Highly efficient silicon solar cells

UNIK 4450/9450 – Schedule

- 30/8 Solar cell fundamentals
- 6/9 Solar cell efficiency
- 13/9 Semiconductor theory
- 20/9 Generation
- 27/9 Recombination and lifetime
- 4/10 Silicon
- 11/10 Junctions
- 18/10 Solar cells
- 25/10 Silicon solar cells I (@IFE)
- 1/11 Silicon solar cells II
- 8/11 Light management
- 15/11 Alternative solar cells
- 29/11 Solar modules & systems
- 6/12 Q&A

- Oral exam December 12th

Overview

- Standard solar cells revisited
- Efficiency limits
  - The Shockley-Queisser limit
  - Loss mechanisms in real silicon solar cells
  - Improved design rules
- Gradual improvements of conventional solar cells
  - Case 1: Acidic texturing
  - Case 2: Improving the blue response
- Highly efficient silicon solar cells
  - Industrial solar cells
  - Laboratory solar cells

Clever student question:

”How good can a silicon solar cell be?”

The Shockley-Queisser limit

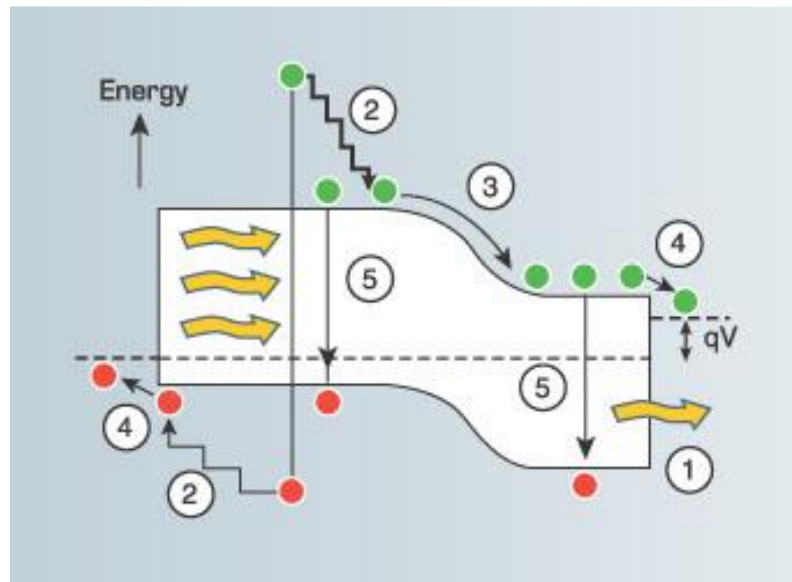
- Si p-n homojunction solar cell: 29.4 % efficiency
- Assumptions
  - All photons incident on cell captured
  - Complete absorption of all photons with $\mathrm{E} > \mathrm{E_g}$
  - Complete thermalization occurs
  - Lossless transport and collection of charge carriers
  - Ideal materials: auger and/or radiative recombination dominating recombination mechanism

Clever student question rephrased:

”How good can a silicon solar cell *really* be?”

Fundamental loss mechanisms

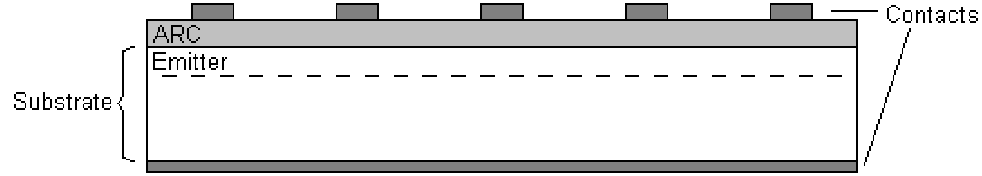
1. Insufficient photon energies
   - $E < E_g$
2. Thermalization of energetic carriers
   - If $E > E_g$, $E \rightarrow E_g$
3. Energy loss across p-n junction
4. Energy loss at contacts
5. Recombination



M.A. Green, UNSW

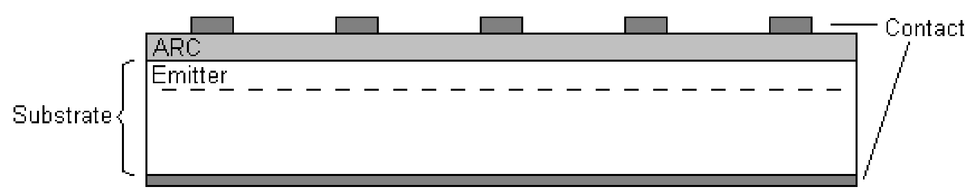
Avoidable losses – generation

- The reflectance of a standard solar cell is too high
  - Alkaline texturing not suited for mc-Si
  - Shading is too high (~5 %)
  - A single-layer ARC is good but far from optimal
- Transmission becomes more important as the solar cell thickness is reduced



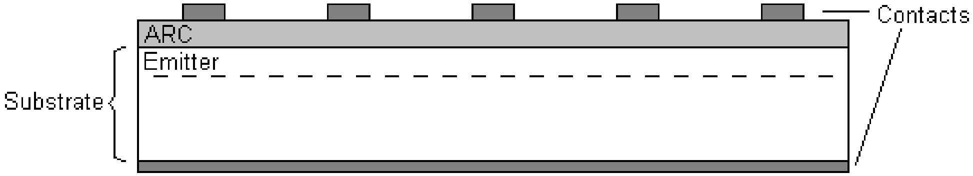
Avoidable losses – recombination

- Recombination still occurs in a standard solar cell
  - Surface recombination
    - Front surface: detrimental to blue response
    - Rear surface: detrimental for longer wavelengths
  - Emitter recombination
    - The recombination in a heavily doped front side emitter reduces the blue response
  - Contact recombination
    - A metal-semiconductor interface is generally a highly recombinative surface
  - Bulk recombination
    - SRH recombination



Avoidable losses – resistive losses

- Resistive losses must be taken into account
  - Series resistance
    - Sheet resistance in emitter increases with thinner and less doped emitters
    - Resistance in finger contact increases with decreasing finger width
  - Shunt resistance
    - Process and material induced shunts degrade the performance of many industrial solar cells



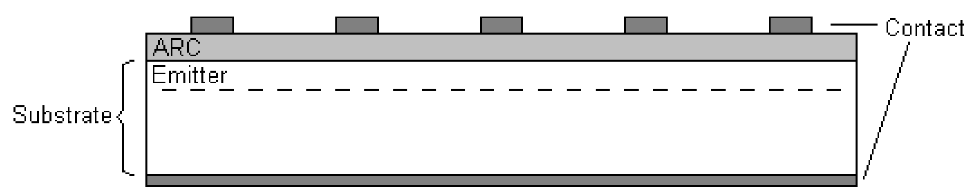
Improved design rules

- What factors limit the performance of standard solar cells?
  - The higher efficiencies we want to achieve, the more minor loss mechanisms must we take into account!

- How can we reduce the impact of these factors and make better solar cells?

Improved design rules

- General comments: many trade-offs must be made:
  - Emitter doping
    - Blue response versus sheet conductivity?
  - Finger contacts
    - Shading versus contact resistance?
  - Cost versus performance



Generation

- The reflectance of a standard solar cell is too high
  - Alkaline texturing not suited for mc-Si
    - *Use isotropic texturing*
      - *Plasma texturing, acidic texturing, laser texturing*
    - *Optimal texture is not random*
      - *Photolithography*
  - Shading is too high (7 – 8 %)
    - *Minimize front contact area*
    - *Back-side contacted solar cells*
  - A single-layer ARC is good but far from optimal
    - *Use a double- or multi-layer ARC*
- Transmission becomes more important as the solar cell thickness is reduced
  - Light trapping

Recombination

- Recombination still occurs in a standard solar cell
  - Surface recombination
    - Front surface: detrimental to blue response
    - Rear surface: detrimental for longer wavelengths
    - *Good surface passivation is required on both sides*
  - Emitter recombination
    - The recombination in a heavily doped front side emitter reduces the blue response
    - *Reduce emitter thickness and/or doping*
  - Contact recombination
    - A metal-semiconductor interface is generally a highly recombinative surface
    - *Use selective doping beneath contacts*
    - *Minimize contact area*
  - Bulk recombination
    - *Use thinner wafers*

Resistive losses

- Resistive losses must be taken into account
  - Series resistance
    - Sheet resistance in emitter increases with thinner and less doped emitters
    - Resistance in finger contact increases with decreasing finger width
    - *Move contacts and emitter to the rear of the solar cell*
    - *Reduce resistance at metal-semiconductor interface is by doping region beneath contact heavily*
  - Shunt resistance
    - Can be reduced to acceptable levels

Origins

Bell System Solar Battery Converts Sun's Rays into Electricity!

Bell Telephone Laboratories invention has great possibilities for telephone service and for all mankind

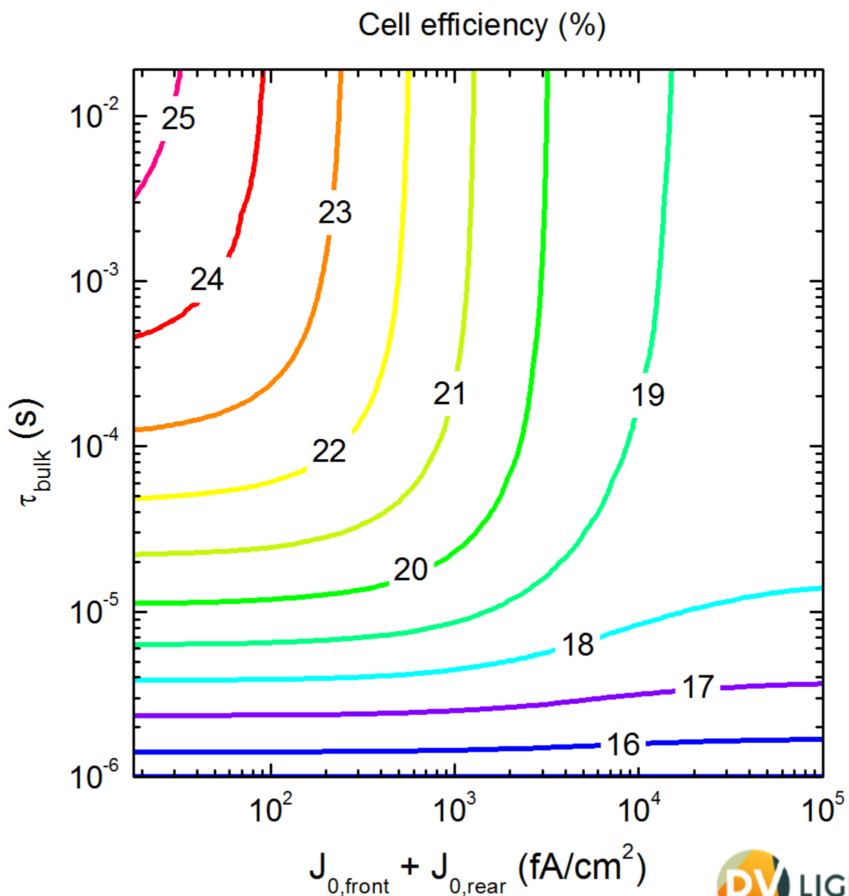
Bell Labs / Wikipedia

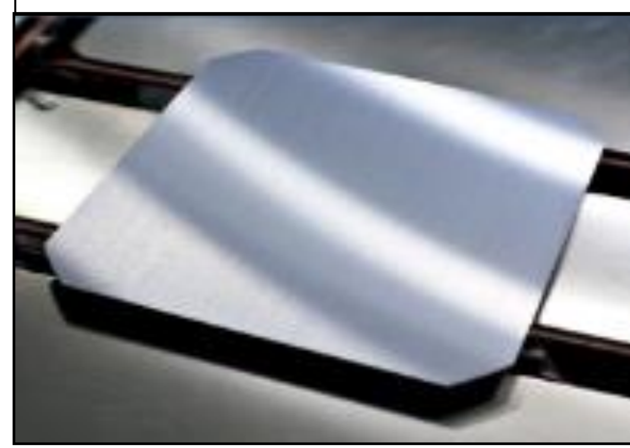
Opportunities?

- Silicon production technology
  - Norwegian example: the centrifugal CVD reactor
  - High troughput
  - High material quality
  - Record low energy consumption
  - Potential for REALLY low cost

Opportunities?

