Future cell technology

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Levelized Cost of Electricity LCOE

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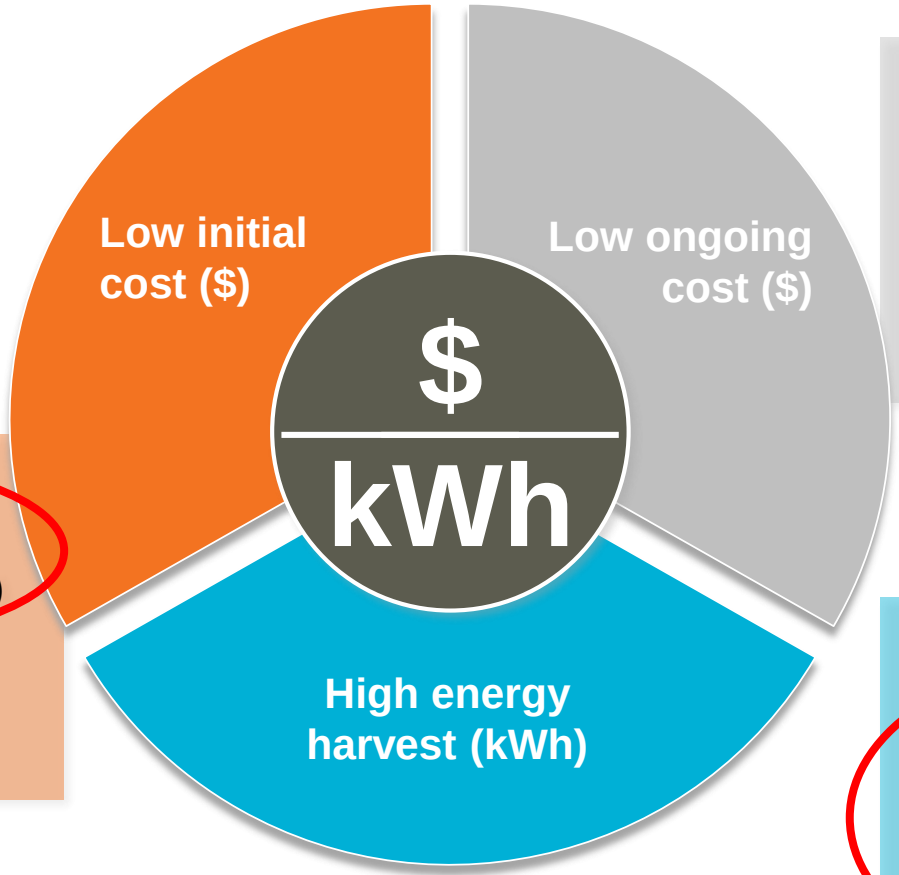
LCOE ($/kWh)

- Initial cost ($)
- Ongoing cost ($)
- Energy harvest (kWh)



- Modules
- Balance of system (BOS)
- Development / EPC
- Financing

- Operations & Maintenance (O&M)
- Insurance
- Taxes
- Others

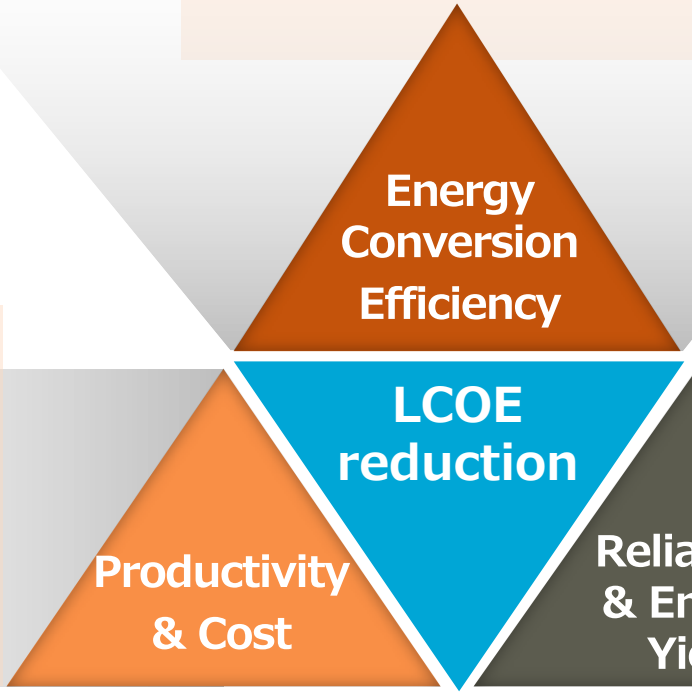
- Irradiation
- Power plant performance
- Module degradation
- Low-light-behavior
- Temperature coefficient

Electricity is commodity: main parameter is LCOE

LCOE Reduction: Key Technology Levers

New technologies: optimization of productivity, efficiency and reliability

- PERC / PERL Technology
- Next Gen. Emitter
- Superfine Line Print
- Alternative Metallization
- Power Optimized Module
- System Performance



- Throughput
- Automation
- MES / Wafer Tracking
- Yield
- Ag Reduction
- Consumables
- Bill Of Materials Module

