High quality cost effective n-type ingots

Yu Hu and Øyvind Nielsen, NorSun AS
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Our vision

Our vision is a sustainable future with clean energy for all.

Our mission

Our mission is to be a leading manufacturer of silicon ingots and wafers for high efficiency solar cells, through innovative technology and operational excellence.

Our values

Our values are: Dedication, Innovation, Inclusivity and Integrity.

Outline

- Introduction of NorSun
- Ingot production cost
  - Recharge
  - Cooling jacket
- Ingot quality
  - Resistivity
  - Carbon
  - Minority carrier lifetime (MCL)
  - Oxygen
  - Grown-in defects
- Summary

NorSun

- Norwegian company with 200 employees
- Monocrystalline ingots and diamond wire sliced wafers for high-end solar cells
- Capacity 370 MW/year
- Low cost CO_2 free hydropower
- Leading-edge high-end PV experience and technology
- Survived major industry crisis, net result of 19.8 MNOK in 2015

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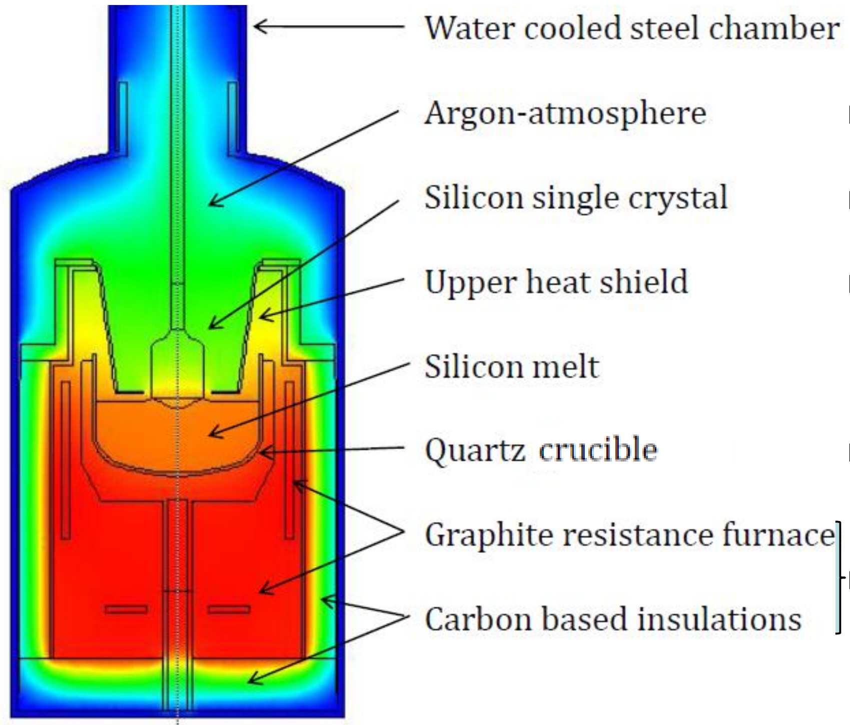
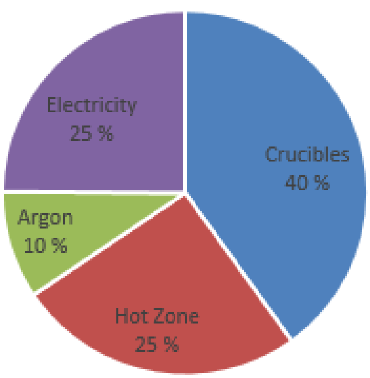
Ingot production: Process, cost, and cost reduction potential



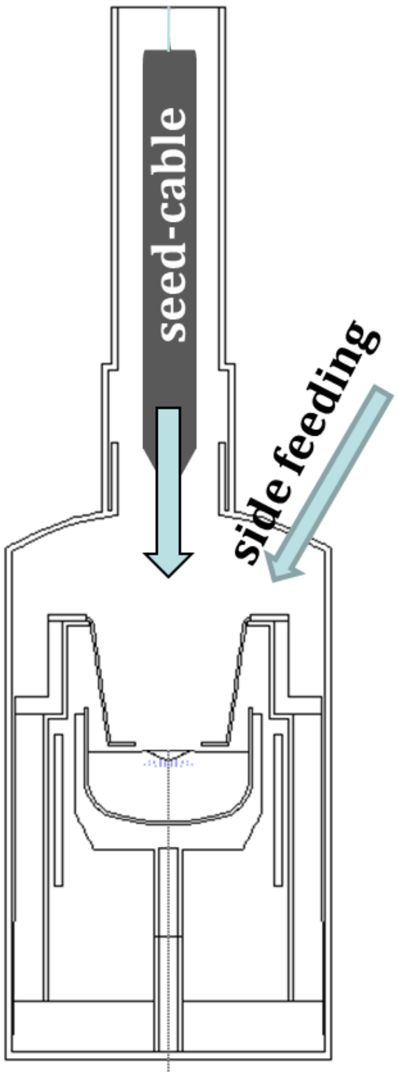
- Argon-atmosphere → Cost reduction: Internal Ar recycling
- Silicon single crystal → Cost reduction: Reduce structure loss
- Upper heat shield → Cost reduction: Active cooling, grow faster
- Quartz crucible → Cost reduction: Recharging + crucible optimization
- Graphite resistance furnace, Carbon based insulations → Cost reduction: New design and materials



