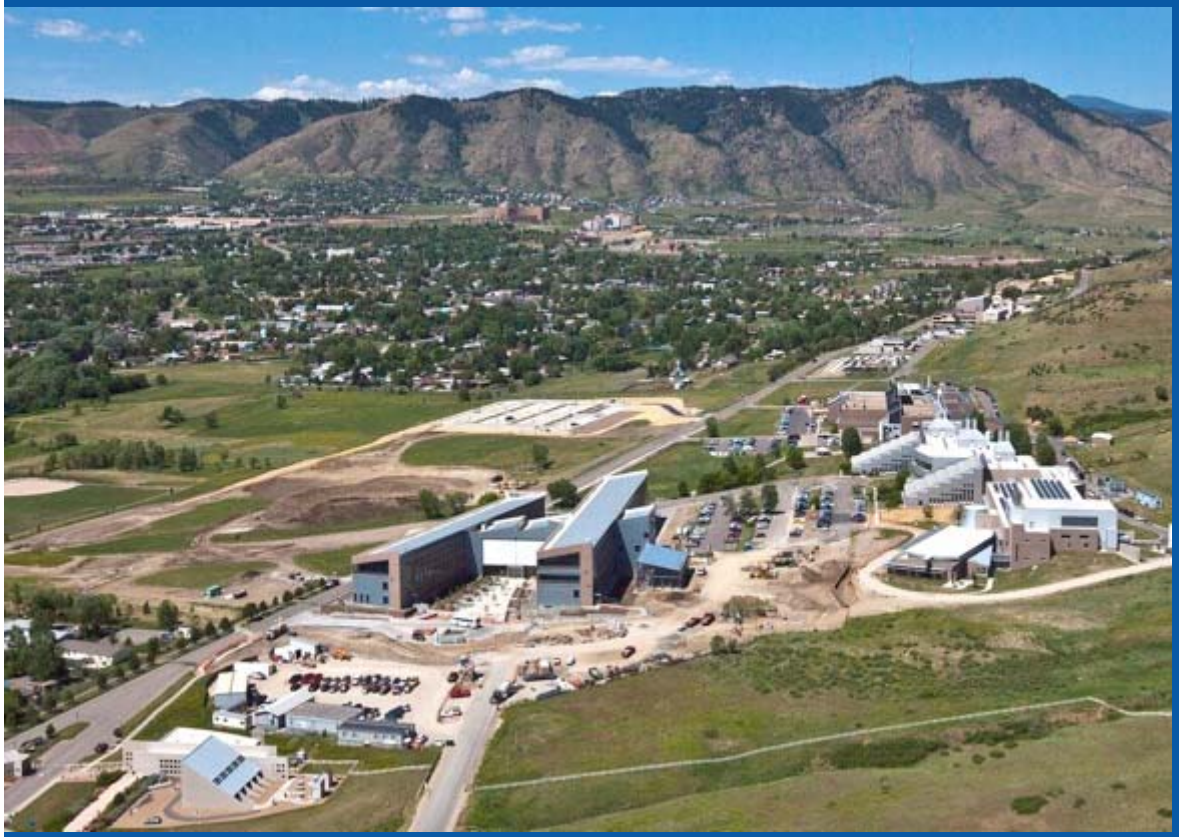
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

U.S. DEPARTMENT OF ENERGY

Research Paths to a Solar Powered World



2011 UC Solar Research Symposium

Sarah Kurtz (and many others)

Dec. 9, 2011

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Outline

Phenomenal growth of PV Industry

A mixture of technologies? Or will silicon be king forever?

Research pathways for:

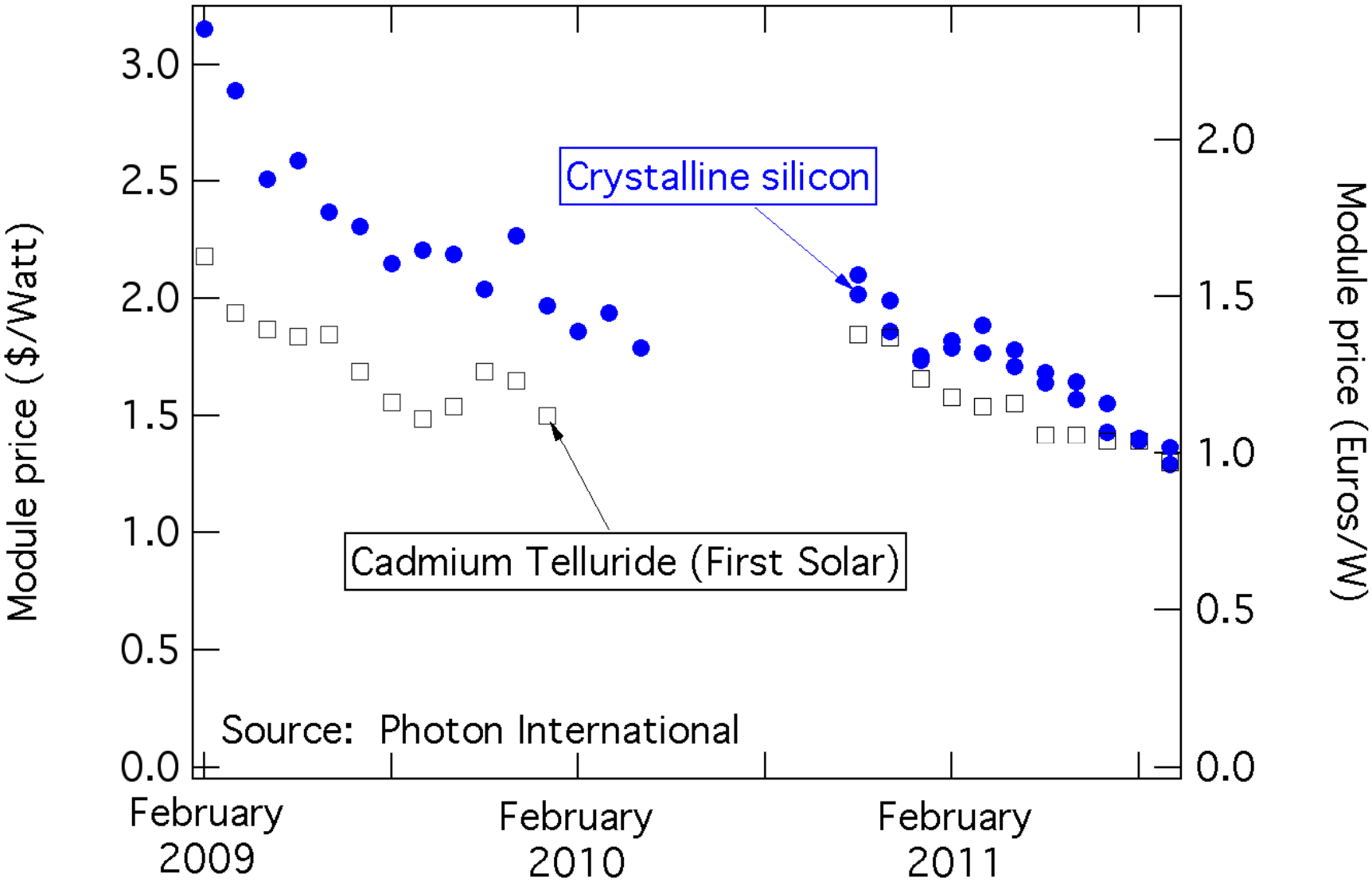
- CPV (multijunction cells – Defer discussion of optics and light management to the experts)
- Thin films (CdTe, CIGS)
- Silicon

