High efficiency silicon and perovskite-silicon solar cells for electricity generation

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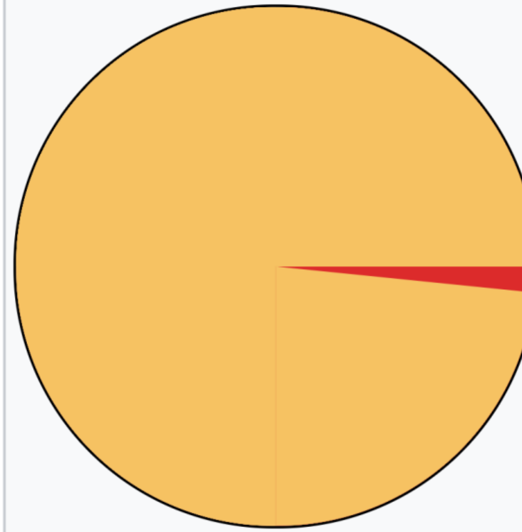
From Solar Energy to Electricity



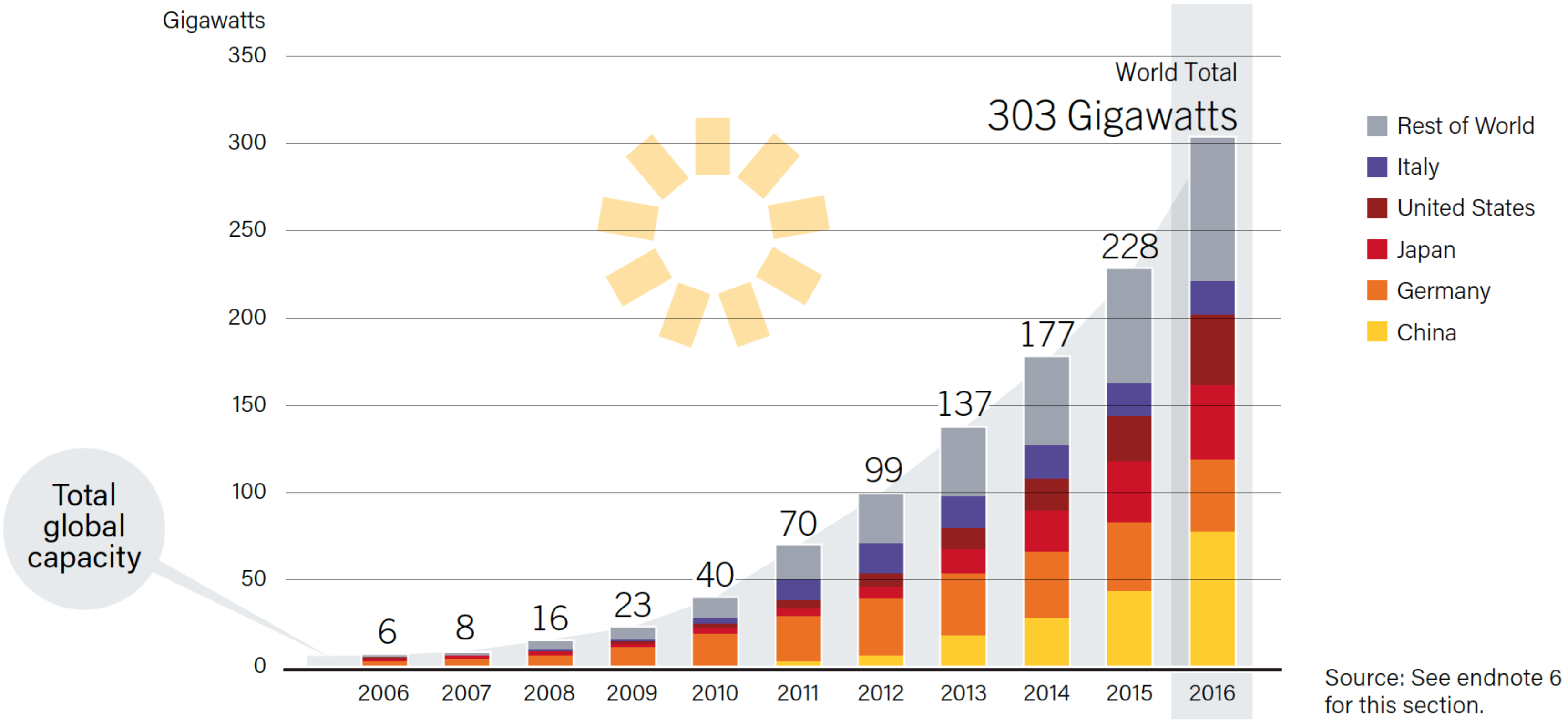
Worldwide electric capacity of solar power by technology. Total of 308 GW in 2016.[1]

PV-technology (98.4%)

CSP-technology (1.6%)

Global accumulative PV installed

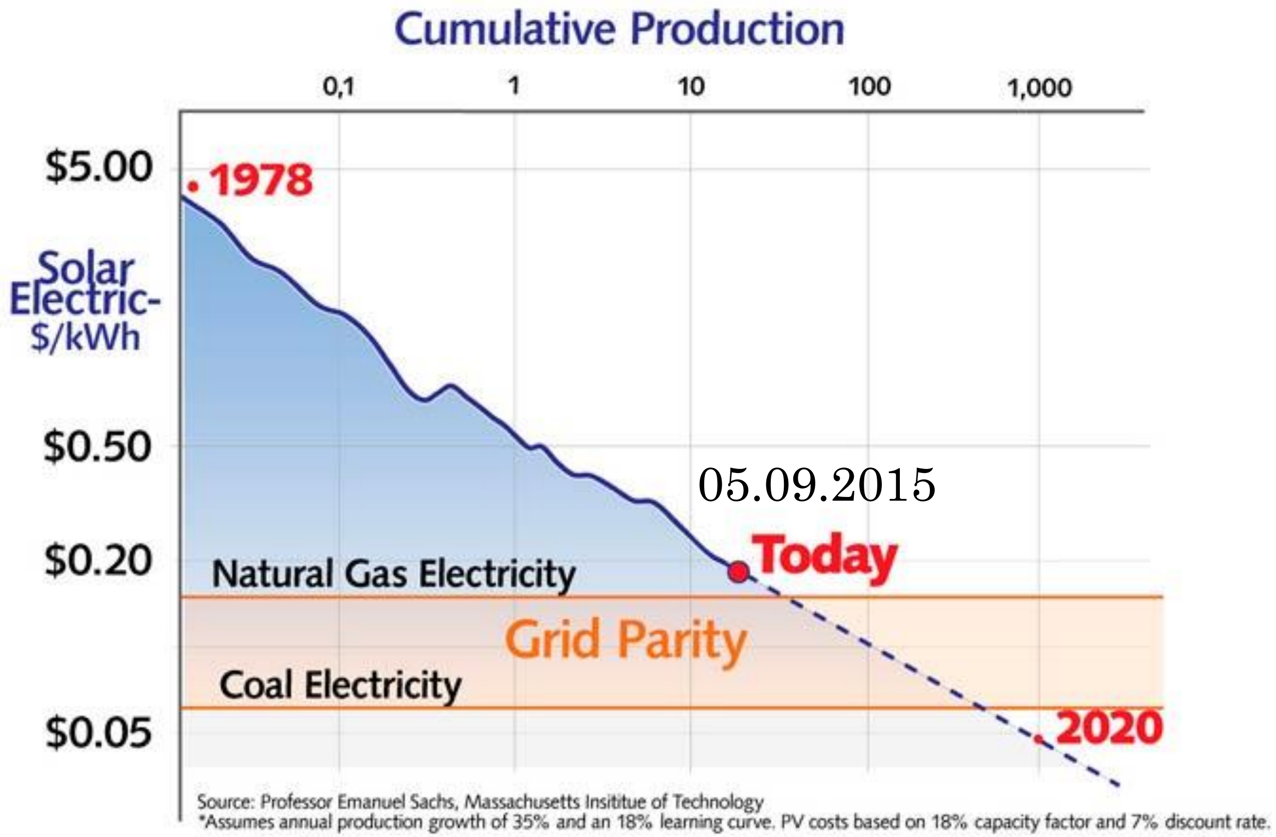
Figure 16. Solar PV Global Capacity, by Country and Region, 2006-2016



In Iran it is about 100 MW.
Total national grid capacity 75 GW.

Grid-parity in PV is already there

- Swanson PV curve.