- Testing /Characterization
- Failure Modes (e.g. LID)
- Material Characterization
- Climate Effects
- Aging Models

Increase productivity in multi GW production

- **10 GW/a cell production**
  - ~1 800 000 000 cells per year
  - ~ 5 000 000 cells per day
  - ~ 60 cells per second
  - ~ 800 process tools

- **Needs fully automated production and manufacturing control**

Increase productivity in multi GW production
TRA.Q - Single wafer tracking

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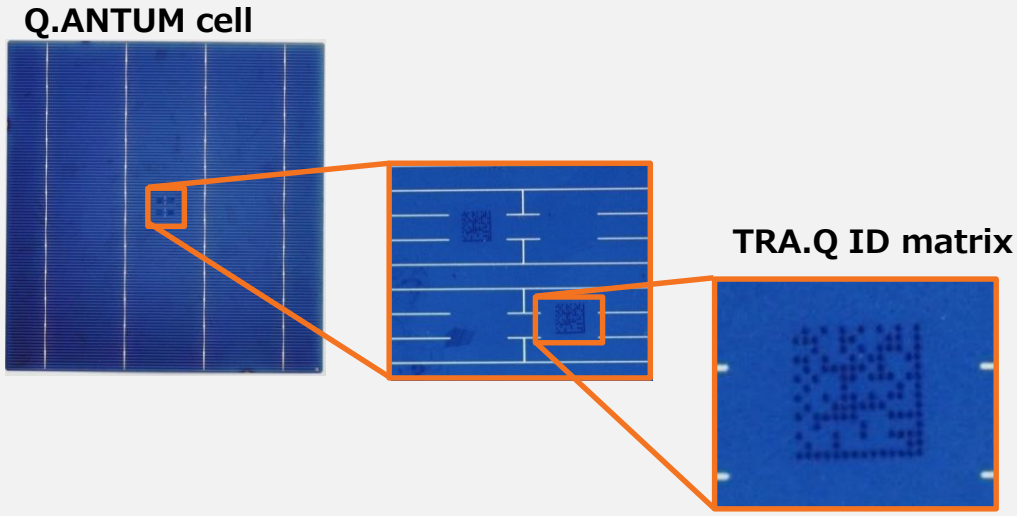
Single wafer tracking for efficient development and manufacturing control



- Each wafer marked with unique ID matrix
- ID can be linked with relevant process and measurement stations
- Worldwide standardization within SEMI
- TRA.Q manufacturing experience at Hanwha Q Cells since 2009

→ **Via TRA.Q:** Correlation of process parameters with Inline measured data and cell parameters possible

- Very powerful for GW scale production → efficient data mining possible
- Without any additional cell handling and cell withdrawals

S. Wanka et al. "Tra.Q: Laser Marking for Single Wafer Identification- Production Experience of 100 Million Wafers" in Proc. 26th EUPVSEC, 821-826, Hamburg, Germany, 2011

Increase productivity in multi GW production
TRA.Q - Analysis of wafer material influence

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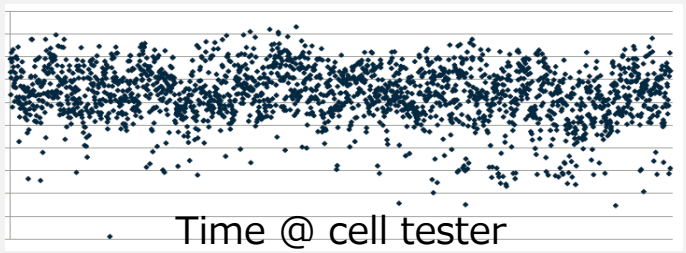
Continuous improvement Analysis of wafer material influence

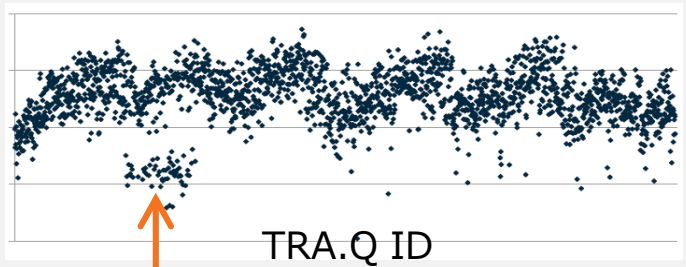
Cell efficiency (arb. Units)



Efficiency Data from 2300 cells ordered by time

→ Broad distribution of cell efficiency

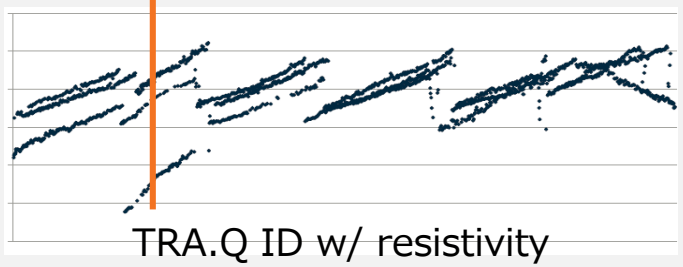
Cell efficiency (arb. Units)



