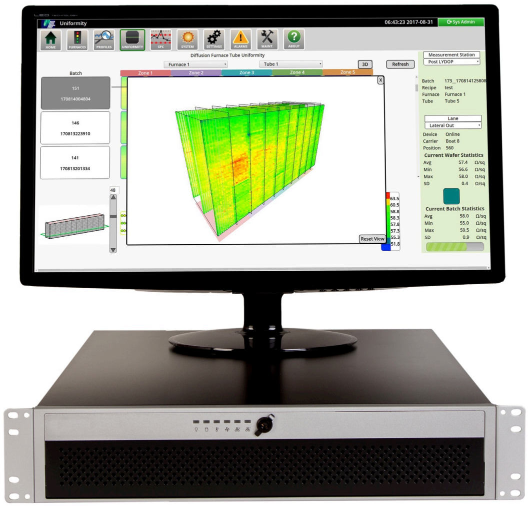
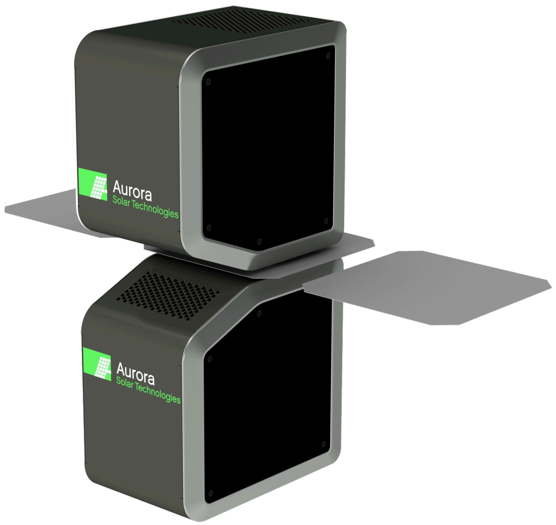
Aurora
Solar Technologies

Accurate inline characterization of BSF and emitter fabrication processes for high-volume bifacial cell production





Gordon Deans, Aurora Solar Technologies

4th Bifacial PV Workshop

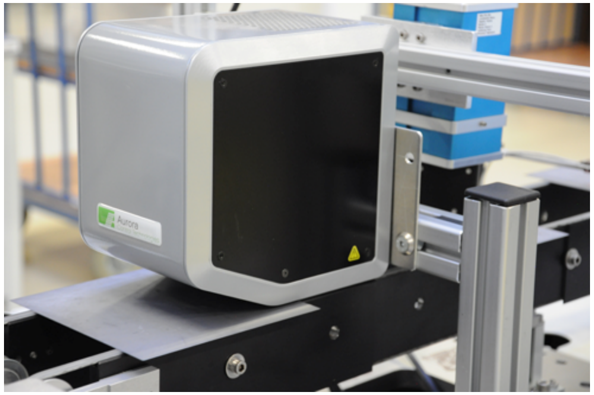
Konstanz, Germany

26 October 2017

Aurora Solar Technologies

- Mission – Deliver superior results to the PV industry through measurement and control of critical processes
- Product line for measurement, visualization, and control of Si PV cell fabrication processes
  - Decima™ inline sheet resistance measurement systems
    - p+, n+, n++/n, bifacial doped layers measured to 6 σ standards in real time
    - Discrete mapping of sheet resistance across wafer surfaces
  - Aurora Veritas™ production controller
    - Immediate "MRI"-like spatial view of process tool performance using Decima measurements
    - Networked to all Decimas for integrated measurement and control
- Proven with top-tier solar manufacturers and process equipment vendors worldwide