The importance and challenge of predicting PV reliability

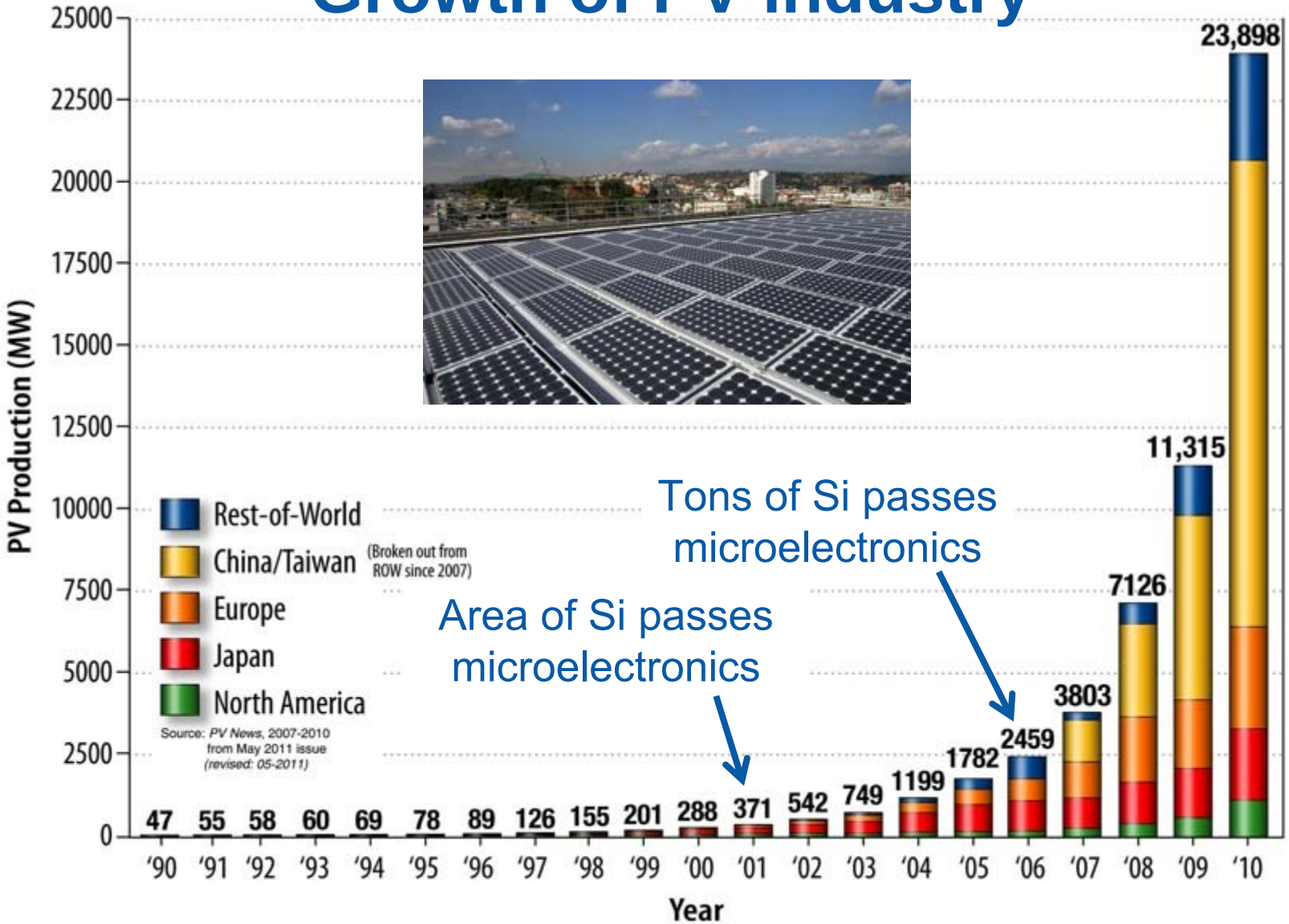
- Failure modes
- Research pathways/results

Summary

News of 2011: PV module prices are low!

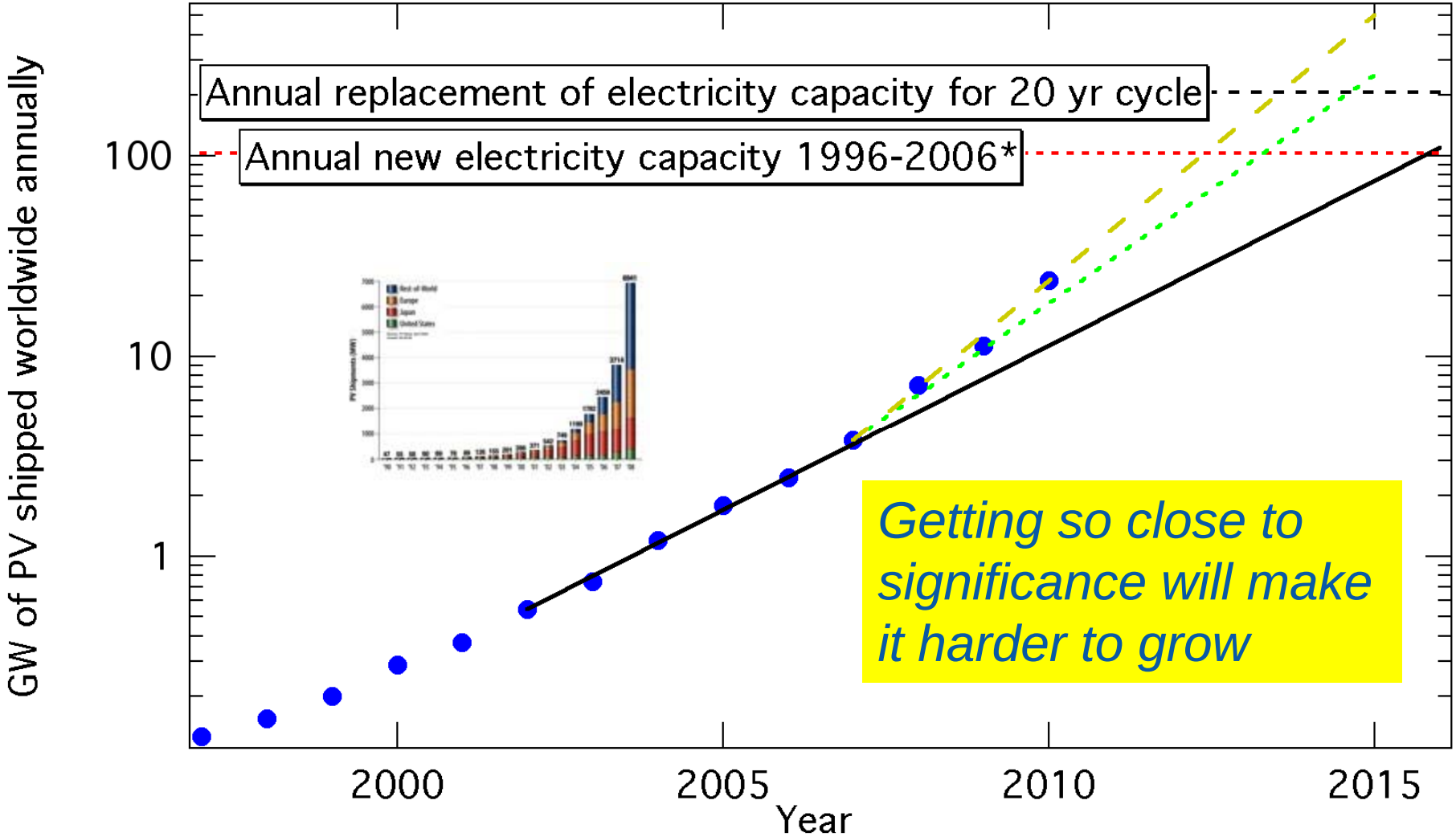


Growth of PV industry



PV shipments have been doubling every two years

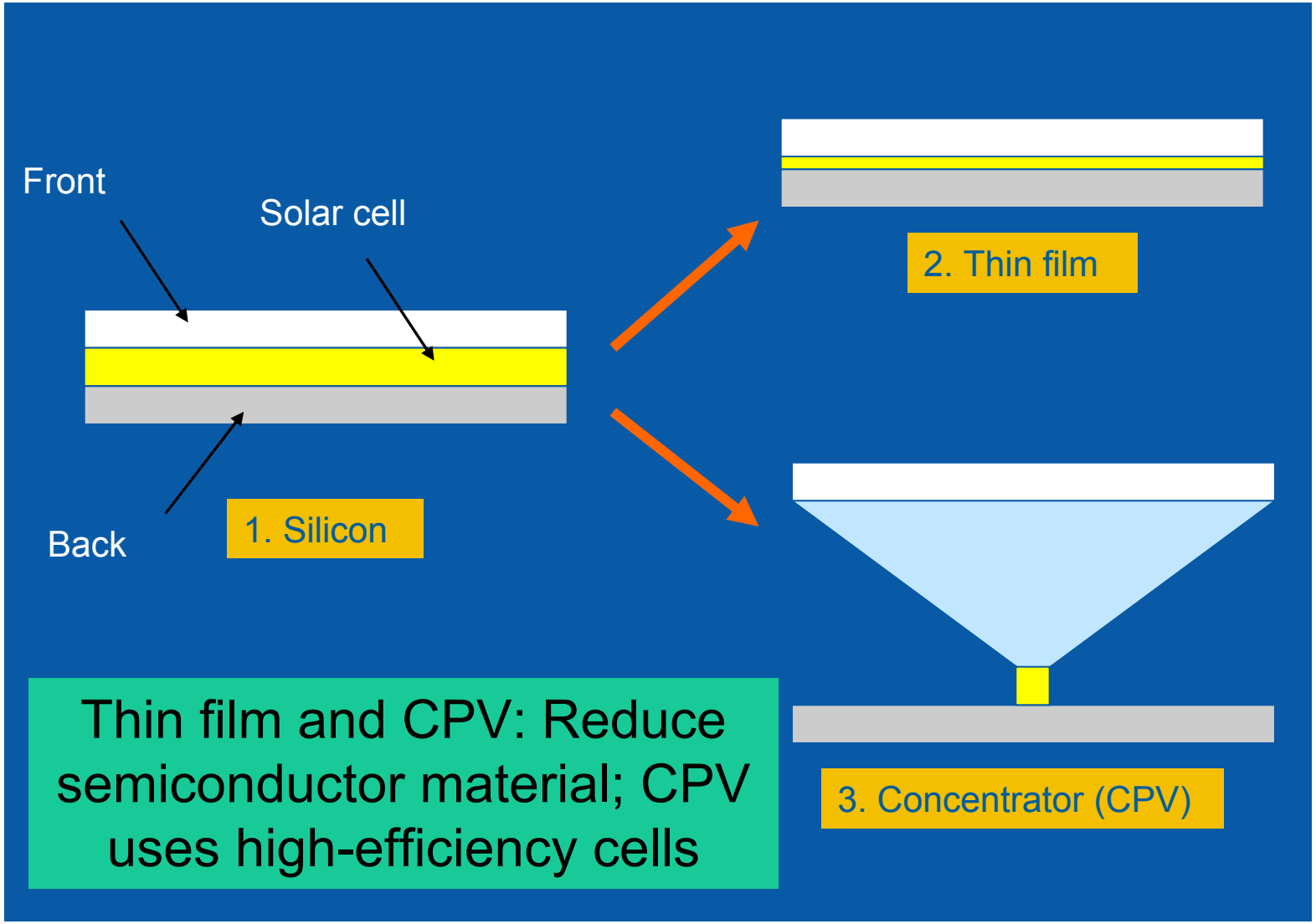
Growth of PV industry



*www.eia.doe.gov/emeu/international/electricitycapacity.html (4012-2981 GW)/10 yr

