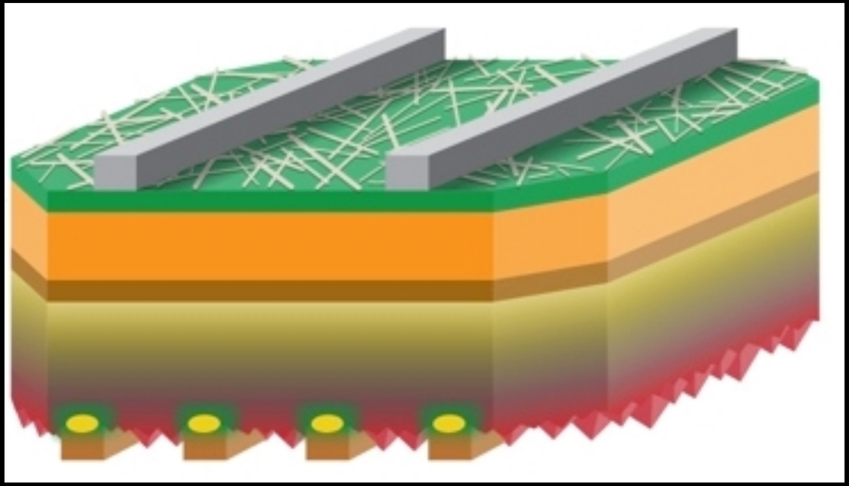
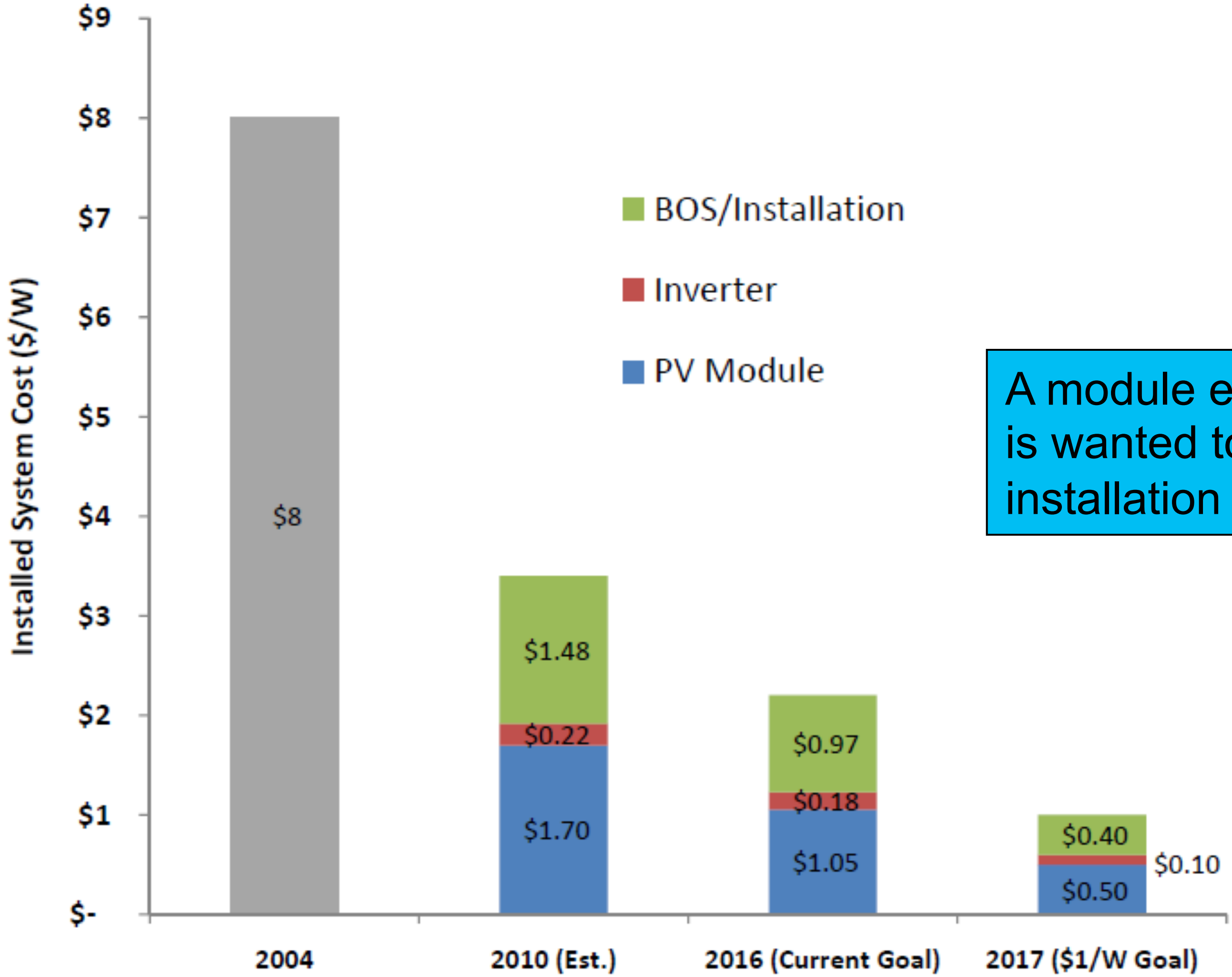
Emerging High-Efficiency Low-Cost Solar Cell Technologies



Mike McGehee

Materials Science and Engineering
Center for Advanced Molecular Photovoltaics
Bay Area Photovoltaic Consortium
Precourt Institute for Energy
Stanford University

DOE's Sunshot Goal: $1/W by 2017



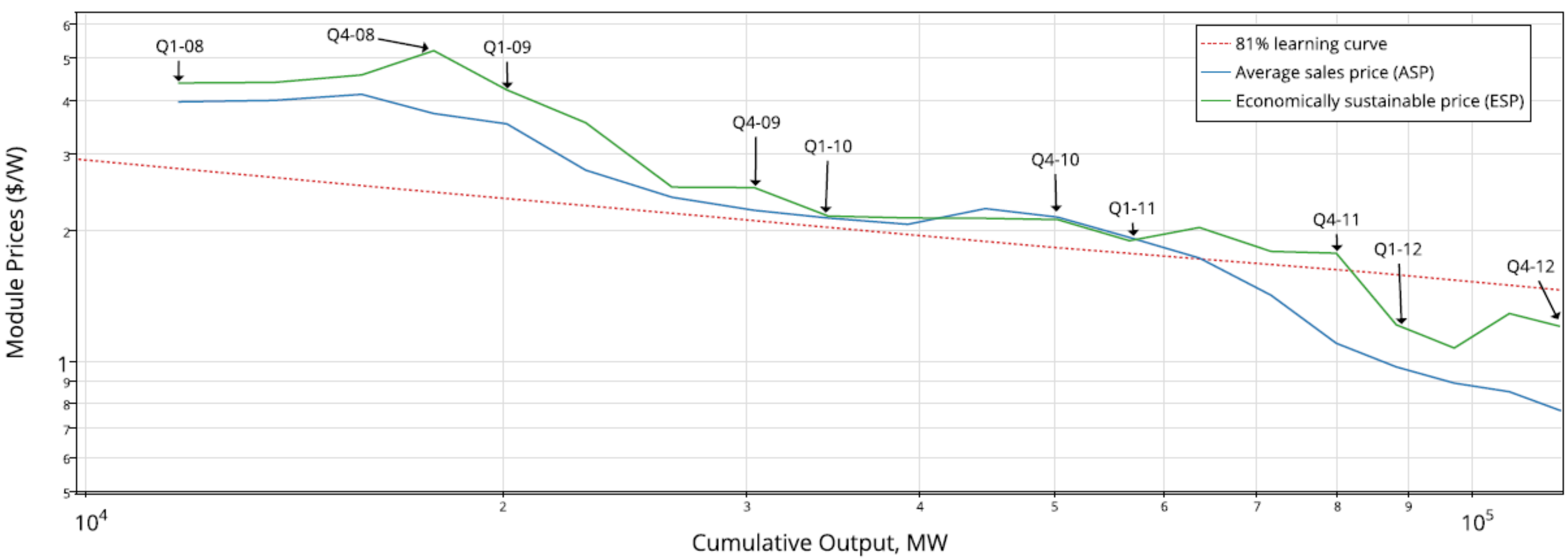
A module efficiency of 25 % is wanted to enable the installation cost reductions.

Source: US DOE report "$1/W Photovoltaic Systems," August 2010.

Last Week's Lecture by Anshu Sahoo and Stefan Reichelstein

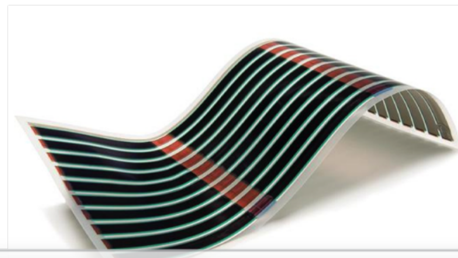
Silicon is currently competitive in favorable locations with the current subsidies.

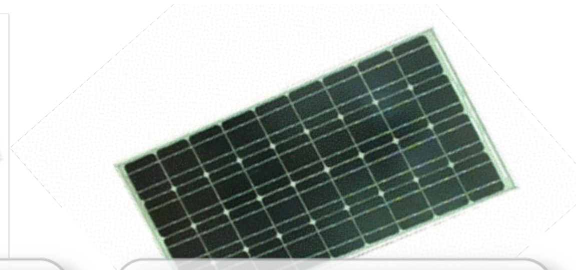
Average Sales Prices of Modules and Cumulative Module Output



In 2017 the cost of silicon cells will probably be $0.65/W.

There are many approaches to making PV cells and experts do not agree on which one is the best





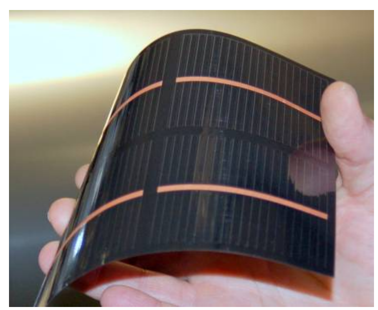
CPV — MARKET
- Ground Mounted
- Rooftop Mounted

Thin Films — MATERIAL
- Amorphous Silicon
- CdTe / CIGS
- Organic

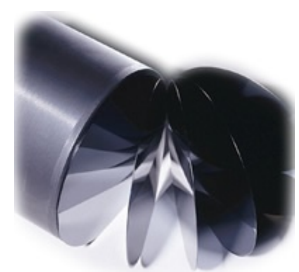
Crystalline Silicon — STRUCTURE
- Multi-Crystalline
- Mono-Crystalline

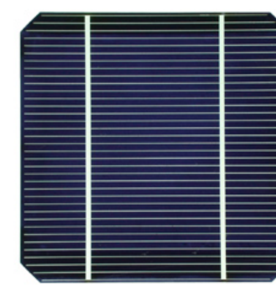
20x-100x

500x

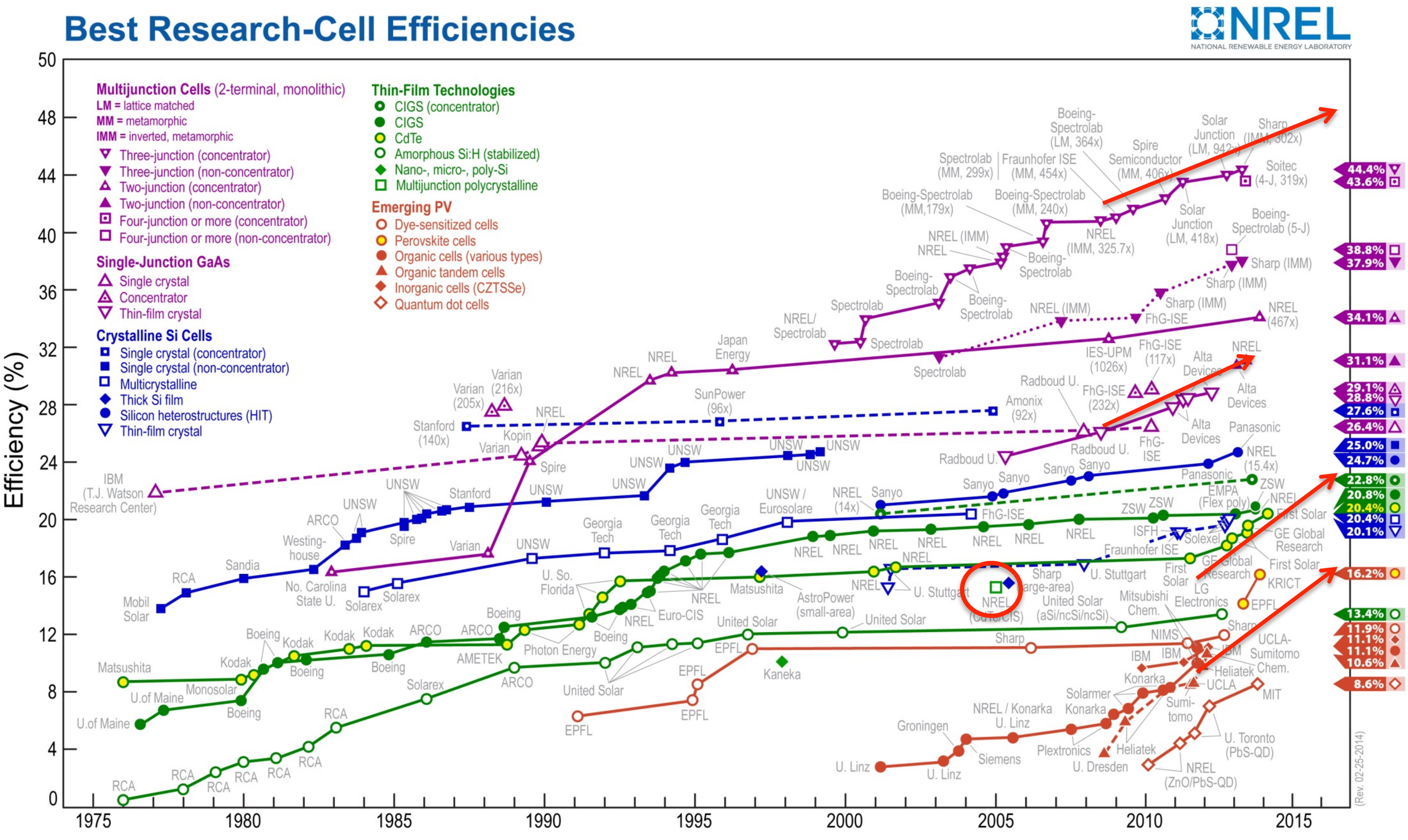


$Cu(In,Ga)Se_2$ ~ 1-2 um



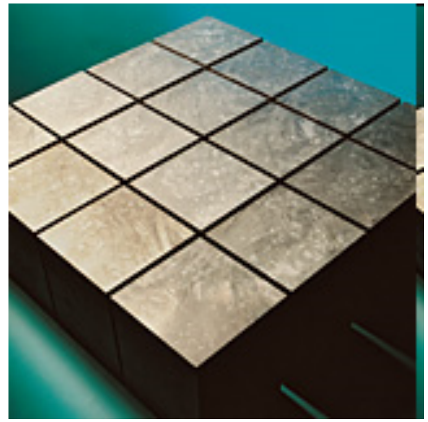
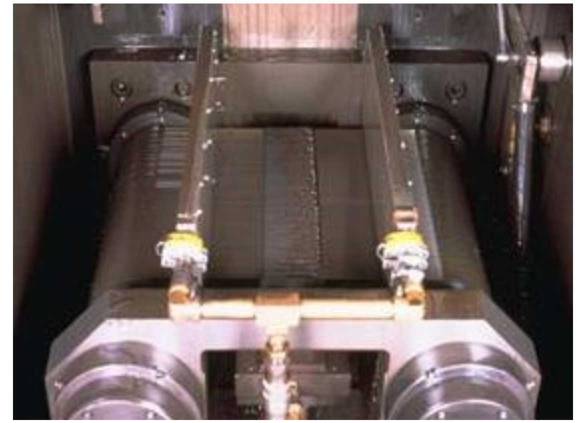


c-Si ~ 180 um



Efficiency Records Chart available at: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg. The chart above was downloaded on 2/27/2014.