Aurora headquarters: Vancouver, Canada



Aurora Technology in c-Si Cell Production

Inline measurements provide vital information and insights

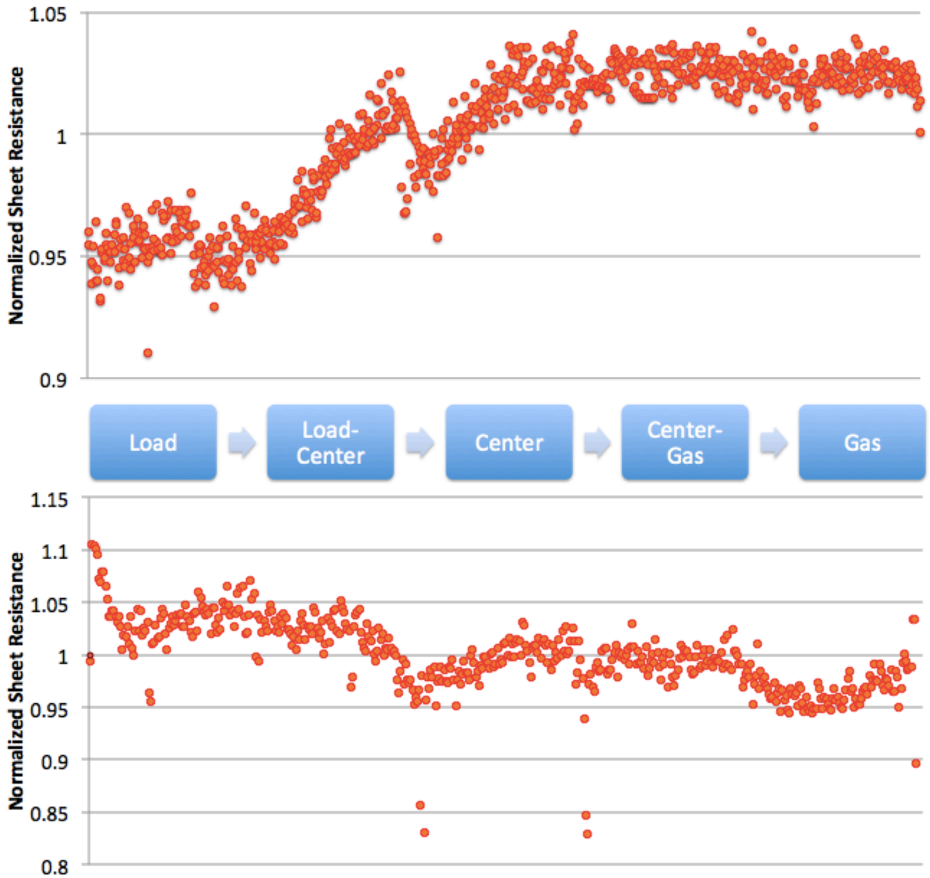
- Faster, more precise line commissioning
- Data to support continuous improvement of the line
- Data to support device design improvement
- Best possible quality control
- Evaluation and cost control of raw material supply

Increasingly important with higher-efficiency cell designs

Example: inline bifacial cell measurement

Process tool behaviour is the key

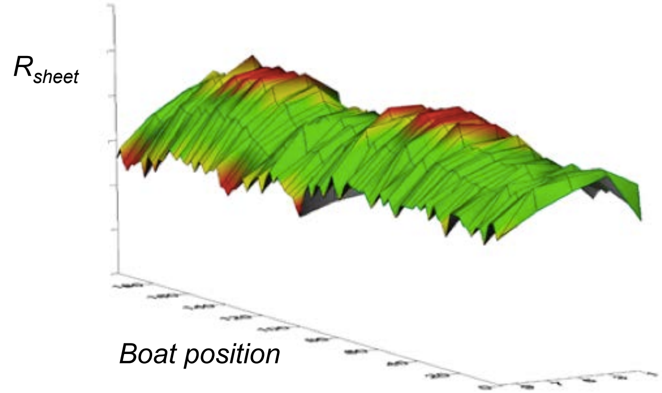
- Behaviour as shown here is not uncommon …
- … hence sparsely sampled measurements hide useful information
- How can we reveal the true variations and their significance?