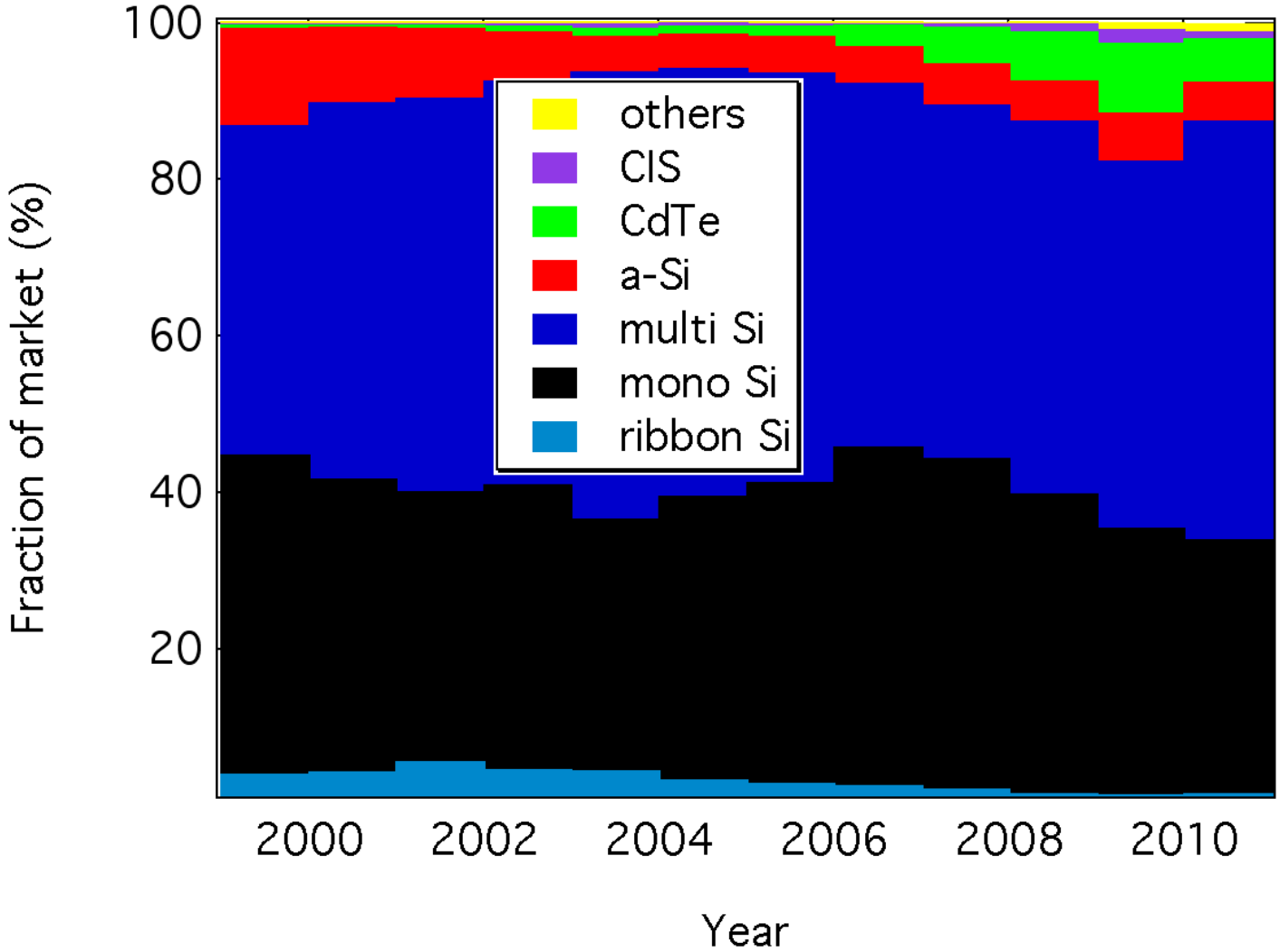
In some parts of Germany, on sunny days, PV may supply > 25% of electricity

Three approaches to PV (and lower cost)

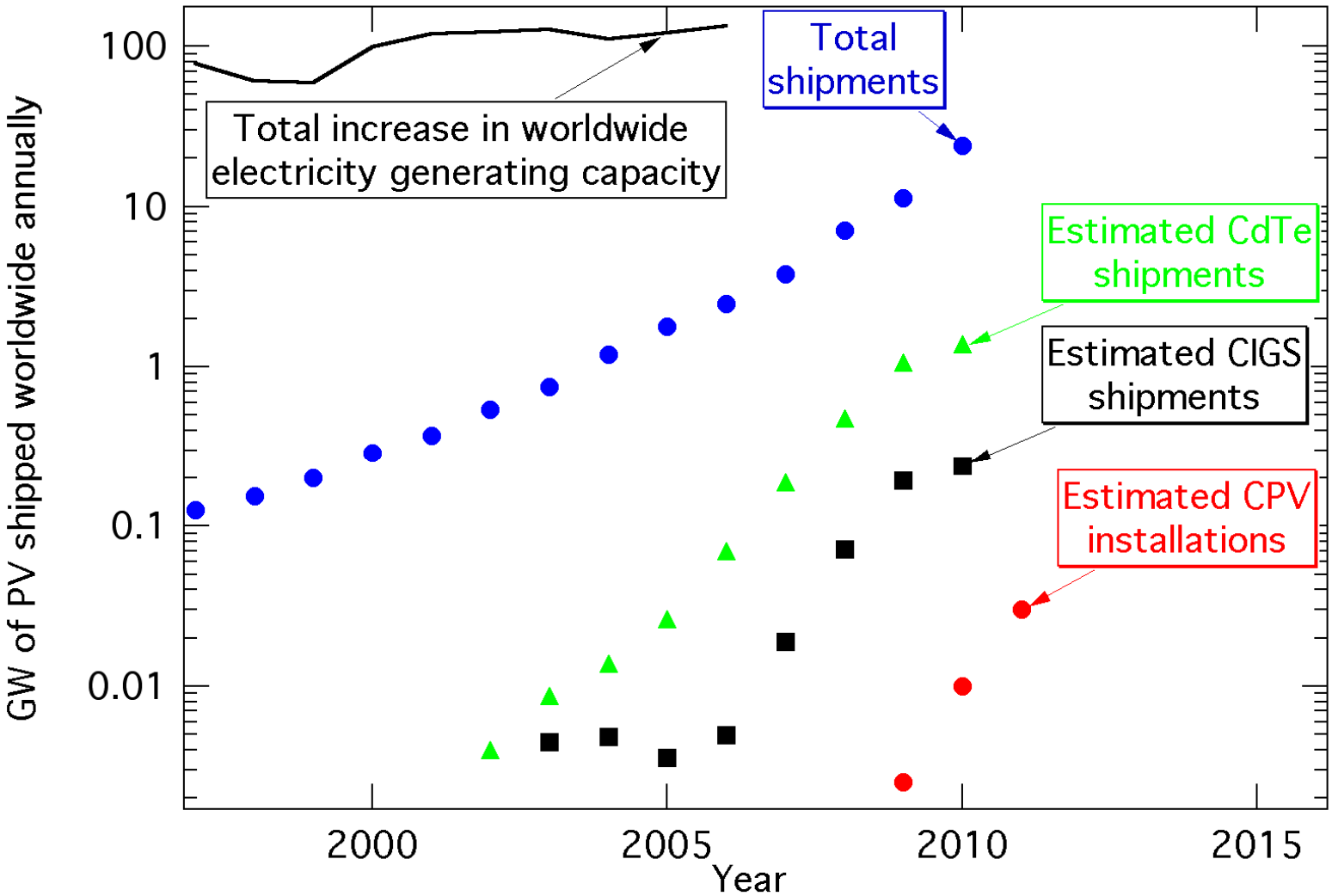


Thin film and CPV: Reduce semiconductor material; CPV uses high-efficiency cells

PV Technology trends:



Growth of PV industry – Technology Trends



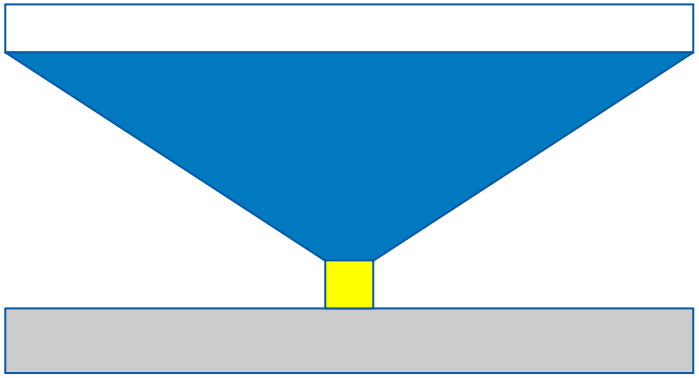
New technologies are growing, but have a long way to go to catch up with silicon

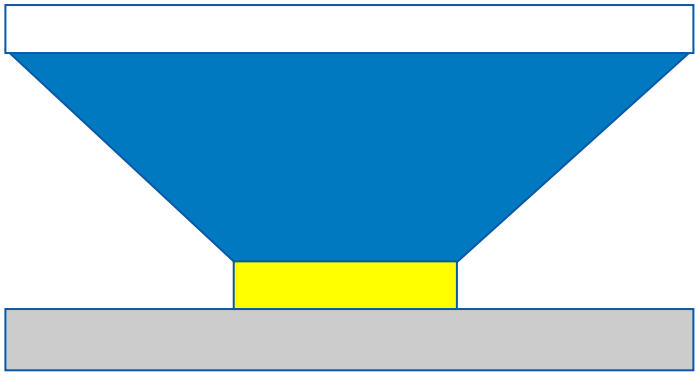
Research Pathways for CPV

Two primary concentrator (CPV) approaches

Amonix

Skyline Solar





High concentration
- 35% - 40% III-V cells
- 400X – 1500 X

Low concentration
- 15% - 25% Silicon cells
- 2X – 100 X

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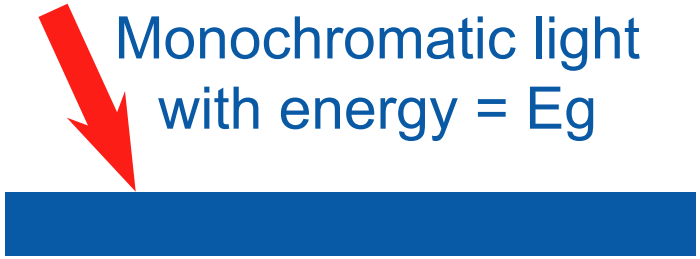
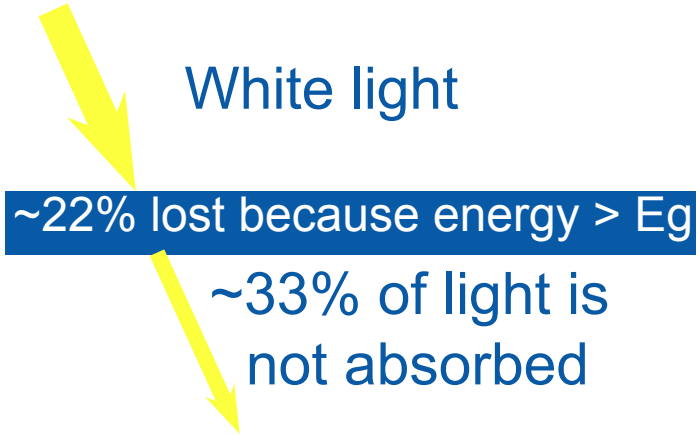
Why not 100% efficiency?: White