Silicon PV

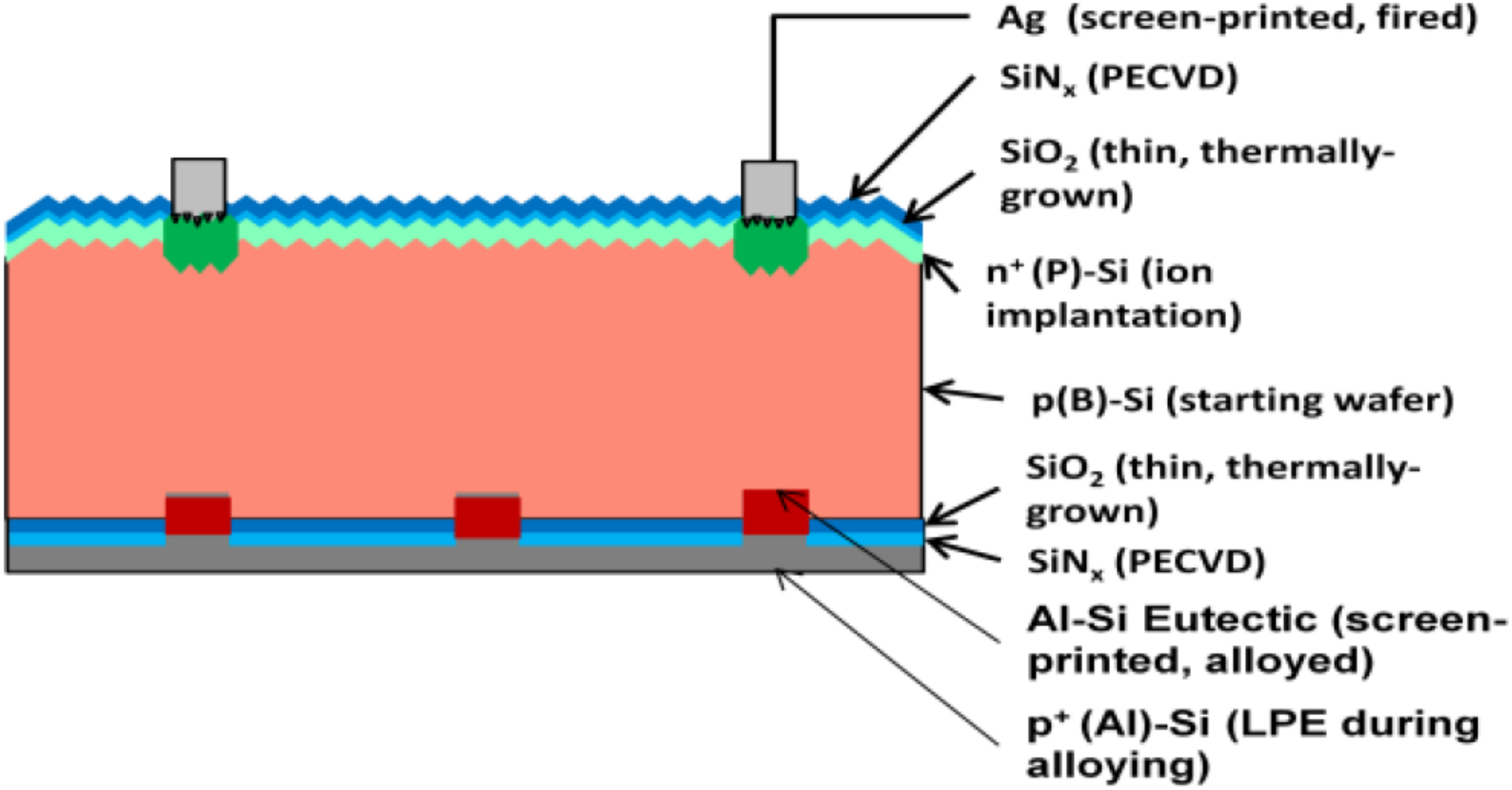




Silicon Feedstock → Ingot Growth → Slicing Wafers

Cell Fabrication → Module Encapsulation → Photovoltaic System

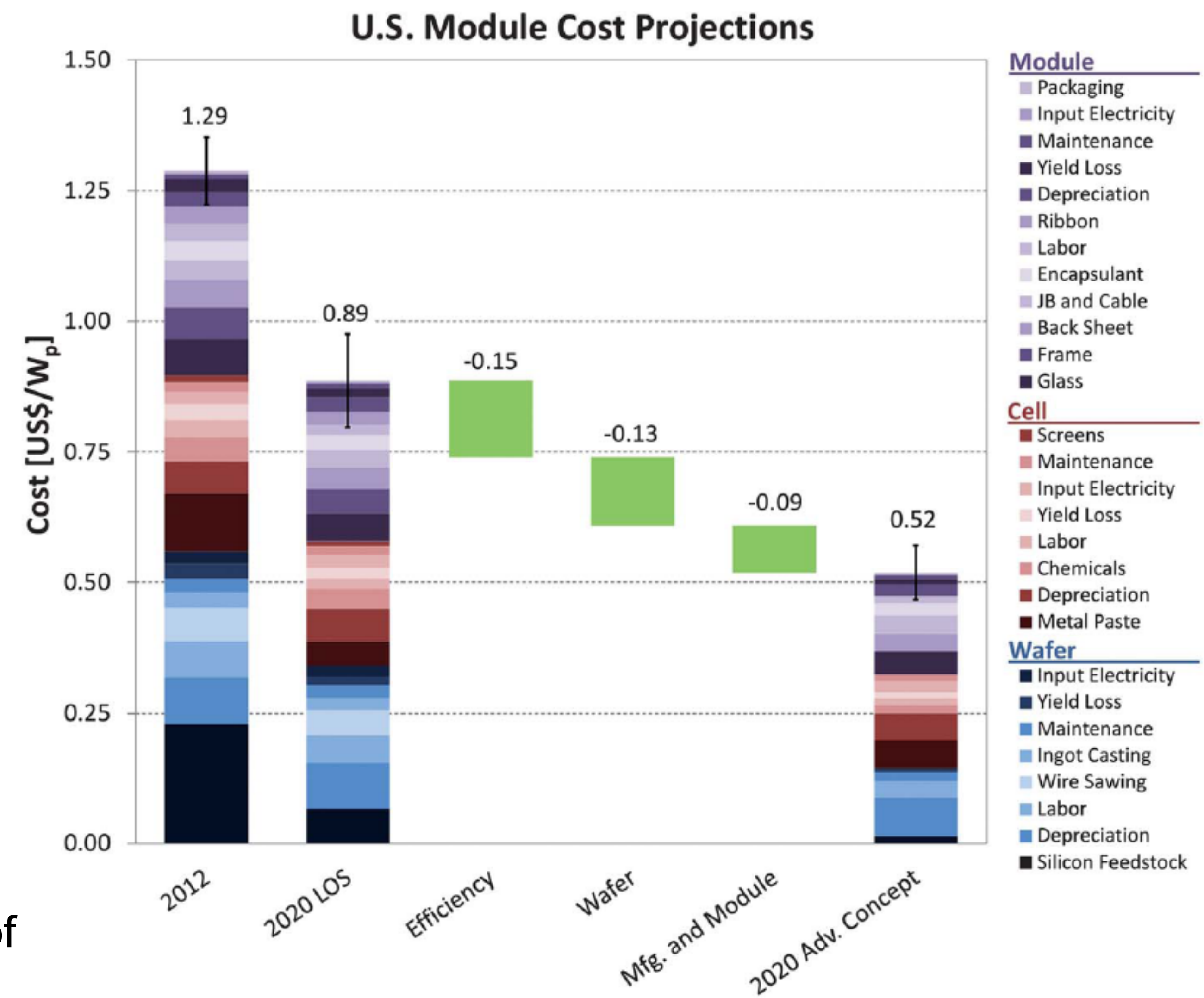


19.6% efficient planar cells on silicon



Source: J-H Lai, IEEE PVSC, June 2011

Cost analysis of Si Modules



LOS is line of sight

Tonio Buonassisi et al., *Energy and Env. Sci.* **5** (2012) p. 5874.

Table 2 Data table of cost analysis results as displayed in Fig. 2

	2012 Cost [US$/$W_p$]	2020 LOS Cost [US$/$W_p$]	2020 Adv. Concept Cost [US$/$W_p$]
Wafer			
Silicon feedstock	0.229	0.067	0.014
Depreciation	0.090	0.088	0.073
Labor	0.069	0.053	0.032
Wire sawing	0.064	0.049	0.000
Ingot casting	0.029	0.023	0.000
Maintenance	0.027	0.024	0.018
Yield loss	0.028	0.017	0.004
Input electricity	0.024	0.020	0.003
Cell			
Metal paste	0.111	0.047	0.054
Depreciation	0.063	0.061	0.051
Chemicals	0.045	0.039	0.017
Labor	0.034	0.020	0.013
Yield loss	0.030	0.020	0.011
Input electricity	0.024	0.026	0.021
Maintenance	0.018	0.016	0.013
Screens	0.013	0.010	0.000

Tonio Buonassisi et al., *Energy and Env. Sci.* **5** (2012) p. 5874.

Table 2 Data table of cost analysis results as displayed in Fig. 2

	2012 Cost [US$/$W_p$]	2020 LOS Cost [US$/$W_p$]	2020 Adv. Concept Cost [US$/$W_p$]
Module			
Glass	0.073	0.056	0.047
Frame	0.060	0.046	0.000
Back sheet	0.050	0.038	0.032
JB and cable	0.040	0.036	0.036
Encapsulant	0.039	0.030	0.025
Labor	0.034	0.020	0.013
Ribbon	0.032	0.025	0.000
Depreciation	0.028	0.028	0.023
Yield loss	0.025	0.017	0.010
Maintenance	0.009	0.008	0.007
Input electricity	0.003	0.004	0.003
Packaging	0.003	0.002	0.002
Total	**1.293**	**0.890**	**0.523**

Tonio Buonassisi et al., *Energy and Env. Sci.* **5** (2012) p. 5874.

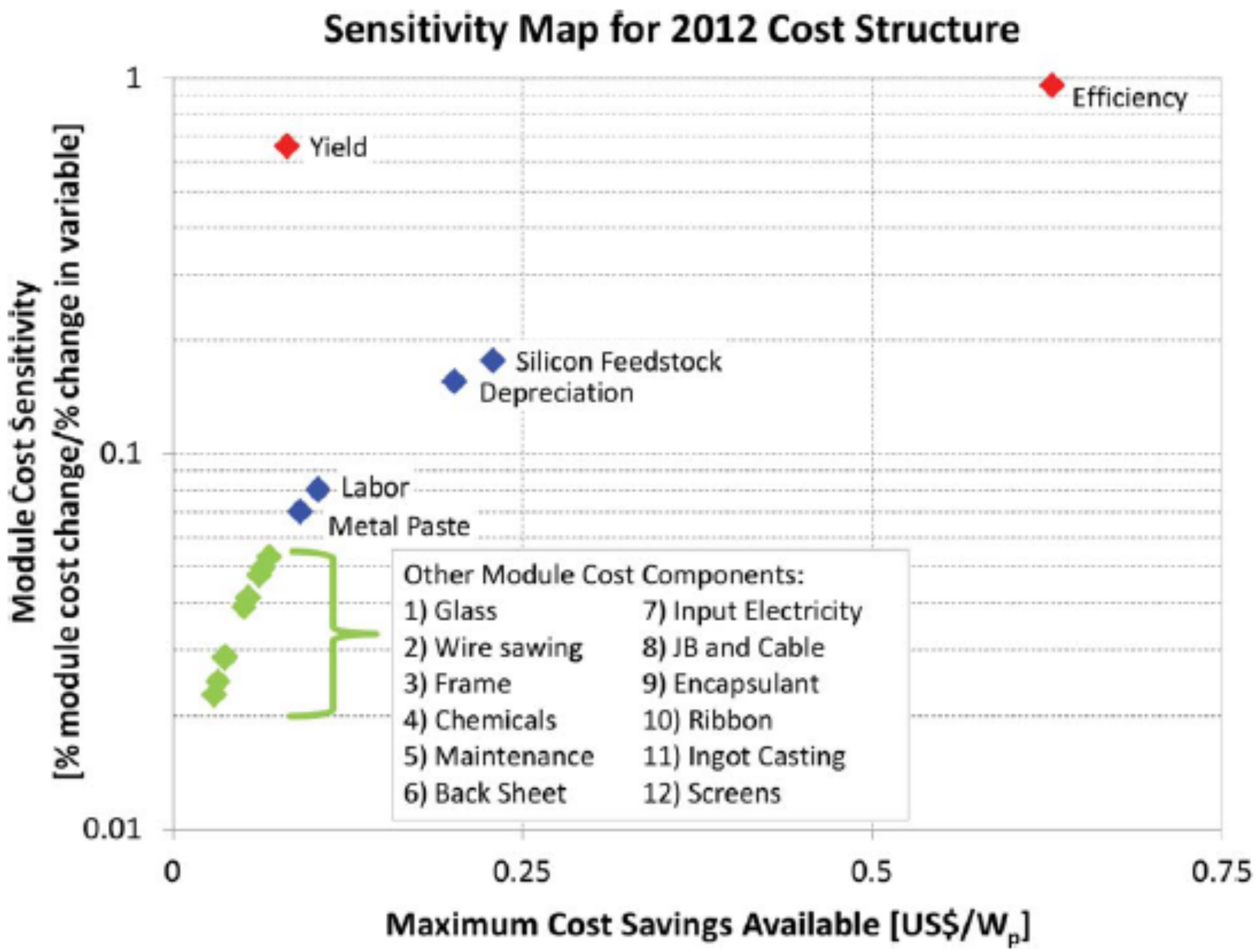


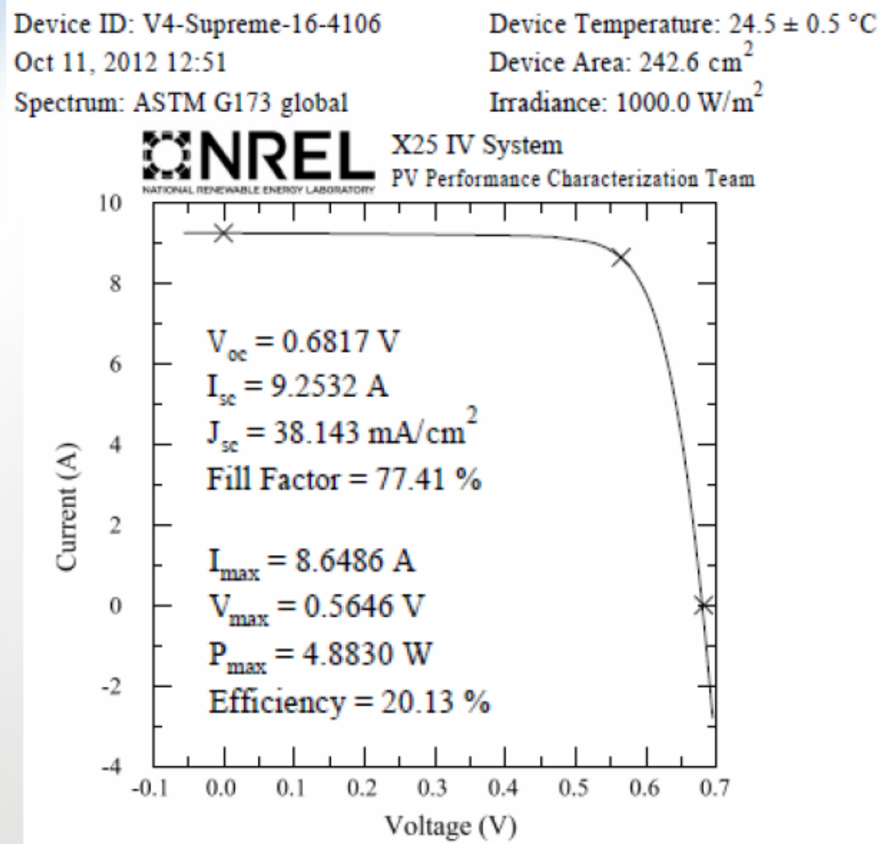
Fig. 3 Sensitivity study for the 2012 module cost structure. Input variables that strongly determine module cost are shown toward the top of the plot, while variables that have a large cost reduction potential are shown toward the right.

