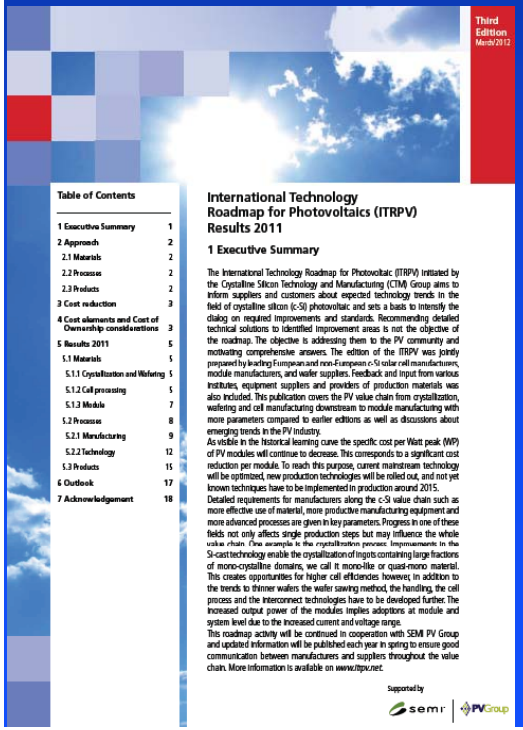
ARC Photovoltaics Centre of Excellence

"2012 SEMI Roadmap for Photovoltaics: Bigger, Thinner, Faster, Cheaper"


Third Edition March/2012

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International Technology Roadmap for Photovoltaics (ITRPV) Results 2011

1 Executive Summary

The International Technology Roadmap for Photovoltaic (ITRPV) initiated by the Crystalline Silicon Technology and Manufacturing (CTM) Group aims to inform suppliers and customers about expected technology trends in the field of crystalline silicon (c-Si) photovoltaic and sets a basis to intensify the dialog on required improvements and standards. Recommending detailed technical solutions to identified improvement areas is not the objective of the roadmap. The objective is addressing them to the PV community and motivating comprehensive answers. The edition of the ITRPV was jointly prepared by leading European and non-European c-Si solar cell manufacturers, module manufacturers, and wafer suppliers. Feedback and input from various institutes, equipment suppliers and providers of production materials was also included. This publication covers the PV value chain from crystallization, wafering and cell manufacturing downstream to module manufacturing with more parameters compared to earlier editions as well as discussions about emerging trends in the PV industry.

As visible in the historical learning curve the specific cost per Watt peak (WP) of PV modules will continue to decrease. This corresponds to a significant cost reduction per module. To reach this purpose, current mainstream technology will be optimized, new production technologies will be rolled out, and not yet known techniques have to be implemented in production around 2015.

Detailed requirements for manufacturers along the c-Si value chain such as more effective use of material, more productive manufacturing equipment and more advanced processes are given in key parameters. Progress in one of these fields not only affects single production steps but may influence the whole value chain. One example is the crystallization process. Improvements in the Si-cast technology enable the crystallization of ingots containing large fractions of mono-crystalline domains, we call it mono-like or quasi-mono material. This creates opportunities for higher cell efficiencies however, in addition to the trends to thinner wafers the wafer sawing method, the handling, the cell process and the interconnect technologies have to be developed further. The increased output power of the modules implies adoptions at module and system level due to the increased current and voltage range.

This roadmap activity will be continued in cooperation with SEMI PV Group and updated information will be published each year in spring to ensure good communication between manufacturers and suppliers throughout the value chain. More information is available on www.itrpv.net.

Supported by semi | PVGroup

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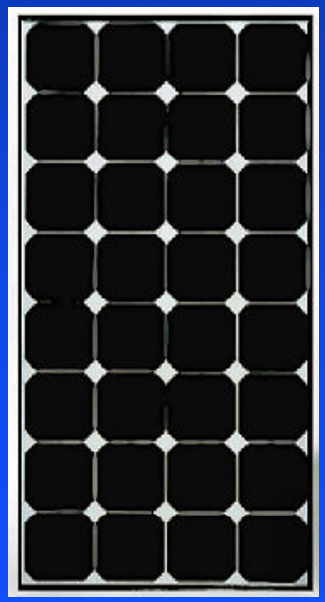
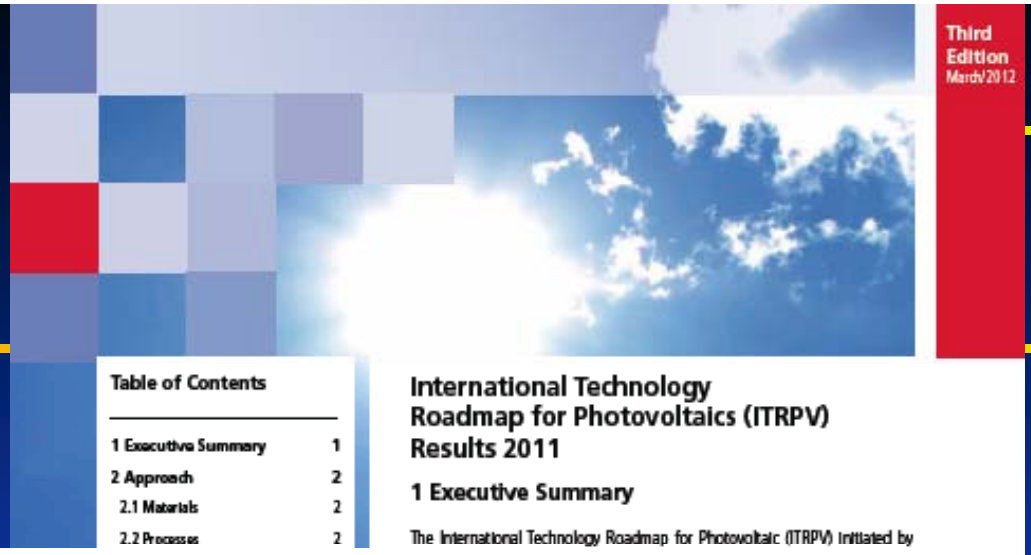
University of New South Wales

Sydney, Australia



Photovoltaics - Electricity from Sunlight

SEMI roadmap



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List of Authors

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Axel Tischer; Solarwatt
Ji-Weon Jeong; LG Electronics
Fernando Suarez; cel.celis
Yong Liu; JA Solar

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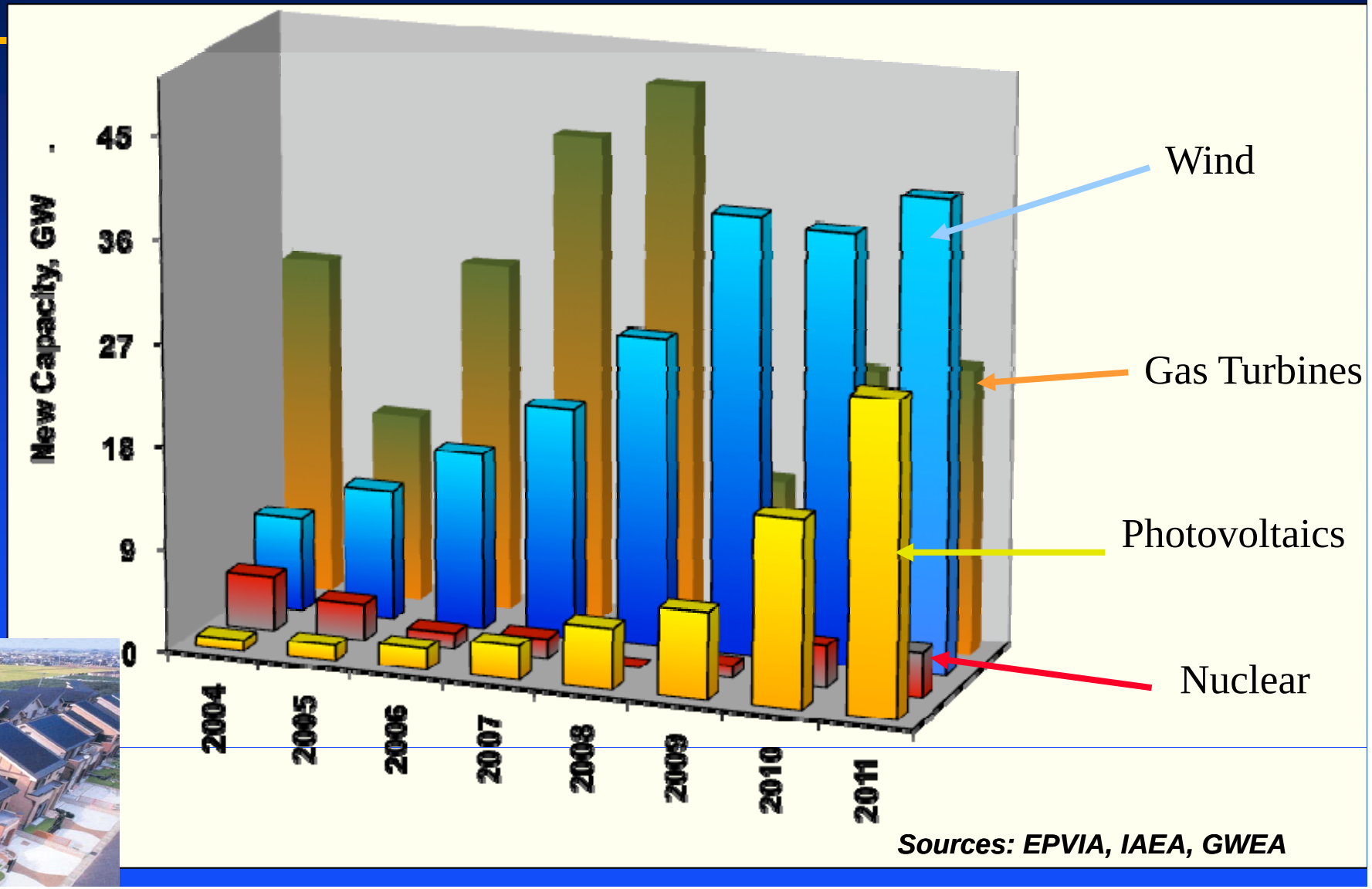
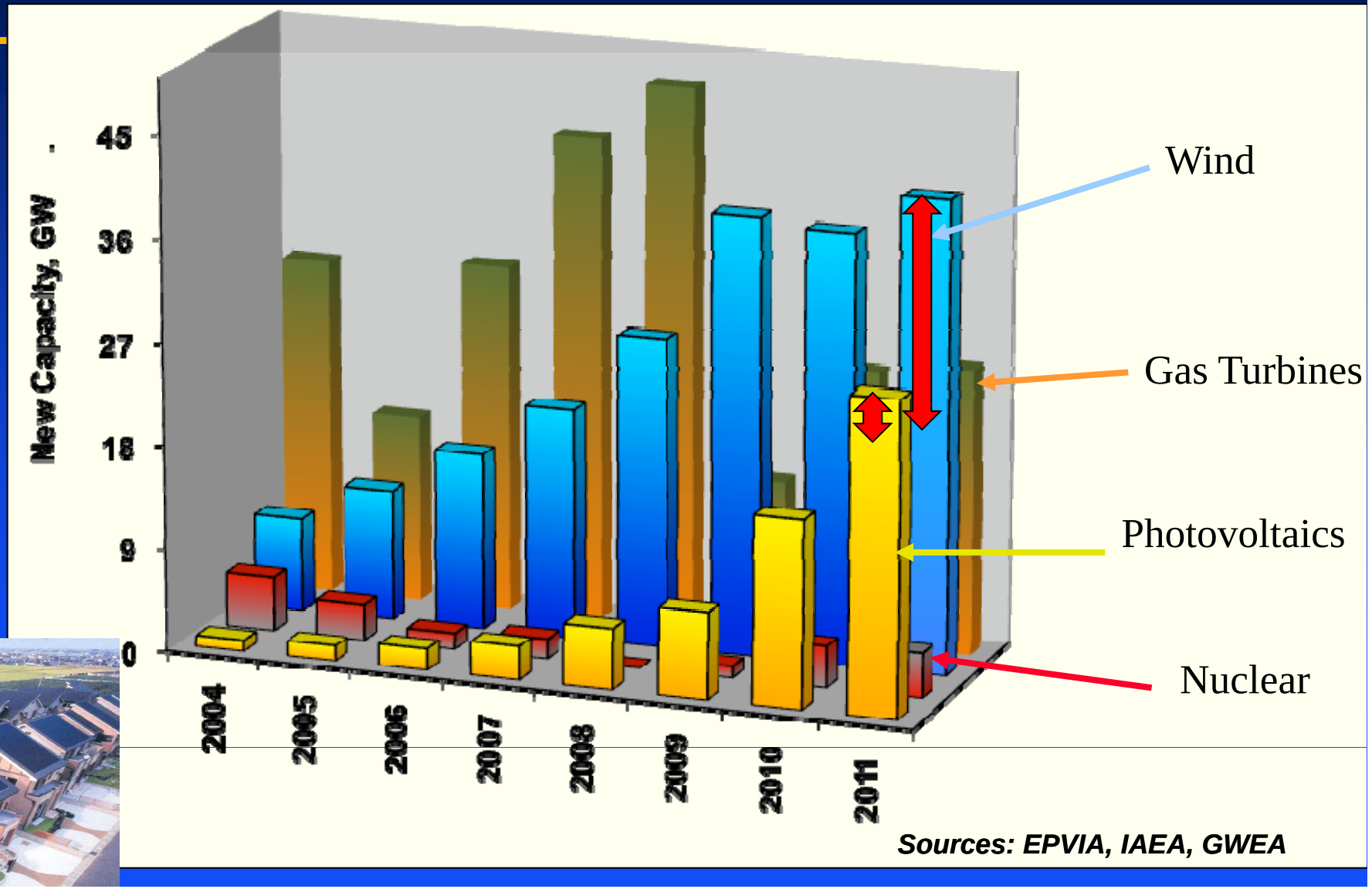
Annual capacity increase



Sources: EPVIA, IAEA, GWEA

Annual capacity increase

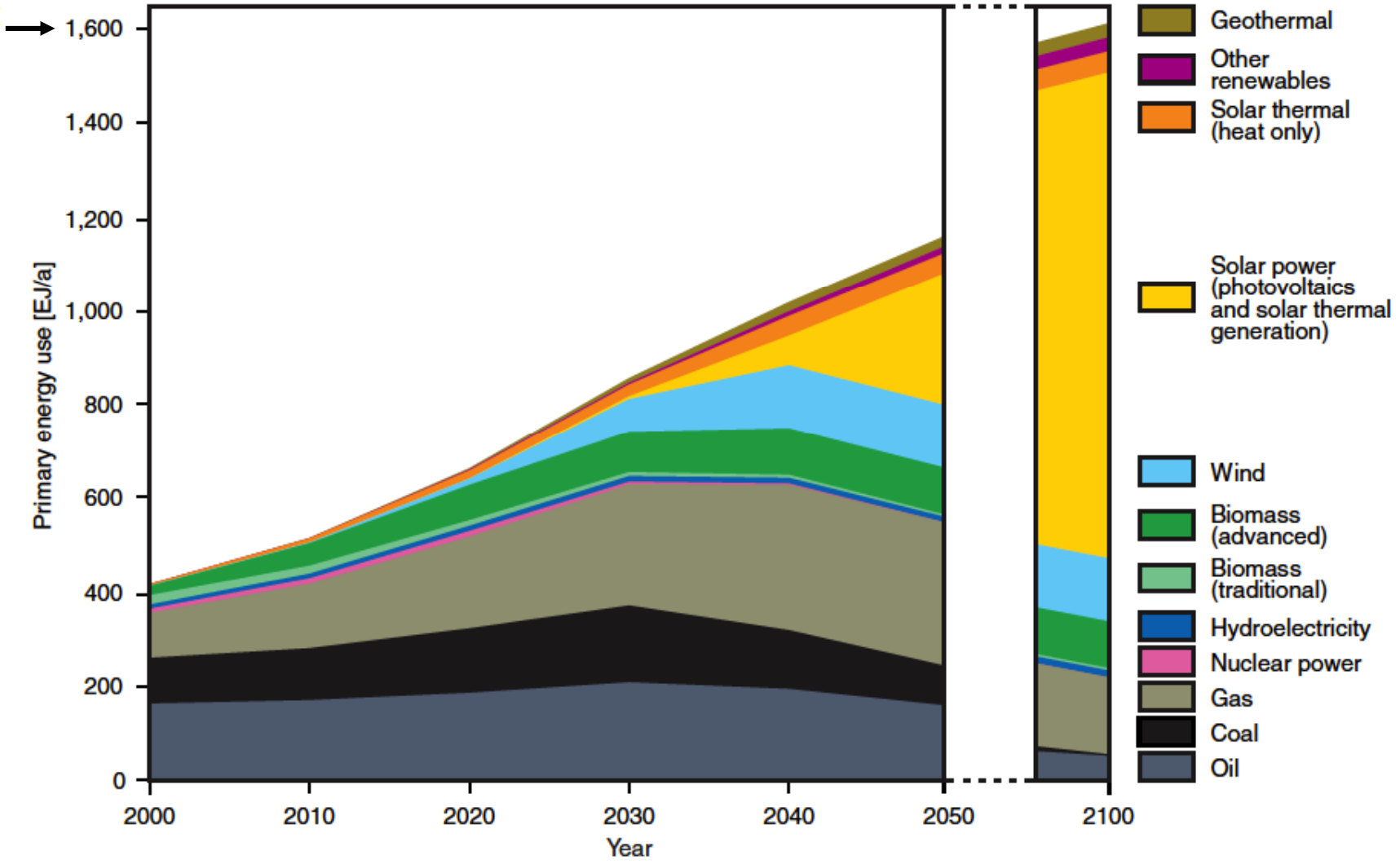


Sources: EPVIA, IAEA, GWEA

Where ultimately?

German Advisory Council on Global Change (WBGU) *2003*

50.7 Terawatt



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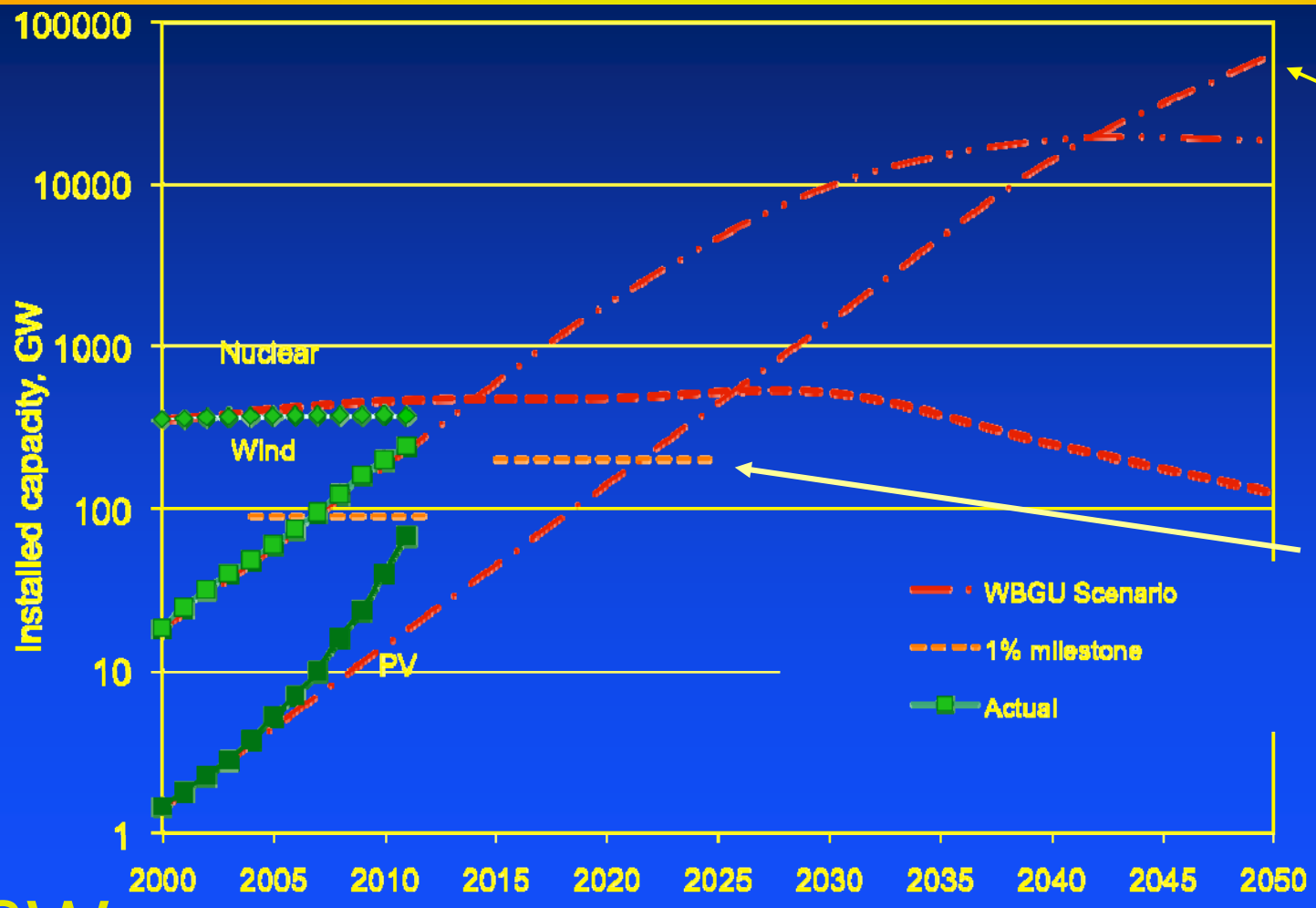
“Submerged” progress



25% World’s energy

1% World’s electricity

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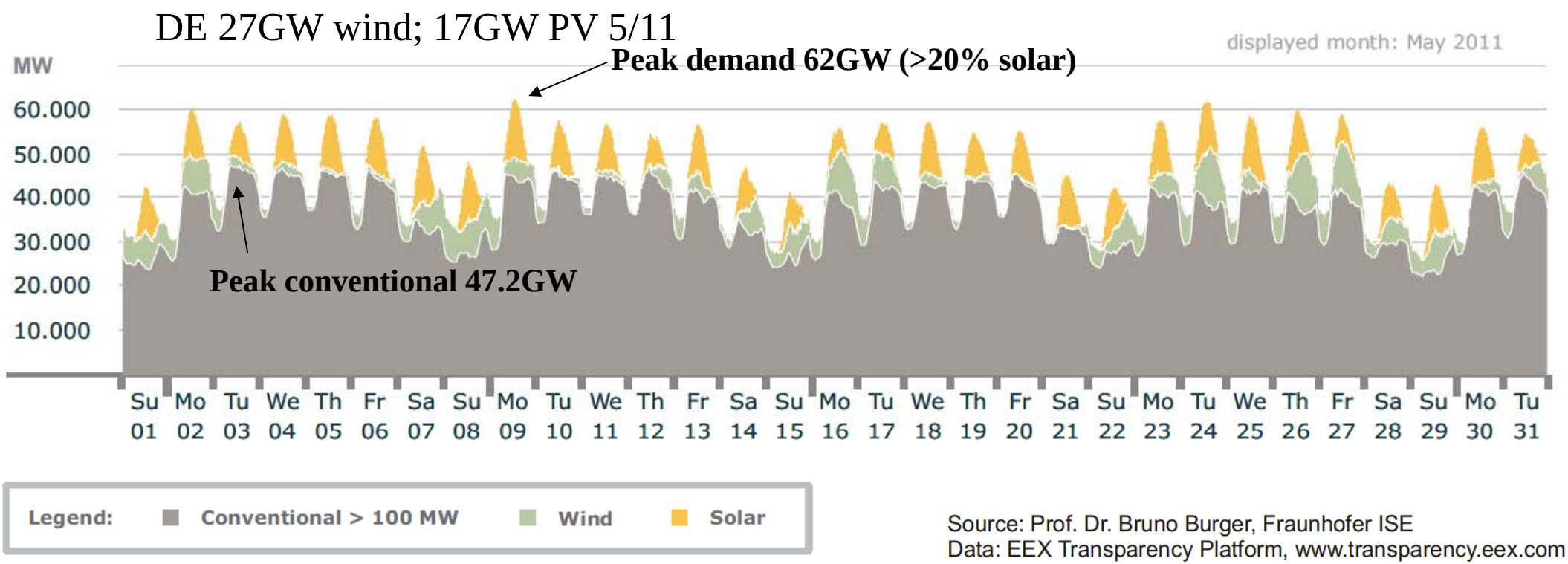
German grid: May 2011

Actual production

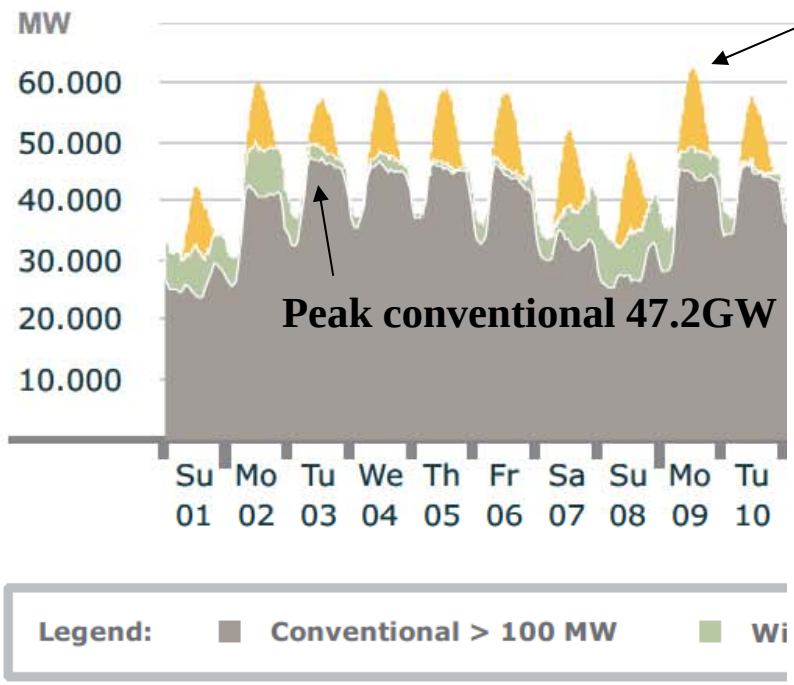


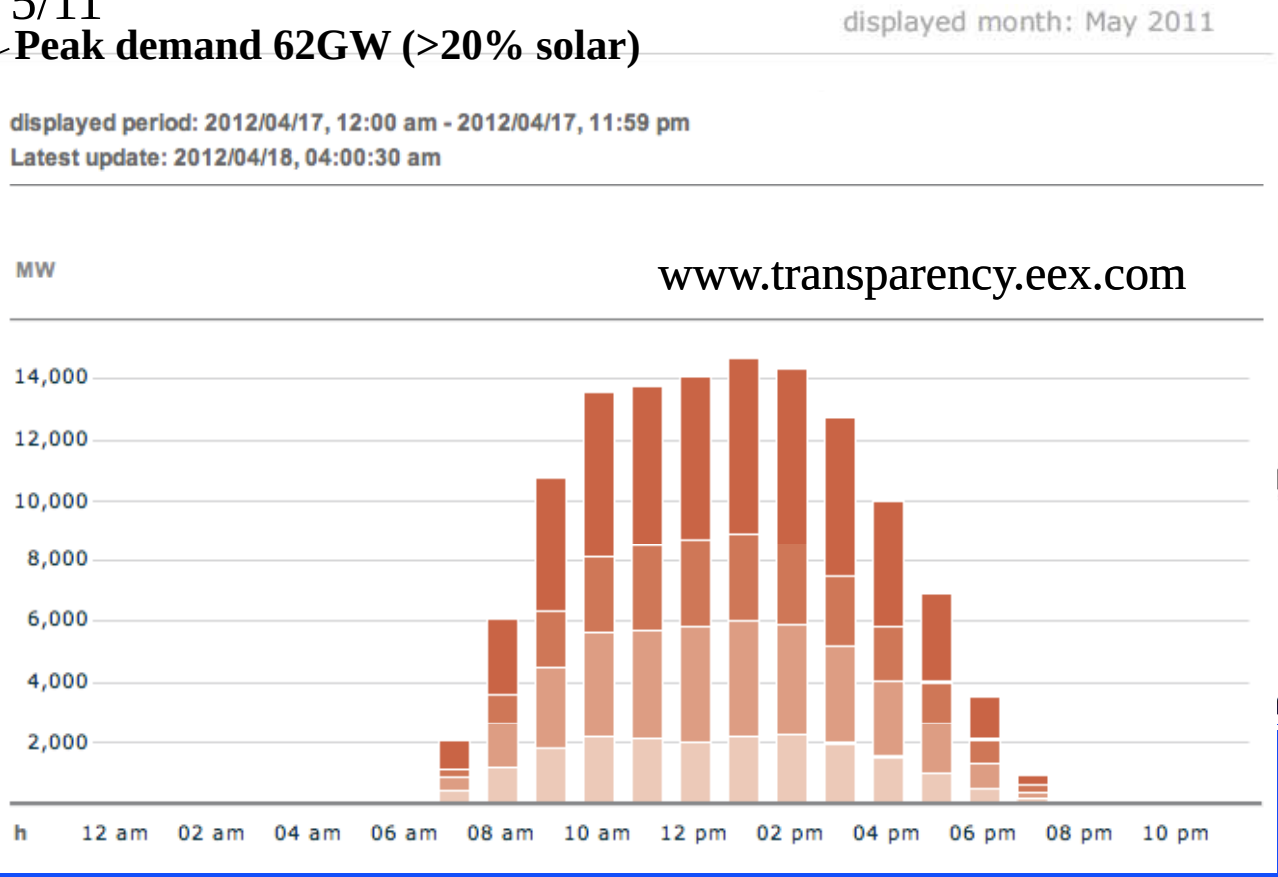
Source: Prof. Dr. Bruno Burger, Fraunhofer ISE
Data: EEX Transparency Platform, www.transparency.eex.com

German grid: May 2011

Actual production

DE 27GW wind; 17GW PV 5/11





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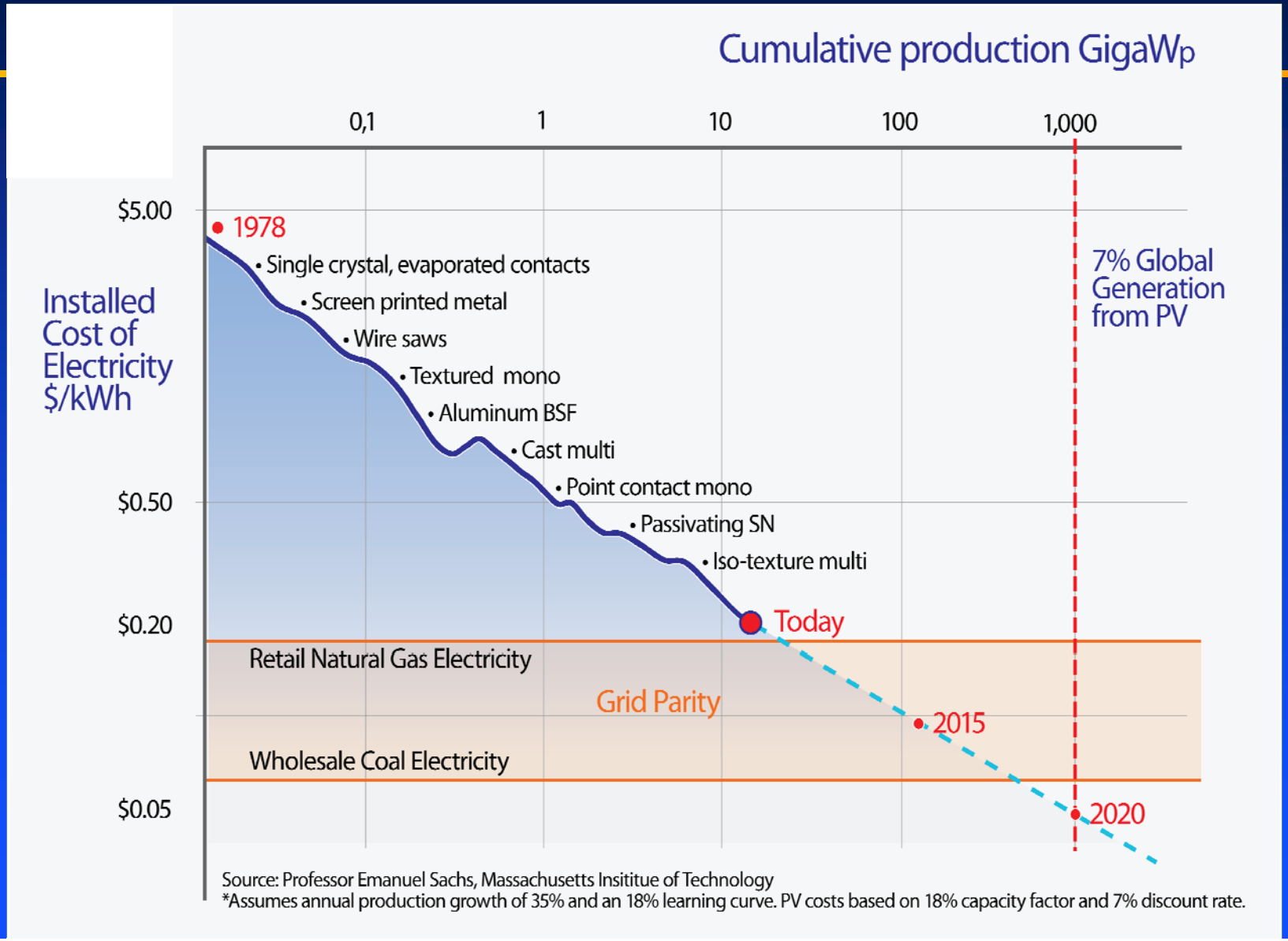
Cost – down rapidly



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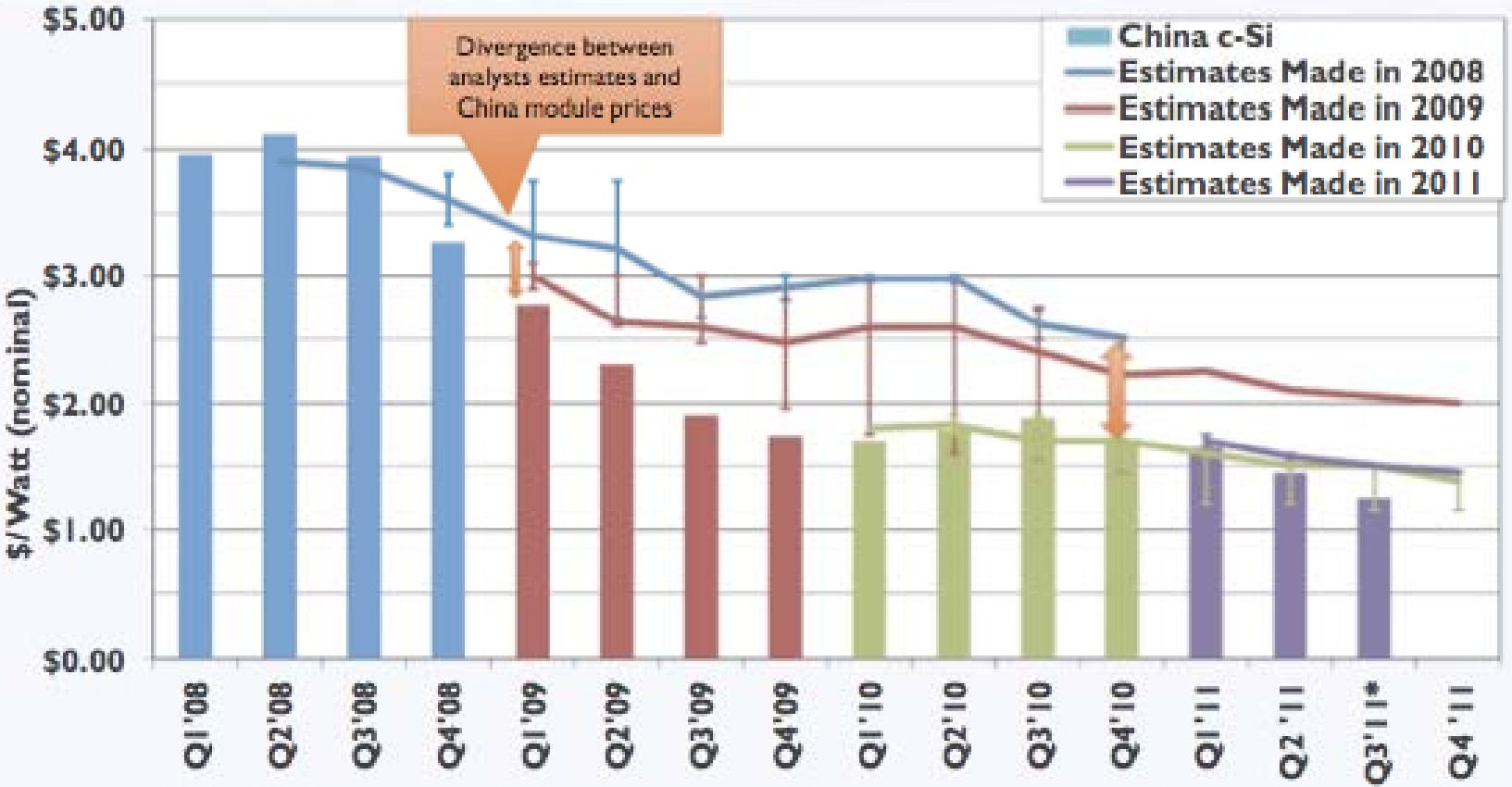
Actual Module ASP vs. Analyst Estimates