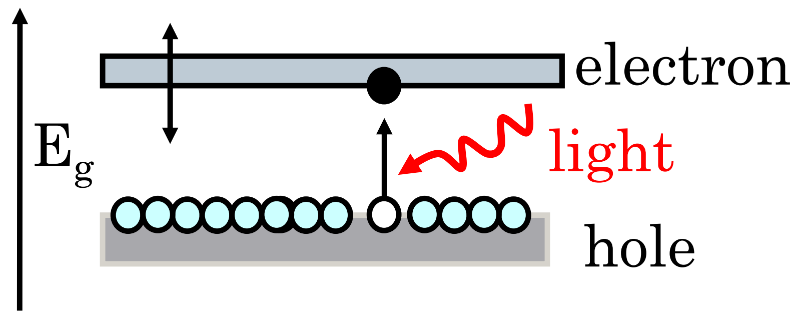


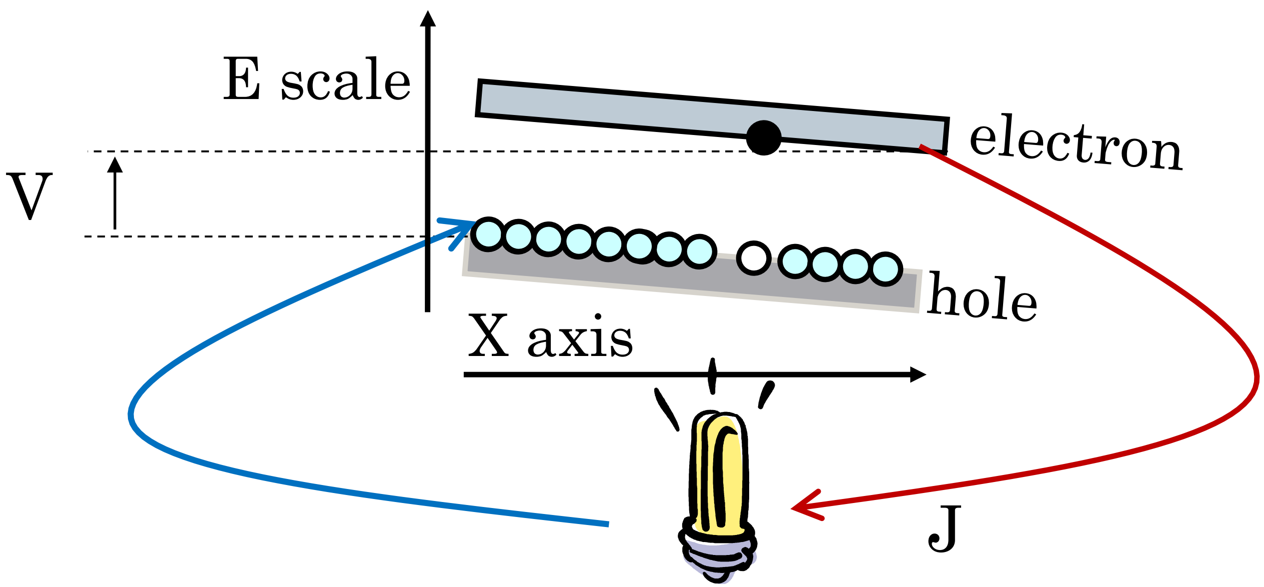
Photovoltaics Technology

Photovoltaics

1) Sunlight is absorbed by a semiconductor material and its energy is transferred to an electron

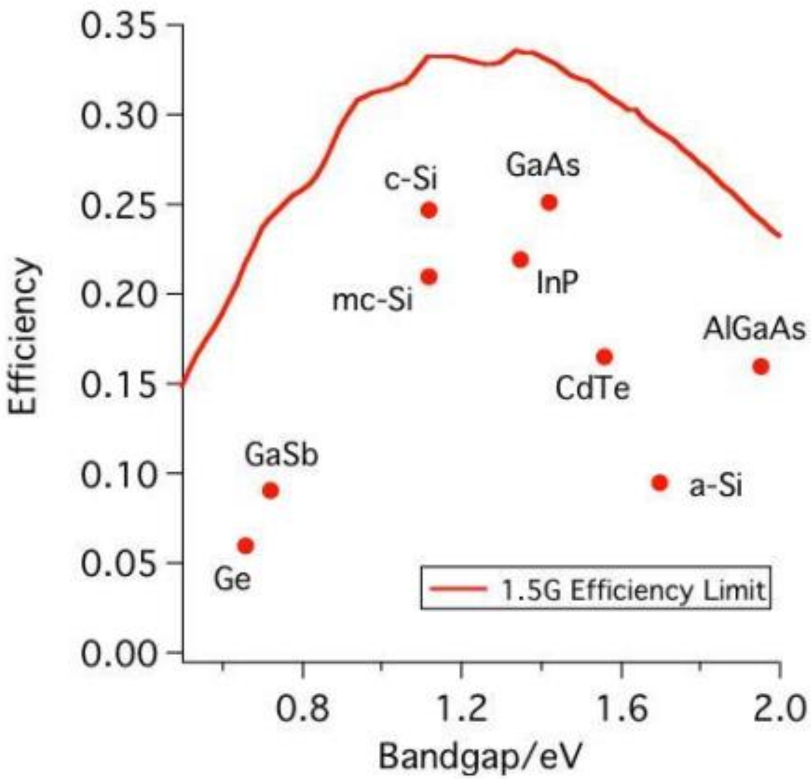
2) In presence of an electric field, electric charges can be separated





3) The electricity can be used ! ☺

Fundamental limit of efficiency



Source U. Sydney, only bandgap
Ok, efficiencies might have increased

Single junction ~
In the *Schockley-Queisser radiative limit*
(radiative equilibrium of cell with the sun for a single semiconductor junction)
→ 33%

Under concentration can be increased by a few percent !

Radiative Recombination Limit:
W. Shockley and H. J. Queisser, J. Appl. Phys. 32, 510 (1961).

Major PV technologies

Market

Crystalline silicon
Mono and multicrystalline

Status: main market share

Thin films
CIGS, CdTe, Thin film silicon

Status: stabilised market share

Concentrator technologies
Mostly III-V based

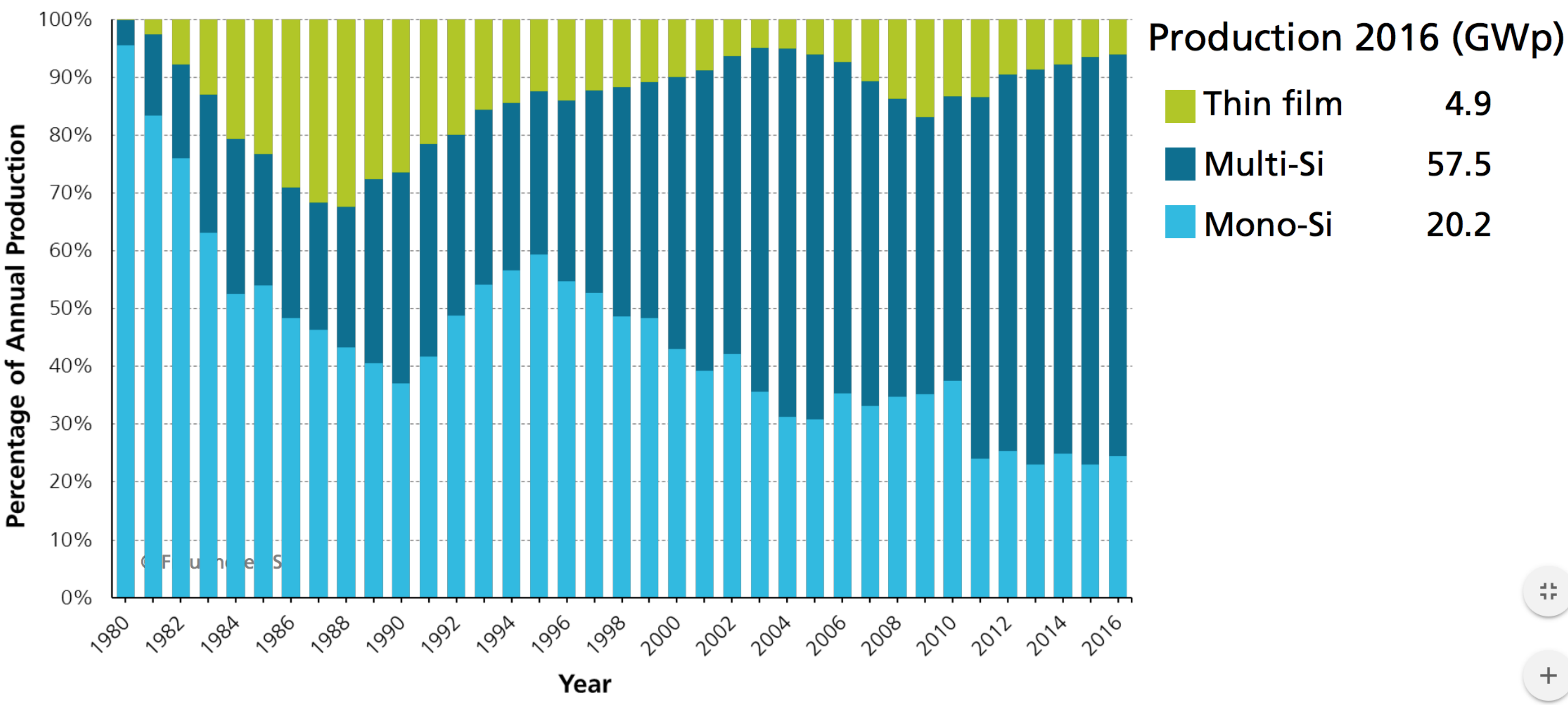
Status: trying entering the market, many start-ups