Tonio Buonassisi et al., *Energy and Env. Sci.* **5** (2012) p. 5874.

World Record 156 mm x 156 mm Full-Square Cell Efficiency Using 43 µm Epitaxial Silicon Cell Absorber

SOLEXEL

NREL-Certified Full-Area Cell Efficiency = 20.13%

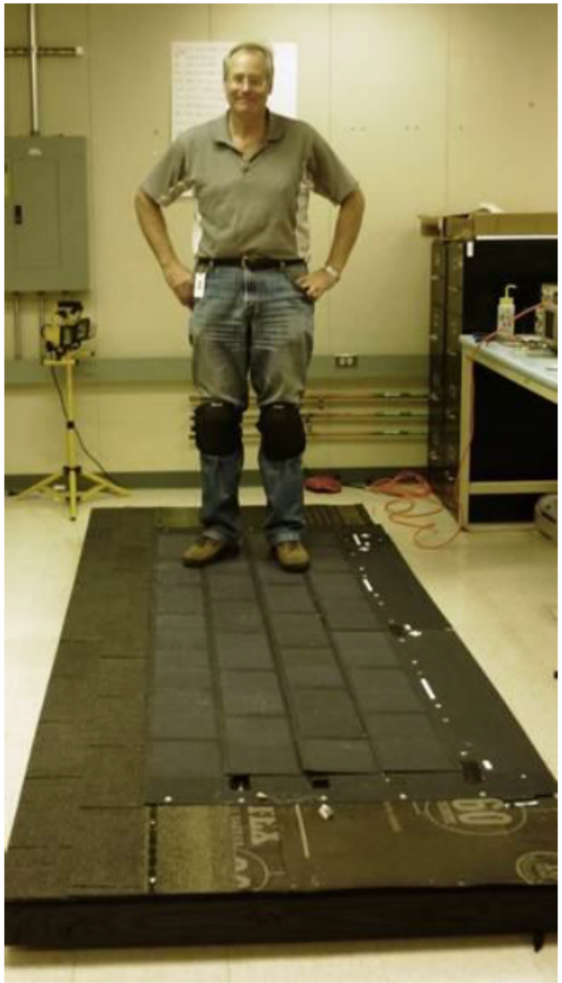


- $156 \times 156\ mm^2$ full-square cell ($242.6\ cm^2$)
- 43 µm epitaxial Si cell, FSRV < 10 cm/s
- Voc = 681.7 mV
- Jsc = $38.14\ mA/cm^2$
- FF = 77.41%
- Cell Max Power = 4.88 Wp; I_{sc} = 9.25 A

Lightweight, Thin, Simple BIPV Shingle Packaging

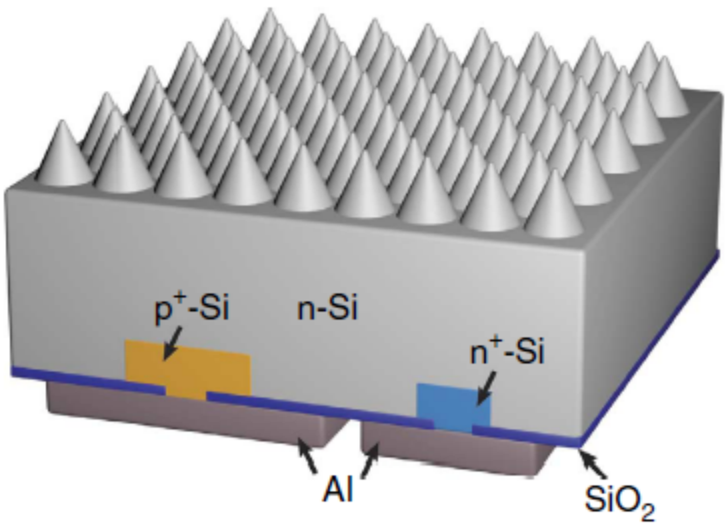
SOLEXEL

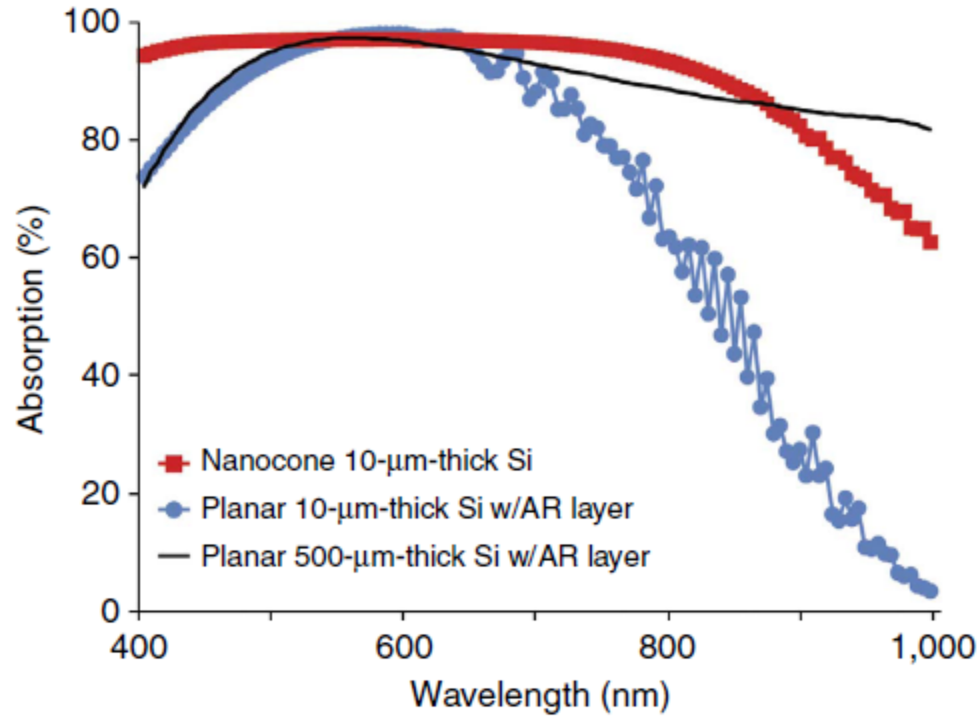
- Capability of supporting walking



- Lightweight BIPV solution:
  - 7 kg/m^2 for BIPV shingle demo system
  - BIPV is < half the weight of typical framed glass-covered modules
  - 2/3 the weight of asphalt shingles
  - Distributed shade management
- Simple, flat box packaging for shipment and storage

Using nanocones to enable complete light absorption in thin Si

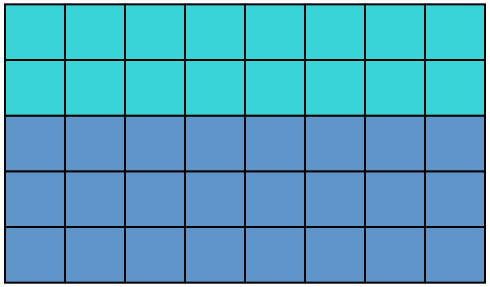


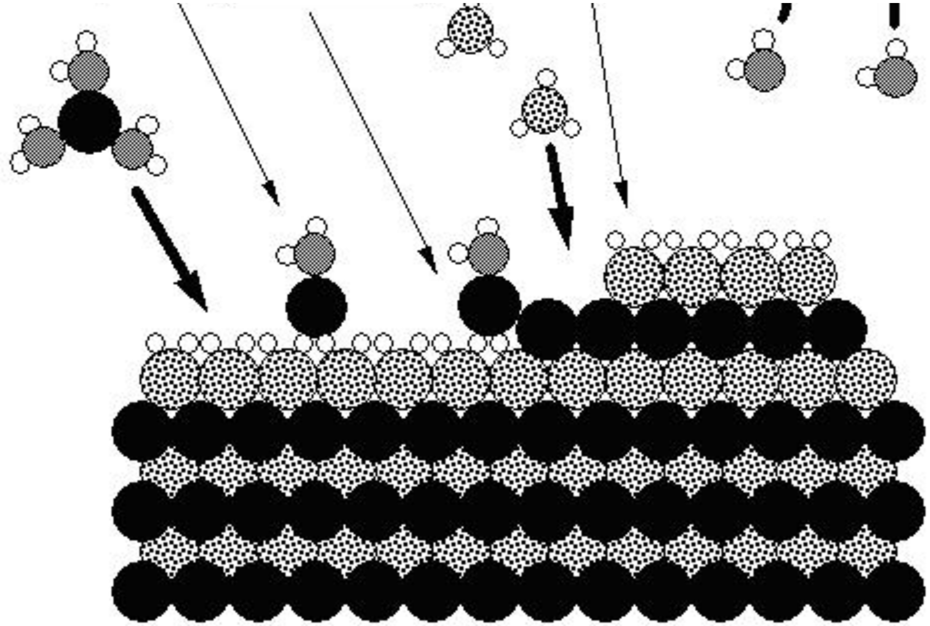


Sangmoo Jeung, Mike McGehee, Yi Cui, *Nature Comm*. in press.

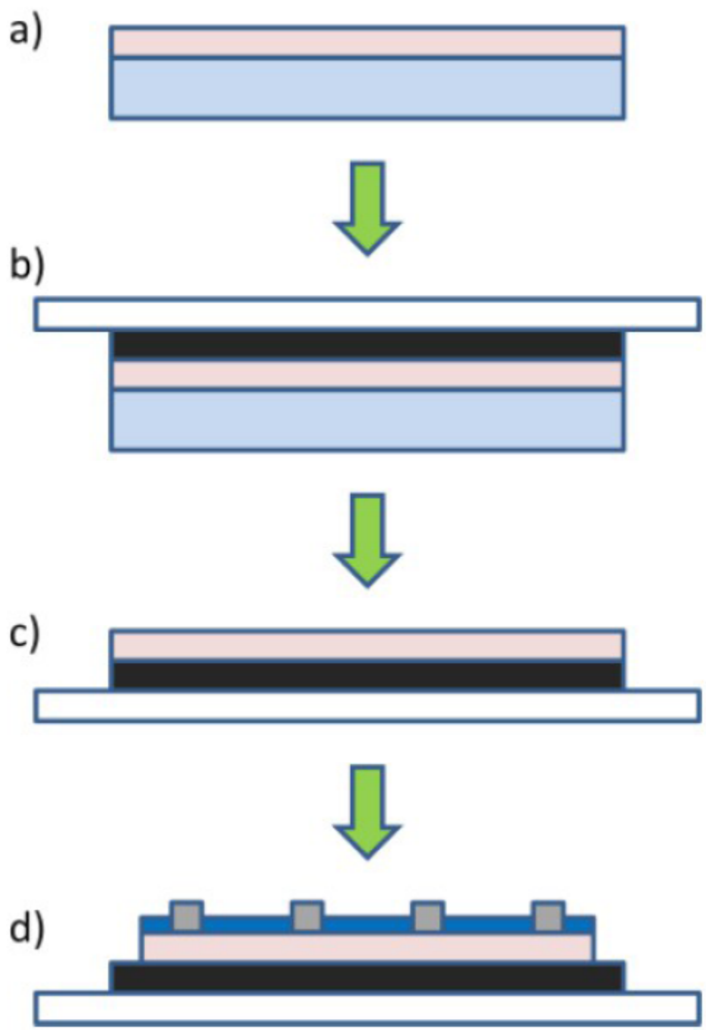
Gallium Arsenide

- The 1.4 eV band gap is ideal for solar cells.
- High quality films are grown on single crystal substrates with MOCVD.





Alta Devices 28.8% efficient thin-film GaAs cell



a) MOCVD growth of device structure on reusable GaAs substrate.

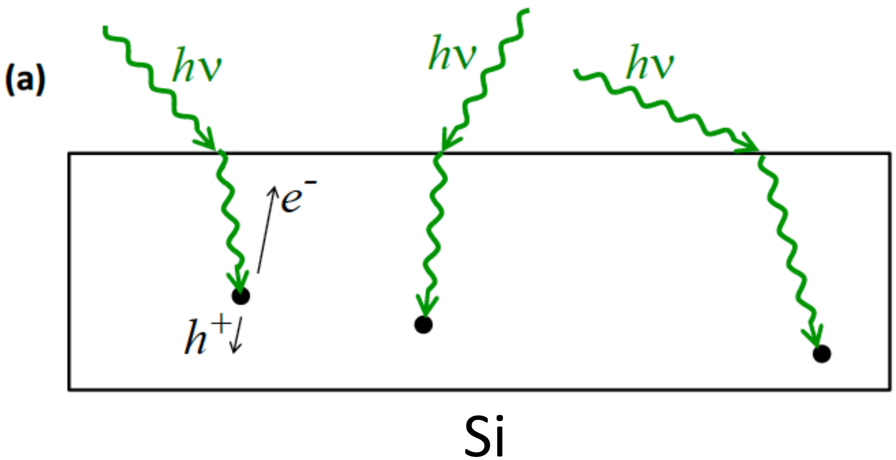
b) Deposition of back contact metals and bonding of sample to flexible handle.

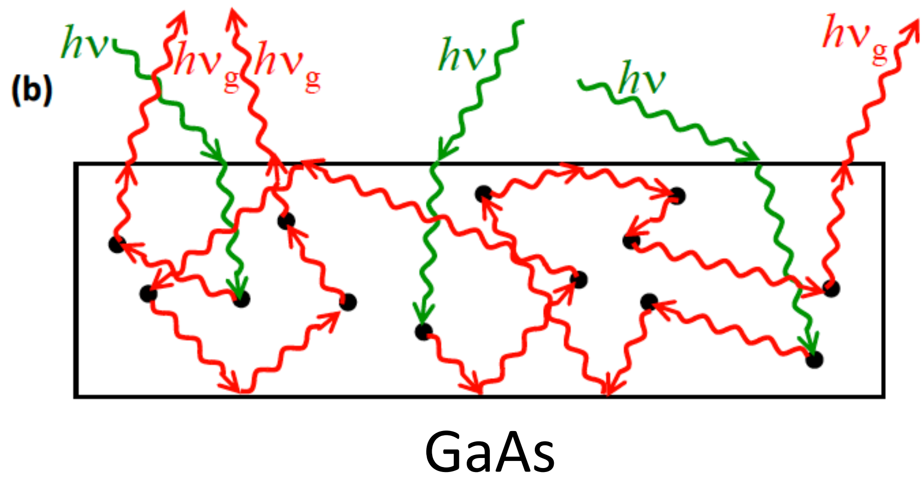
c) Dissolution of AlAs release layer to produce thin-film device on metal and flexible backing.

d) Completion of device fabrication.