- In Q1 2009, independent industry analysts were expecting PV module prices to remain strong and above $2/W into 2011
- Chinese made PV modules are now selling as low as $1.15/W

*Q3 '11 through 9/16/11

Sources: : For 2007-2011 Actual Module Selling Price: Q1'07 to Q2'09: Barclays Capital (12/14/09) and Stifel Nicolaus (5/5/11), Q3'09 onward: UBS Securities, LLC(2/12/10, 4/23/10, 7/29/10, 10/29/2010,1/24/11, 6/3/11, 8/17/11, 9/16/11). For Analyst Estimates 2008-10: analyst reports, Barclays (5/1/09,11/15/10); Deutsche Bank (5/27/08, 1/23/09, 5/6/10, 1/5/11); Lazard (11/4/08, 4/2/09); Stifel Nicolaus (10/6/09, 4/8/10); UBS(8/22/10, 3/8/11)

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SEMI roadmap

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International Tech
Roadmap for Pho
Results 2011

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and updated information will be
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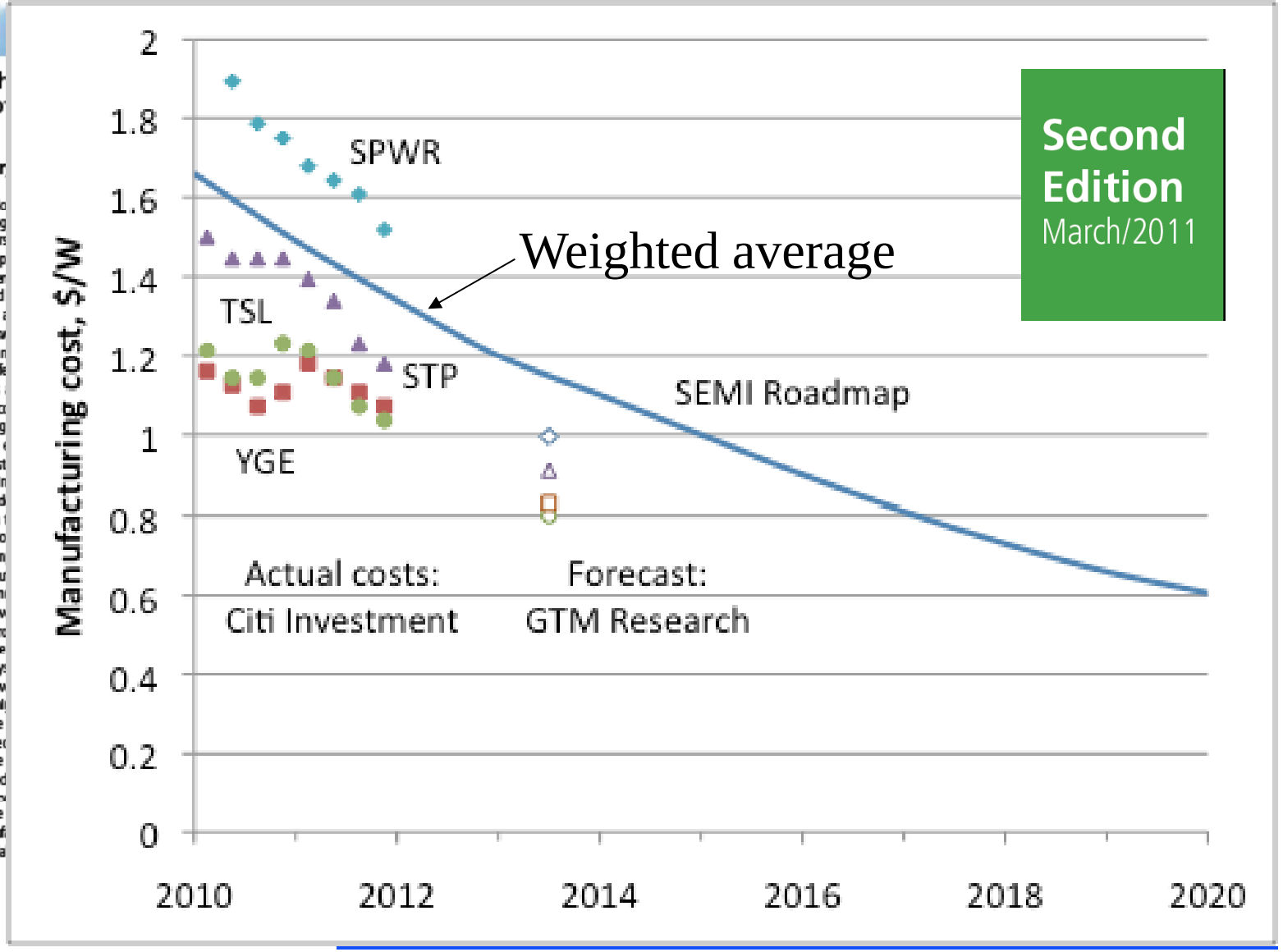


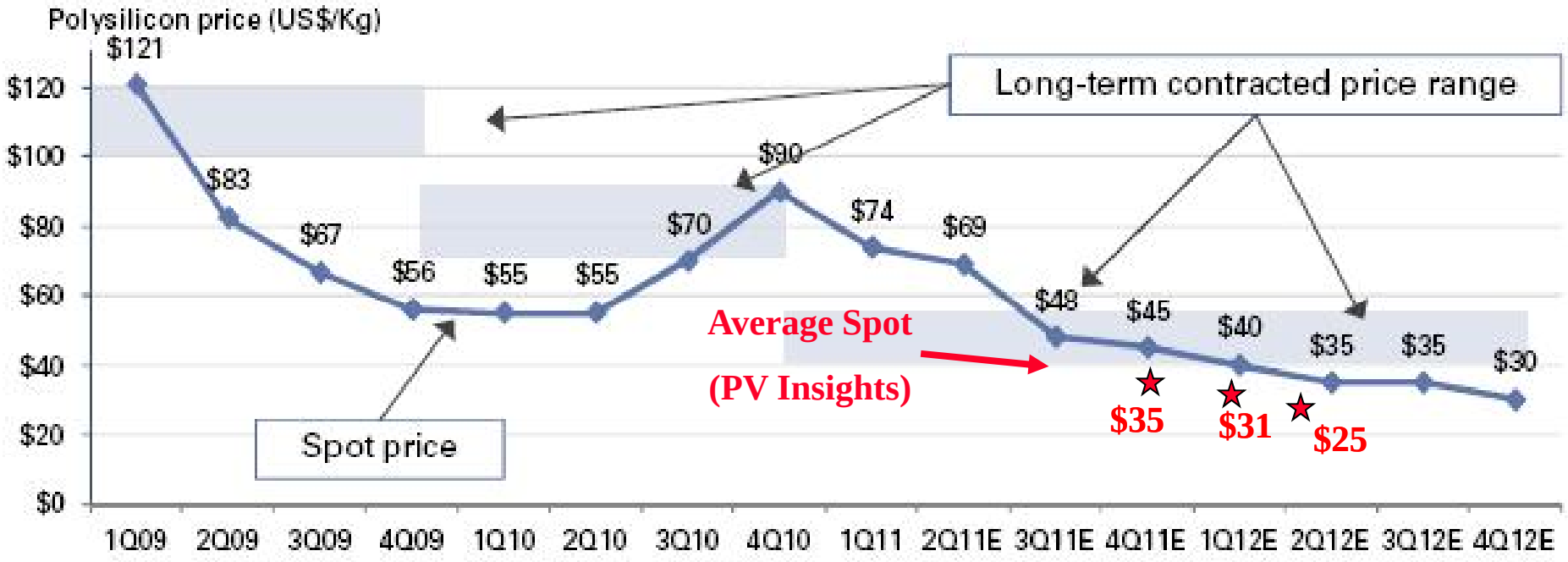
Polysilicon

LDK 15Mt (2GW) Si facility, Xinyu

Cheaper polysilicon

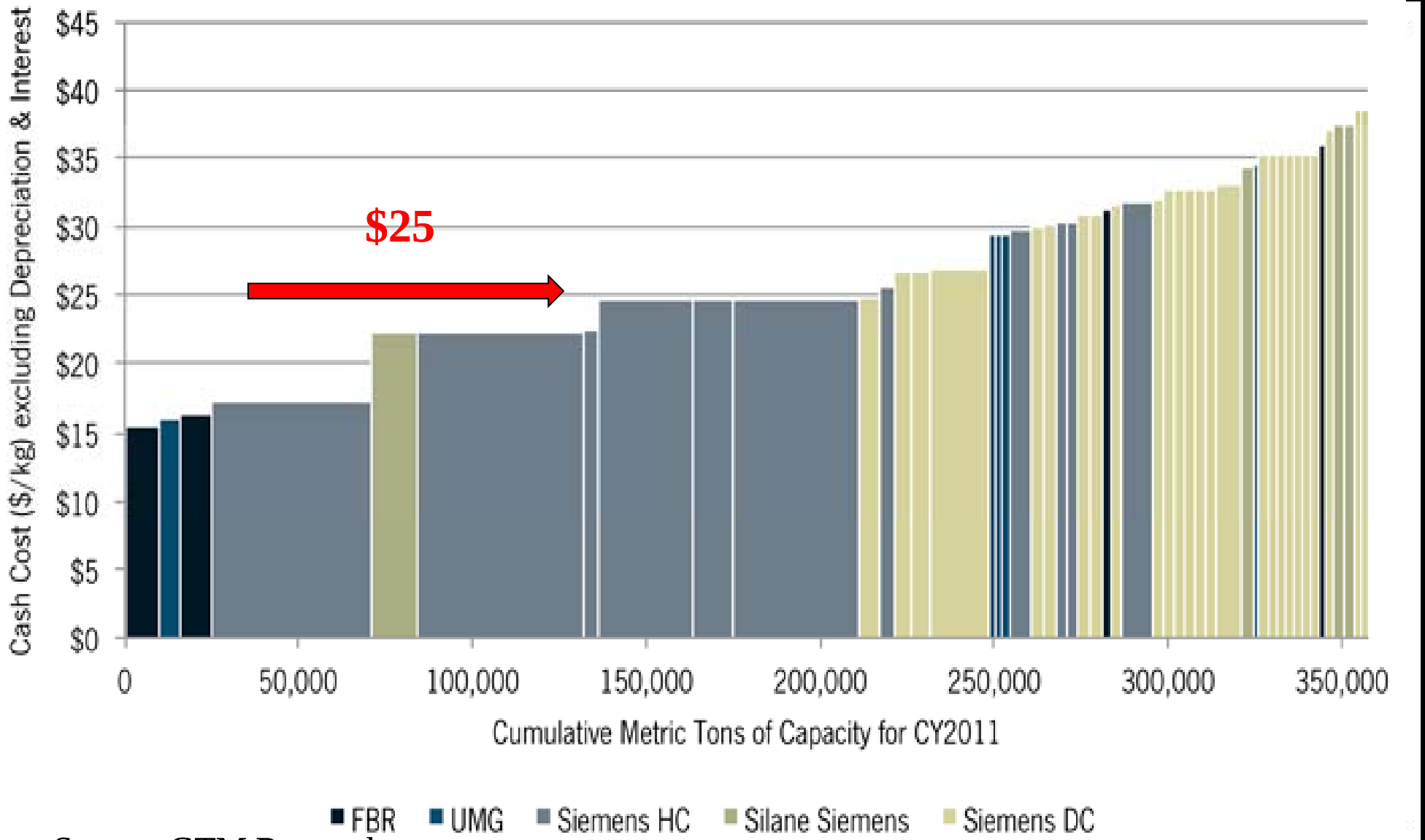
Exhibit 10: We expect a spot price in the mid-$30s/kg by 2012, with contract prices stepping down on a multi-month lag

Poly-silicon spot and contract price 1Q09-4Q12E



Source: Goldman Sachs Research estimates.

Cheaper polysilicon

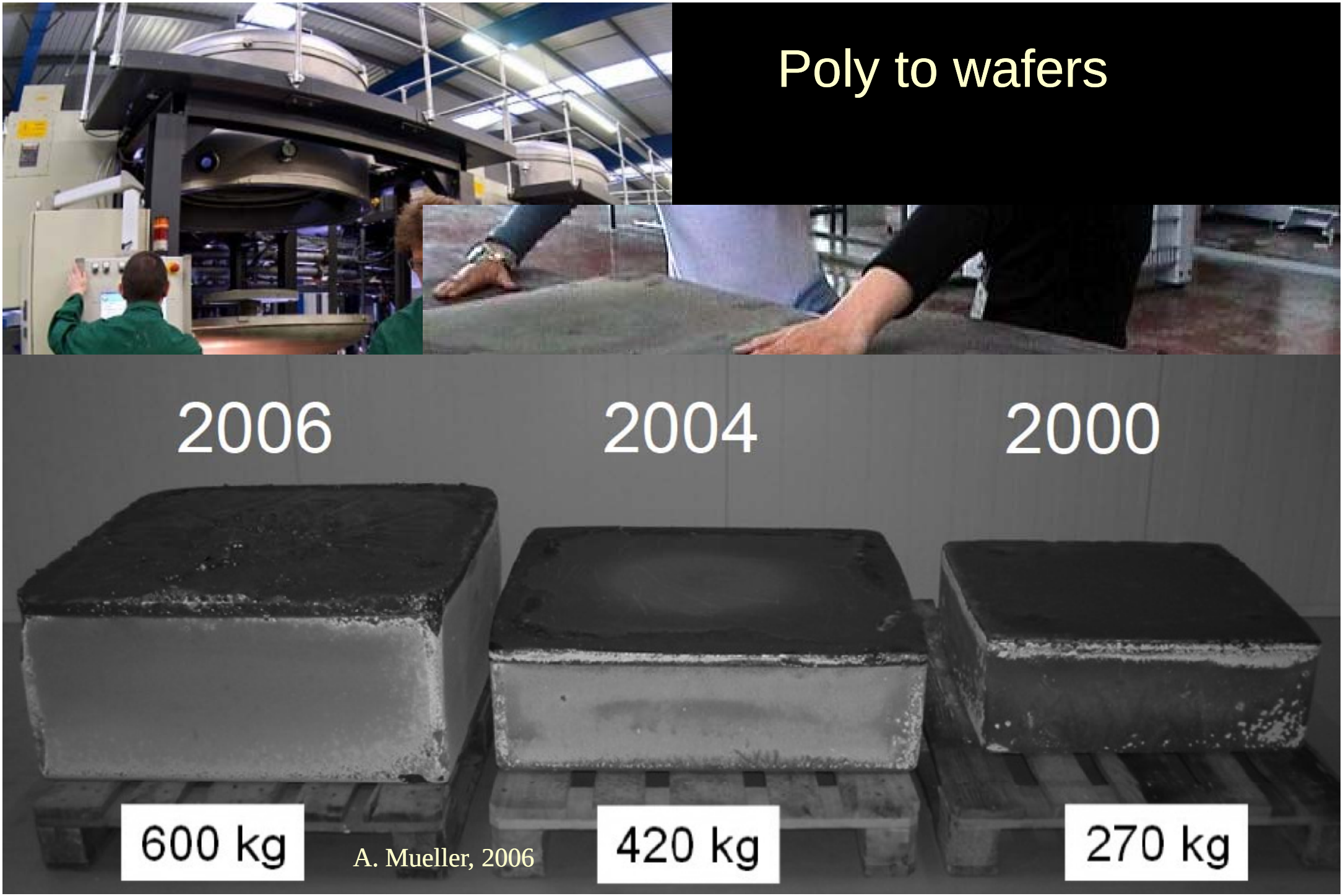


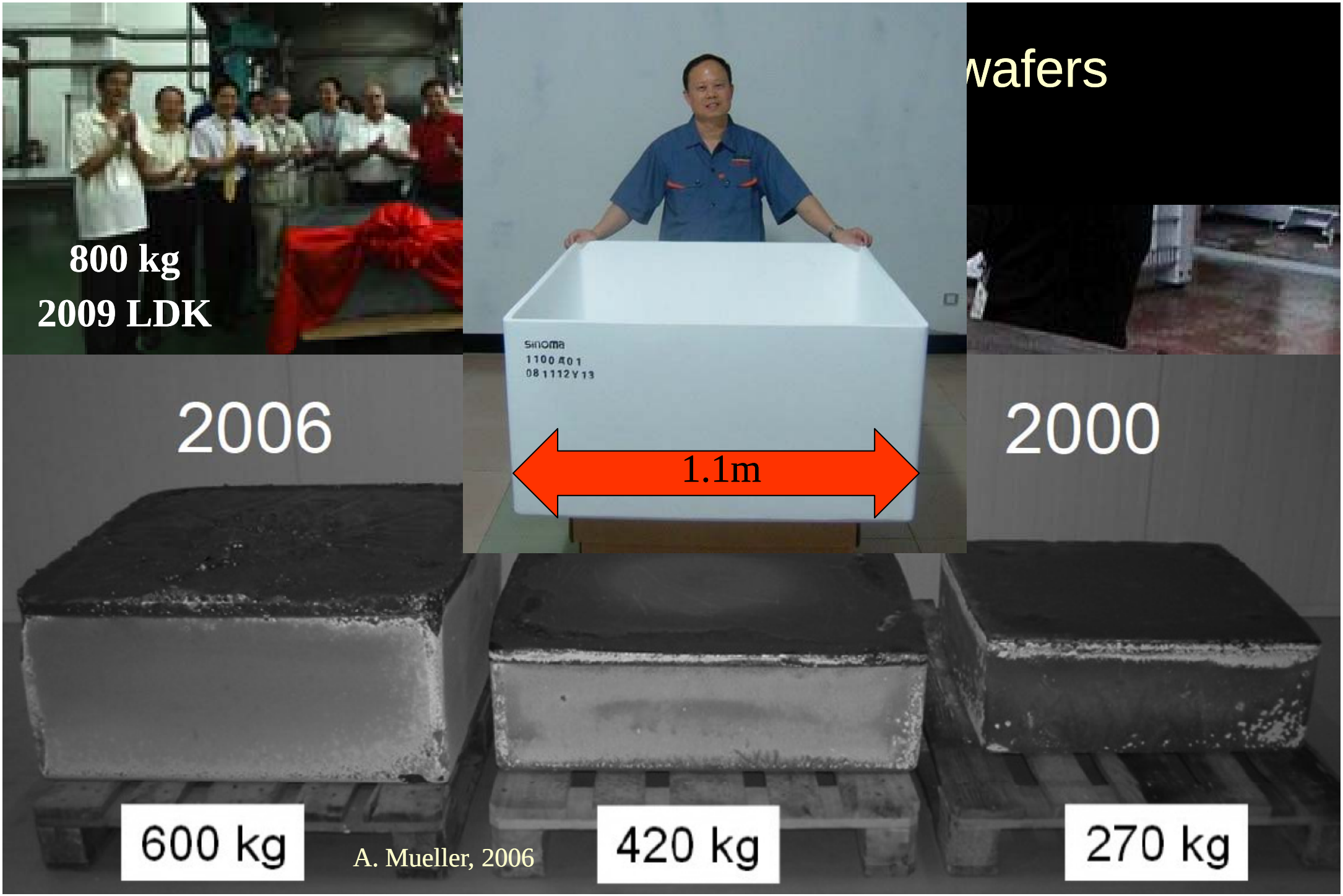
Source: GTM Research

Poly to wafers

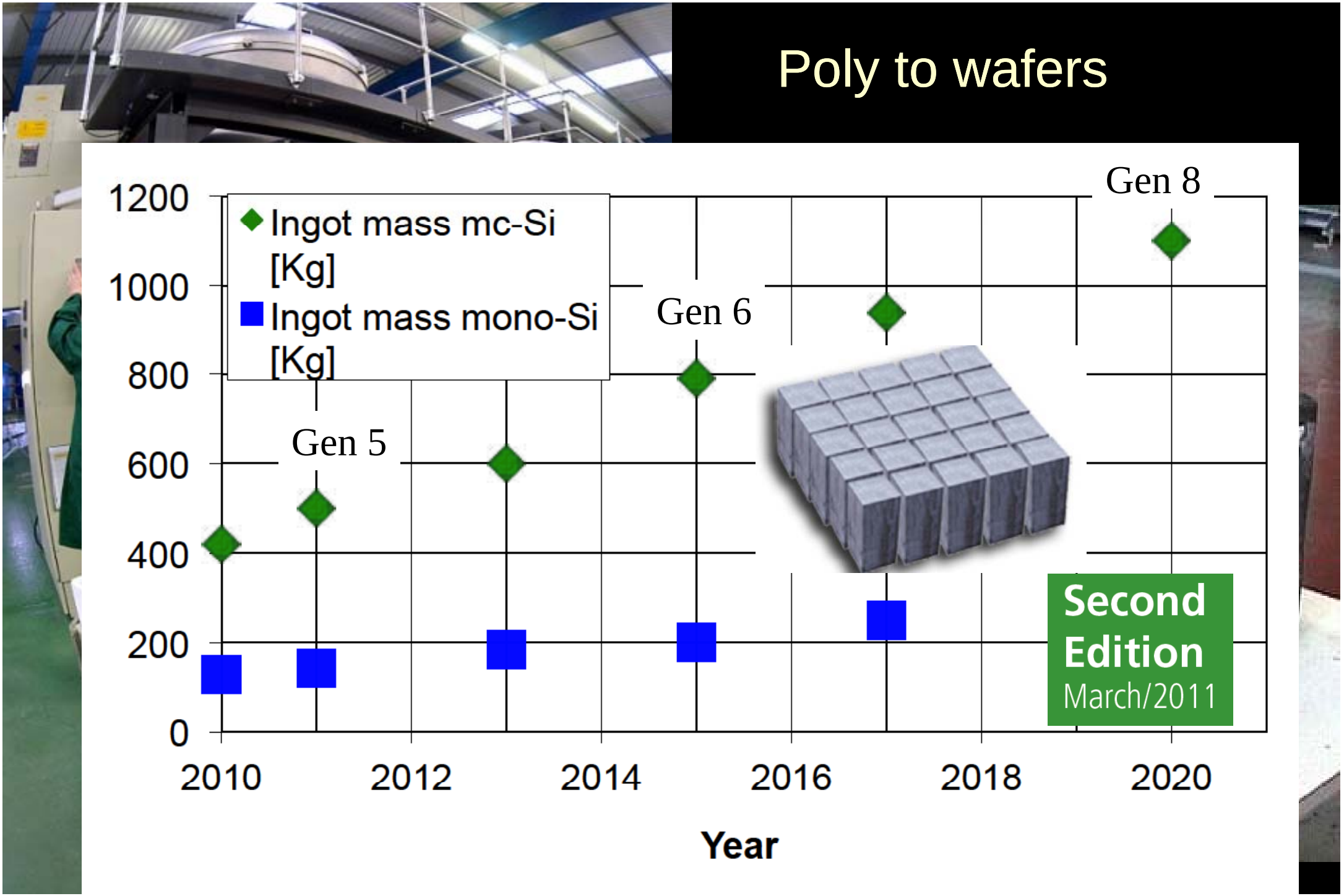
Poly to wafers

Poly to wafers

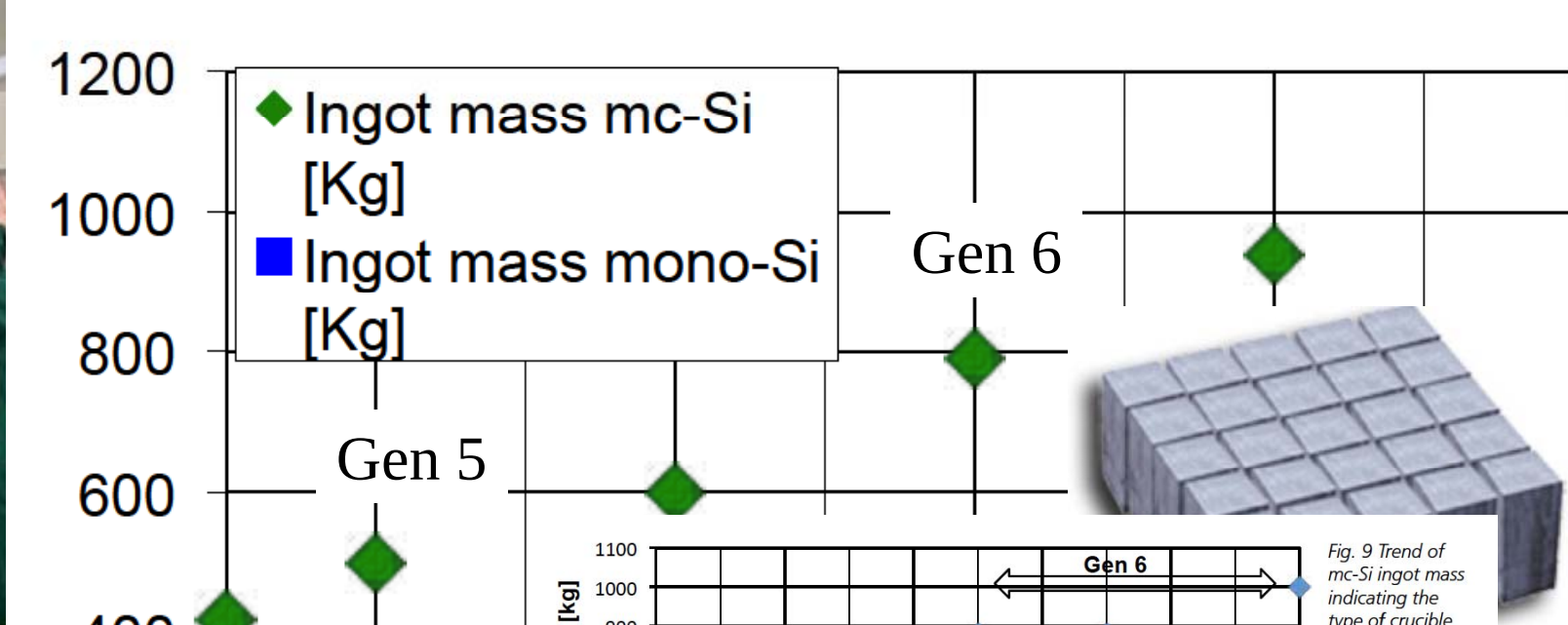



800 kg
2009 LDK
wafers
SINOMA
1100401
081112Y13
1.1m
2006
2000
600 kg
A. Mueller, 2006
420 kg
270 kg

Poly to wafers



Poly to wafers



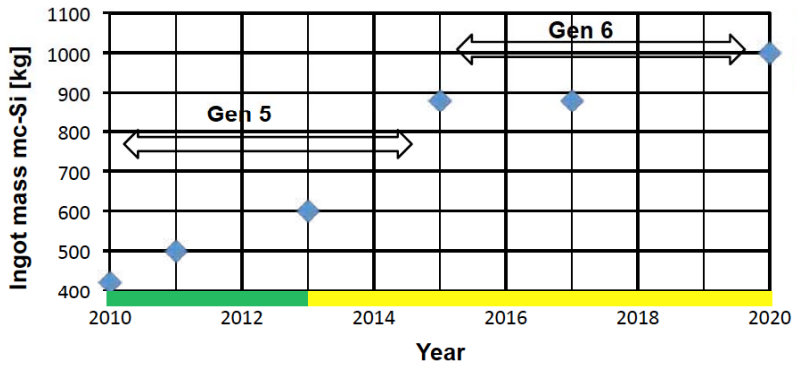


Fig. 9 Trend of mc-Si ingot mass indicating the type of crucible generation used in the newest production lines (mc-Si only).

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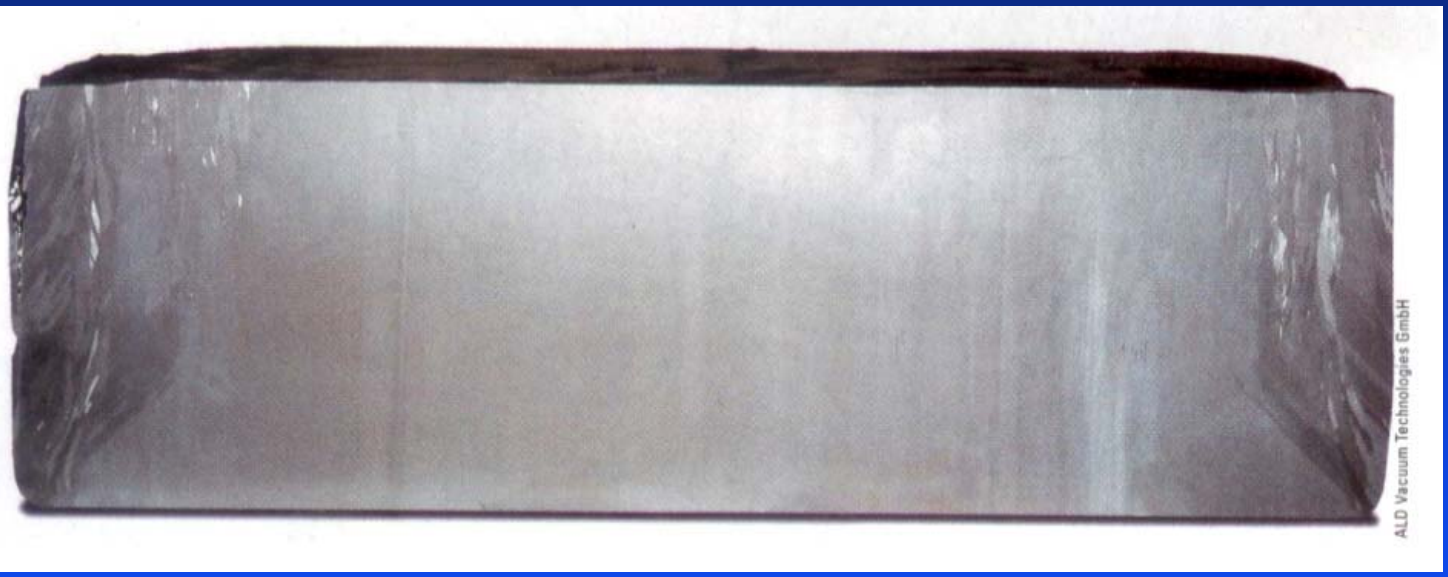
Better ingot quality: eg. Quasi-mono



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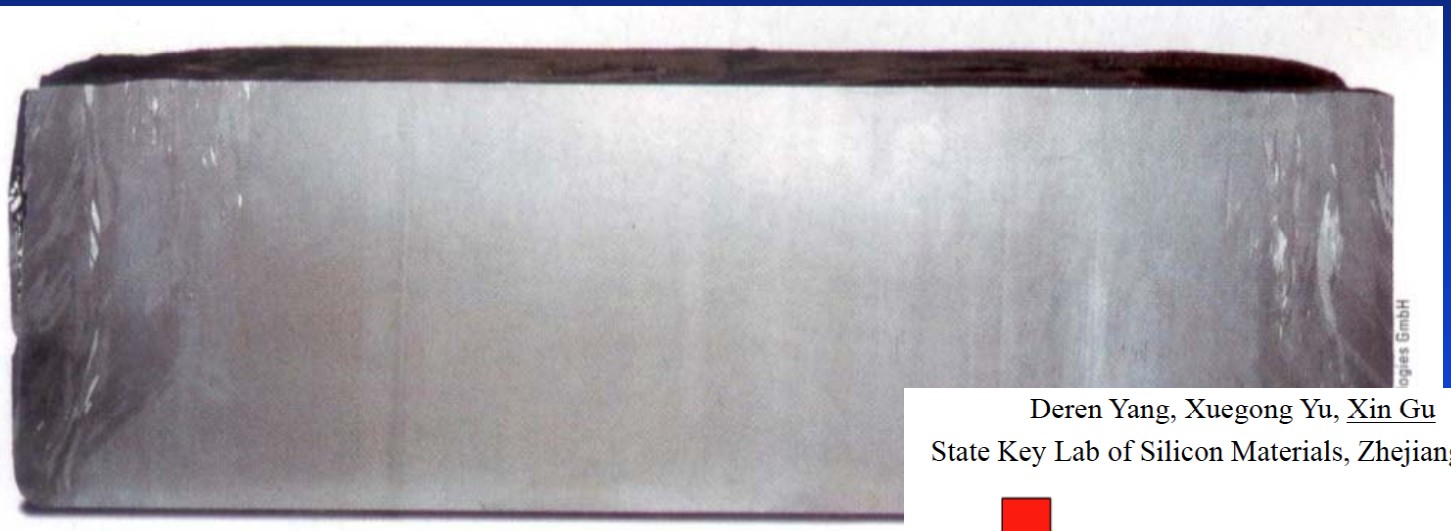

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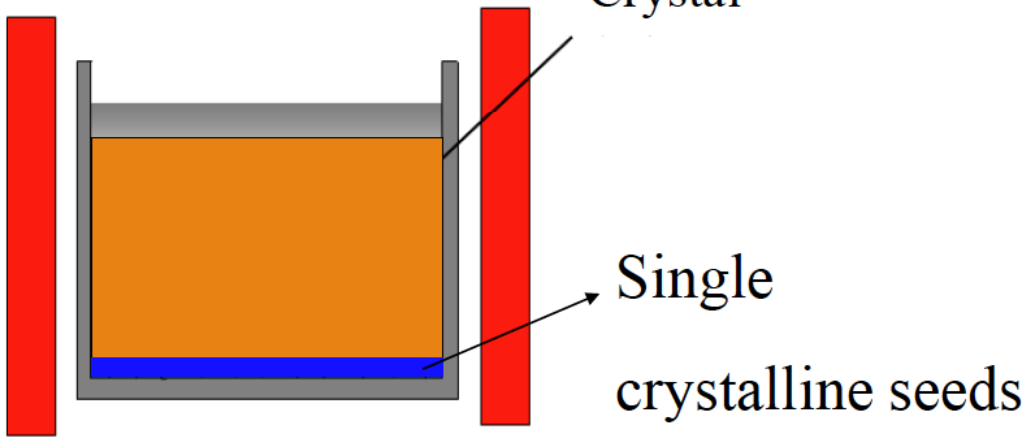

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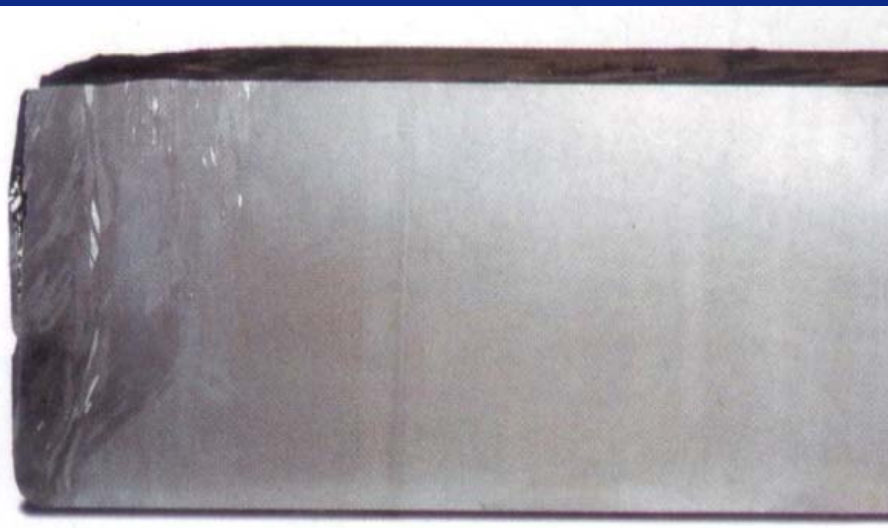
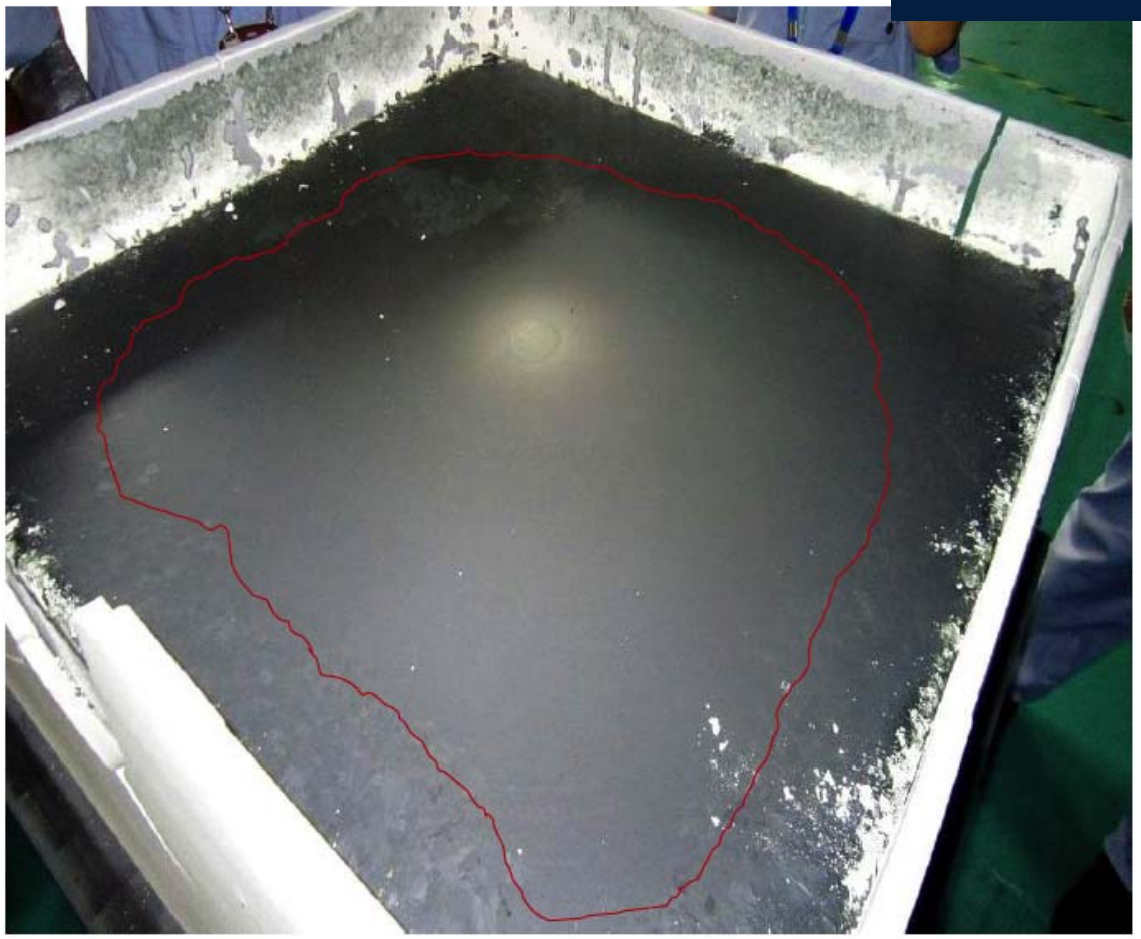
Better ingot quality: eg. Quasi-mono