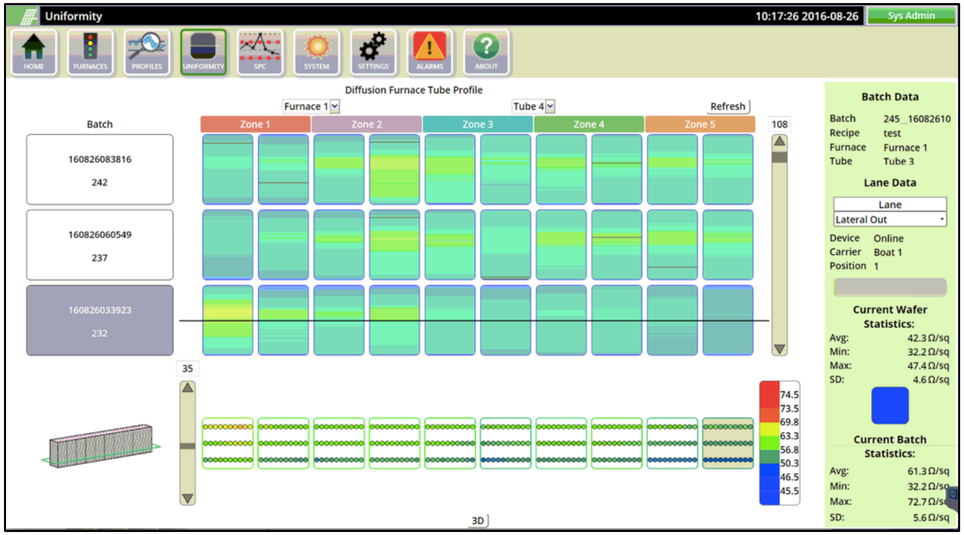
Two emitter sheet resistance profiles, showing significant non-uniformity along quartz tubes

Understanding process variation

- See what the process tools are doing
- Spatial variation
  - Intra-wafer
  - Tubes or lanes
  - Tool-by-tool
- Time variation (batch-to-batch)



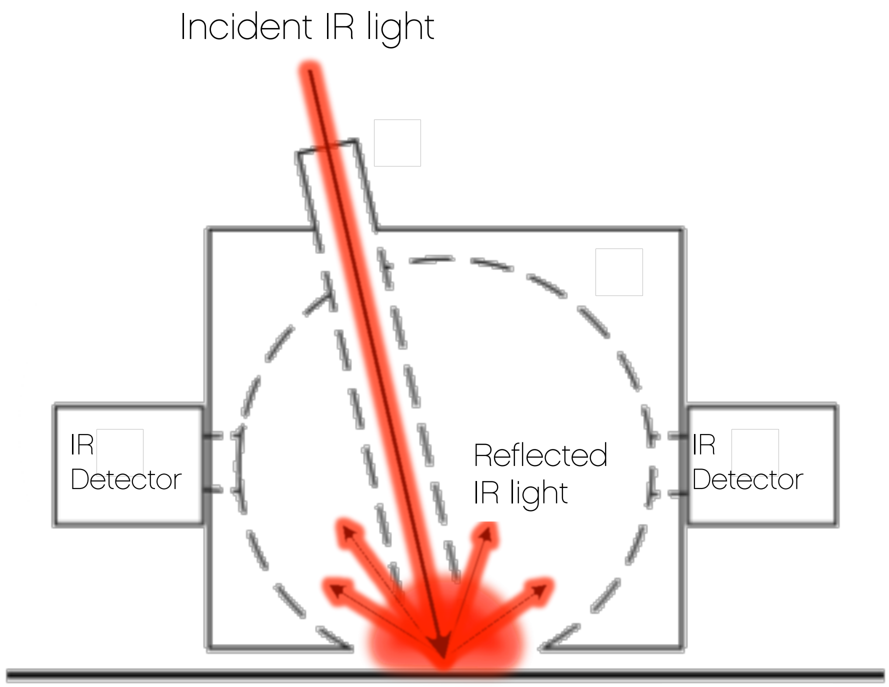
Wafer edge-to-edge emitter sheet resistance measurements along furnace tube



Three successive batches from "horizontal" furnace tube. Colors indicate emitter sheet resistances for each wafer compared to the SPC targets