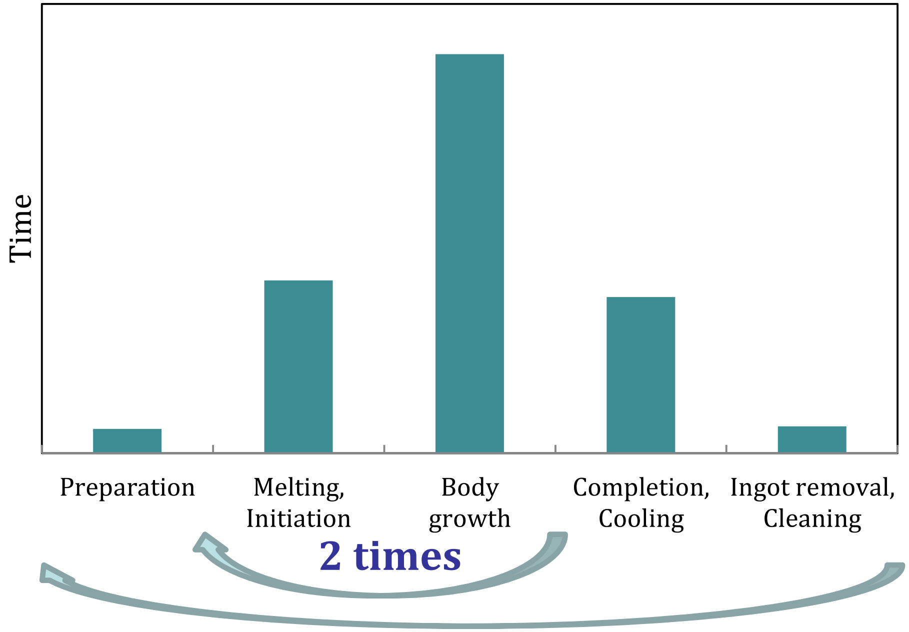
Typical variable cost distribution in ingot production without recharging

- To reduce **Variable cost**, pulling several ingots from each crucible and Ar recycling are key activities.
- To reduce **Fixed costs (incl manpower)** per kg ingot, increasing pull speed and reducing structure loss are key activities (higher productivity).

NorSun



Recharging



- Advantages of recharging *versus* standard batch CZ:
  - Reduced crucible and hot-zone cost per kg as-grown ingot
  - Increased yield (less potscrap) and throughput (avoid heating/cooling time)
  - Less polysilicon consumption per kg (inherent potscrap recycling)
- Two technologies developed by NorSun and implemented in production:
  - External recharging (**side feeding**, fully automated, some investment)
  - Internal recharging (**seed cable**, manual, negligible investment)
- Long-life low-cost crucibles developed with suppliers
- 100% of pullers on recharging (2 ingots/cycle) from Q1, 2013

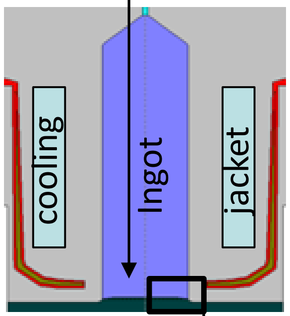
Energy balance on melt/ingot boundary:

