NeoGrowth Silicon:
Low oxygen, high purity, proven crystal growth method for 450mm + silicon optics

Developed at
SolarWorld Americas

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Plan

- Introduce NeoGrowth crystal growth
  - Principles of operation
  - Distinctions relative to other methods
- Properties of NeoGrowth silicon
  - Dislocations
  - Impurities and lifetime
  - Doping

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NeoGrowth Silicon: What is it?

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- Basics: most similar to pedestal growth
  - Continuous, Float Zone like process with balanced input and freezing of liquid
  - Non-contact solidification: no containing crucible
  - Large area seeding process with a seed having a cross-section close to that of the finished ingot
  - Capable of extremely low thermal stresses even at high growth speed
  - Capable of producing circular or squarish cross-sections
- Stoddard et al, Progress in Photovoltaics, 1/2018
- Stoddard et al, Journal of Crystal Growth vol 452

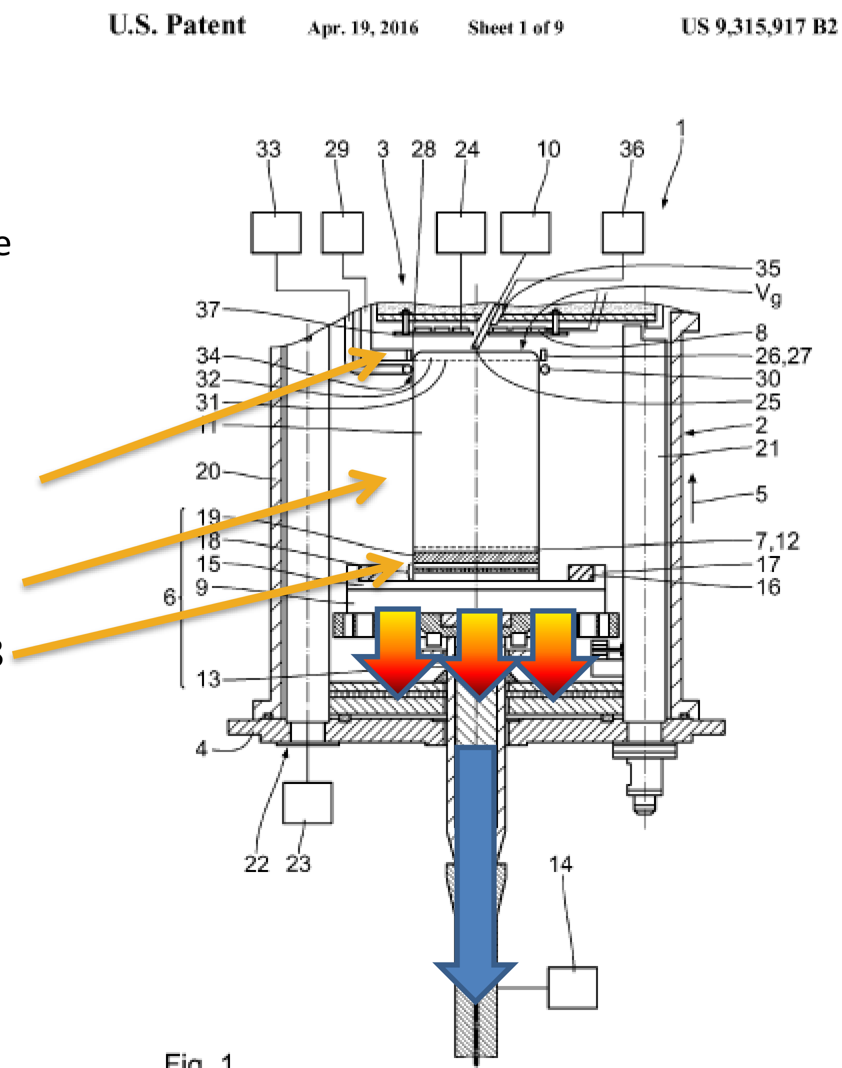
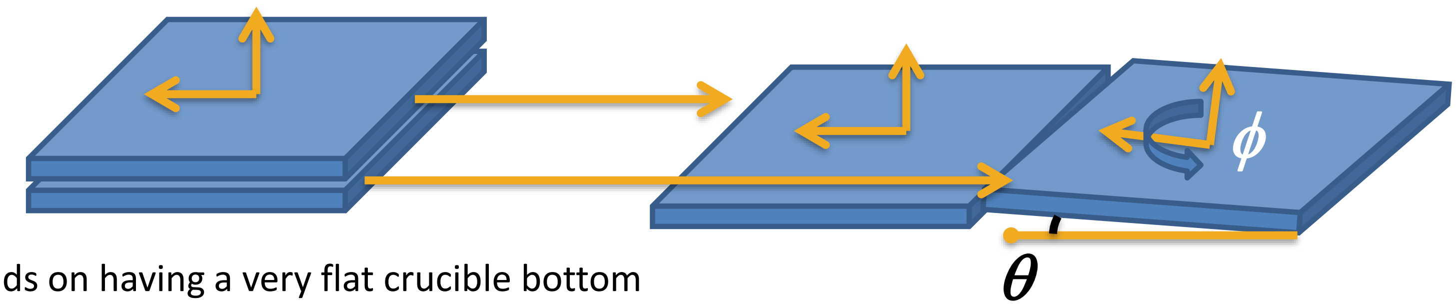