Measurement Technique

- Non-contact IR reflection and transmission sensing
- Mid-IR light is directed at the sample and the reflection and transmission are captured
- Magnitude of these signals is proportional to free carrier density
- Correlated to 4pp sheet resistance
- Benefits:
  - Can be spatially resolved
  - No junction required for doped layer sensing - separation of BSF from wafer bulk
  - Insensitive to surface electrical properties
  - Tolerant to production facility “noise”



Reflection-only is shown for simplicity

Scientific basis

- IR reflection (λ > 1.1 **μm**) depends on free carrier concentration and mobility
  - At normal incidence the reflection from silicon in air is

$$R = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2}$$

  - This is related to the dielectric function by

$$\varepsilon(\omega) = (n - i\kappa) = \varepsilon_0 - \frac{\omega_p{}^2}{\omega(\omega + \iota\gamma)}$$

  - Dielectric function depends on doping; therefore, variations in doping levels of the emitter lead to wavelength dependent variation in reflection from the surface, as shown below:

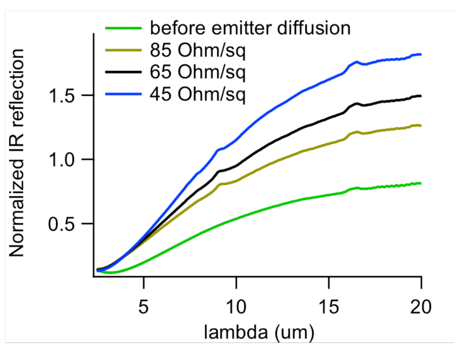


Figure 1 – Spectrally resolved IR reflection from four PV wafers with diffused emitters. Samples were measured on a Thermo-Nicolet 8700 FTIR. Figure reproduced from [3].

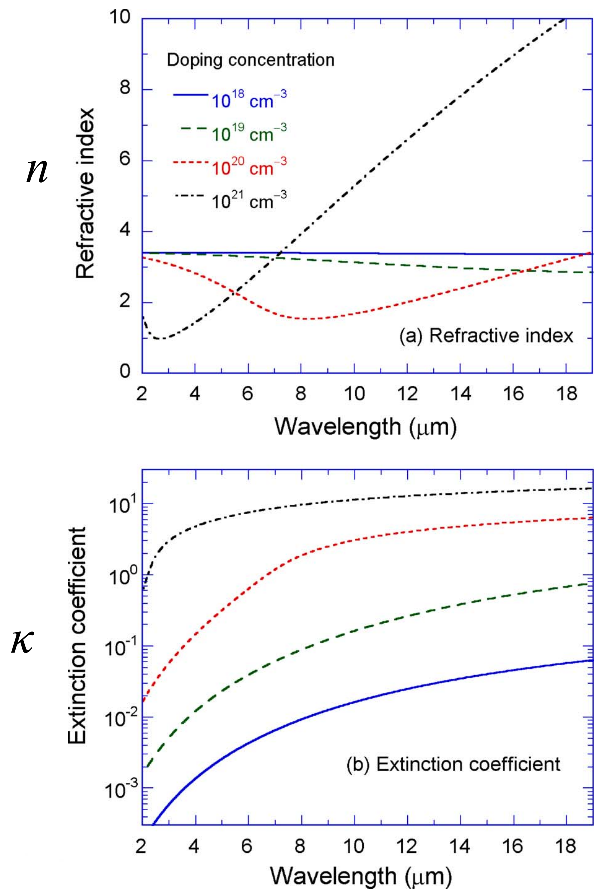
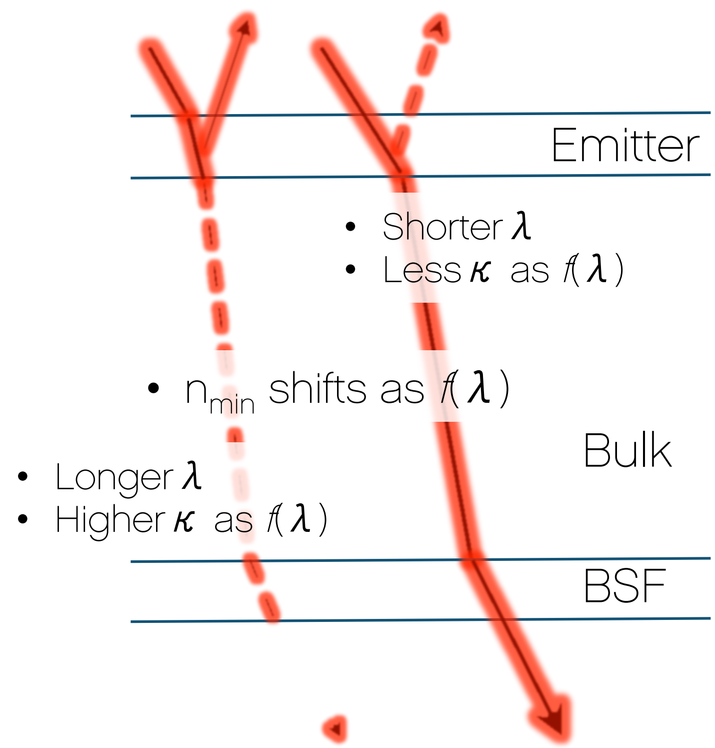