830mm x 830mm square Ingot Crucible

JA SOLAR



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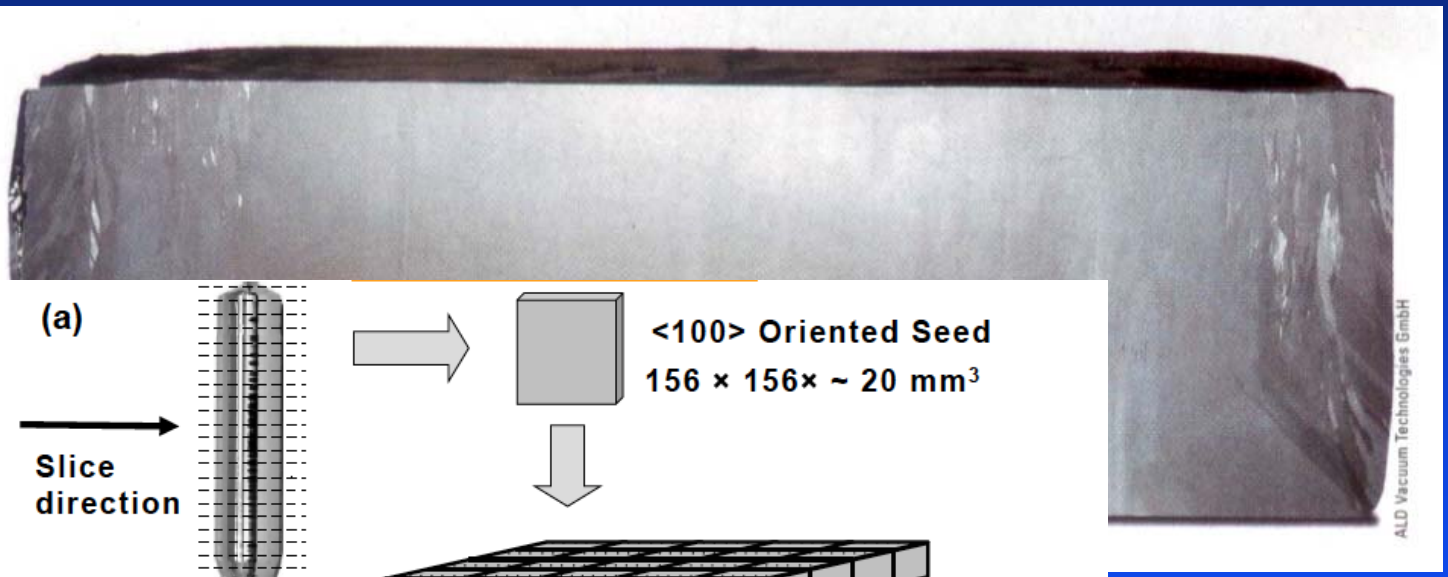

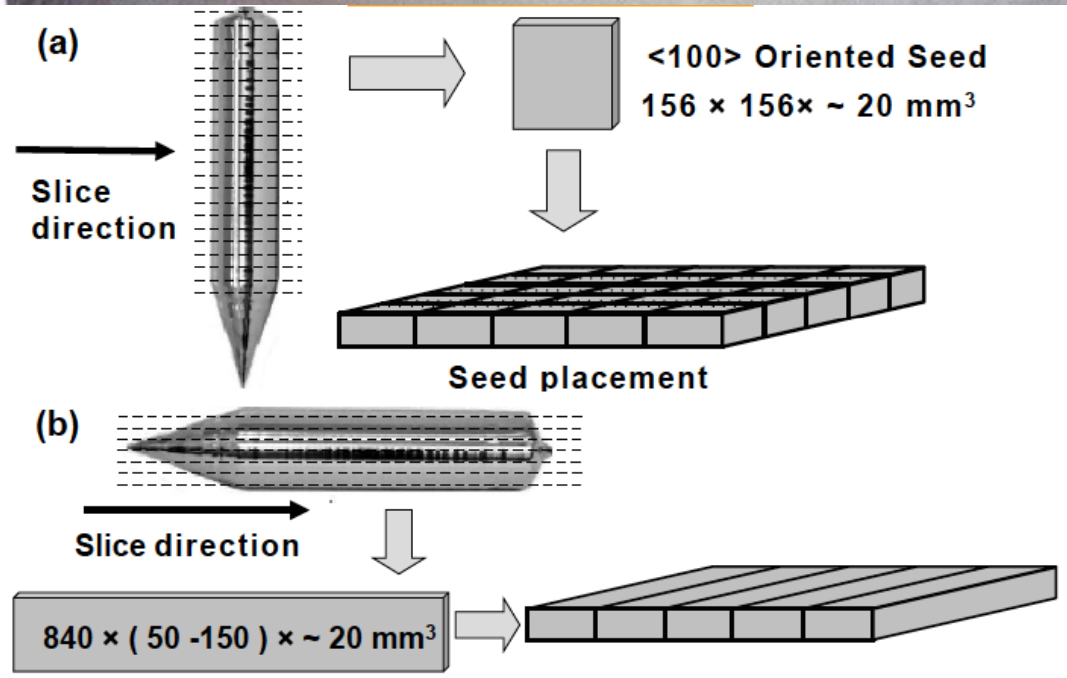

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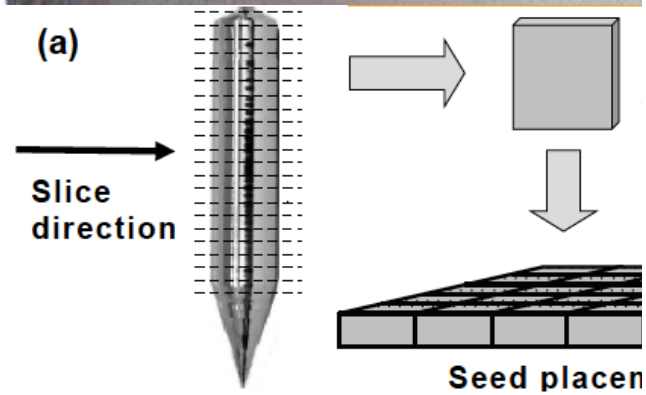

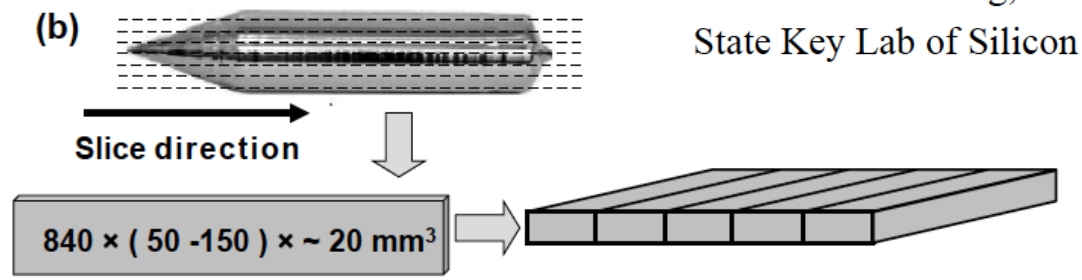

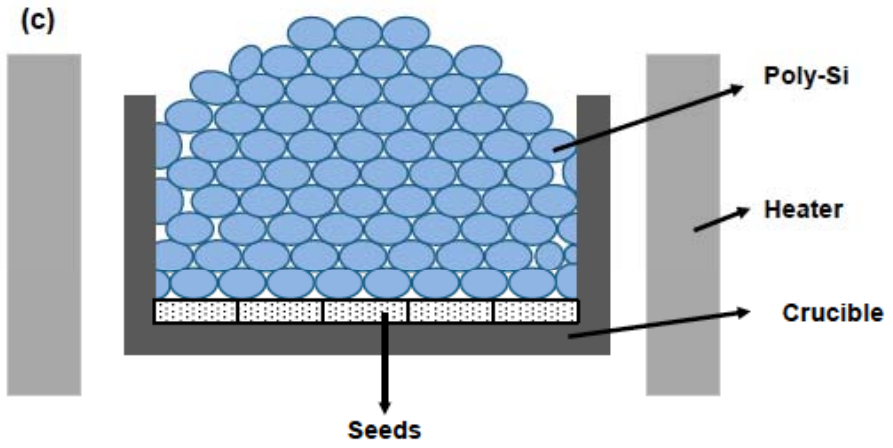

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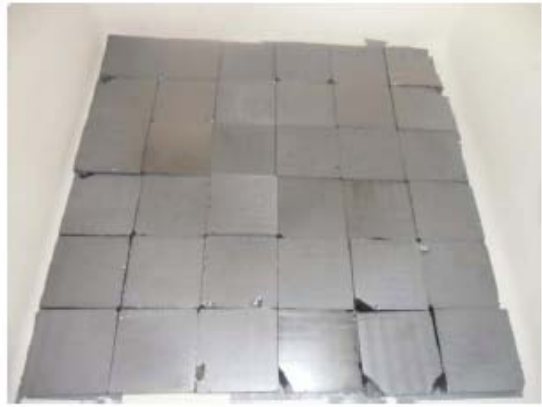
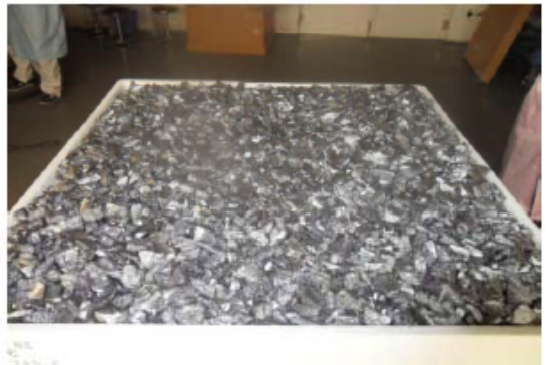
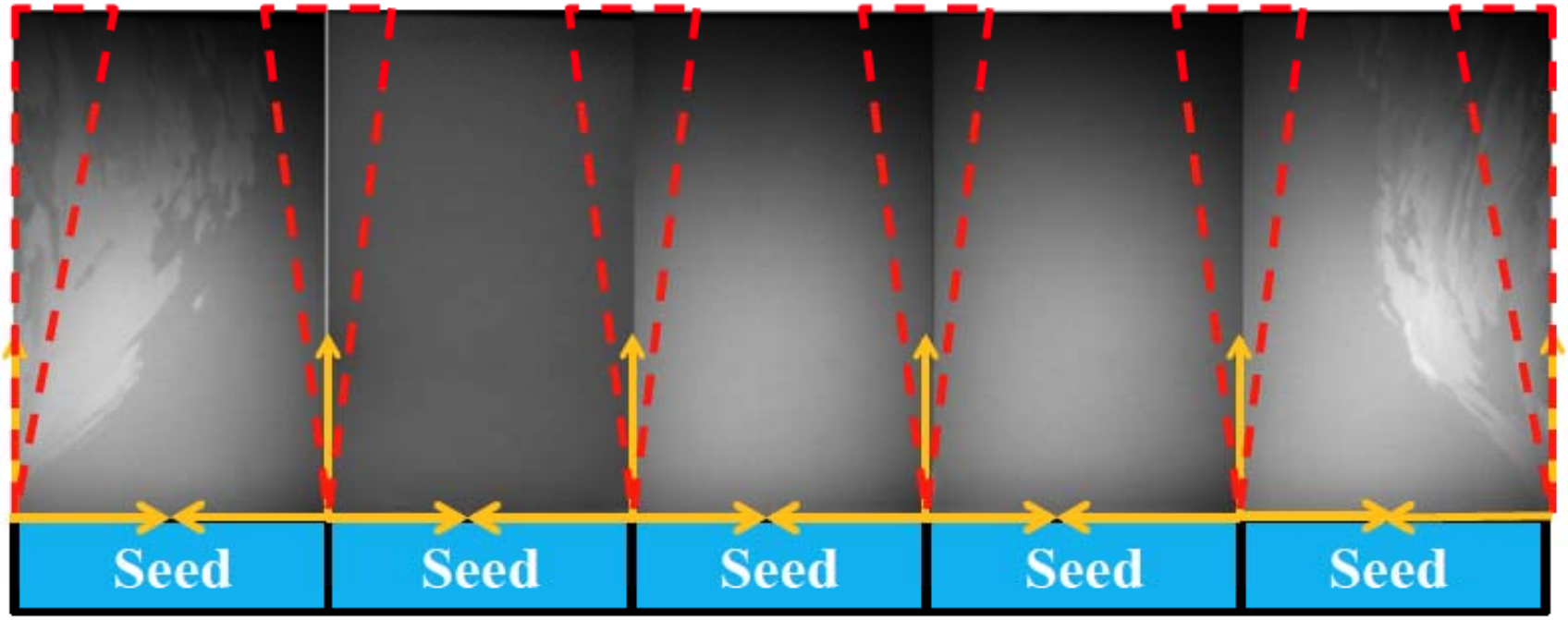


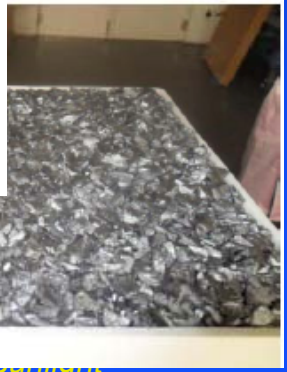


Better ingot quality: eg. Quasi-mono



Propagation of dislocations

Dislocation clusters always appear in the region outlined by red lines.



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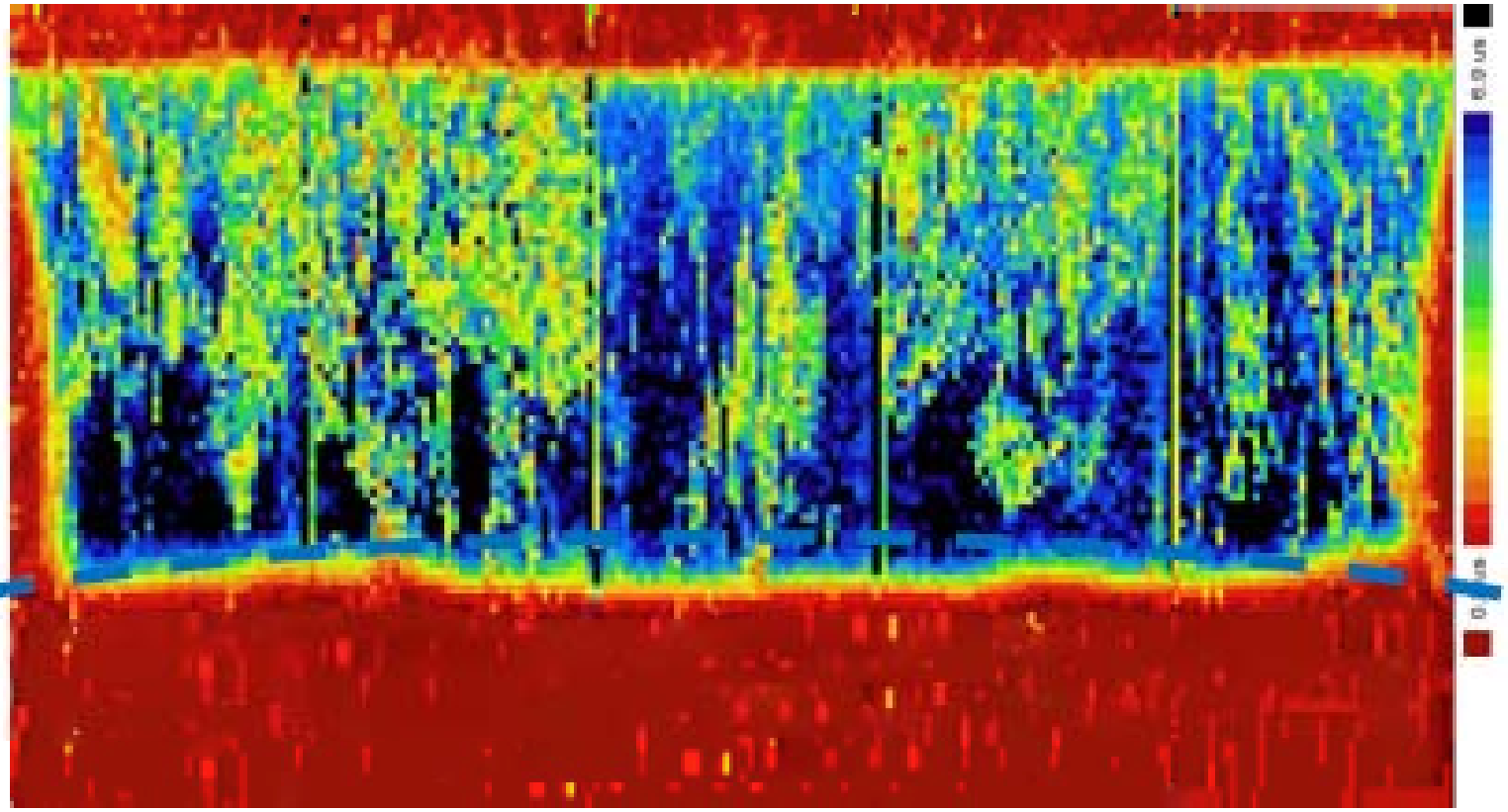

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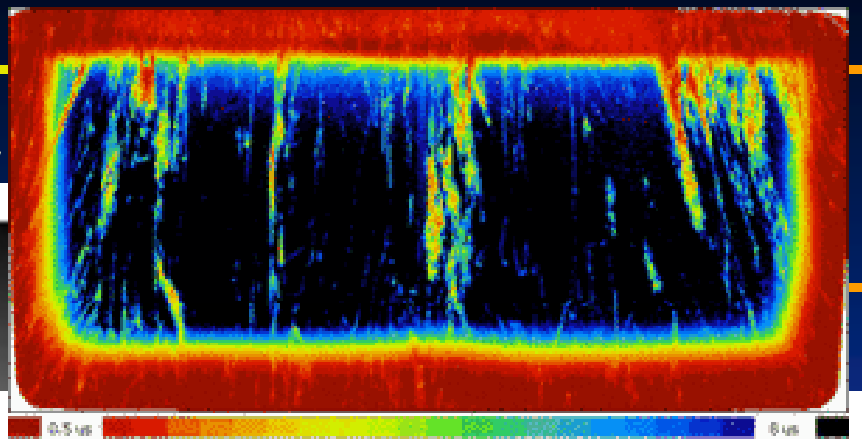

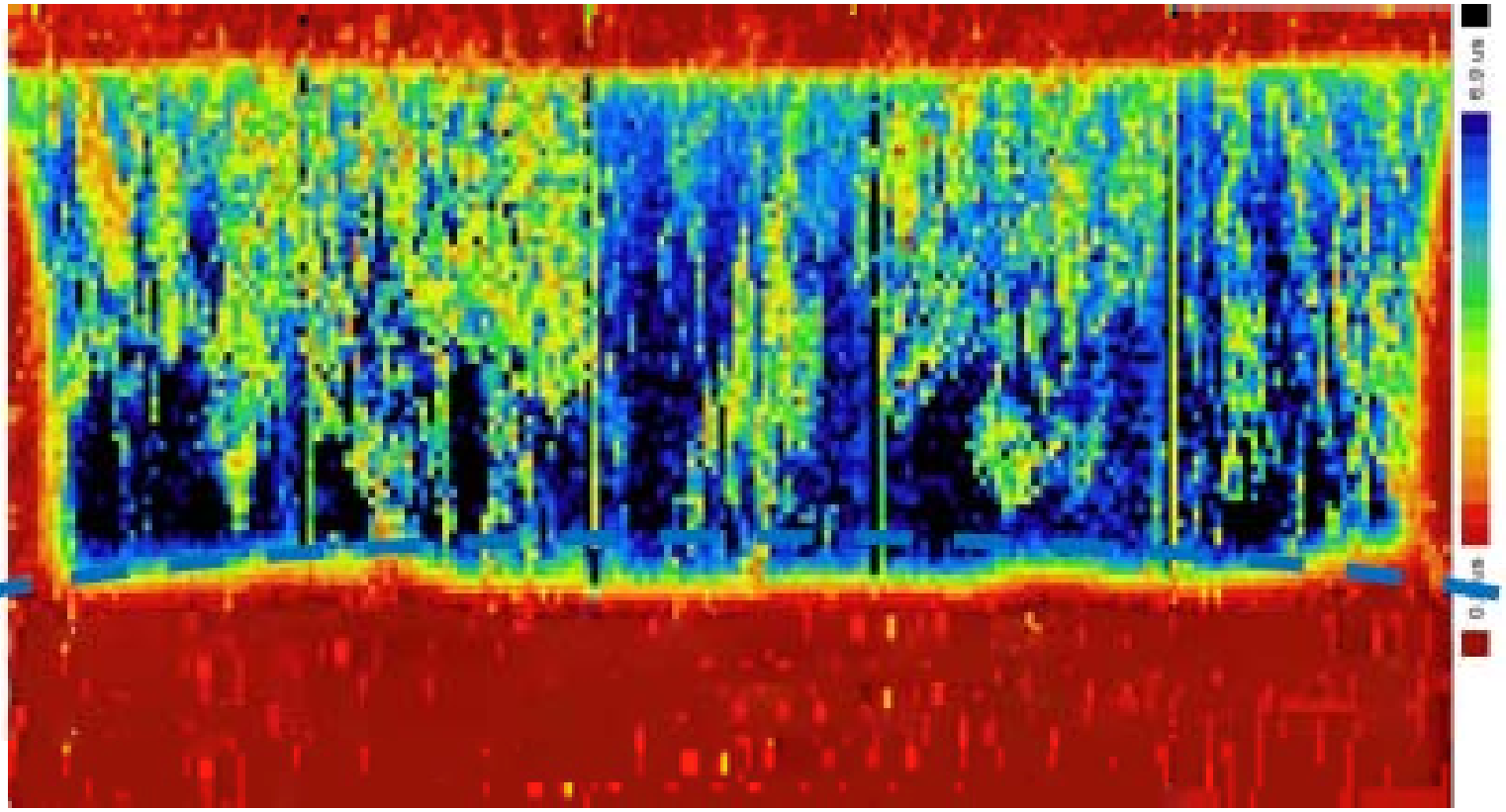

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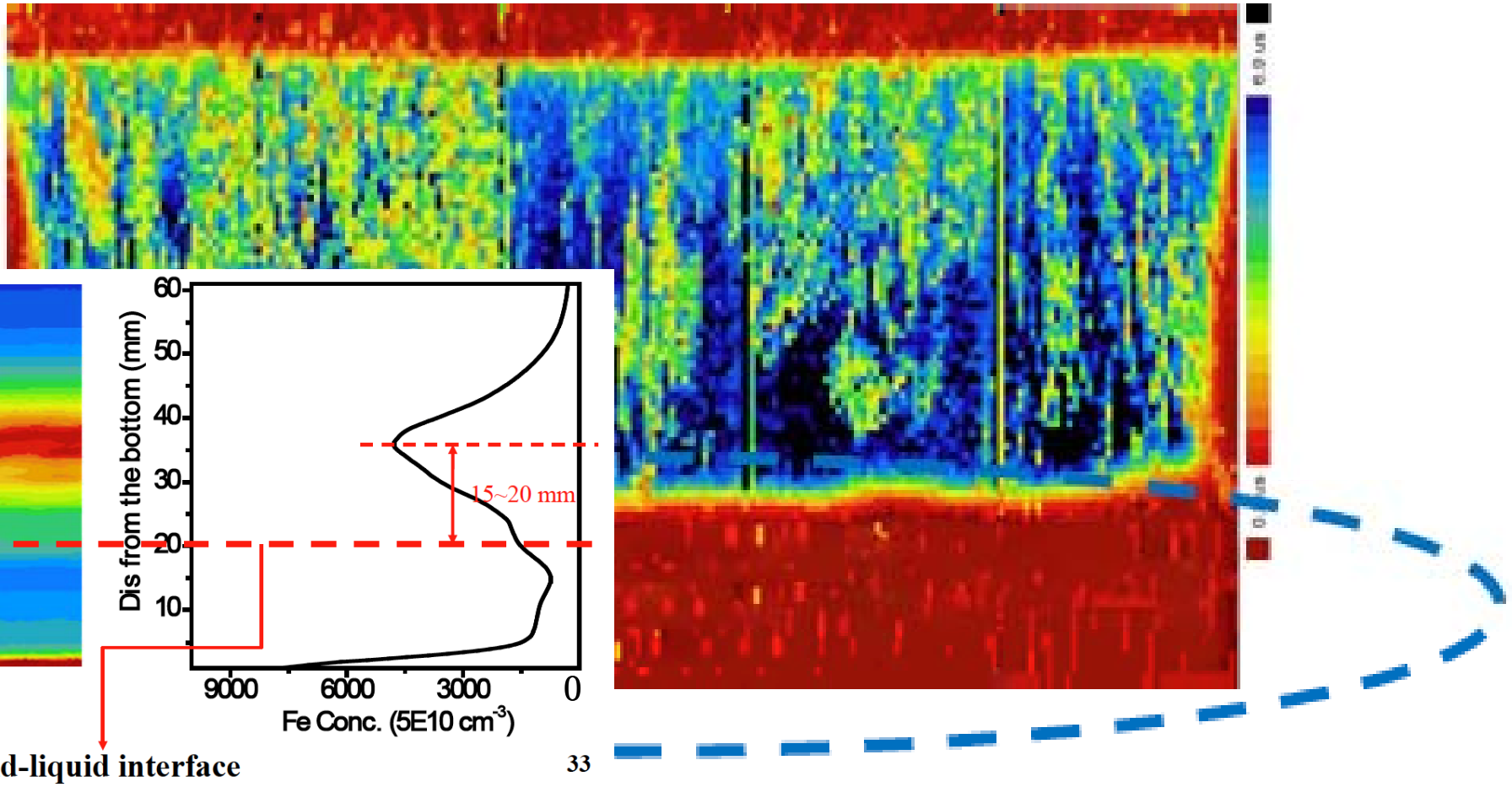

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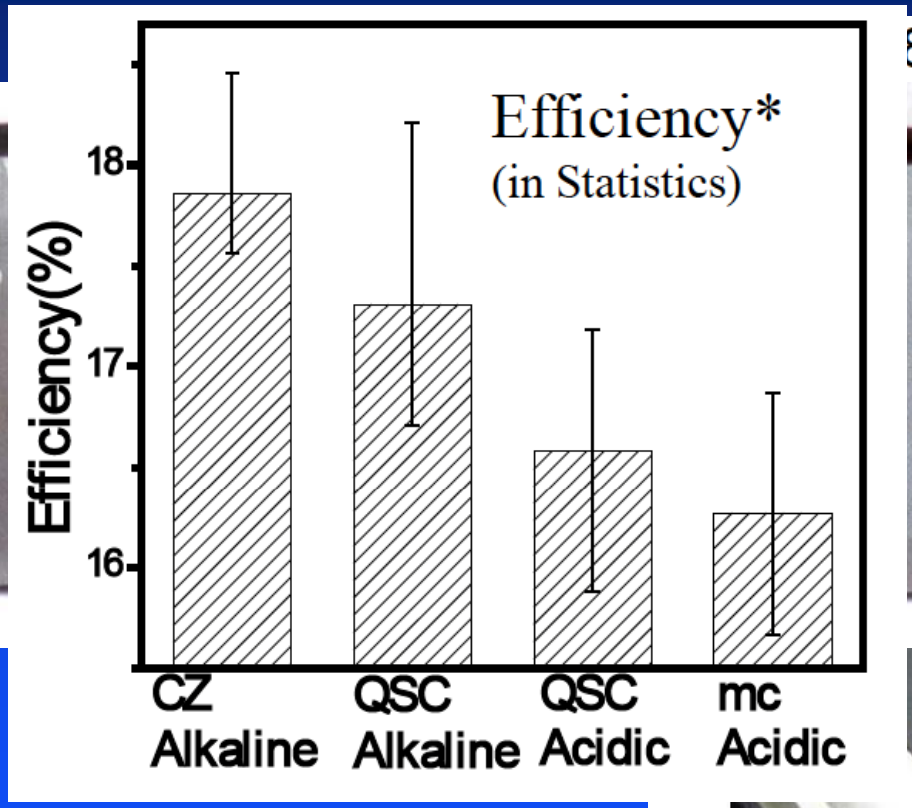
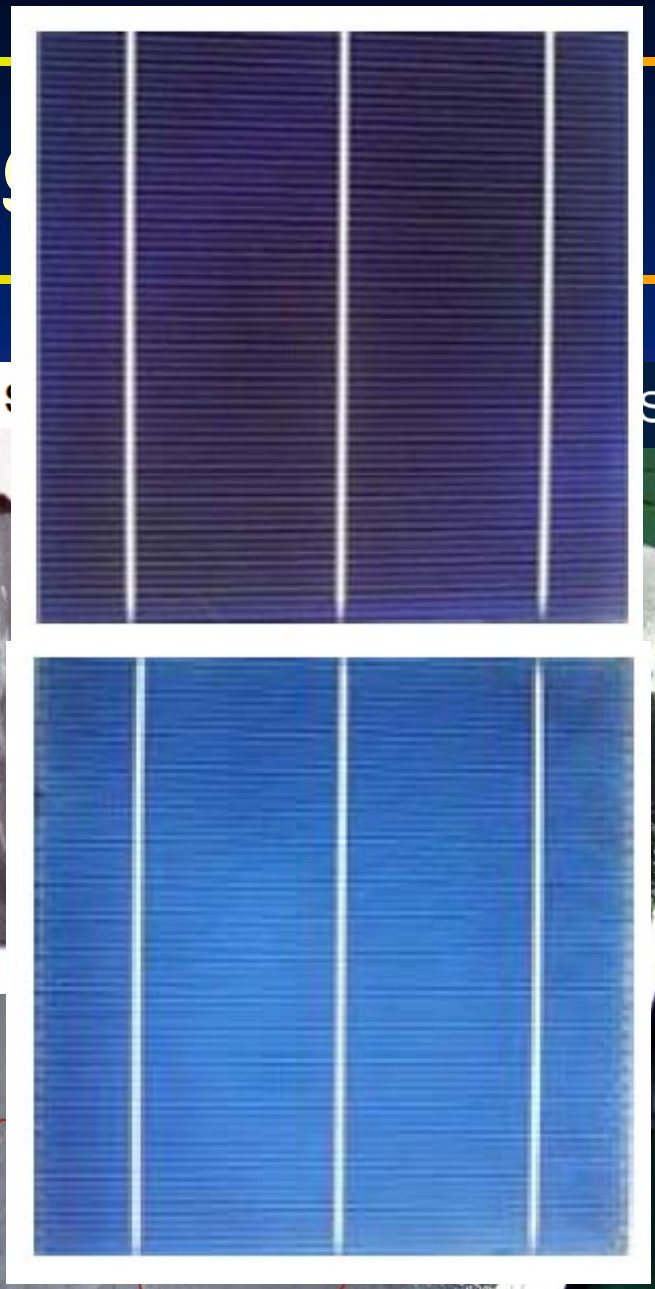


830mm s

SOLAR



UNSW

Better ingot quality: eg. Quasi-mono

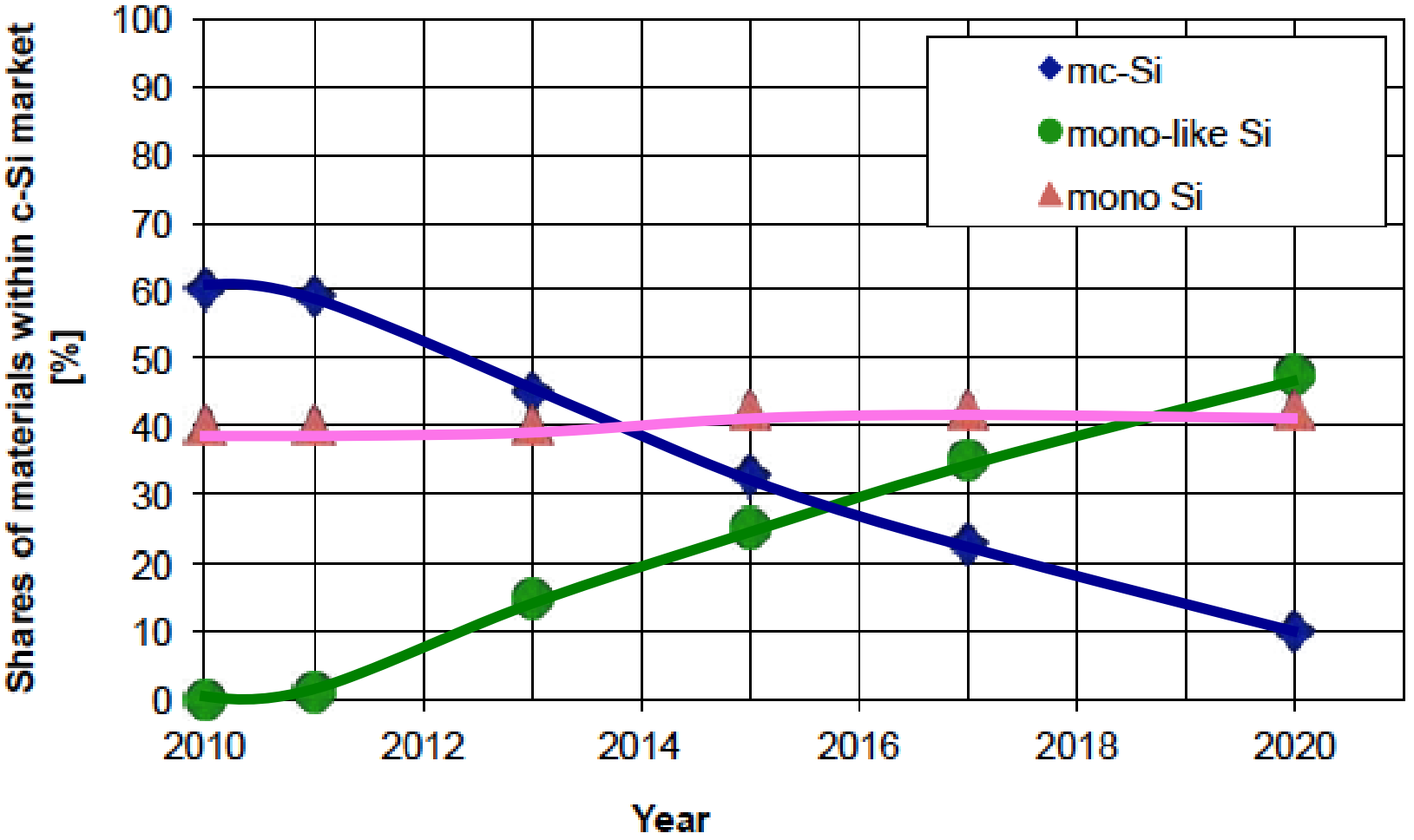
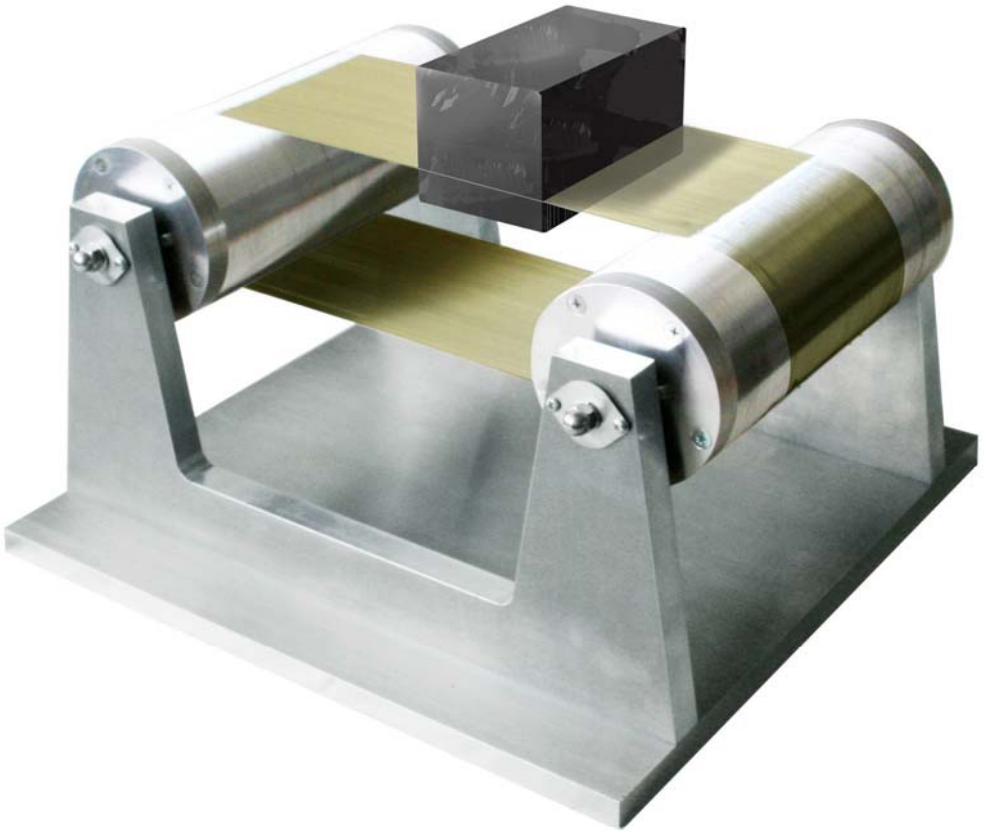


Fig. 26 Expected share of mc-Si, mono-Si and mono-like Si material.