Emerging technologies
Nano inorganic (Quatum dot)
Organic-Polymer, perovskites
Dye sensitized and variations

Status: niche application

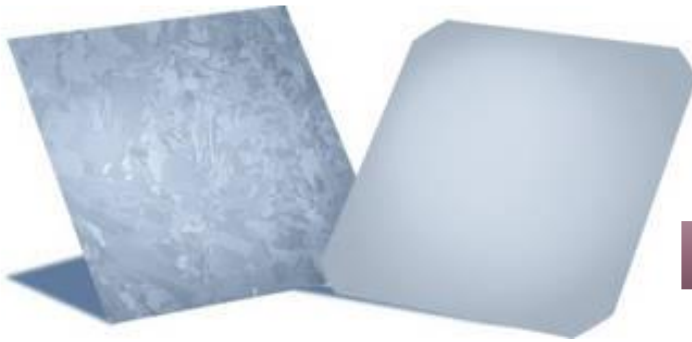
PV Technologies market share

- Crystalline Si technology does and will hold >90% of PV market share.
- Alternative low-cost technologies have not came close to Si efficiencies and price levels.



Crystalline Si terminology

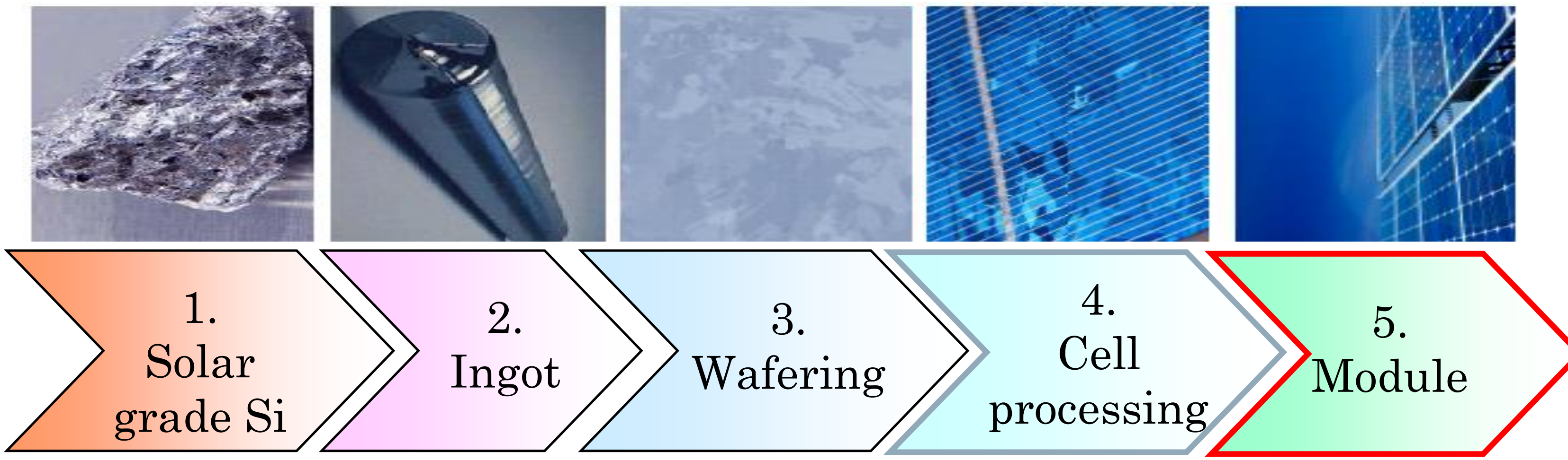
- Wafer



- Cell: processed wafer (20-30 steps)

- Module (a number of cells that are put in series with a two socket as energy output)

Crystalline Si supply chain



Features

- Full metal rear side
- Screen printed front grid
- no local features

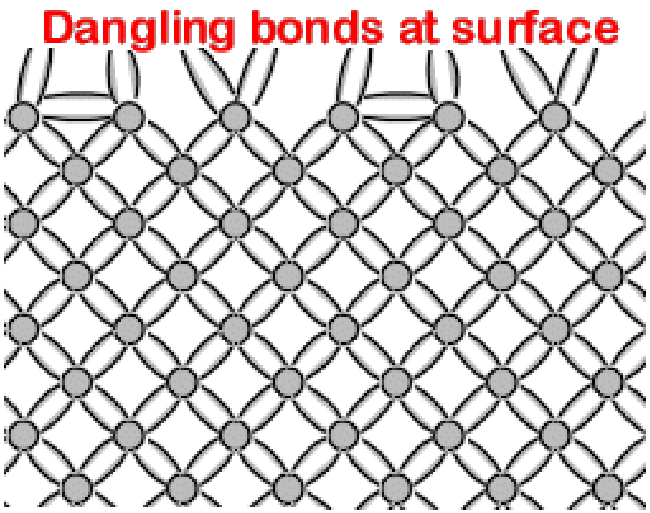
On the market:
η = 14-21% on monocrystalline Si PV modules
η = 12-18% on multicrystalline Si PV modules

Dangling bonds and surface passivation

At any semiconductor surface the crystal symmetry is broken

→ Localized electronic states in the bandgap (whatever the surface condition: bare, in contact with a metallic or oxidized surfaces)

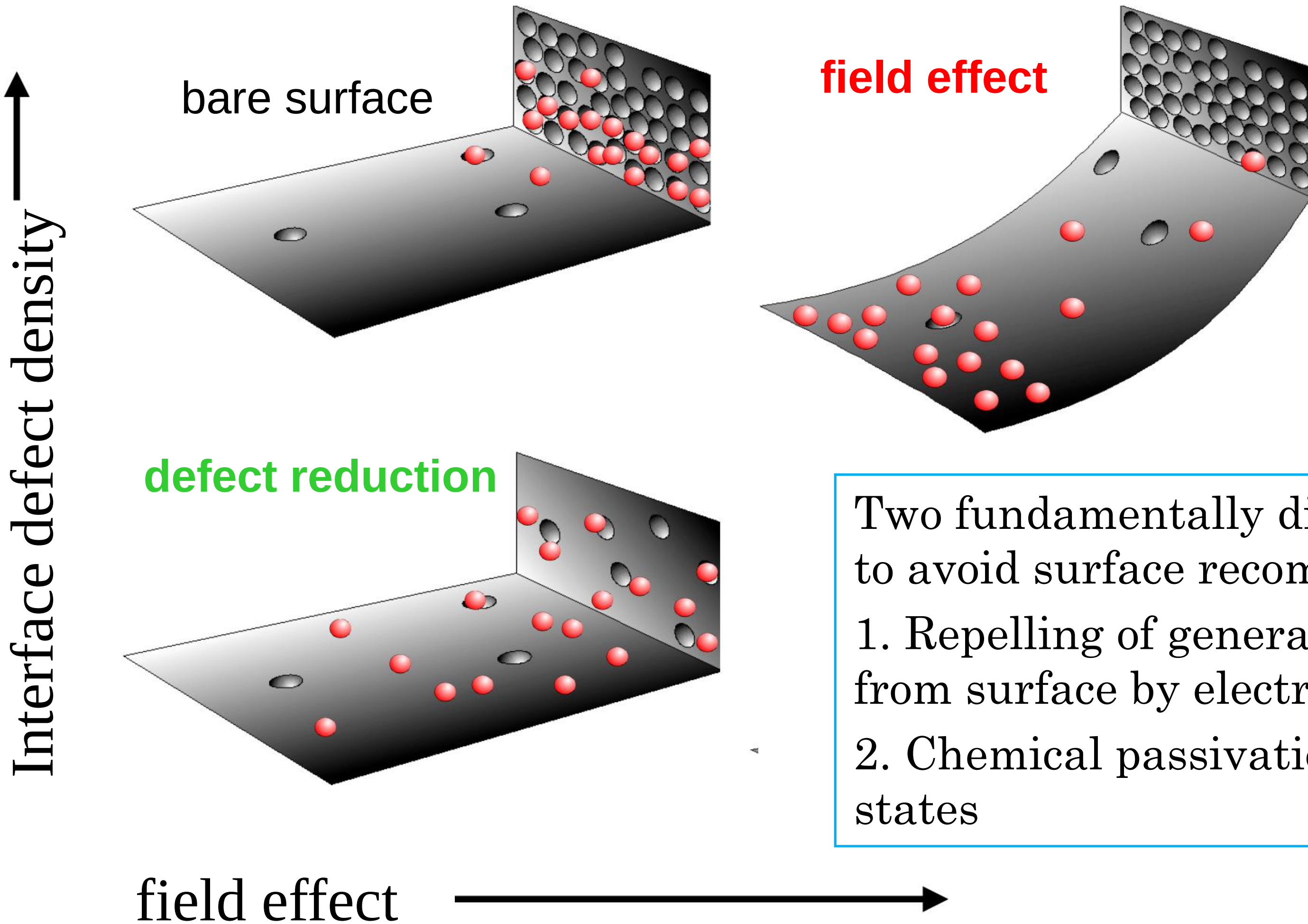
→ recombination sink for carriers.