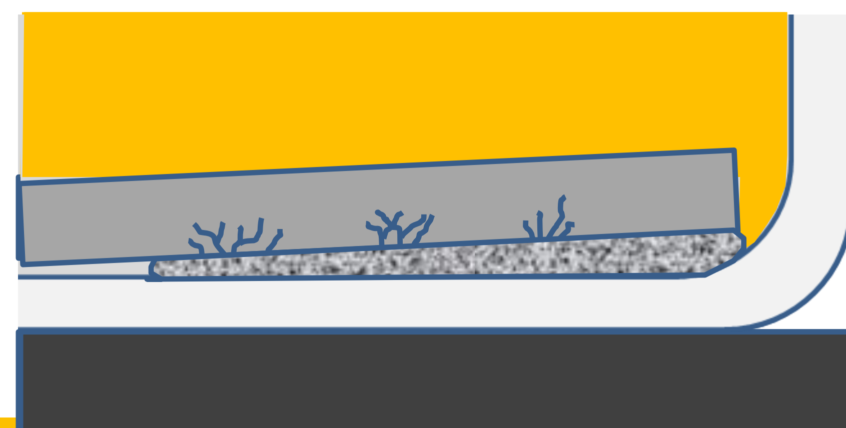
Fig. 1

CM-Si Challenges: Seeding

- Seed boundaries
  - Angle mismatch of >0.1 degrees can lead to sub-grain boundary
  - Two seeds cut to square from the same block can meet this requirement for ϕ



  - θ depends on having a very flat crucible bottom
    - small chips, coating variations, crucible bumps and corners can cause problems
- Liquid silicon undercutting also causes significant problems
  - The liquid can come down the edges or between seeds
  - As it pushes in, it is cooled and solidifies
  - Expansion on solidification causes stress
    - Heavy dislocations in seed
    - Lifts and misaligns seeds, creating small angle GB's between seeds

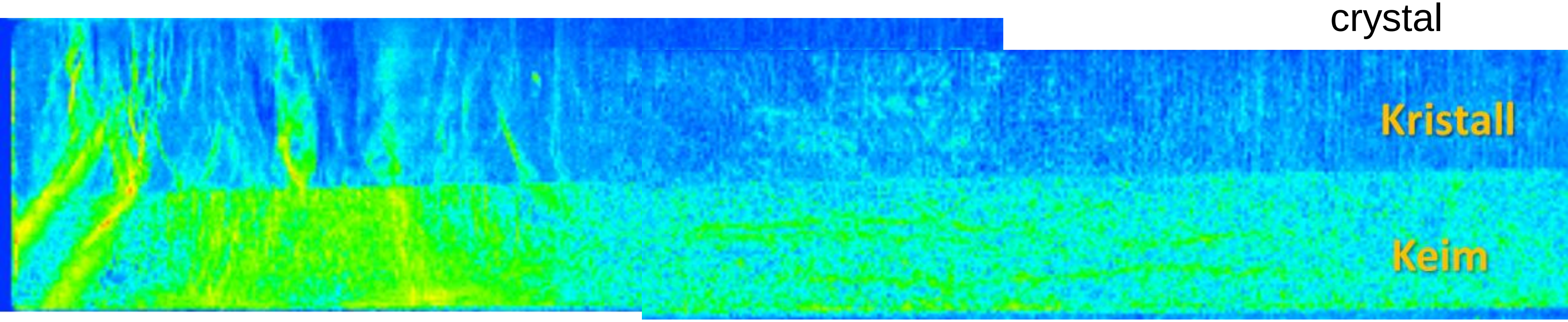


CM difficulties: crucible and coating

- The crucible is an unavoidable source of impurites
  - Dissolved oxygen, nitrogen, metals
  - Nitride particles

vertical cross section

crystal



seed

- Uneven support of the seeds and weight loading of heavy feedstock cause seed dislocations
  - Good news: most do not propagate
  - Bad news: many still do

Traditional Mono challenges

- Czochralski Growth
  - High oxygen concentration (15-25 ppma)
  - Small cross-section
  - Batch doping limitations
  - Long times for seed-in, stabilization, tail
  - That Czech name
- Float Zone
  - Feedstock limitations (high density polysilicon rods)
  - Diameter limitations (200 mm max)
  - High Frequency Inductive heater

- So how about some details on NeoGrowth?