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edition of the ITRPV was jointly
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rs. Feedback and input from various
viders of production materials was

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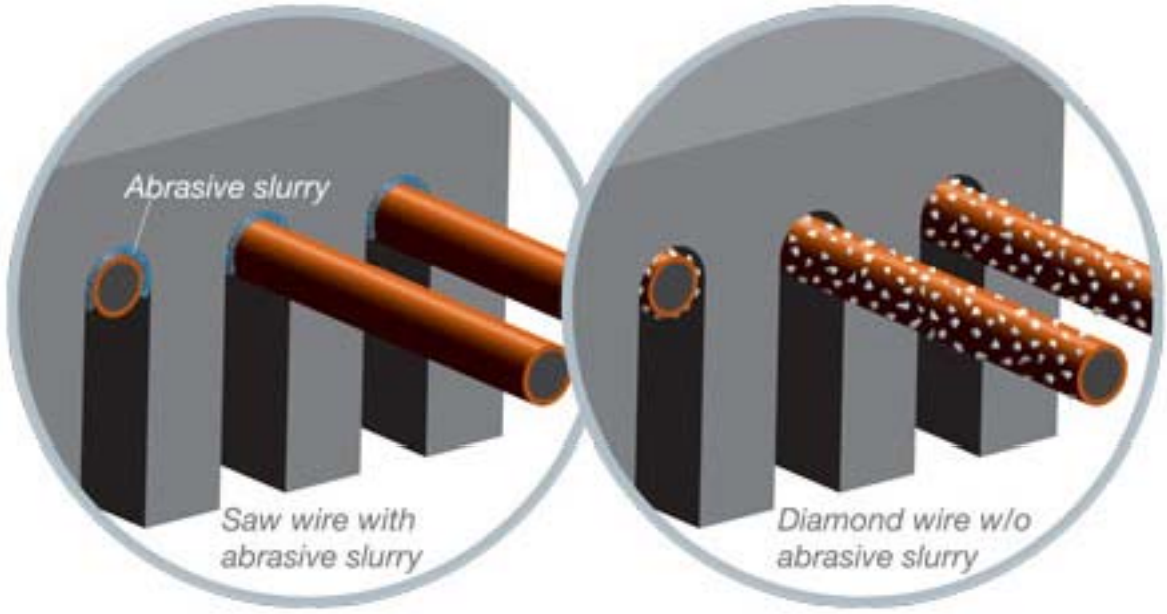

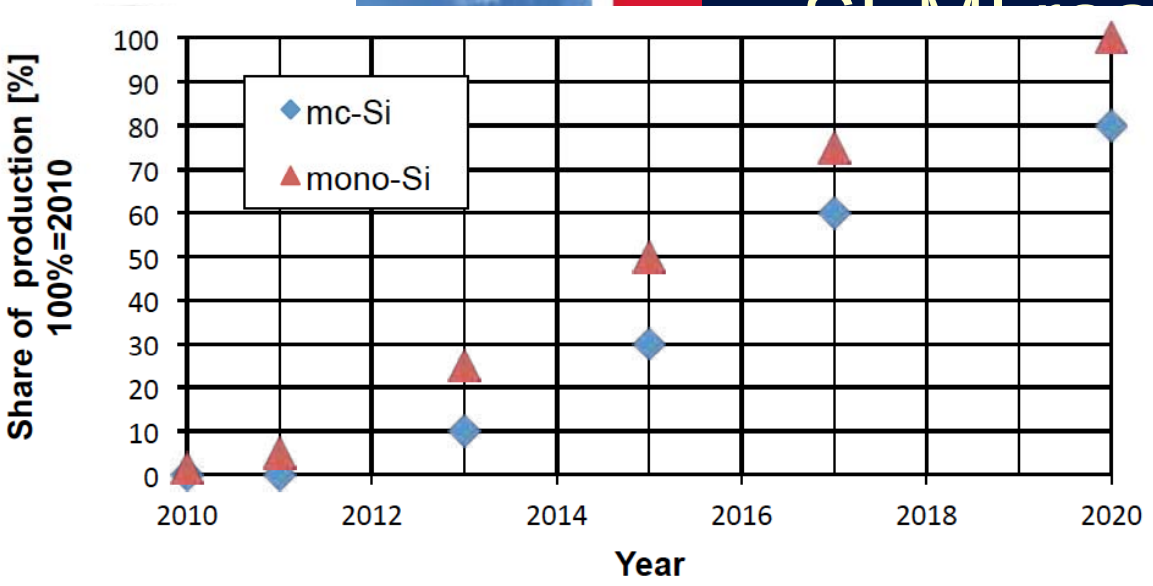

Fig 3 Share of diamond wire technology based wafering vs. slurry based wafering for mono- and mc-Si (2010 = 100% slurry based wafering).

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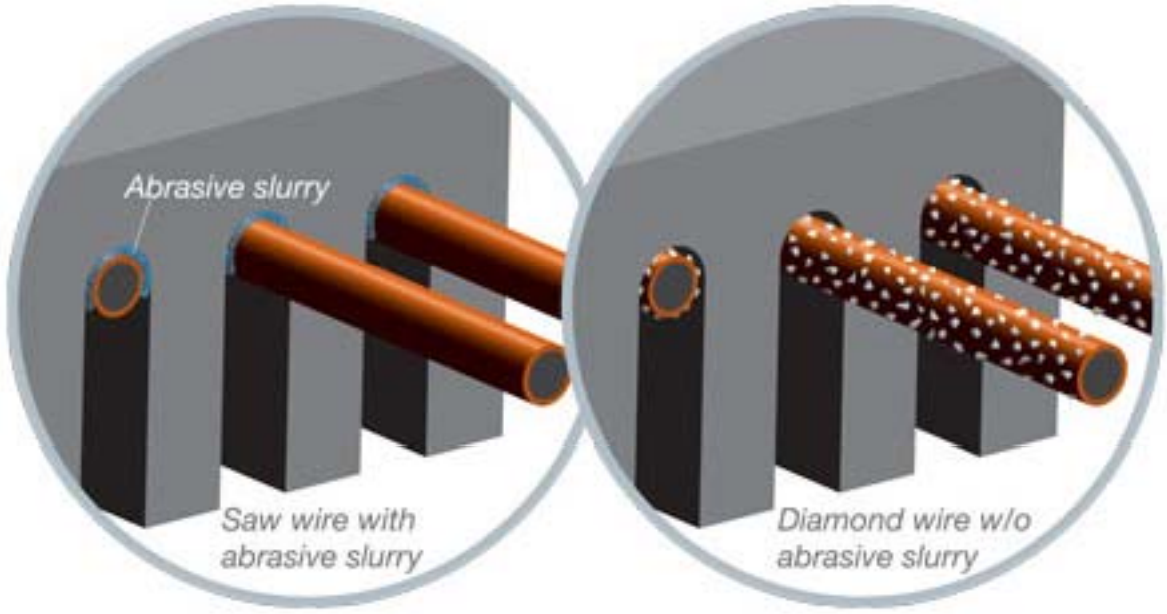

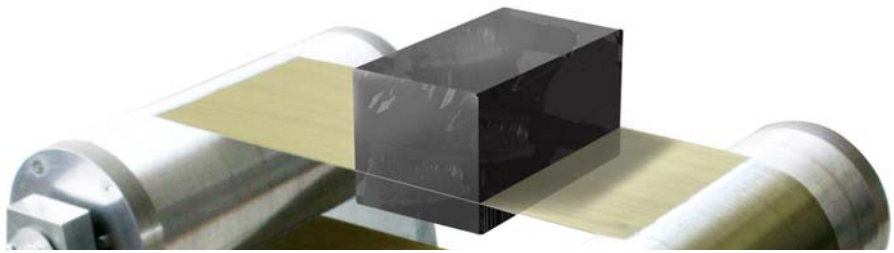

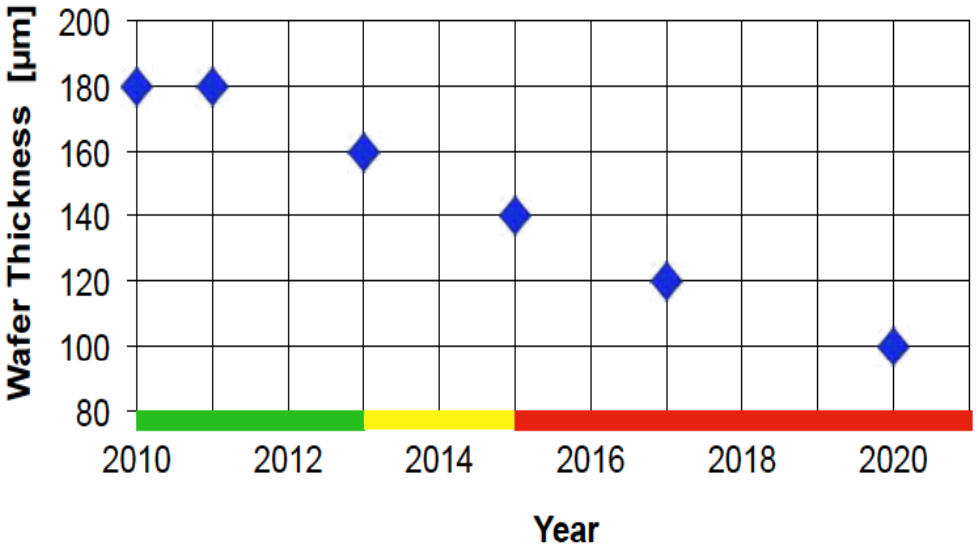

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Fig. 5: Trend of minimum wafer thickness processed in mass production of solar cells.

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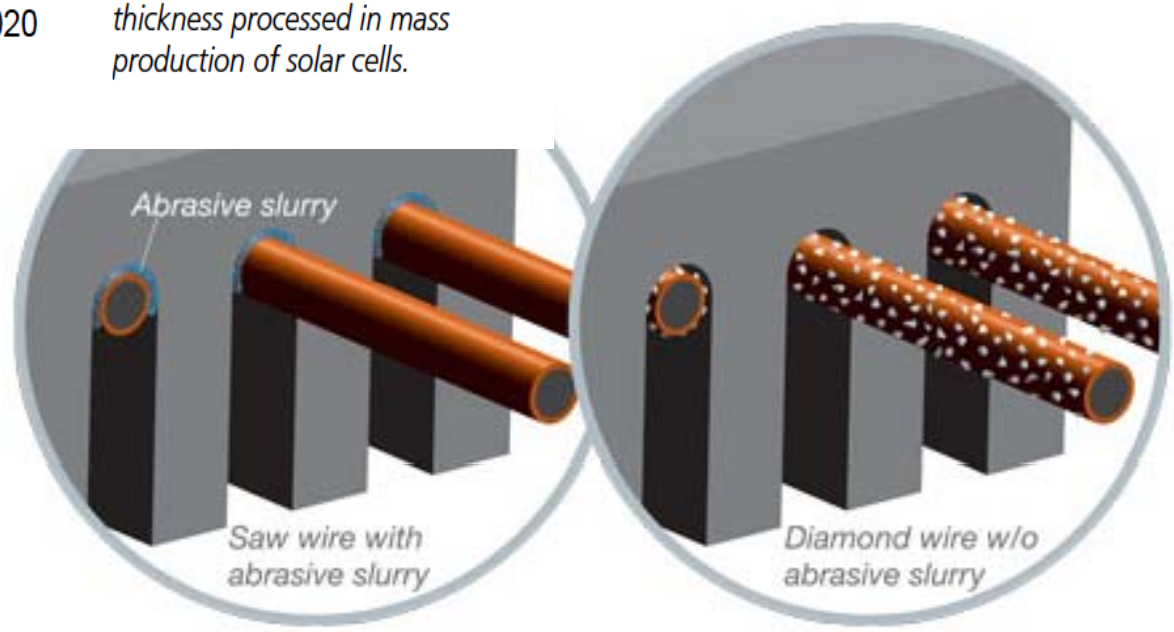

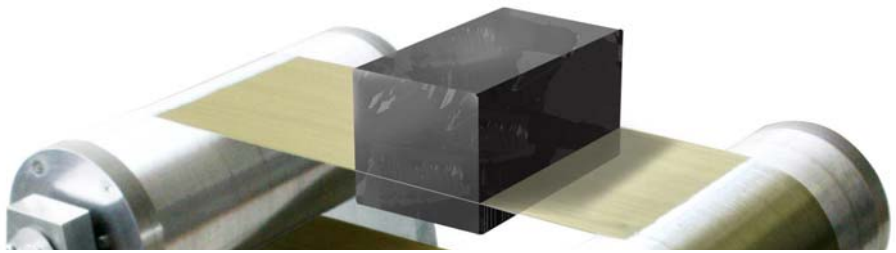

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SEMI roadmap

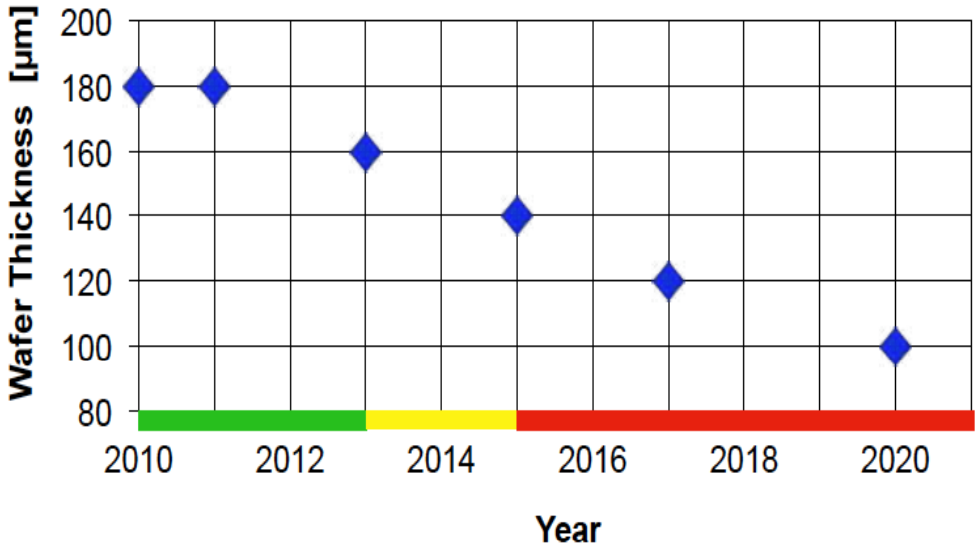

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Fig. 5: Trend of minimum wafer thickness processed in mass production of solar cells.

Green	Industrial solution exists and is being optimized in production.
Yellow	Industrial solution is known but not yet in mass production.
Orange	Interim solution is known, but too expensive or not suitable for production.
Red	Industrial solution is not known.

Saw wire with abrasive slurry

Diamond wire w/o abrasive slurry

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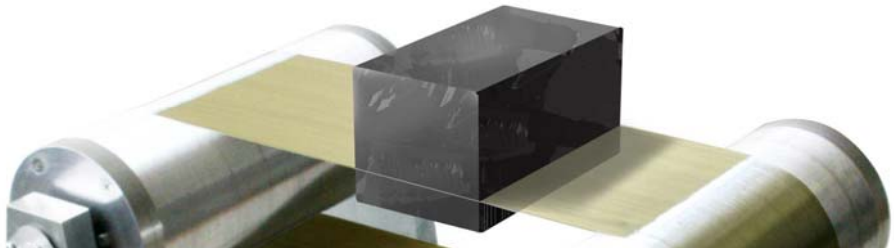

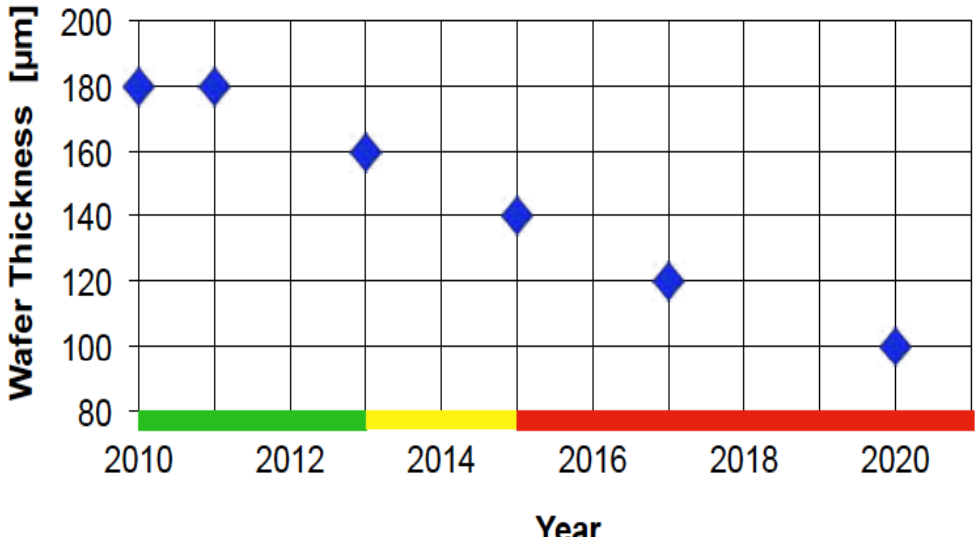

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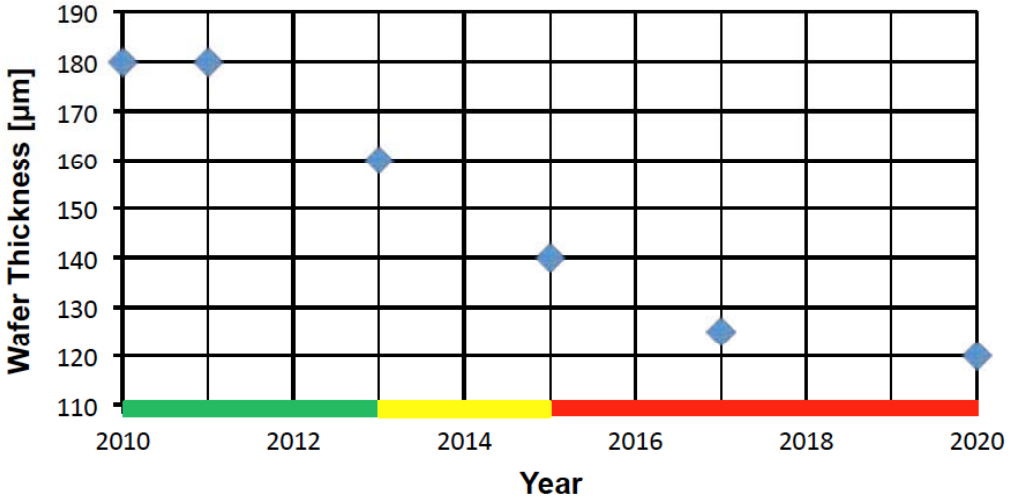
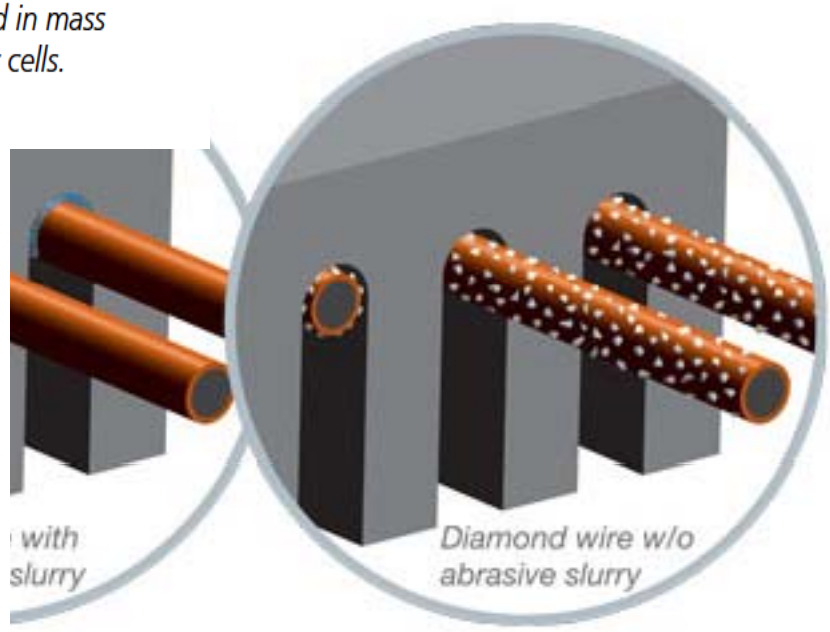
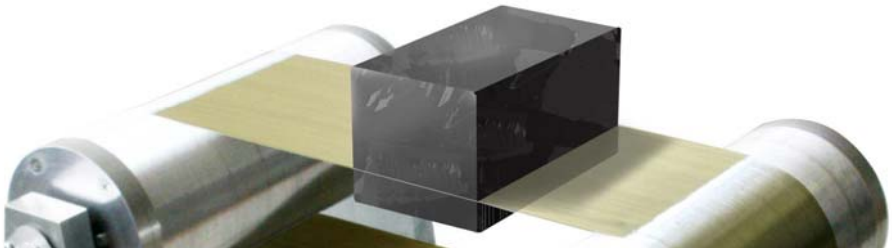
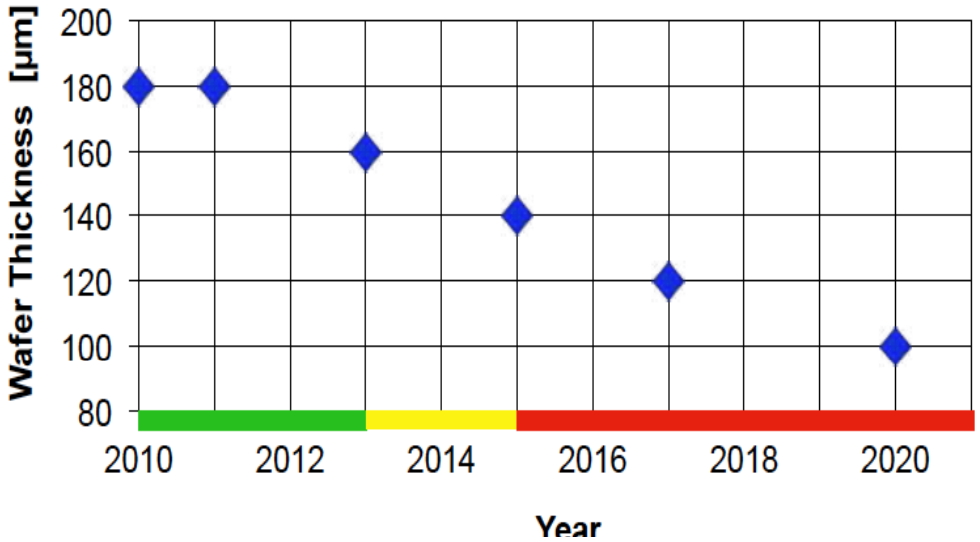


Fig. 4 Trend of minimum as-cut wafer thickness processed in mass production of solar cells.







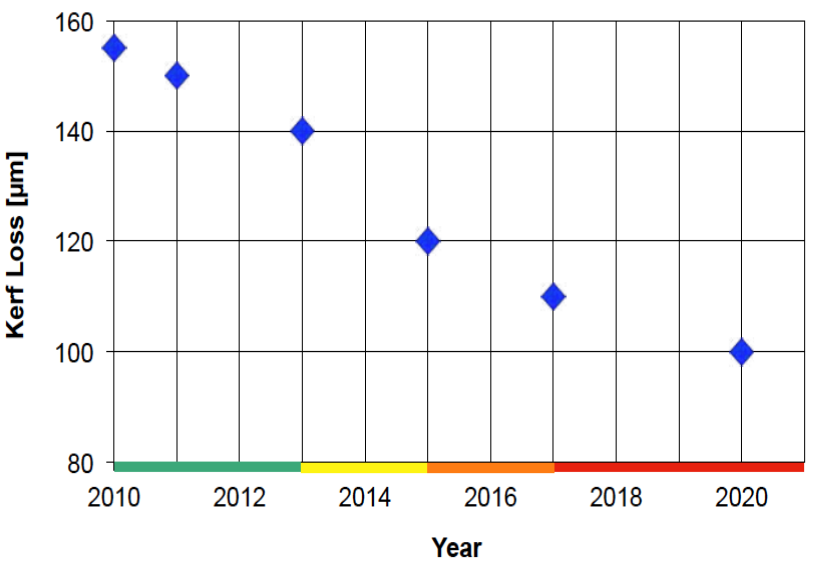


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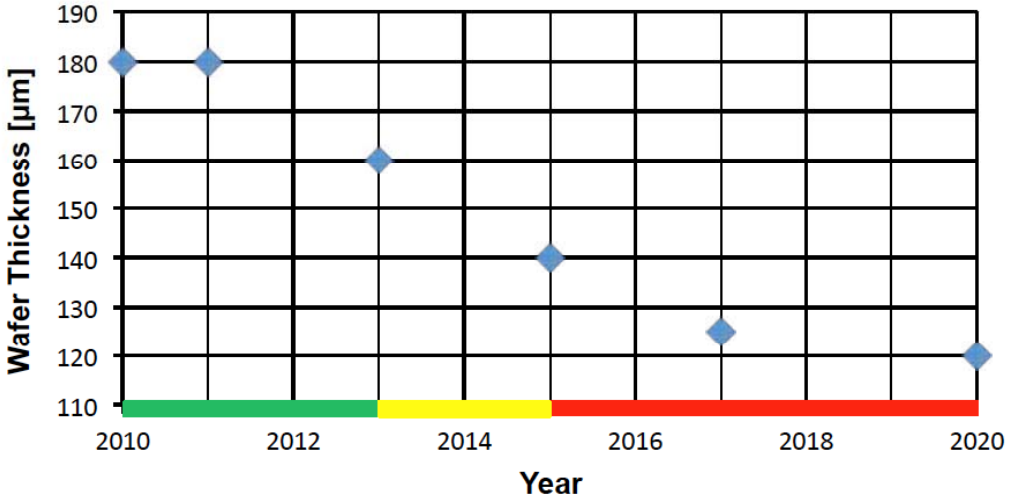
Fig. 21: Kerf loss reduction trend expected by the roadmap.



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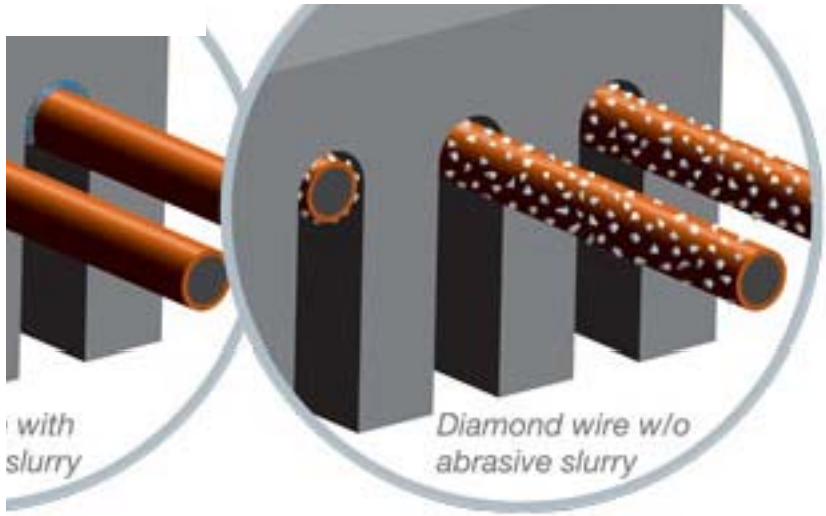

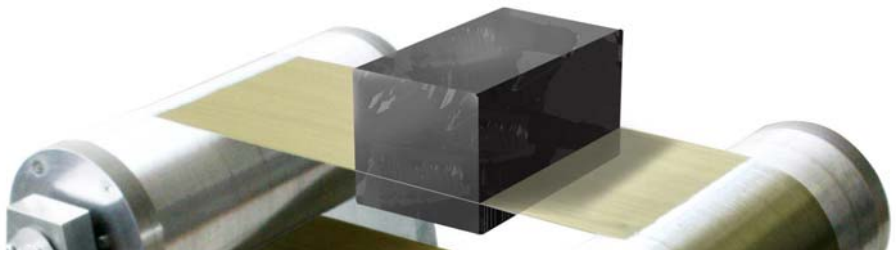

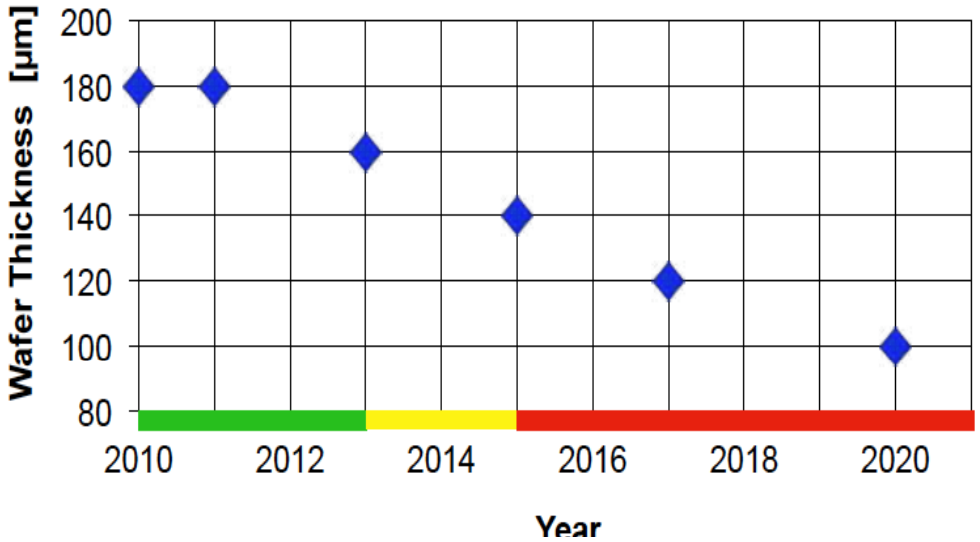

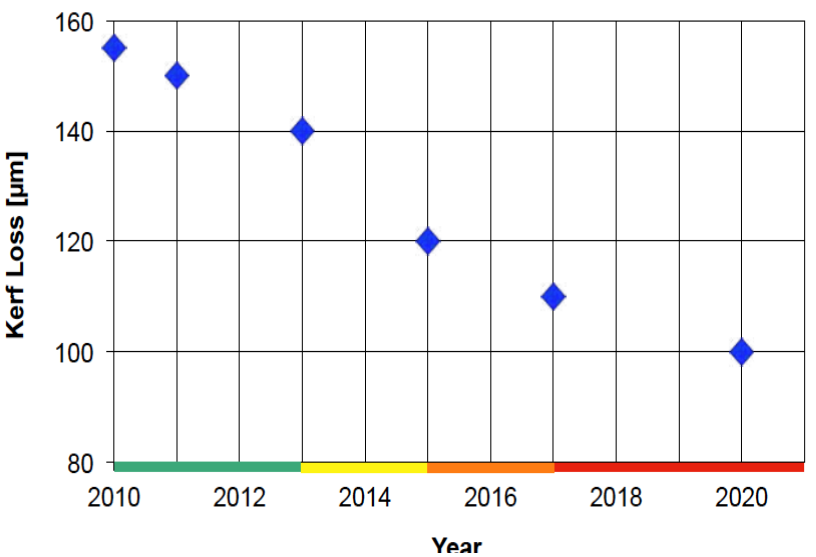

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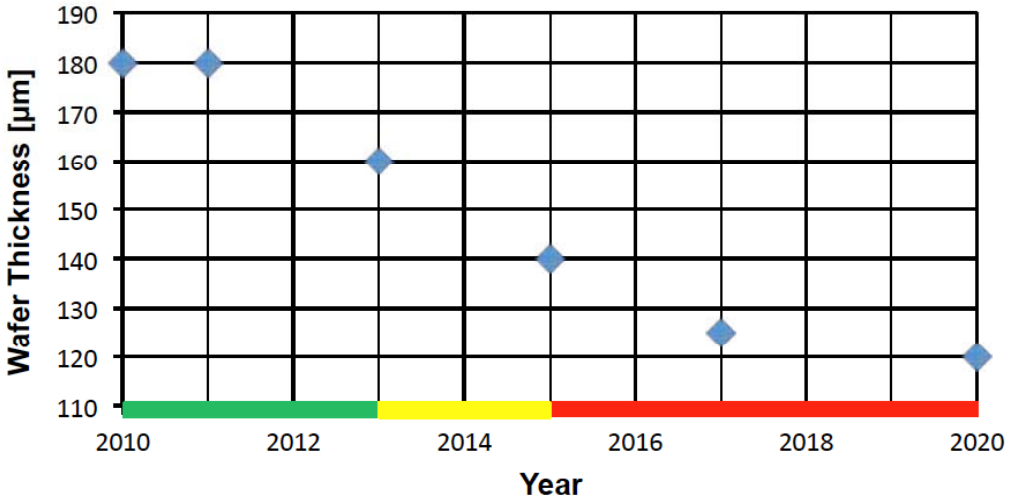