- High quality silicon crystals
  - Required for high efficiency silicon solar cells





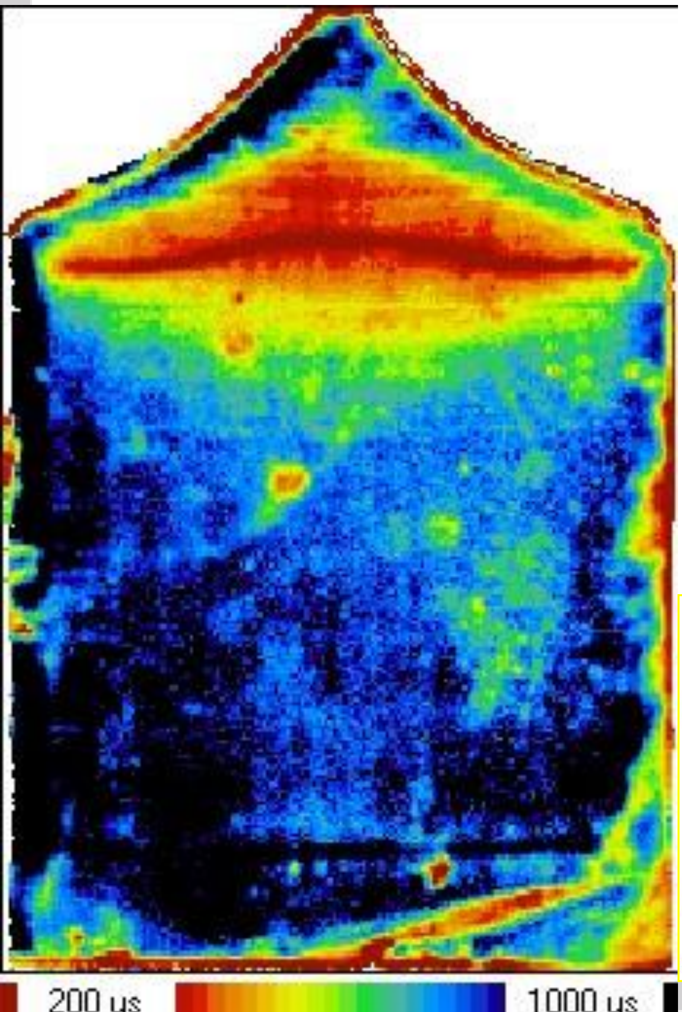
IFE/Norsun

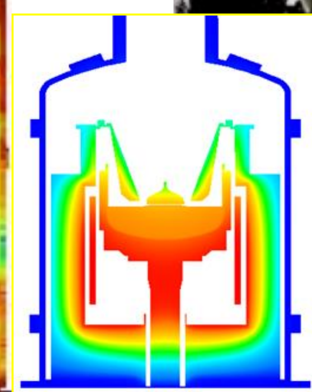
Opportunities

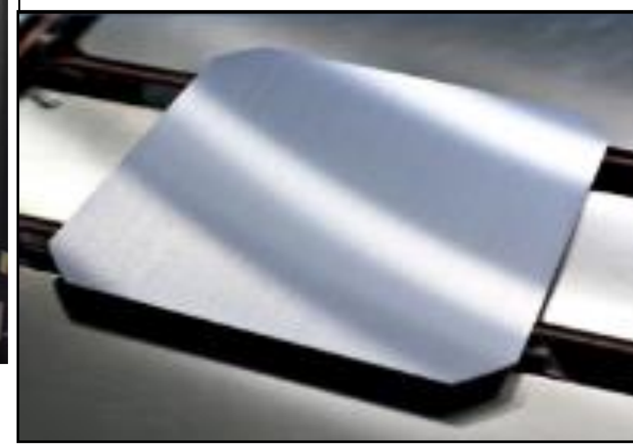
NorSun

- High quality silicon crystals
  - Required for high efficiency silicon solar cells

SHARP
SANYO
Panasonic
SUNPOWER
VOLTEC solar
HEVEL SOLAR
AUO AUO Crystal
Trina solar



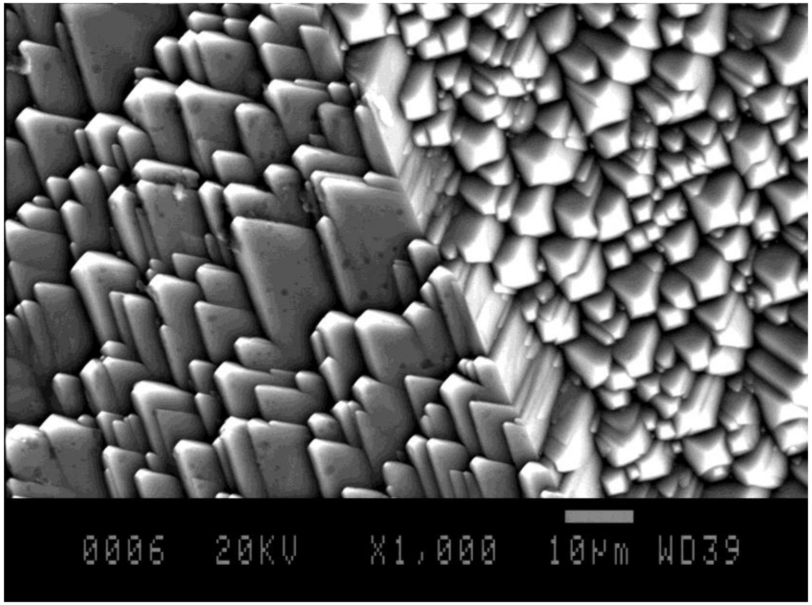


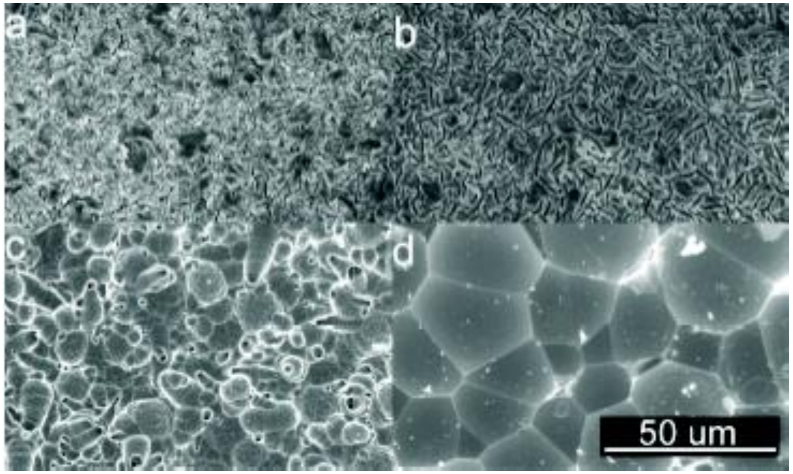


IFE/SINTEF/Norsun

Gradual improvements

Case 1: Acidic texturing



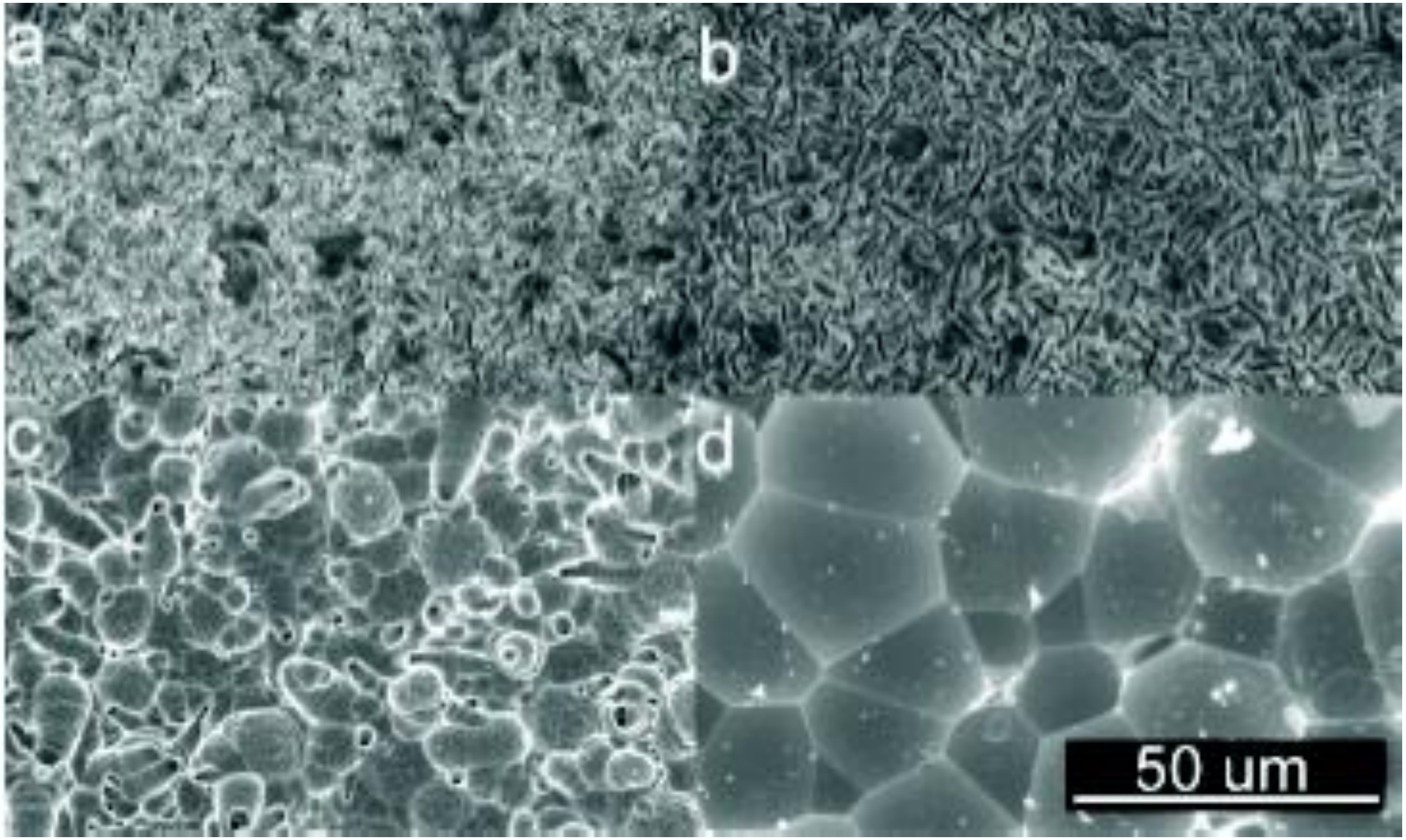


- Etch rates of Si in alkaline solutions very orientation dependent
- Reflectance will vary from grain to grain

- Isotropic textures can be made by several methods, including acidic texturing

IFE

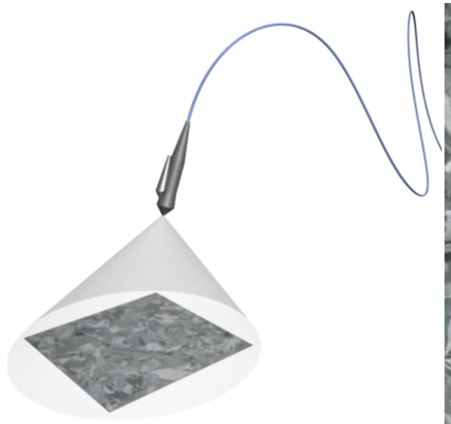
Case 1: Acidic texturing

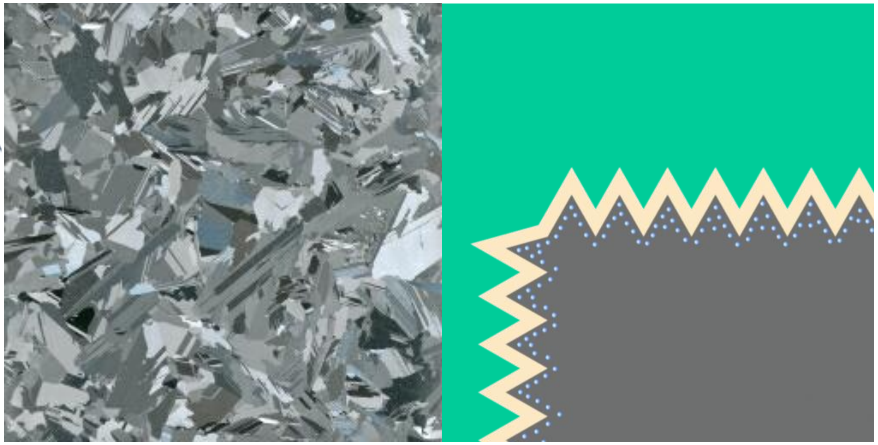


MarsteinIFE

Case 2: Improving the blue response

Emitter formation

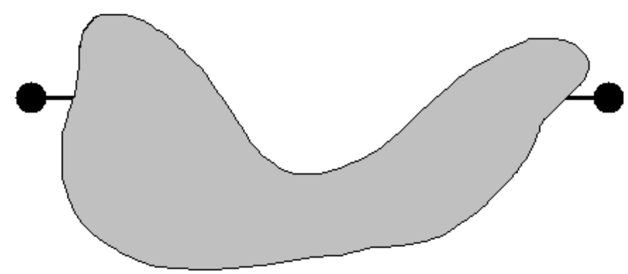




- Phosphorous diffusion
  - Gas diffusion from $POCl_3$ gas most common
  - Spraying, spinning, mist evaporation and screen-printing possible
  - High temperature diffusion (~900 ^oC)
  - A glass layer forms during diffusion and must be removed using HF
  - Gettering occurs simultaneuously