Efficiency Data ordered by TRA.Q ID

→ Distribution of cell efficiency shows pattern

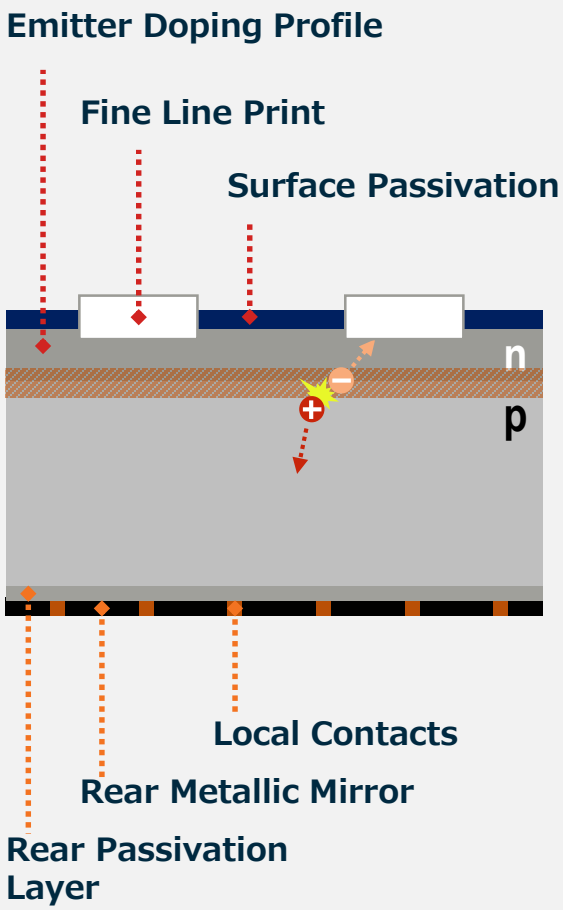
Cell efficiency (arb. Units)



Wafer base resistivity ordered by TRA.Q ID

→ Distribution shows characteristic pattern

Increase efficiency cost effectively
Evolutionary Cell Device Optimization:



Front

Targets
- **Reduced light shading and silver consumption**
- **Increased blue response**

Approach
- Fine line contacts
  → reduced metal coverage, contact to optimized emitter
- Emitter doping profile
  → reduced Auger recombination
- Surface passivation
  → optimized emitter passivation

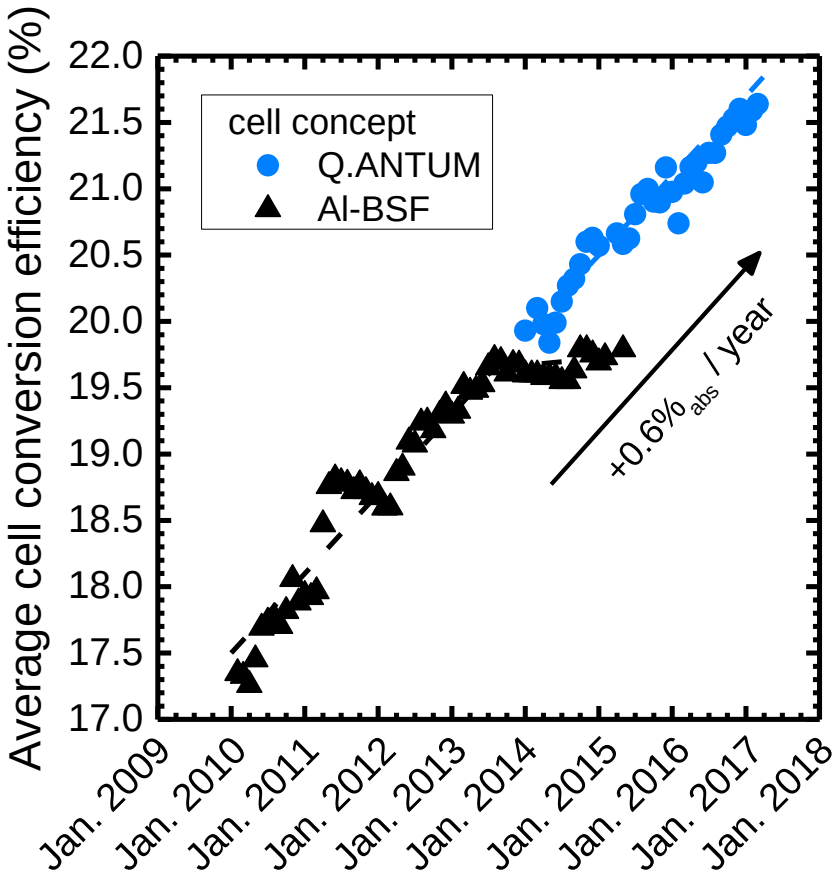
Rear

Targets
- **Improve surface passivation, increased red response**

Approach
- Optimized rear passivation layer
  → reduced recombination
- Improved rear metallic mirror
  → increased light trapping
- Passivated local contacts
  → reduced recombination