Fig. 4 Optical constants of *p*-type silicon for different doping concentrations calculated using the Drude model, including accurate values of carrier mobility and ionization: (*a*) refractive index, and (*b*) extinction coefficient. The legends are the same for both figures.

Applied to measuring doped layers in Si

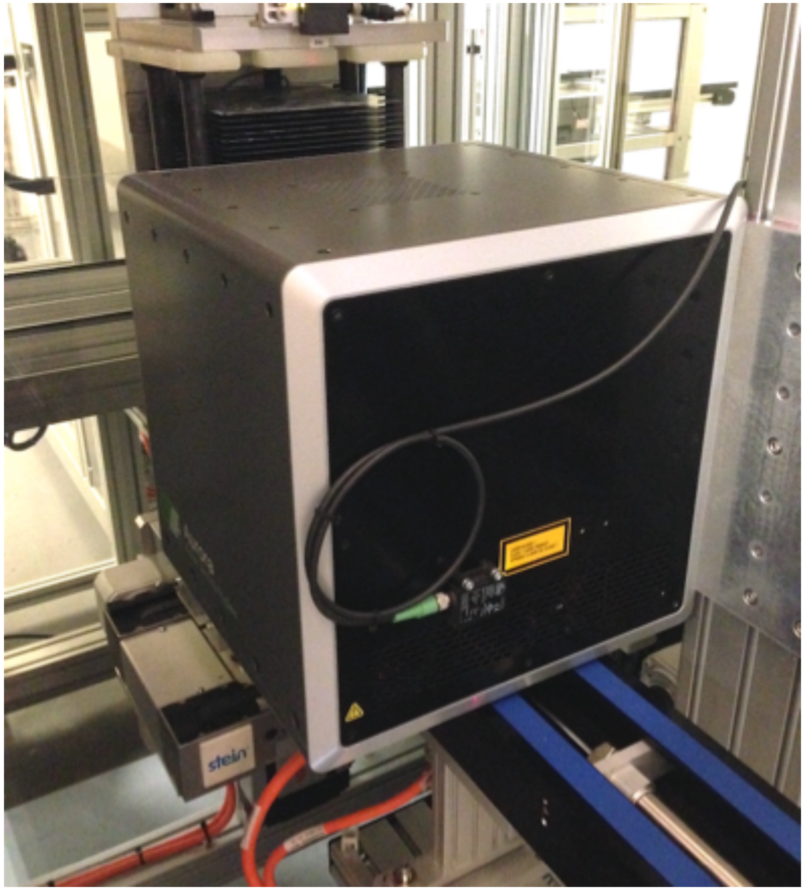
- IR complex refractive index (n and κ) of IR varies by dopant concentration N and wavelength λ
- Therefore, use of certain mid-IR bands allow resolution of highly-doped layers near the top and bottom wafer surfaces
- Because polarity of the doped layers does not matter **the BSF dopant concentration can be isolated in an n++/n or p++/p BSF/bulk structure**