Resistance (R)

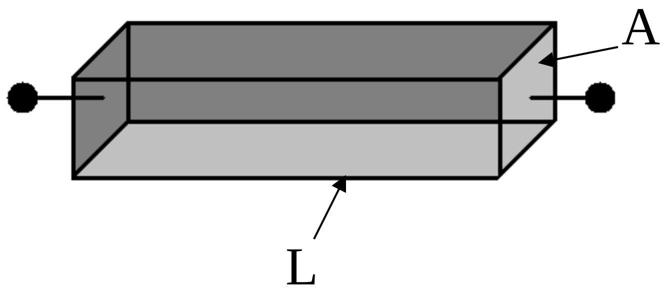
- The resistance (Ω) is a macroscopic quantity
- Contains both material and topological information



Resistivity (ρ)

- The resistivity ($\Omega \cdot \mathrm{cm}$) is a material specific quantity
- Resistance of box-shaped resistance

$$R = \rho\, L/A$$



- The resistivity of Si is doping dependent

$$\rho = (q(\mu_n n + \mu_p p))^{-1}$$

Sheet resistance ($R_{\bullet}$)

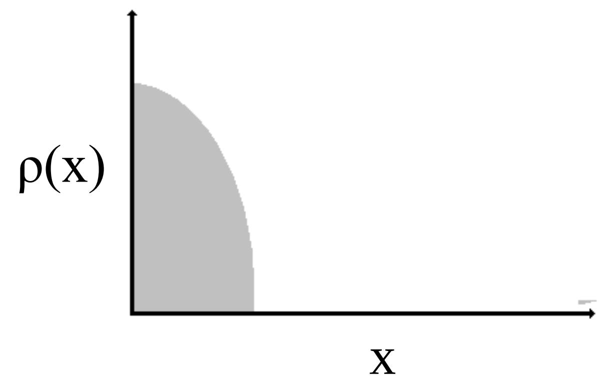
- Emitters are inhomogenously doped
- Resistivity will vary with emitter depth (x)
- The sheet resistance (Ω/•) is a useful quantity

$$R_{\bullet} = 1/q \int \mu_n(n(x))n(x)dx$$
$$\approx 1/q\mu_{eff} \int n(x)dx$$

- Example: box emitter with depth d

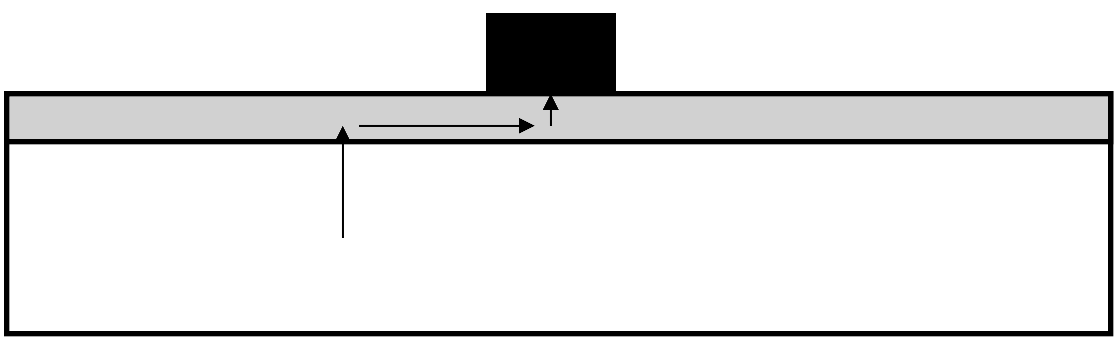
$$R_{\bullet} = 1/q\mu_{eff}\, n_{em}\, d = \rho/d$$

- Typical values: ~ 50 Ω/ •



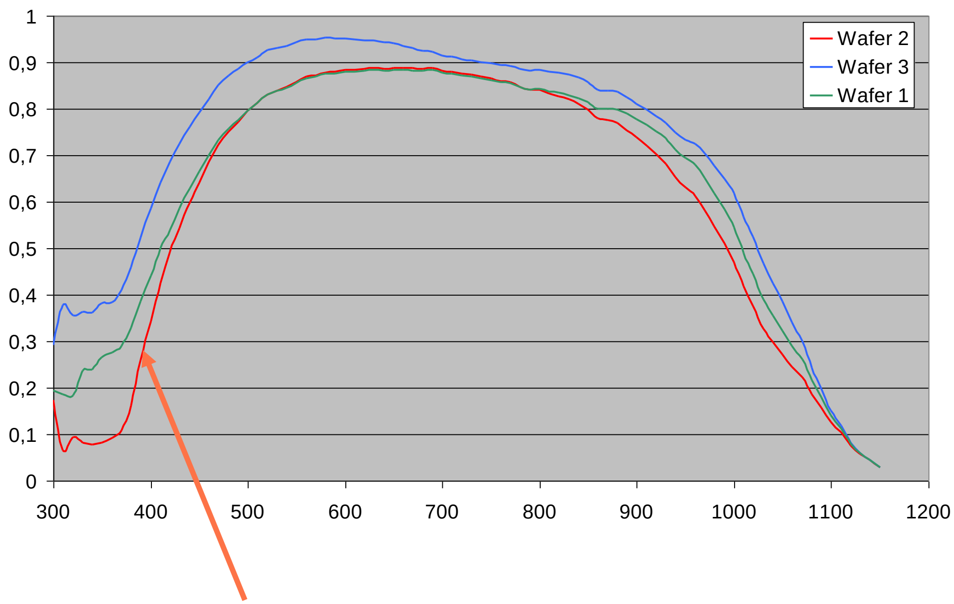
Series resistance

- The series resistance for electron transport through exceedingly thin emitters can be significant
- Contact firing is also sensitive to emitter sheet resistances
  - Contact resistance problems



Blue response

- The emitter is a place of high recombination rates in a solar cell
- To improve the blue response, thinner and/or less doped emitters must be used
- After gettering, many impurities are located in the emitter



Blue response

Efficient Si solar cells

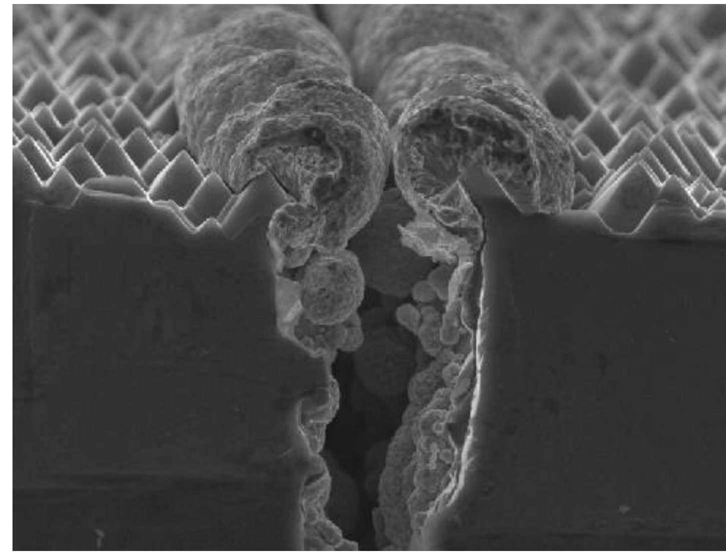
New solar cell designs

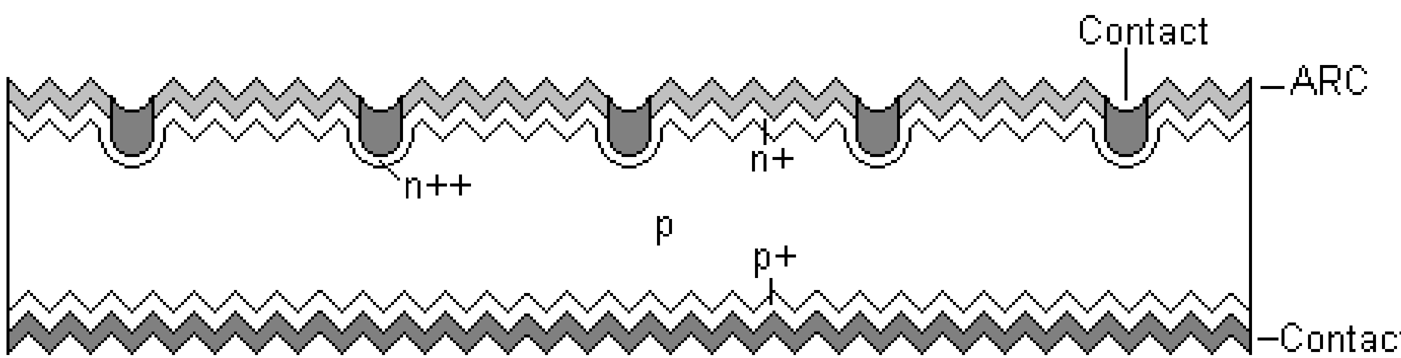
- Industrial solar cells
  - Cost-efficiency achieved by increasing efficiency
  - Examples
    - BP Buried contact solar cell
    - SunPower back-contacted solar cell
    - Panasonic (Sanyo) HIT cell
    - Kaneka IBC-HIT
    - Yingli PANDA cell
    - Q-cells Q.ANTUM cell

- Laboratory solar cells
  - Efficiency at all costs
  - Small area solar cells
  - World record cells:
    - sc-Si: PERL (UNSW)
    - mc-Si: LFC (ISE FhG)
  - Examples:
    - PERL
    - LFC
    - RISE
    - COSIMA

Buried contact solar cell (BP)

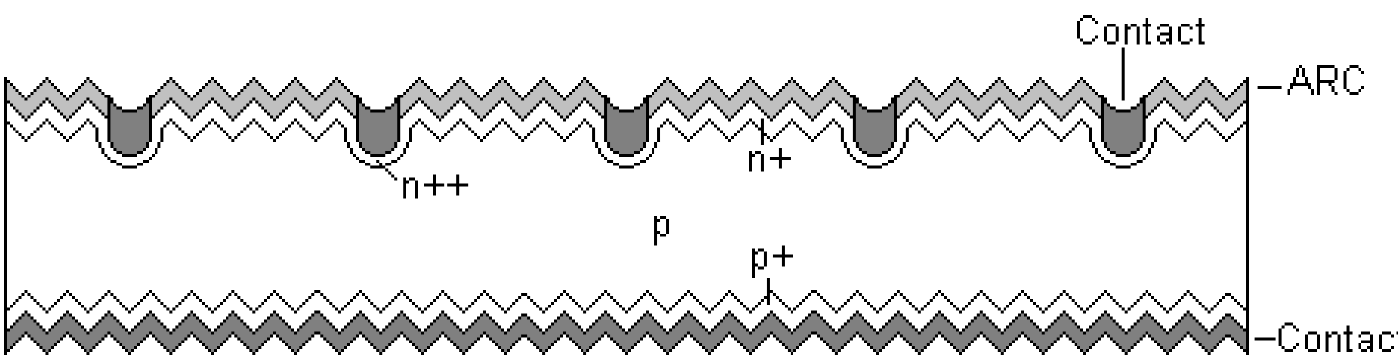
- BP Saturn solar cell
- Main concept
  - Reduce shading by burying contacts in wafer
- Efficiency
  - ~20 %





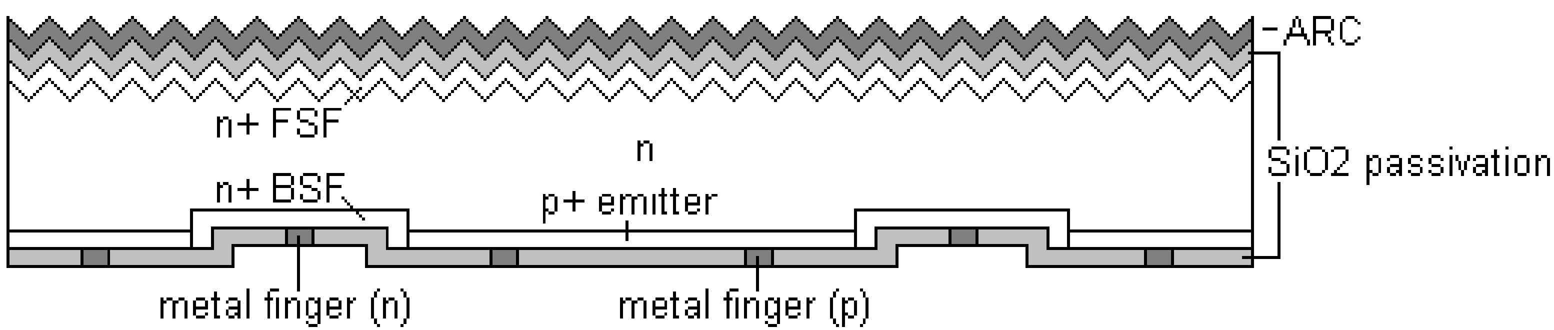
Buried contact solar cell (BP)