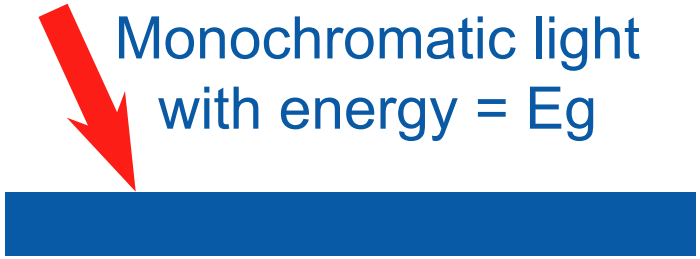
Temperature	Maximum efficiency
0 K	100%



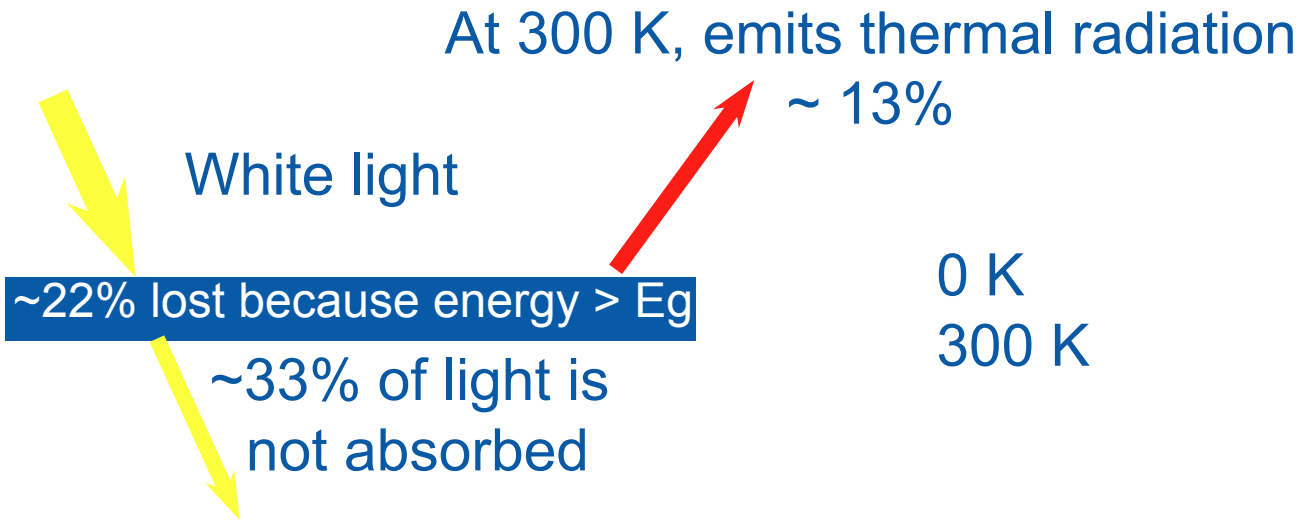
0 K	45%

Calculation assumes band gap of 1.4 eV

Why not 100% efficiency?: Temperature



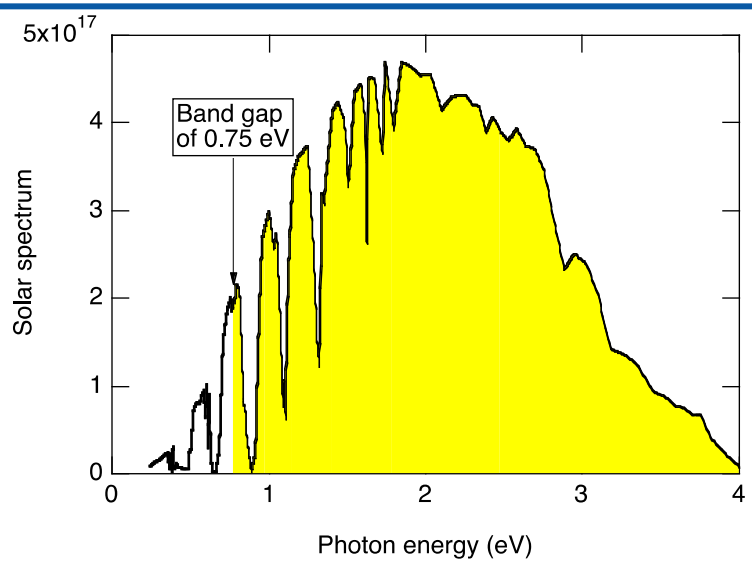
Temperature	Maximum efficiency
0 K	100%



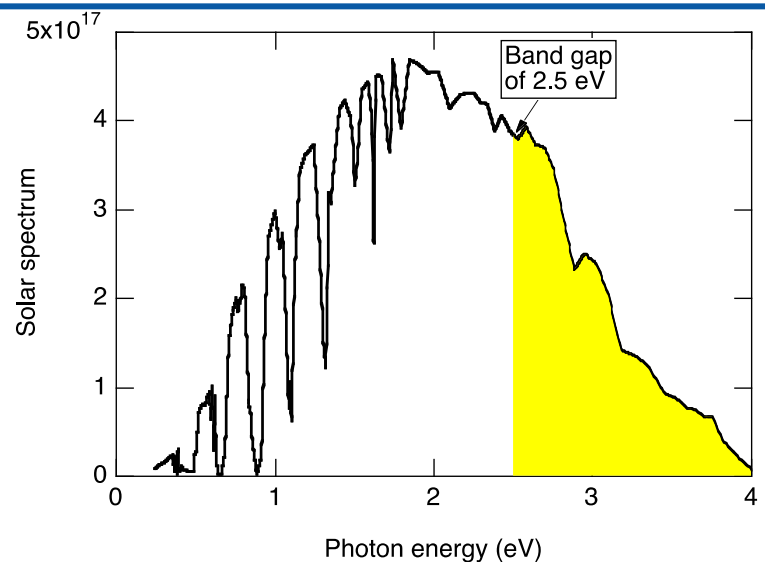
0 K	45%
300 K	32%

Calculation assumes band gap of 1.4 eV

Why multijunction? Power = Current X Voltage



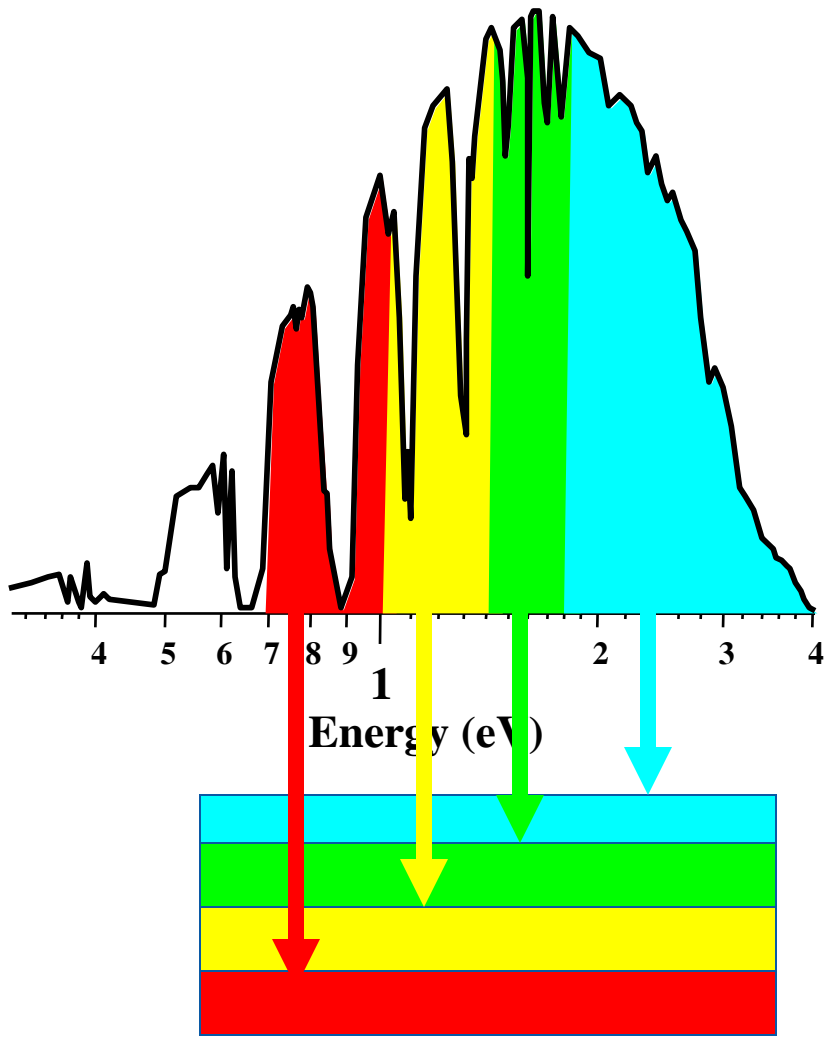
High current, but low voltage
Excess energy lost to heat



High voltage, but low current
Subbandgap light is lost

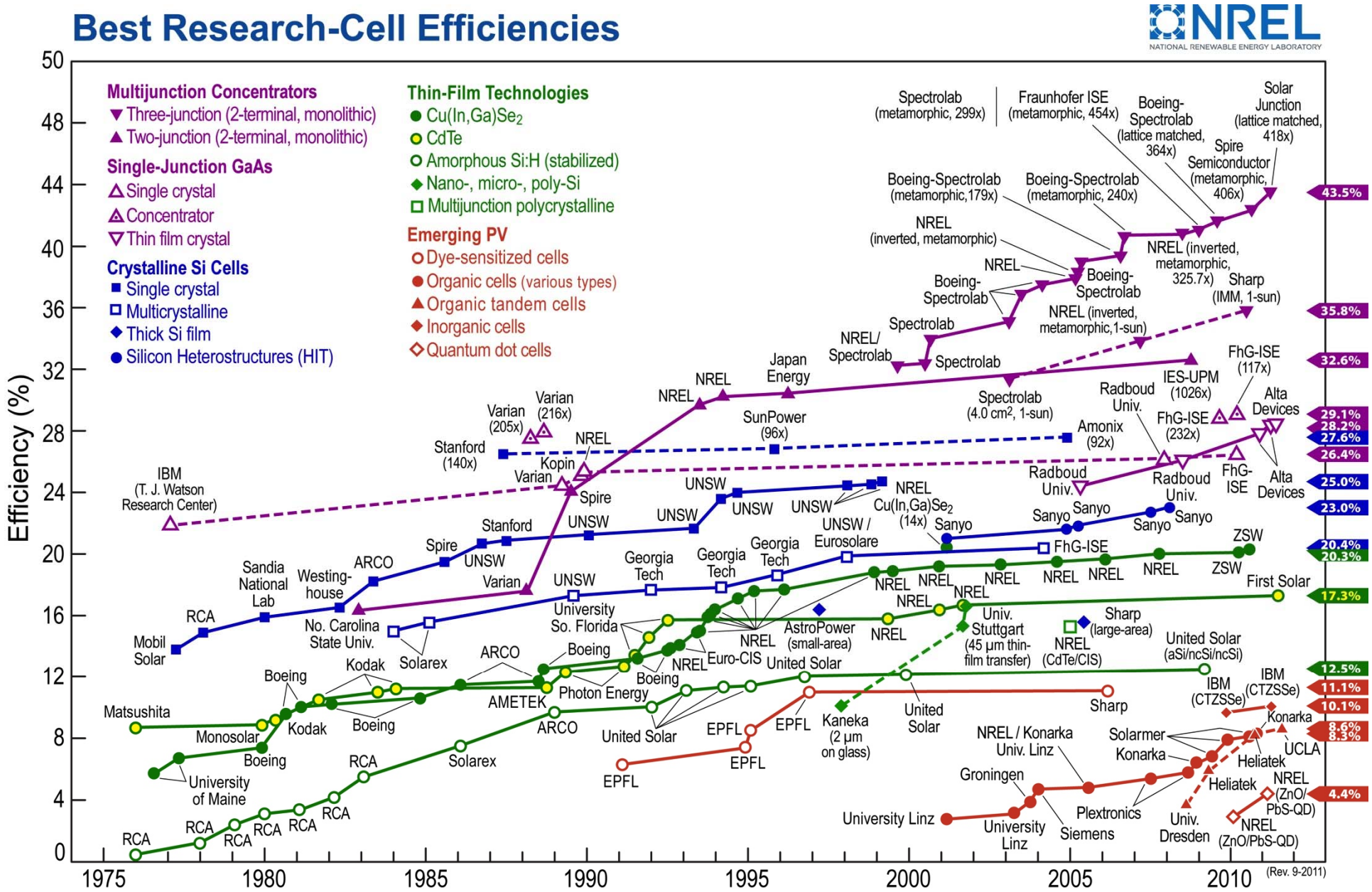
White light can be converted most efficiently by multiple materials