NeoGrowth melt supply

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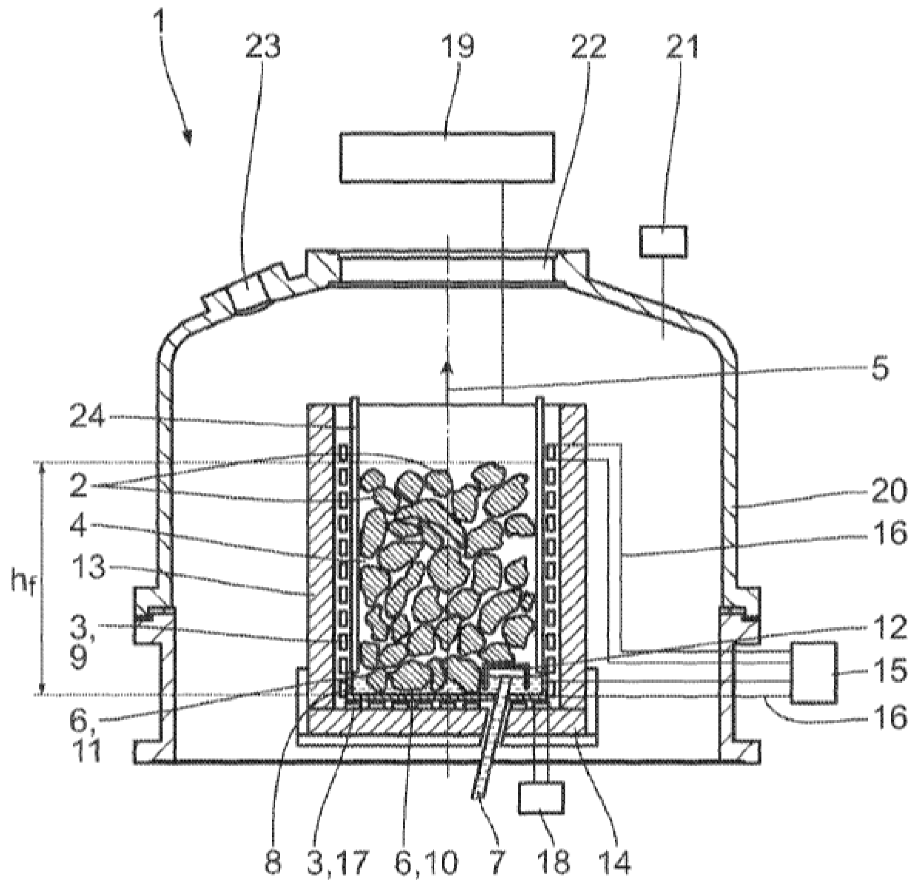
- Requirements for melt supply
  - Mass flow must match crystal growth rate in order to prevent build up or diminishing of melt puddle height
  - Smooth flow preferred to avoid melt vibrations
  - Through-flow of unmelted bits of feedstock material must be avoided



- Nice to have
  - Feedstock flexibility
  - Reusability over multiple runs
  - Minimal liquid contact with foreign material

NeoGrowth Properties

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- We have grown crystals at 230mm, 300mm and 450mm diameter in square and circular cross-sections
- Dislocations present from seeding do not cause structure loss
  - Maintaining low thermal stress during growth prevents the evolution into dislocation clusters and small-angle grain boundaries
- We have not yet been able to grow a dislocation-free crystal, but that has not been a main goal
- We have found a tendency for twins to form at the nodes of the crystal unless great care is taken

- Height
- Growth rate

NeoGrowth and Dislocations

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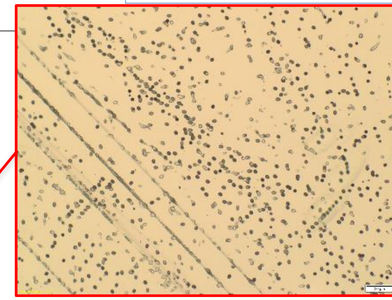
Huge amount of twins/SF's and dislocations in last-to-freeze

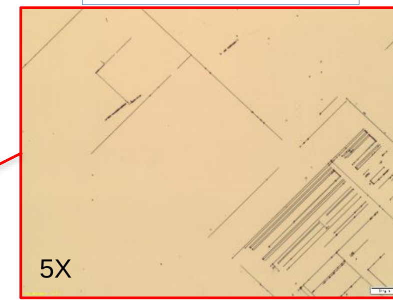
5X

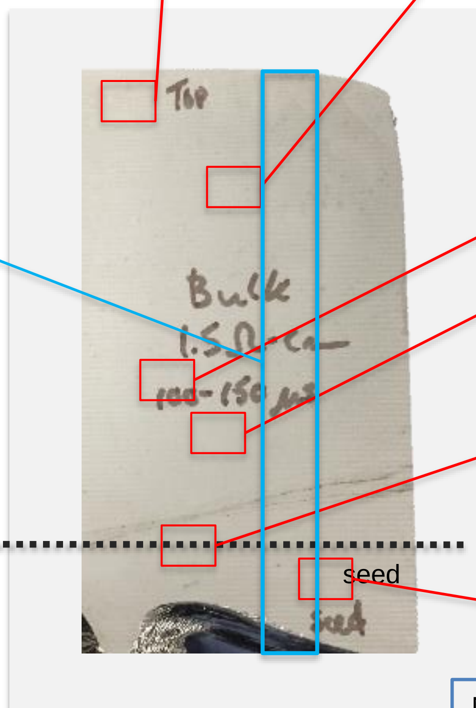
Some defect 'slip-back' near top

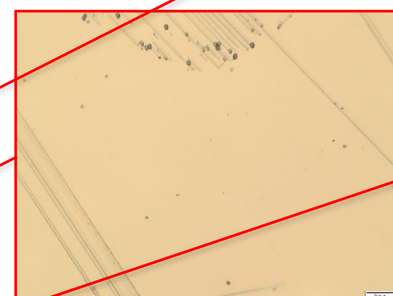


50X

Twins/SF's: some decorated by dislocations







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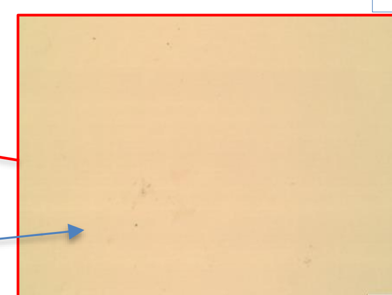
seed/melt interface

Few Twins and Disl initiated at the seed/melt interface



50X

No dislocations are visible in the seed!!