- Modified process steps
  1. Deposit ARC
     - ARC acts as mask for plating
  2. Make grooves
     - Laser grooving or mechanical grooving
  3. Make local contact doping to reduce contact recombination and resistance
  4. Create buried contacts by plating in laser grooves



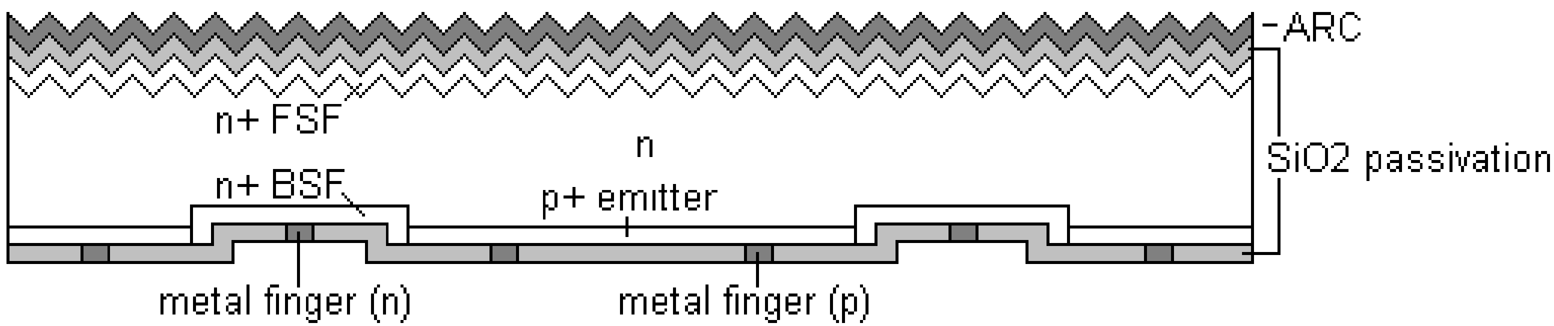
Back contacted solar cell (Sunpower)

- Main concept
  - Back-sided contacting
    - Avoid shading losses entirely
    - Improve blue response
- Requirement
  - High lifetime (~1 ms)
    - N-type FZ or Cz Si



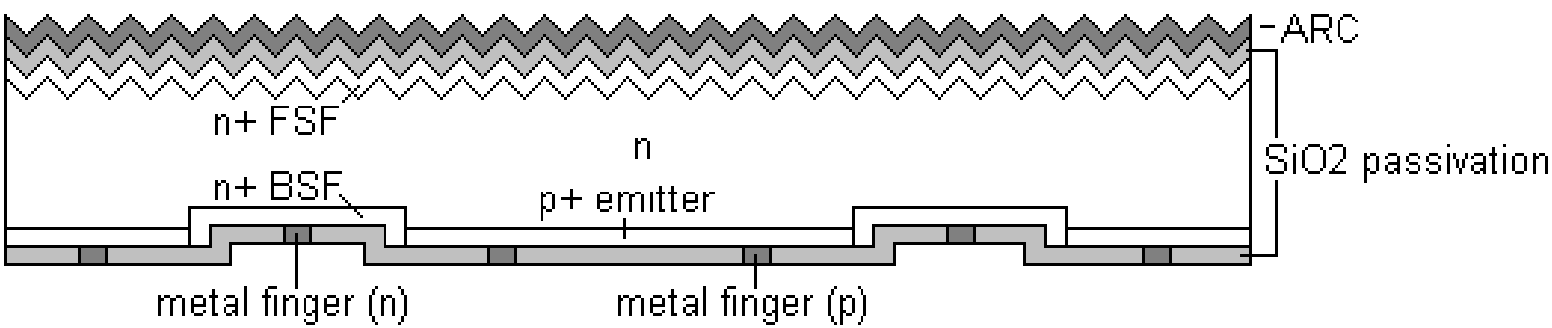
Back contacted solar cell (Sunpower)

- Efficiency
  - Large area record: 25.0 %



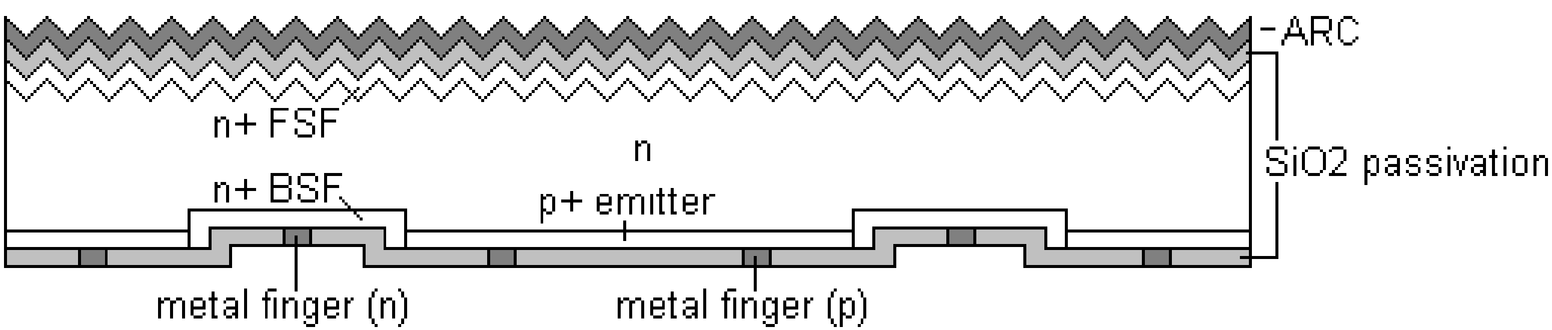
Back contacted solar cell (Sunpower)

- Maintaining high lifetime
  - n-type substrate
  - Excellent surface passivation
    - Two-sided SiO_2
    - Reduced contact area



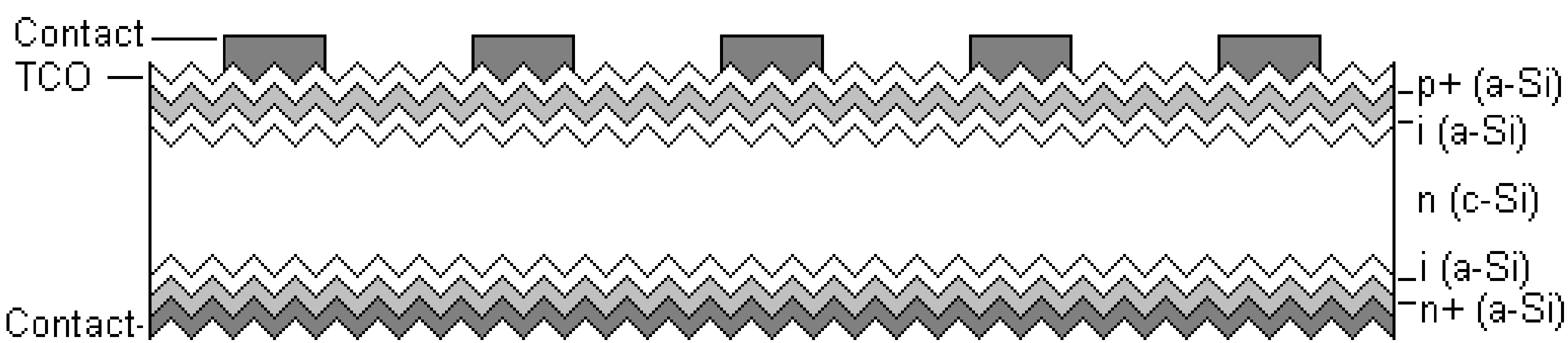
Back contacted solar cell (Sunpower)

- Modified process steps
  - Photolithography or screen-printing used for pattern definition
    - Contacts
    - Emitter
  - Single- or double-layer ARC



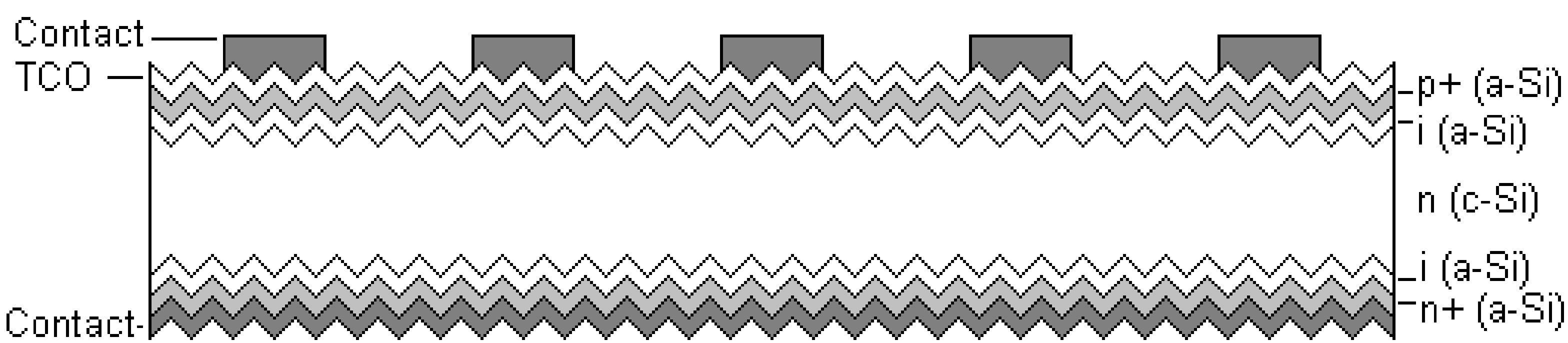
HIT solar cell (Sanyo/Panasonic)

- Main concept
  - A heterojunction solar cell with superior surface passivation
  - a-Si:H emitter
- Efficiency
  - Large area record: 24.7%
  - Thickness: 96 µm
  - Approximately 20 % in production



HIT solar cell (Sanyo/Panasonic)

- Modified process steps
  - Deposition of passivating a-Si:H layers on both sides
    - Emitter
    - Passivating layers
  - Low sheet resistance assured by using transparent conductive oxide (TCO)
  - N-type Si assures high lifetime



Q.ANTUM

Q.ANTUM – Q-CELLS NEXT GENERATION HIGH-POWER SILICON CELL & MODULE CONCEPT

P. Engelhart*, D. Manger, B. Klöter, S. Hermann, A.A. Stekolnikov, S. Peters, H.-C. Ploigt, A. Eifler, C. Klenke, A. Mohr, G. Zimmermann, B. Barkenfelt, K. Suva, J. Wendt, T. Kaden, S. Rupp, D. Rychtarik, M. Fischer, J.W. Müller, P. Wawer
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26th European Photovoltaic Solar Energy Conference, 5–9 September 2011, Hamburg, Germany

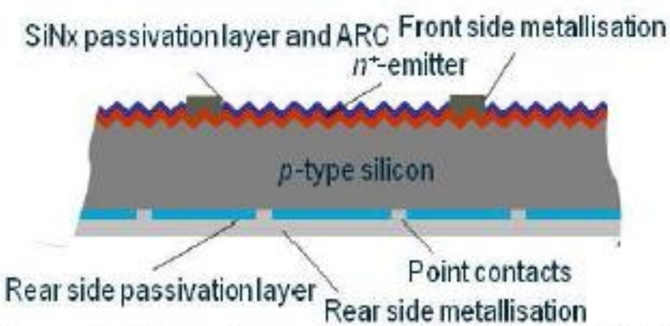


Figure 1: Schematic cross-section of the Q.ANTUM solar cell design with passivated rear (not to scale).

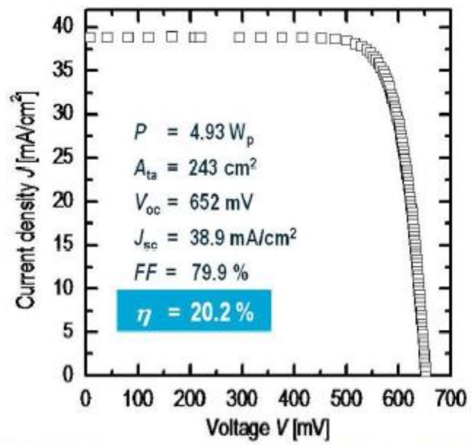


Figure 4: *J-V*-curve and parameters of our record *p*-type Cz large area Q.ANTUM cell. The data were independently confirmed by Fraunhofer ISE CalLab.