$$k_S G_S - k_L G_L = \rho_S \Delta H V$$

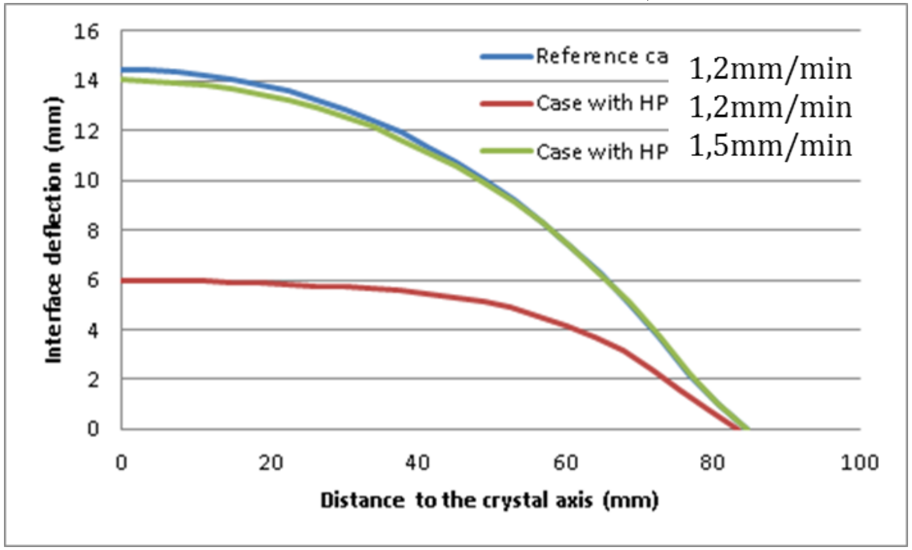
Increase by cooling jacket

Difficult to decrease

Pull speed



- K_S and K_L are thermal conductivities of crystal and melt
- G_S and G_L are the thermal gradients in the solid and melt
- ρ_s crystal density
- ΔH heat of fusion
- V pulling speed



Ingot growth rate can increase via more effective cooling

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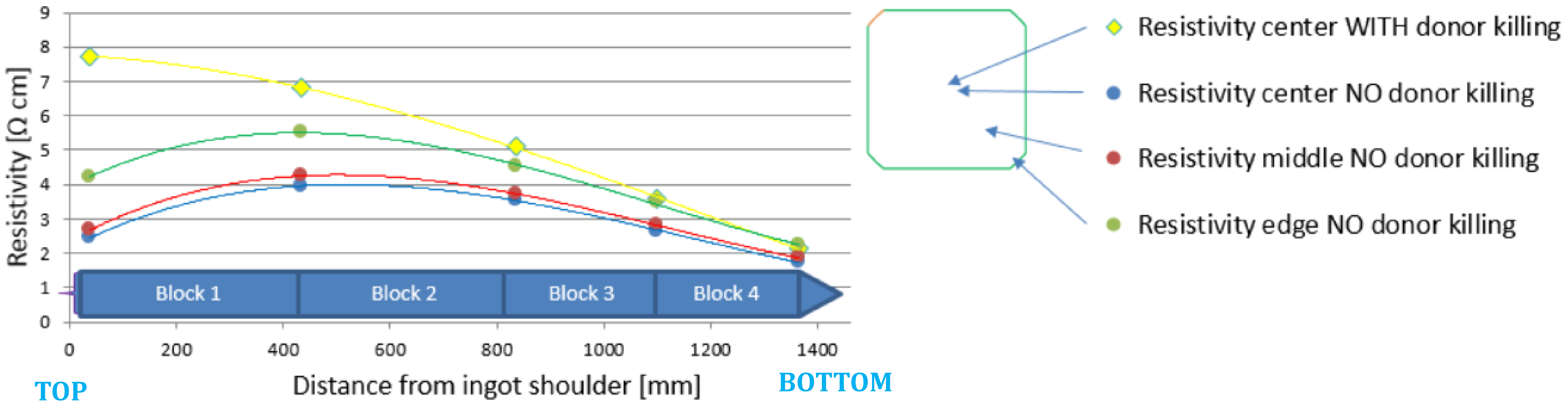
Silicon wafers for high-end solar cells