Source: B. Kayes, IEEE PVSC, June 2011

Photon recycling

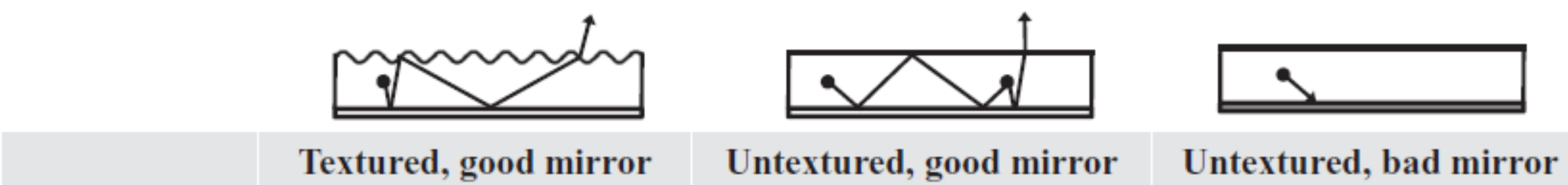




Eli Yablonovitch et *al., IEEE J. of Photovoltaics*, 2 (2012) p. 303.

Why thin film GaAs is better

- Remitted photons are weakly absorbed and can easily travel more than a carrier diffusion length away from the junction in a wafer-based device.
- In a thin cell, a mirror keeps photons near the pn junction.



Eli Yablonovitch et *al., IEEE J. of Photovoltaics*, 2 (2012) p. 303.

Theoretical limits

TABLE I

V_{OC}, J_{SC}, AND EFFICIENCY VALUES FOR THREE POSSIBLE GEOMETRIES AND RELEVANT CELL THICKNESSES

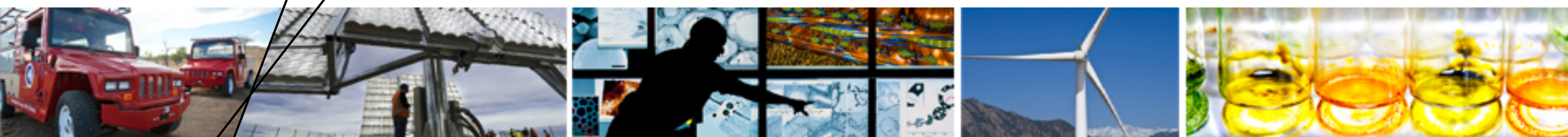


	Textured, good mirror			Untextured, good mirror			Untextured, bad mirror		
Thickness	500nm	1μm	10μm	500nm	1μm	10μm	500nm	1μm	10μm
Voc (volts)	1.14	1.13	1.12	1.16	1.15	1.14	1.08	1.08	1.07
Jsc (mA/cm^2)	32.3	32.7	33.5	29.5	31.6	32.8	25.2	29.5	32.6
Fill Factor	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
efficiency %	32.8	33.1	33.4	30.6	32.6	33.3	24.3	28.3	30.9

A good rear mirror is crucial to a high open-circuit voltage and, consequently, to efficiencies above 30%.

Eli Yablonovitch et *al., IEEE J. of Photovoltaics*, 2 (2012) p. 303.

A Manufacturing Cost Analysis Relevant to Photovoltaic Cells Fabricated with III-Vs



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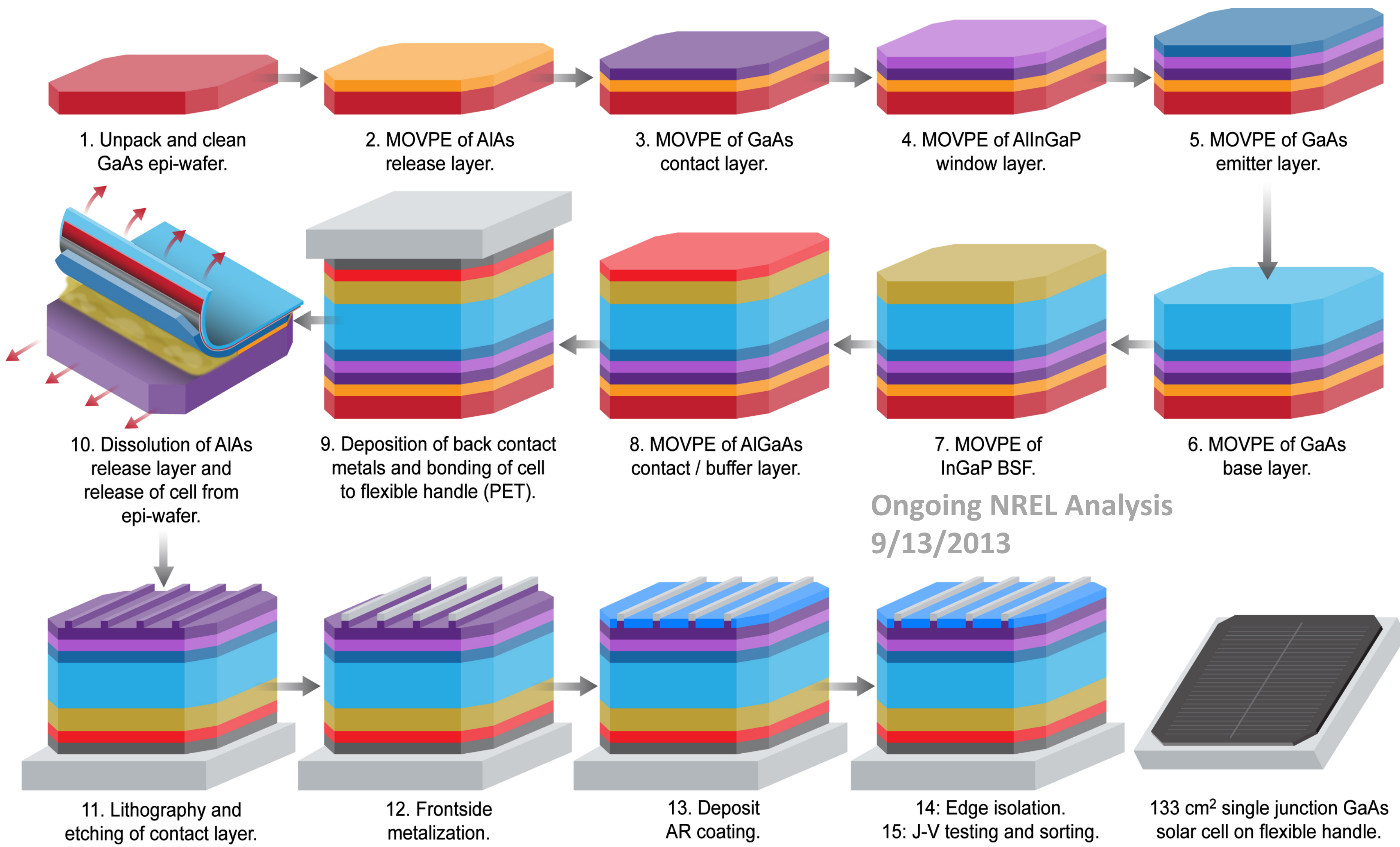
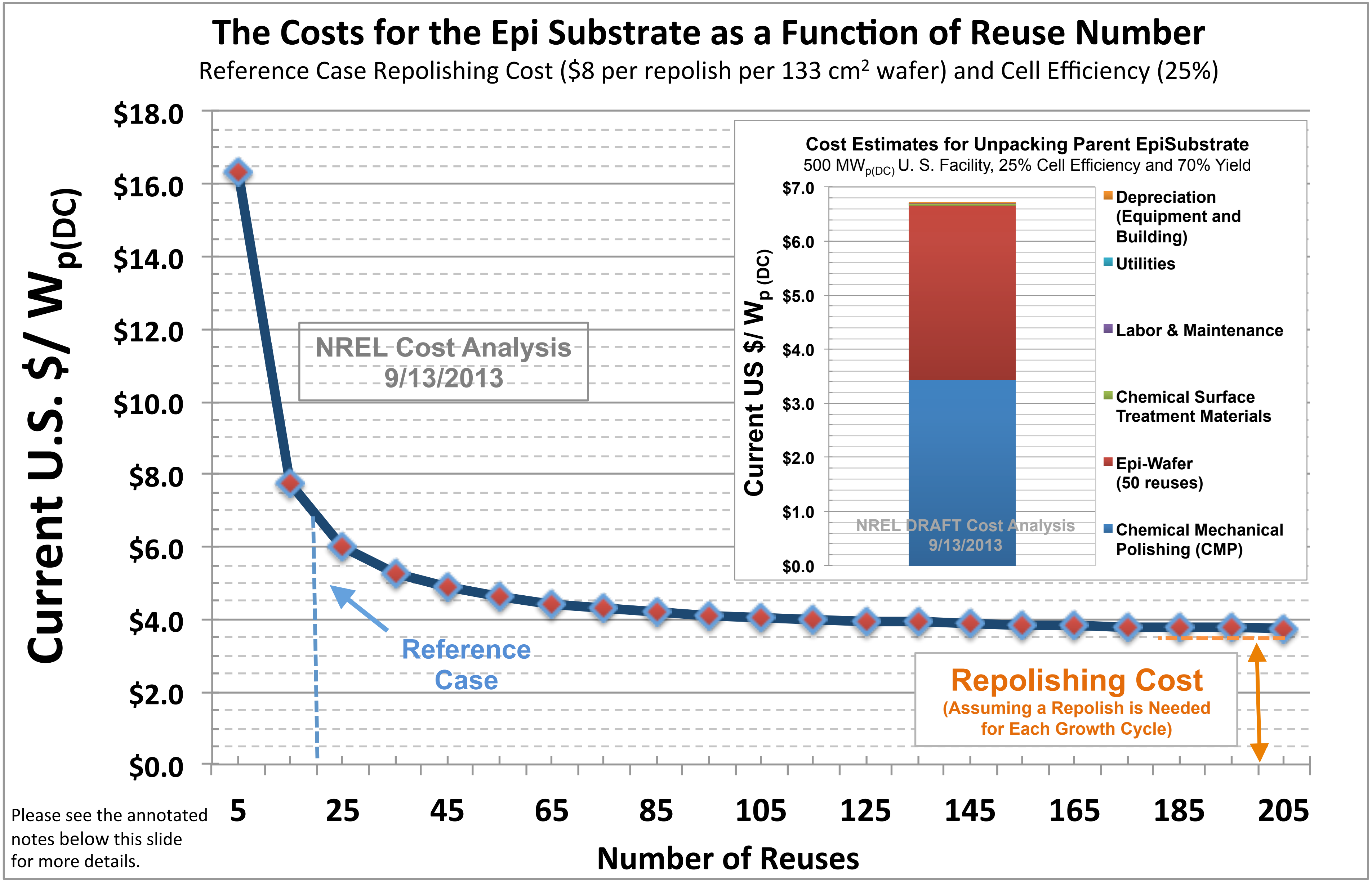
NREL/PR-6A20-60126
Contract Number:
NREL: DE-AC36-08GO28308

An Example Process Flow for Making Single-Junction III-V Devices by ELO



Step 1: Unpack and Clean GaAs Parent Epi-Substrate—3

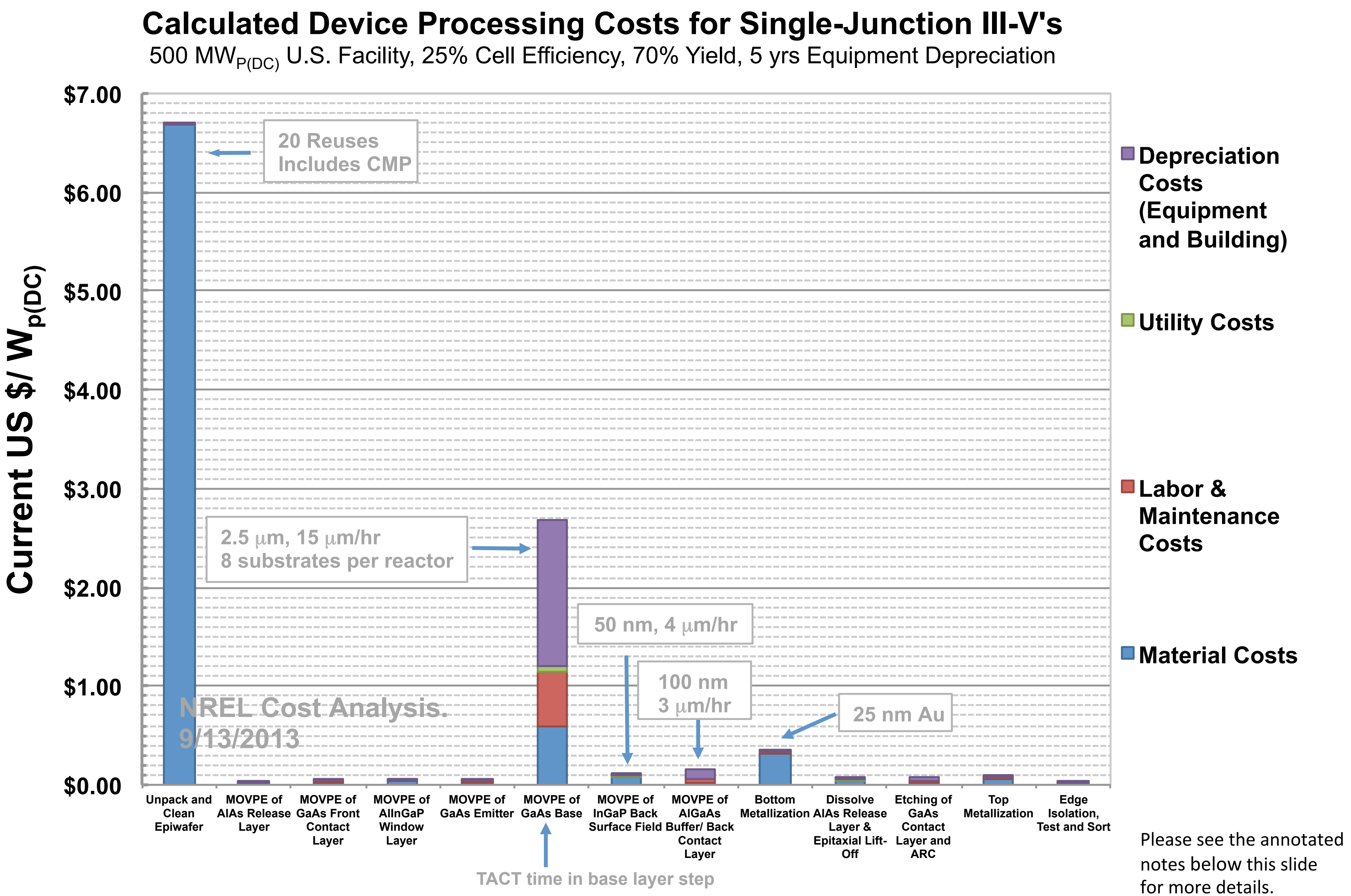
(The Reference Case Scenario in the Bar Chart Assumes 50 Reuses and 70% Yields)



Please see the annotated notes below this slide for more details.