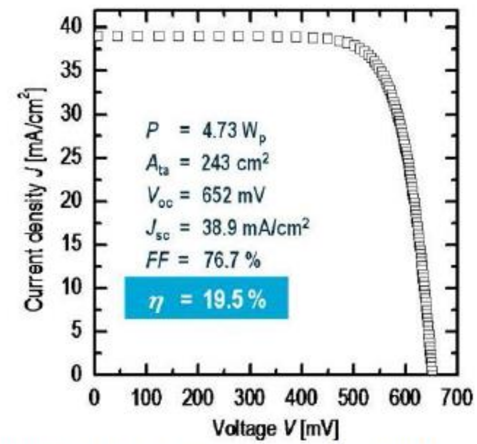


Figure 5: *J-V*-curve and parameters of our World Record multi-crystalline large area Q.ANTUM cell. The data were independently confirmed by Fraunhofer ISE

P. Engelhardt et al., Proceedings of the 26th EUPVSEC (2011)

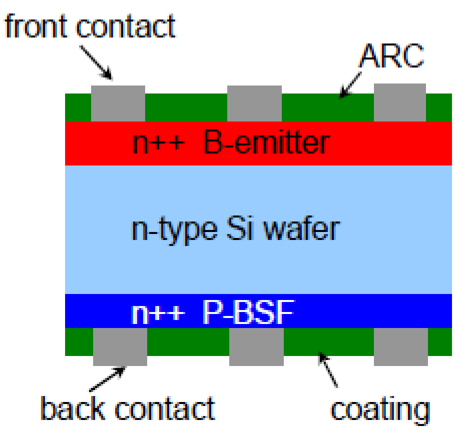
PANDA

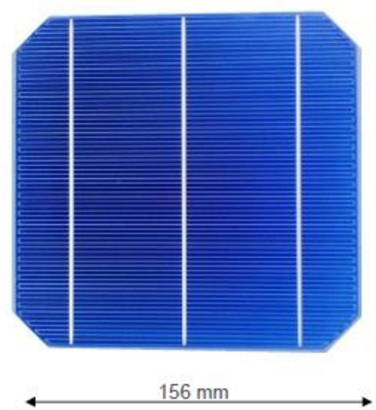
ECN

Energy research Centre of the Netherlands

19.5% efficient n-type solar cells made in production

Teun Burgers



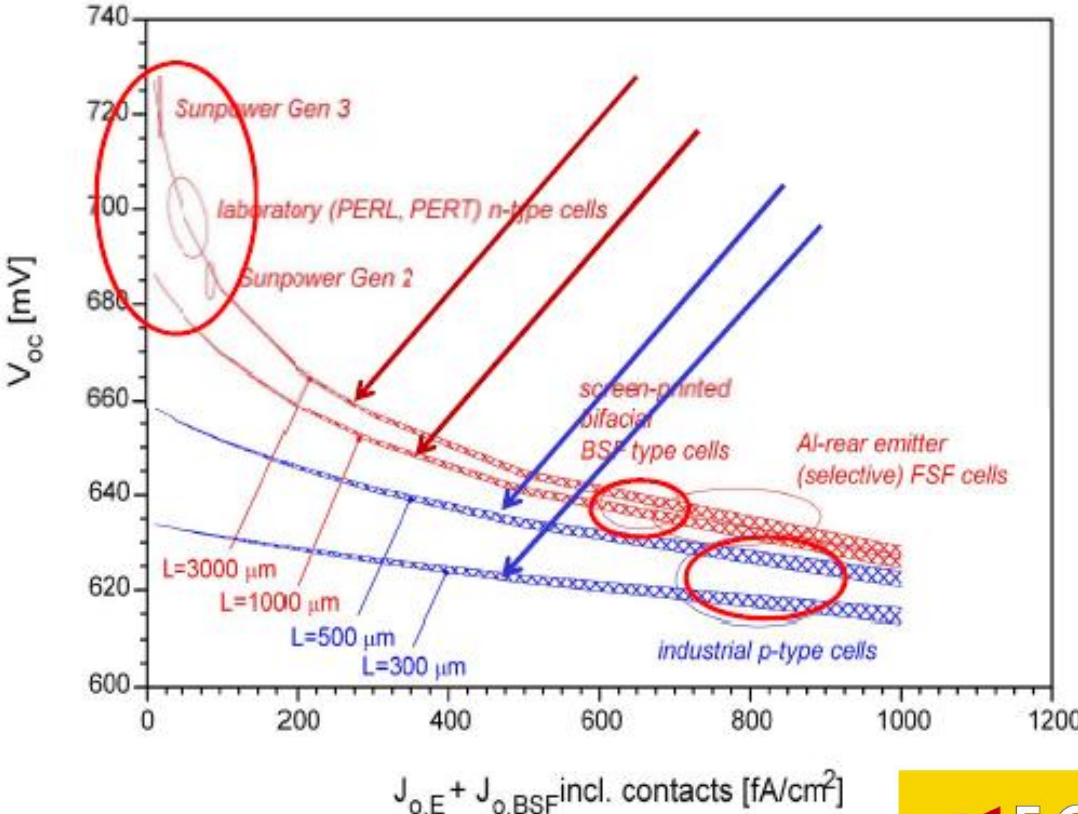


YL265C-30b

Production efficiency: 19.5% (confirmed at FhG-ISE)

P. Engelhardt et al., Proceedings of the 26th EUPVSEC (2011)

V_{oc}: surface recombination and diffusion length



$$V_{oc} = \frac{kT}{q} \ln\left(\frac{J_L}{J_{0e} + J_{0b}} + 1\right)$$

J_0 sources

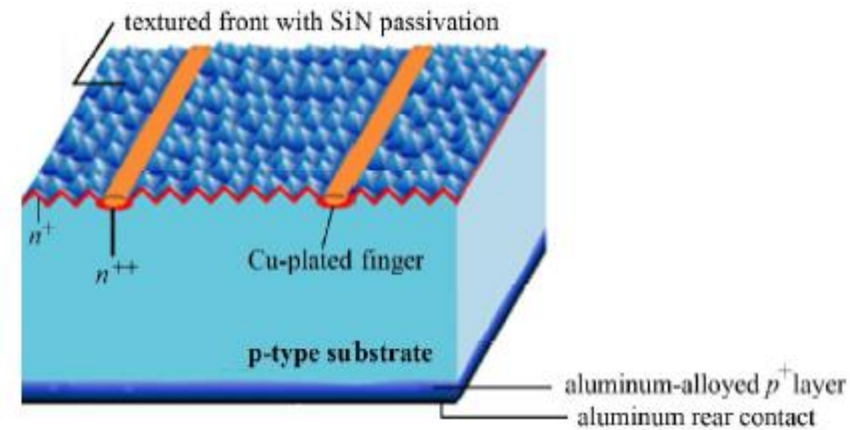
- Material
- Contacts
- High doping
- Surfaces

Teun Burgers

PLUTO

SUNTECH

Solar powering a green future™



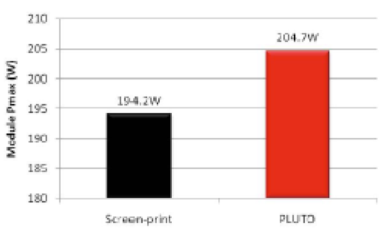


Figure 4: *Average power of monocrystalline modules made from Pluto and screen-print technologies during the same production period. The improved technology incorporated into Pluto results in an additional 10W in a 72-cell configuration module, using standard 125mm monocrystalline silicon wafers.*

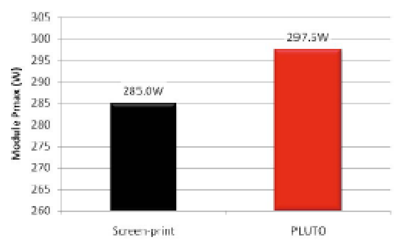


Figure 5: *Graph showing the average power of multicrystalline modules made with Pluto and screen-print technologies using standard 156mm multicrystalline silicon wafers showing Pluto delivers an additional 12W+ in a 72-cell configuration module.*

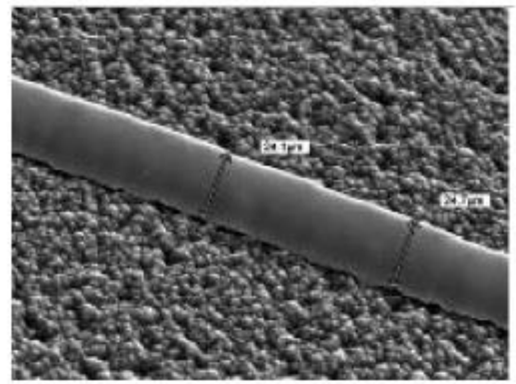
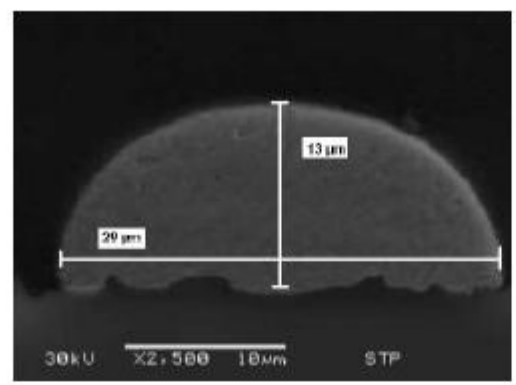


Figure 2:

(a) A Scanning Electron Microscope (SEM) image of typical Pluto metal finger



(b) the corresponding cross-sectional image showing line width, height and aspect ratio.

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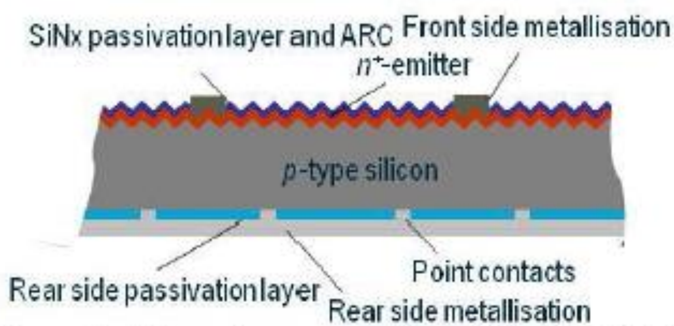

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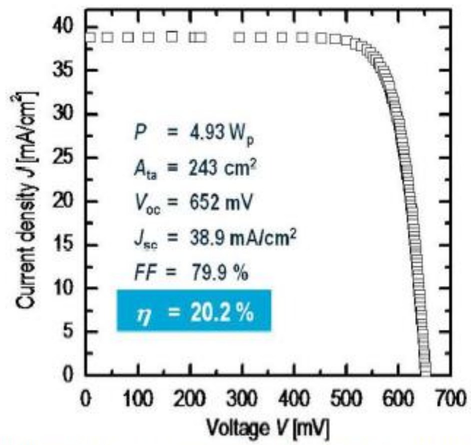


Figure 4: *J-V*-curve and parameters of our record *p*-type Cz large area Q.ANTUM cell. The data were independently confirmed by Fraunhofer ISE CalLab.