Choose materials with band gaps that span the solar spectrum

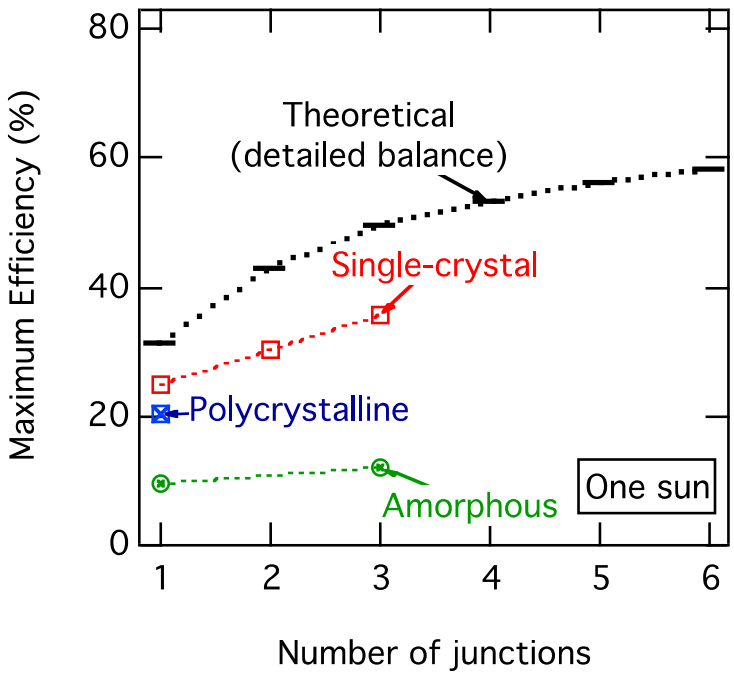


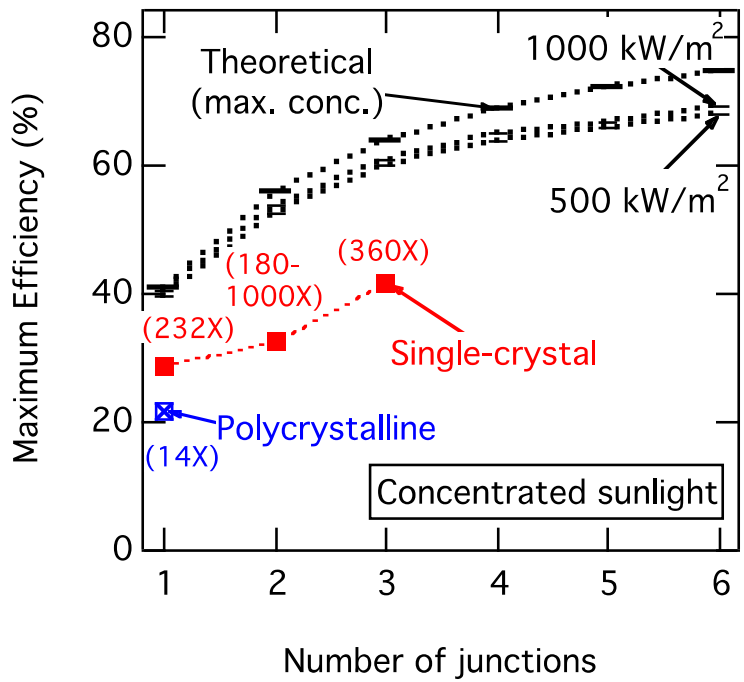
Multiple junctions – currently 3 junctions in champion cells

Champion Solar Cell Efficiencies



Efficiency limits for multijunction cells

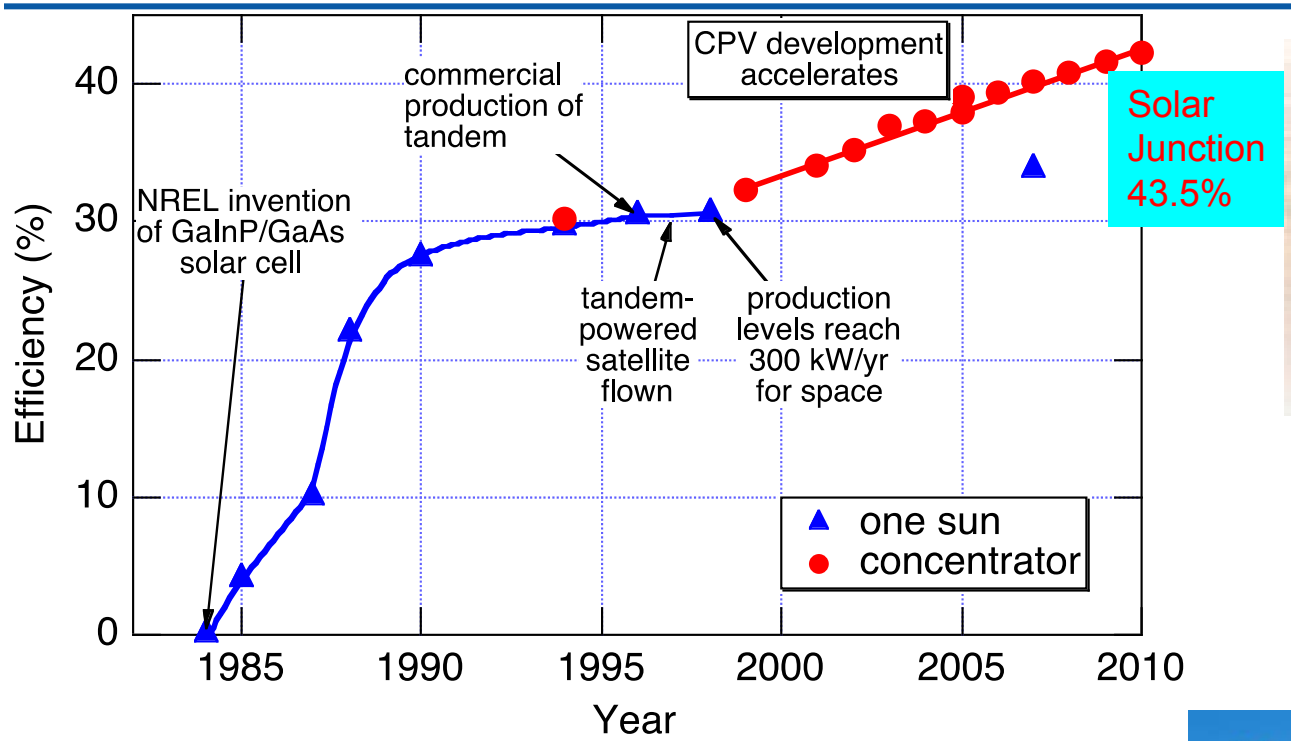


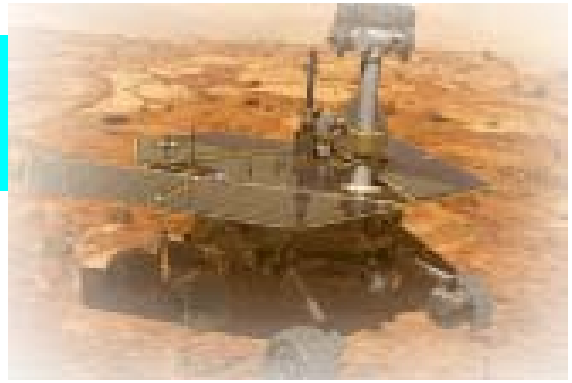


Kurtz, Prog. In PV, 2008.

45% may be practical; 50% may be achievable

Success of GaInP/GaAs/Ge cell





Mars Rover powered by GaInP/GaAs/Ge cells

Not a laboratory curiosity: records are often set on production hardware

Currently, eight groups claim ≥ 40% cells with six cell architectures

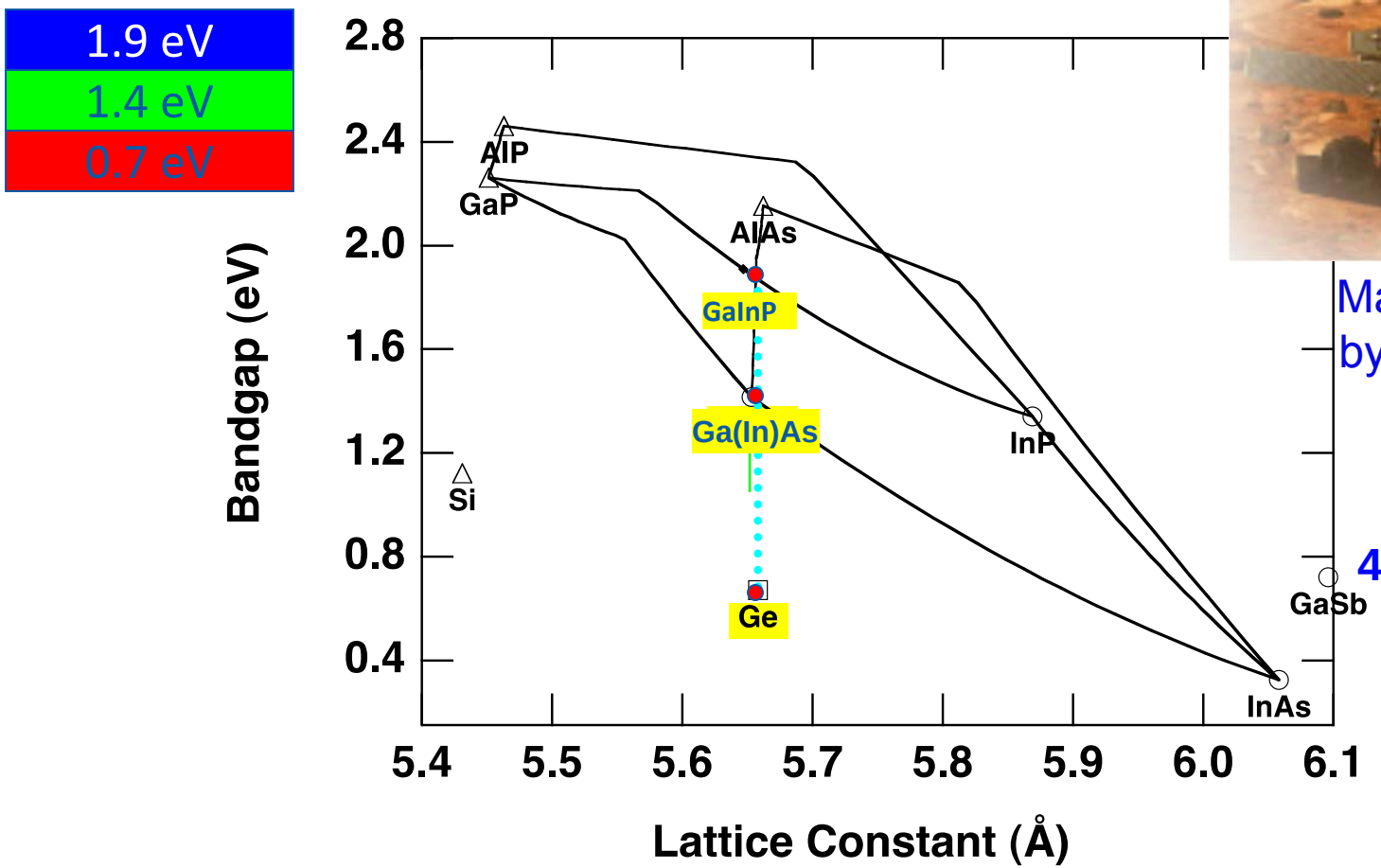
This very successful space cell is currently being engineered into systems for terrestrial use