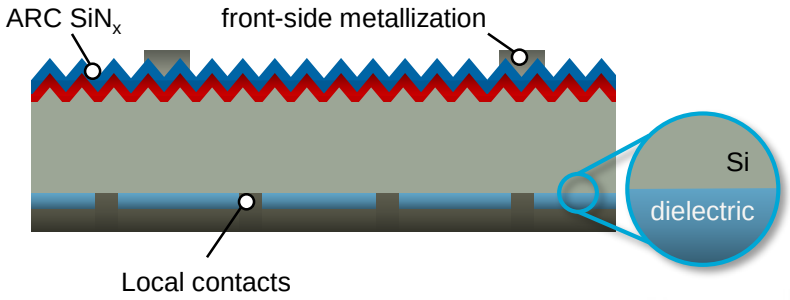
Boundary condition
- Cost effective and module compatibility

Increase efficiency cost effectively
Evolutionary Cell Device Optimization:



powered by Q.ANTUM

Q.ANTUM Technology[2,3]



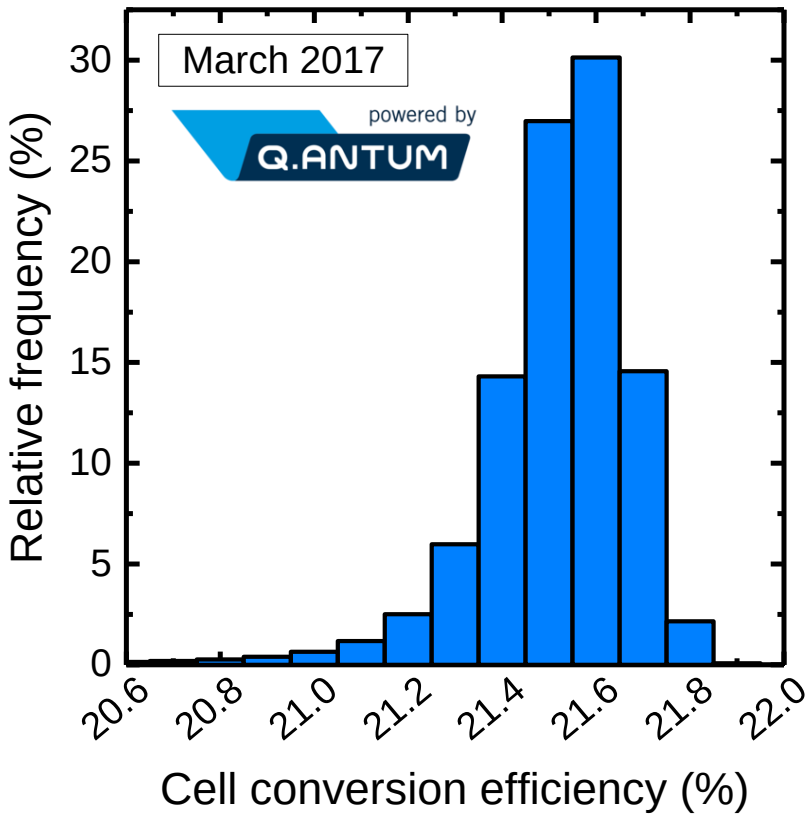
- Increased photo generation
- Reduced rear-surface recombination
- Additional features to PERC

Q CELLS YIELD SECURITY

- ANTI PID TECHNOLOGY (APT)
- HOT-SPOT PROTECT (HSP)
- TRACEABLE QUALITY (TRA.Q™)
- ANTI LID TECHNOLOGY (ALIDT)

[1] J. Mandelkorn and J.H. Lamneck "Simplified Fabrication of Back Surface Electric Field Silicon Cells and …" in Proc. 9th IEEE PVSC, 66-71, Silver Springs, USA, 1972.
[2] P. Engelhart *et al.* "Q.ANTUM - Q-Cells Next Generation High-Power Silicon Cell & Module Concept" in Proc. 26th EUPVSEC, 821-826, Hamburg, Germany, 2011.
[3] A. Mohr *et al.* "20%-Efficient Rear Side Passivated Solar Cells in Pilot Series …" in Proc. 26th EUPVSEC, 2150-2153, Hamburg, Germany, 2011