NeoGrowth seeding interface

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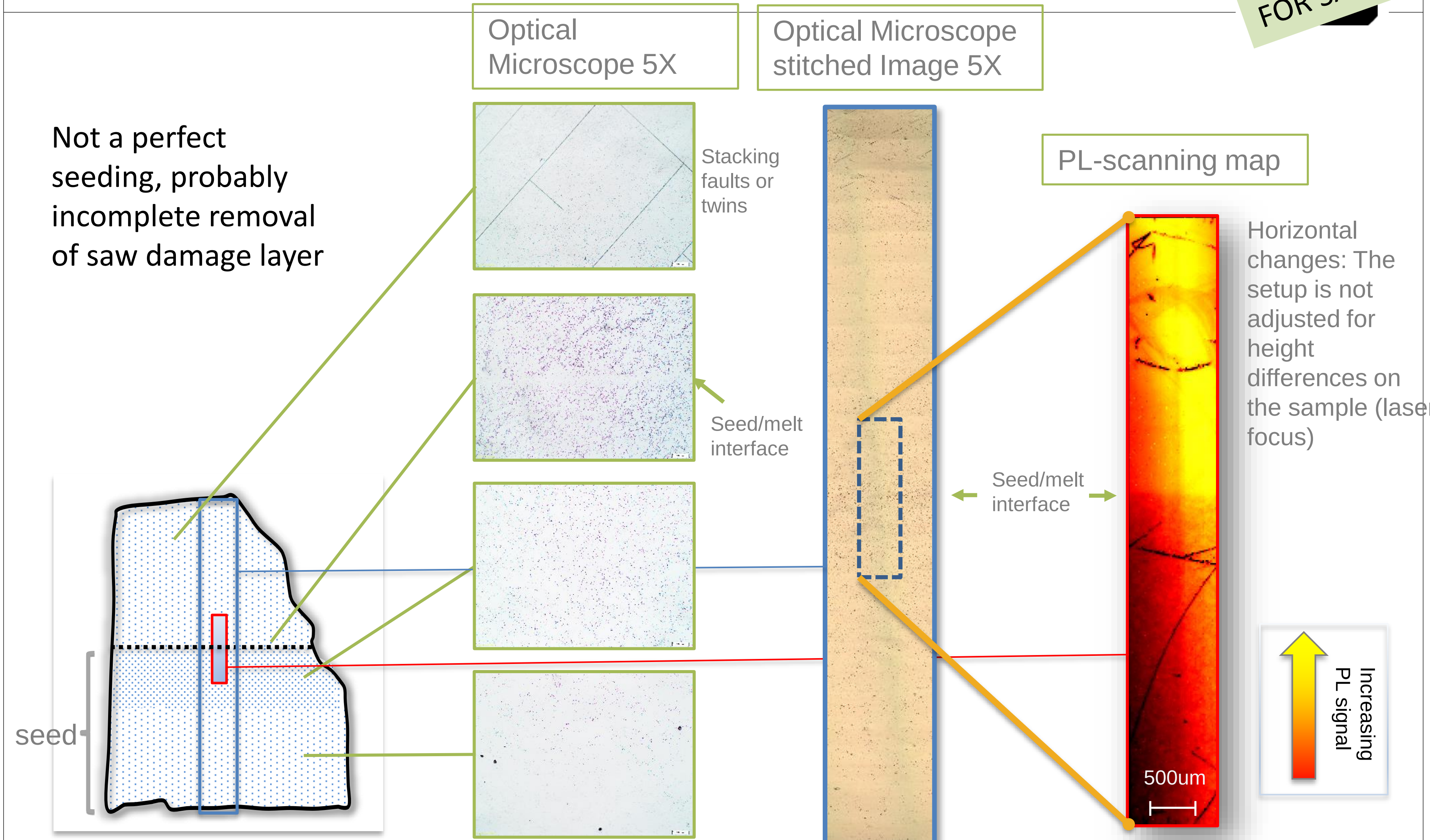
Not a perfect seeding, probably incomplete removal of saw damage layer



No initial low lifetime layer!!

