplication, pile-up and restructuring to subgrain boundaries
- Dislocation clusters with dominant influence on solar cell efficiency

ありがとうございました。

References

- K Arafune *et al*: Phys. B **376** (2006) 236.
- L Bragg, JF Nye: Proc Royal Soc Lond Ser A (1947) 474.
- O Breitenstein: Sol En Mater Sol Cells **107** (2012) 381.
- D Oriwol *et al*: Acta Mater **61** (2013) 6903.
- I Tarasov *et al*: Phys. B **273-274** (1999) 549.