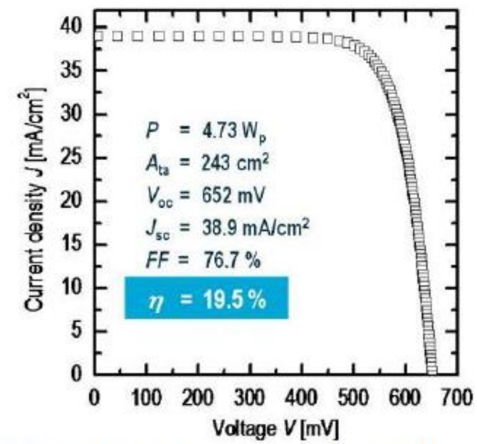
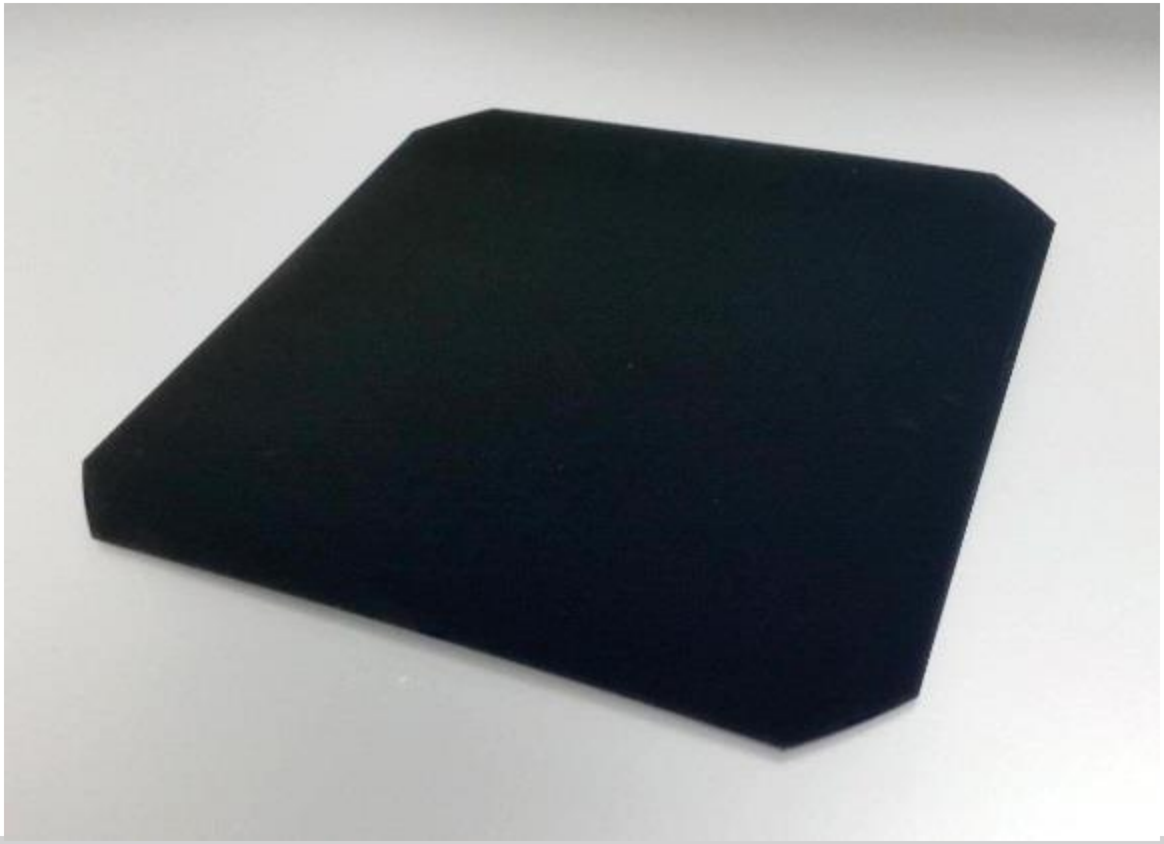


Figure 5: *J-V*-curve and parameters of our World Record multi-crystalline large area Q.ANTUM cell. The data were independently confirmed by Fraunhofer ISE

P. Engelhardt et al., Proceedings of the 26th EUPVSEC (2011)

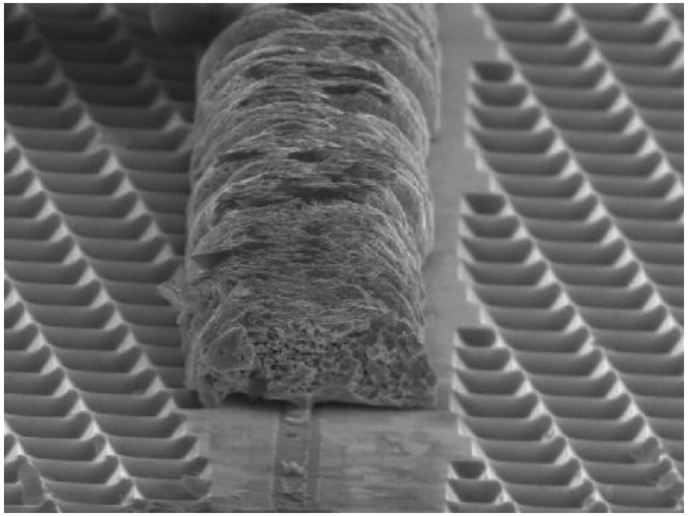
IBC-HIT

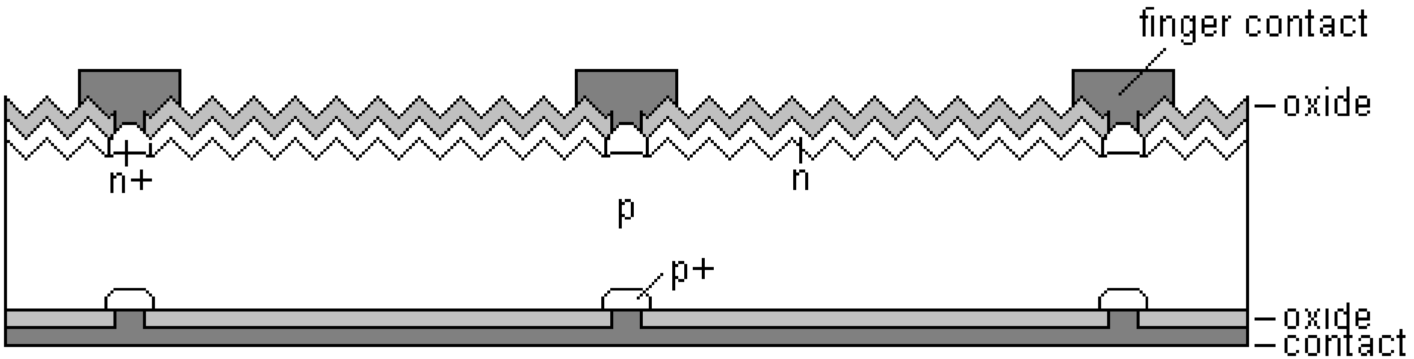
- Current and past world record
  - 2016: Kaneka 26.6 %



PERL solar cell

- Main concept
  - World record holder on sc-Si wafers until ‘14
  - Superior performance over cost-efficiency
  - Uses (almost?) every smart trick in the book
- Efficiency
  - 25.0 %

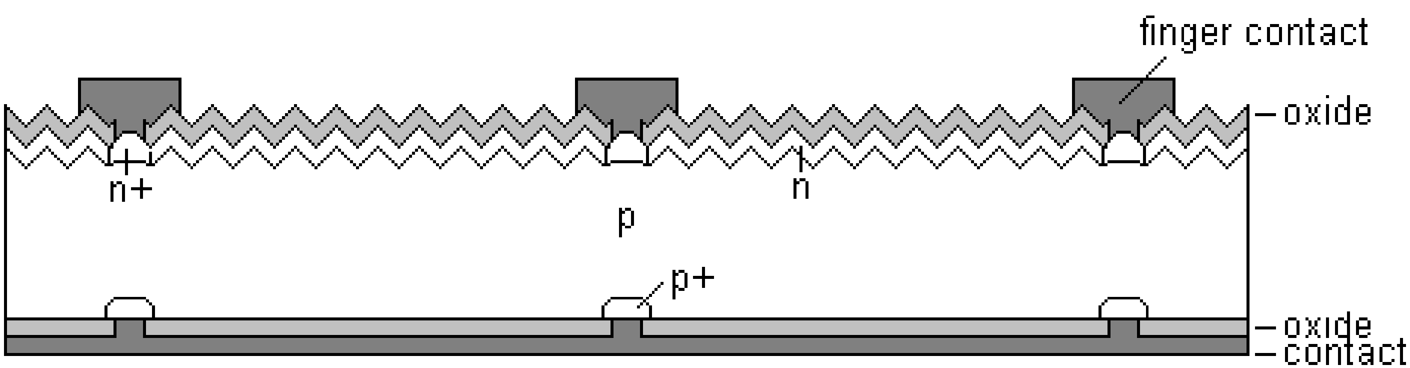




pveducation.org

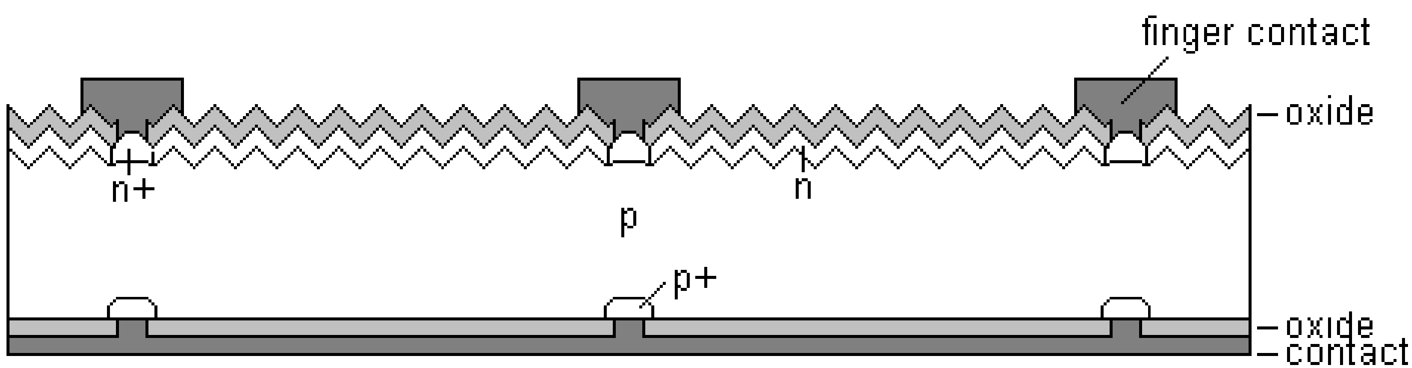
PERL solar cell

- Modified steps
  - Photolithographically defined texture
    - Very low reflectance, large optical thickness
  - Two-sided oxide passivation
    - Very low surface recombination velocities



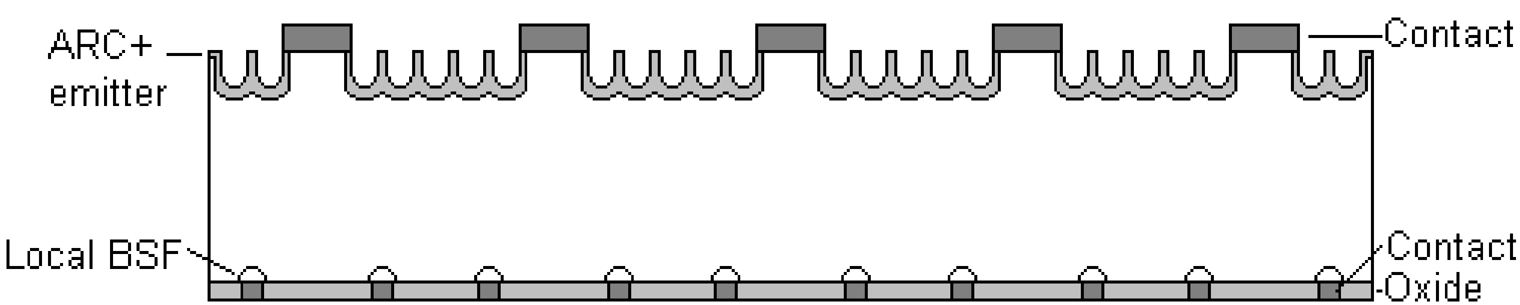
PERL solar cell

- Modified steps
  - Photolithograpically defined contacts
    - Small contact area on both sides
    - Localized rear contacts and doping reduces contact resistance

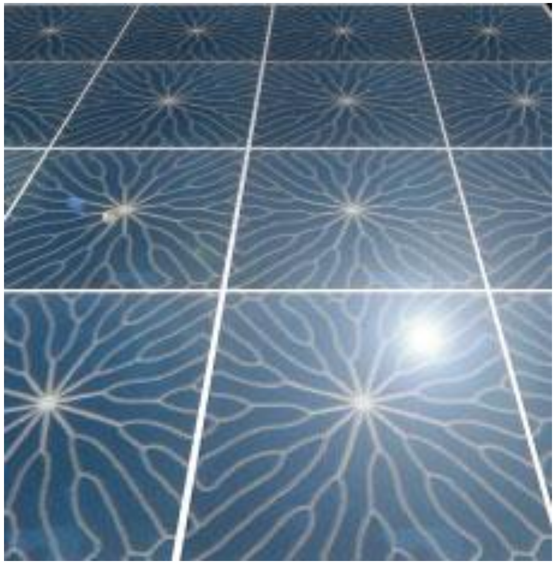


Laser fired contact solar cell (LFC)

- Features:
  - Isotropic plasma texture
  - Two-sided oxide passivation
  - Laser-fired contacts
  - Local BSF around contacts
- Efficiency:
  - 20.4% on small area