Dislocation evolution

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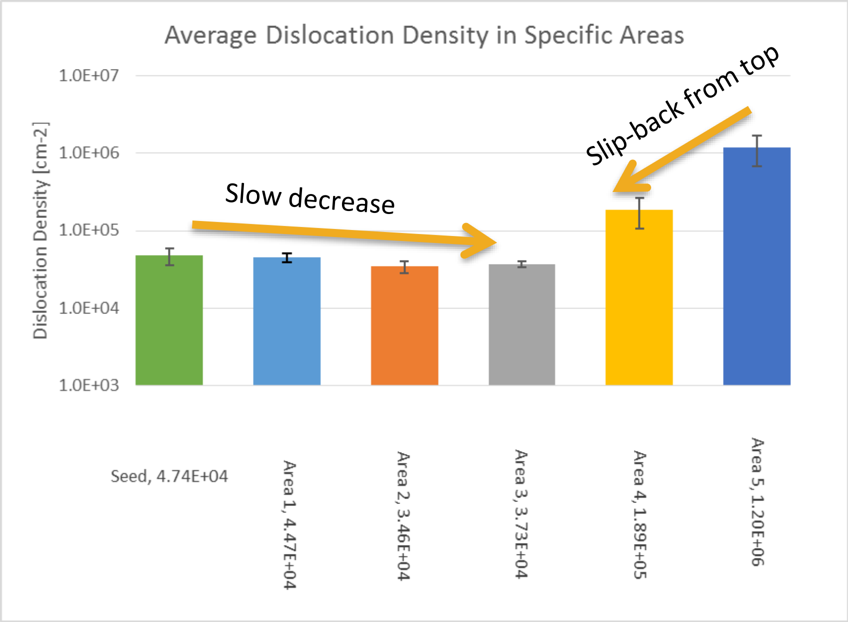
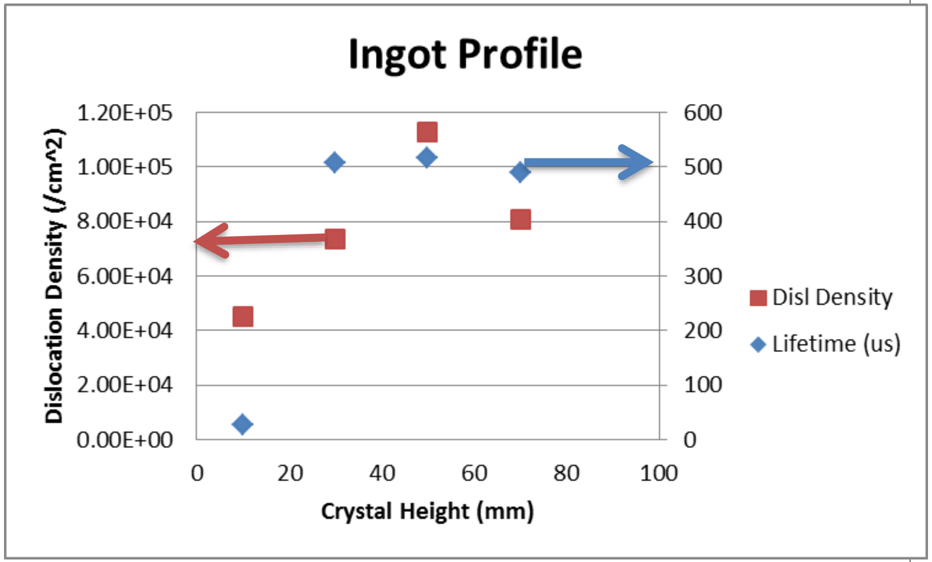
- Cool-down stress can change things, but we often see a slow decrease in dislocation density as ingot growth proceeds (left, typical)
- Up to low 10^5 disl/cm^2, we see no significant correlation of dislocation density and MCL





A word about dislocation cascades

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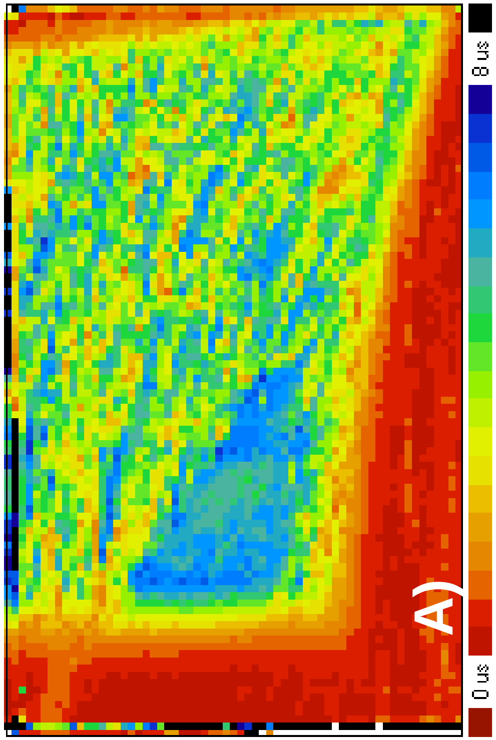
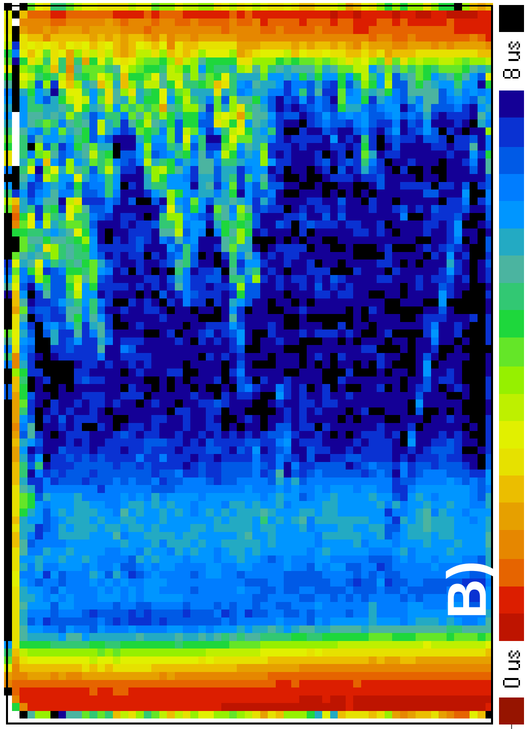
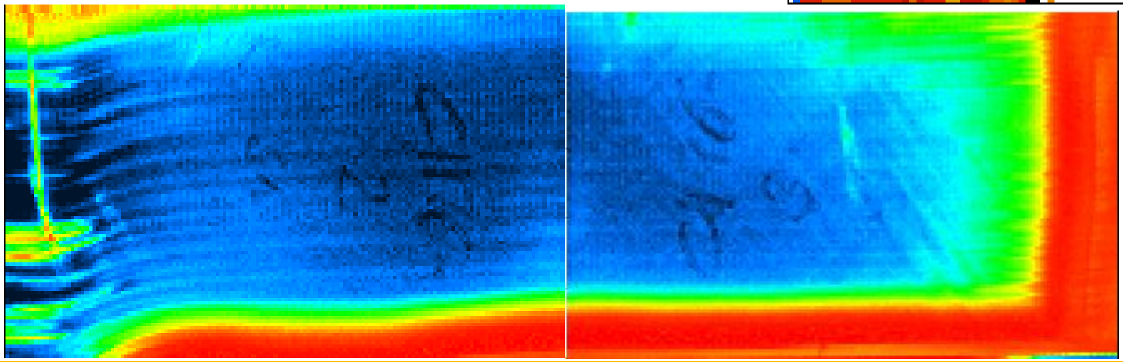
- One of the biggest limitations of the Mono² / quasi-mono process is the presence of dislocation cascades
  - Generated at seed tile boundaries
  - Generated higher from inclusions and built-up stress
- NeoGrowth has no seed tile boundaries
- NeoGrowth has no inclusions
- NeoGrowth has very low simulated stress even at >50 cm (< 5MPa)