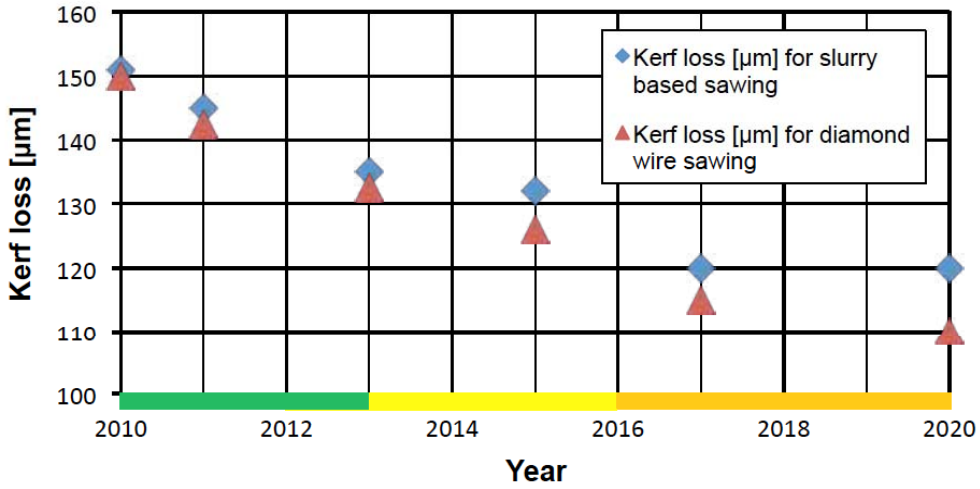
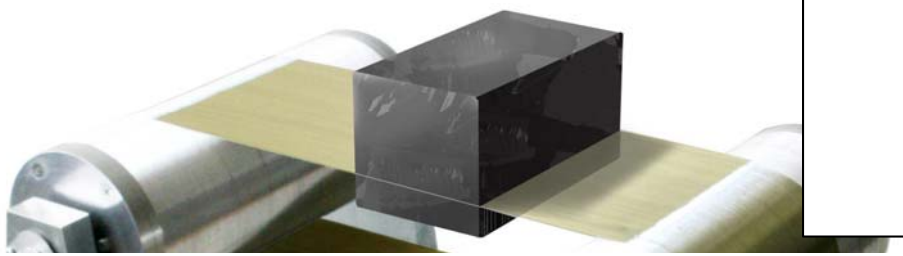
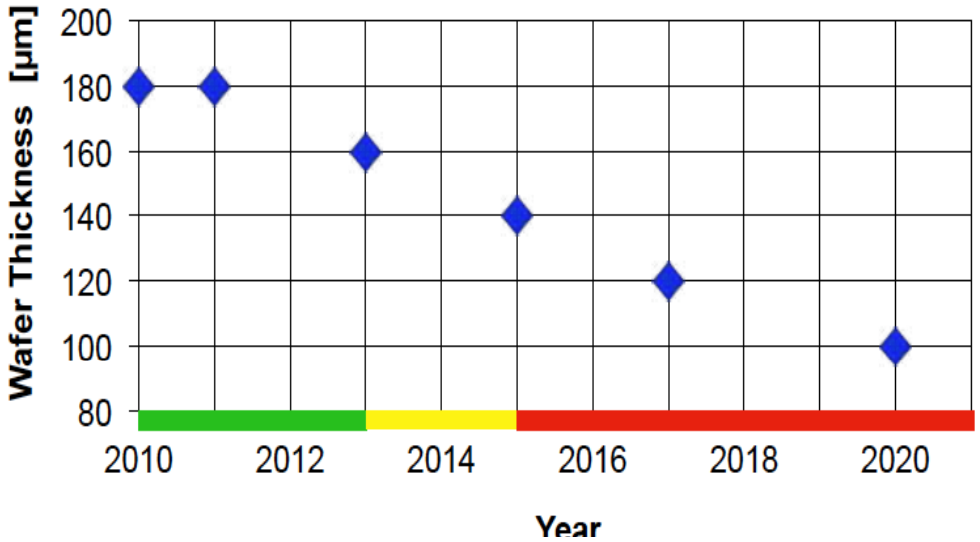
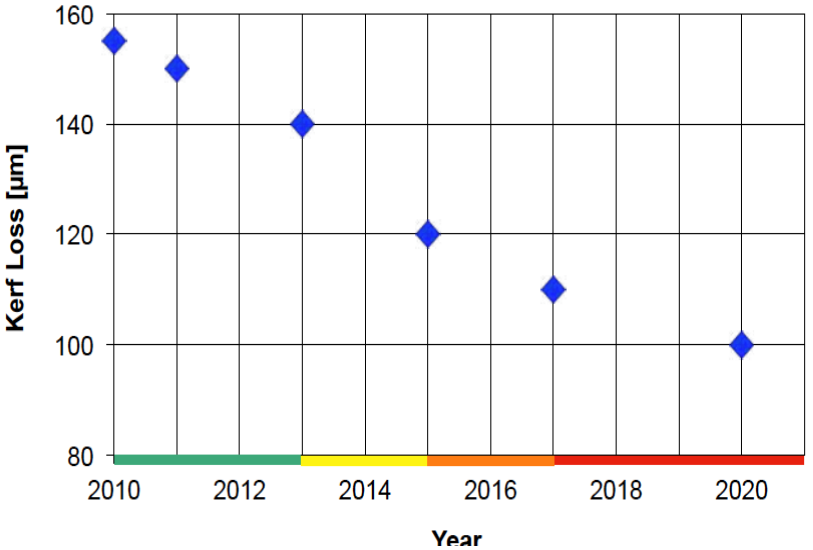


Fig. 20 reductic expecte roadma



2012: 32 wafers/cm
2020: 42 wafers/cm (slurry)
43.5/cm diamond





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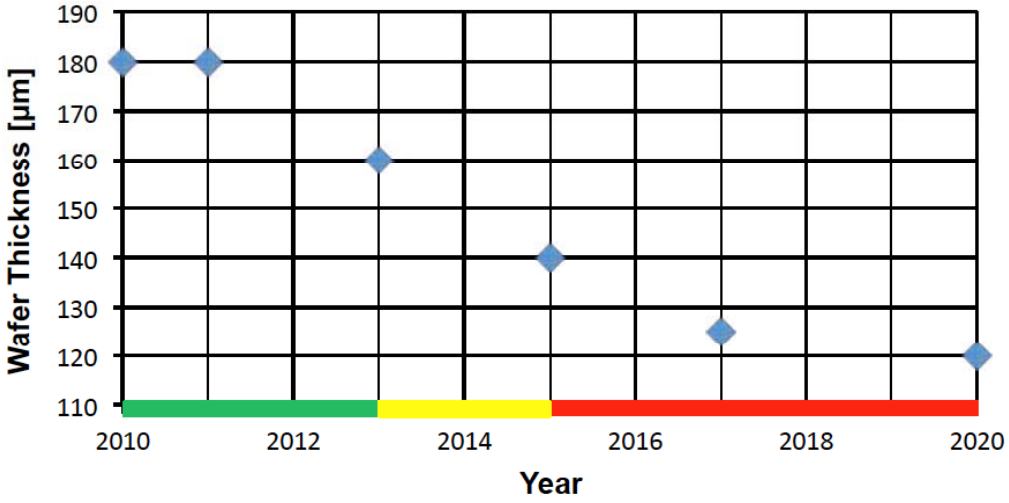


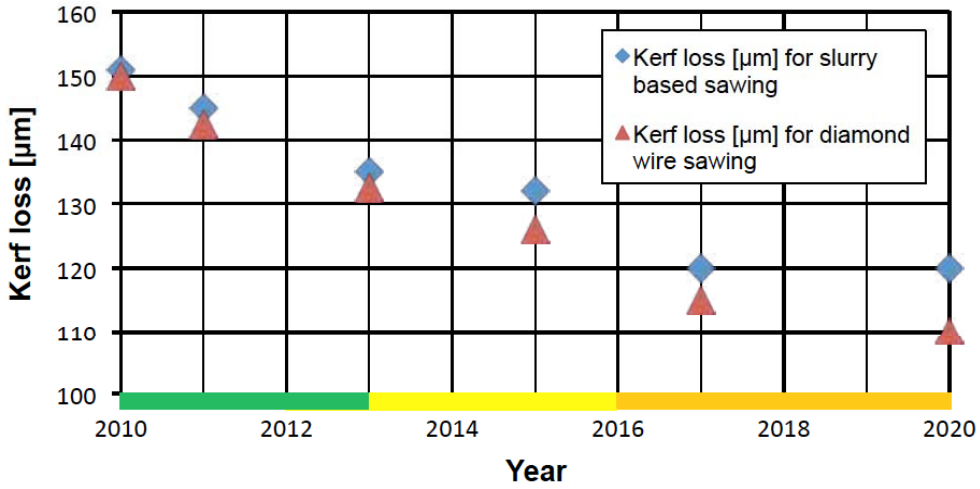
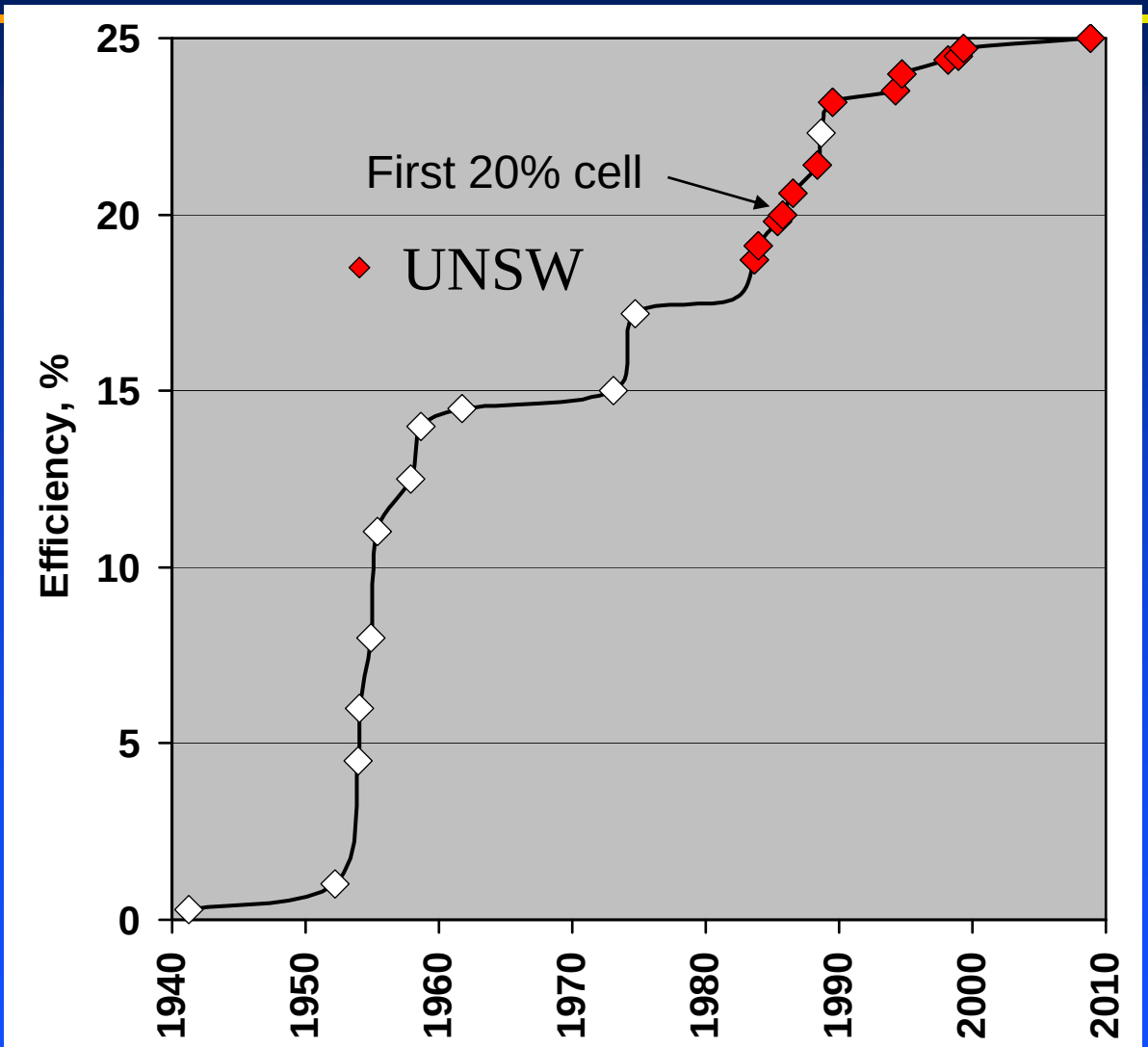
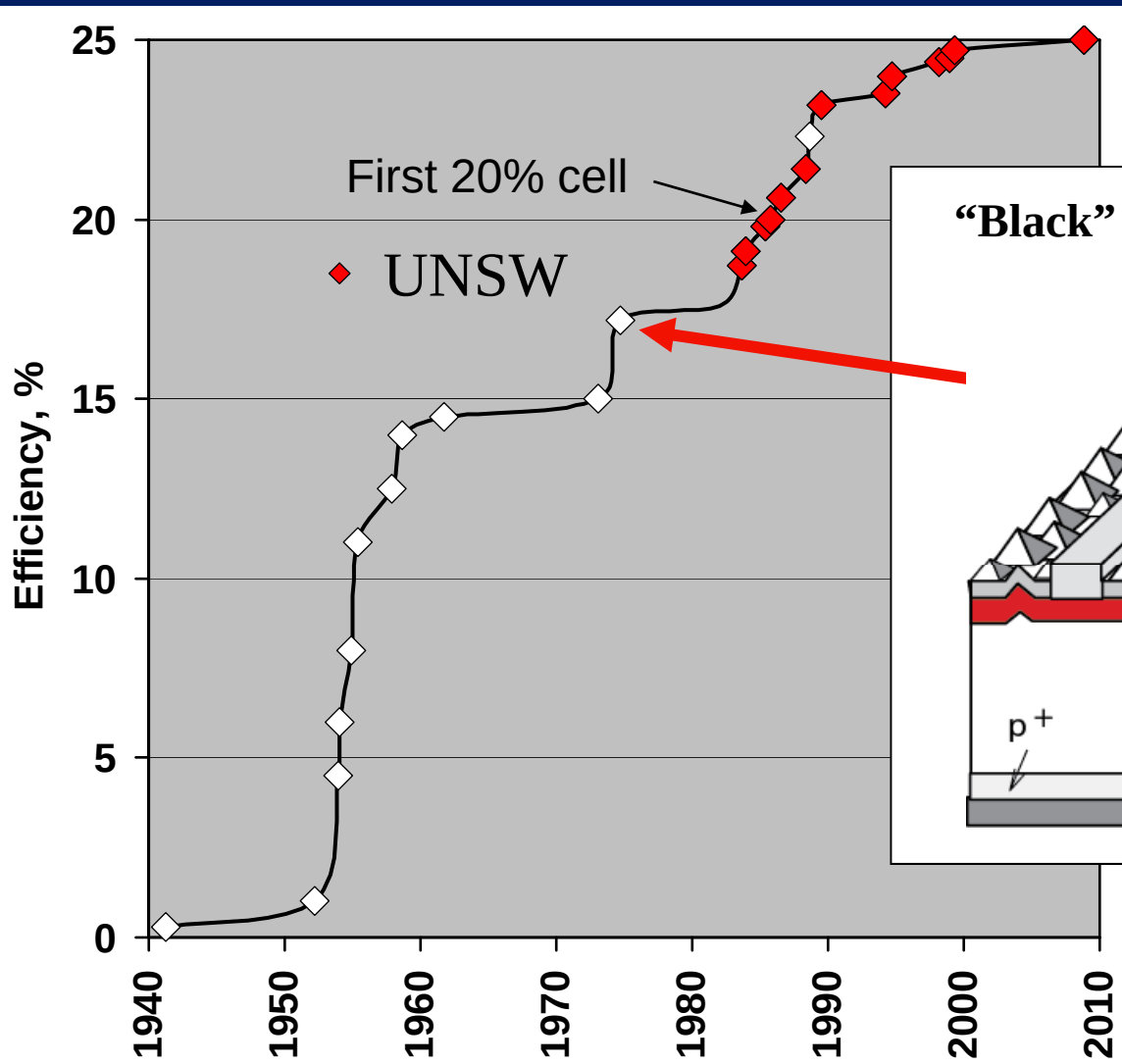