NorSun

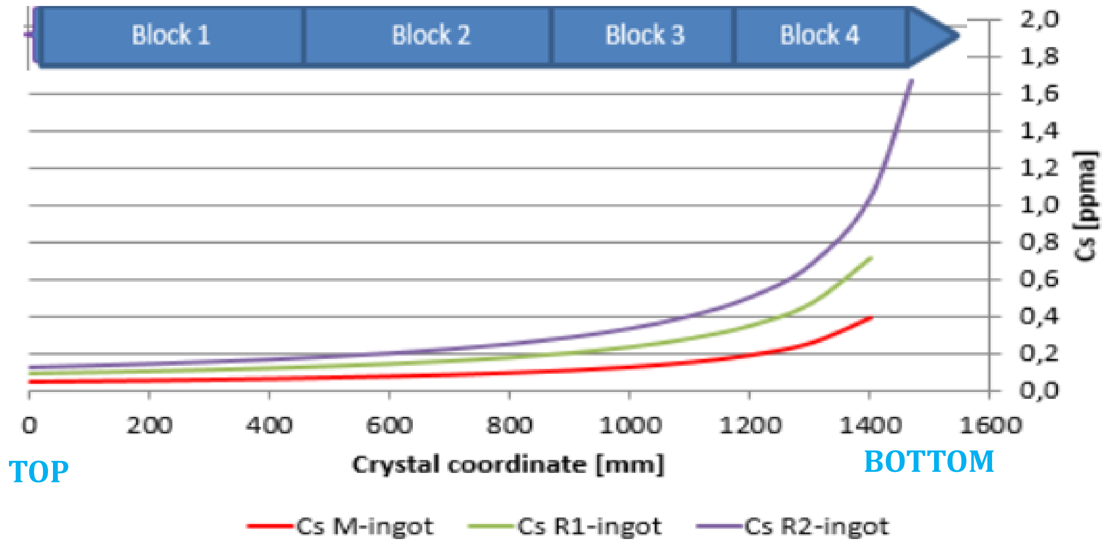
- Monocrystalline (CZ)
- n-type (phosphorus doped)
- Electrical resistivity 0.5 to 25 Ω cm
- Minority carrier lifetime 0.5 to 10 ms
- Interstitial oxygen 7 to 18 ppma
- Substitutional carbon 0 to 2 ppma
- Wafer thickness 130 to 180 µm

Ingot quality: Resistivity



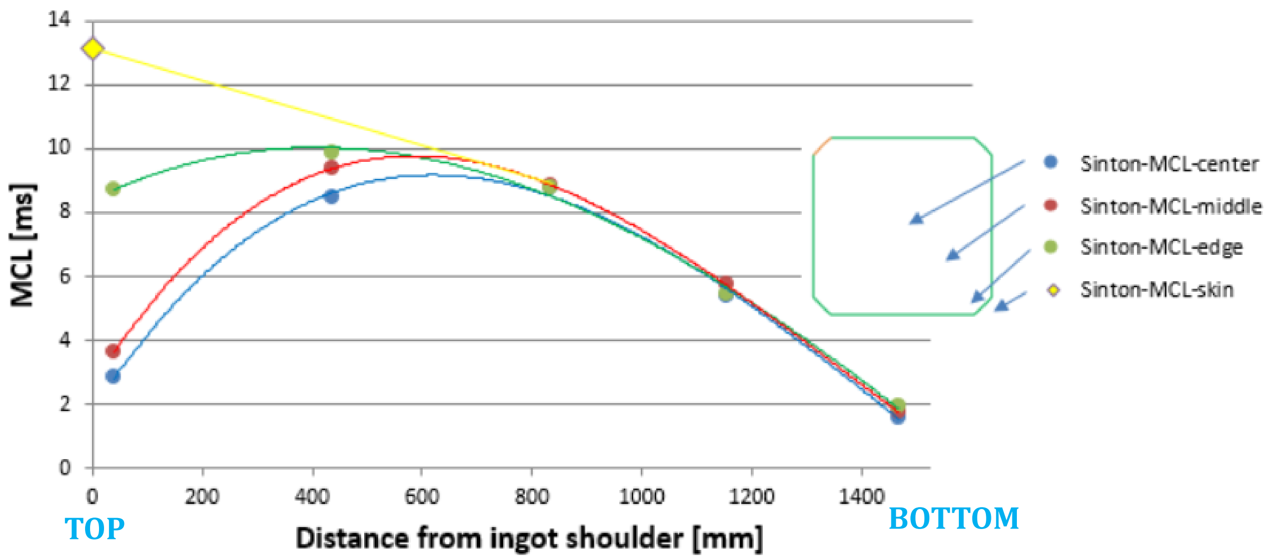
- Resistivity NO donor killing (equivalent to low temperature cell processing) is lower than Resistivity WITH donor killing due to presence of thermal oxygen donors that adds to the phosphorus donors.
- Thermal oxygen donor concentration increase with (i) increasing oxygen concentration, (ii) decreasing cooling rate.
  - TOP has high oxygen concentration and low cooling rate => low resistivity
  - CENTER has high oxygen concentration => low resistivity
- NorSun ingots and wafers are delivered as NO donor killing (no heat treatment performed after ingot production).
- Resistivity WITH donor killing is controlled by phosphorus segregation.
  - Rule of thumb: TOP = 7 x BOTTOM.
- The thermal donor effect can give a significantly smaller interval for resistivity than expected from phosphorus segregation.
- It should be noted that because oxygen is very low at the perimeter of the crystal, there will be an area close to the edge at the wafer chamfer in which the resistivity is close to the TOP = 7 x BOTTOM rule, even with NO donor killing.