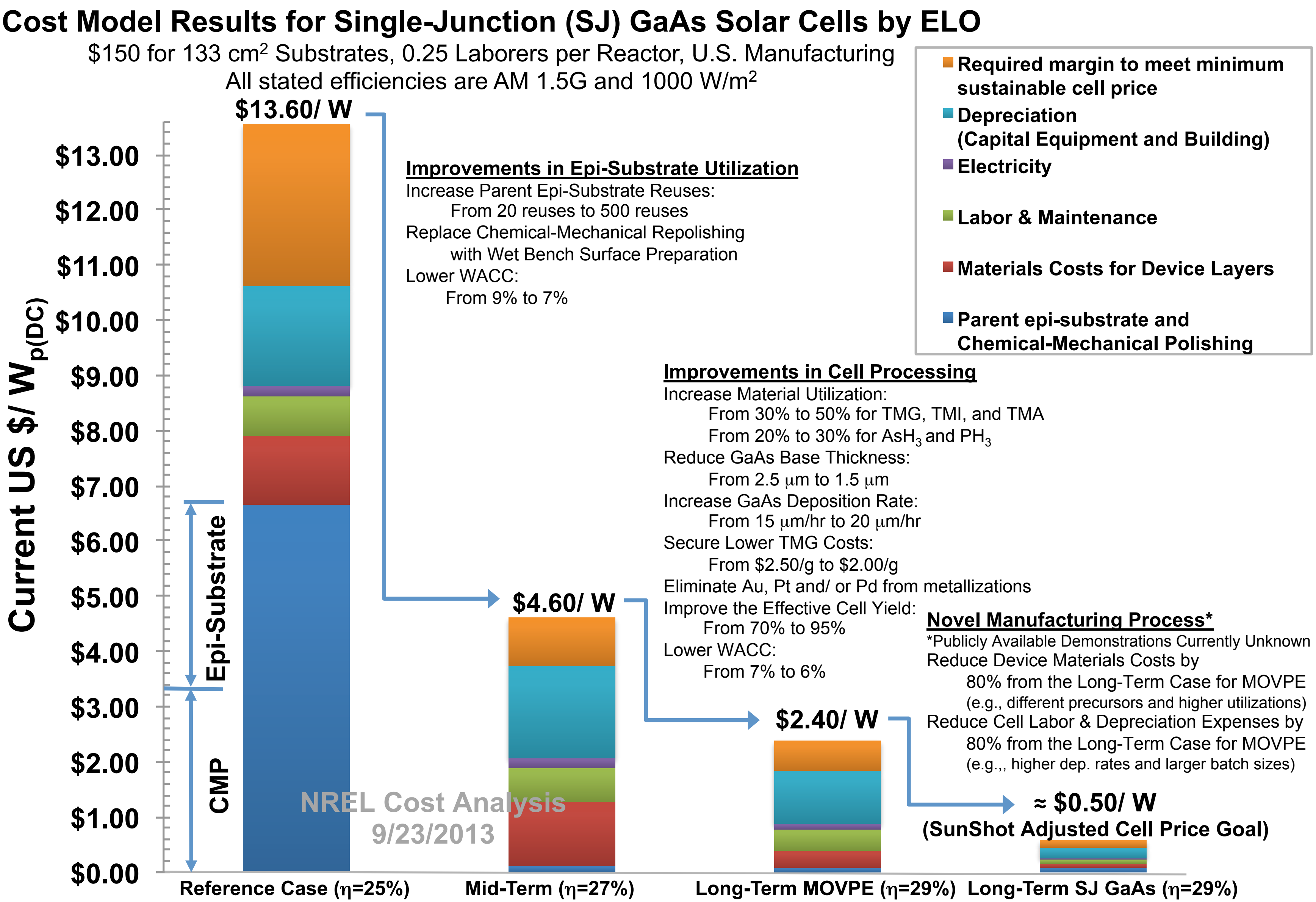
Cost Summary, by Step, for the Reference Case.

(20 substrate reusages, precursor utilizations of 30% for the III- source and 20% for the V- source, 15 μm/hr GaAs, 70% effective cell yield)

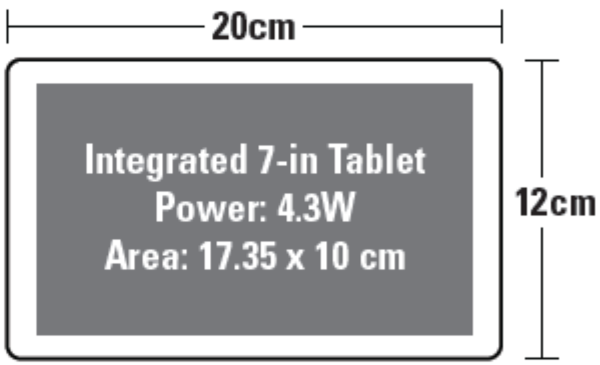


Please see the annotated notes below this slide for more details.

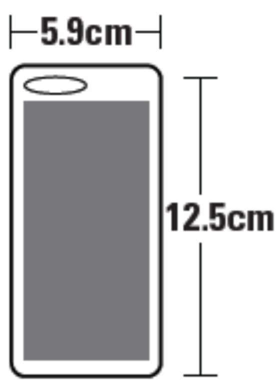
Technology Roadmap Simulations for Single-Junction III-V's (GaAs Base)



Sample Products



Smartphone Case
Power: 1.3W
Area: 5 x 10.5 cm

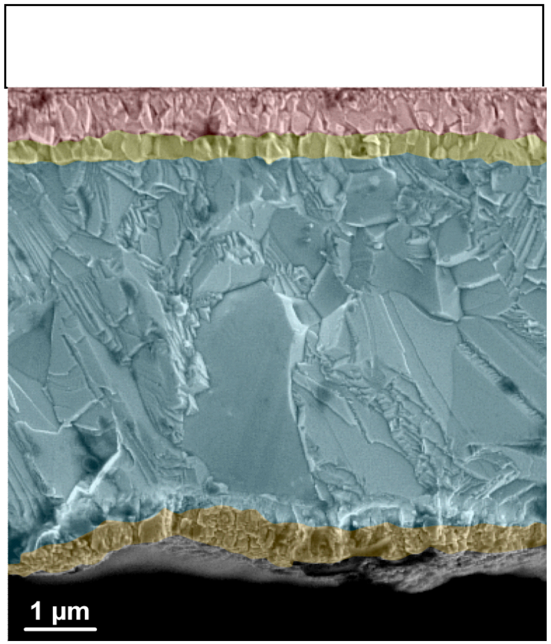


Tablet and Smartphone Cases

What can be done to bring the costs down?

- Huge breakthrough in reducing materials deposition cost.
- Light trapping to reduce film thickness. See Jim Harris's 2013 GCEP talk at http://gcep.stanford.edu/symposium.
- Use concentrators. With epitaxial liftoff, 500 X concentrators might not be necessary. Trackers for 10 X concentrators are relatively cheap.

Cadmium Telluride Solar Cells



CdS/CdTe

- Direct bandgap, E_g=1.45eV
- High module production speed
- Very inexpensive
- 20.4 % efficiency

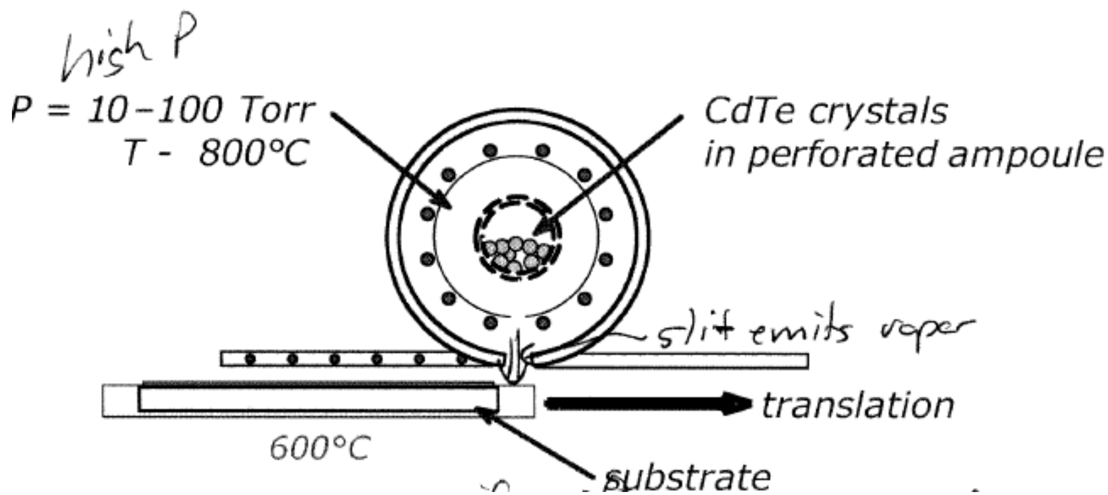
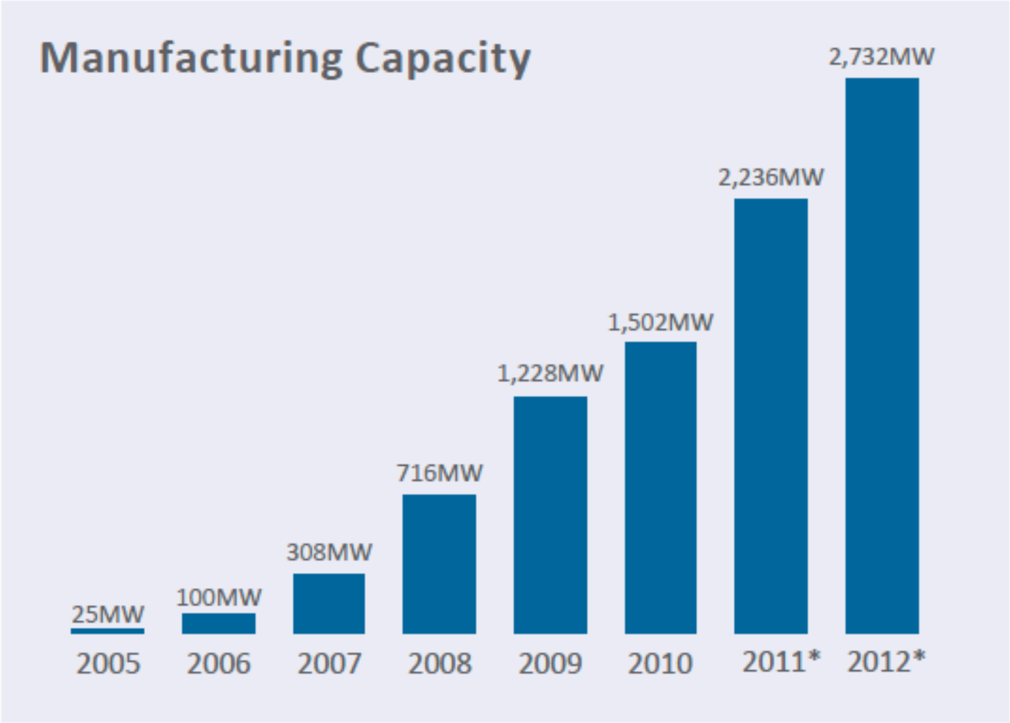


Image from Rommel Noufi
Schematic from Bulent Basol

CdTe: Industrial Status

First Solar is the leader. It takes them 2.5 hours to make a 13.4 % module.



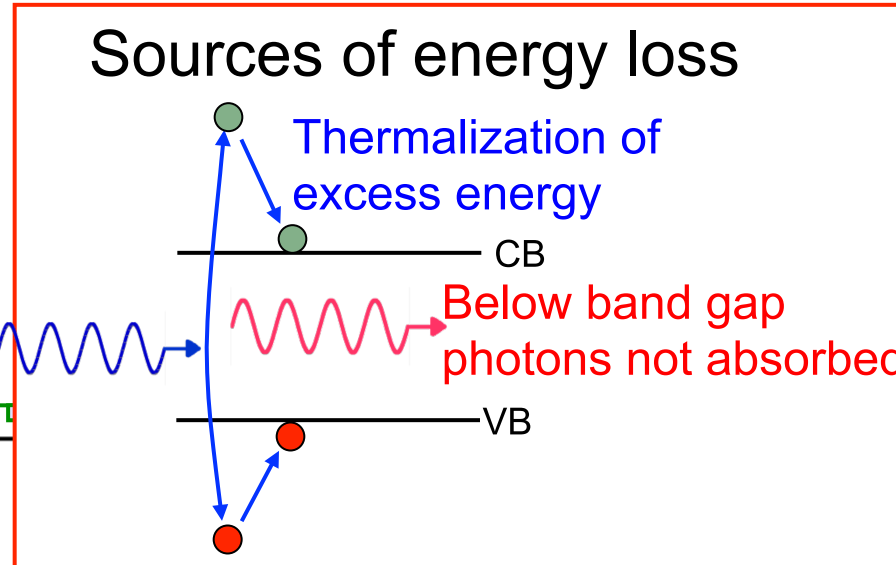
The energy payback time is 0.8 years.

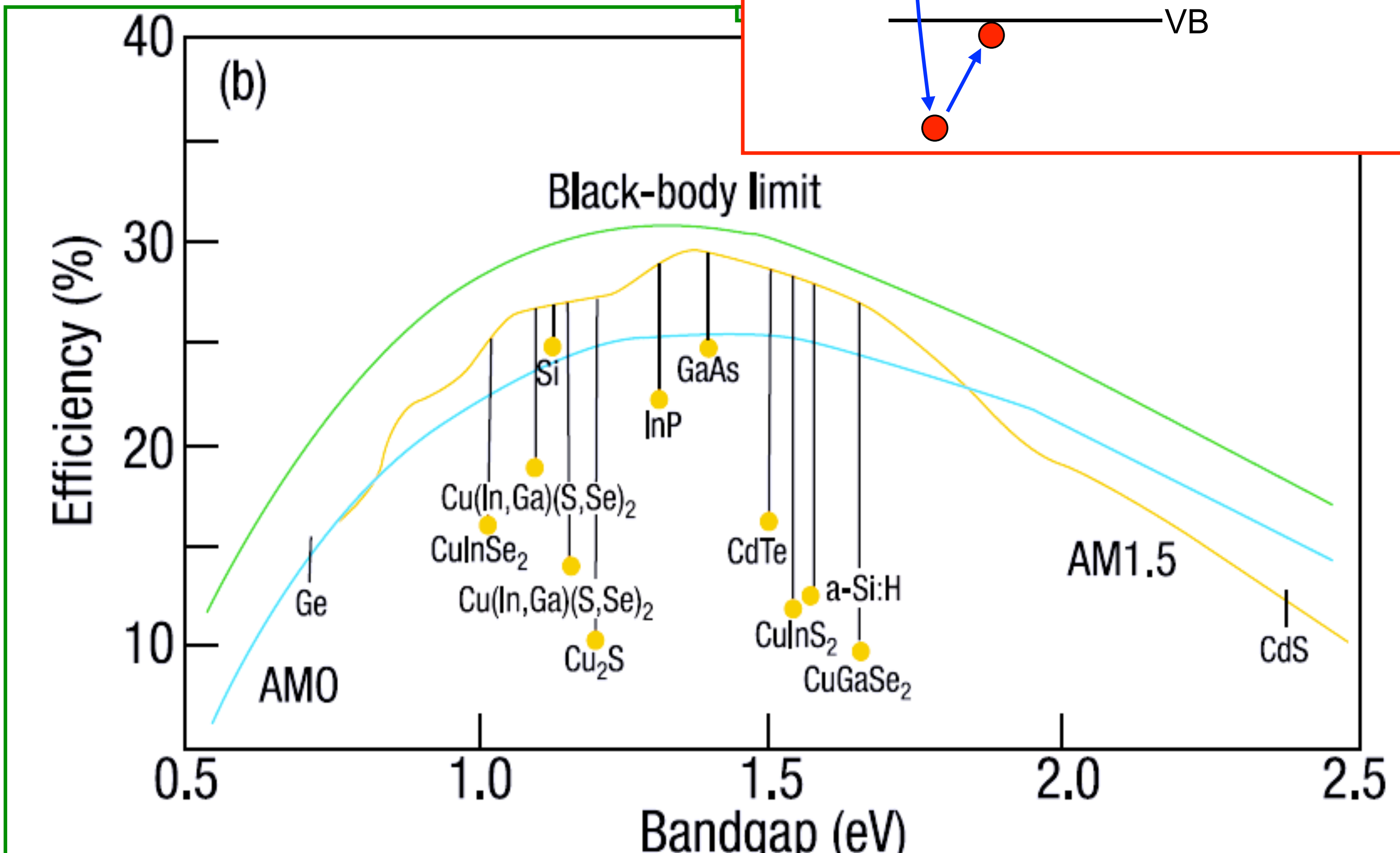
Average Manufacturing Cost

2006: $1.40/watt
2007: $1.23/watt
2008: $1.08/watt
2009: $0.87/watt
2010: $0.77/watt
2011: $0.74/watt
2012: $0.64/watt
2013: $0.53/watt

