International conference on
Extended defects in semiconductors, Göttingen 2014

Dislocation clusters in multicrystalline silicon

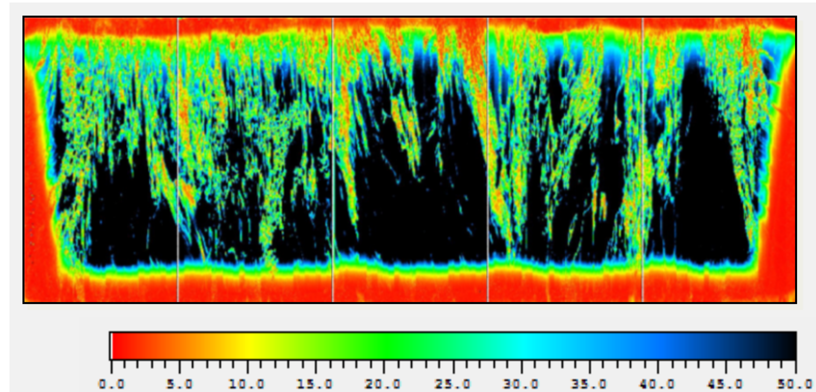
Daniel Oriwol, Hartmut S. Leipner, Andreas N. Danilewsky,
Lamine Sylla, Winfried Seifert, Martin Kittler, Jan Bauer

SolarWorld
Mit uns wird Sonne Strom.

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

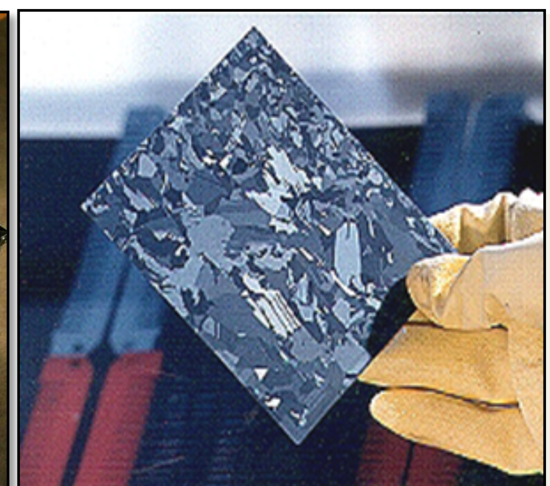


Minority carrier lifetime (µs)

Ingot

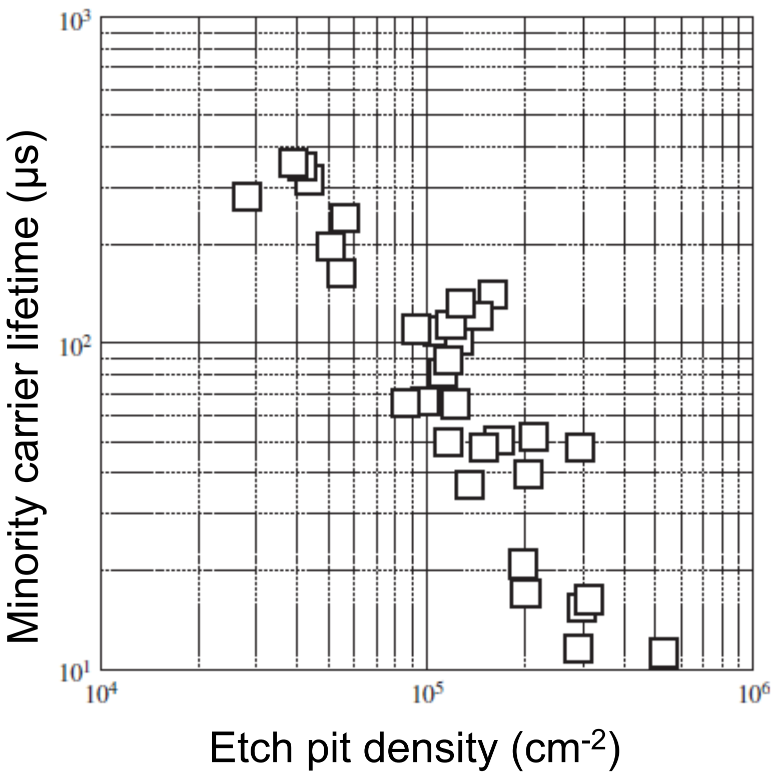
Bricks

Wafers



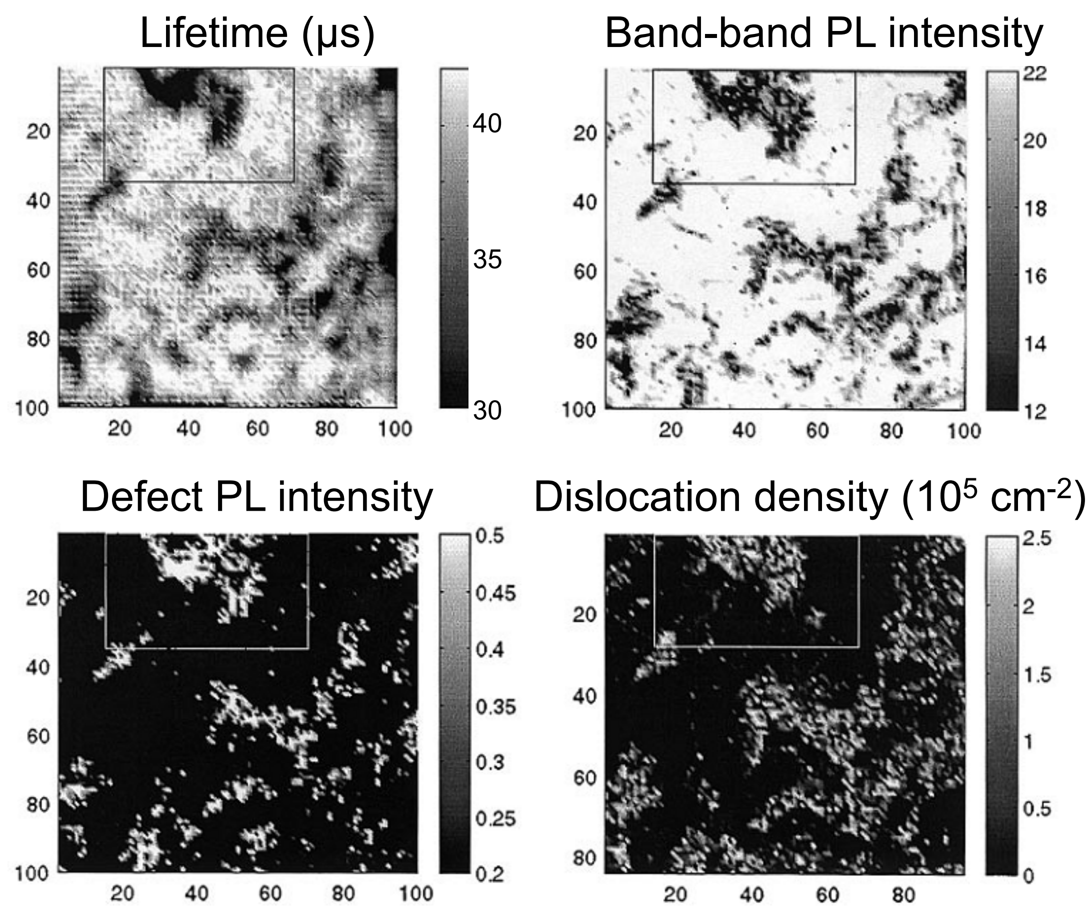
Dislocation issues in mc Si

Minority carrier lifetime *vs* etch pit density



[Arafune 2006]

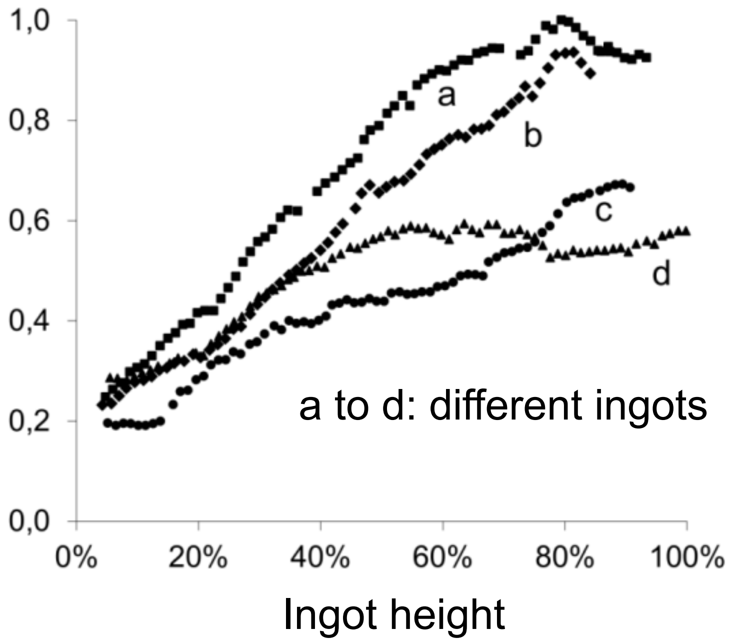
Carrier lifetime, photoluminescence and dislocation density