Ingot quality: Carbon



- Controlled by carbon segregation
  - Rule of thumb: pulling one ingot per crucible (no recharge), the bottom of the ingot will have the same carbon concentration as the silicon charge itself
- Sources of carbon in silicon charge:
  - Polymer particles in polysilicon
  - Surface carbon in polysilicon and ingot recycles
  - Hot-zone (furnace parts made of graphite)
- Typical carbon spec in PV grade polysilicon is 0.5 to 1 ppma
- Pulling two or three ingots per crucible (recharging), the carbon content increases
- NorSun’s spec is Cs < 2 ppma; no negative impact on cell process shown at this level

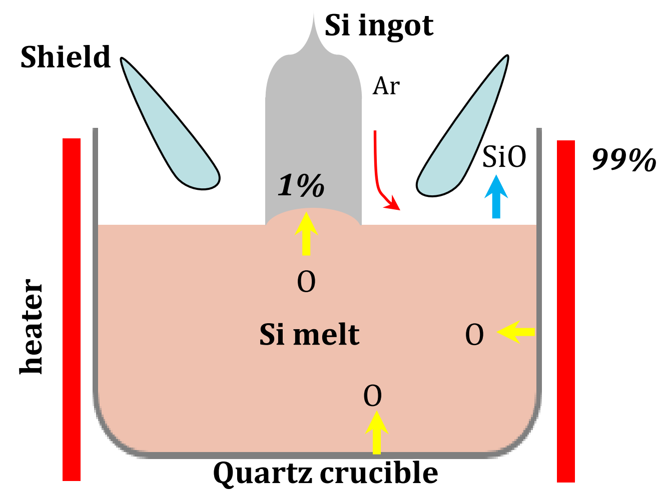
Ingot quality: Minority carrier lifetime (MCL)



- Minority carrier lifetime in delivered ingots/wafers controlled by
  - Oxygen in the TOP (low in center, high on chamfer)
  - Metals in the BOTTOM
    - Metal segregation gives lowest MCL in center or homogeneous distribution.
    - Metall in-diffusion from hot-zone gives lowest MCL on chamfer («skin» effect).
- Presently, 2nd and 3rd ingot from crucible has significantly lower lifetime
  - Still 2nd ingot can be well controll within > 1 ms for resistivity > 1.5 Ω cm
  - NorSun is working on a method to give all recharge ingot same MCL as 1st ingot
- Lack of oxygen control can give low MCL in middle of ingot after cell processing (low lifetime rings caused by oxygen precipitation)

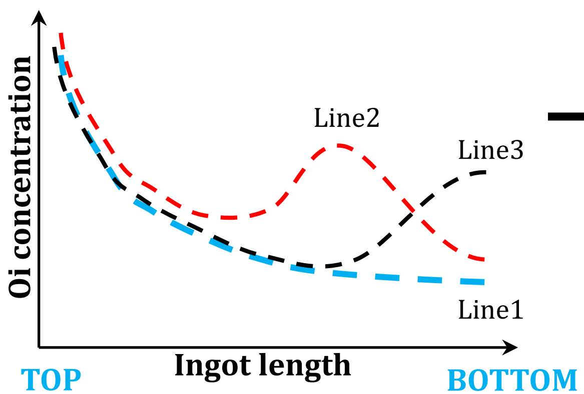
NorSun

- Oxygen source: quartz crucible
  - $SiO_2 \rightarrow Si + 2O$
- O transportation:
  - Most travel to free surface and evaporate as SiO gas, whereas the rest travel to crystal/melt interface and incorporate into Si ingot
- Oxygen profile:
  - Generally, O into Si ingot mainly depends on A_E/A_C. O thus decreases from seed to tail end as Line1.
  - However, O profile could also be like line 2 or 3.