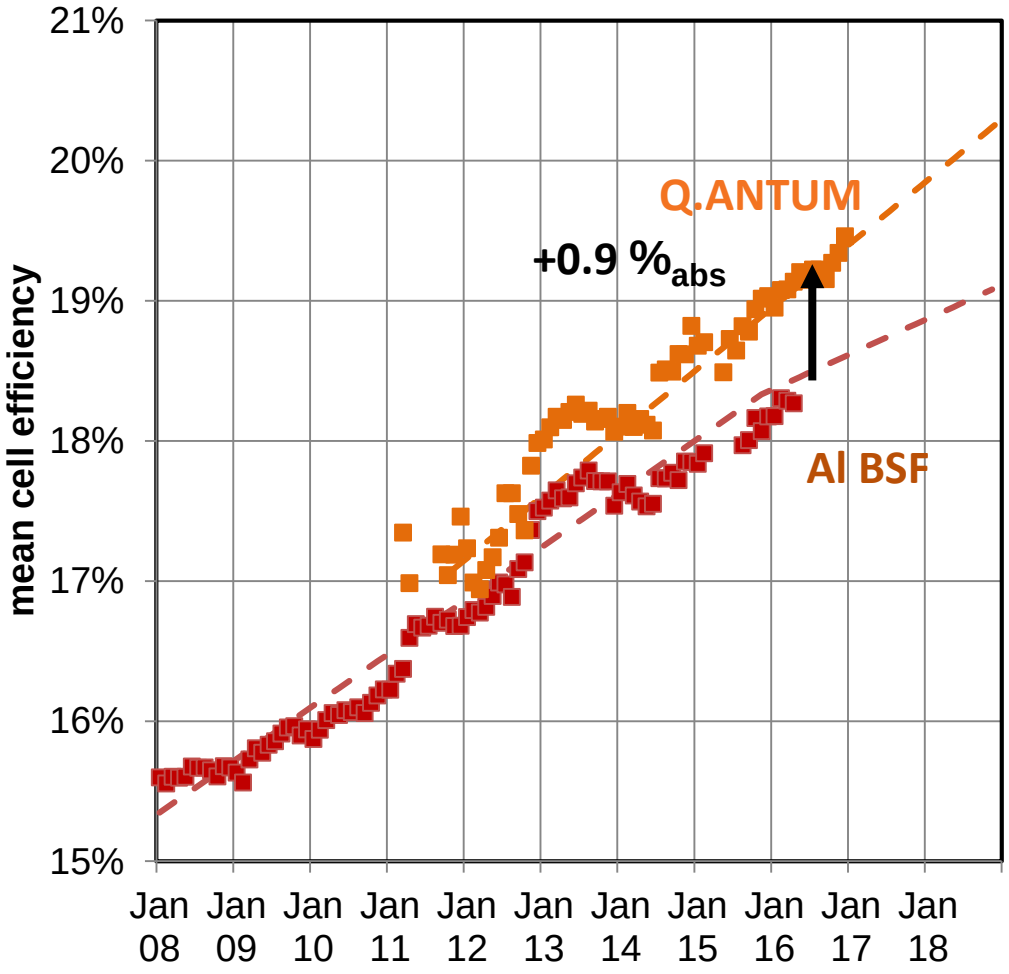
Increase efficiency cost effectively
Mass Production of Q.ANTUM mono



Conversion efficiency distribution

- Very tight distribution with efficiencies > 21.5 %
- Further improvement potential by optics and reduced recombination losses
- Efficiency headroom of Q.ANTUM exceeds 24 %

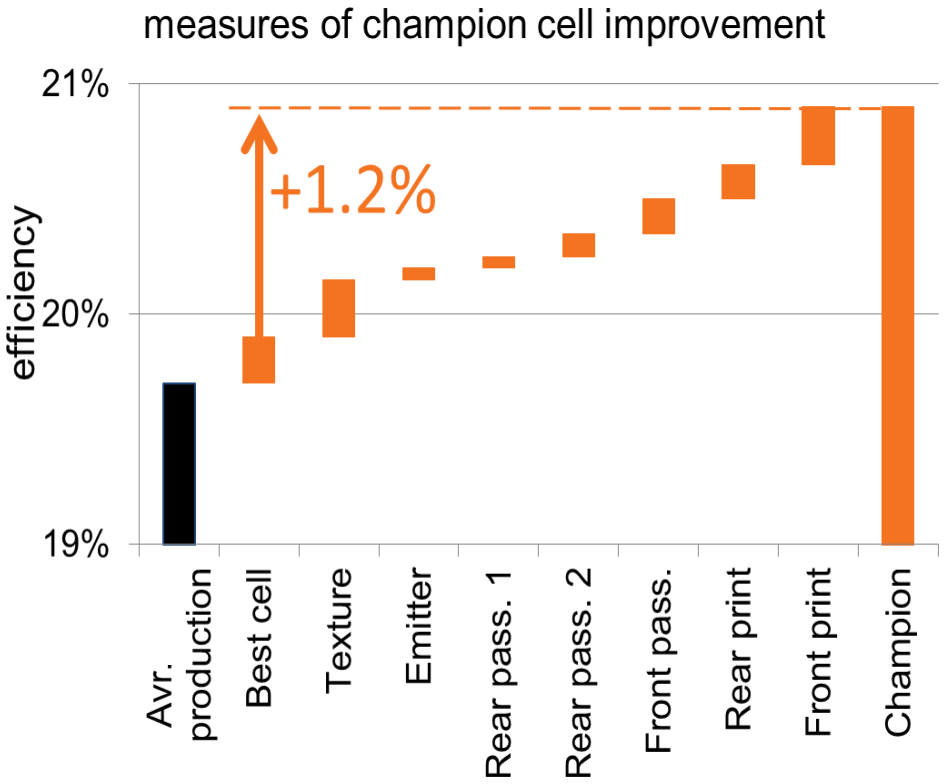
Increase efficiency cost effectively
Multi solar cell efficiency development



- Similar results using multi crystalline wafer
- > 5 years of high-quality **Q.ANTUM mass production:**
  - median cell efficiency: > 19.8 %
  - N_{cell} increase: + 0.5 $\%_{abs}$/a
  - Silver consumption: - 50 %
  - Upgrade of existing tool set
  - Throughput increase
- Currently ~ 3 GW Q.ANTUM multi capacity