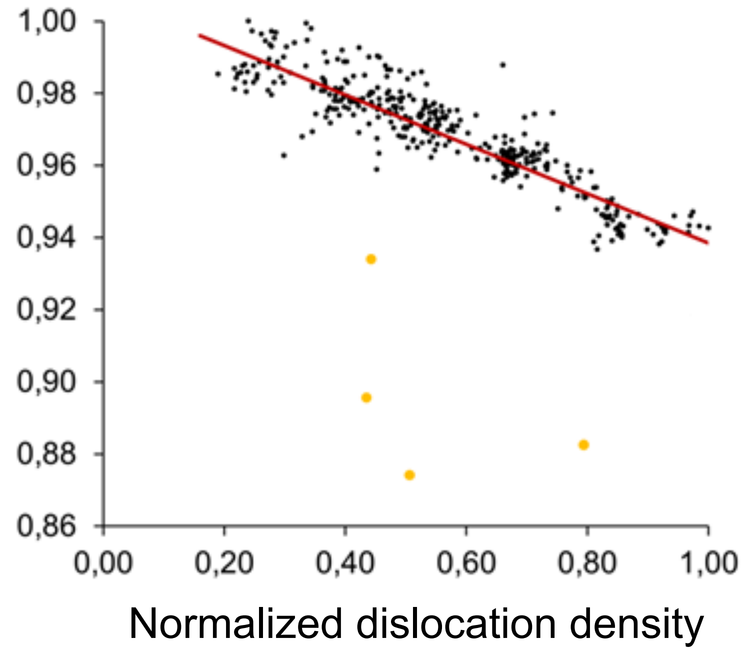
[Tarasov 1999]