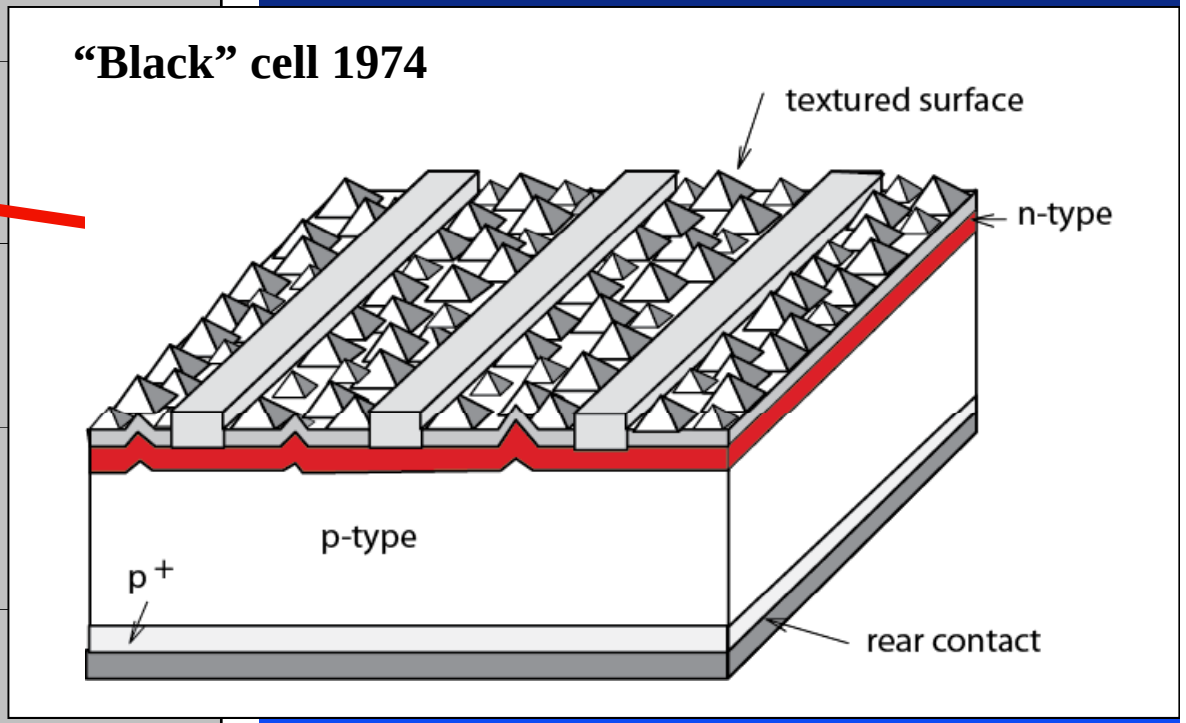
Fig. 20 reductic expecte roadma

Improved efficiency: lab cells

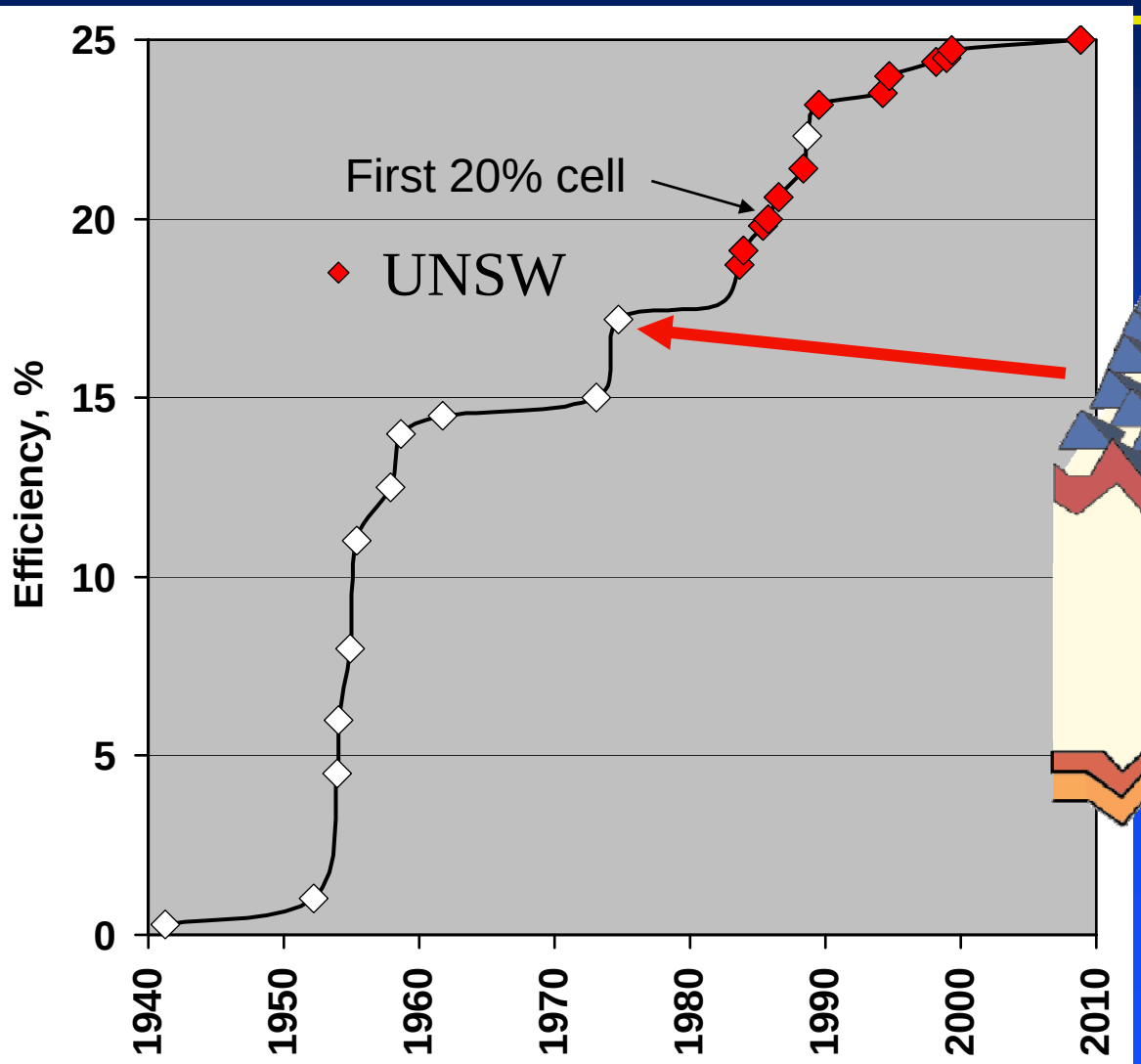


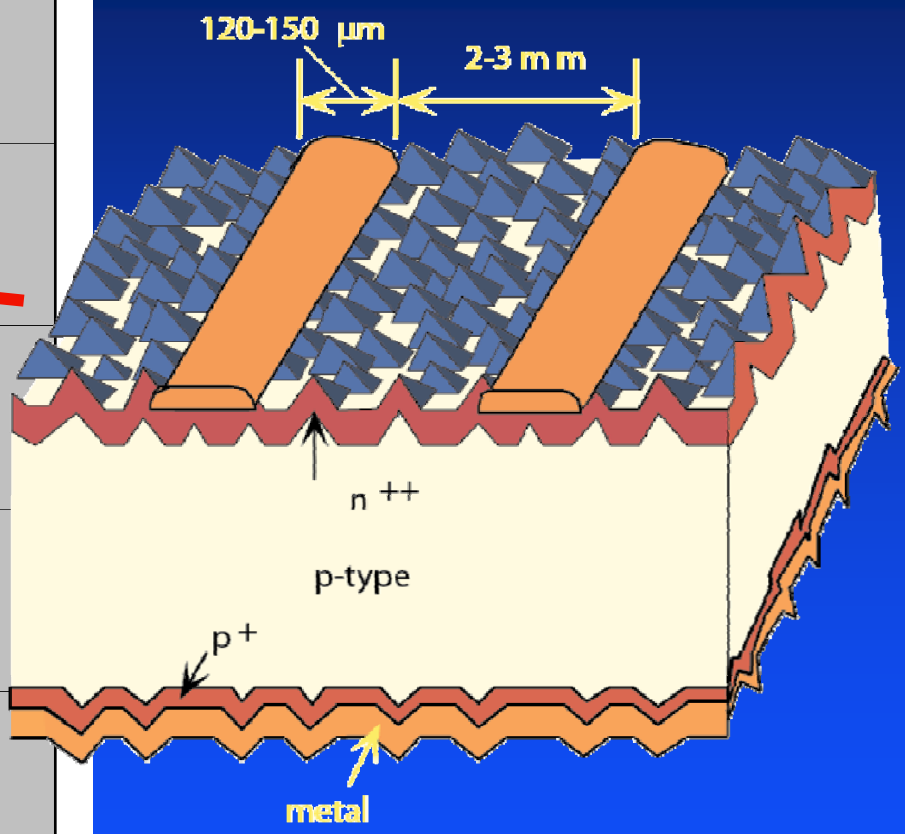
Improved efficiency: lab cells



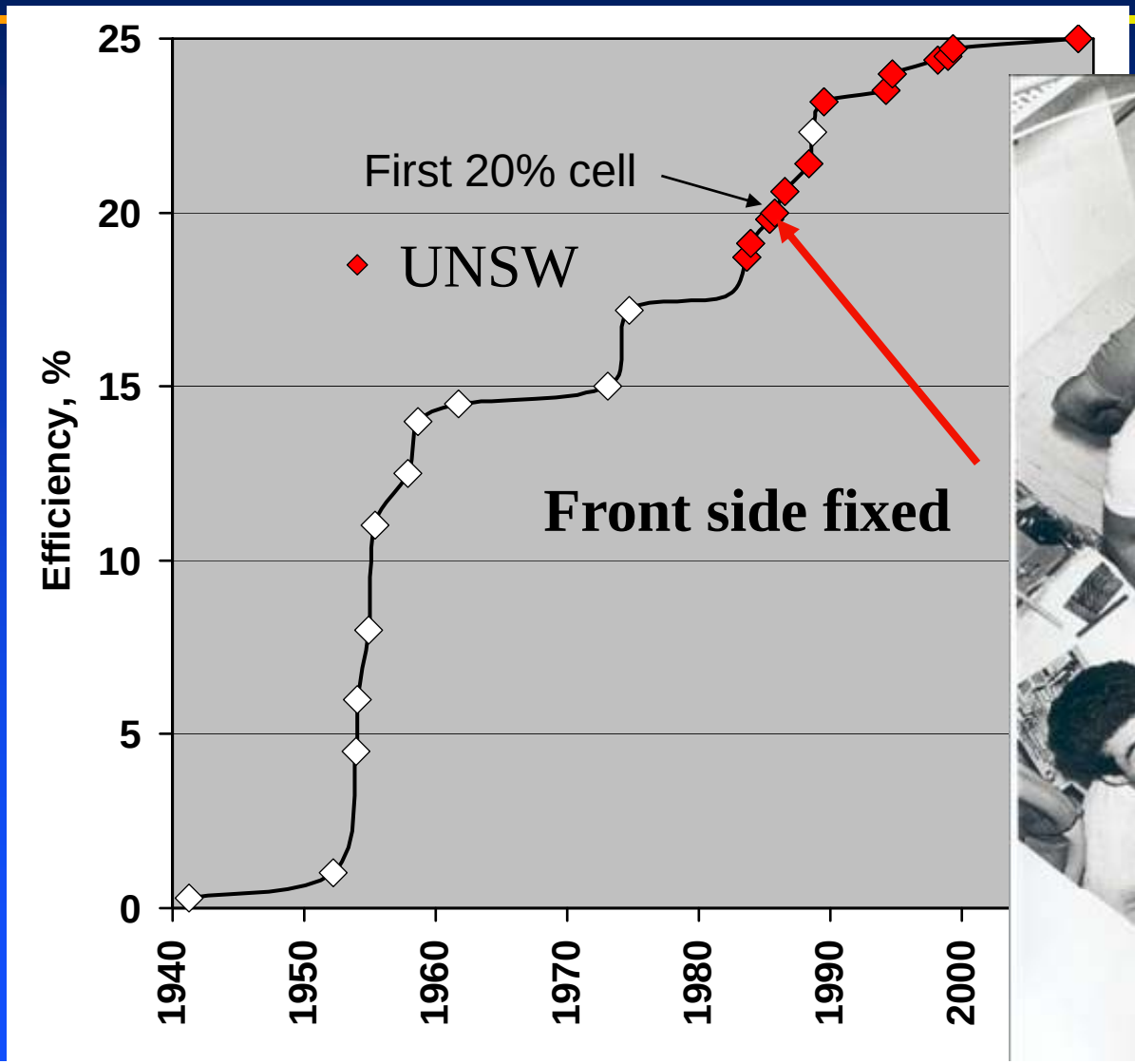


Improved efficiency

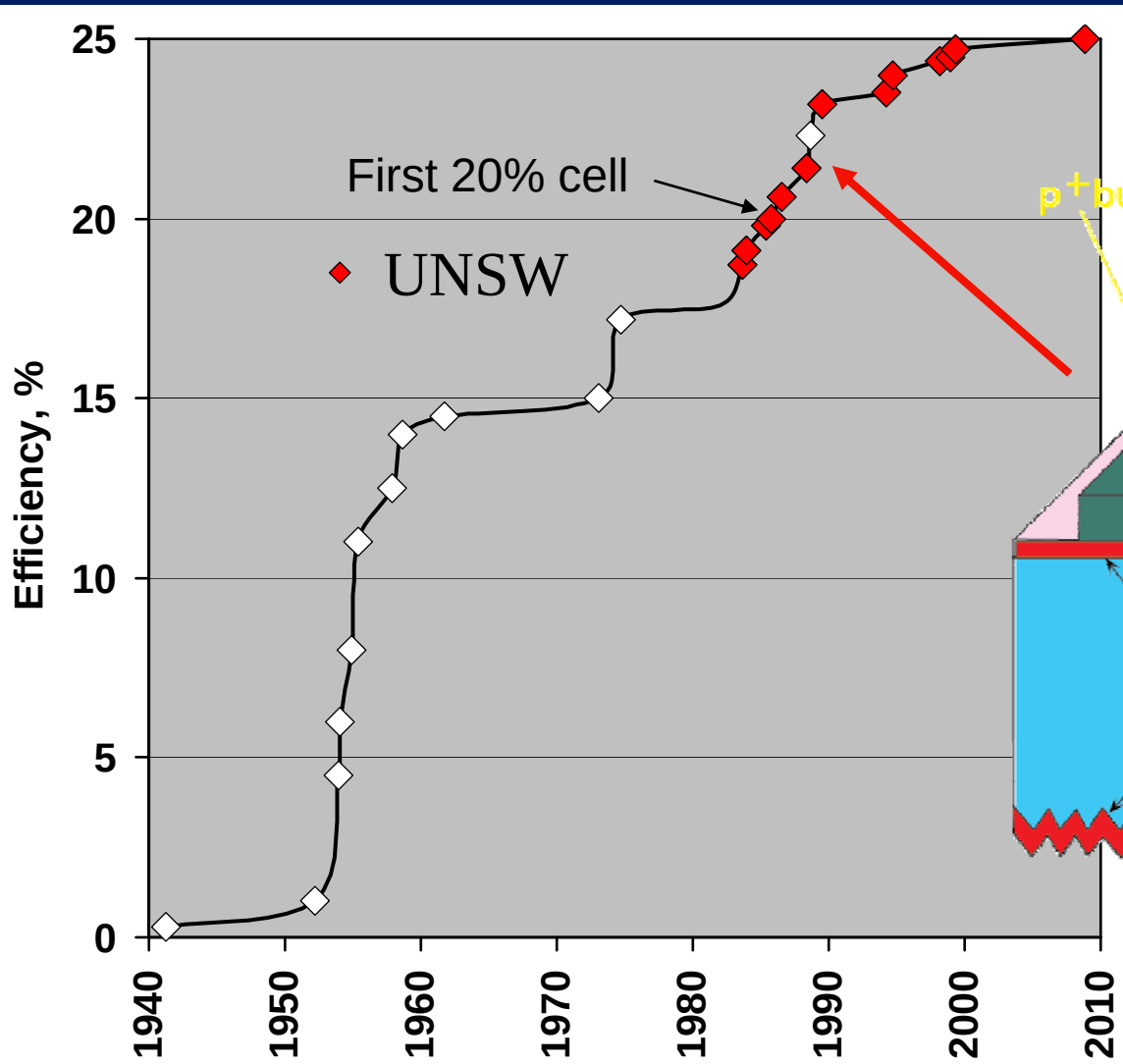


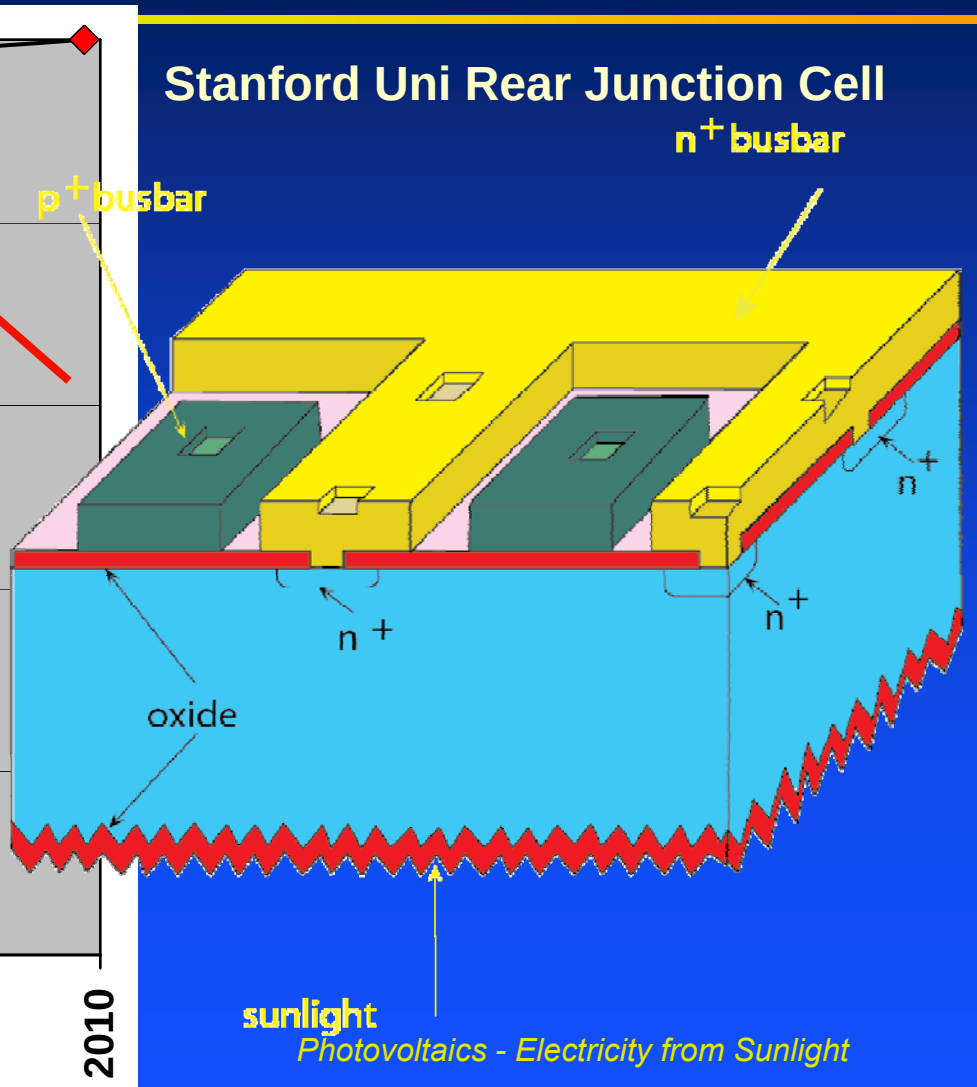


Improved efficiency: 20% and beyond

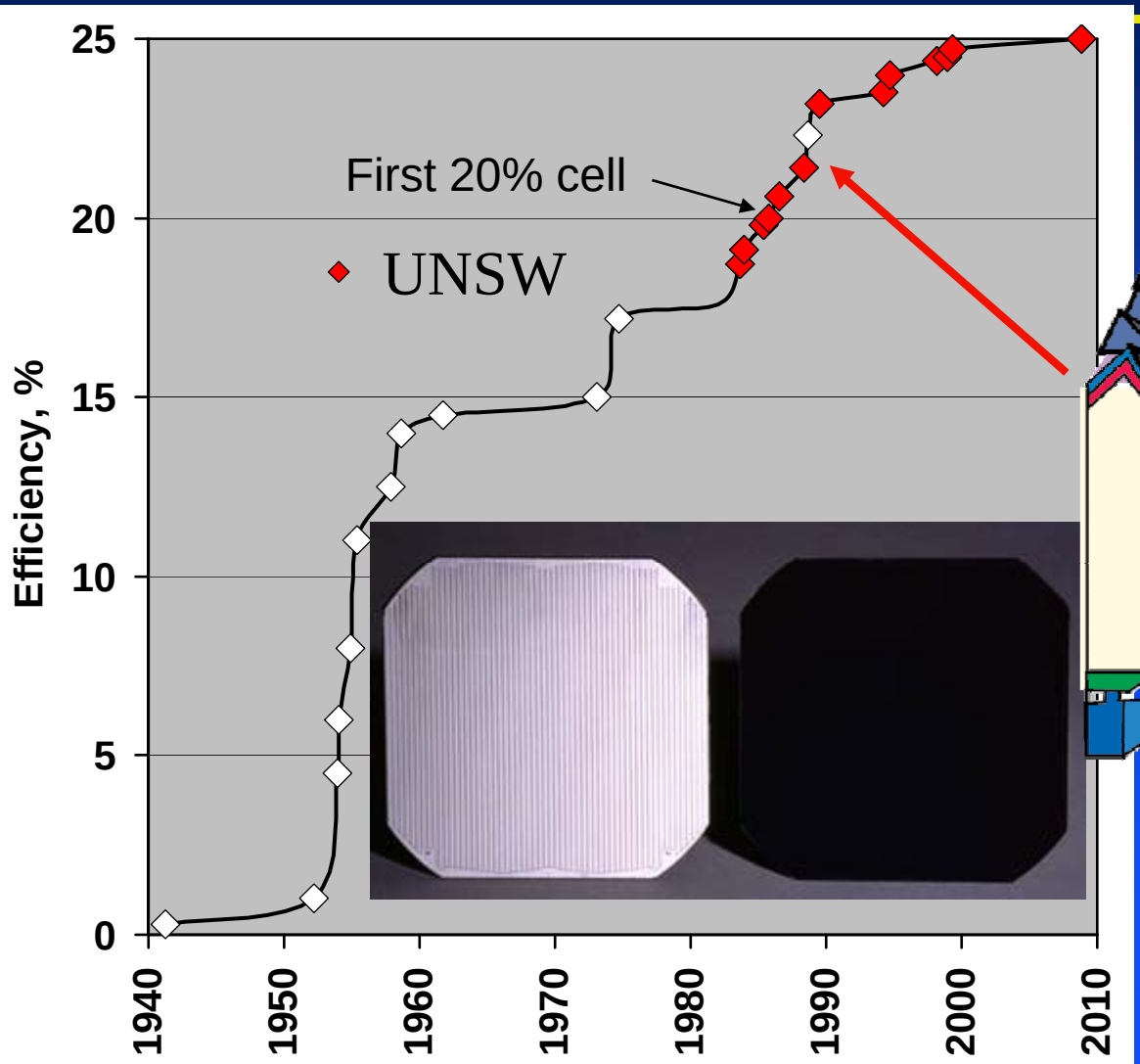


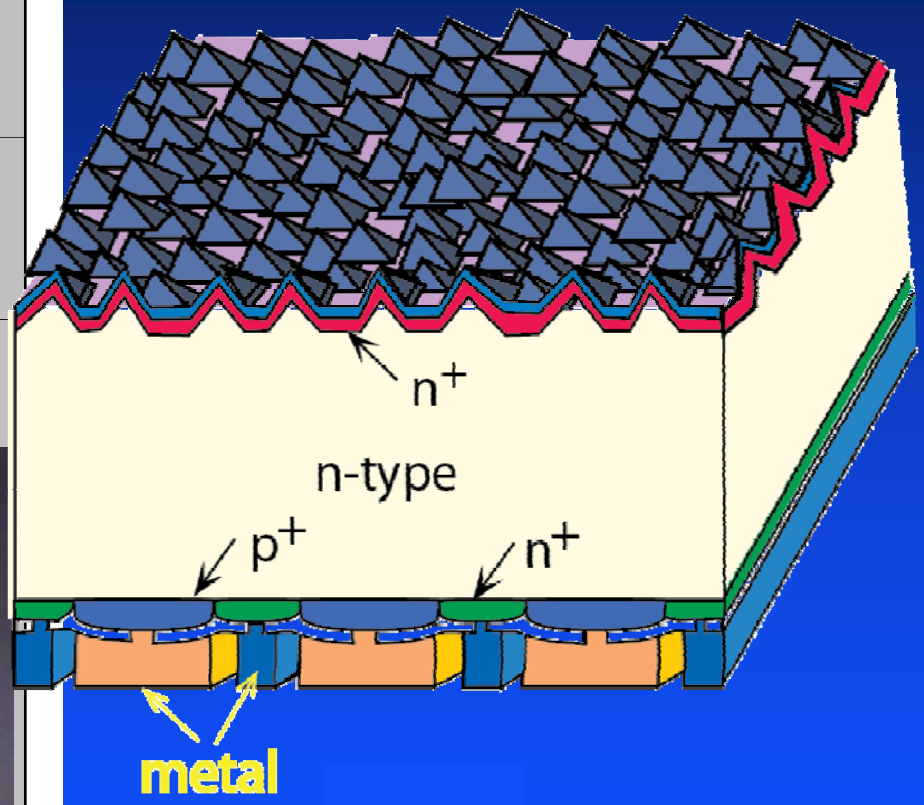
Improved efficiency: 22% cells



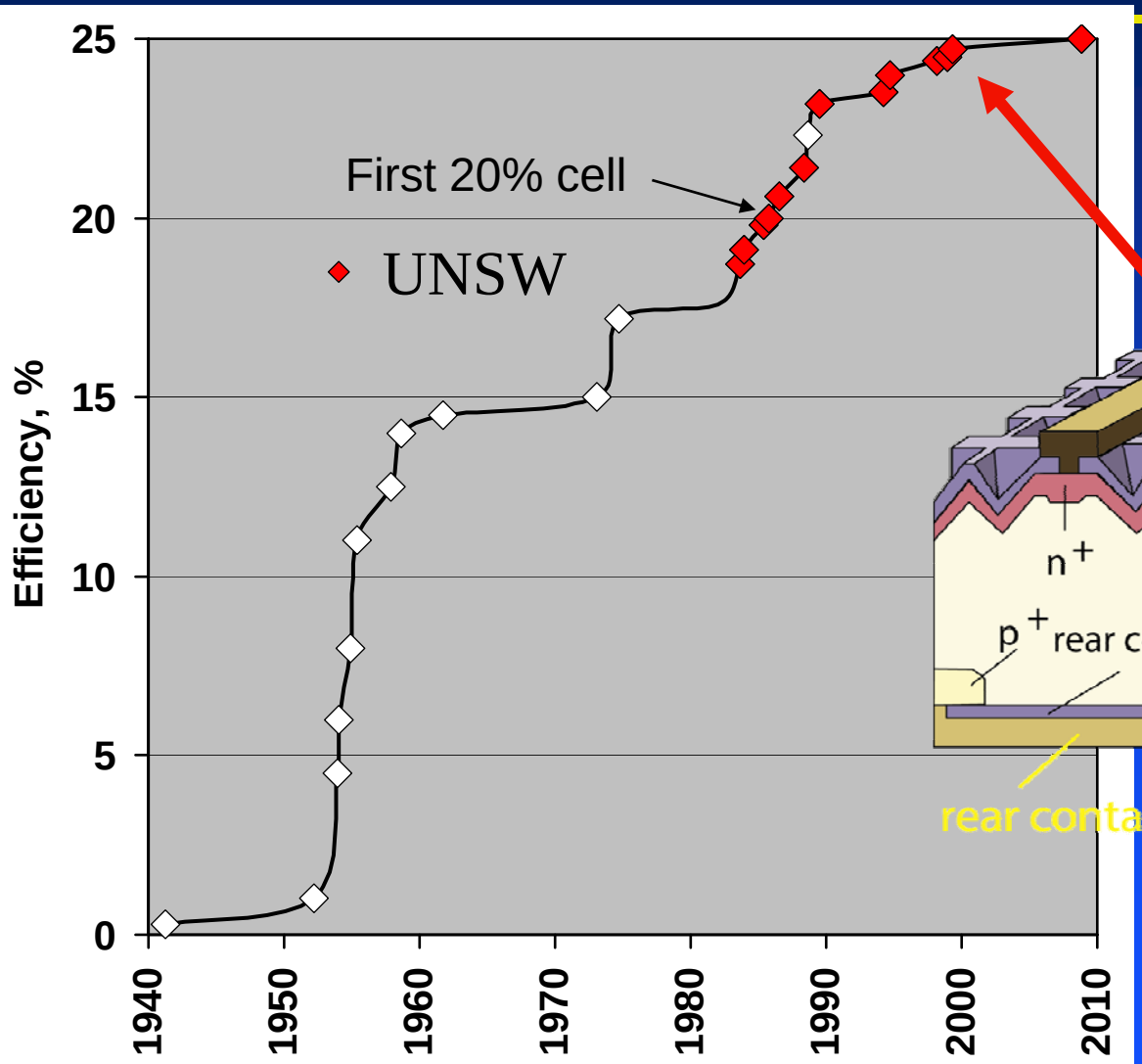


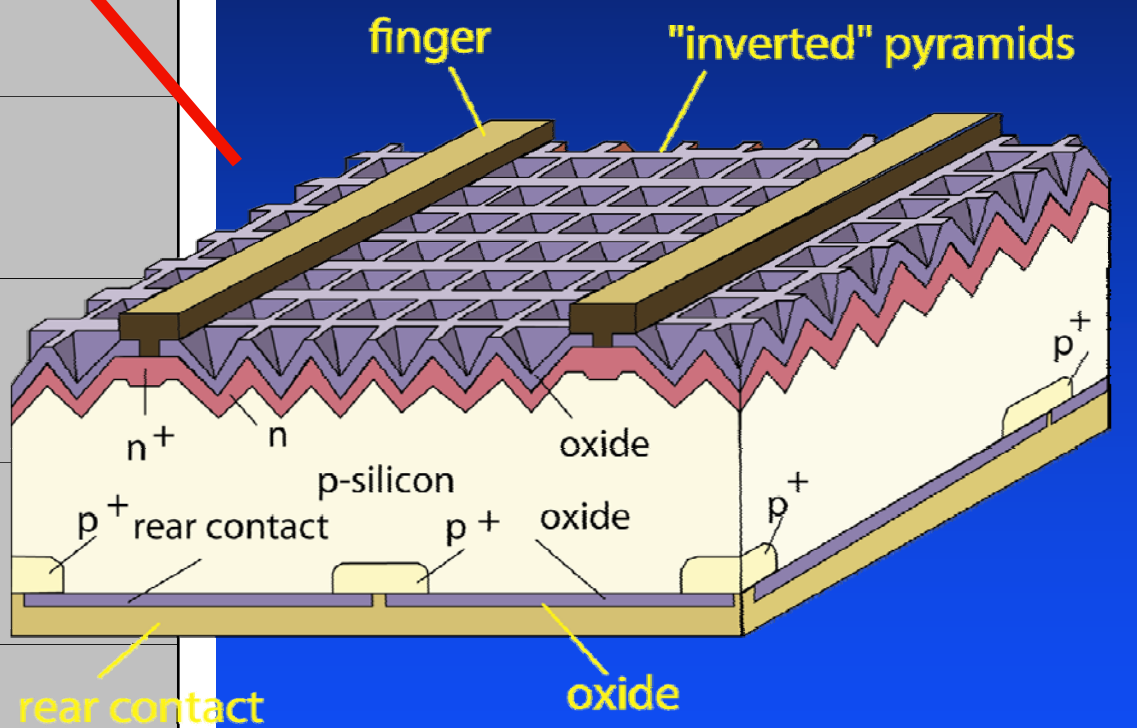
Improved efficiency: 22% cells



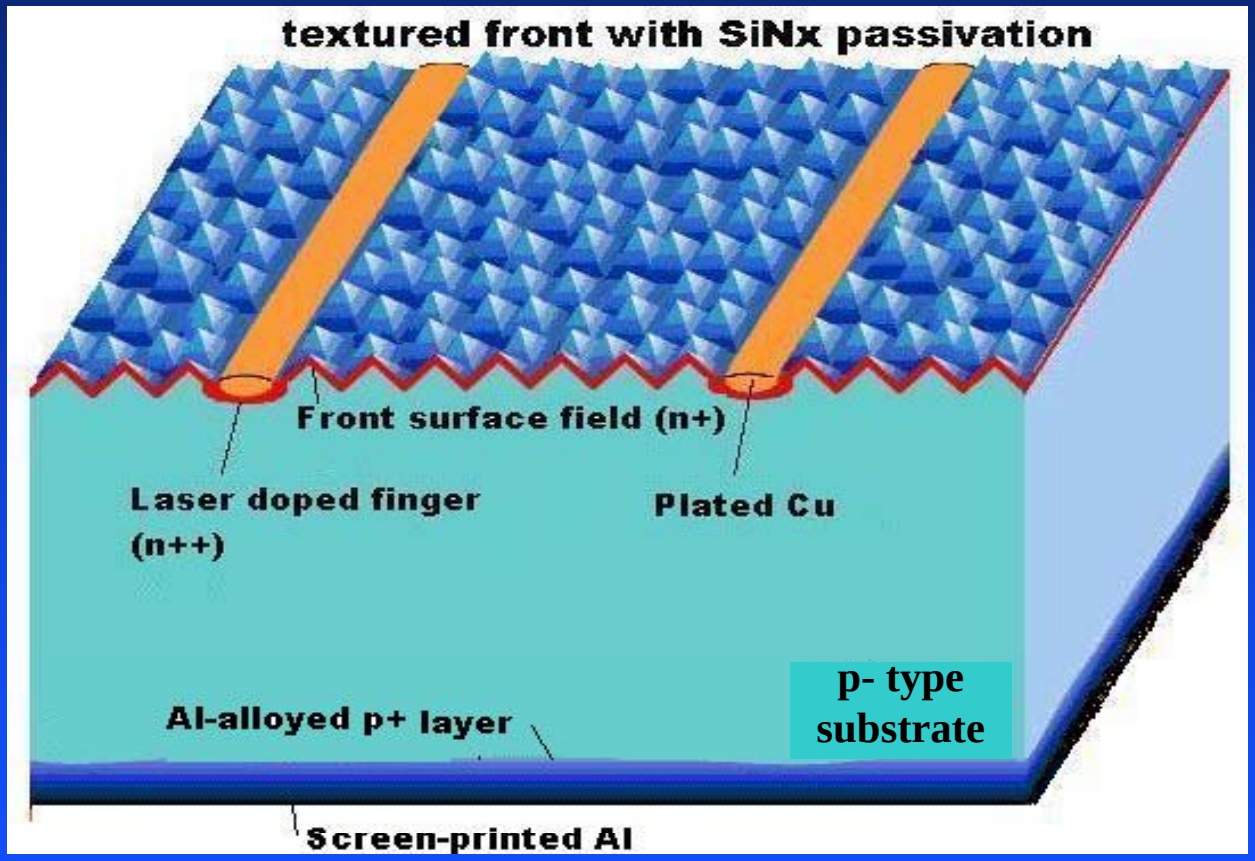


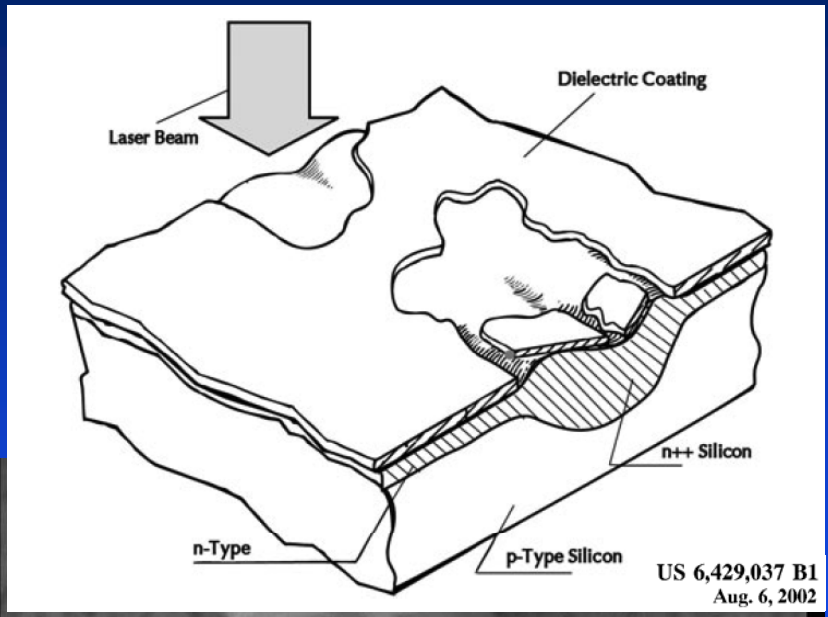
Improved efficiency: 25% cells

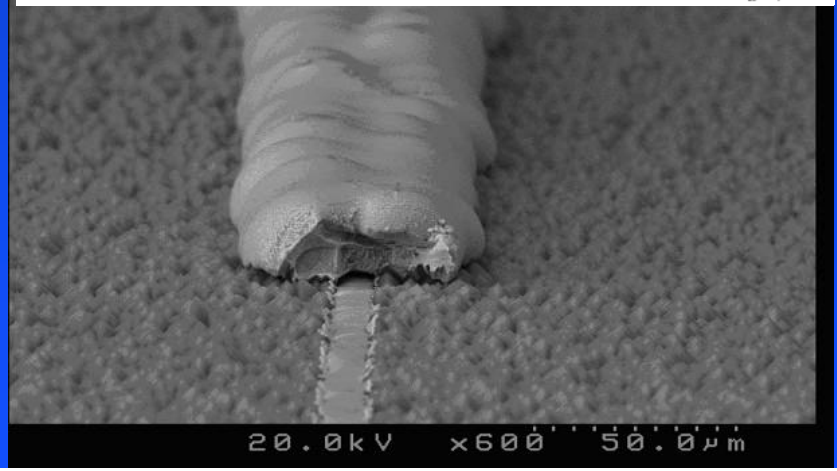




Improved efficiency: LDSE







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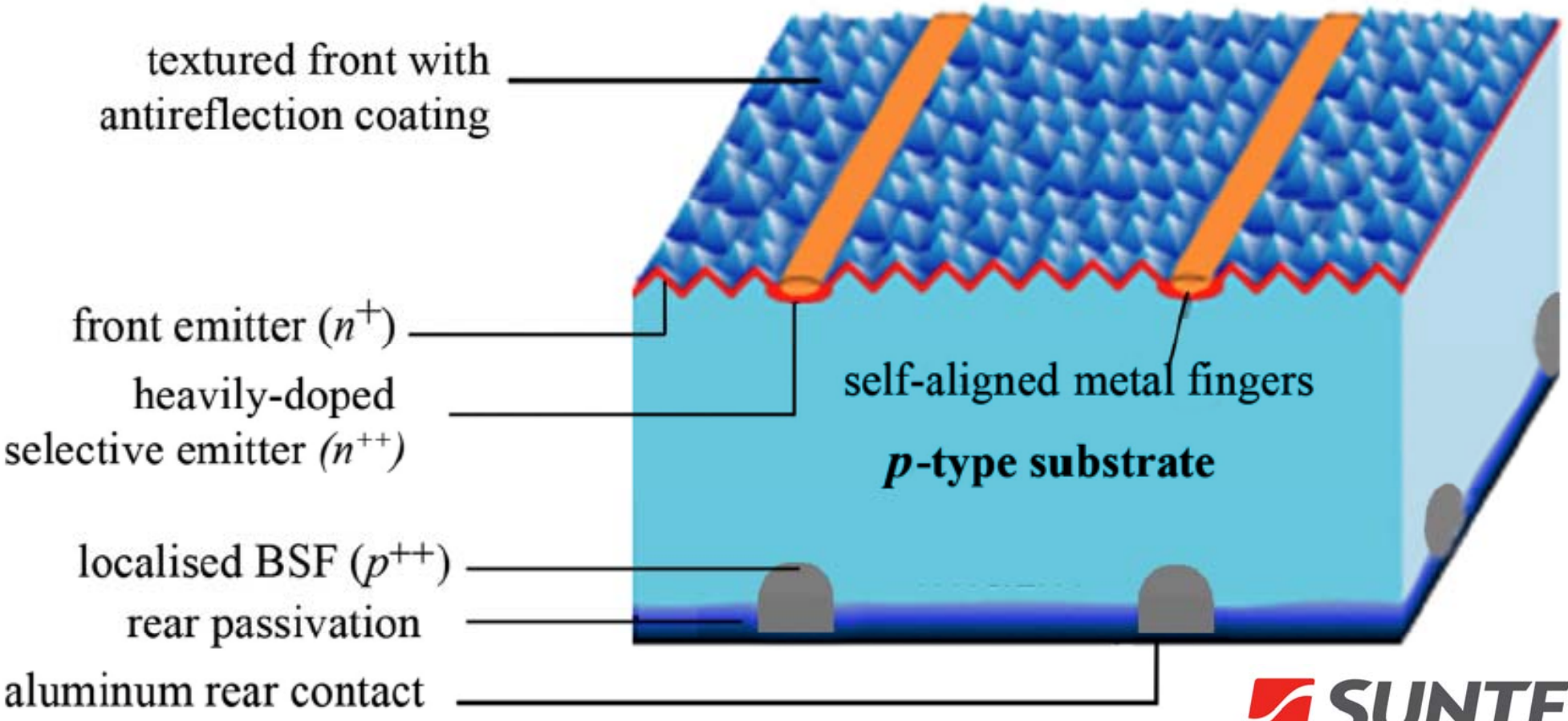
Improved efficiency: 20.3% Pluto cell



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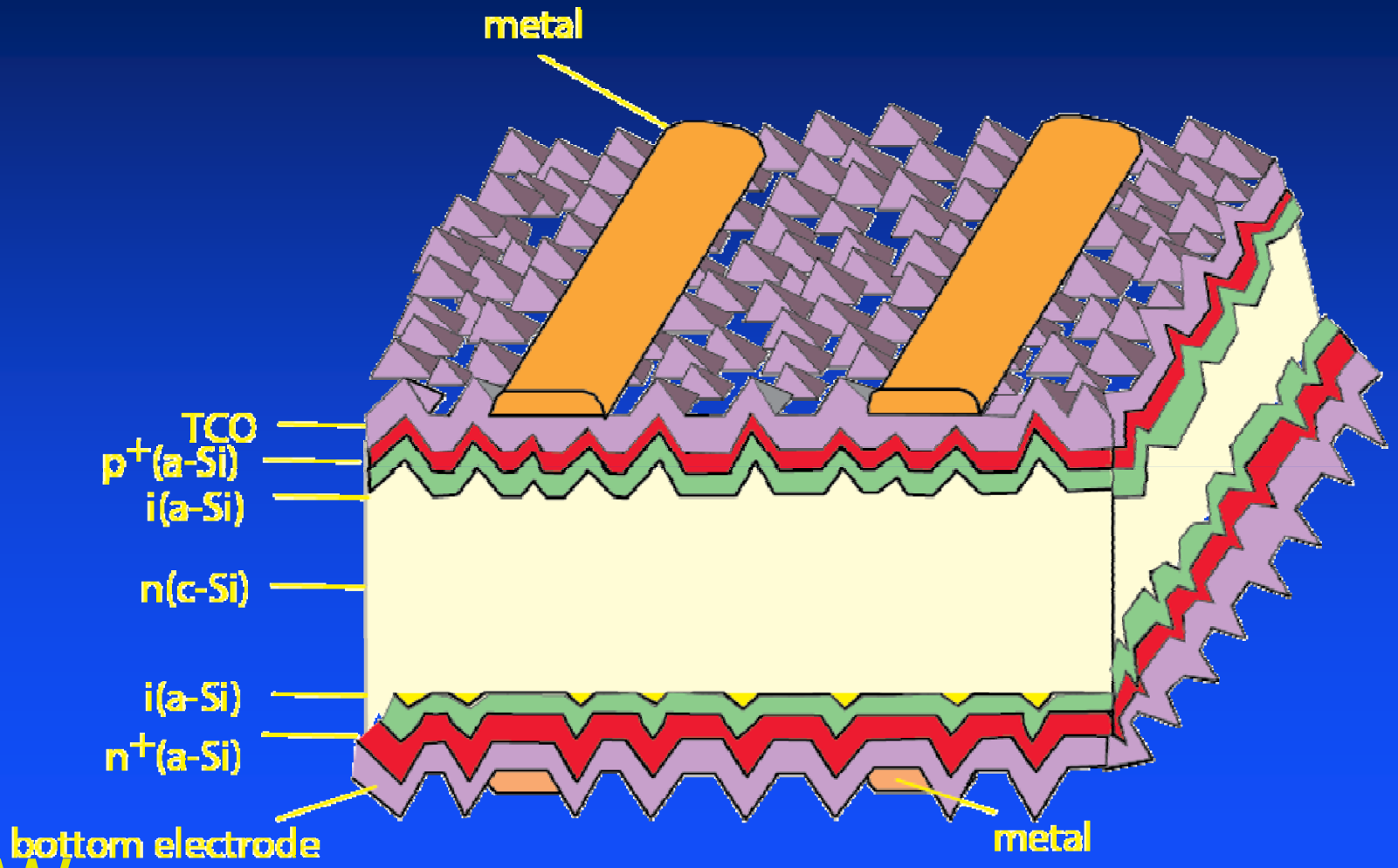
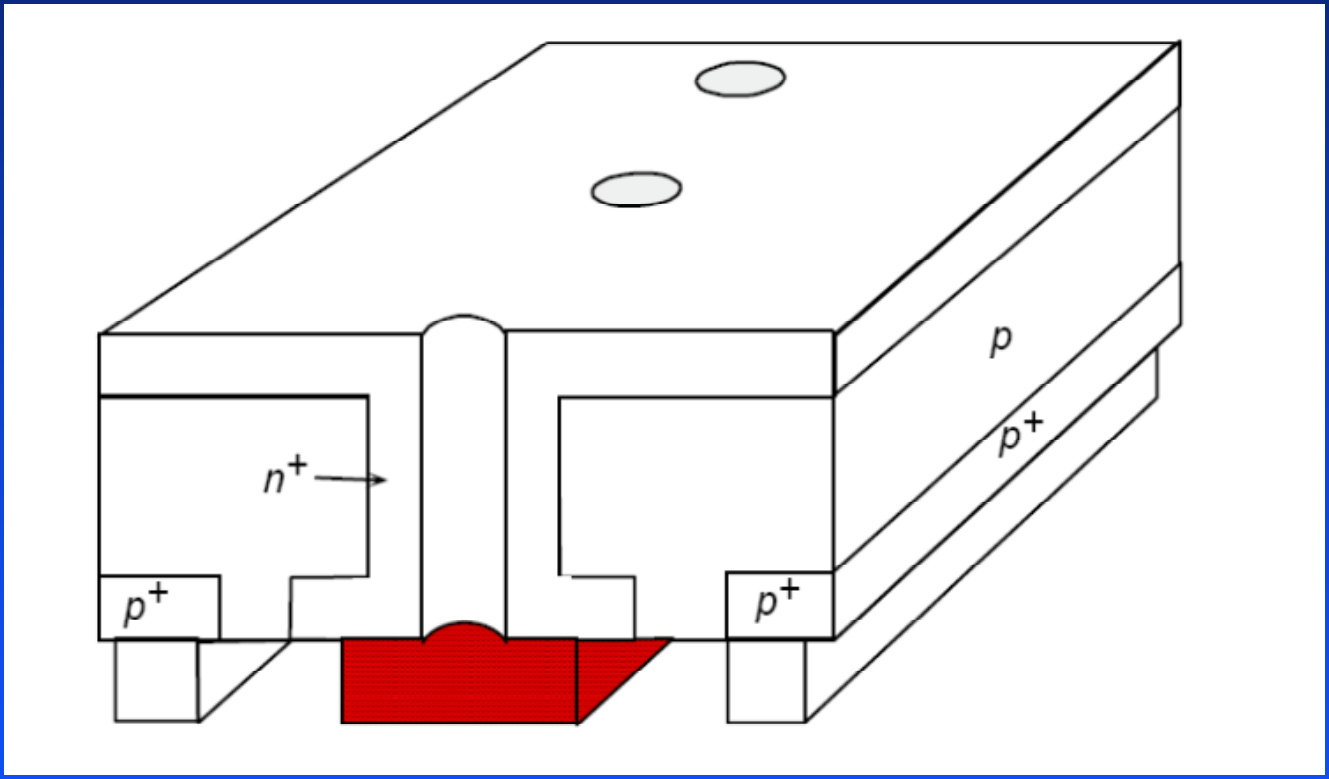
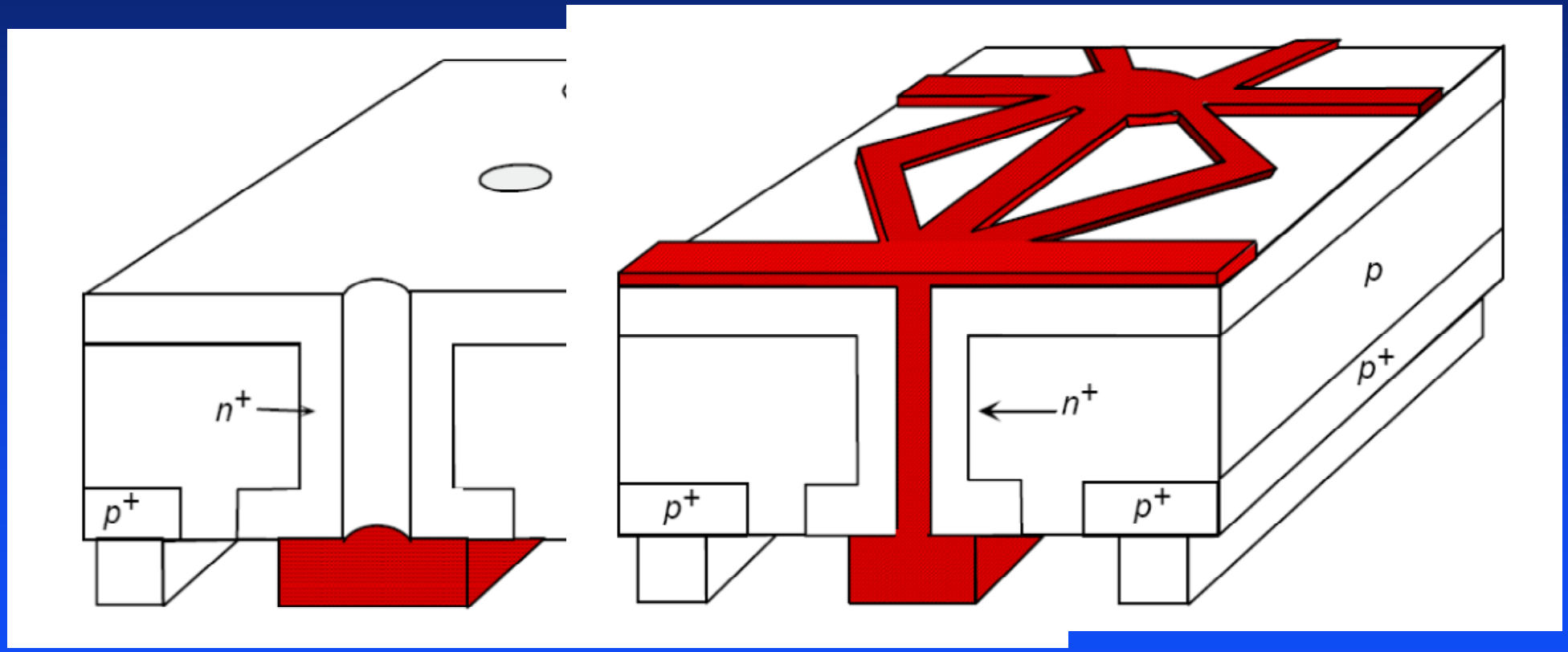
Other approaches: HIT cell



Other approaches: EWT cell



Other approaches: MWT cell



Other approaches: MWT cell

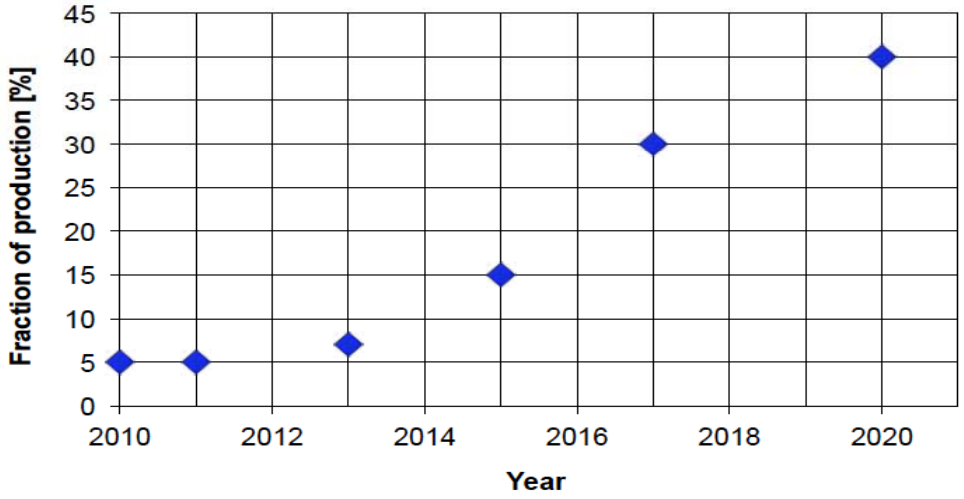


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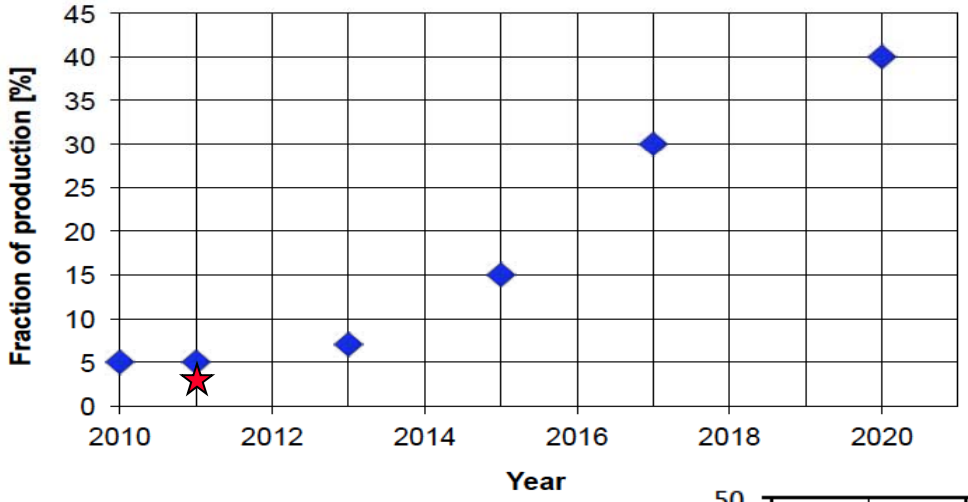
Fig. 30: Share of rear contact cells as fraction of worldwide production. We expect a strong growth in rear contact cells towards 2020.

Other approaches: MWT cell



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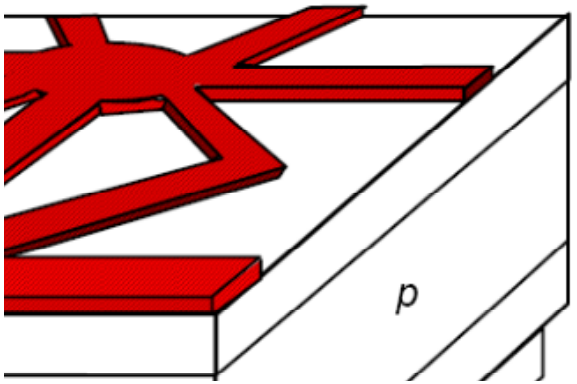

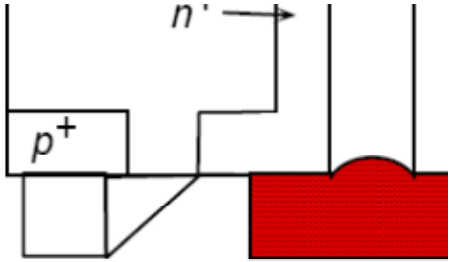

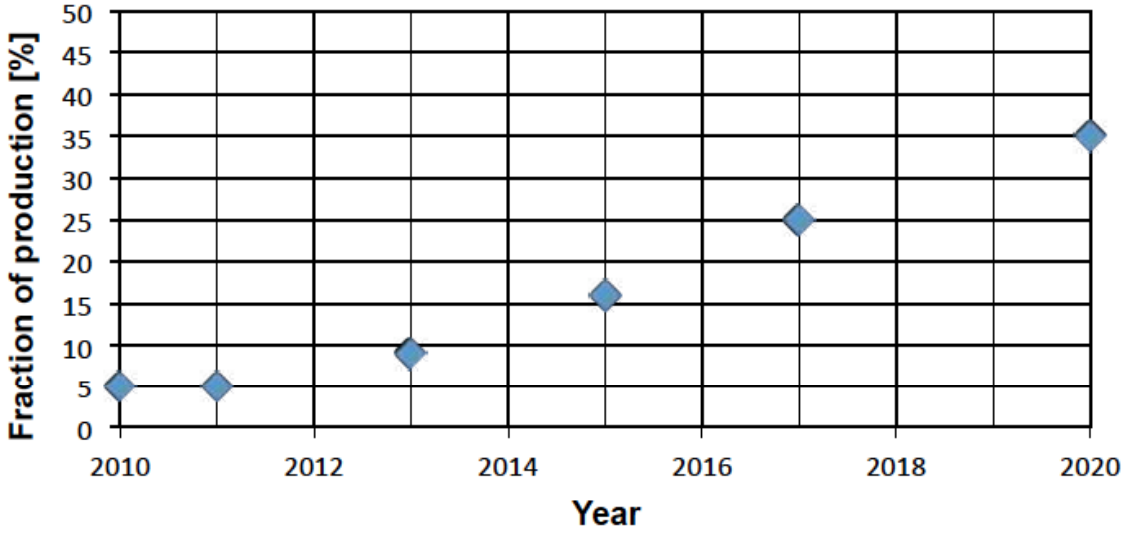

Fig. 30 Share of modules using rear contact cells as fraction of worldwide production.