www.firstsolar.com; greentech media

Efficiency limits





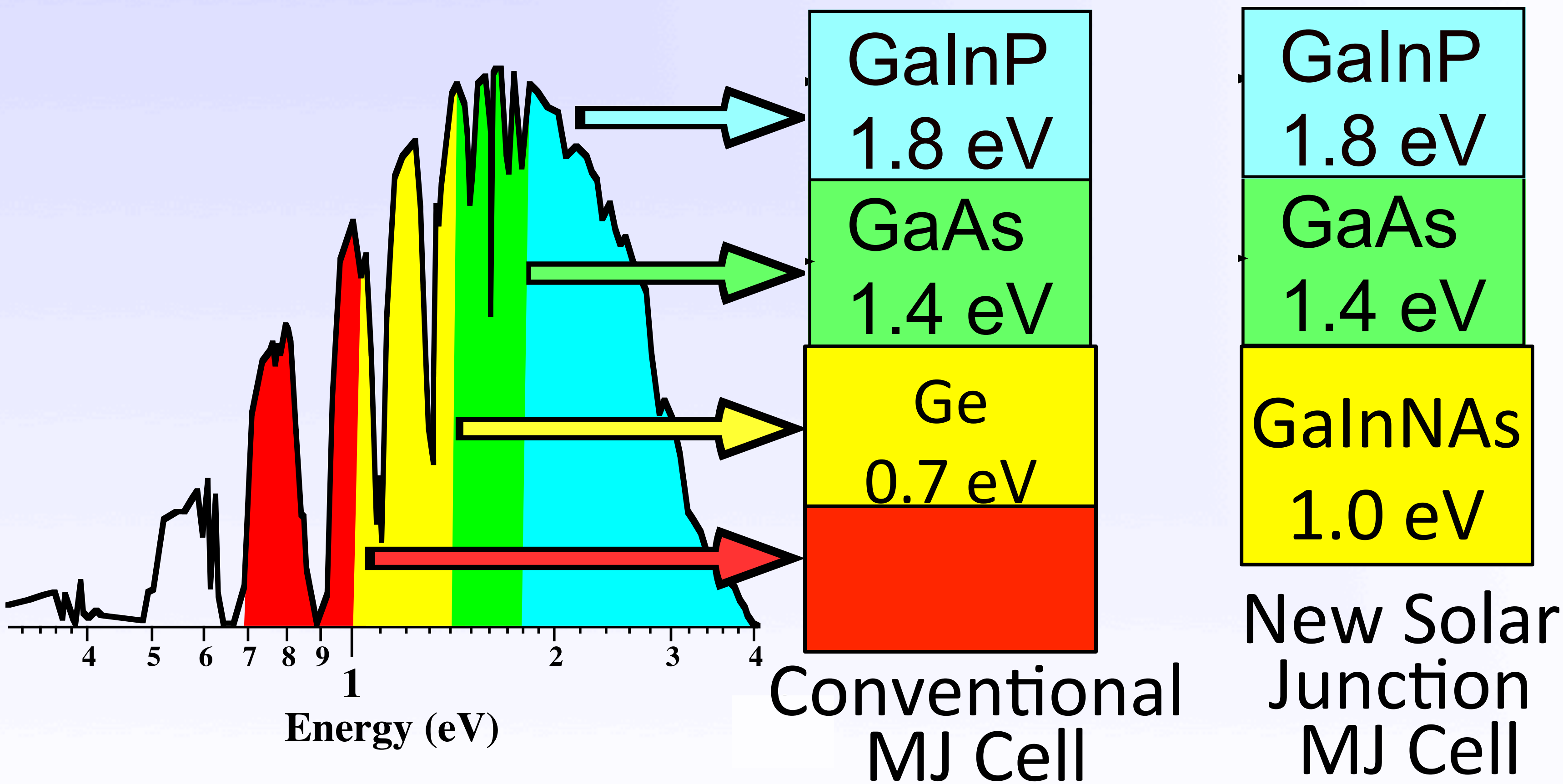
Increasing V_{OC} and decreasing J_{SC} →

There are lots of 3rd Generation ideas to beat the Shockley-Quiesser limit, but only one that works.

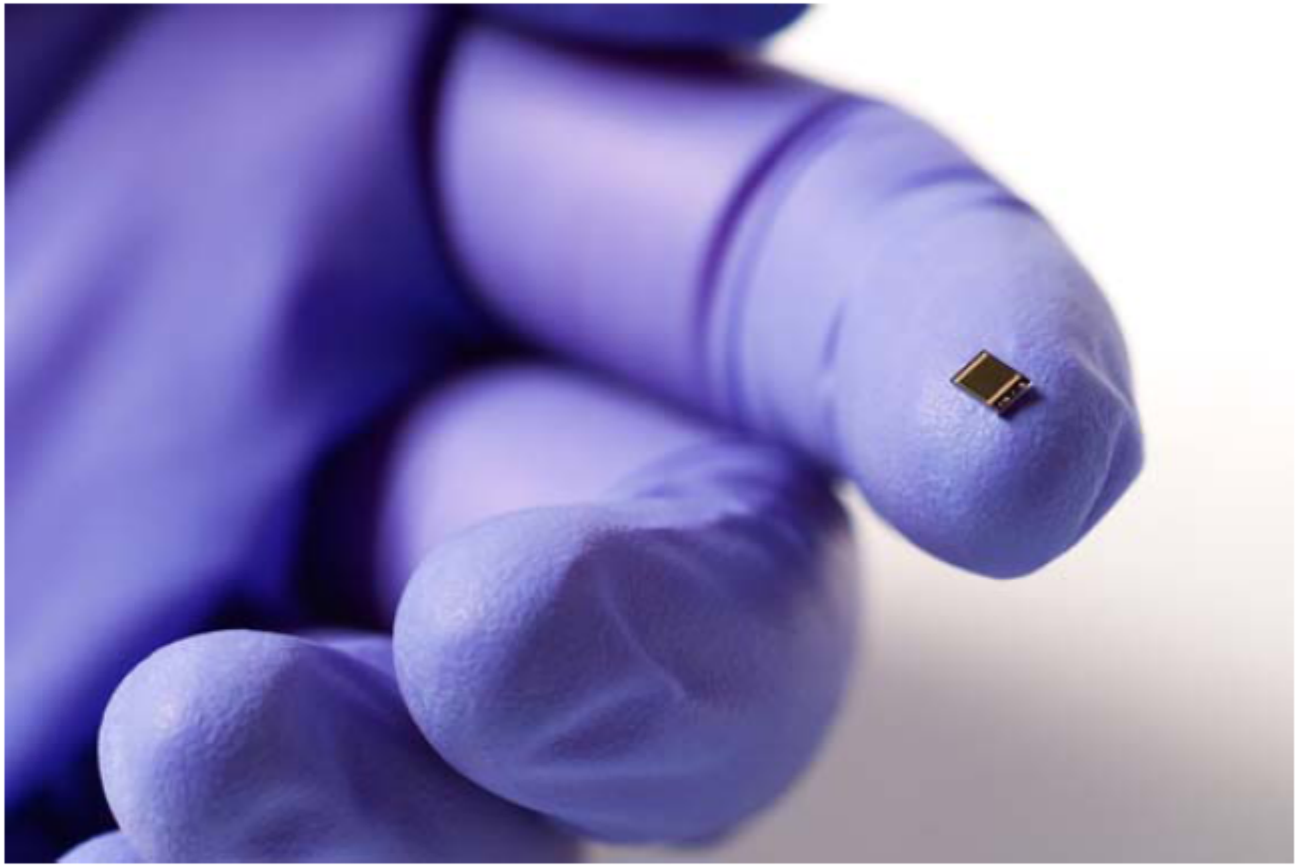
Multijunctions: The Road to Higher Efficiencies

Higher-efficiency MJ cells require new materials that divide the solar spectrum equally to provide current match

Ge provides lattice match but the bandgap is too small



4-junction cell with 44.7 % efficiency at 297 suns



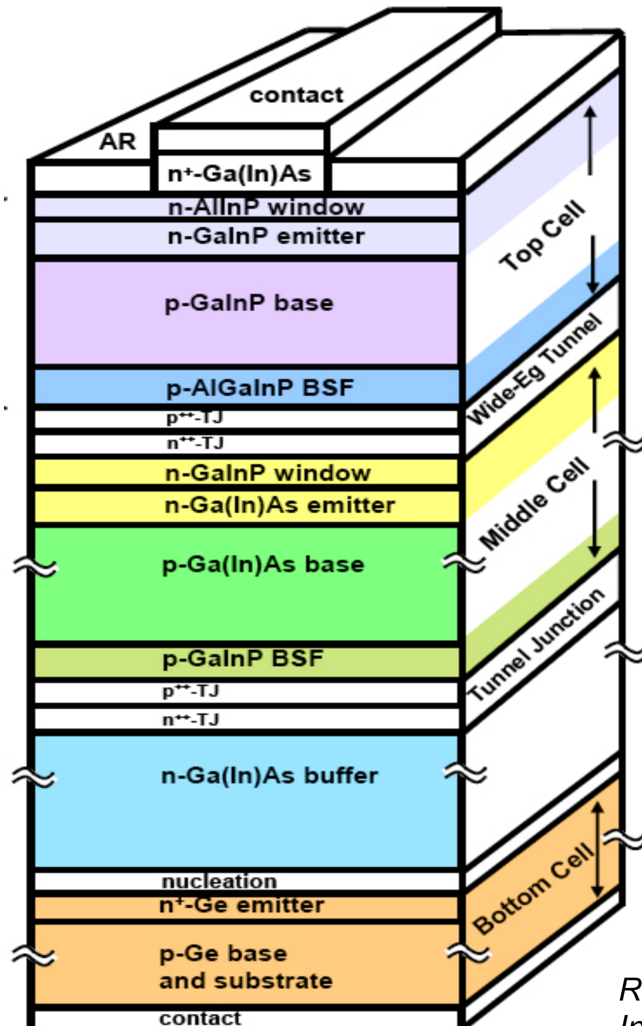
World record solar cell with 44.7% efficiency, made up of four solar subcells based on III-V compound semiconductors for use in concentrator photovoltaics.

Multijunction Cells are Very Expensive

$Ga_{0.50}In_{0.50}P$: Top Cell

$Ga_{0.99}In_{0.01}As$: Middle Cell

Ge substrate: Bottom Cell



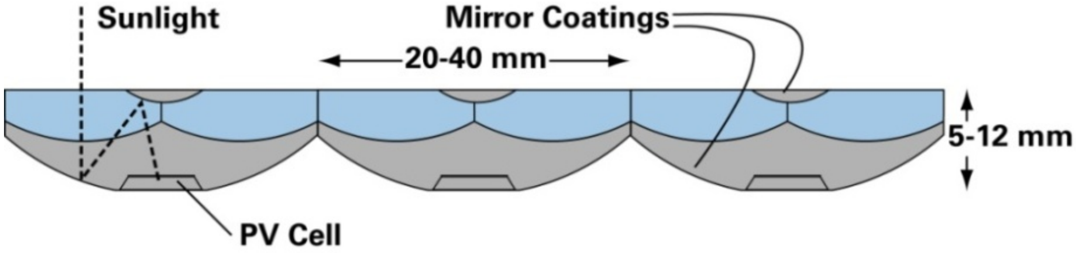
- These complex structures are grown very slowly under high vacuum.
- 37 % cells can be purchased for $50,000/ m^2
- Concentrating the light is essential.

R.R. King; Spectrolab Inc., AVS 54th International Symposium, Seattle 2007

Concentrating Light

It is possible to track the sun and concentrate the light by 500X

Dish Shape



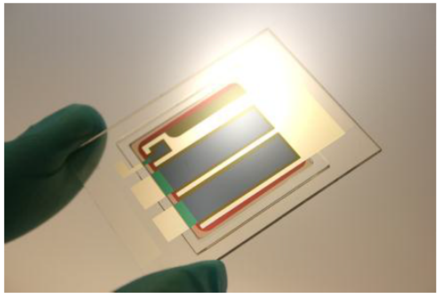
Sol Focus

Hybrid Tandems Are Intended to be a High-Performance Low-Cost Option

Efficiency

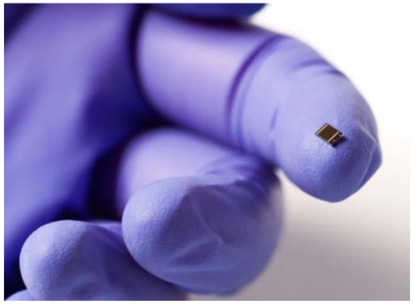
Cost

Organic	Hybrid	Epitaxial Crystalline
12% efficient $30/m^2	30% efficient $100/m^2	45 % efficient $40,000/m^2



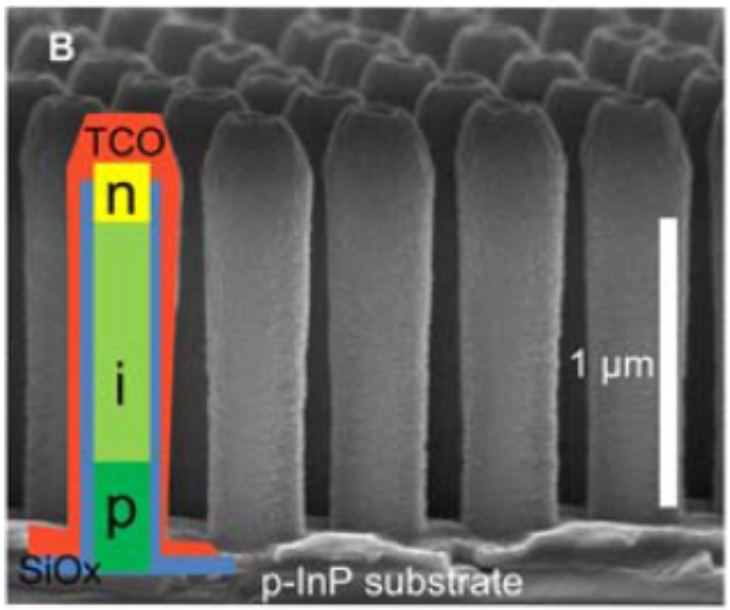
Low Cost Defect-Tolerant Technology: Perovskite, Organic, Nanowires or II-VI
E_g ~ 1.9 eV

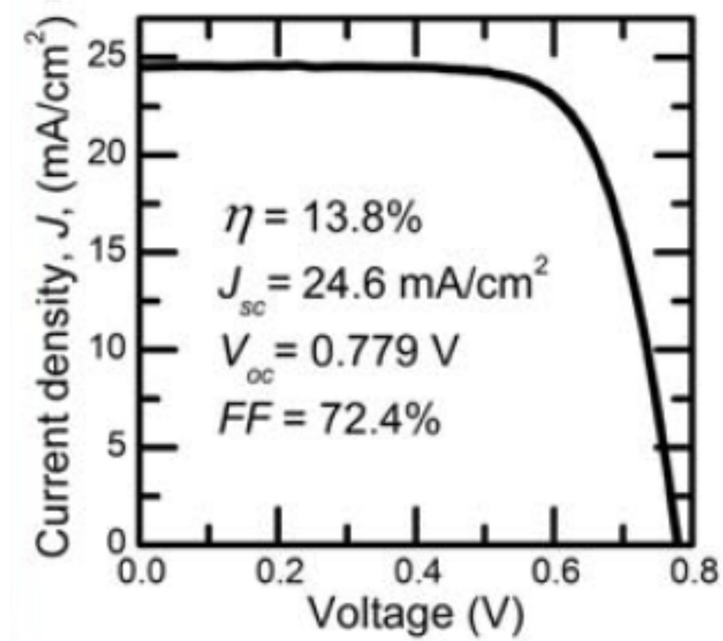
Established Technology: Silicon or CIGS
E_g ~ 1.1 eV



InP Nanowire Array Solar Cells Achieving 13.8% Efficiency by Exceeding the Ray Optics Limit

Jesper Wallentin,[1] Nicklas Anttu,[1] Damir Asoli,[2] Maria Huffman,[2] Ingvar Åberg,[2] Martin H. Magnusson,[2] Gerald Siefer,[3] Peter Fuss-Kailuweit,[3] Frank Dimroth,[3] Bernd Witzigmann,[4] H. Q. Xu,[1,5] Lars Samuelson,[1] Knut Deppert,[1] Magnus T. Borgström[1]*





Surface recombination velocity = 170 cm/s

Science 339 (2013) p. 1057.