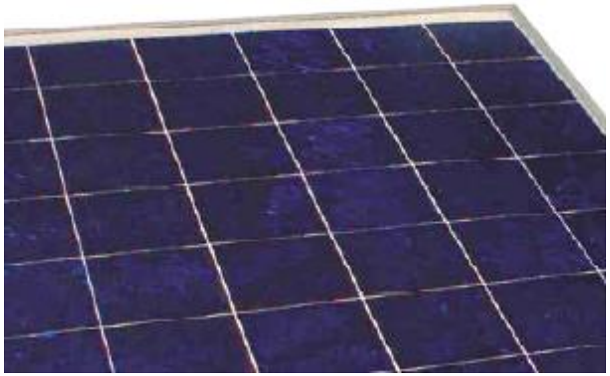


Back contact solar cells



Metallization wrap-through (MWT) cells in a module from Solland

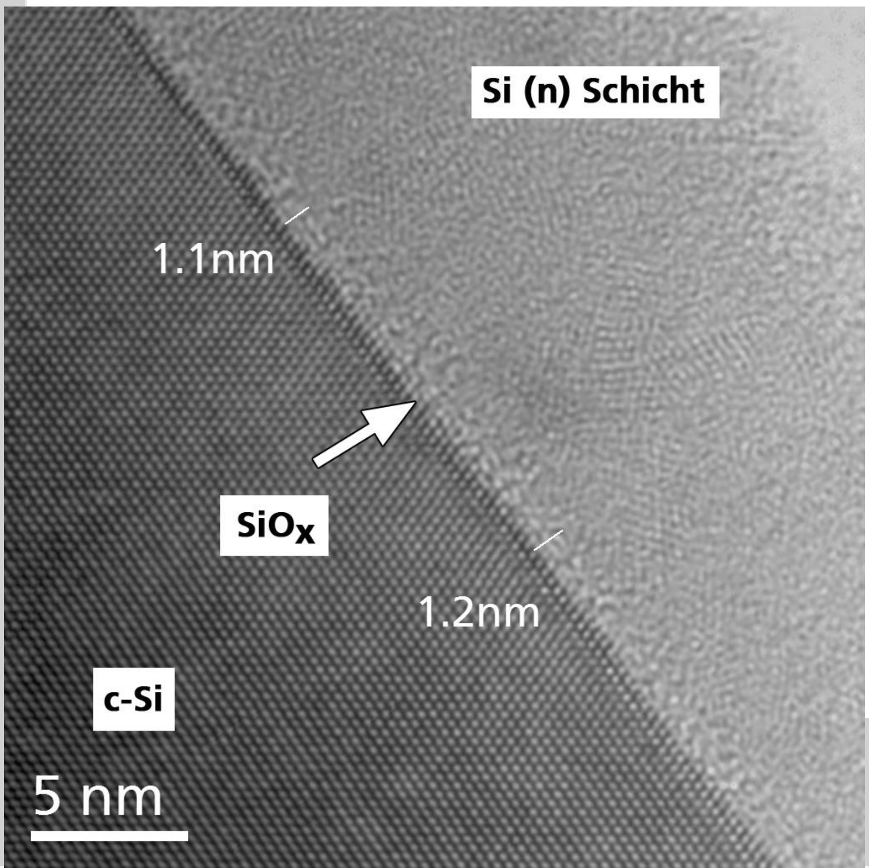
Sunpower module



Emitter wrap-through (EWT) cells in a module from Advent Solar

TOPCon

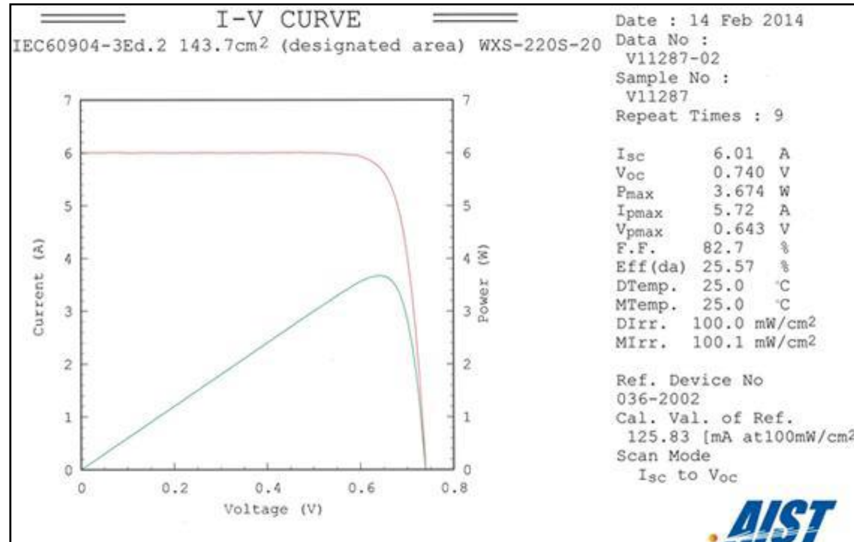
- Features:
  - Tunnel Oxide Passivated Contact
  - Full-area passivated rear contact



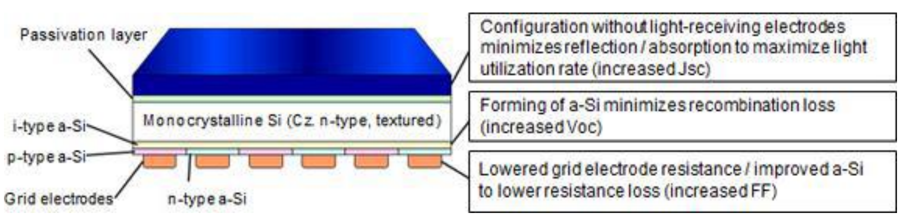
Fraunhofer ISE

New world record in 2014!

- Breaking a 15 year record
- Panasonic : IBC-HIT concept in a HIT® solar cell
- Efficiency: **25.6%** (up 0.6%)
- Area: **143.7 cm²**

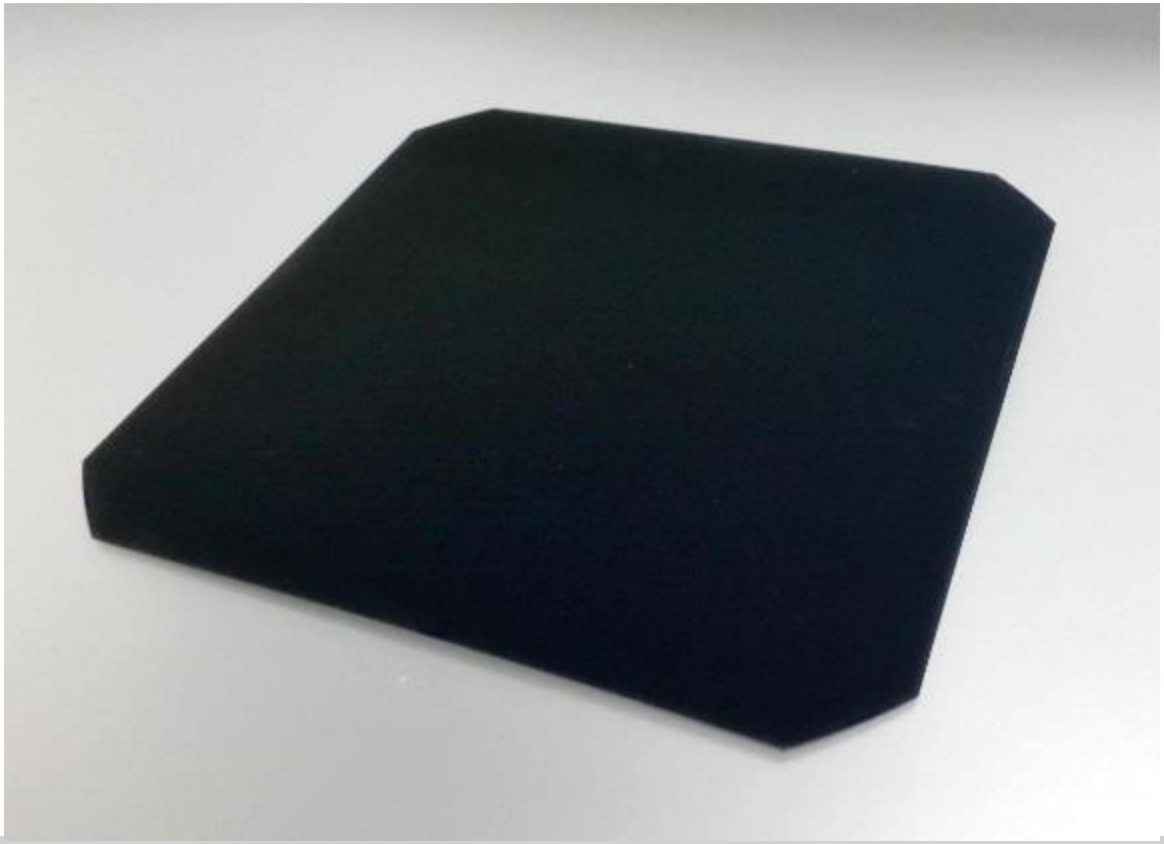


Open-circuit voltage (Voc):	0.740 V
Short circuit current (Isc):	6.01 A
Short circuit current density (Jsc):	41.8 mA/cm²
Fill factor (FF):	0.827
Cell conversion efficiency:	25.6%
Cell area:	143.7 cm²



Even newer records

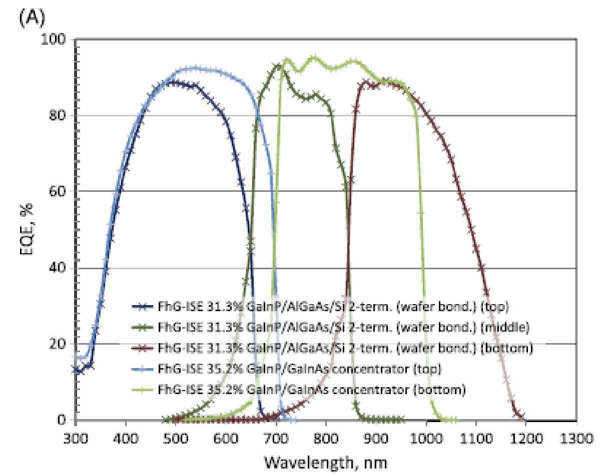
- High efficiency crystalline silicon solar cells:
  - Kaneka – IBC-HIT 26.6% (90.5% of theoretical limit!)



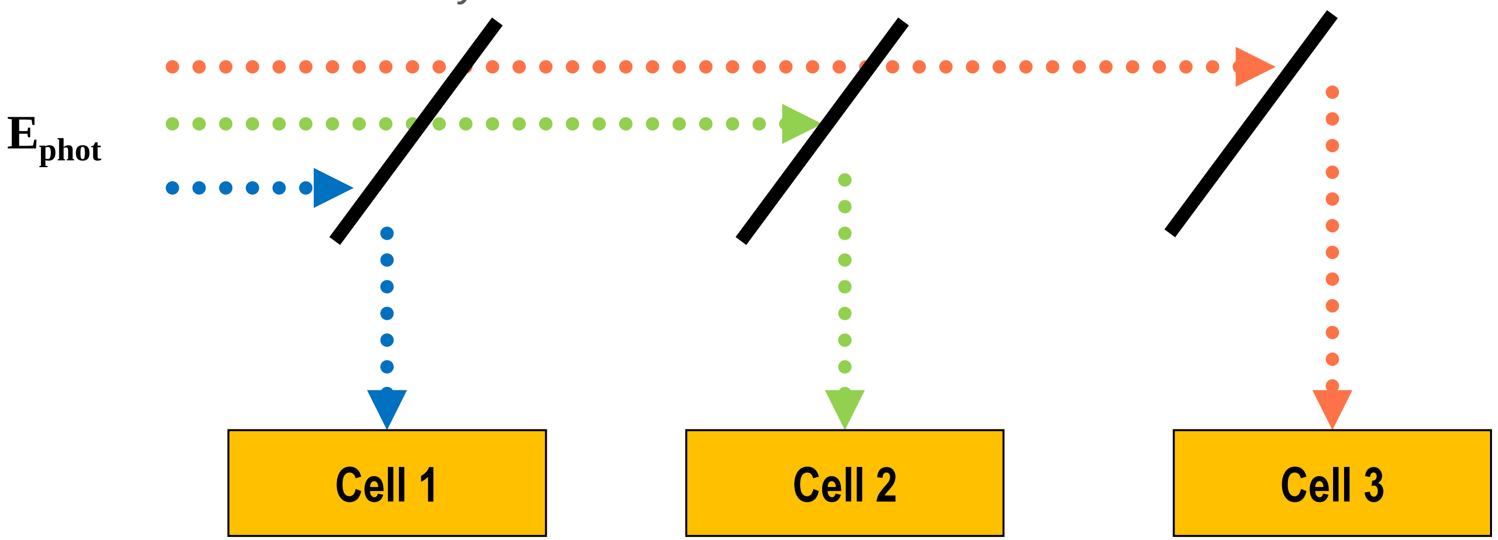
Kaneka/NEDO

Si tandem solar cell

Tandem



- High efficiency crystalline silicon solar cells:
- Beyond Shockley Queisser:
- Three main approaches:
  1. "The solar cell is fine, change the Sunlight instead!"
  2. **"One cell for every wavelength!"**
  3. "Thermalization is your friend!"