Dislocations and solar-cell efficiency

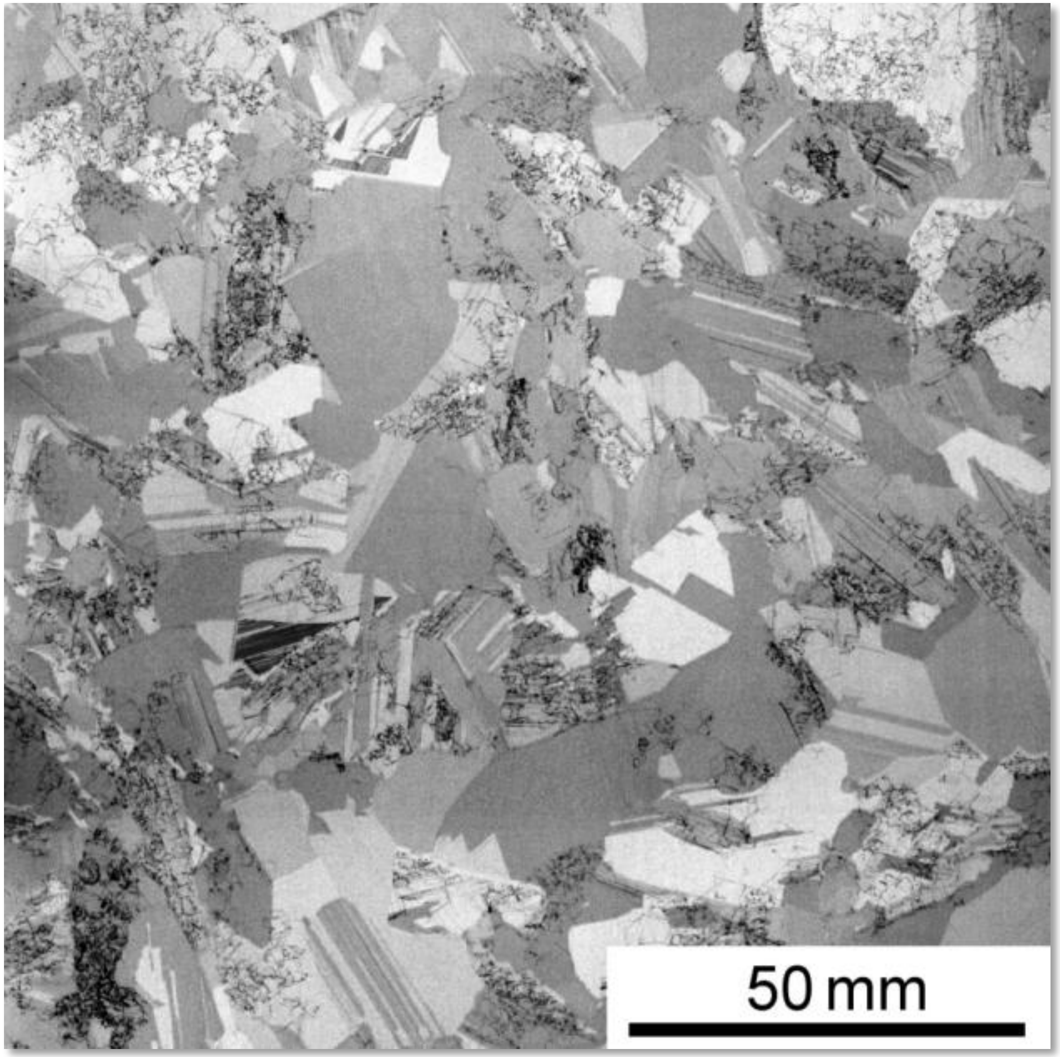
Normalized dislocation density



Solar-cell efficiency η

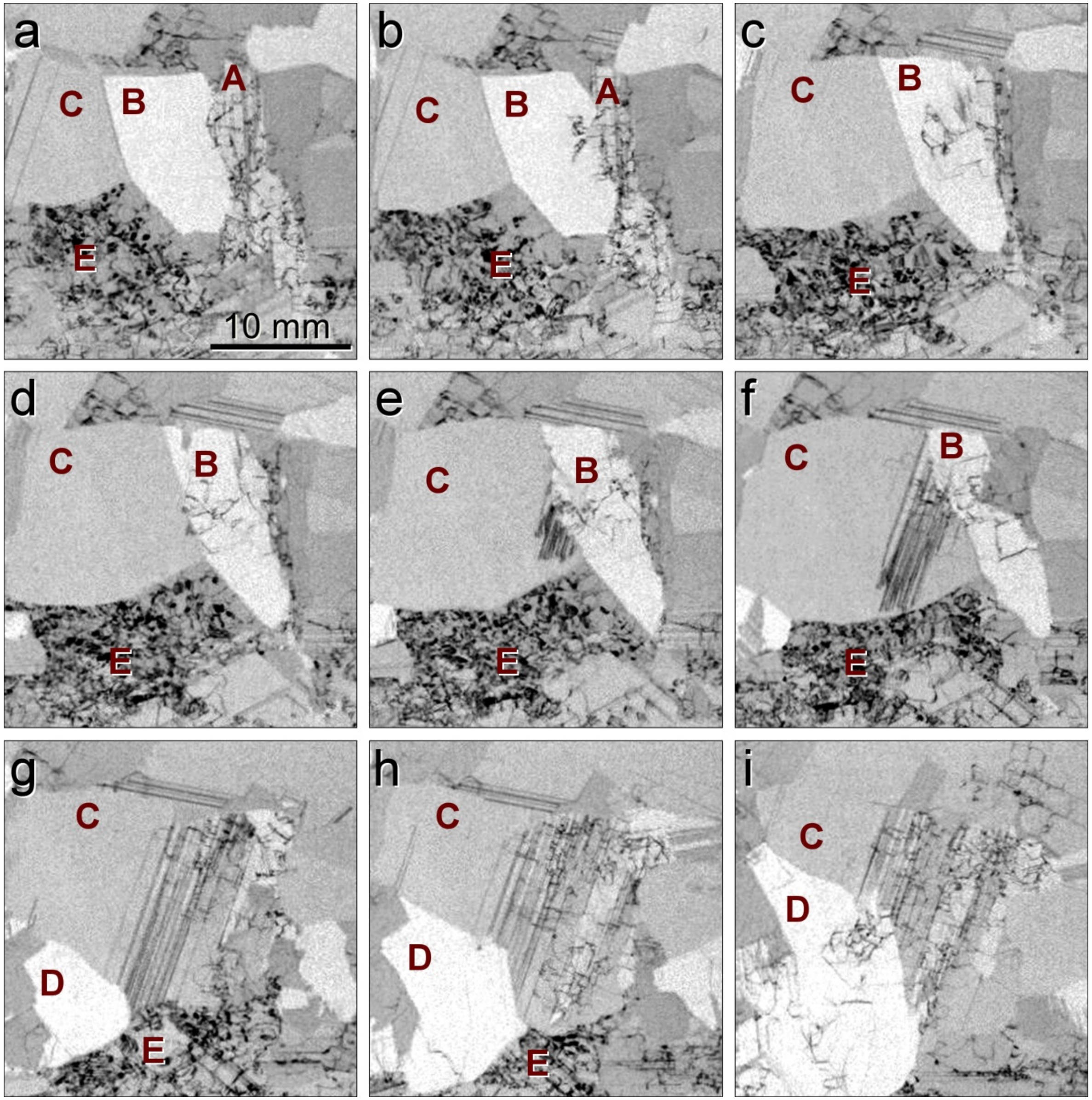


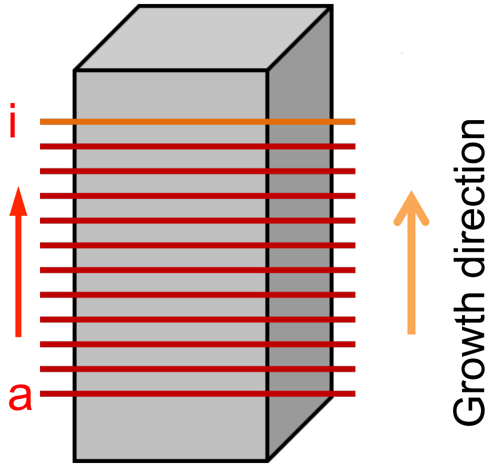
Etched wafer surface



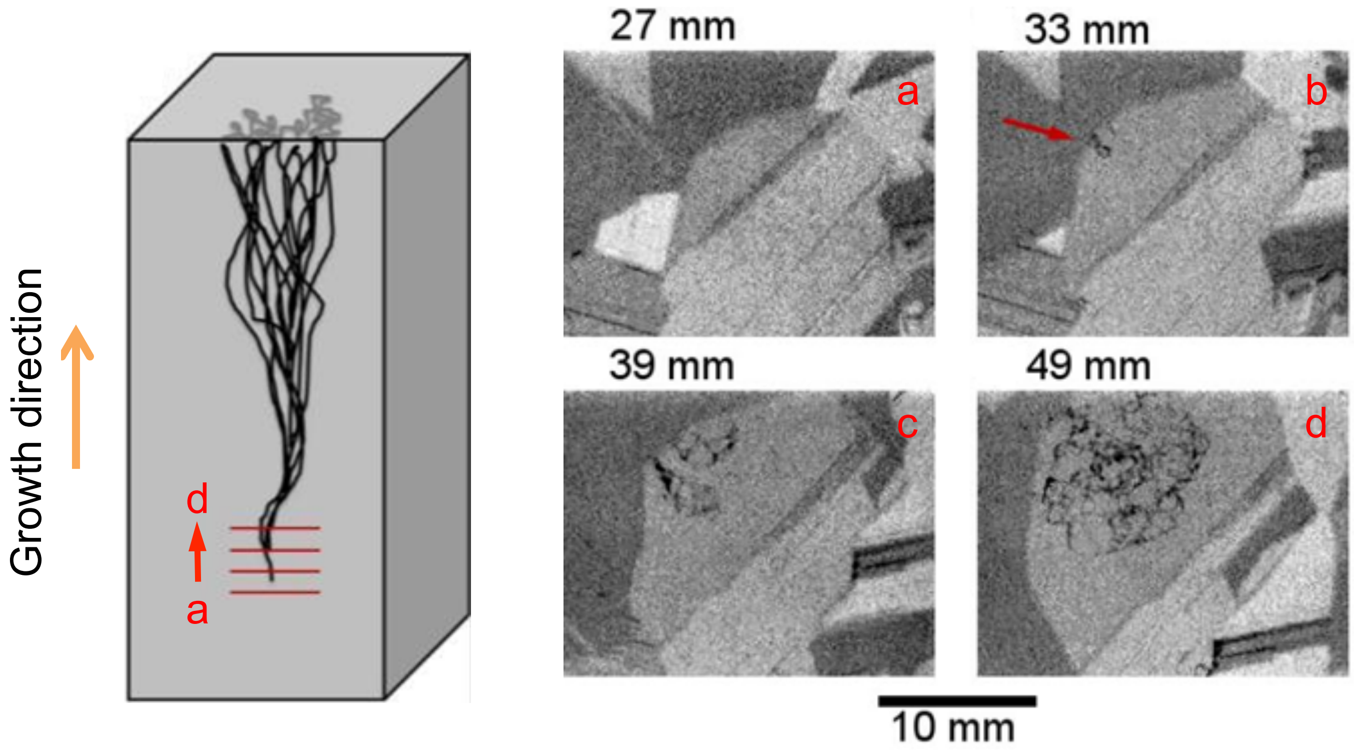
Typical defect distribution

Change of defect distribution in the ingot





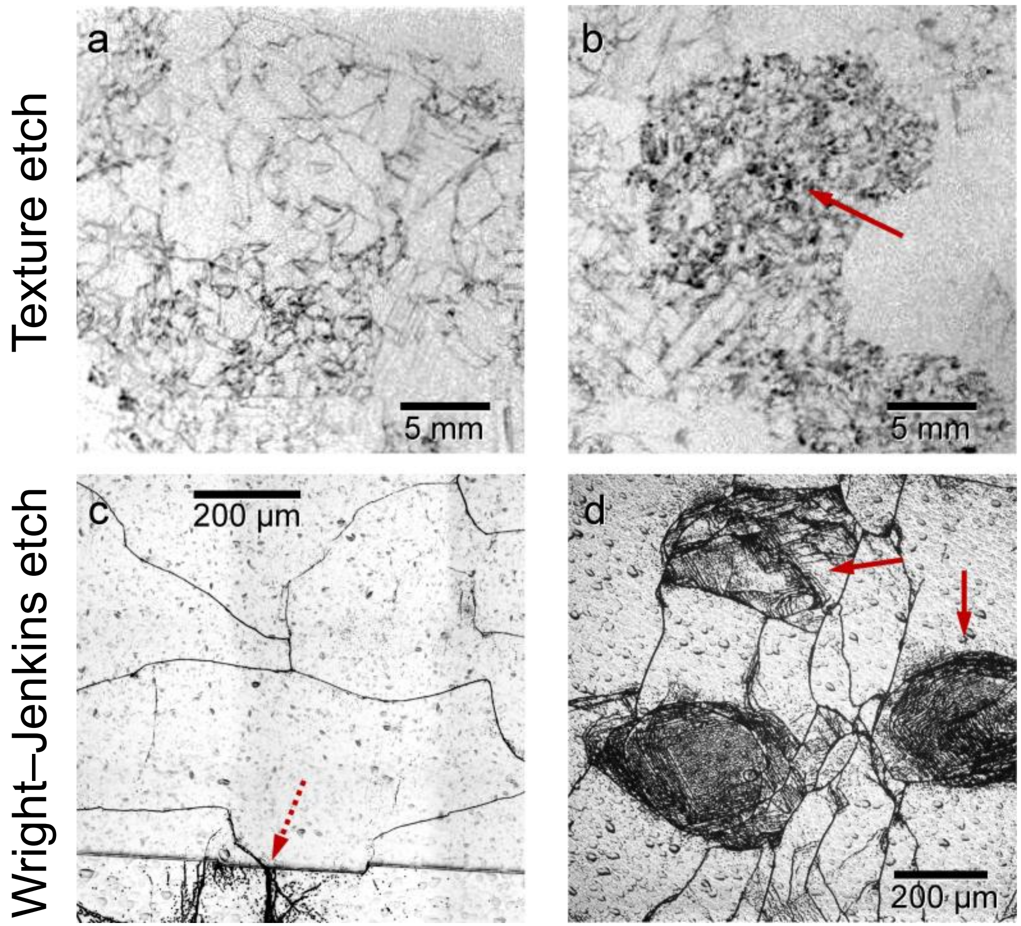
Evolution of dislocations

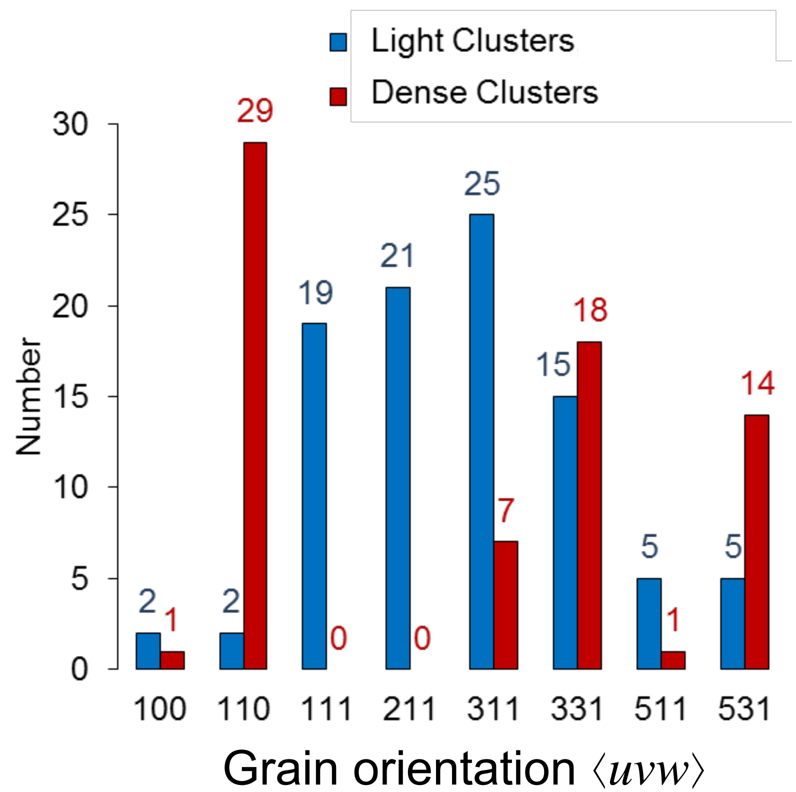


- Dislocation clusters mainly generated at grain boundaries
- Atomistic source of the spontaneous dislocation generation not known

Grain orientation effect

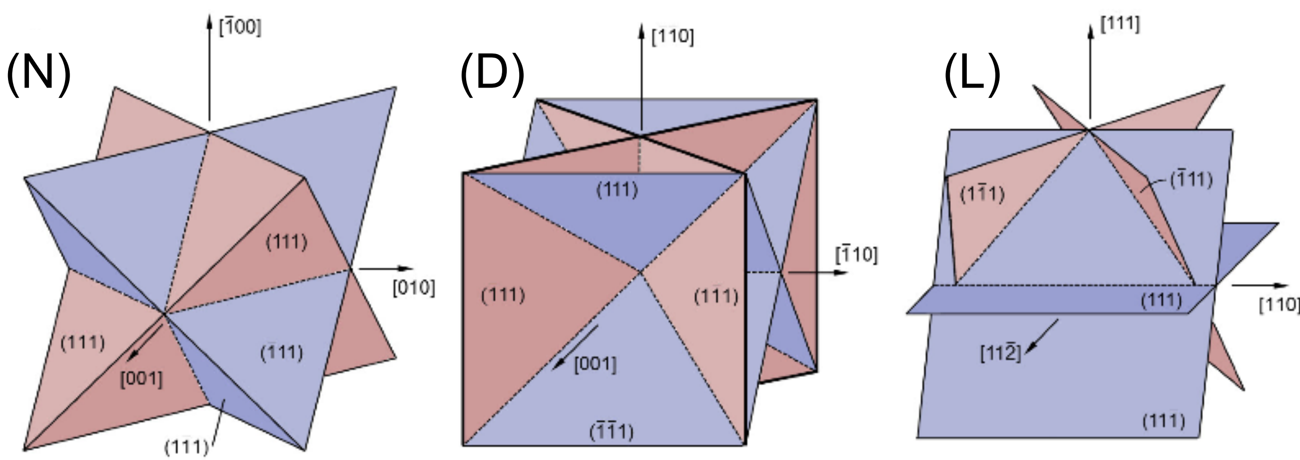
Light clusters (L) | **Dense clusters (D)**