Stion, Khosla-Funded PV Startup, Hits 23.2% Efficiency With Tandem CIGS

Greentech Media

February 24, 2014

‘Perovskite’ Describes a Crystal Structure Class

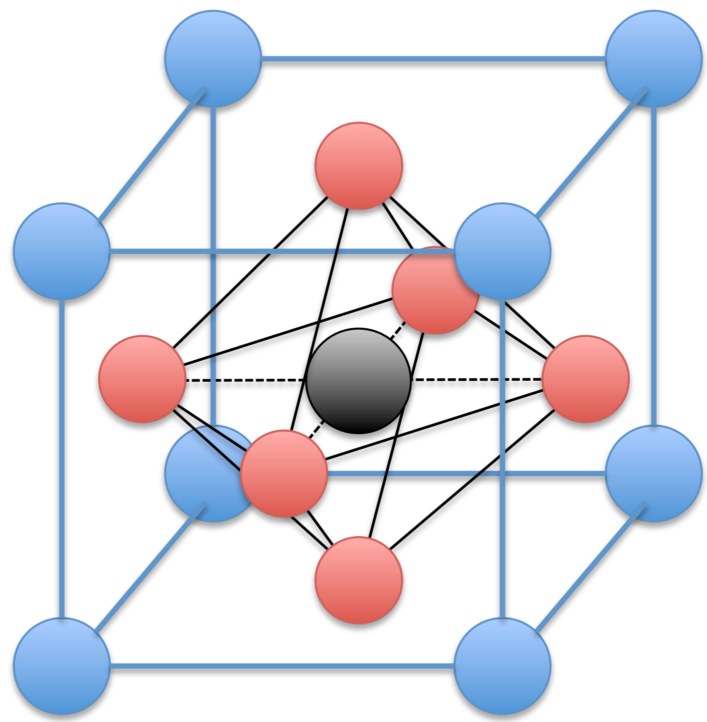
Generic formula: ABX_3

A B X

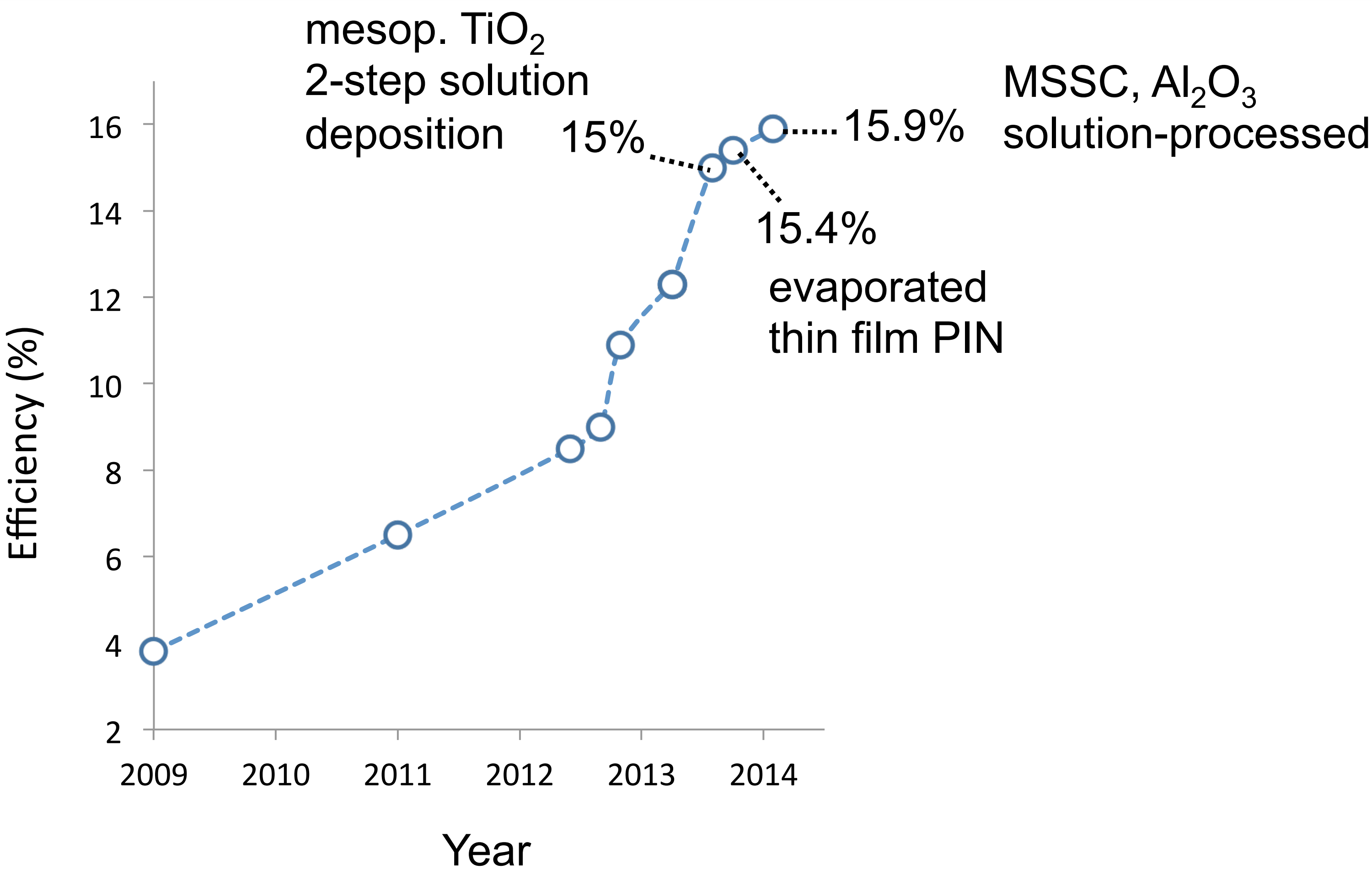
$CH_3NH_3^+$ Pb^{2+} I^-

$CH_3NH_3PbI_3$

Methylammonium-lead-iodide

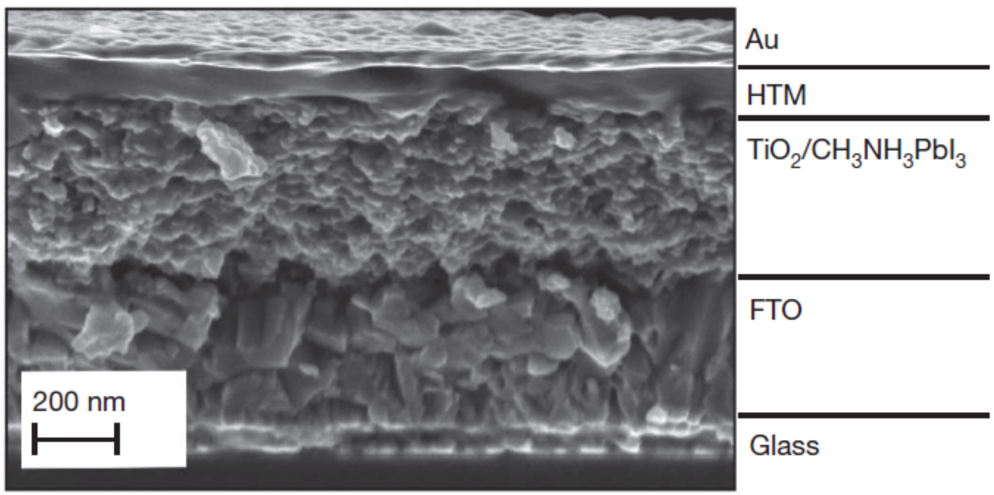


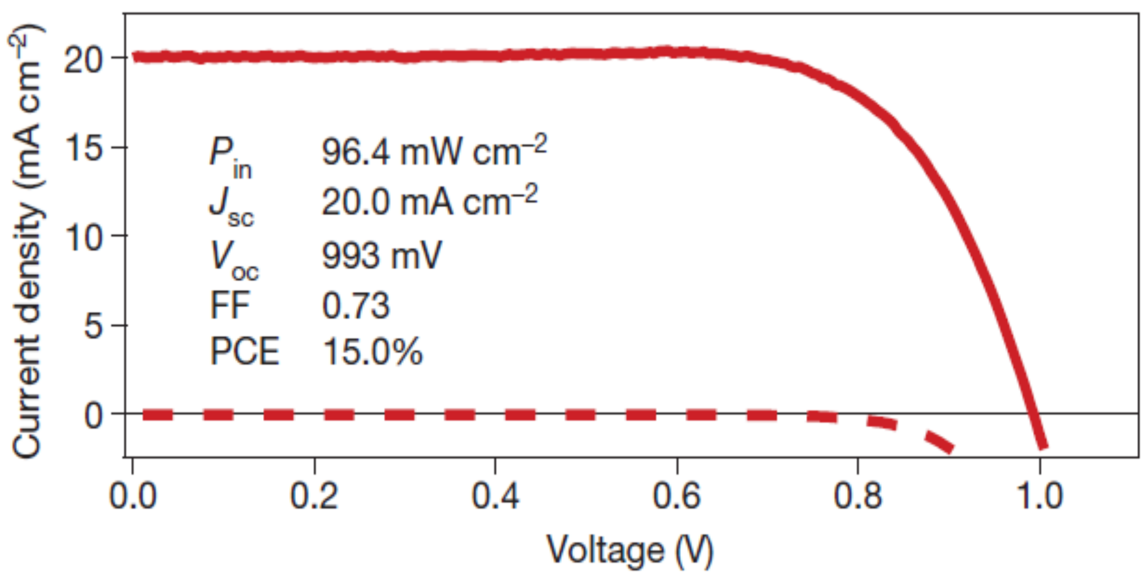
Perovskite Solar Cells are Soaring



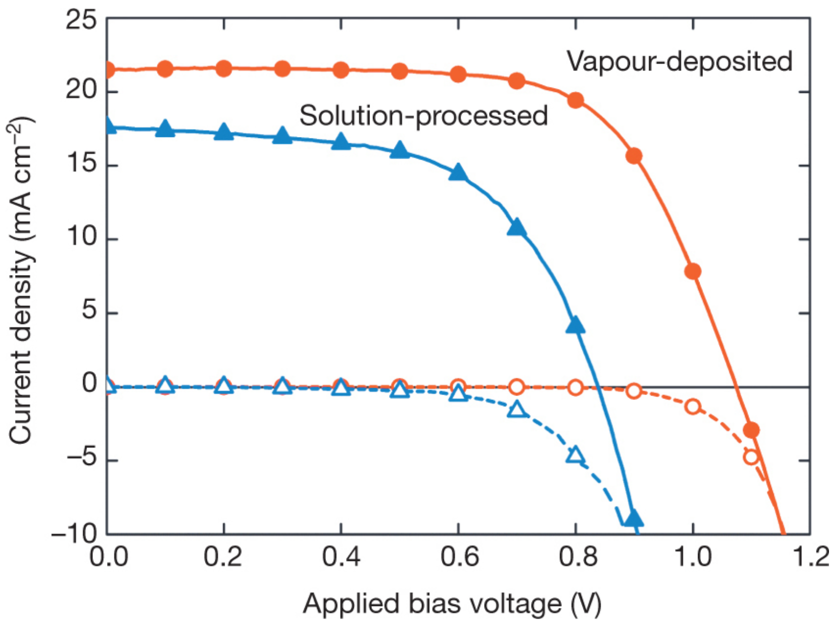
Snaith et al., *En. Env Sci.* Jan 2014
Snaith et al., *Nature* Sep 2013
Grätzel et al., *Nature* Jul 2013

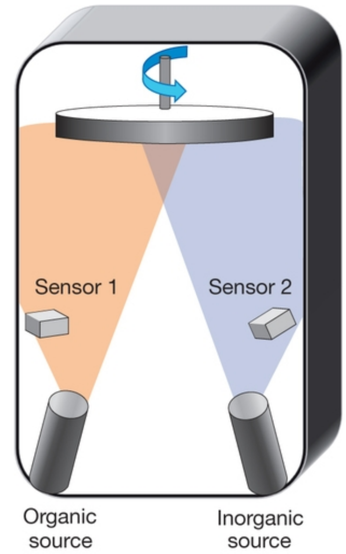
Perovskite Solar Cells Evolved From the Dye-Sensitized Solar Cell

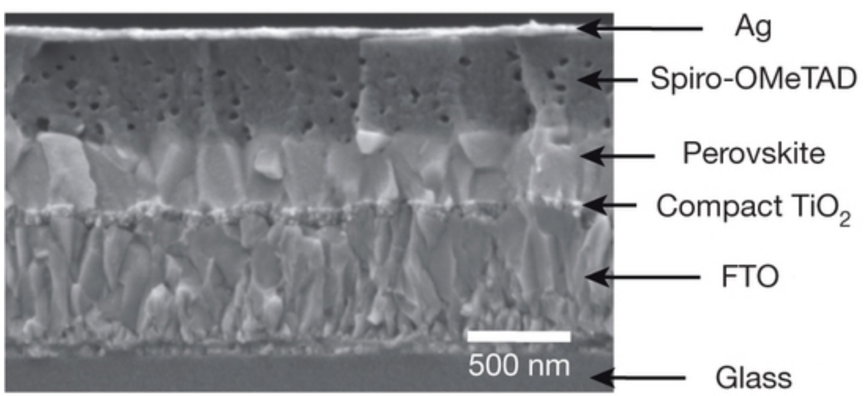




Perovskites Are Compatible With A Planar P-I-N Architecture







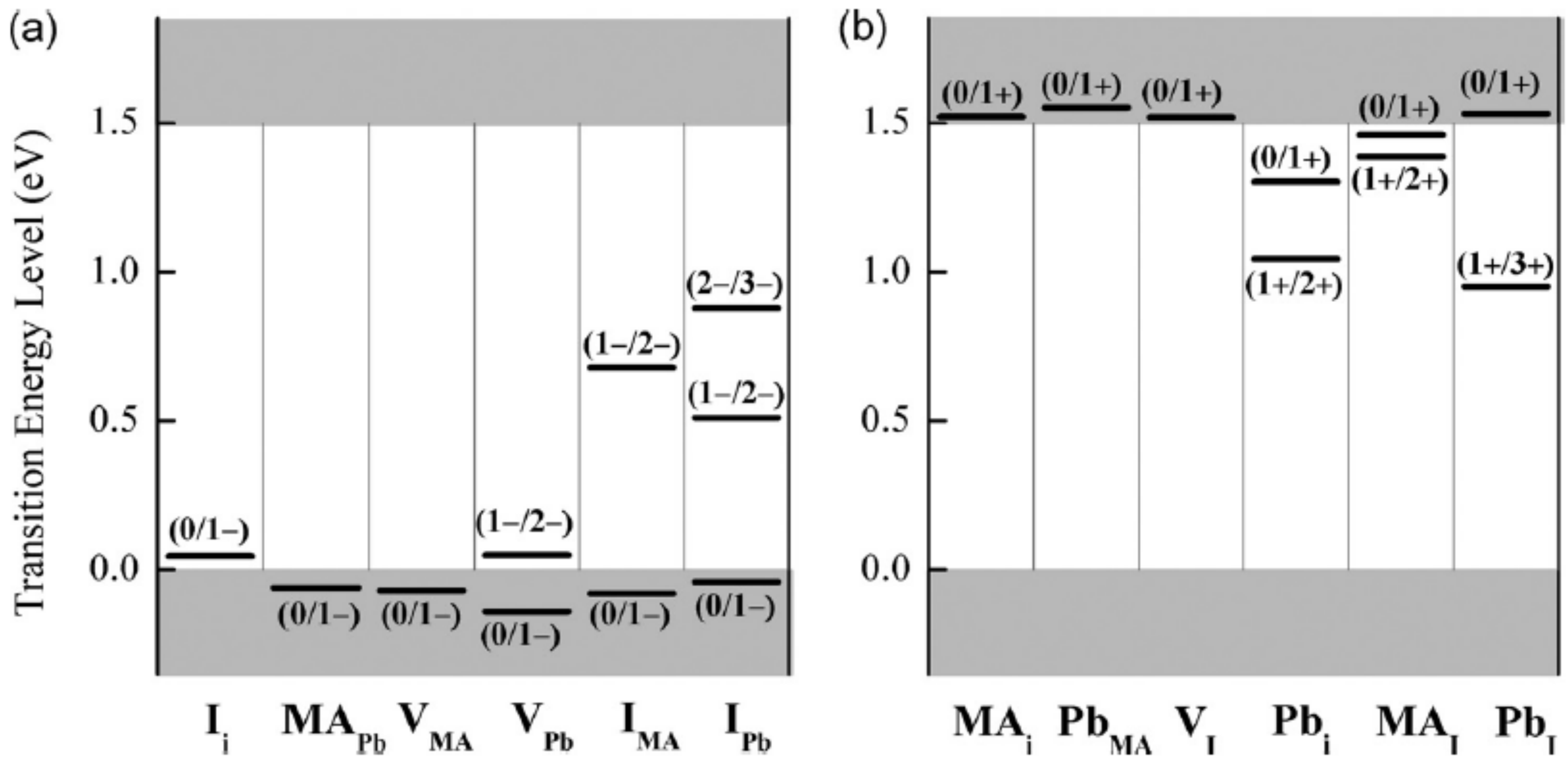
Jsc = 21.5 mA/ cm^2
Voc = 1.07 V
FF = 0.68
η = 15.4%