Multijunction (MJ) solar cells ≥ 40% - multiple designs

These can be assembled in many ways

National Renewable Energy Laboratory

Lattice-matched 3 junction is commercially available

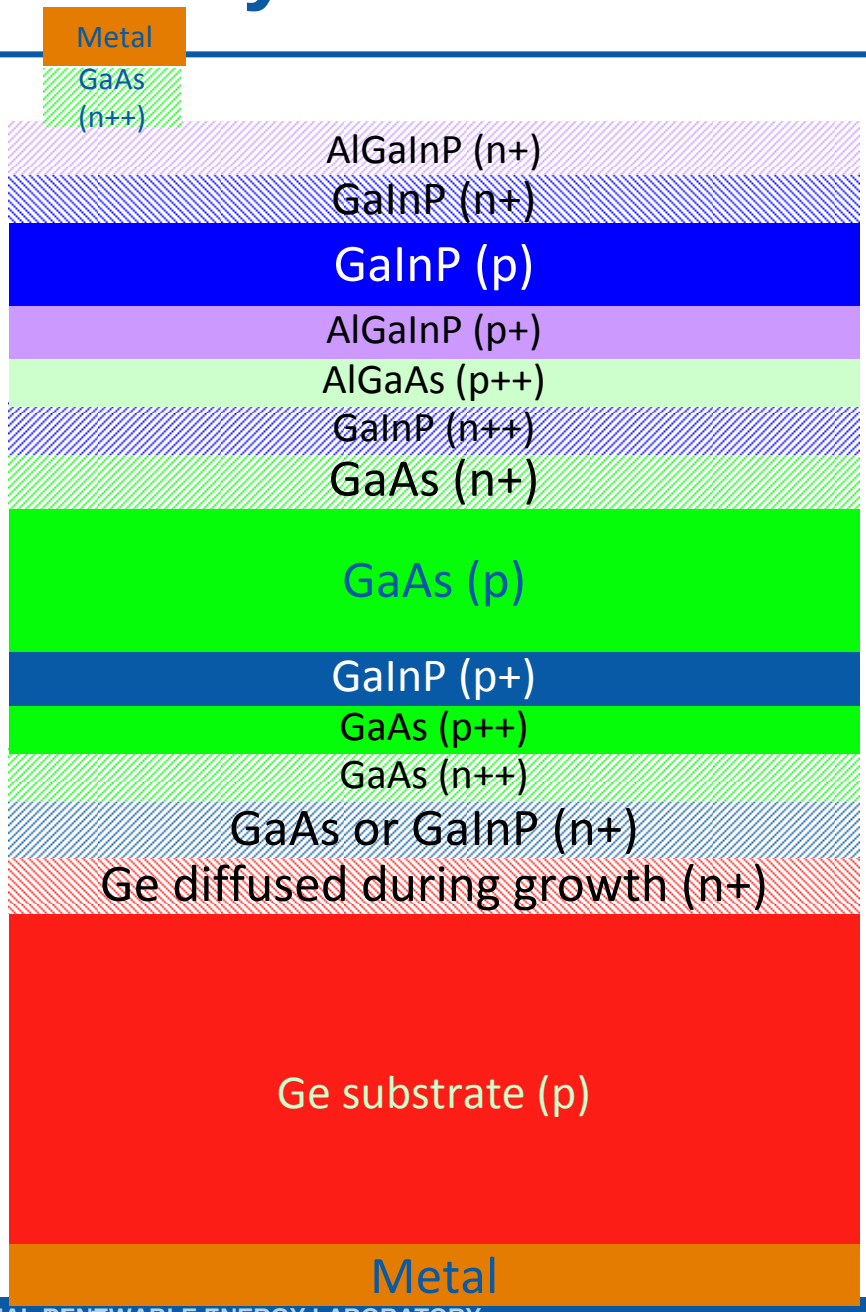


Mars Rover powered by multijunction cells

41.6% @ 364 suns
King 2009;
24th PVSEC
Spectrolab

Lattice matched materials give high crystal quality though they do not provide optimal band gap combination

Anatomy of a MJ cell – structure



1st junction

tunnel junction

2nd junction

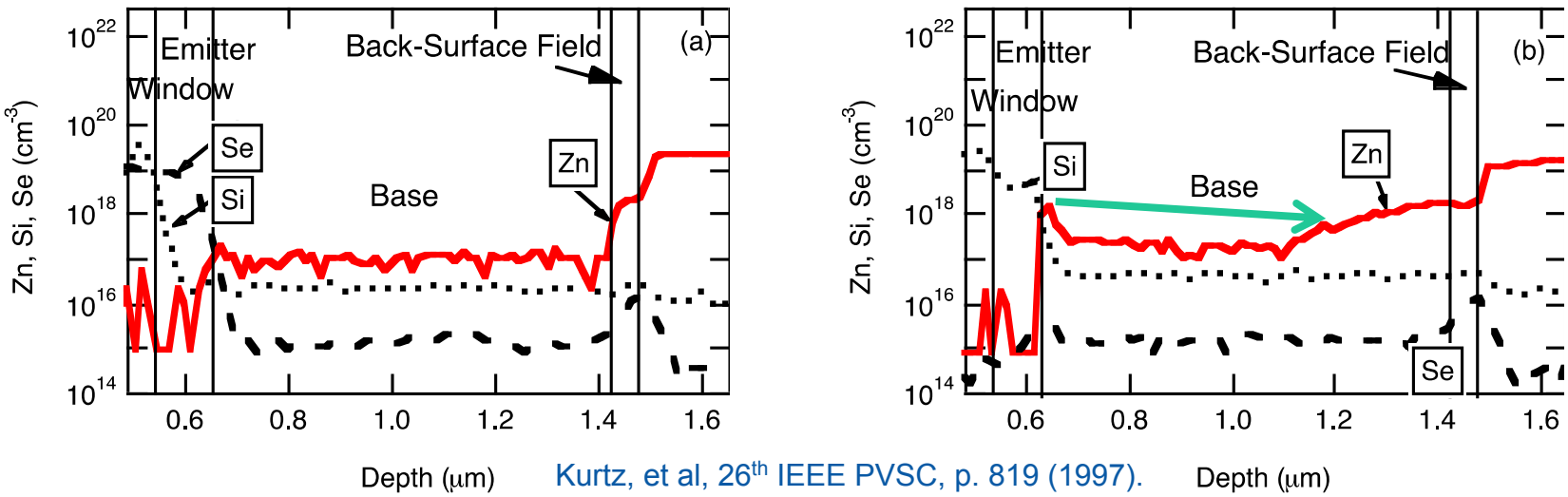
tunnel junction

3rd junction

- structure is simplified and not to scale
- every interface can add defects or series resistance

Research opportunities for MJ cells - dopants

Growth of n-type layers at front of cell causes diffusion



Kurtz, et al, 26th IEEE PVSC, p. 819 (1997).

When Se dopant is used, the Zn stays put (for these conditions)