B. Klöter et. al., 32nd EU-PVSEC 2016

Increase efficiency cost effectively
Q.ANTUM Multi: Champion cell result



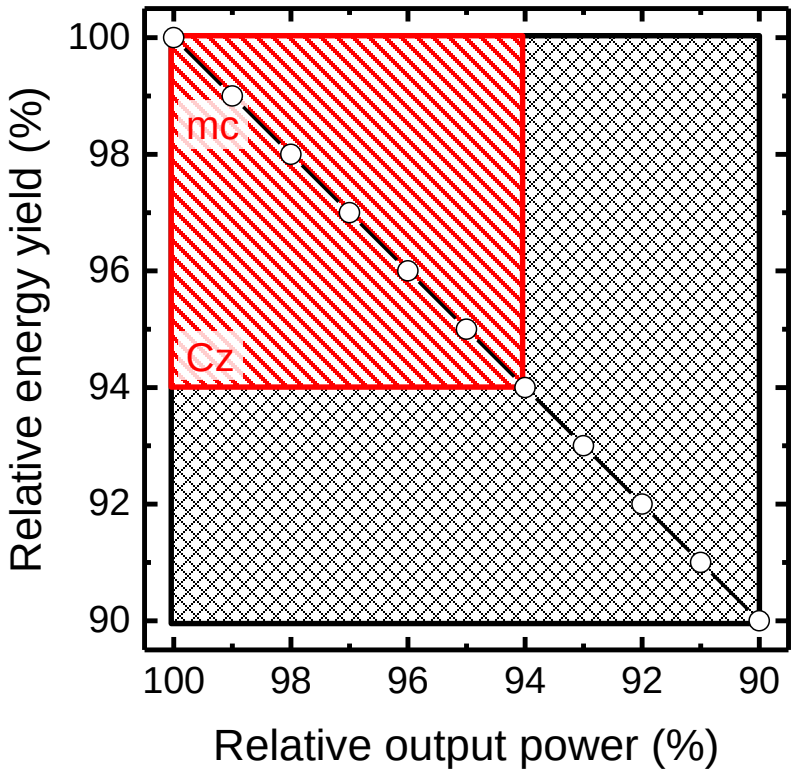
- 5 years of high-quality Q.ANTUM production:
  - Median cell efficiencies of 19.8 %
- Further improved optics and reduced recombination losses
- Champion cell efficiency 21.9%*
- Cost effective processes suitable for mass production
- Efficiency headroom of Q.ANTUM multi exceeds 22 %

B. Klöter et. al., 32nd EU-PVSEC 2016

* measurements independently confirmed by FhG ISE CalLab

Increase reliability
LID/LeTID in PERC Solar Cells and Modules

LID degradation



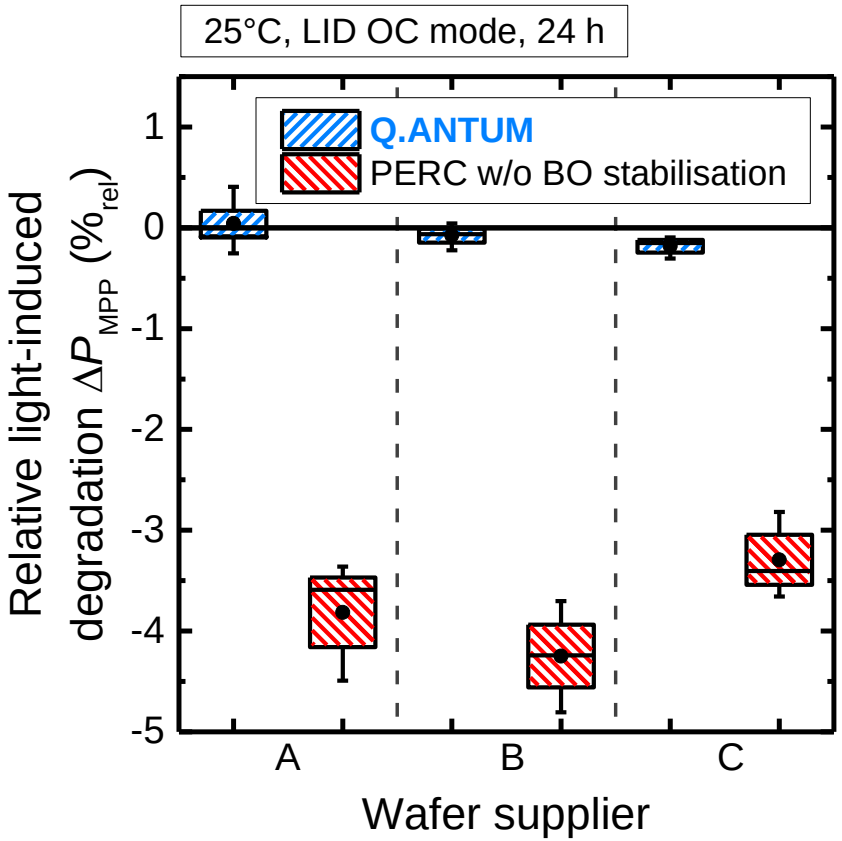
- BO complex[1,2]
- LeTID[3-5]