Recombination can be avoided by

- Minimizing the number of defects at the surface
- By creating a local electrical field that repels the minority carriers
  - a) with additional dopants n^+ or p^-
  - b) with fixed charges that can create an inversion layer
- By combining the different effects

How does surface passivation work?



Two fundamentally different ways to avoid surface recombination:

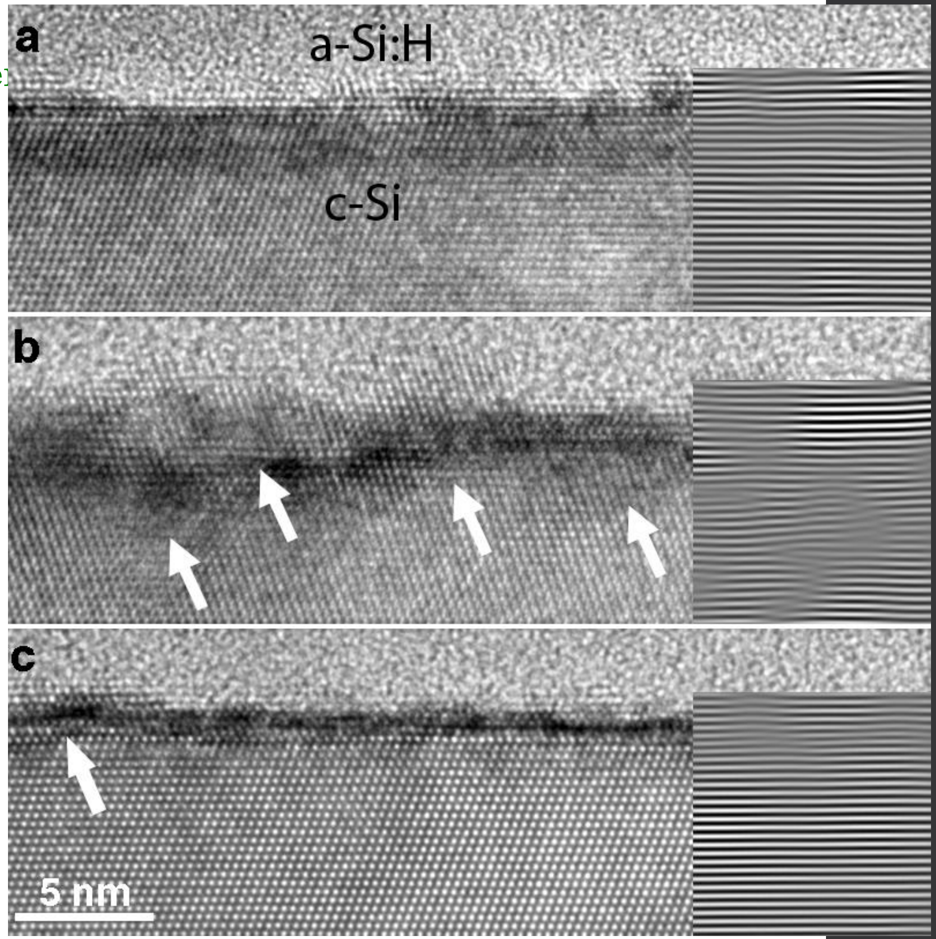
1. Repelling of generated carriers from surface by electrical field
2. Chemical passivation of surface-states

For good devices:

•Go towards the amorphous-to-crystalline transition as much as possible, but NO EPITAXY !

- Use highly depleted silane plasmas
- H_2 plasma during a-Si:H growth ('layer-by-layer

- Layer properties
  - Increase in hydrogen content
  - Increase in band gap
  - More disordered
  - Etching effect if H_2 plasma is too long



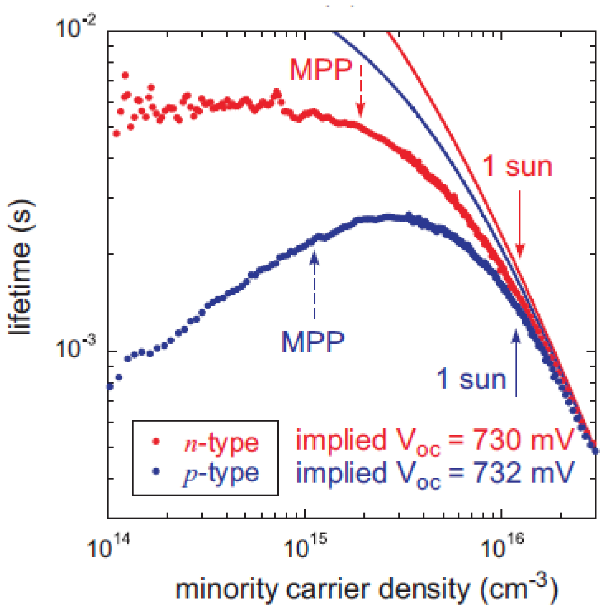
- Globally beneficial for devices

➡ 5-20 mV gain in V_{oc}

[Geissbuehler *et al*., APL **102**, 231604 (2013)]

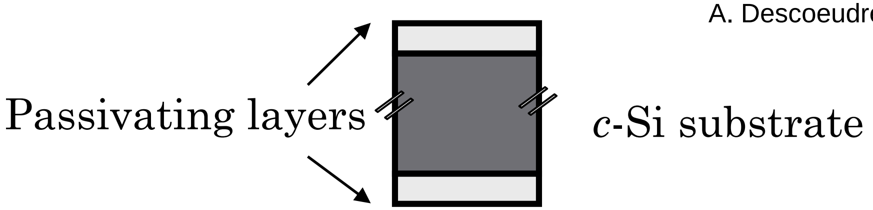
Surface passivation measurement

- Measurement of the photoconductivity
- ➔ Linked with the carrier density in the wafer
- If τ_{bulk} is high, surface passivation quality may be evaluated.