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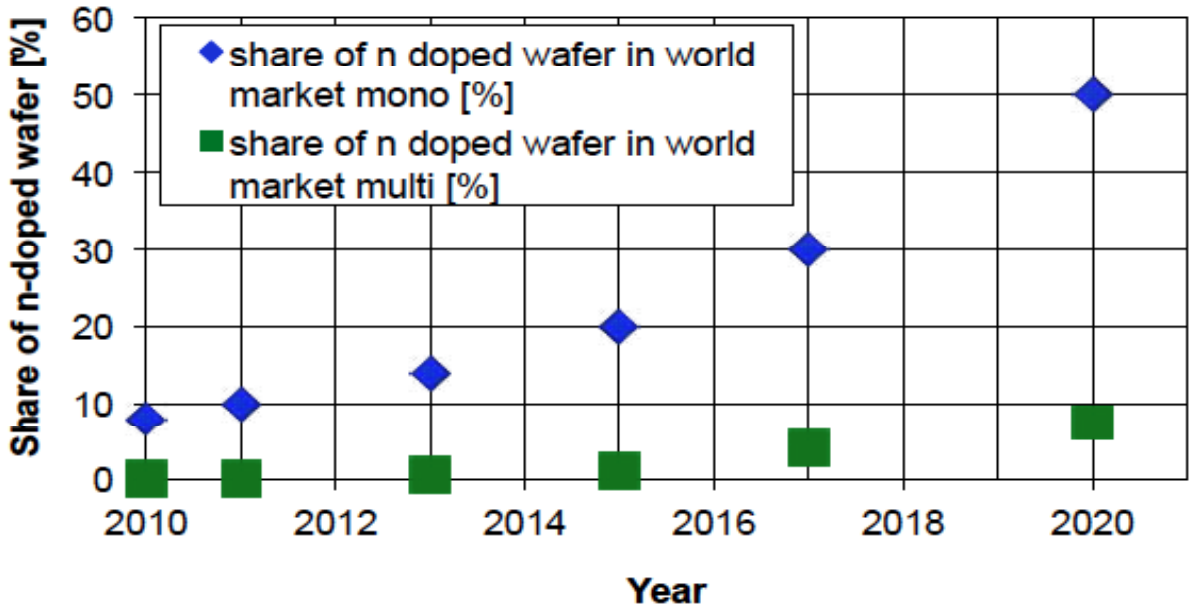

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Fig. 27: Expected share of n-type material on world production of c-Si solar cells.

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admap

also included. This publication covers the PV value chain from crystallization, wafering and cell manufacturing downstream to module manufacturing with more parameters compared to earlier editions as well as discussions about emerging trends in the PV industry.

As visible in the historical learning curve the specific cost per Watt peak (WP) of PV modules will continue to decrease. This corresponds to a significant cost reduction per module. To reach this purpose, current mainstream technology will be optimized, new production technologies will be rolled out, and not yet known techniques have to be implemented in production around 2015.

Detailed requirements for manufacturers along the c-Si value chain such as more effective use of material, more productive manufacturing equipment and more advanced processes are given in key parameters. Progress in one of these fields not only affects single production steps but may influence the whole value chain. One example is the crystallization process. Improvements in the Si-cast technology enable the crystallization of ingots containing large fractions of mono-crystalline domains, we call it mono-like or quasi-mono material. This creates opportunities for higher cell efficiencies however, in addition to the trends to thinner wafers the wafer sawing method, the handling, the cell process and the interconnect technologies have to be developed further. The increased output power of the modules implies adoptions at module and system level due to the increased current and voltage range.

This roadmap activity will be continued in cooperation with SEMI PV Group and updated information will be published each year in spring to ensure good communication between manufacturers and suppliers throughout the value chain. More information is available on *www.itpv.net*.

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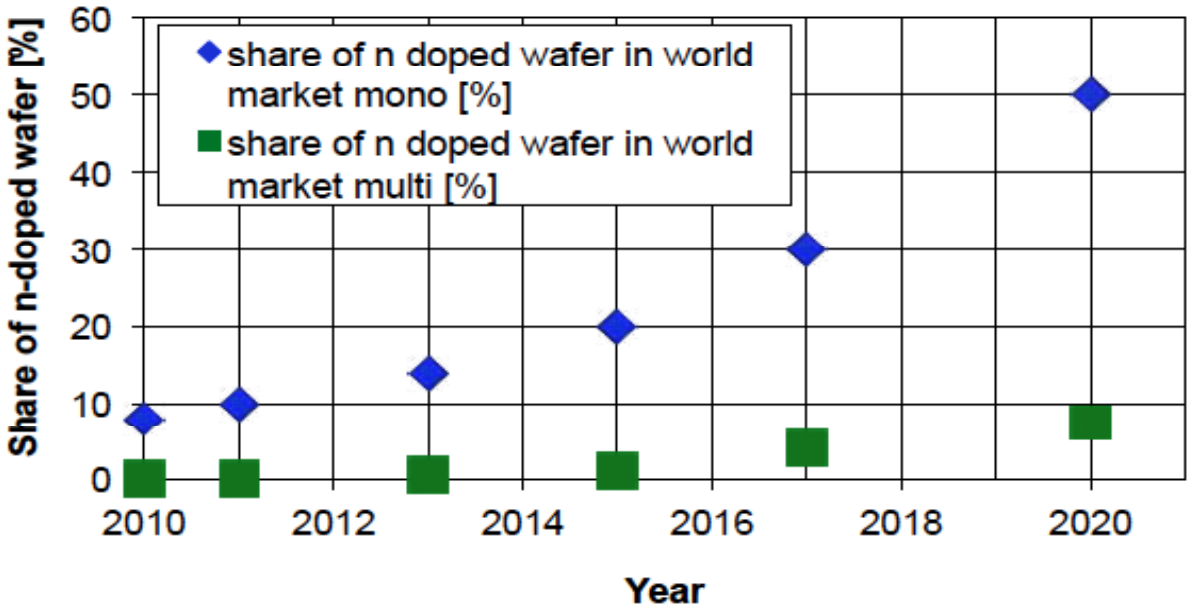

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Fig. 27: Expected share of n-type material on world production of c-Si solar cells.

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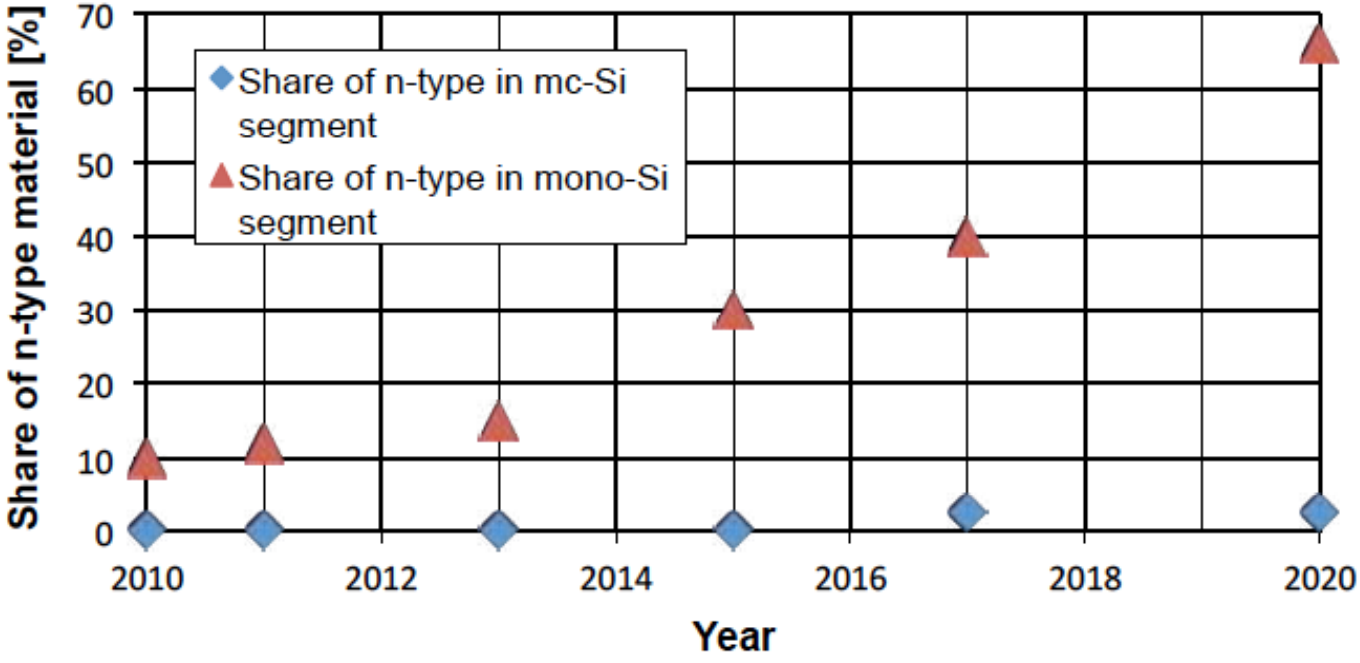

Fig. 27 Expected share of n-type material on world production of c-Si solar cells.

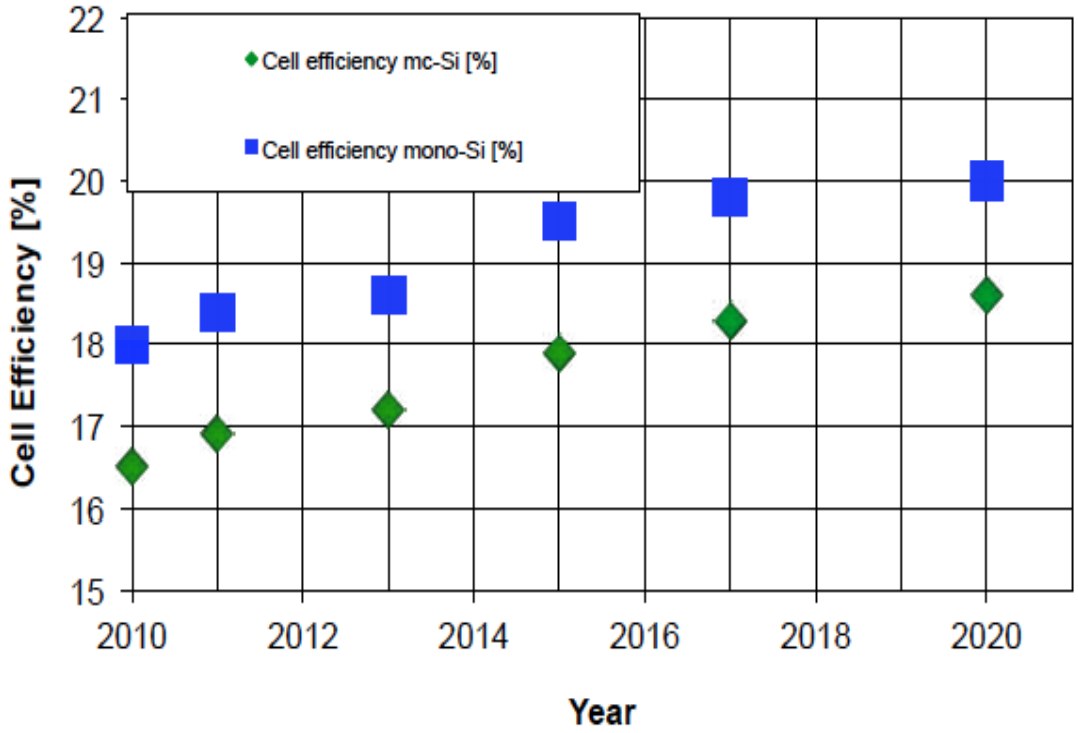

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Fig. 28: Stabilized efficiency trend curve of p-type c-Si solar cells in mass production.

l roadmap

also included. This publication covers the PV value chain from crystallization, wafering and cell manufacturing downstream to module manufacturing with more parameters compared to earlier editions as well as discussions about emerging trends in the PV industry.

As visible in the historical learning curve the specific cost per Watt peak (WP) of PV modules will continue to decrease. This corresponds to a significant cost reduction per module. To reach this purpose, current mainstream technology will be optimized, new production technologies will be rolled out, and not yet known techniques have to be implemented in production around 2015.

Detailed requirements for manufacturers along the c-Si value chain such as more effective use of material, more productive manufacturing equipment and more advanced processes are given in key parameters. Progress in one of these fields not only affects single production steps but may influence the whole value chain. One example is the crystallization process. Improvements in the Si-cast technology enable the crystallization of ingots containing large fractions of mono-crystalline domains, we call it mono-like or quasi-mono material. This creates opportunities for higher cell efficiencies however, in addition to the trends to thinner wafers the wafer sawing method, the handling, the cell process and the interconnect technologies have to be developed further. The increased output power of the modules implies adoptions at module and system level due to the increased current and voltage range.

This roadmap activity will be continued in cooperation with SEMI PV Group and updated information will be published each year in spring to ensure good communication between manufacturers and suppliers throughout the value chain. More information is available on *www.itpv.net*.

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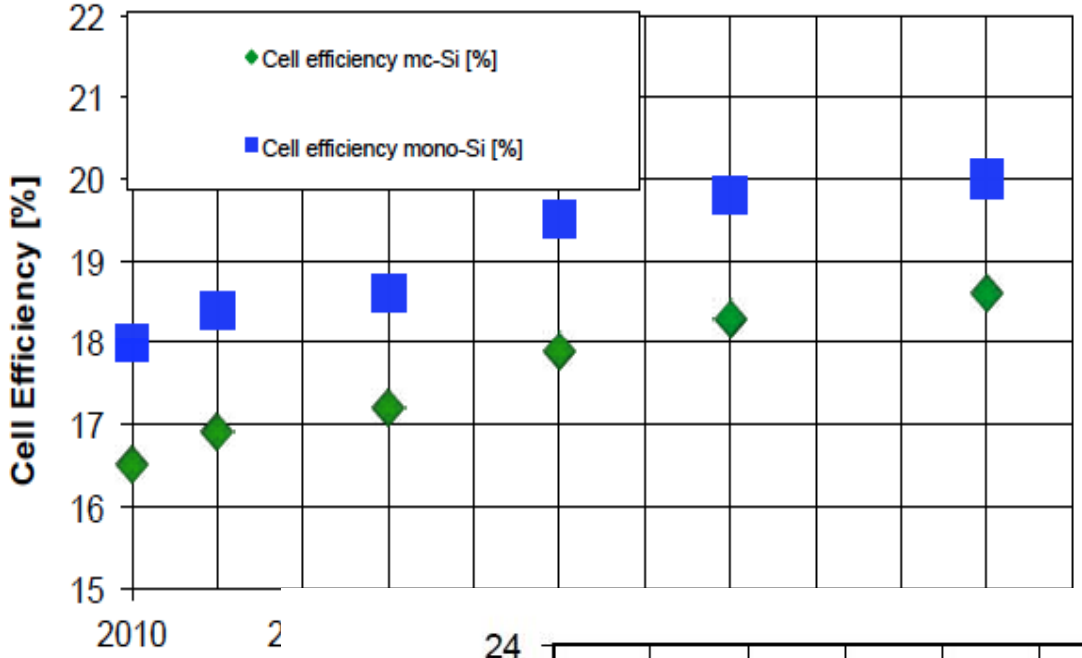

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Fig. 28: Stabilized efficiency trend

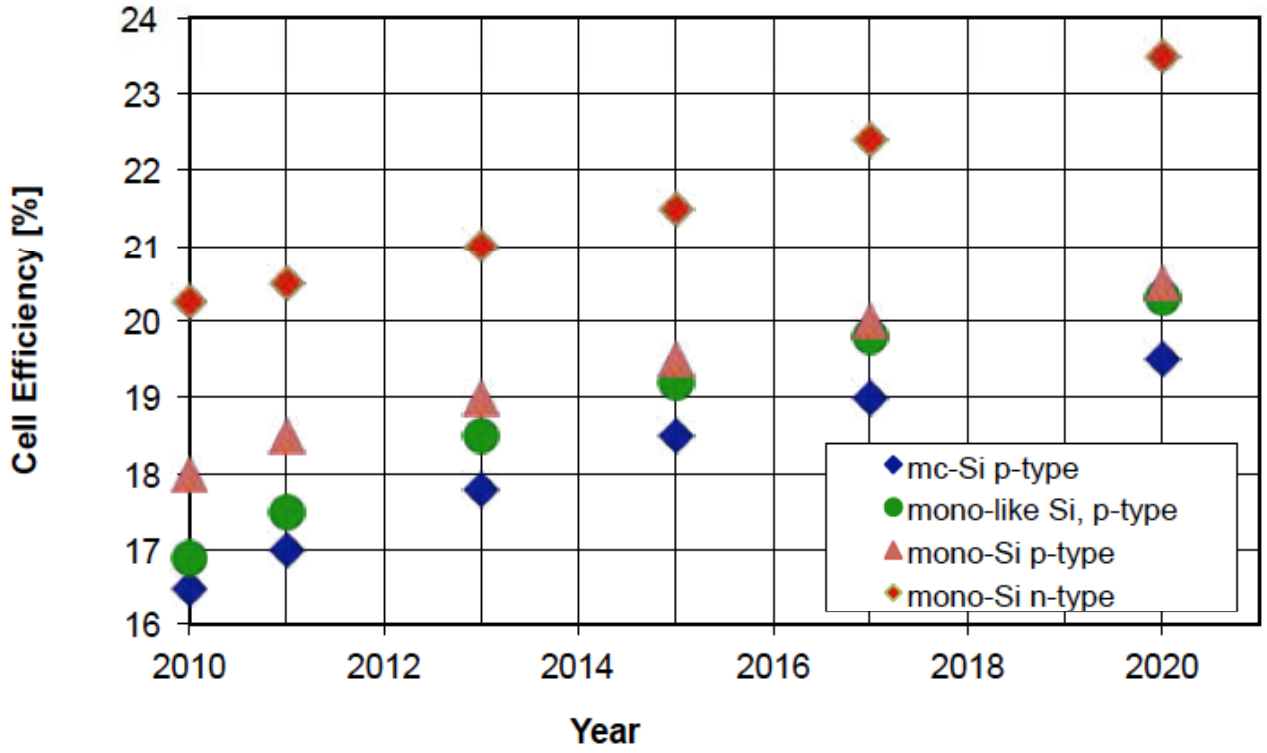

Fig. 28 Stabilized cell efficiency trend curve for mc-Si, mono-like and mono-Si.

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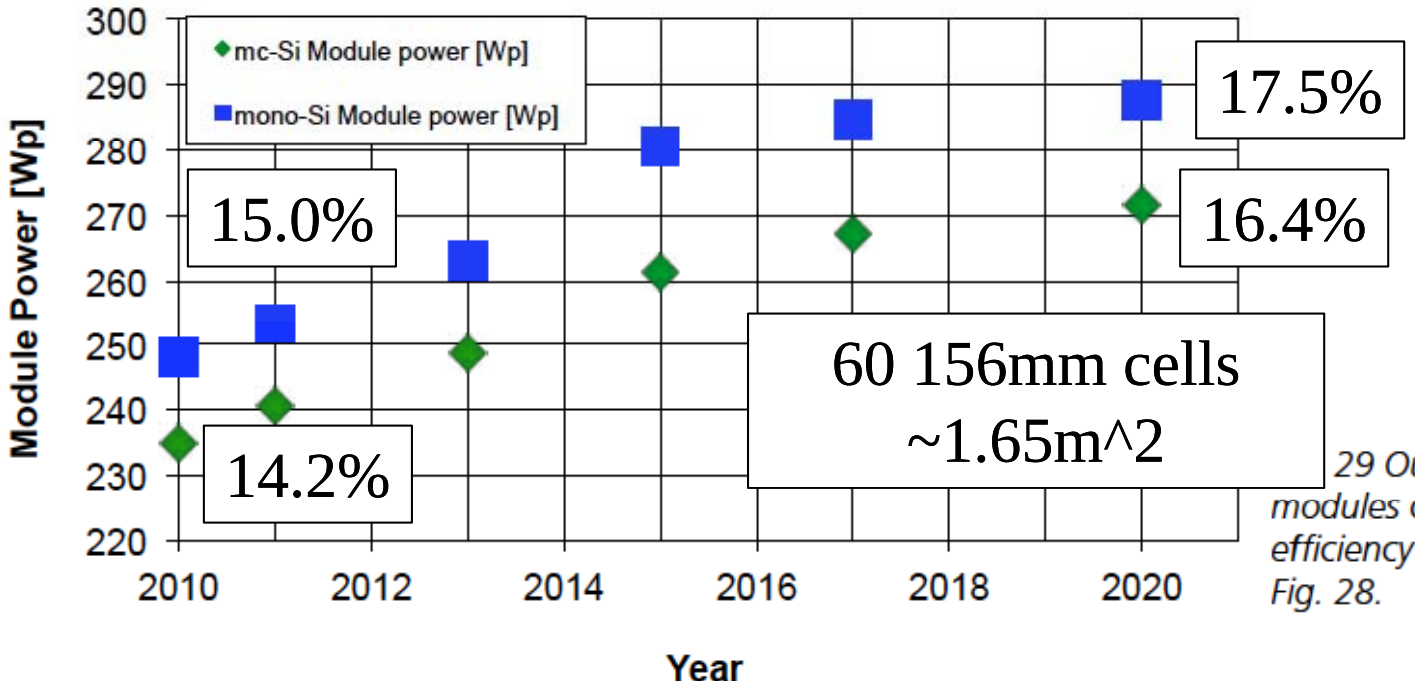

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29 Output power of 60 cell modules corresponding to the efficiency development shown in Fig. 28.

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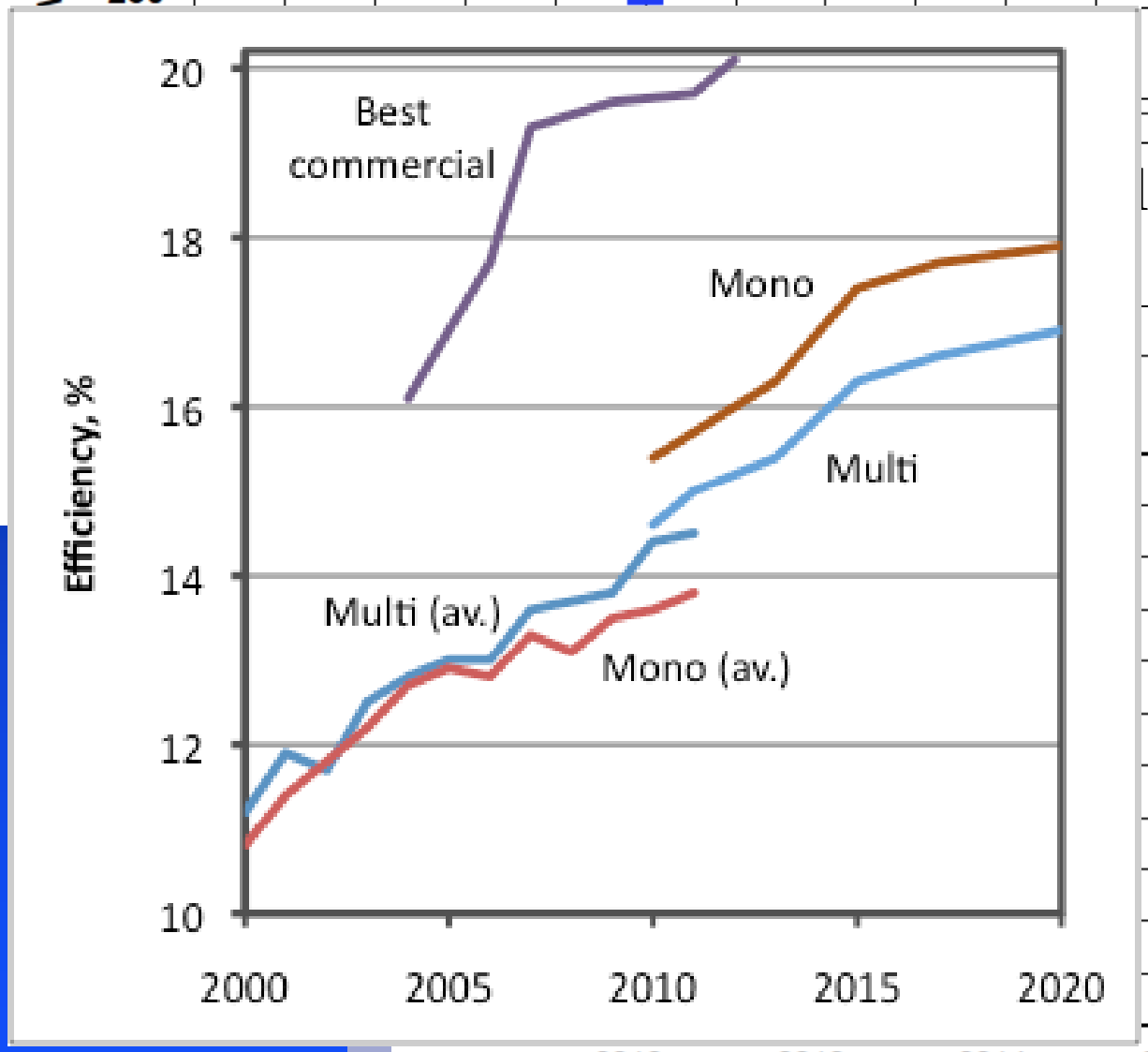

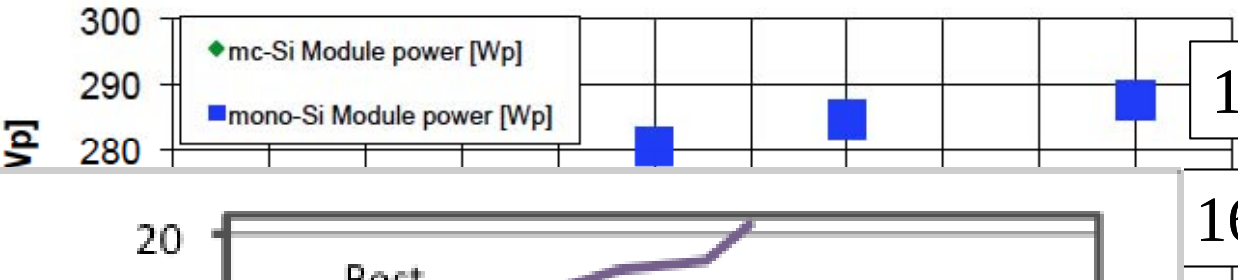

17.5%

16.4%

lls

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29 Output power of 60 cell modules corresponding to the efficiency development shown in Fig. 28

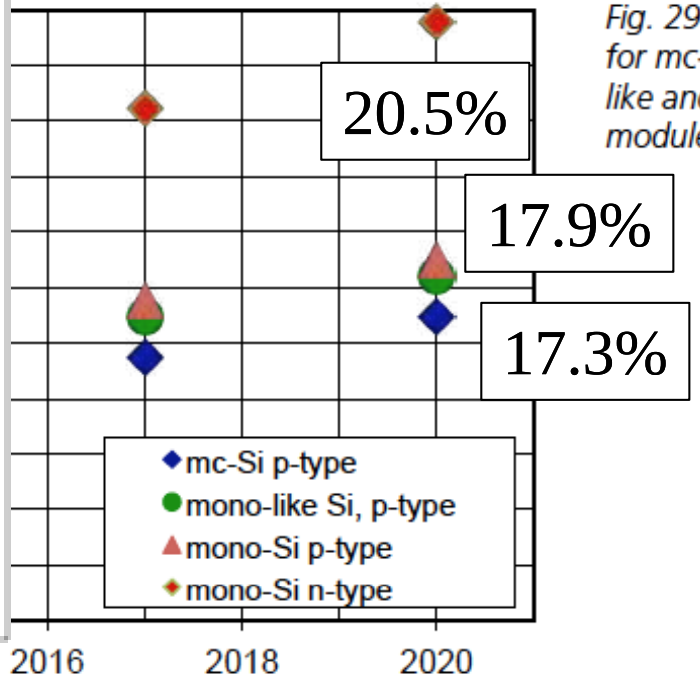

Fig. 29 Trend curve for mc-Si, mono-like and mono-Si module power.

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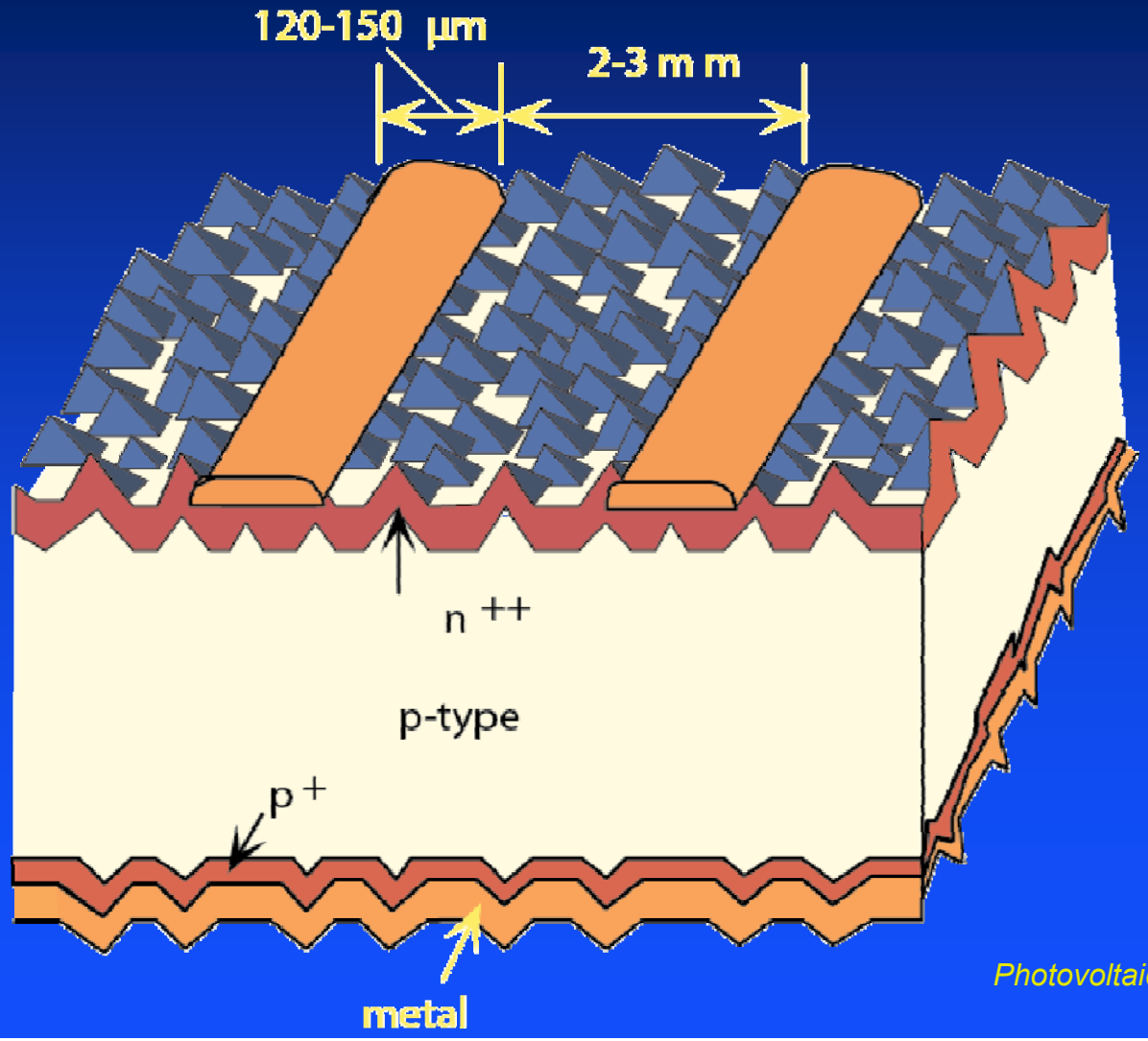

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SEMI roadmap

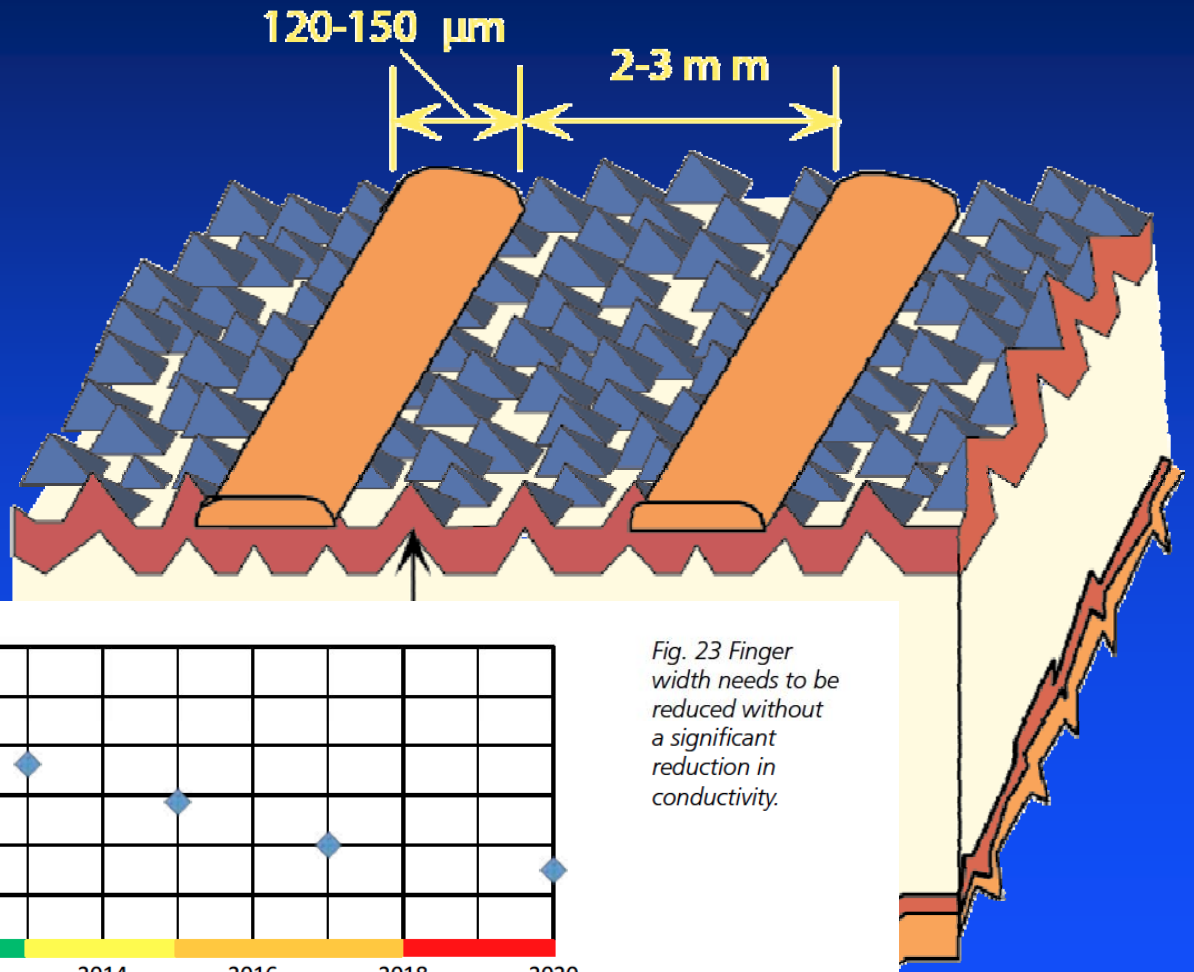
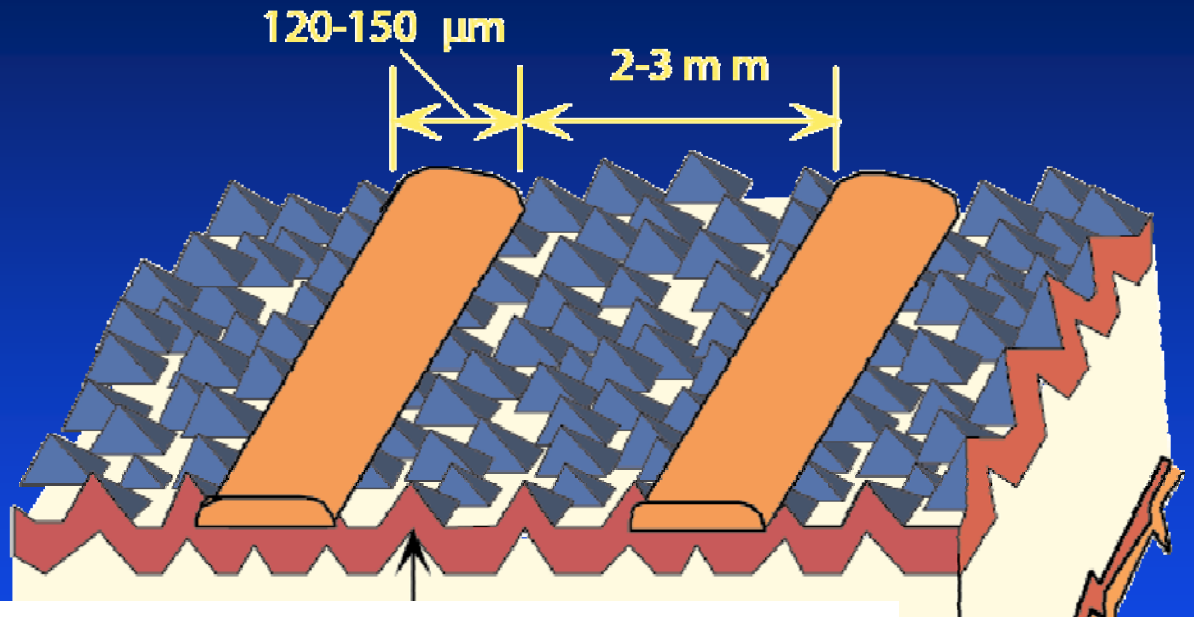
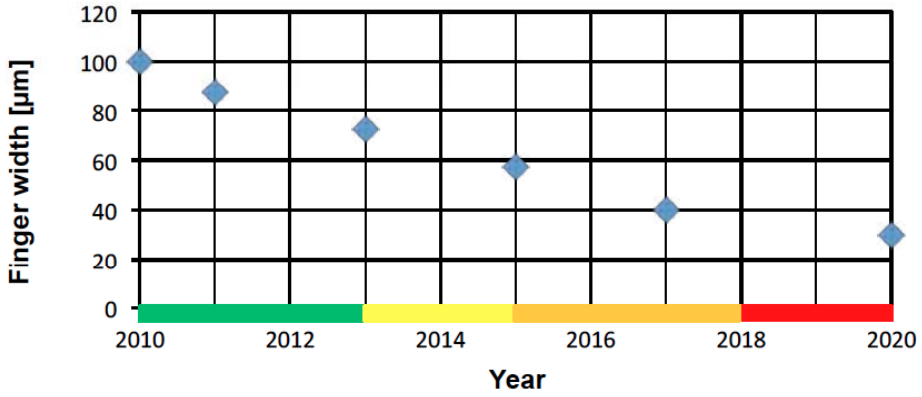


Fig. 23 Finger width needs to be reduced without a significant reduction in conductivity.