LID degradation

- More severe w/ increasing eta
- If not suppressed, severe problem for Cz and mc-Si PERC cells
- **Dedicated measures mandatory** to suppress degradation

[1] S. Rein *et al.*, in: Proc. 17th EUPVSEC, 1555–1560, Munich, Germany, 2001.
[2] J. Schmidt and K. Bothe, Phys. Rev. B **69**, 024107, 2004.
[3] K. Ramspeck *et al.* in Proc. 27th EUPVSEC, 861–865, Frankfurt, Germany, 2012.
[4] F. Fertig *et al.,* phys. stat. sol. (RRL) **9**, 41–46, 2015.
[5] F. Kersten *et al.,* Sol. Energ. Mat. Sol Cells **142**, 83–86, 2015.

Increase reliability
LID in PERC Solar Cells and Modules



LID due to BO complex

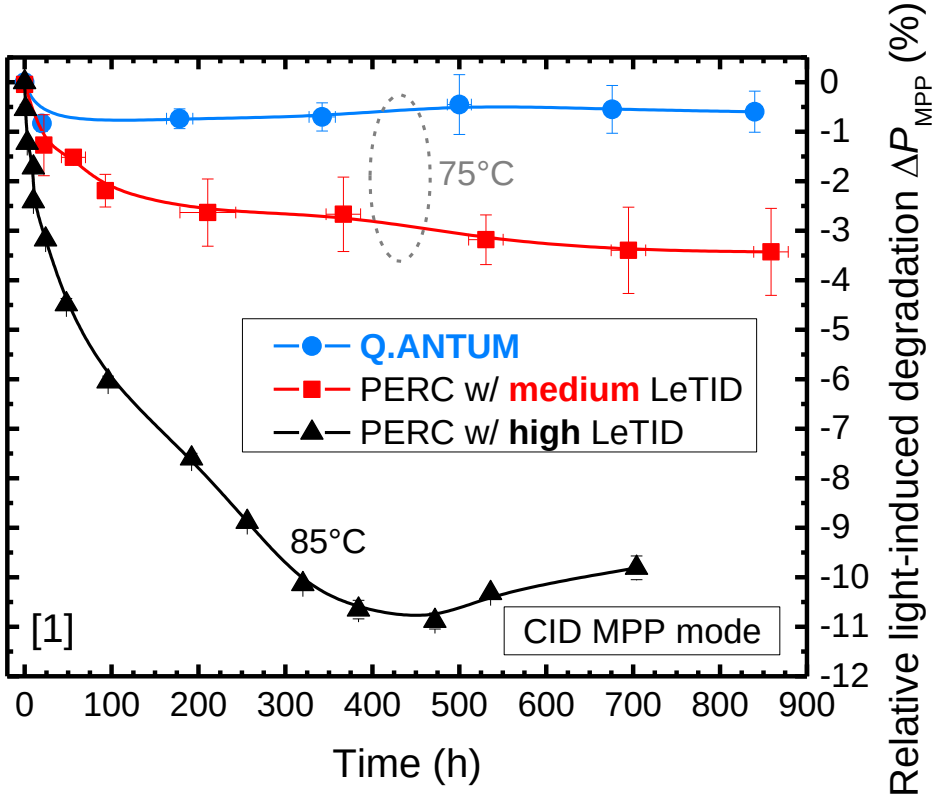
- First observed in the 70s[1]
- Most prominent LID mechanism in commercial Cz silicon
- More severe w/ increasing eta
- Possibility to permanently deactivate has been first presented in 2006[2]
- Intensively researched by many groups
- Solutions for MP commercially available

→ Q.ANTUM suppresses LID due to BO complex

[1] H. Fischer and W. Pschunder "Investigation of Photon and Thermal Induced Changes in Silicon Solar Cells" in Proc. 10th IEEE PVSC, 404-411, Palo Alto, USA, 1973.
[2] A. Herguth *et al.* "A New Approach to Prevent the Negative Impact of the Metastable Defect in Boron Doped Cz …" in Proc. 4th WCPEC, 940-943, Hawaii, USA, 2006