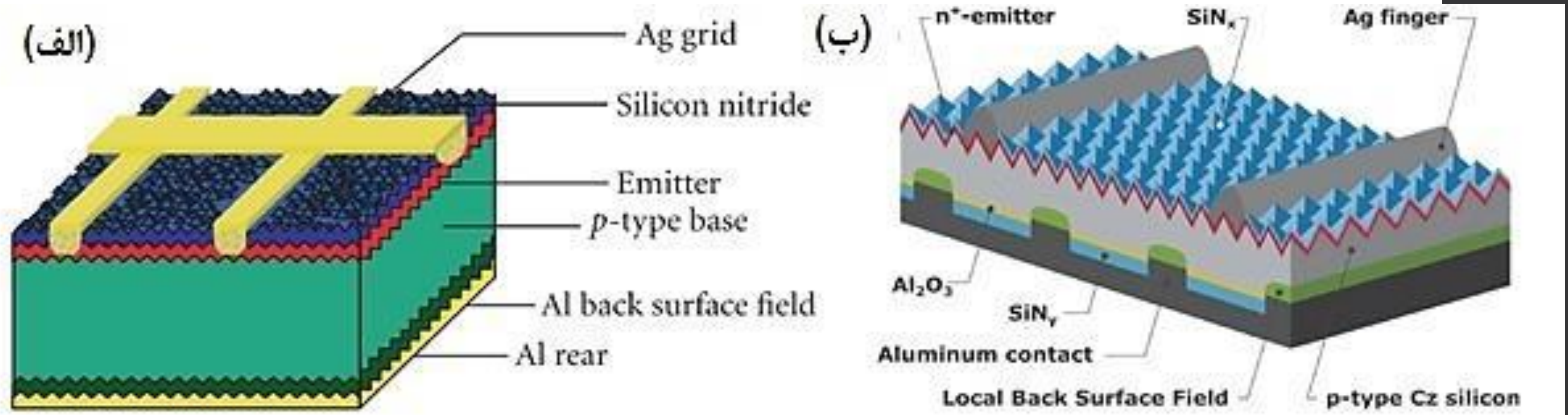


A. Descoeudres et al. IEEE JPV 2013

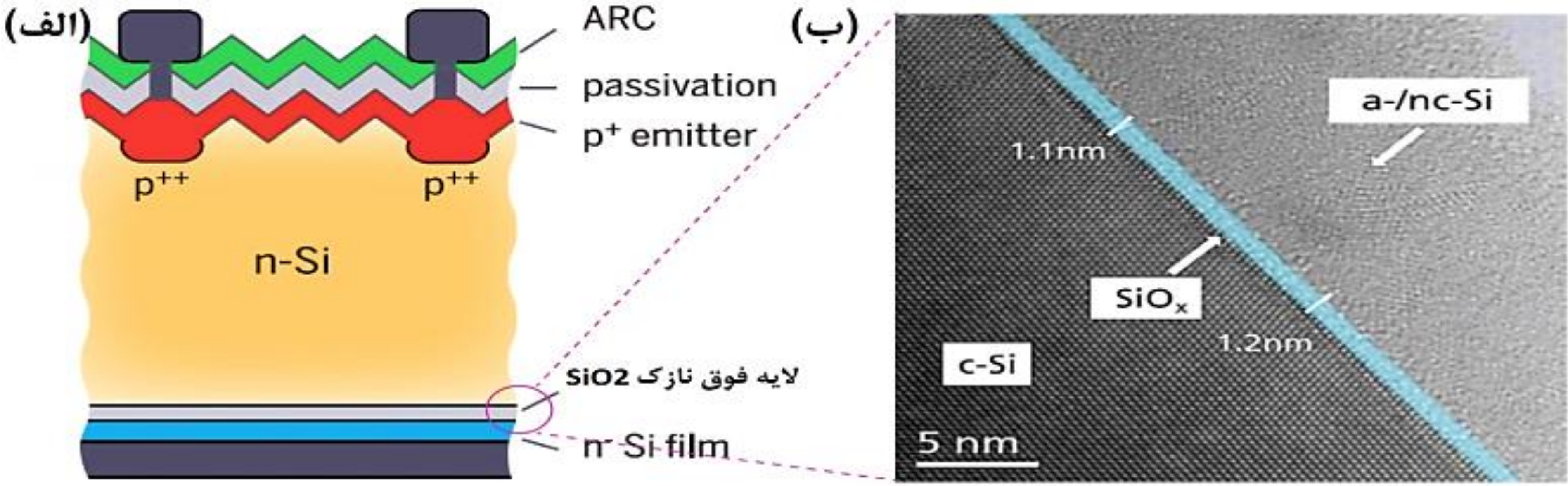
http://www.sintoninstruments.com



Al-BSF, PERC

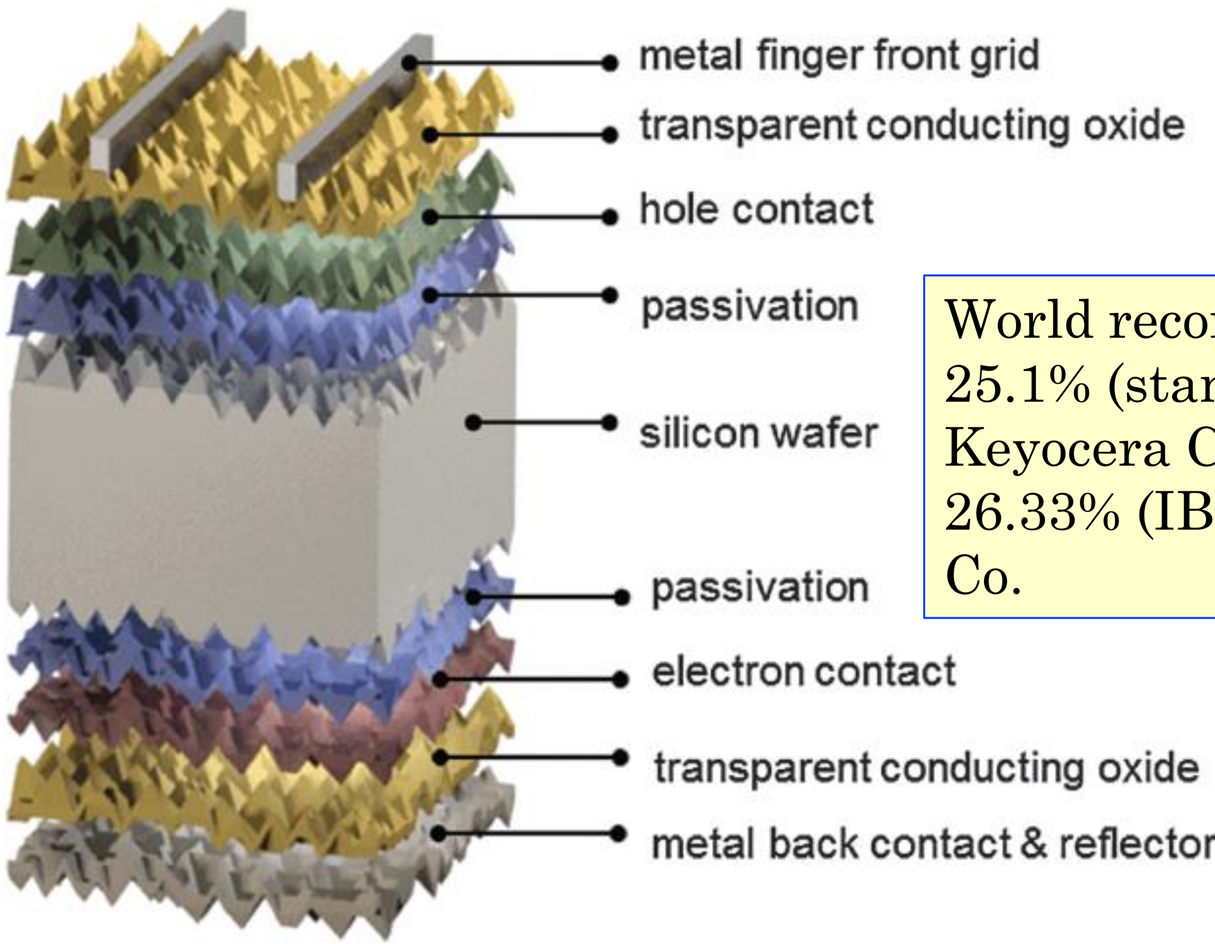

(الف)
Ag grid
Silicon nitride
Emitter
p-type base
Al back surface field
Al rear
(ب)
n⁺-emitter
SiNx
Ag finger
Al2O3
SiNy
Aluminum contact
Local Back Surface Field
p-type Cz silicon

TOP-Con



2014 by Fraunhofer ISE, 25.1%

Heterojunction solar cell (Panasonic HIT®)



World records:
25.1% (standard): Keyocera Co.
26.33% (IBC): Kaneka Co.

World record of Silicon PV with HIT technology

nature energy

ARTICLES

PUBLISHED: 20 MARCH 2017 | VOLUME: 2 | ARTICLE NUMBER: 17032

Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%

Kunta Yoshikawa*, Hayato Kawasaki, Wataru Yoshida, Toru Irie, Katsunori Konishi, Kunihiro Nakano, Toshihiko Uto, Daisuke Adachi, Masanori Kanematsu, Hisashi Uzu and Kenji Yamamoto