Low Bandgap – q·V_{oc} Loss in Perovskite Solar Cells

Material	Bandgap (eV)	q·Voc (eV)	Energy loss (eV)
GaAs	1.43	1.12	0.31
Silicon	1.12	0.75	0.37
CIGS	~1.15	0.74	0.41
Perovskite ($CH_3NH_3PbI_3$)	**1.55**	**1.07**	**0.48**
CdTe	1.49	0.90	0.59
a-Silicon	1.55	0.89	0.66

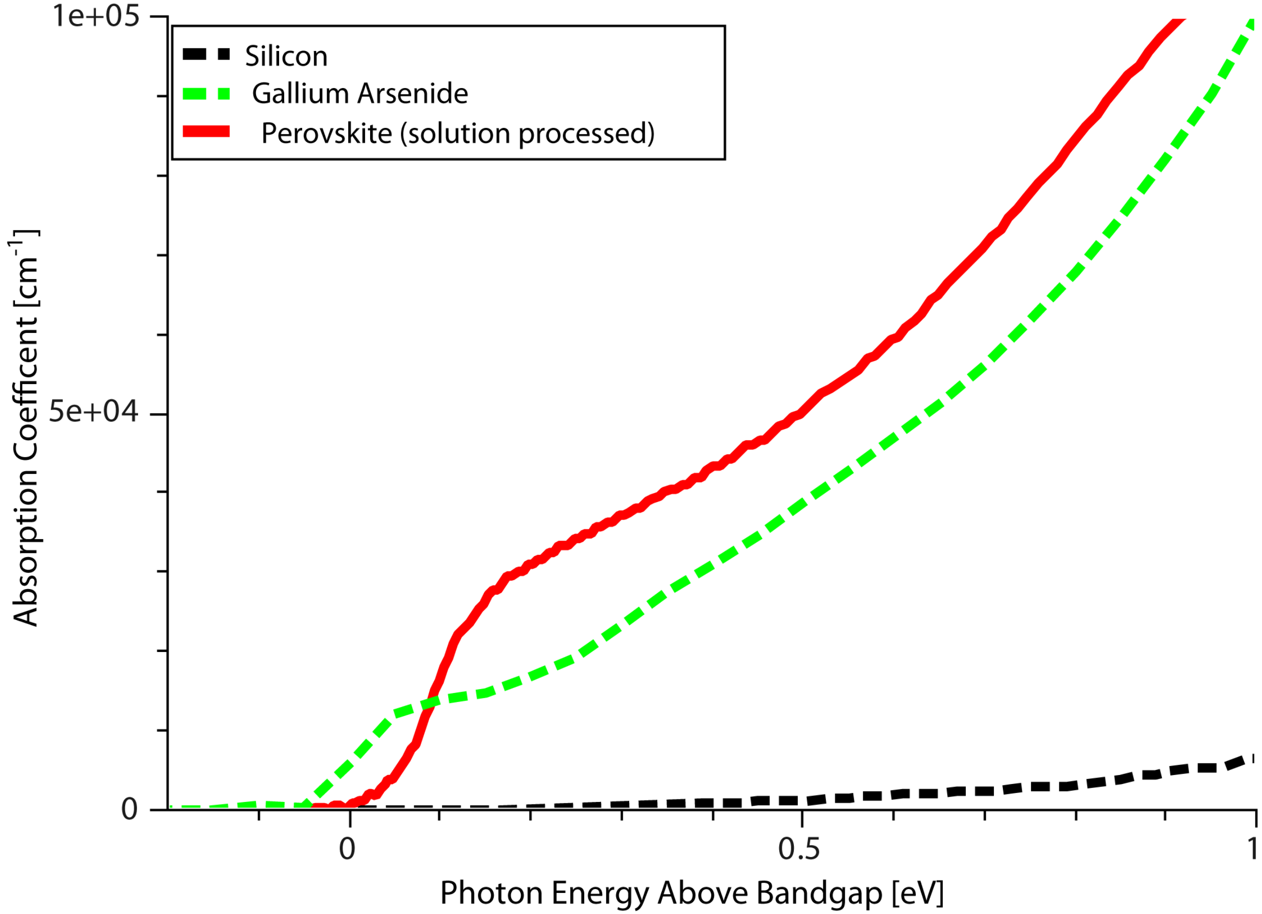
M. Green et al. Solar cell efficiency tables (version 42) July 2013

The traps are shallow



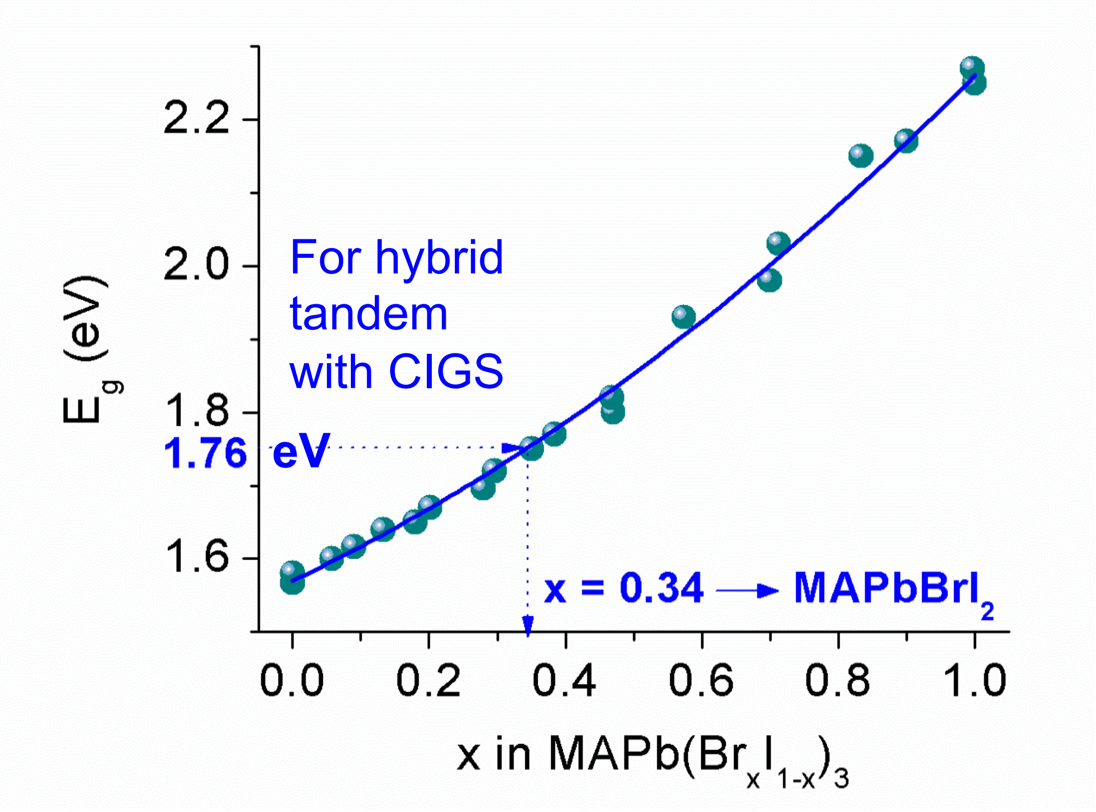
Yanfa Yan et al., *Appl. Phys. Lett.* 104 (2014) 63903.

The Perovskite is a Strongly-Absorbing Direct Band Gap Semiconductor



The Perovskite Bandgap can be tuned by Chemical Substitution

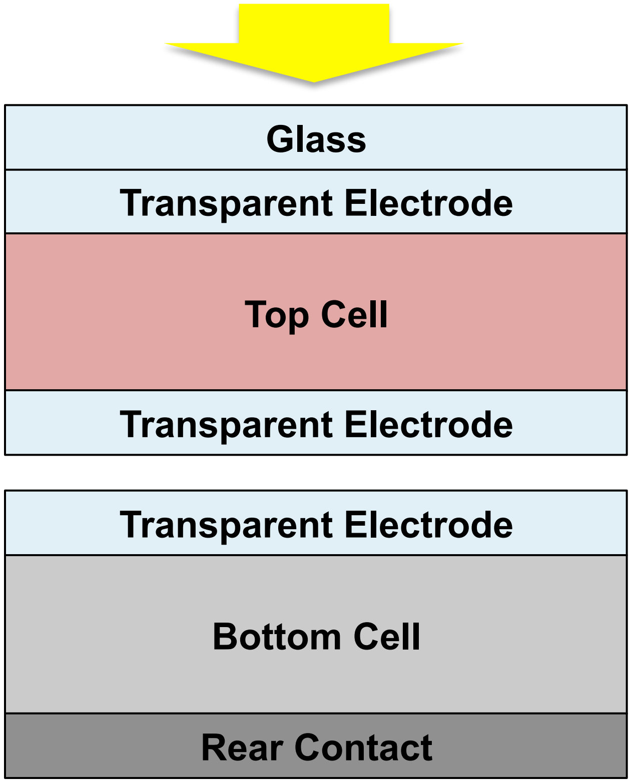
The band gap can be tuned from 1.57 eV to 2.23 eV by substituting bromine for iodine in $CH_3NH_3Pb(Br_xI_{1-x})_3$

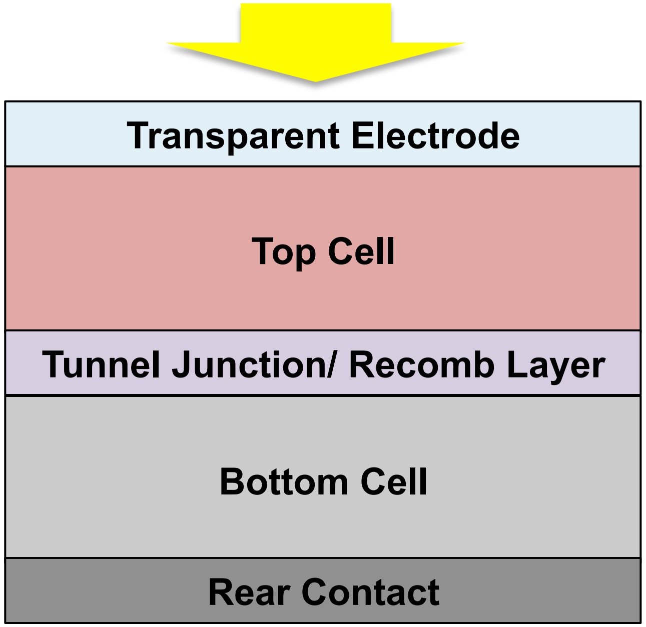


data by McGehee group and Noh et al., *Nano Lett.* 2013

Eva Unger

Hybrid Tandem Architectures

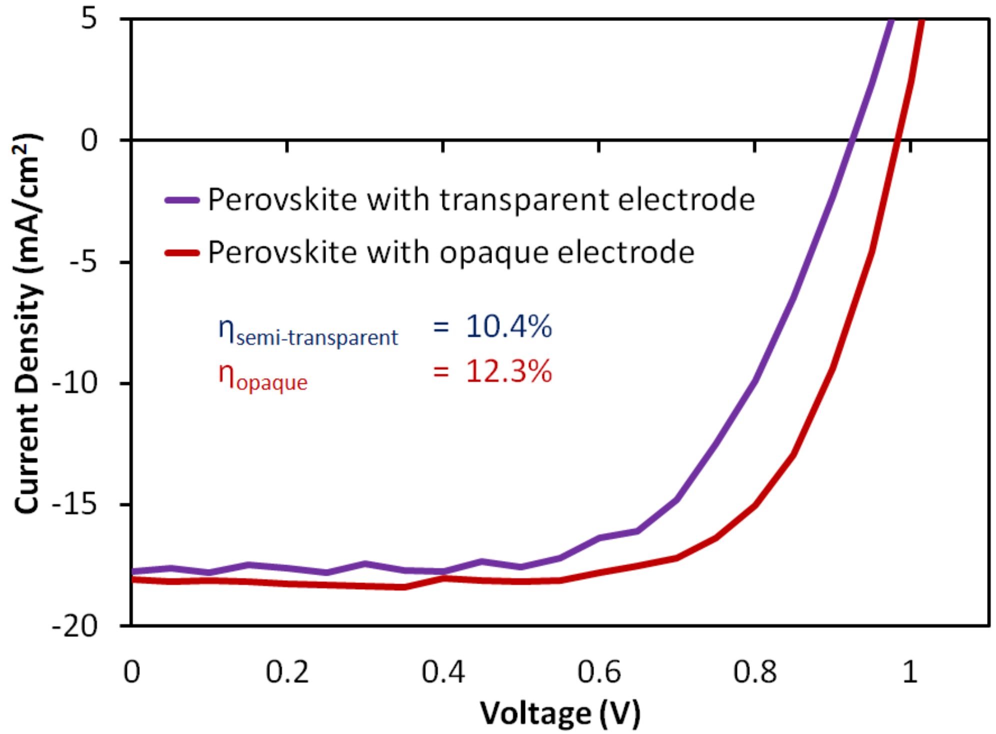




4 Terminal
- Easier prototyping
- No current matching required
- No tunnel junction or recombination layer required

2 Terminal
- Fewer layers that parasitically absorb
- Module fabrication easier

Our Semitransparent Perovskite Cells



Colin Bailie, Grey Christoforo

Preliminary Cost Estimates

	Today's Silicon	Silicon-Perovskite
Efficiency	19.4 %	25 %
Cost/Area	$\$153/m^2$	$\$167/m^2$
Cost/Watt	\$0.79/W	\$0.67/W

Expected improvements in silicon technology will take the cost below \$0.5/W!

Conclusions

- Conventional silicon leads the solar cell race, but will not take us where we need to go.
- Several technologies could take over in the next 10 years.
- We are still discovering new materials with substantially better properties.
- I think multijunction solar cells will be thin, light, cheap and > 30 % efficient.

Final thoughts

- We have to solve the energy problem.
- Any technology that has good potential to cut carbon emissions by > 10 % needs to be explored aggressively.
- Researchers should not be deterred by the struggles some companies are having.
- Someone needs to invest in scaling up promising solar cell technologies.