LeTID: Light and elevated Temperature Induced Degradation

mc silicon



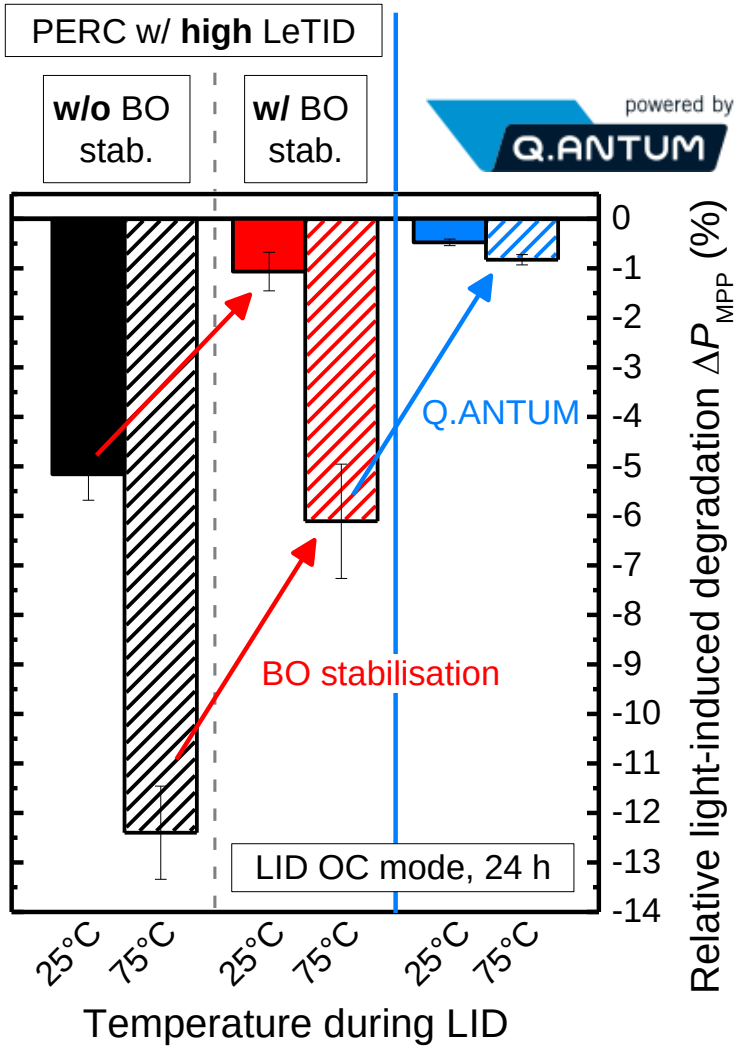
Characteristics and implications

- First observed in mc-Si PERC
- If not suppressed, severe problem for mc-Si PERC cells
- Forms under charge carrier injection at elevated temperatures
- Formation kinetics depend on temperature and excess charge carrier density
- $T \uparrow$, $\Delta n \uparrow \rightarrow$ formation rate $\uparrow$
- Severity can be manipulated

- Q.ANTUM suppresses LeTID in mc-Si

[1] F. Kersten *et al.* "Degradation of multicrystalline silicon solar cells and modules after illumination at elevated temperature," Sol. Energ. Mat. Sol Cells **142**, 83–86, 2015.

Increase reliability
LeTID in PERC Solar Cells and Module



Cz silicon

- **LeTID** not only in *p*-type mc PERC but **also in *p*-type Cz PERC**
  - → big challenge for MP of *p*-type Cz-Si PERC cells
  - → much more difficult to control than BO complex formation
- **Q.ANTUM technology suppresses LID and LeTID in Cz silicon**

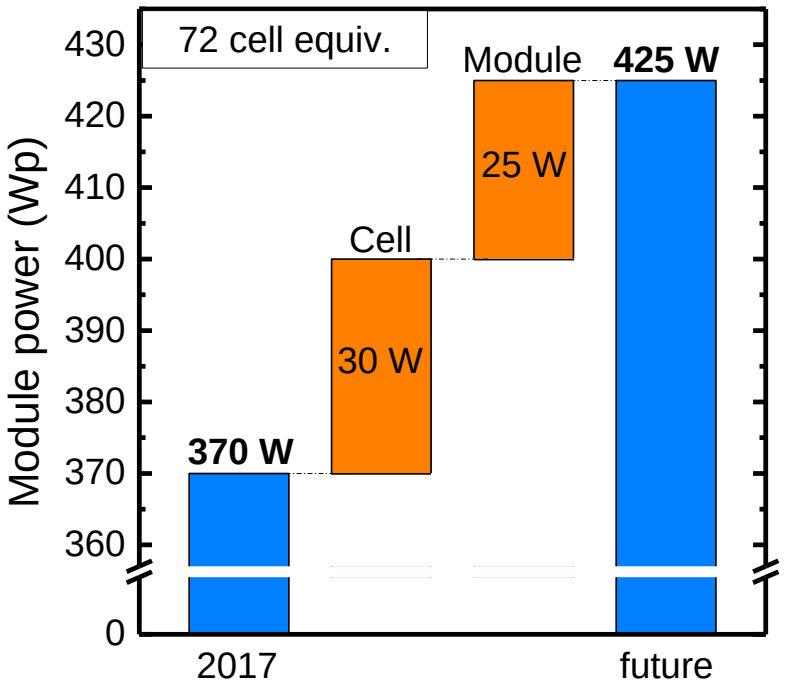
Outlook

- Electricity is commodity, **LCOE** is main development criteria, price reduction will continue
  → **cost per piece**, **efficiency** and **reliability** are crucial

- Increase **productivity** in multi GW production:
  - Several Mio cells per day needs powerful MES
  → **Single wafer tracking** for efficient HVM

- Increase **efficiency** cost effectively:
  - Still **significant headroom** for efficiency improvements via evolutionary development
  → keep **Q.ANTUM platform** for the coming years

- Increase **reliability:**
  - Degradation (e.g. LID/LeTID) can severely affect energy yield
  → Dedicated measures to suppress any degradation



Thank you.