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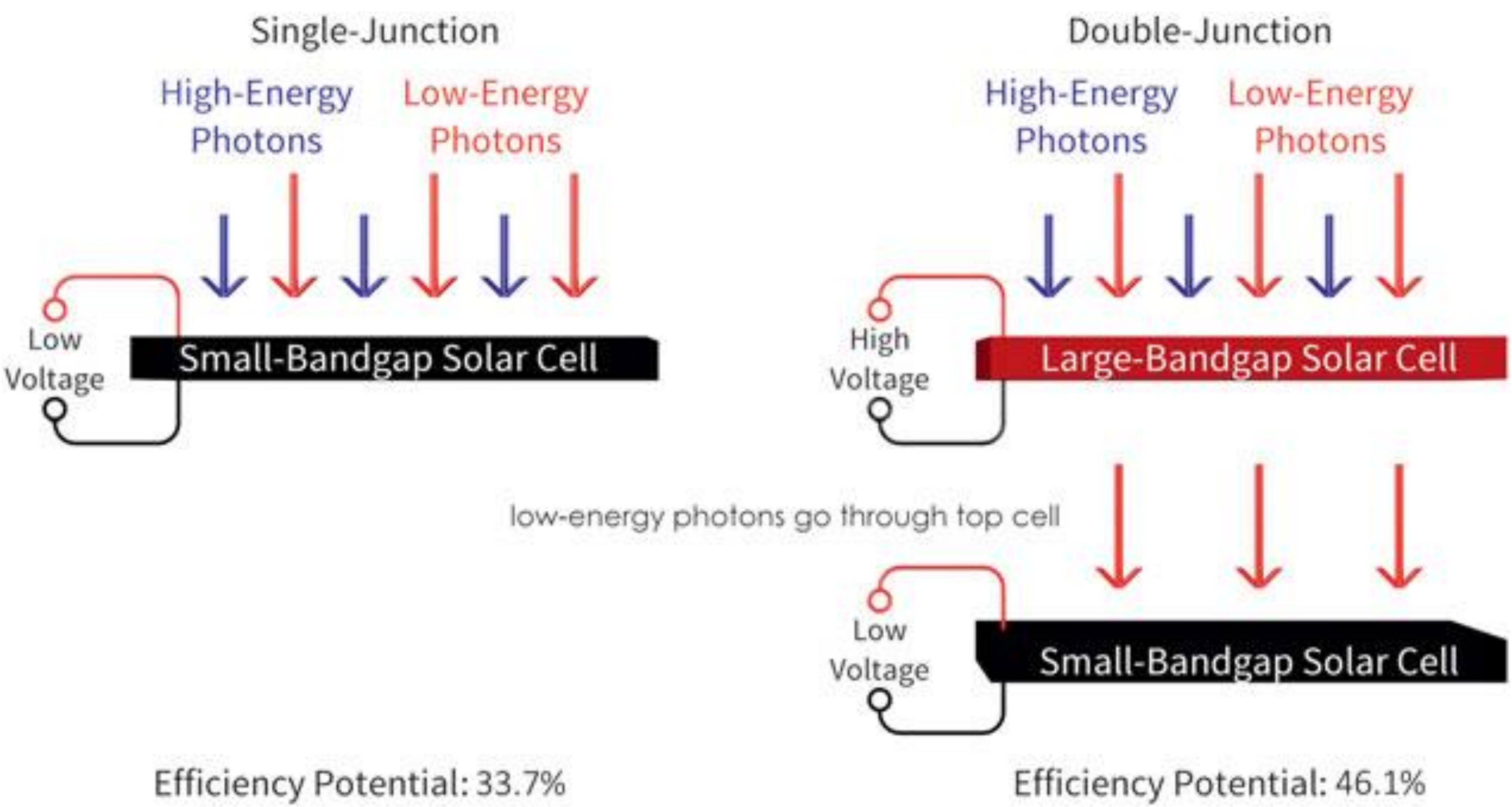
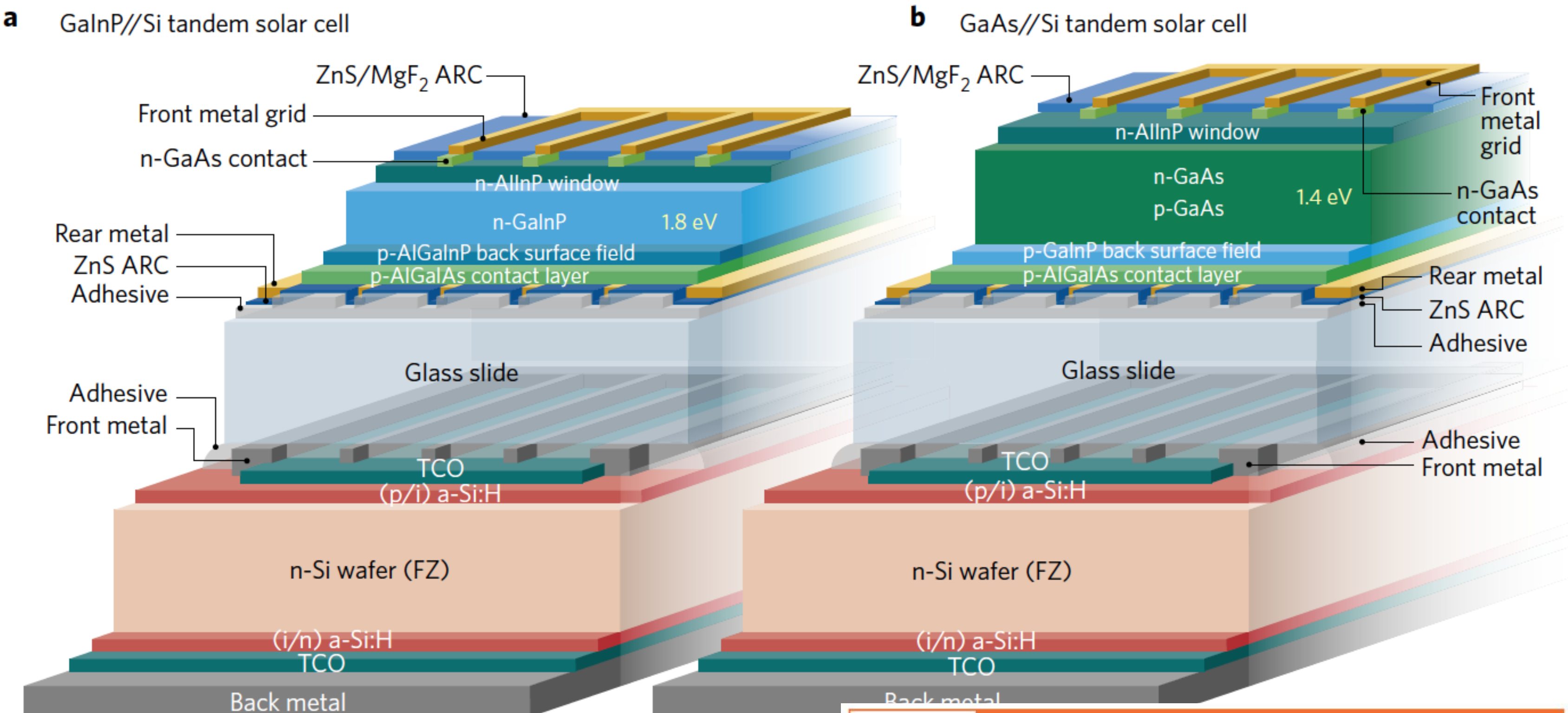
March 2017

Efficiences Beyond Si Fundamental Limits

Multijunction concept



III-V+ Si Tandems

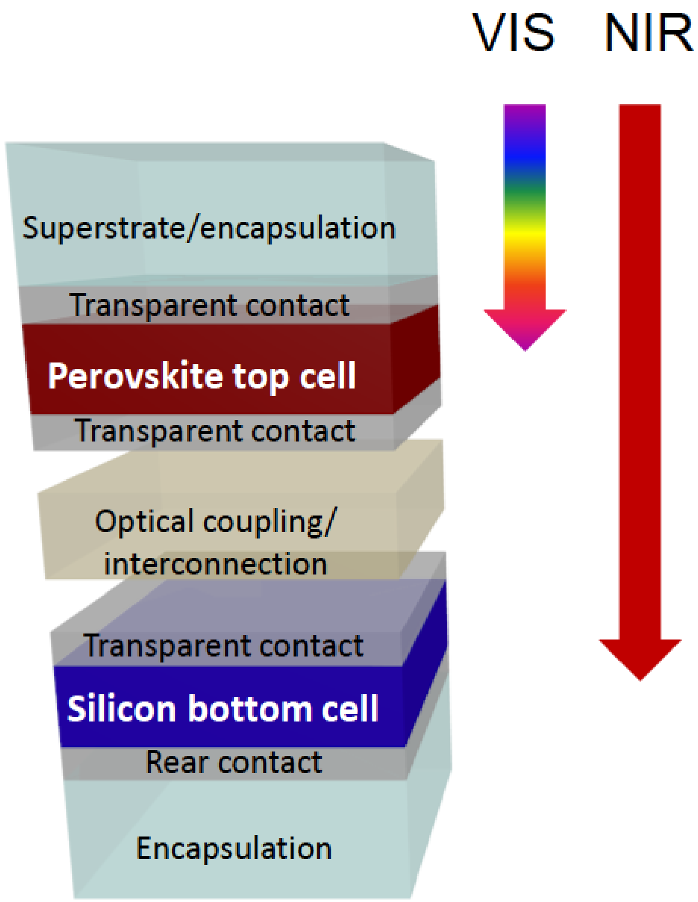


nature energy ARTICLES
PUBLISHED: 25 AUGUST 2017 | VOLUME: 2 | ARTICLE NUMBER: 17144

Raising the one-sun conversion efficiency of III–V/Si solar cells to 32.8% for two junctions and 35.9% for three junctions

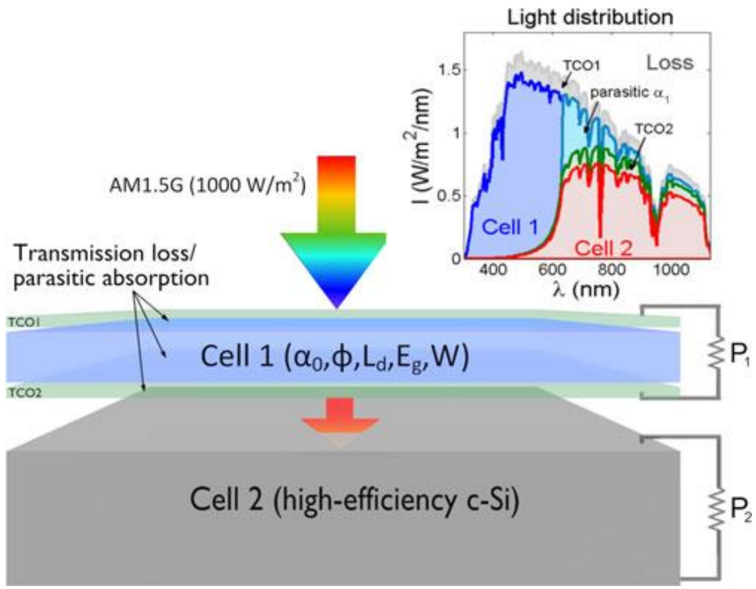
Stephanie Essig[1*], Christophe Allebé[2], Timothy Remo[3], John F. Geisz[3], Myles A. Steiner[3], Kelsey Horowitz[3], Loris Barraud[2], J. Scott Ward[3], Manuel Schnabel[3], Antoine Descoeudres[2], David L. Young[3], Michael Woodhouse[3], Matthieu Despeisse[2], Christophe Ballif[1,2] and Adele Tamboli[3]