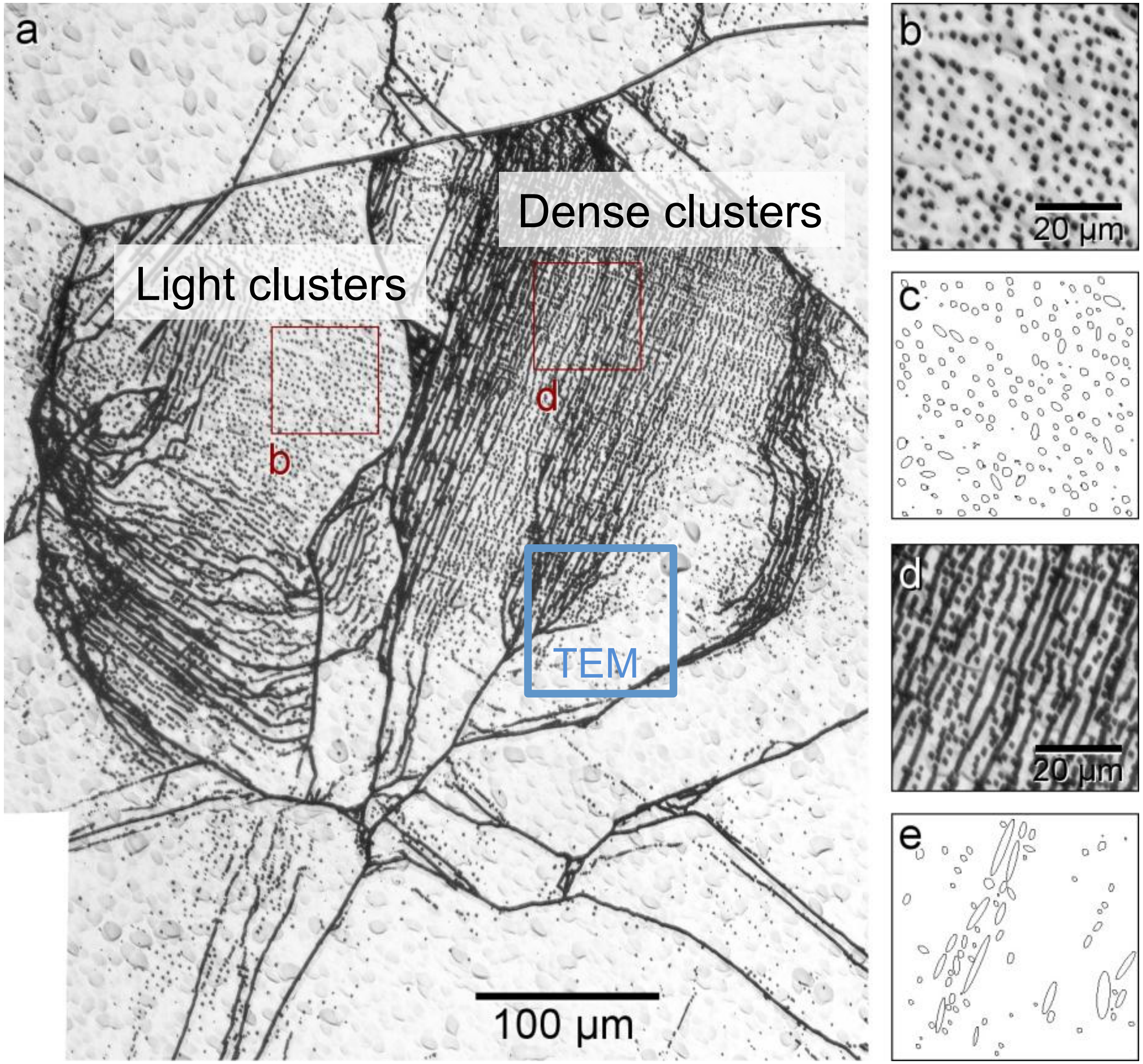


Slip planes in relation to growth direction

- Angle ω between growth direction and slip plane normal important for cluster formation
- (N) High ω for all slip planes *or* moderate ω for one plane:
  no clusters, *e. g.* $\langle 100 \rangle$, $\langle 511 \rangle$ grains
  (D) Low ω for several slip planes:
  dense clusters, *e. g.* $\langle 110 \rangle$, $\langle 331 \rangle$, $\langle 531 \rangle$ grains
  (L) Moderate ω for several slip planes *or* low ω for one plane:
  light clusters, *e. g.* $\langle 111 \rangle$, $\langle 211 \rangle$, $\langle 311 \rangle$ grains



Dislocation arrangements

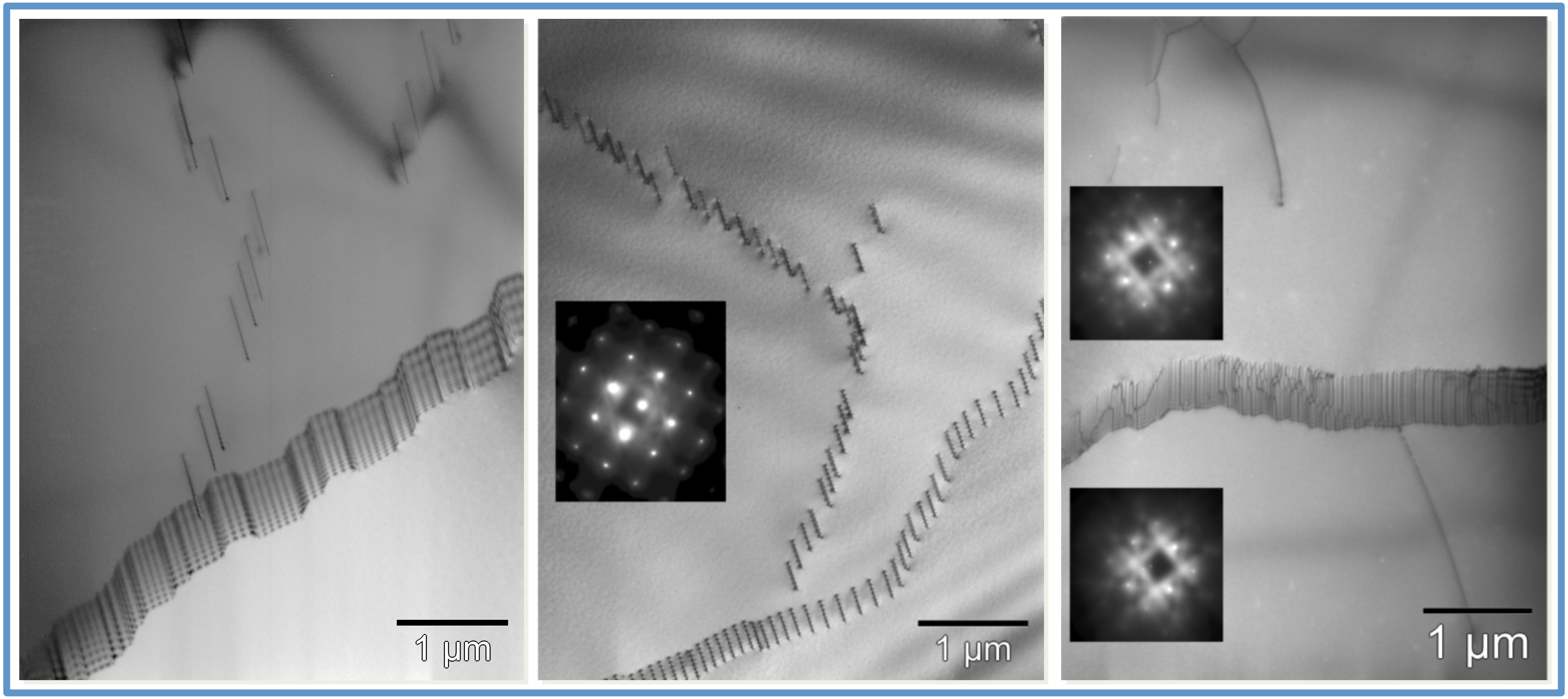


EPD ~ 1×10^5 cm^{-2}

~~EPD 2×10^5 cm^{-2}~~

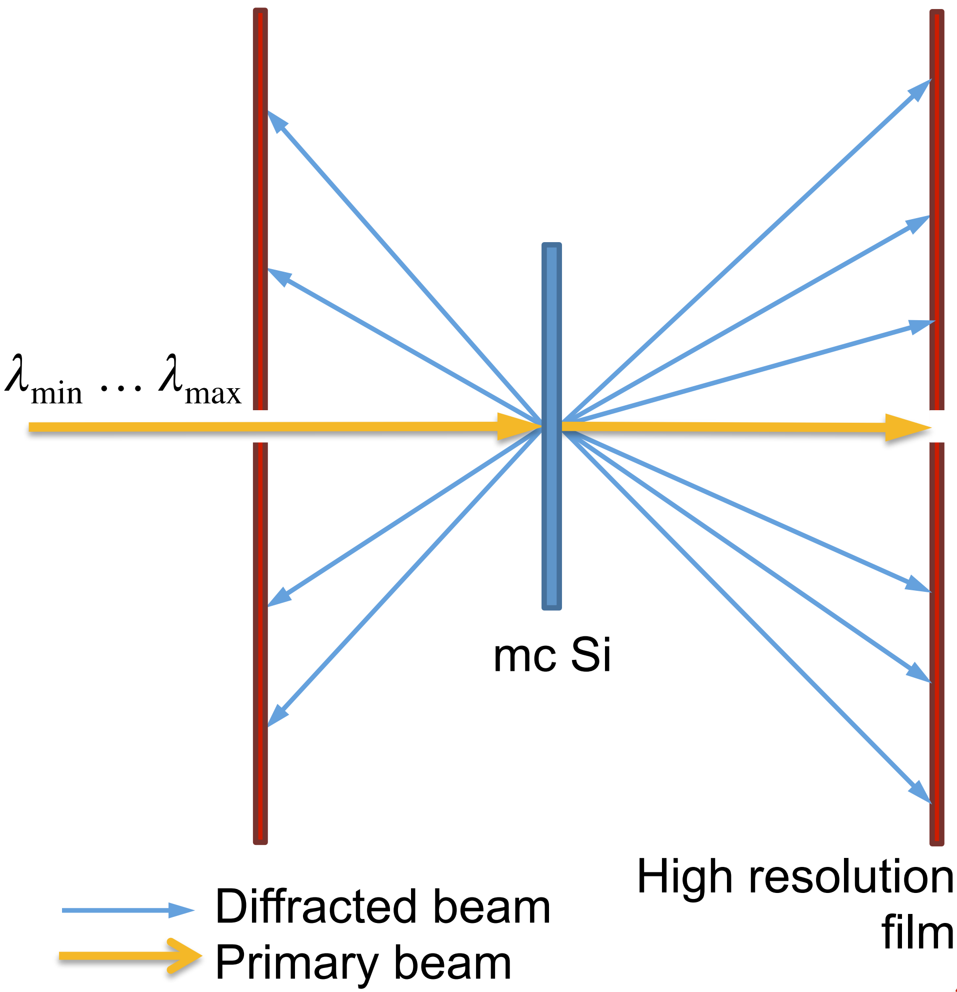
Too low for dislocation pile-ups/subgrain boundaries