Mono² Bricks







Impurities

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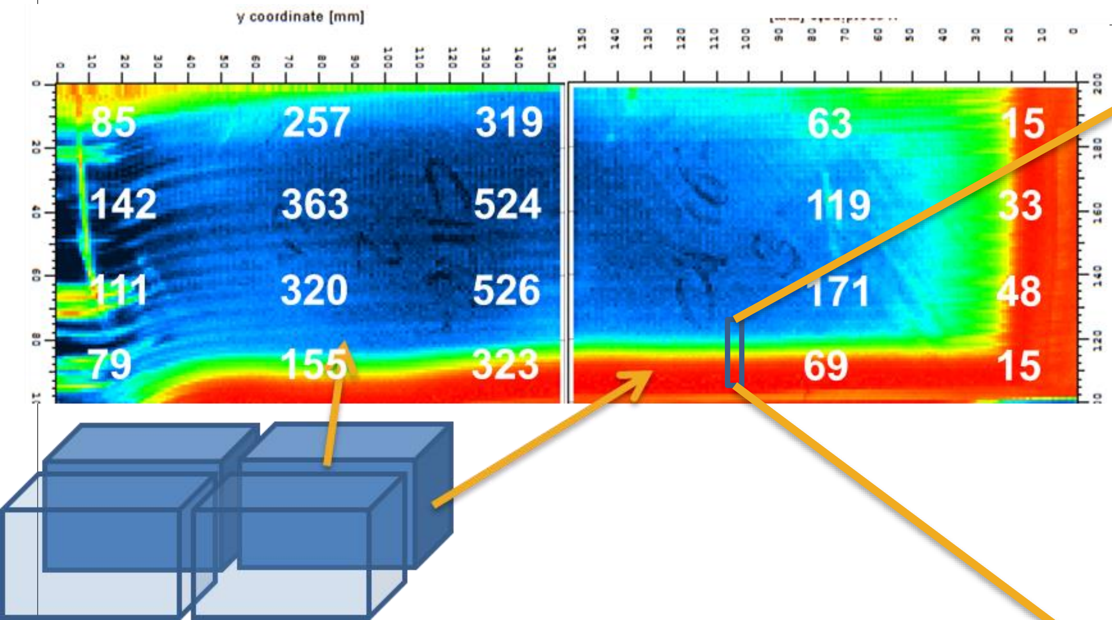
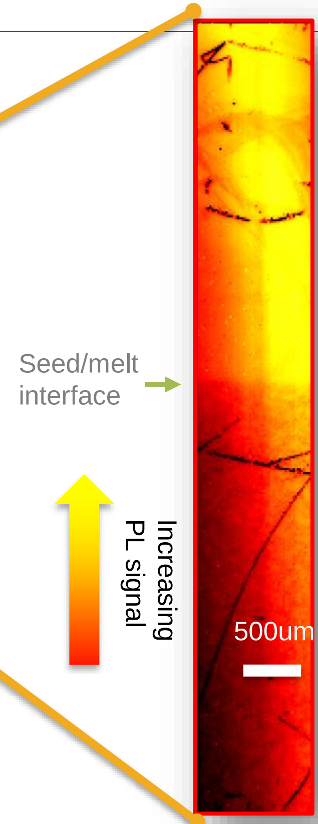
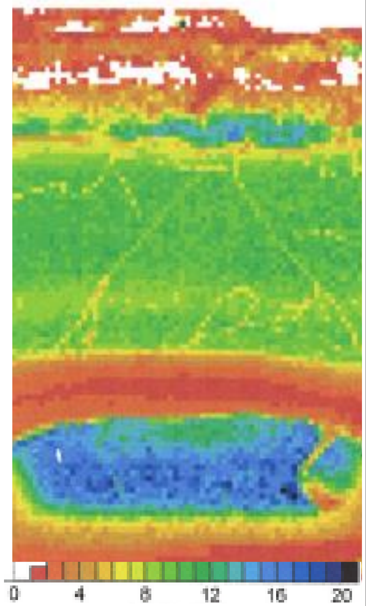