Efficiency

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WILEY

ACCELERATED PUBLICATION

Solar cell efficiency tables (version 50)

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TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
Silicon							
Si (crystalline cell)	**26.7 ± 0.5**	**79.0 (da)**	**0.738**	**42.65[a]**	**84.9**	**AIST (3/17)**	**Kaneka, n-type rear IBC[5]**
Si (multicrystalline cell)	**21.9 ± 0.4[b]**	**4.0003 (t)**	**0.6726**	**40.76[a]**	**79.7**	**FhG-ISE (2/17)**	**FhG-ISE, n-type[6]**
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[c,d]	80.3	NREL (4/14)	Solexel (35 µm thick)[7]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[c]	72.1	FhG-ISE (8/07)[e]	CSG Solar (<2 µm on glass)[8]
III-V cells							
GaAs (thin film cell)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[f]	86.5	NREL (5/12)	Alta Devices[9]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate[10]
InP (crystalline cell)	**24.2 ± 0.5[b]**	**1.008 (ap)**	**0.939**	**31.15[a]**	**82.6**	**NREL (9/12)**	**NREL[11]**
Thin film chalcogenide							
CIGS (cell)	**21.7 ± 0.5**	**1.044 (da)**	**0.718**	**40.70[a]**	**74.3**	**AIST (1/17)**	**Solar Frontier[12]**
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[d]	79.4	Newport (8/14)	First Solar, on glass[13]
CZTS (cell)	**10.0 ± 0.2**	**1.113 (da)**	**0.7083**	**21.77[a]**	**65.1**	**NREL (3/17)**	**UNSW[14]**
Amorphous/microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[e,b]	1.001 (da)	0.896	16.36[d]	69.8	AIST (7/14)	AIST[15]
Si (microcrystalline cell)	**11.9 ± 0.3[b]**	**1.044 (da)**	**0.550**	**28.72[a]**	**75.0**	**AIST (2/17)**	**AIST[16]**
Perovskite							
Perovskite (cell)	19.7 ± 0.6[e,h]	0.9917 (da)	1.104	24.67[i]	72.3	Newport (3/16)	KRICT/UNIST[17]
Perovskite (minimodule)	**16.0 ± 0.4[e,h]**	**16.29 (ap)**	**1.029[c]**	**19.51[c,a]**	**76.1**	**Newport (4/17)**	**Microquanta, 6 serial cells[18]**
Dye sensitised							
Dye (cell)	11.9 ± 0.4[j]	1.005 (da)	0.744	22.47[k]	71.2	AIST (9/12)	Sharp[19]
Dye (minimodule)	10.7 ± 0.4[j]	26.55 (da)	0.754[c]	20.19[c,l]	69.9	AIST (2/15)	Sharp, 7 serial cells[19]
Dye (submodule)	8.8 ± 0.3[j]	398.8 (da)	0.697[c]	18.42[c,m]	68.7	AIST (9/12)	Sharp, 26 serial cells[20]
Organic							
Organic (cell)	11.2 ± 0.3[n]	0.992 (da)	0.780	19.30[d]	74.2	AIST (10/15)	Toshiba[21]
Organic (minimodule)	9.7 ± 0.3[n]	26.14 (da)	0.806	16.47[c,l]	73.2	AIST (2/15)	Toshiba (8 series cells)[22]

TABLE 2 Confirmed multiple-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	Voc (V)	Jsc (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
III-V Multijunctions							
5 junction cell (bonded)	38.8 ± 1.2	1.021 (ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab, 2-terminal[23]
(2.17/1.68/1.40/1.06/0.73 eV)							
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[a]	86.7	AIST (2/13)	Sharp, 2 term.[24]
GaInP/GaAs(monolithic)	31.6 ± 1.5	0.999 (ap)	2.538	14.18[b]	87.7	NREL (1/16)	Alta Devices, 2 term.[25]
Multijunctions with c-Si							
GaInP/GaAs/Si (mech. stack)	**35.9 ± 0.5[c]**	**1.002 (da)**	**2.52/0.681**	**13.6/11.0**	**87.5/78.5**	**NREL (2/17)**	**NREL/CSEM/EPFL, 4-term.[26]**
GaInP/GaAs/Si (wafer bonded)	**31.3 ± 1.1[c]**	**3.981 (ap)**	**3.046**	**11.7[d]**	**87.5**	**FhG-ISE (3/17)**	**Fraunhofer ISE, 2-term.[27]**
GaInP/GaAs/Si (monolithic)	19.7 ± 0.7[c]	3.943 (ap)	2.323	10.0[e]	84.3	FhG-ISE (8/16)	Fraunhofer ISE[28]
GaAs/Si (mech. stack)	**32.8 ± 0.5[c]**	**1.003 (da)**	**1.09/0.683**	**28.9/11.1**	**85.0/79.2**	**NREL (12/16)**	**NREL/CSEM/EPFL, 4-term.[26]**
Perovskite/Si (monolithic)	23.6 ± 0.6[f]	0.990 (ap)	1.651	18.09[e]	79.0	NREL (8/16)	Stanford/ASU[29]
GaInP/GaInAs/Ge; Si(spectral split minimodule)	34.5 ± 2.0	27.83 (ap)	2.66/0.65	13.1/9.3	85.6/79.0	NREL (4/16)	UNSW/Azur/Trina, 4-term.[30]
a-Si/nc-Si Multijunctions							
a-Si/nc-Si/nc-Si (thin-film)	14.0 ± 0.4[g,c]	1.045 (da)	1.922	9.94[e]	73.4	AIST (5/16)	AIST[31]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4%[g,c]	1.000(da)	1.342	13.45[h]	70.2	AIST (10/14)	AIST[15,32]

TABLE 3 Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Effic. (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (A)	FF (%)	Test Centre (date)	Description
Si (crystalline)	24.4 ± 0.5	13177 (da)	79.5	5.04[a]	80.1	AIST (9/16)	Kaneka (108 cells)[5]
Si (multicrystalline)	19.9 ± 0.4	15143 (ap)	78.87	4.795[a]	79.5	FhG-ISE (10/16)	Trina Solar (120 cells)[33]
GaAs (thin film)	**24.8 ± 0.5**	**865.3 (ap)**	**11.07**	**2.288[b]**	**84.7**	**NREL (11/16)**	**Alta Devices[34]**
CIGS (Cd free)	**19.2 ± 0.5**	**841 (da)**	**48.0**	**0.456[b]**	**73.7**	**AIST (1/17)**	**Solar Frontier (70 cells)[35]**
CIGS (large)	15.7 ± 0.5	9703 (ap)	28.24	7.254[c]	72.5	NREL (11/10)	Miasole[36]
CdTe (thin-film)	18.6 ± 0.6	7038.8 (ap)	110.6	1.533[d]	74.2	NREL (4/15)	First Solar, monolithic[37]
a-Si/nc-Si (tandem)	12.3 ± 0.3[e]	14322 (t)	280.1	0.902[f]	69.9	ESTI (9/14)	TEL Solar, Trubbach Labs[38]
Organic	8.7 ± 0.3[g]	802 (da)	17.47	0.569[h]	70.4	AIST (5/14)	Toshiba[22]
<u>Multijunction</u>							
InGaP/GaAs/InGaAs	31.2 ± 1.2	968 (da)	23.95	1.506	83.6	AIST (2/16)	Sharp (32 cells)[39]

TABLE 4 "Notable exceptions": "Top dozen" confirmed cell and module results, not class records measured under the global AM1.5 spectrum (1000 Wm^{-2}) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
<u>Cells (silicon)</u>							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7[a]	82.8	Sandia (3/99)[b]	UNSW p-type PERC top/rear contacts[40]
Si (crystalline)	**25.7 ± 0.5**[c]	**4.017 (da)**	**0.7249**	**42.54**[d]	**83.3**	**FhG-ISE (3/17)**	**FhG-ISE, n-type top/rear contacts**[41]
Si (large)	**26.6 ± 0.5**	**179.74 (da)**	**0.7403**	**42.5**[d]	**84.7**	**FhG-ISE (11/16)**	**Kaneka, n-type rear IBC**[5]
Si (multicrystalline)	21.3 ± 0.4	242.74 (t)	0.6678	39.80[e]	80.0	FhG-ISE (11/15)	Trina Solar, large p-type[42]
<u>Cells (III-V)</u>							
GaInP	21.4 ± 0.3	0.2504 (ap)	1.4932	16.31[f]	87.7	NREL (9/16)	LG Electronics, high bandgap[43]
<u>Cells (chalcogenide)</u>							
CIGS (thin-film)	22.6 ± 0.5	0.4092 (da)	0.7411	37.76[f]	80.6	FhG-ISE (2/16)	ZSW on glass[44]
CIGSS (Cd free)	**22.0 ± 0.5**	**0.512 (da)**	**0.7170**	**39.45**[f]	**77.9**	**FhG-ISE (2/16)**	**Solar Frontier on glass**[12]
CdTe (thin-film)	22.1 ± 0.5	0.4798 (da)	0.8872	31.69[g]	78.5	Newport (11/15)	First Solar on glass[45]
CZTSS (thin-film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21[h]	69.8	Newport (7/13)	IBM solution grown[46]
CZTS (thin-film)	**11.0 ± 0.2**	**0.2339(da)**	**0.7306**	**21.74**[d]	**69.3**	**NREL (3/17)**	**UNSW on glass**[14]
<u>Cells (other)</u>							
Perovskite (thin-film)	22.1 ± 0.7[i]	0.0946 (ap)	1.105	24.97[j]	80.3	Newport (3/16)	KRICT/UNIST[17]
Organic (thin-film)	**12.1 ± 0.3**[k]	**0.0407 (ap)**	**0.8150**	**20.27**[d]	**73.5**	**Newport (2/17)**	**Phillips 66**

Abbreviations: CIGSS, CuInGaSSe; CZTSS, $Cu_2ZnSnS_{4-y}Se_y$; CZTS, Cu_2ZnSnS_4; (ap), aperture area; (t), total area; (da), designated illumination area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme.

TABLE 5 "Direct beam" terrestrial concentrator cell and module efficiencies measured under the ASTM G-173-03 direct AM1.5 spectrum at a cell temperature of 25°C. New entries in bold type

Classification	Effic. (%)	Area (cm^2)	Intensity[a] (suns)	Test Centre (date)	Description
Single cells					
GaAs	29.3 ± 0.7[b]	0.09359 (da)	49.9	NREL (10/16)	LG Electronics
Si	27.6 ± 1.2[c]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact[48]
CIGS (thin-film)	23.3 ± 1.2[d,e]	0.09902 (ap)	15	NREL (3/14)	NREL[49]
Multijunction cells					
GaInP/GaAs; GaInAsP/GaInAs	46.0 ± 2.2[f]	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE 4j bonded[50]
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3[d,g]	0.09709 (da)	234	NREL (9/14)	NREL, 4j monolithic[51]
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, 3j inverted metamorphic[52]
GaInP/GaInAs	**35.1 ± 1.1[d,i]**	**0.05376 (da)**	**407**	**FhG-ISE (3/17)**	**Fraunhofer ISE 2j[53]**
Minimodule					
GaInP/GaAs; GaInAsP/GaInAs (wafer bonded)	43.4 ± 2.4[d,j]	18.2 (ap)	340[k]	FhG-ISE (7/15)	Fraunhofer ISE 4j (lens/cell)[54]
Submodule					
GaInP/GaInAs/Ge; Si	40.6 ± 2.0[m]	287 (ap)	365	NREL (4/16)	UNSW 4j split spectrum[55]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[k]	Sandia/UNSW/ENTECH (12 cells)[56]
Three junction (3j)	35.9 ± 1.8[m]	1092 (ap)	N/A	NREL (8/13)	Amonix[57]
Four junction (4j)	38.9 ± 2.5[n]	812.3 (ap)	333	FhG-ISE (4/15)	Soitec[58]
"Notable Exceptions"					
Si (large-area cell)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[k]	UNSW laser grooved[59]
Luminescent minimodule	7.1 ± 0.2	25(ap)	2.5[k]	ESTI (9/08)	ECN Petten, GaAs cells[60]

Quantum efficiency