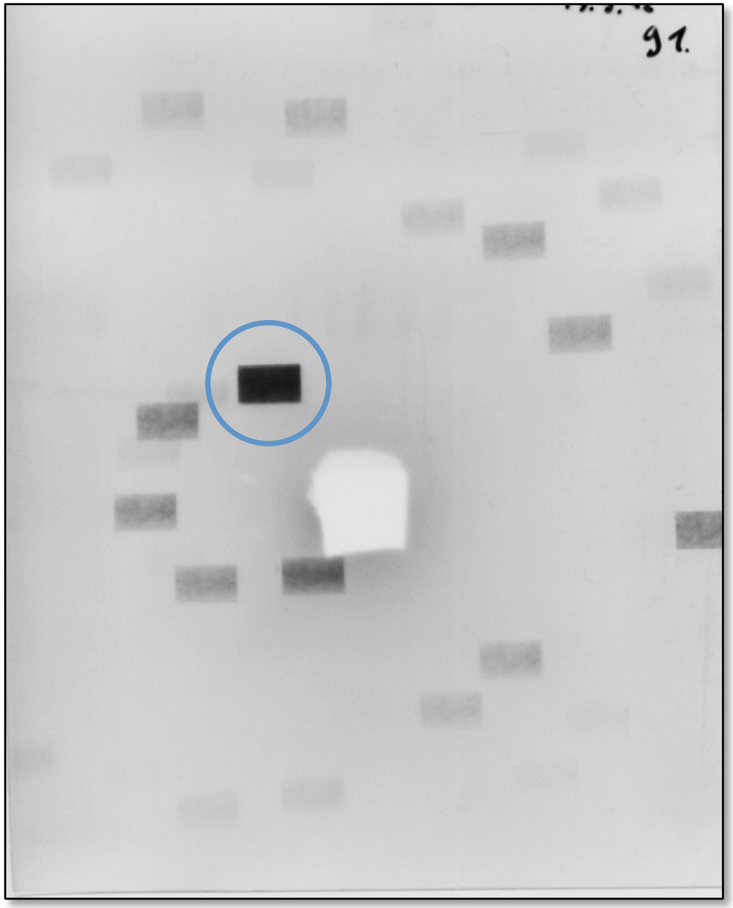
TEM of subgrain boundaries



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

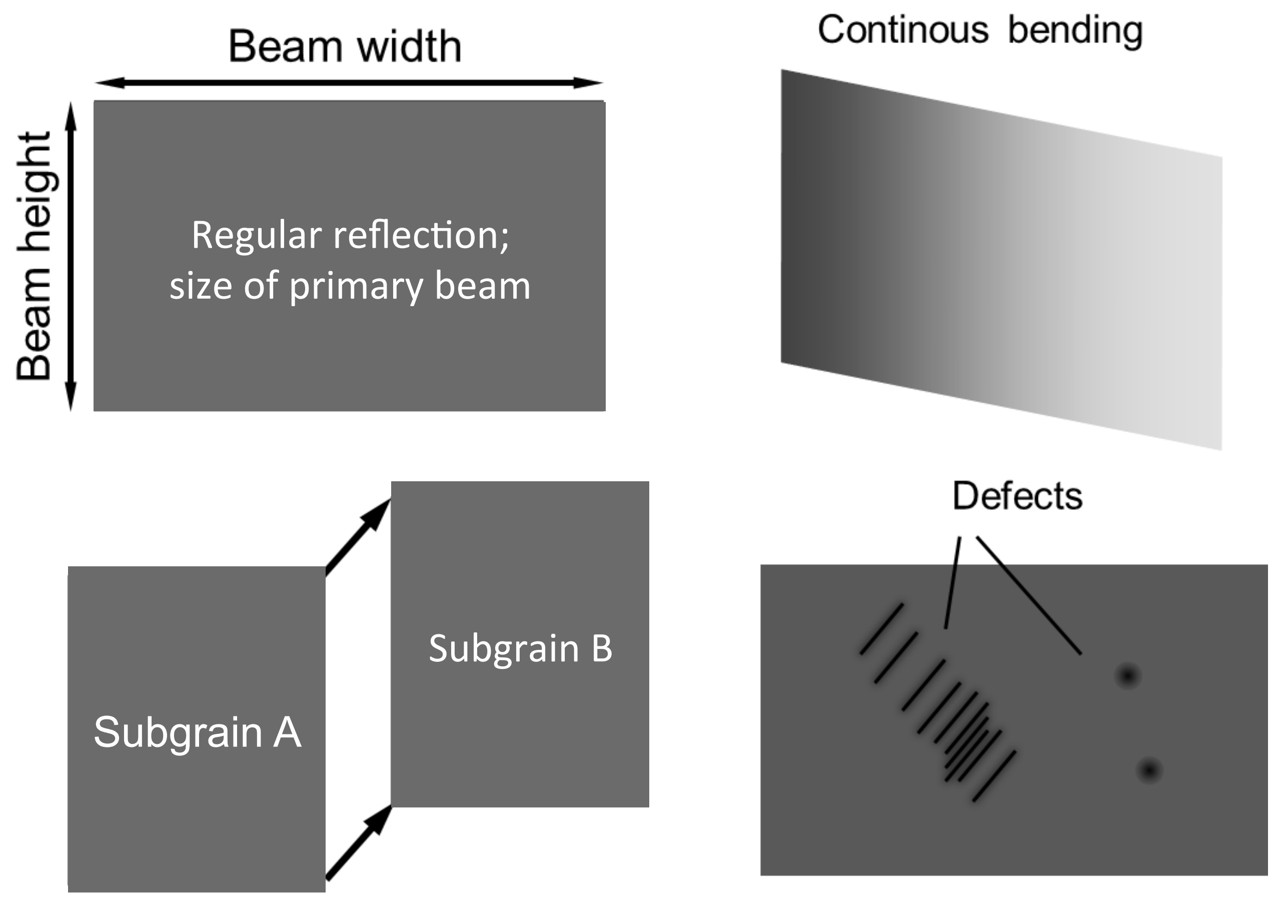
White beam X-ray topography (WB-XRT)