Simplified view

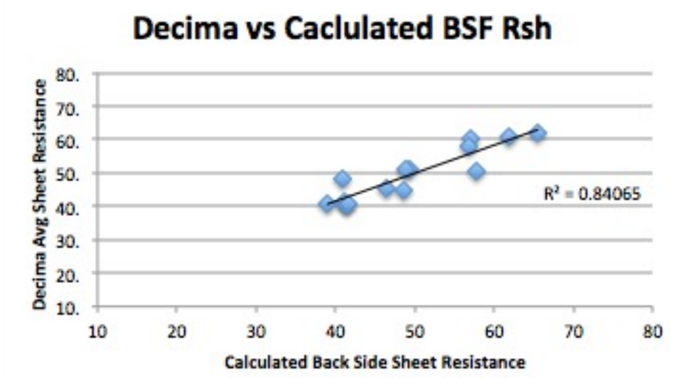
Getting from theory to practice

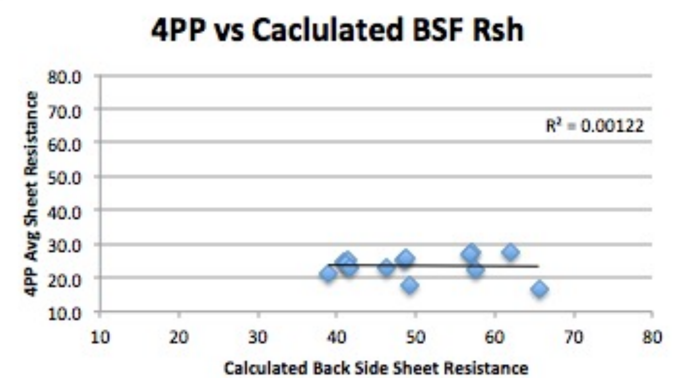
Challenge	Solution
Varying light capture due to surface roughness variations	Optical geometry to direct and consistently collect light
Varying light trapping due to surface roughness variations	Proprietary signal processing to separate surface reflection variation from free carrier reflection
Repeatability for spatial resolution across wafers	High-precision wafer edge and position tracking



Results

- nPERT
  - R^2 (front): 0.89
  - R^2 (rear): 0.96
  - Accuracy: $\sigma < 1.5$ ohms/sq
  - Repeatability: $\sigma \cong 0.7$ ohm/sq
- BiSoN
  - R^2 (front): 0.97
  - R^2 (rear): 0.91
  - Accuracy: $\sigma < 2$ ohms/sq
  - Repeatability: $\sigma < 1$ ohm/sq





Isolation of BSF sheet resistance from bulk resistance

Experience to date

- Taiwan
  - Four systems (three inline, one standalone) since 2015
  - Wafer and process mapping for mono-PERC production
  - Used in process tool profiling, ramp-up and for continuous quality control
- Korea
  - Fourteen systems for mono-PERC production since 2016.
  - Six dual-sensor systems for bifacial production since 2016
  - Used for continuous quality control and wafer accept/reject binning
- Europe
  - Dual-sensor qualification for BiSoN measurement – 2017
  - Sequential single-sensor qualification for nPERT wafers – 2015
  - One system with wafer and process mapping for implanted mono and multi production since 2015
  - Used for continuous quality control
- China
  - Standalone system integrated in wafer transfer station
  - Used for emitter – metal paste optimization
- China (soon)
  - Four systems with wafer and process mapping and both single and dual sensors for bifacial production
  - To be used in ramp-up and continuous quality control