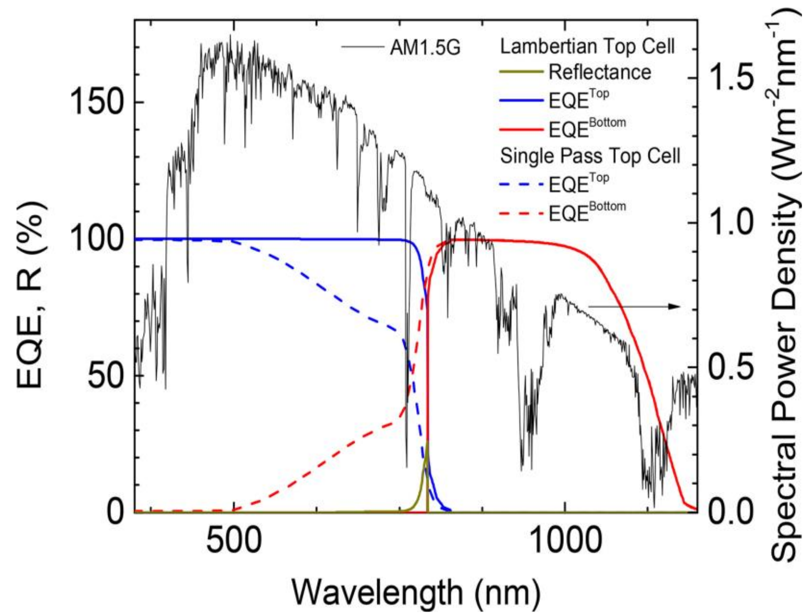
Perovskite/c-Si Multi-junction cell



- $CH_3NH_3PbI_3$ bandgap is 1.56 eV
- c-Si bandgap is 1.1 eV

Efficiency beyond 26.33% using perovskite-Si tandem





		Top Cell					Bottom Cell				Tandem
Optics (Top Cell Interfaces)	Connection	Thickness (nm)	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	η (%)	η (%)
Single Pass (Planar Front/R_b = 0)	2 T (CM)	278.7 nm	21.68	1100	89.1	21.24	21.68	748.9	88.9	14.43	35.67
PLE = 2 (Scattering Front, R_b = 0)	2 T (CM)	139.35 nm	21.68	1100	89.1	21.24	21.68	748.9	88.9	14.43	35.67
Lambertian (Scattering/Scattering)	2 T (CM)	140 nm	17.23	1100	89.1	16.89	17.23	744	88.8	11.4	28.3
Lambertian (Scattering/Scattering)	4 T	140 nm	25.7	1100	89.1	25.2	17.23	744	88.8	11.4	36.6
Lambertian (Scattering/Scattering)	4T	300 nm	26.62	1100	89.1	26.09	16.6	744	88.8	10.95	37.04
Lambertian (Scattering/Scattering)	4 T	500 nm	26.89	1100	89.1	26.35	16.38	743.8	88.8	10.82	37.17

P.Loper et al. IEEE JPV., 2015.

Most efficient monolithic perovskite/silicon tandem

nature materials

ARTICLES

https://doi.org/10.1038/s41563-018-0115-4

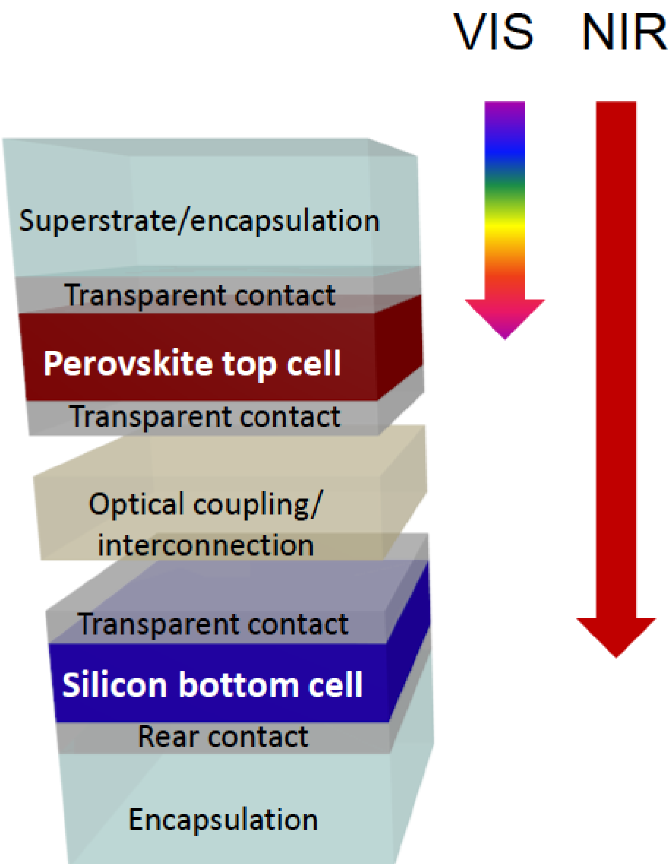
Fully textured monolithic perovskite/silicon tandem solar cells with 25.2% power conversion efficiency

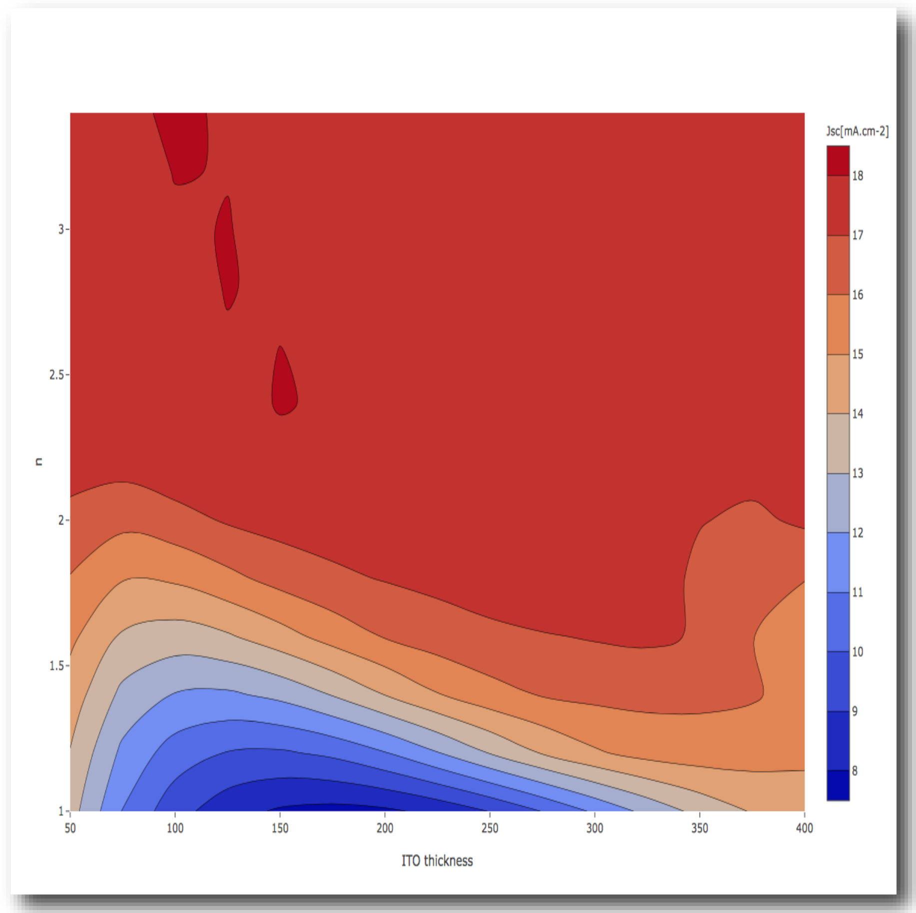
11.06.2018

Florent Sahli[1,3*], Jérémie Werner[1,3], Brett A. Kamino[2], Matthias Bräuninger[1], Raphaël Monnard[1], Bertrand Paviet-Salomon[2], Loris Barraud[2], Laura Ding[2], Juan J. Diaz Leon[2], Davide Sacchetto[2], Gianluca Cattaneo[2], Matthieu Despeisse[2], Mathieu Boccard[1], Sylvain Nicolay[2], Quentin Jeangros[1*], Bjoern Niesen[2] and Christophe Ballif[1,2]