NeoGrowth: No iron contamination at seed interface



Quasi-mono: Iron contamination at seed interface

- The seed sees some elevated iron from the heat-up process
- The grown material has exceedingly high purity
- The exterior of the ingot sees some post-growth iron deposition from the hot zone ambient
  - Hot zone material quality is crucial
- Minority carrier lifetime post diffusion measured as high as 1.7 ms at 1.5 ohm-cm

The Light Elements

- Oxygen source in melter apparatus, but good argon sweeping keeps levels low
- The only carbon source is gaseous:
  - SiO + C -> SiC + CO
  - Carbon is controlled through the atmospheric conditioning

FTIR Concentrations (atoms/cm^3)

$[O_i]$	Center	Half-way	Edge
Top	4.00E+17	3.73E+17	3.87E+17
Middle	5.05E+17	3.88E+17	3.47E+17
Bottom	5.73E+17	4.85E+17	4.18E+17
$[C_s]$	Center	Half-way	Edge
Top	9.43E+16	1.65E+17	9.76E+16
Middle	7.80E+16	9.55E+16	1.27E+16
Bottom	7.11E+16	3.27E+16	< 1E+16

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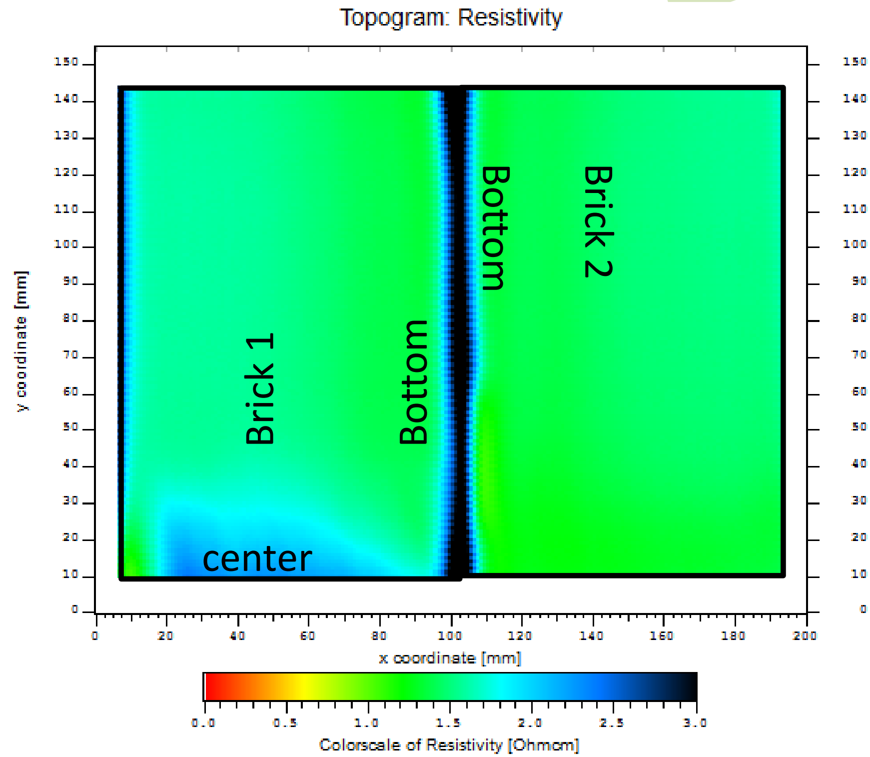
Doping

- Doping does not follow Scheil's equation because there is a constant supply of fresh feedstock
- Low segregation coefficient dopants perform well: dope once at the beginning and slowly deplete the melt concentration
- Evaporation can be an issue, depending on the ambient pressure
- Zone height variations will also change the doping by changing the melt concentration