Thank you

Contact information

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Backup slides

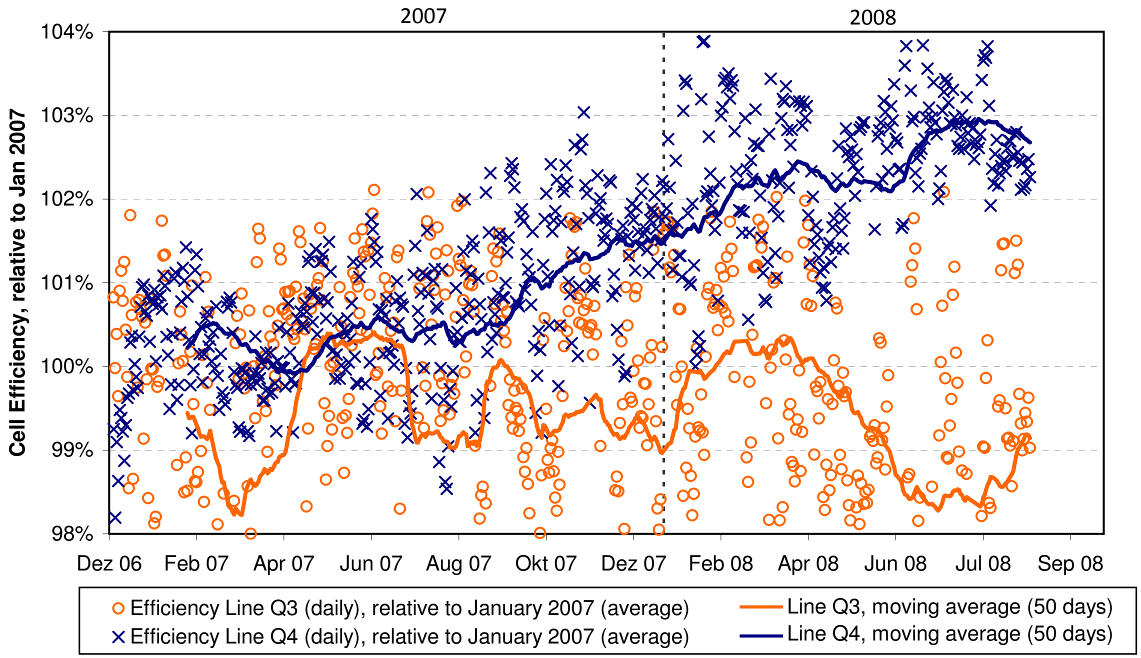
Aurora installations worldwide

★ Aurora HQ,
Vancouver Canada

● Installed in PV cell production (customers)
● Research (own/collaborative)