A_E : *Evaporation area*

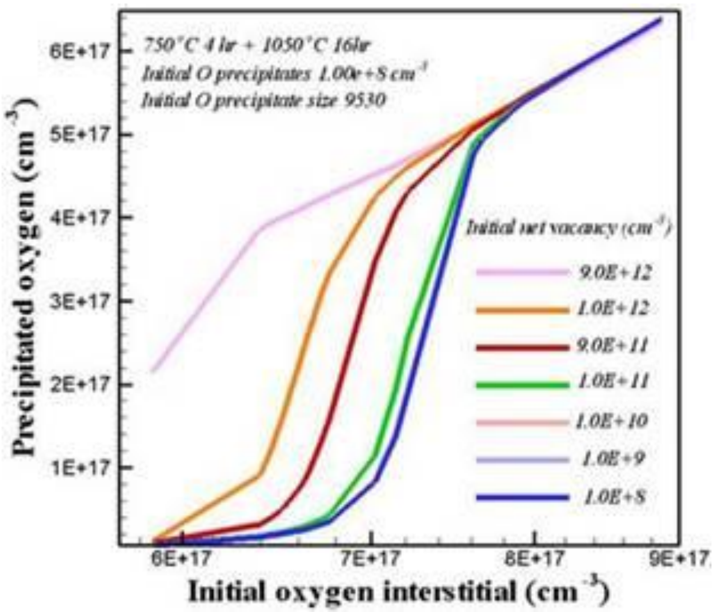
A_C : *Melt/crucible contact area*

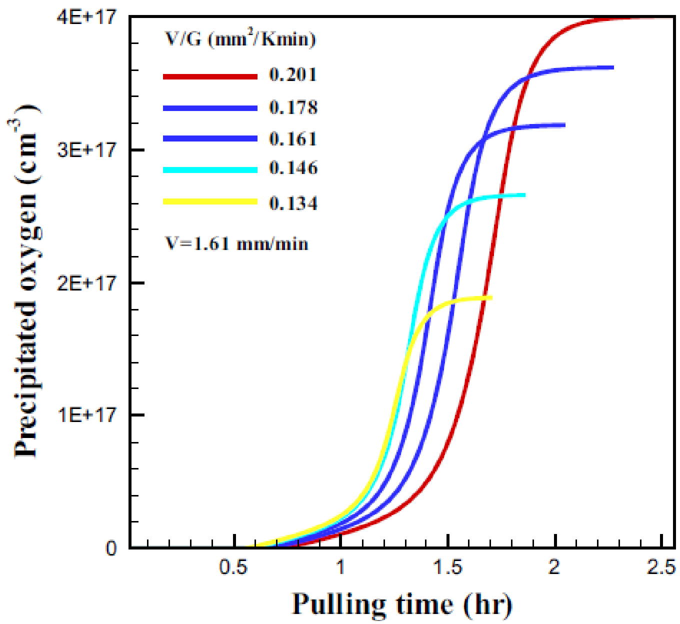


- Case 2 challenge in quality control for ingot producers

- NorSun has developmed method to control oxygen peak in ingots; and the method has been fully implemented since Q2, 2015

- When V/G>(V/G)critical, ingot grows in vacancy-rich mode. Generally, this is the case for Cz ingot production for PV application
  - V: growth rate, G: axial temprature gradient close to cystal-melt interface
- Important to control concentration of vacancy which can increase oxygen precipitation (left figure)
- Under certain pull speed, higher V/G ratio gives mroe oxygen precipites due to increase of vacancy concentration (right figure)





Bing Gao, SINTEF, 2016

Summary

- NorSun in full production, net result of 19.8 MNOK in 2015

- Ingot production cost:
  - Main cost drivers are crucible, electricity, hot-zone (graphite), and argon
  - Productivity is the key to reduce fixed cost
  - NorSun has a robust roadmap for cost reduction with key projects well progressed, *e.g* recharging, active cooling, and argon recycling

- Ingot quality:
  - Thermal donors contribute to reduce resistivity interval along ingot, but leads to radial resistivity gradient in TOP of ingot, because oxygen is low close to wafer chamfer
  - Carbon variations in polysilicon leads to high carbon in ingots produced by recharging
  - Minority carrier lifetime is controlled by oxygen in TOP of ingot but metal segregation in BOTTOM
  - Lifetime is lower in recharging ingots, but NorSun works on method to avoid this problem
  - Controlling oxygen in ingot growing process is a key to avoid low-lifetime rings in solar cells
  - NorSun has fully implemented a method to avoid potential oxygen peak in ingot body
  - Vacancy concentration need also be controled to reduce oxygen precipitation