SEMI roadmap





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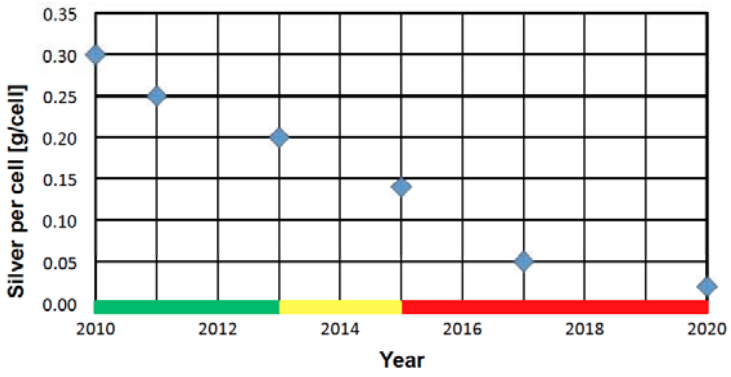
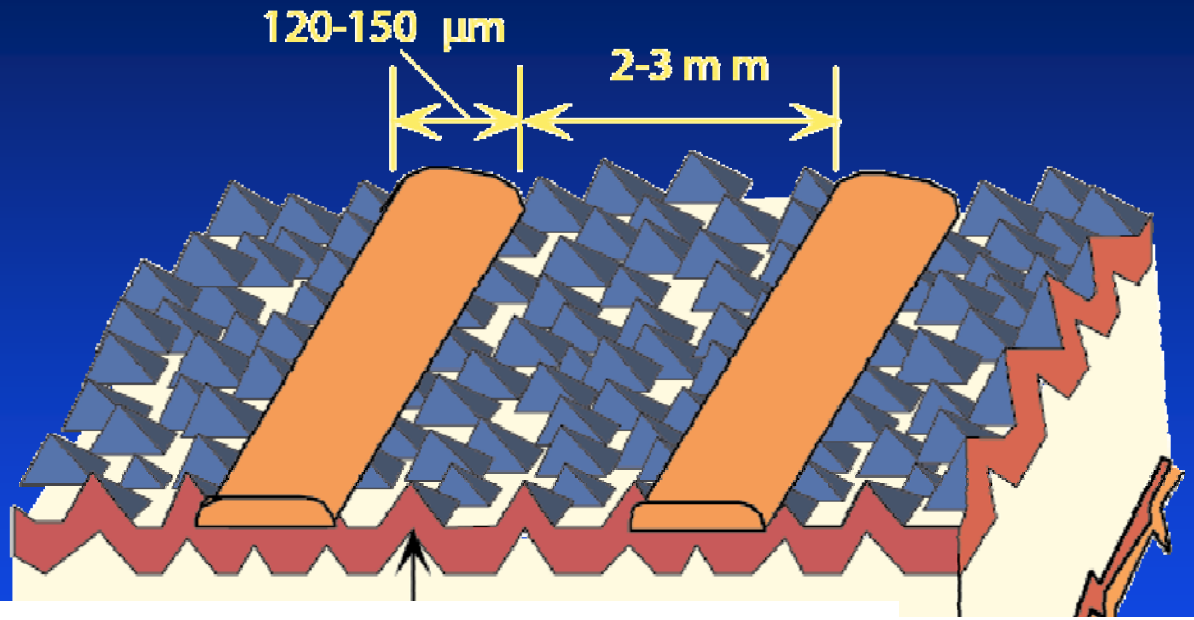
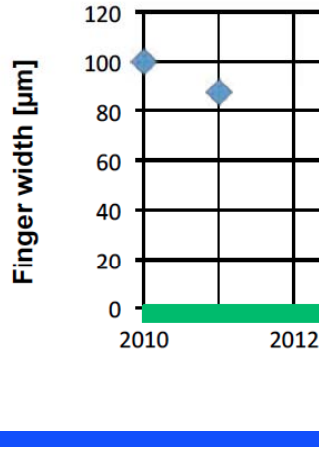


Fig. 5 Remaining portion of silver per cell. A technological development in 2015 is expected to replace silver with copper (CU).

SEMI roadmap





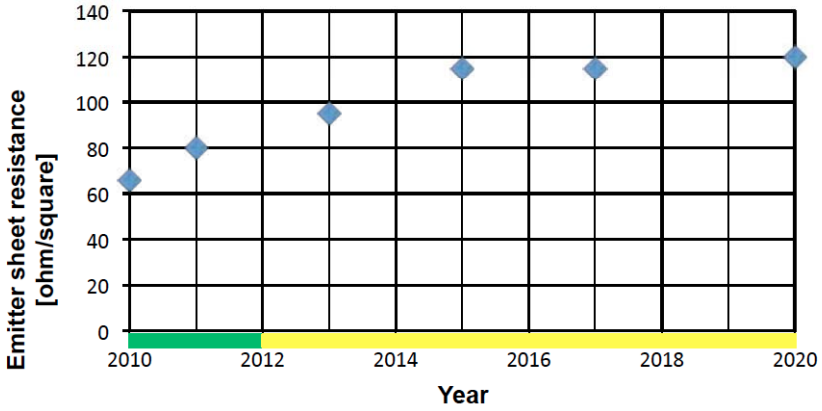
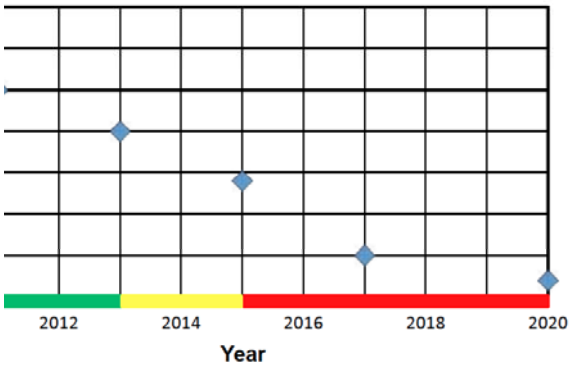


Fig. 22 Expected emitter sheet resistance trend.



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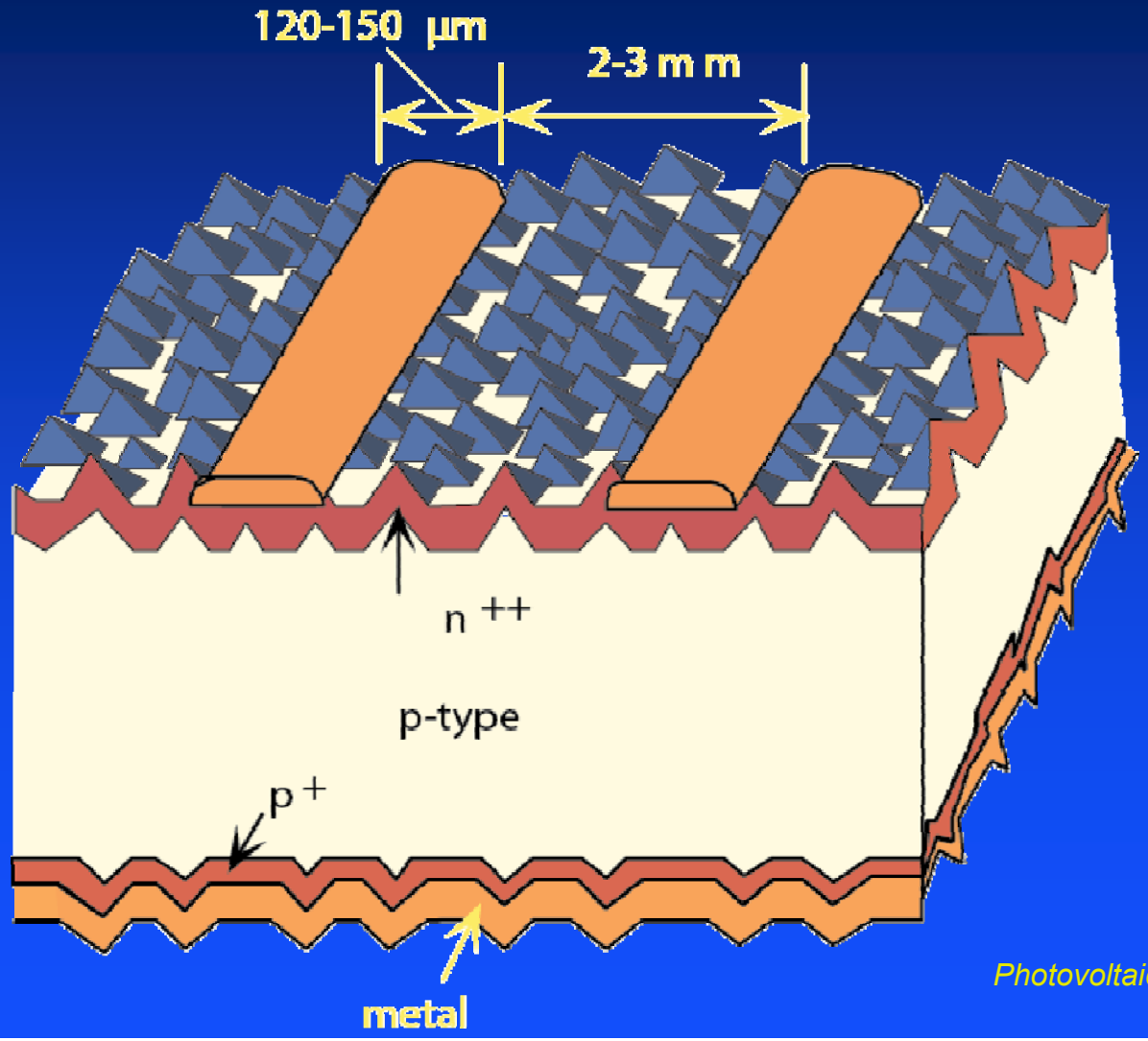
SEMI roadmap



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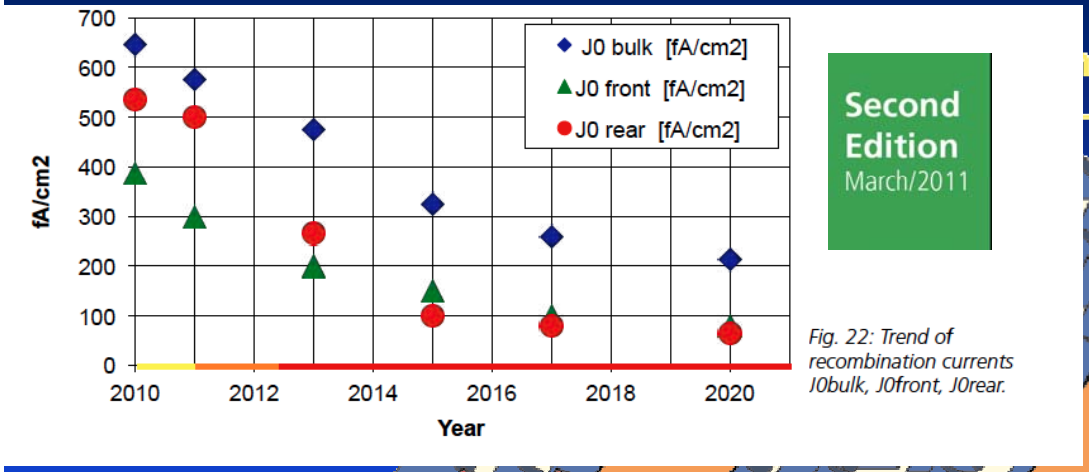

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Fig. 22: Trend of recombination currents J0bulk, J0front, J0rear.

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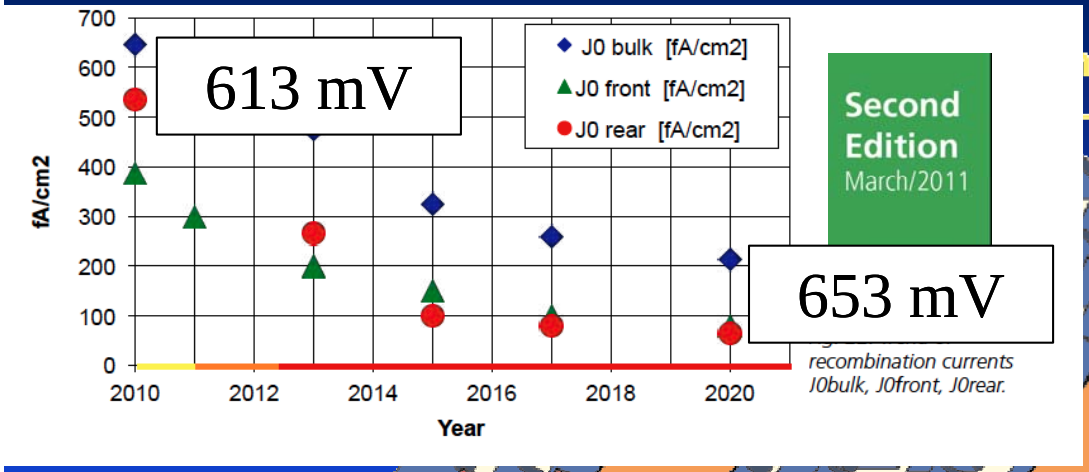

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Photovoltaics - Electricity from Sunlight

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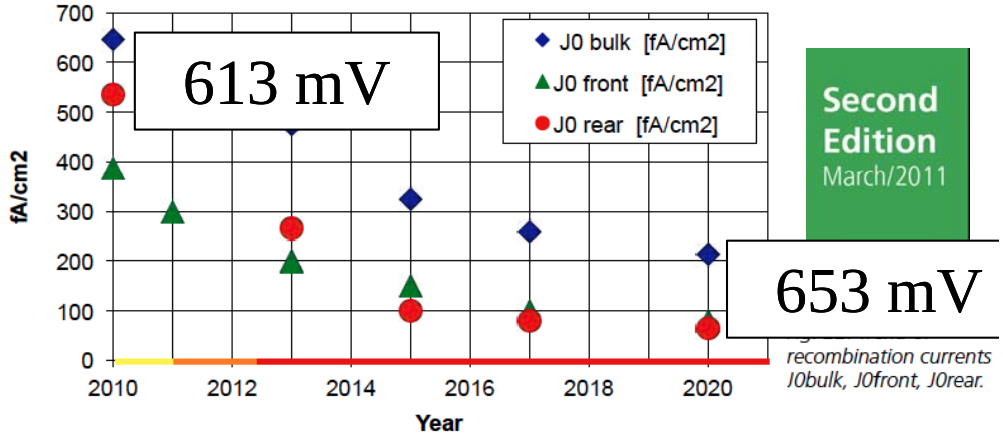


recombination currents J0bulk, J0front, J0rear.

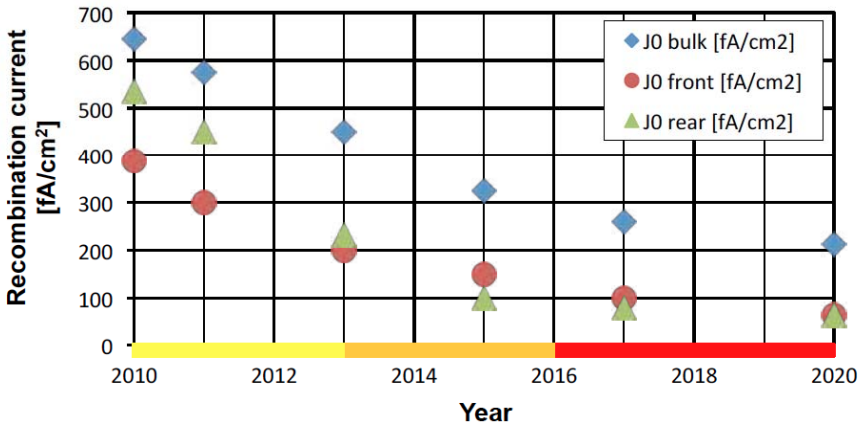
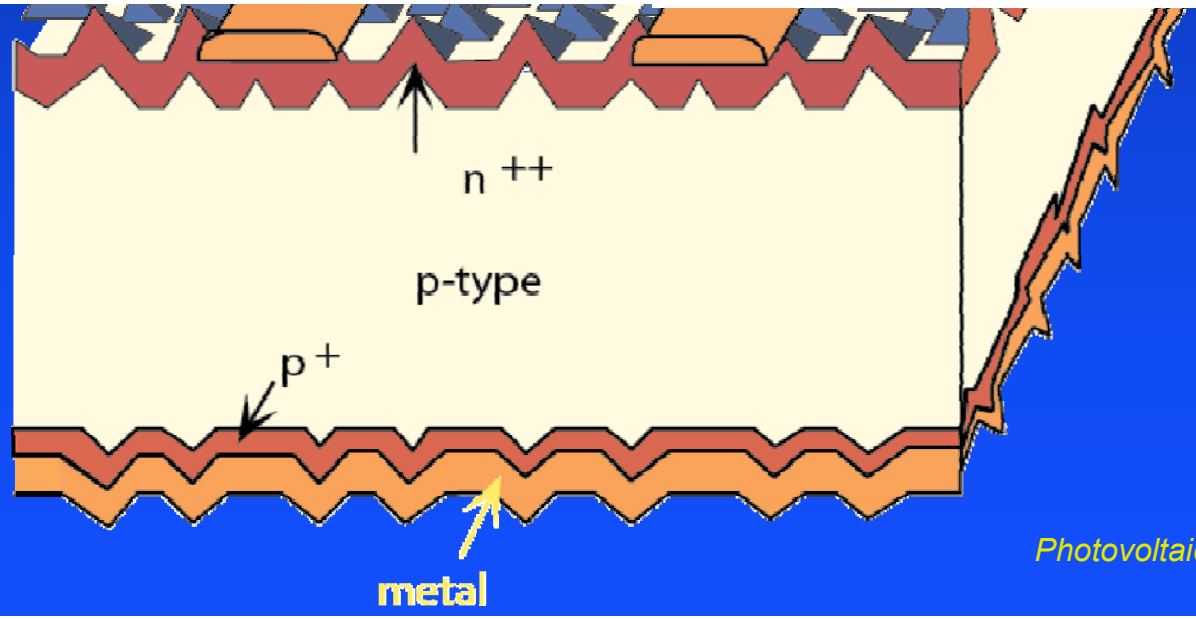


Fig. 21 Trend of recombination currents J0bulk, J0front, J0rear.



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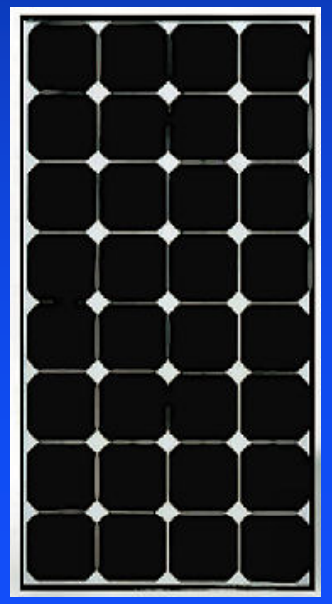
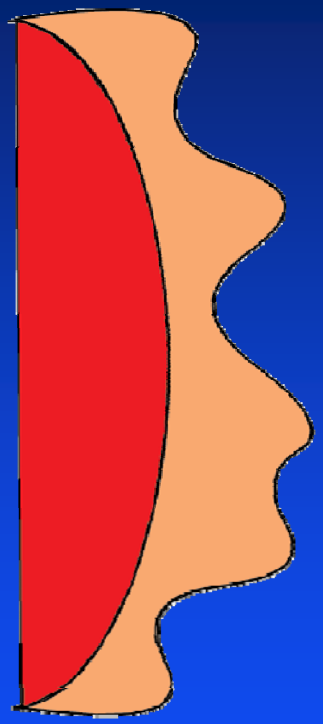
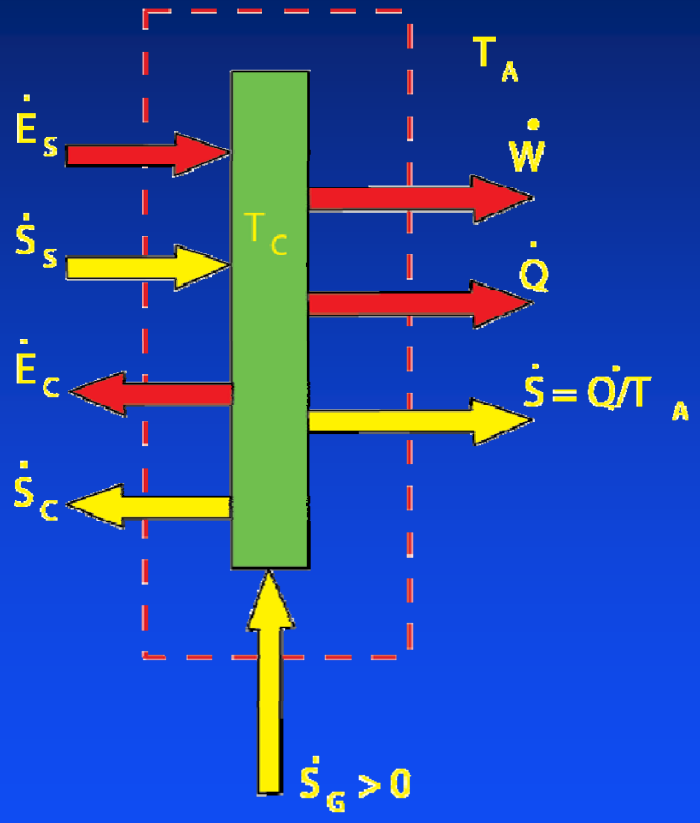
Si photovoltaics

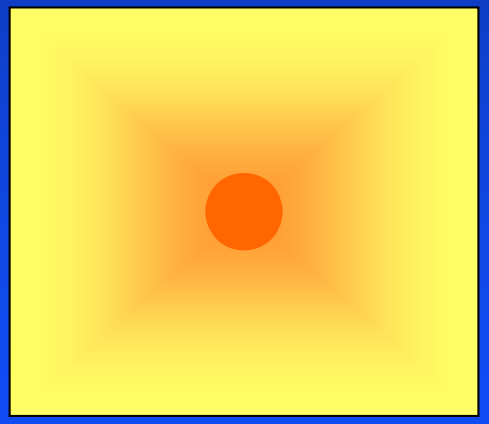
. Where ultimately?



Thermodynamic efficiency limits

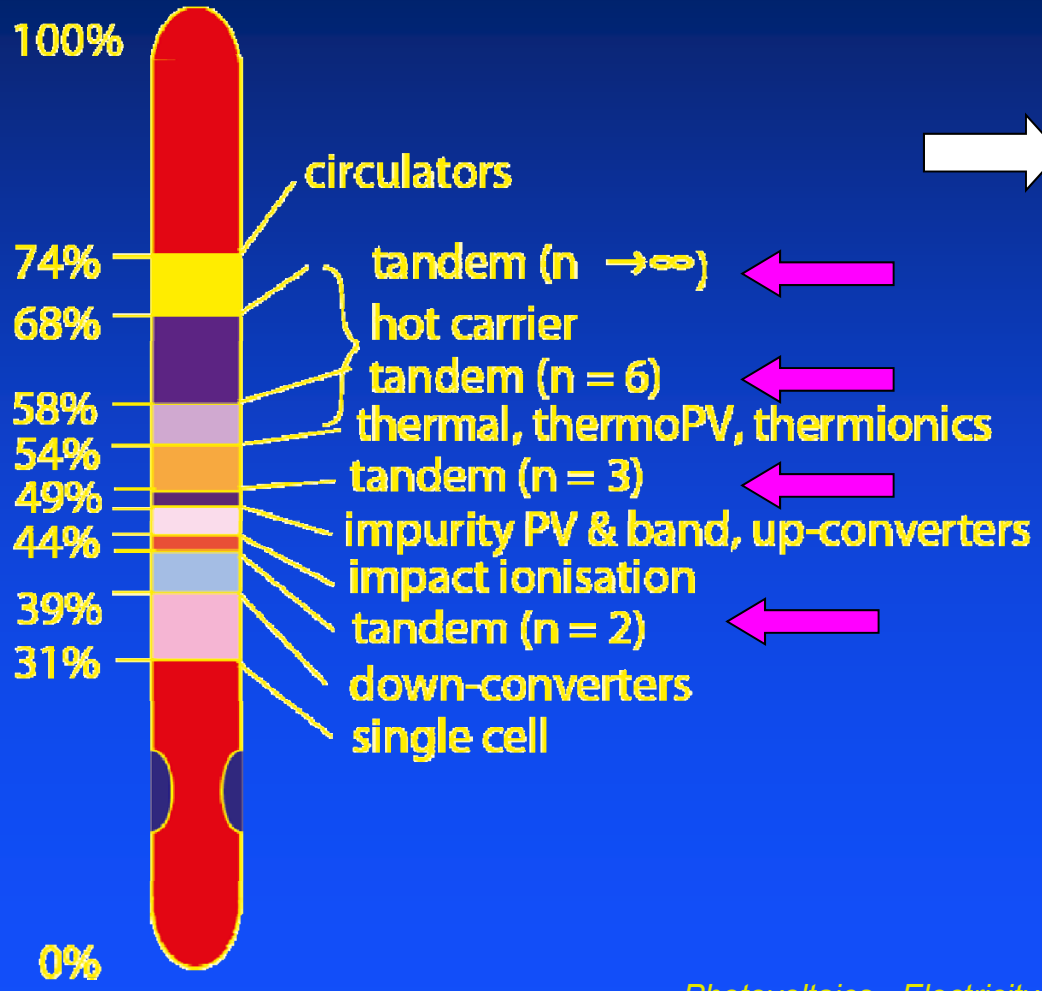


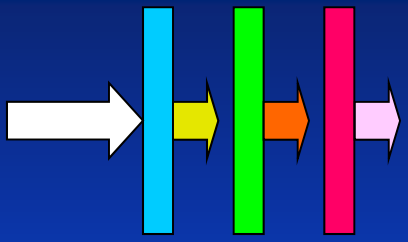




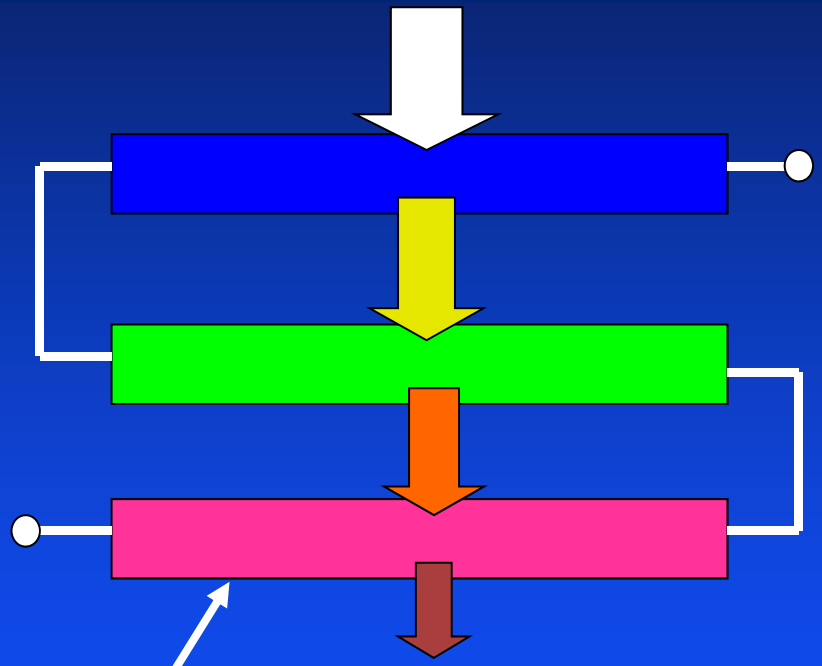
$\eta \leq (1-T_A\dot{S}_s/\dot{E}_s) =$ 93.3% (direct) = 73.7% (global)

Third generation options

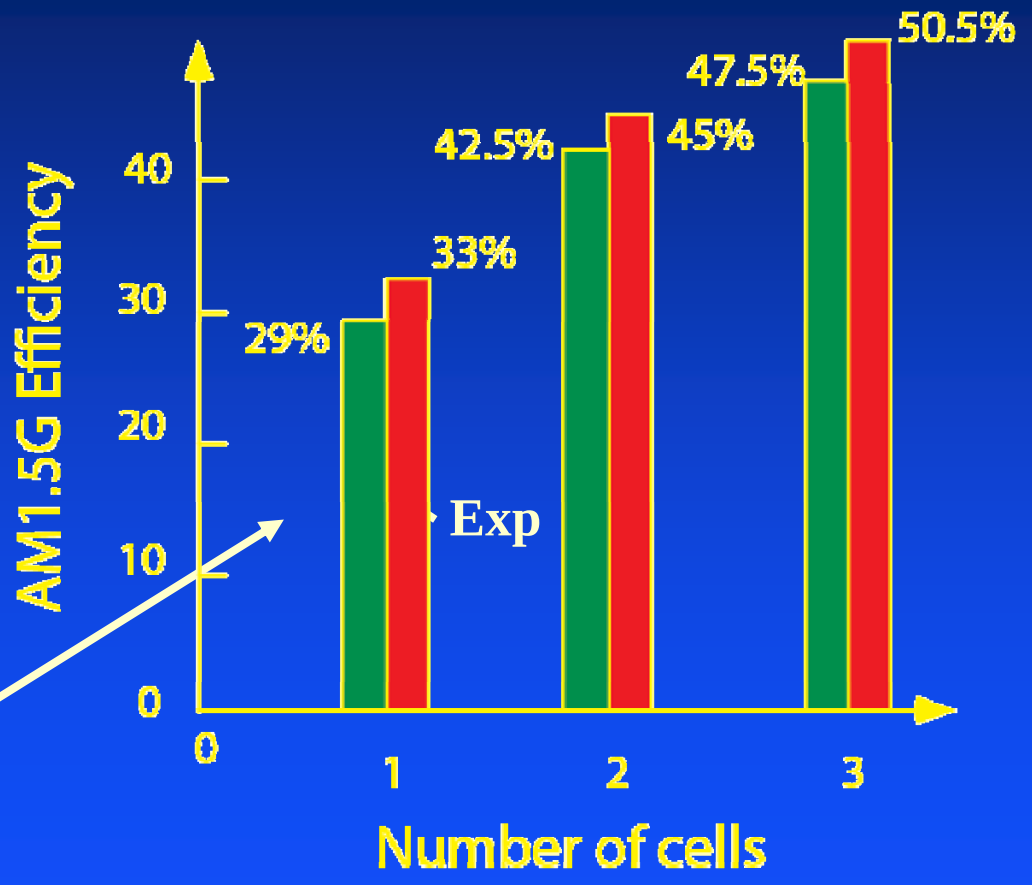




c-Si tandem



Free choice or Si



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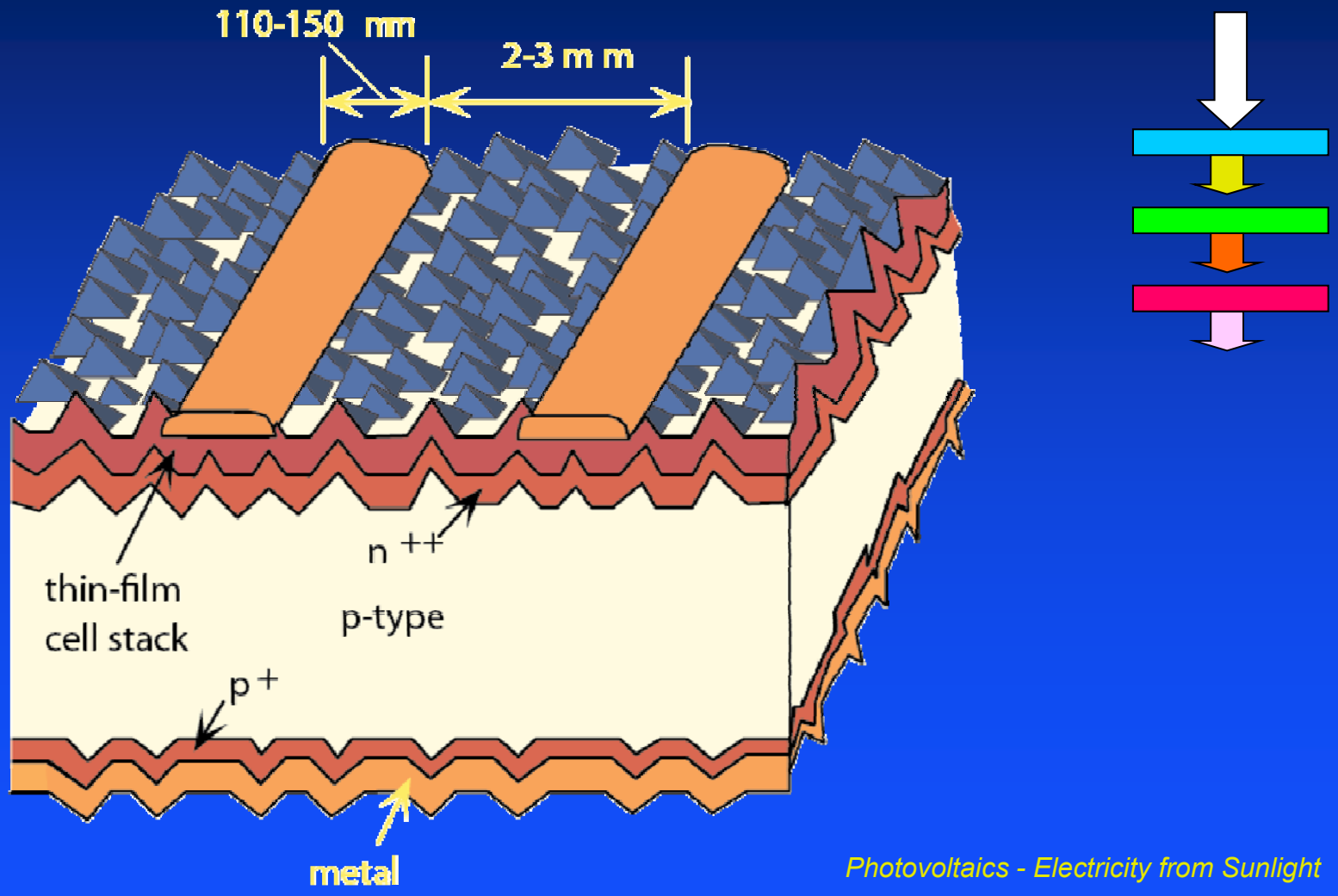
Si wafer-based tandem stack



Summary

- *Silicon hard to dislodge!*
- *Rapidly moving target (ASP <$1.00/W Q1/12)*
- *Peleton vs breakaway effect – but no finish line!*
- *Where ultimately? – cheap, clean substrate for 40% tandem?*