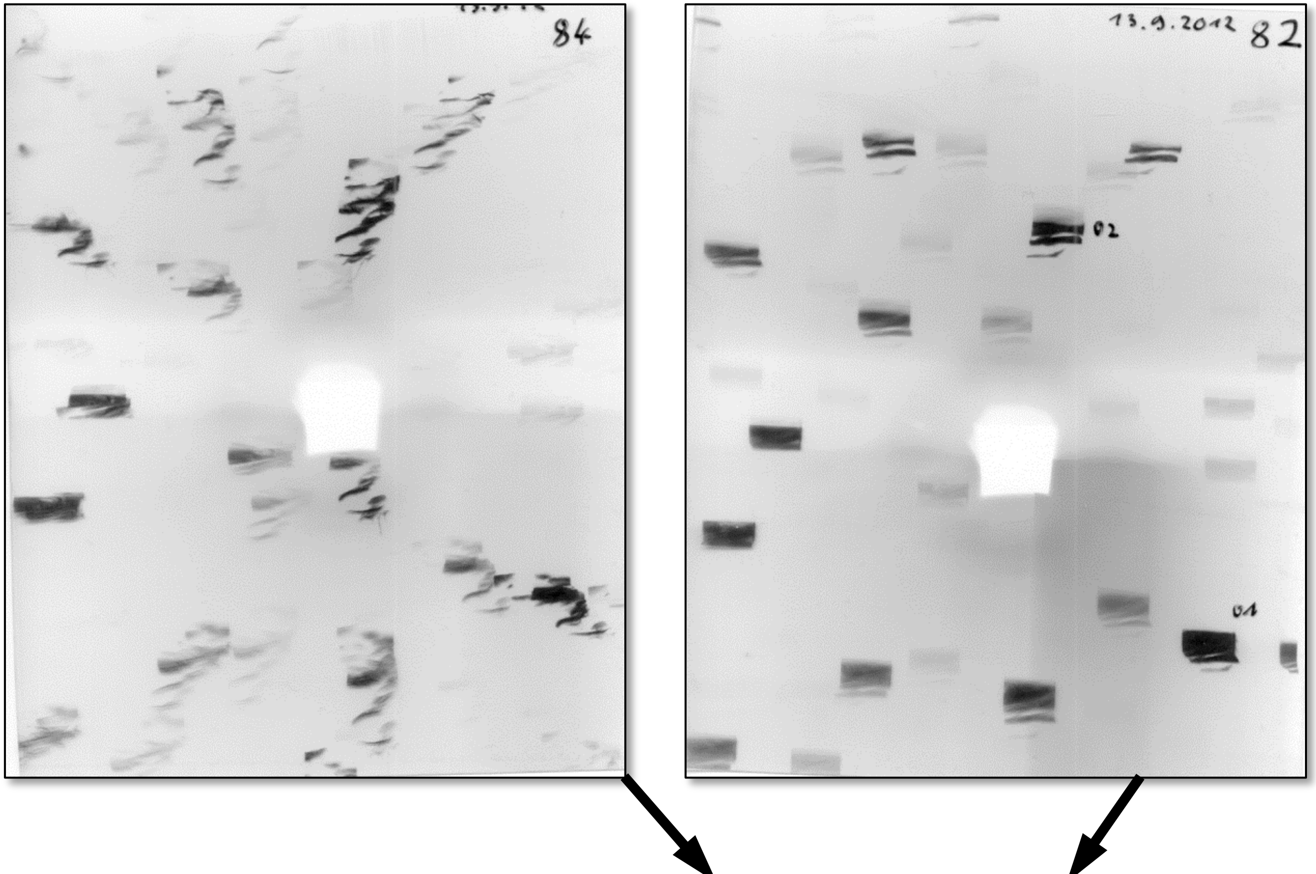
Laue pattern of the grain

Interpretation of WB-XRT contrasts



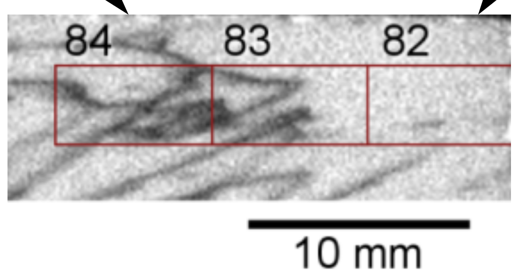
Splitting of the reflection
due to subgrain boundary

Splitting of reflections



WB-XRT Laue patterns

Growth direction

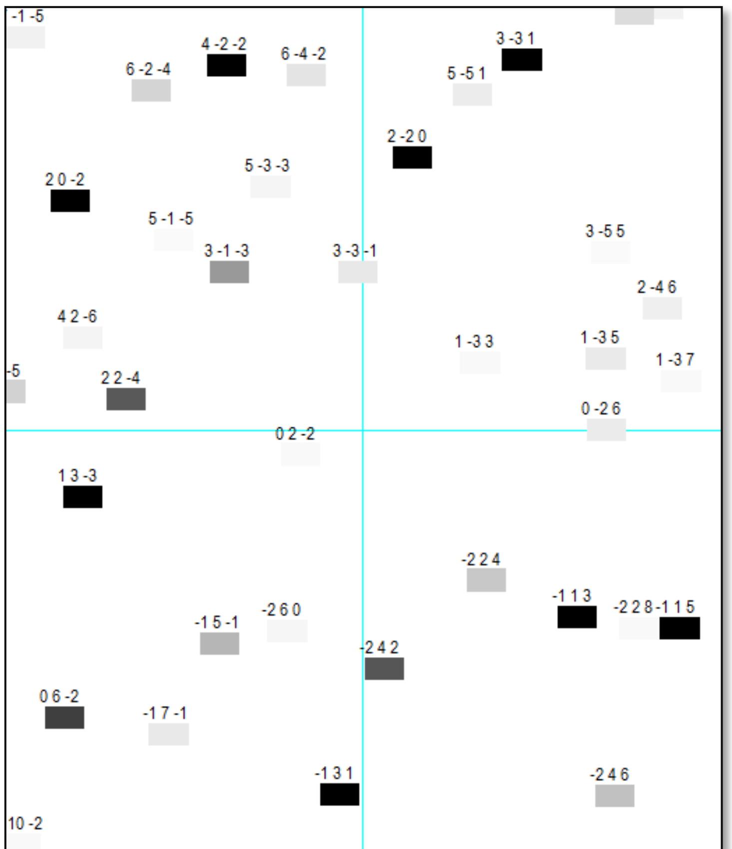


Band-band photoluminescence distribution

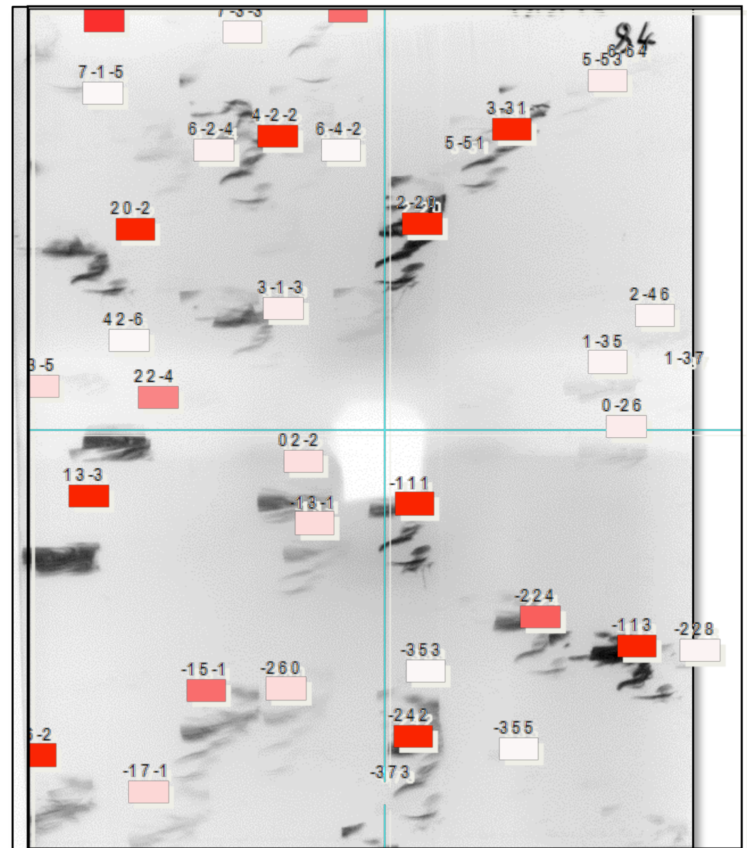
D Oriwol *et al*: Acta Mater **61** (2013) 6903