Oxford PV reports 25.2 % 156 mm x 156 mm perovskite-silicon tandem solar cells at the company’s industrial pilot line in Brandenburg an der Havel, Germany.(15.06.2018)

Our Research at IPM on Si and Tandem Cells (1. Theory and Simulation)

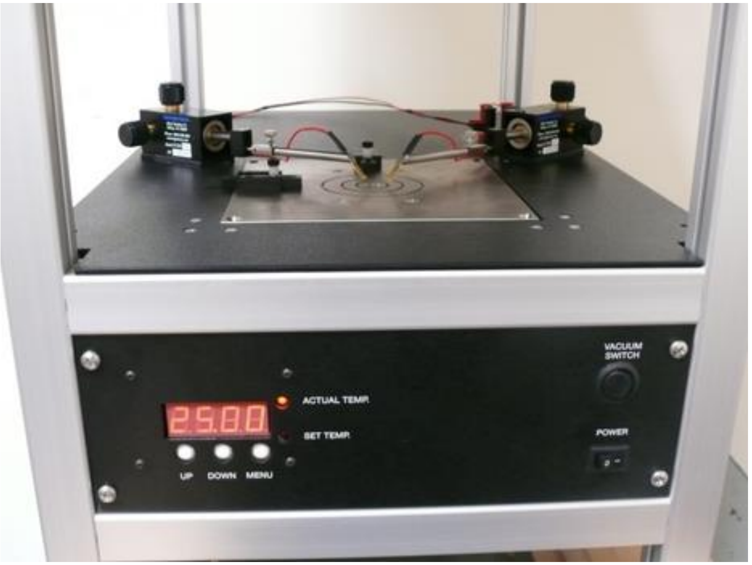




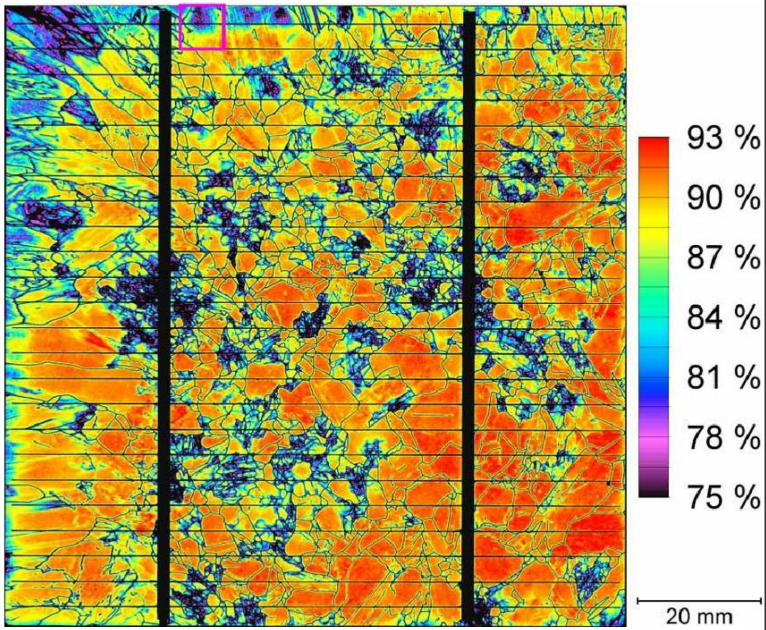
A. Dabirian et al. IEEE Journal of Photovoltaics, 7, 718, (2017).
B. Eftekharinia, et al, (in preparation)

2. Our Research at IPM on Si Solar Cell Characterization

Solar cell measurement setups:
1- Temperature variable IV tester

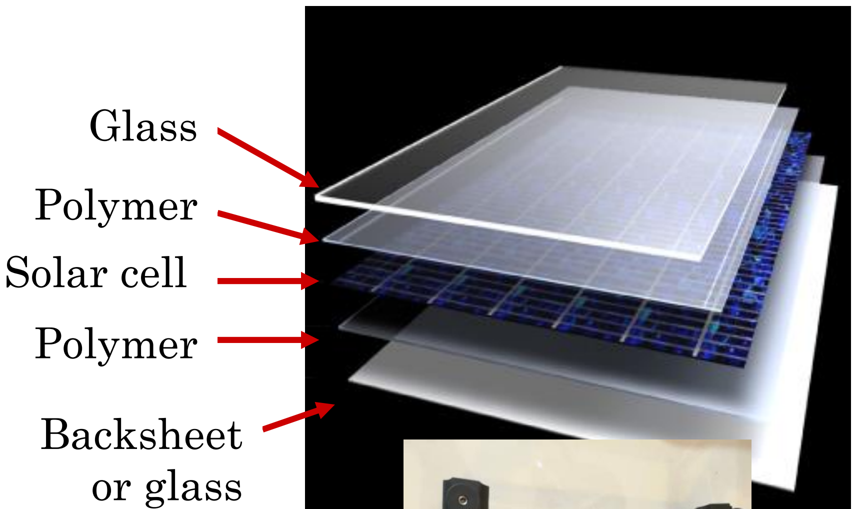


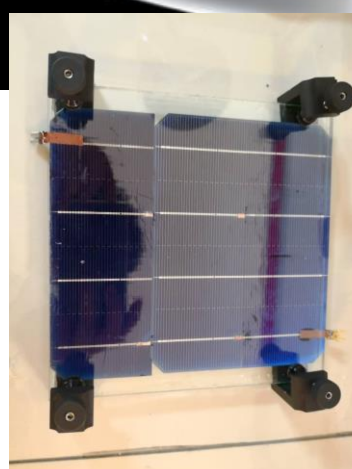
2- Localized characterization of solar cells



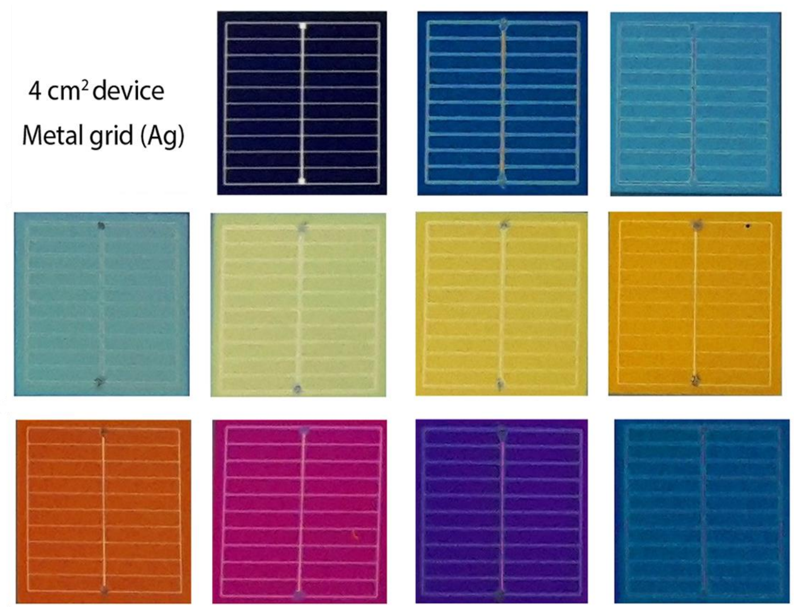
3. Our Research at IPM on Si PV Modules

1- Novel encapsulation methods





2- Colored cells

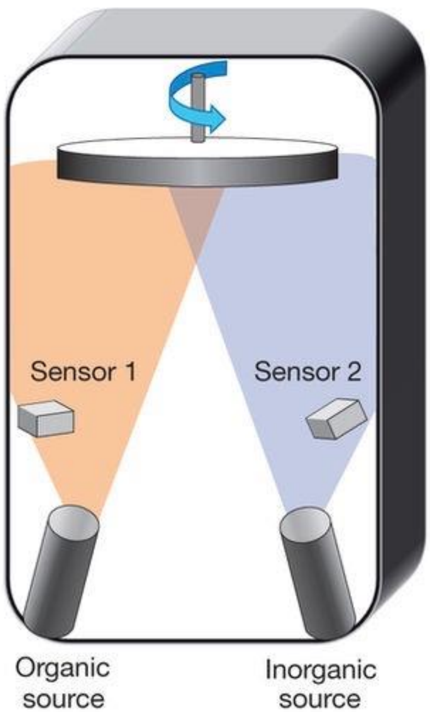


A. Dabirian et al. patent pending.

4. Our Research at IPM on Fabrication of Tandem Cells

Gas-phase deposition of perovskites for tandems

a



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Thank you!

Questions and Answers

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