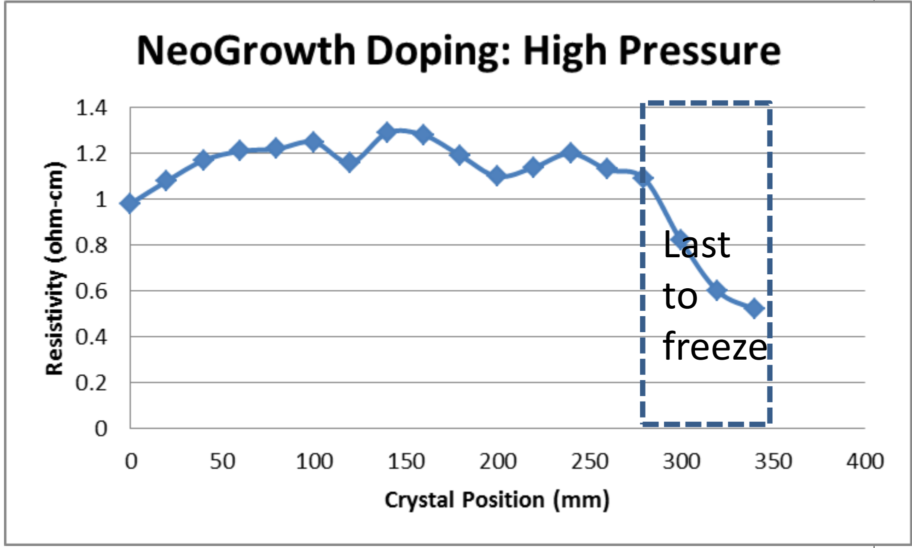
$$C(x) = C_0 * k * e^{-krxA/V}$$

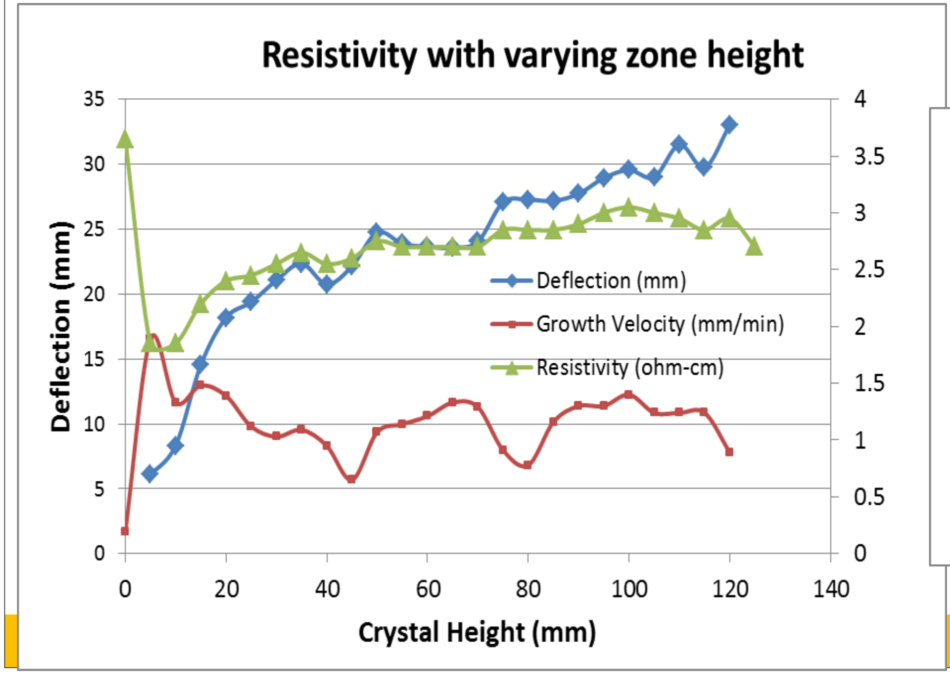
- k is the segregation coefficient
- $r = \rho_s/\rho_l$ is the ratio of densities
- x is the linear crystal position
- A is the cross-section of crystal growth
- V is the liquid volume

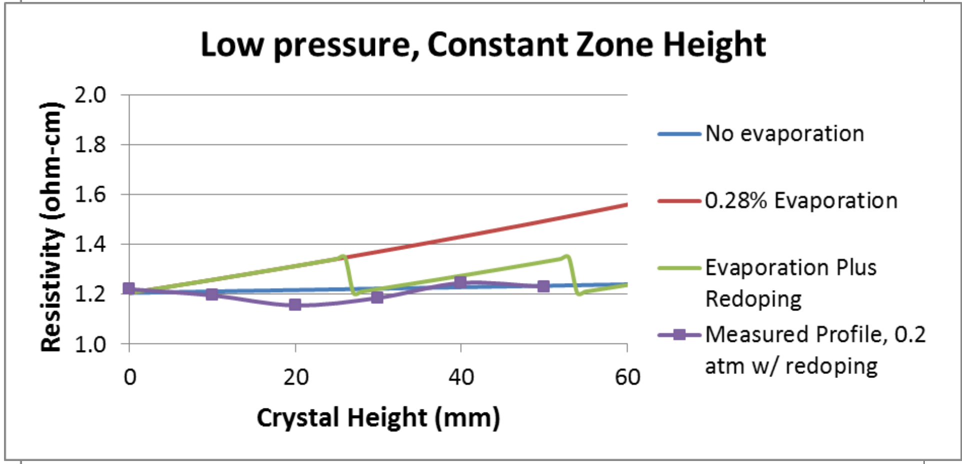
  Or $A/V = 1/h$ where h is the zone height

Doping

- Ambient pressure has a big effect on dopant evaporation
  - High pressure: dope once and done
  - Low pressure: have to redope
- Zone height also has a significant effect







Challenges

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- Early Challenges Overcome
  - Stability of melt puddle
  - Uniformity of melt flow
  - Argon purge design for low carbon
- Current challenges
  - Maintaining low stress to avoid dislocation multiplication narrows the process window
  - Twins coming from the nodes are pernicious
    - Problem solved at 230 mm, but not fully resolved at 450 mm
- Opportunities
  - Dislocation-free seeding seems possible, but not yet repeatable
  - Potential to increase the process stability via melt edge contact

Conclusions

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- NeoGrowth method demonstrated to have good promise for solar substrates
  - Low dislocations, oxygen, metals
  - High throughput drives low cost
  - Good doping and high lifetime
  - Possible extension to dislocation-free technique
  - Technique and equipment are part of the sale of SolarWorld Americas

- Excellent crystal growth advice now available from The Stoddard Consultancy

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Questions?

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