Tilt of subgrains

Growth direction *y*



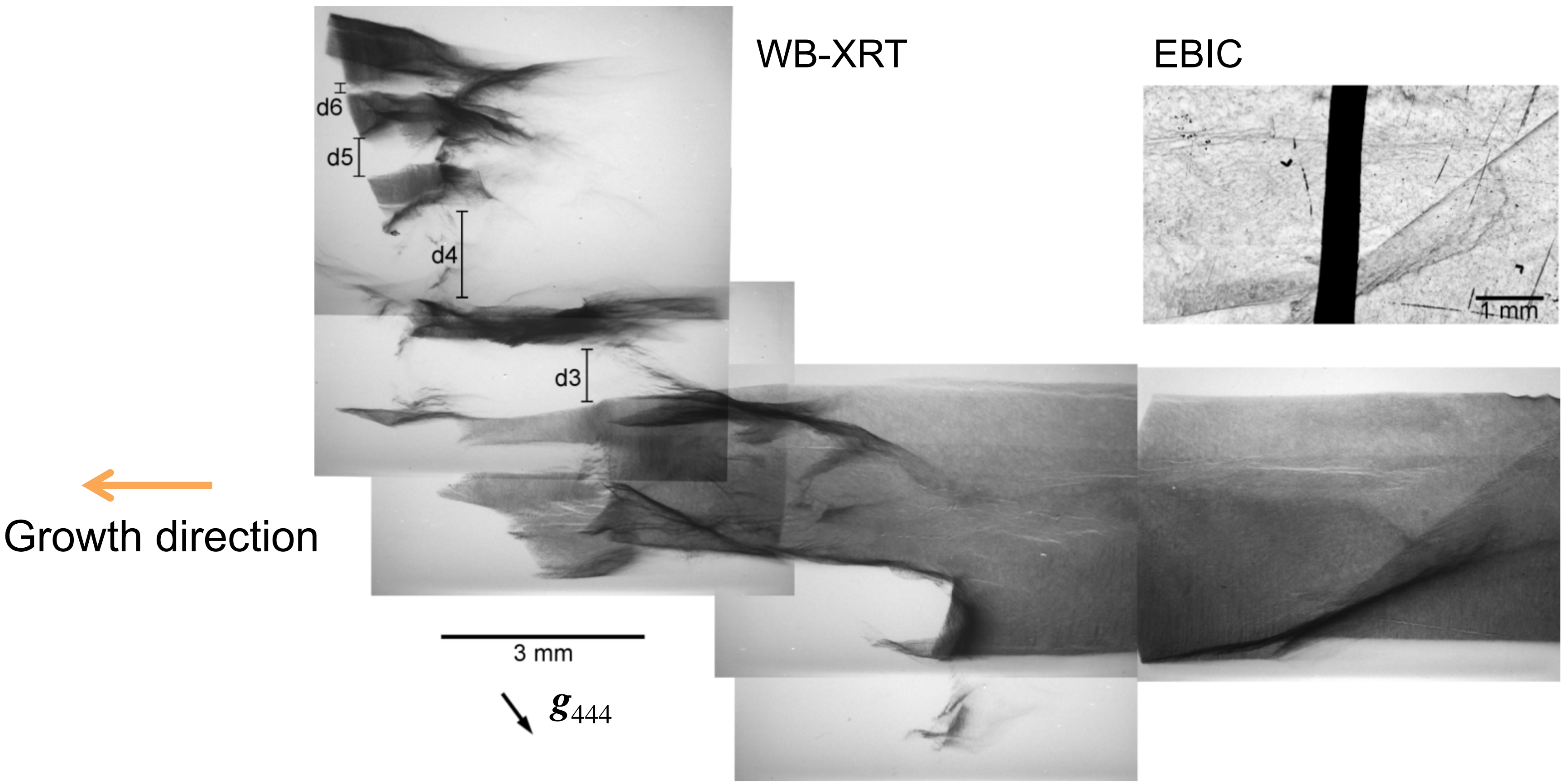
Simulation with **LauePT**



Simulation, rotated by 3° about *y*

Subgrains are tilted about an axis parallel to the growth direction

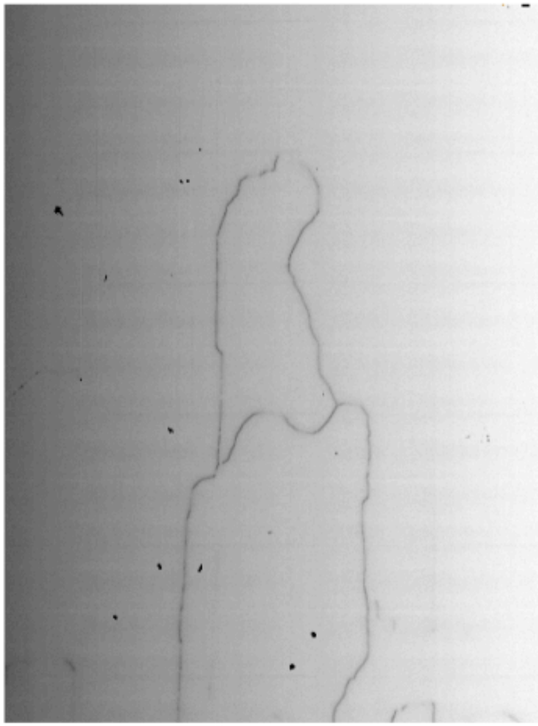
Relation of tilt and subgrain boundaries



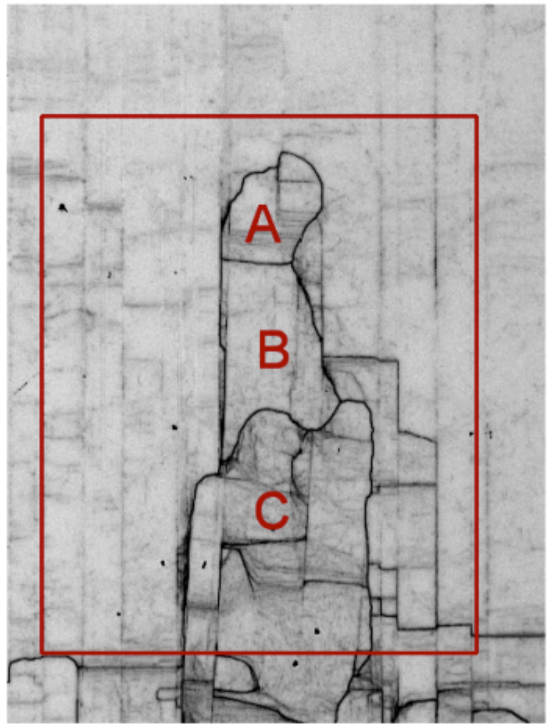
- Tilt = 0.07° (d6) … 0.3° (d4) → dislocation distance h = 800 … 30 nm
- The increase in dislocation density in growth direction leads to a continuous generation of new subgrain boundaries.