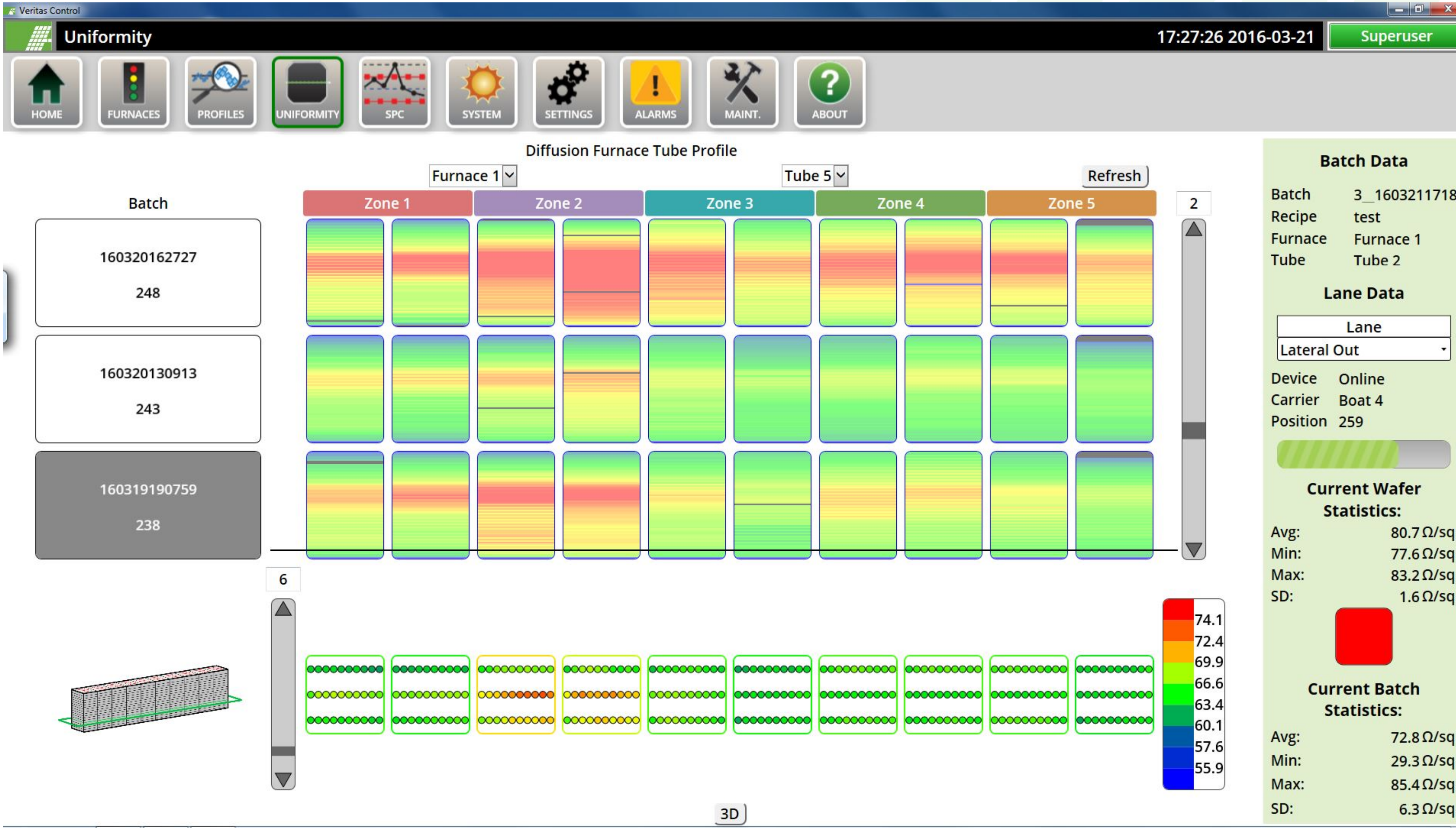
What happens when you control process variations and optimize set-points

- Variation in cell efficiency is reduced
- Manufacturing yield (in terms of MW) is increased
- Corollary: bin distribution narrowed
- *To this day, continuous inline measurement is a key tool for yield management at quality-focused manufacturers*



Effect of quality and variance control program at top-tier manufacturer. Blue indicates production line where program implemented, orange is regular production.

Source: "Integrated Efficiency Engineering in Solar Cell Mass Production ", Ph.D. Thesis, Thomas Dinkel, Jacobs University School of Engineering and Science, May 2010



Veritas Control
Uniformity
17:27:26 2016-03-21
Superuser
HOME
FURNACES
PROFILES
UNIFORMITY
SPC
SYSTEM
SETTINGS
ALARMS
MAINT.
ABOUT
Diffusion Furnace Tube Profile
Furnace 1
Tube 5
Refresh
Batch
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248
160320130913
243
160319190759
238
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5
2
6
74.1
72.4
69.9
66.6
63.4
60.1
57.6
55.9
3D
Batch Data
Batch 3_1603211718
Recipe test
Furnace Furnace 1
Tube Tube 2
Lane Data
Lane
Lateral Out
Device Online
Carrier Boat 4
Position 259
Current Wafer Statistics:
Avg: 80.7 Ω/sq
Min: 77.6 Ω/sq
Max: 83.2 Ω/sq
SD: 1.6 Ω/sq
Current Batch Statistics:
Avg: 72.8 Ω/sq
Min: 29.3 Ω/sq
Max: 85.4 Ω/sq
SD: 6.3 Ω/sq