EBIC and X-ray topography

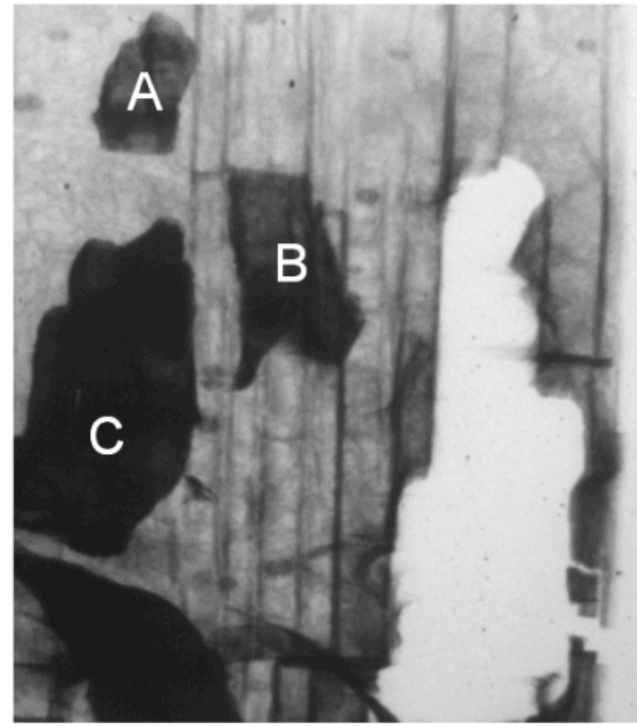
EBIC at RT



EBIC at 77 K

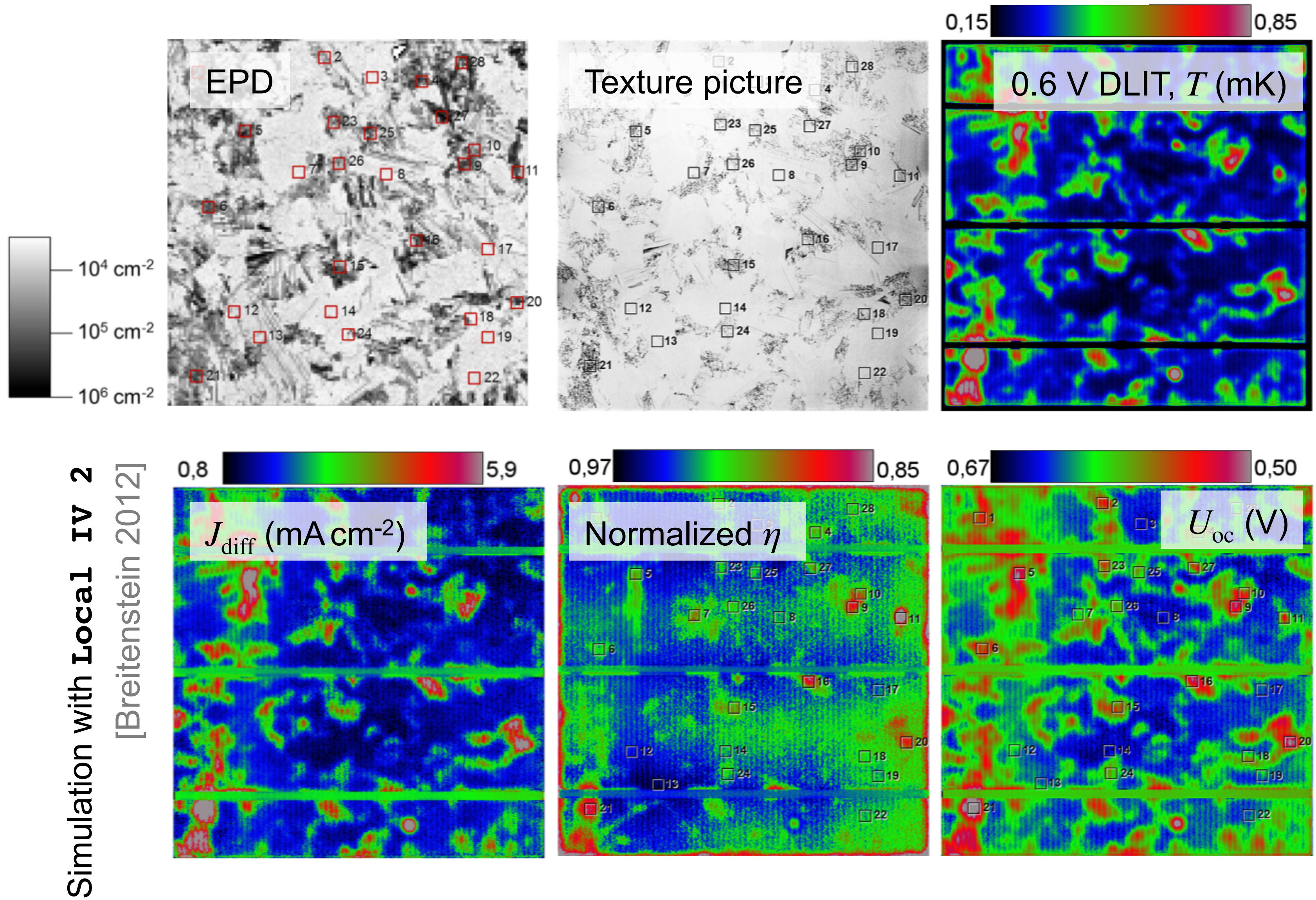


WB-XRT

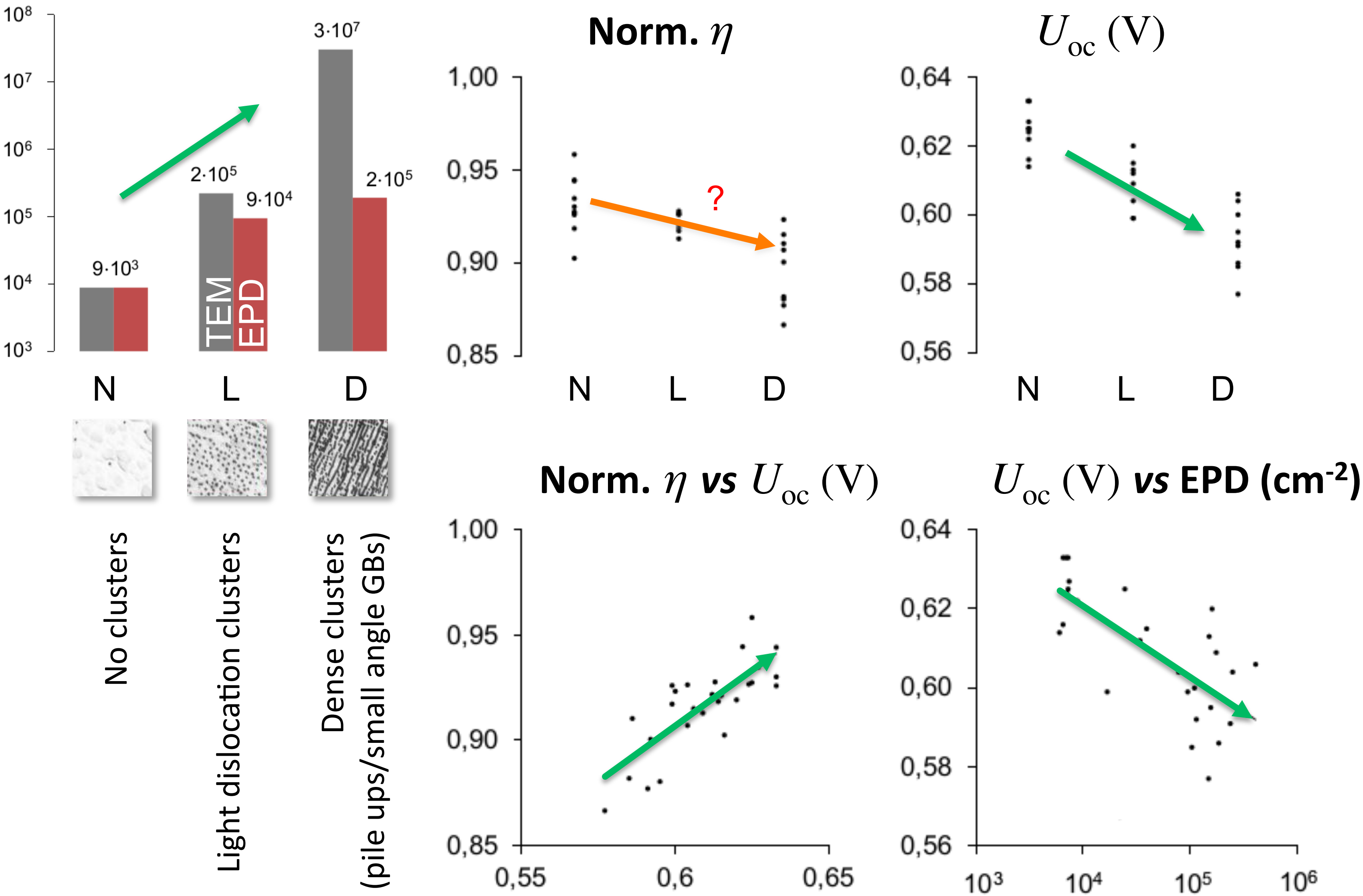


1 mm

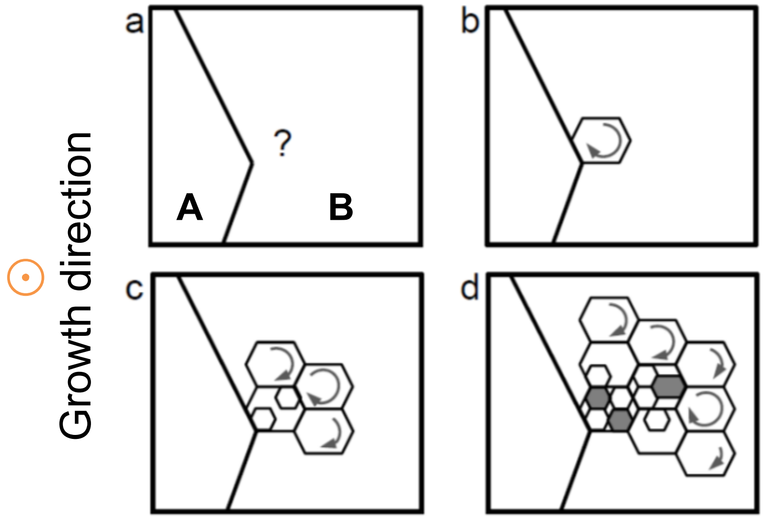
Dark lock-in thermography (DLIT)

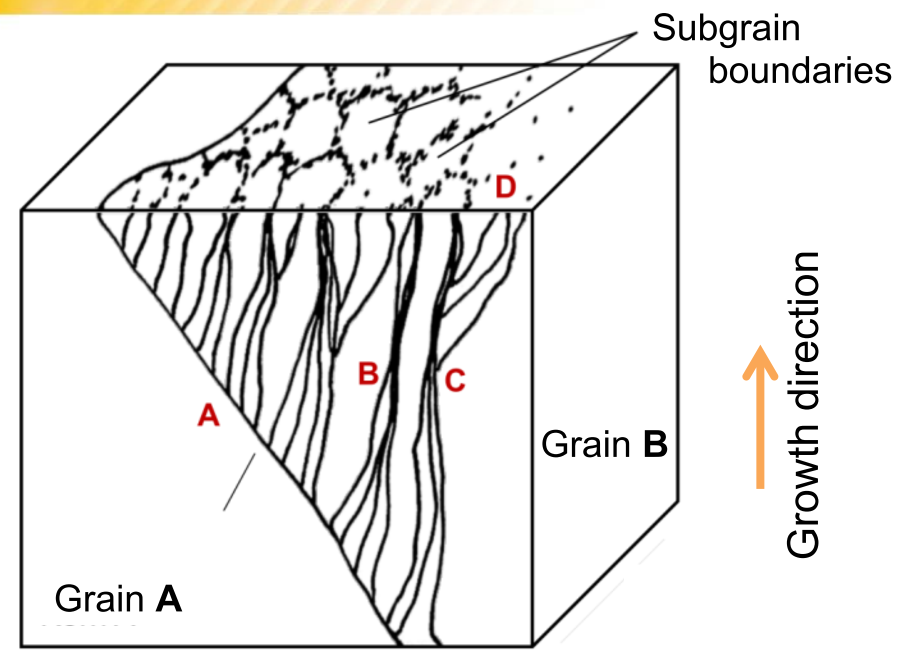


Correlation analysis



Conclusions

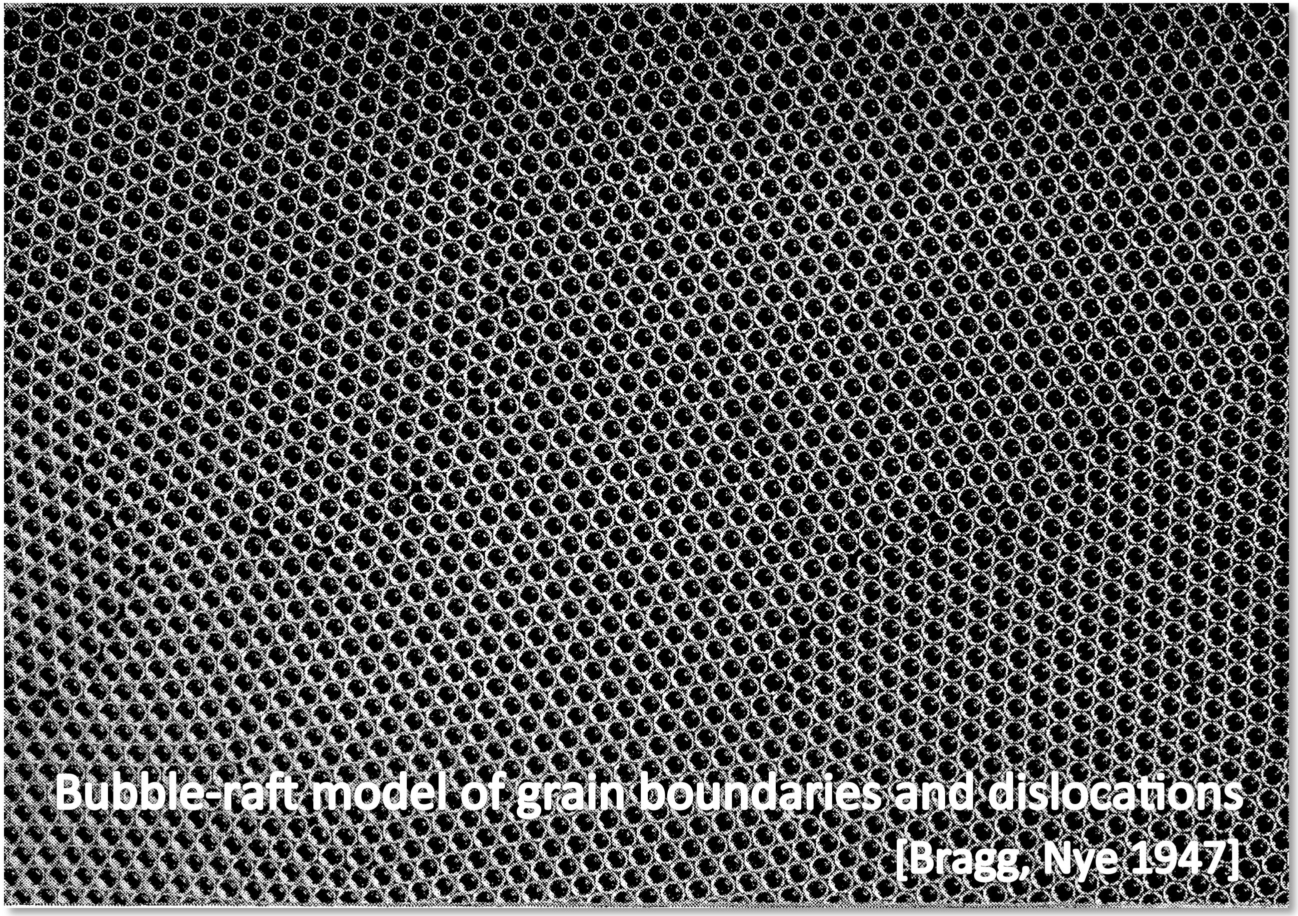




Evolution of dislocation pattern

- Initial generation, mostly at grain boundaries
- Inhomogeneous dislocation distribution on different scales, (N) → (L)
- Multiplication, pile-up and restructuring to subgrain boundaries, (D)
- Dense dislocation clusters with dominant influence on solar cell efficiency

Źěkujom se wutšobnje.



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.