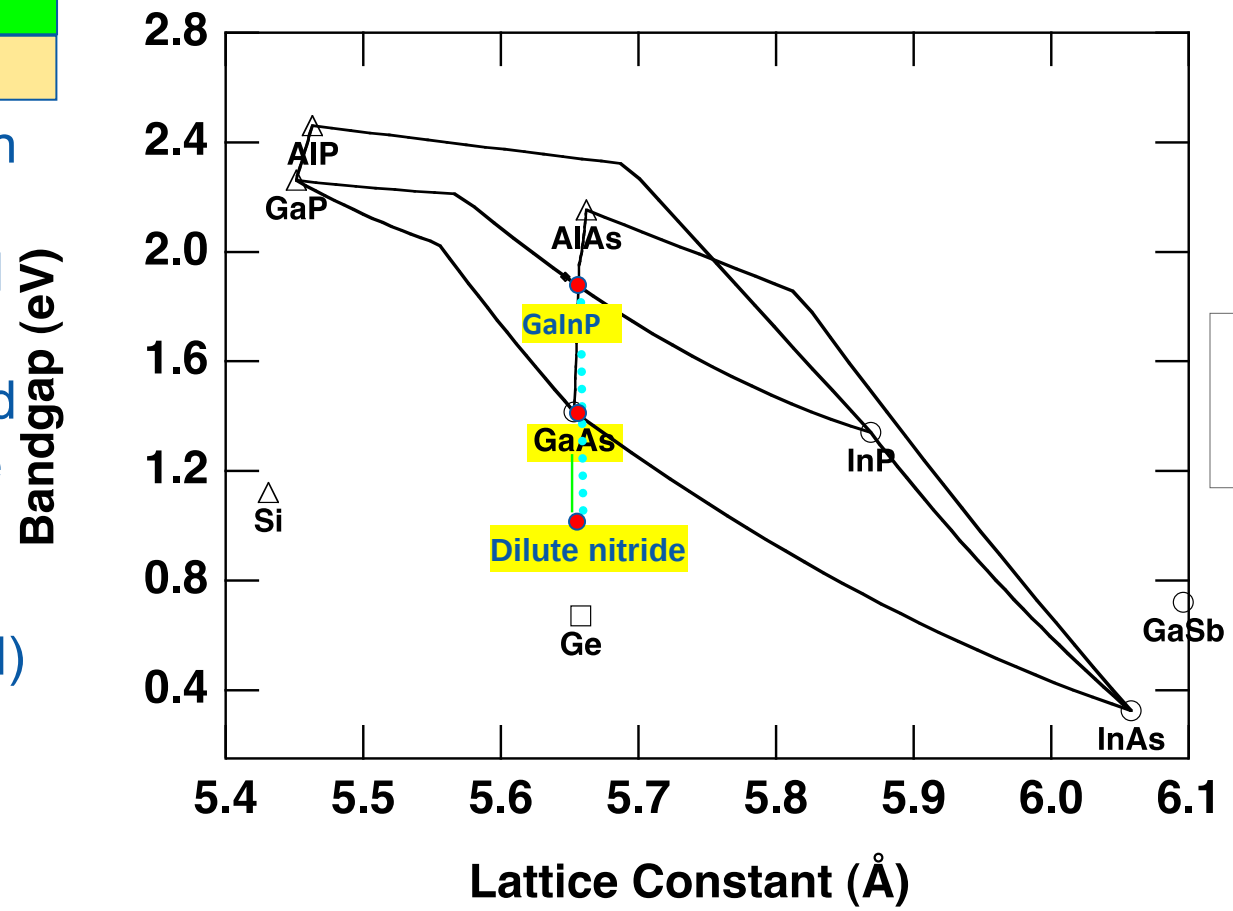
When Si dopant is used, the Zn moves

Dopants may not end up where you think they should!
Fermi level pinning at growth surface changes equilibrium concentration of point defects: Deppe, APL, 1990.

New World Record: Dilute nitride unique to Solar Junction

1.9 eV
1.4 eV
1.0 eV

3-junction lattice matched (Details estimated because result is not published)



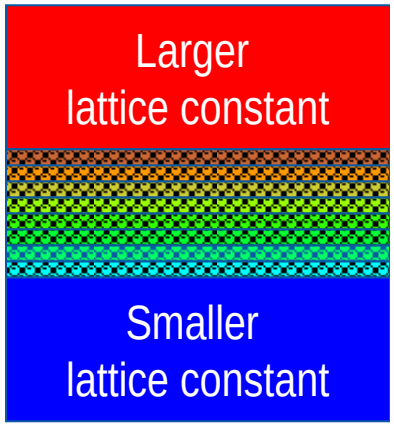
43.5% by Solar Junction

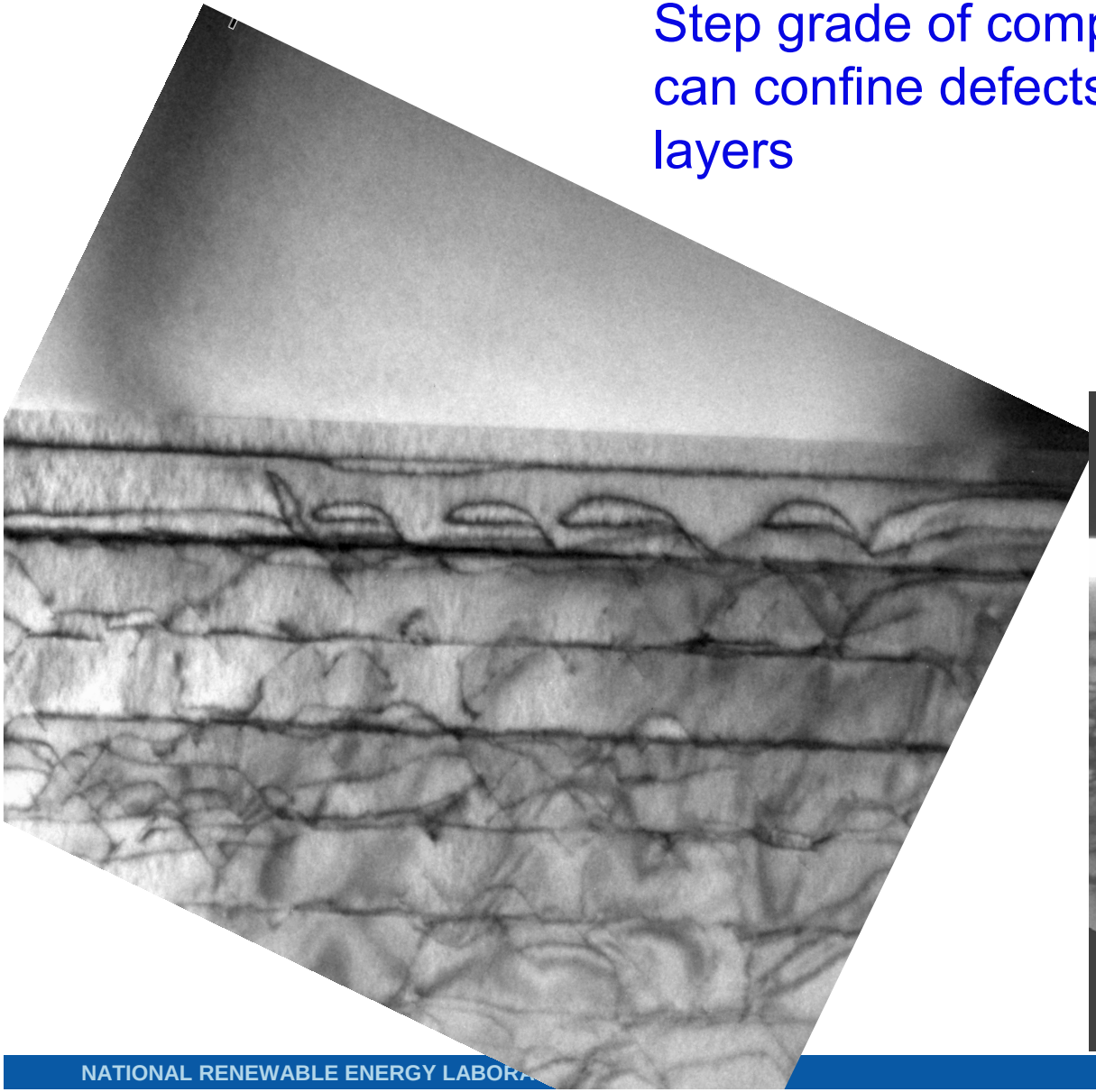
Dilute nitride bottom junction with Eg of 0.8 -1.4 eV

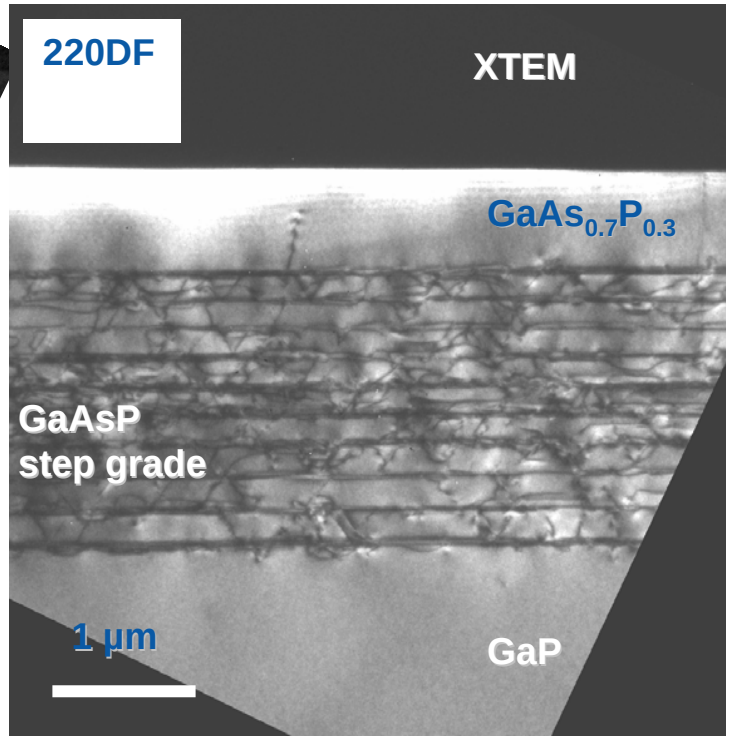
CVD-grown dilute nitride is heavily compensated by H- and C-related defect
Most groups gave up on the dilute nitride a few years ago

Lattice mismatched growth gives new opportunities

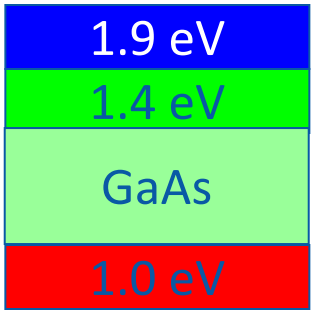
Step grade of composition can confine defects to graded layers



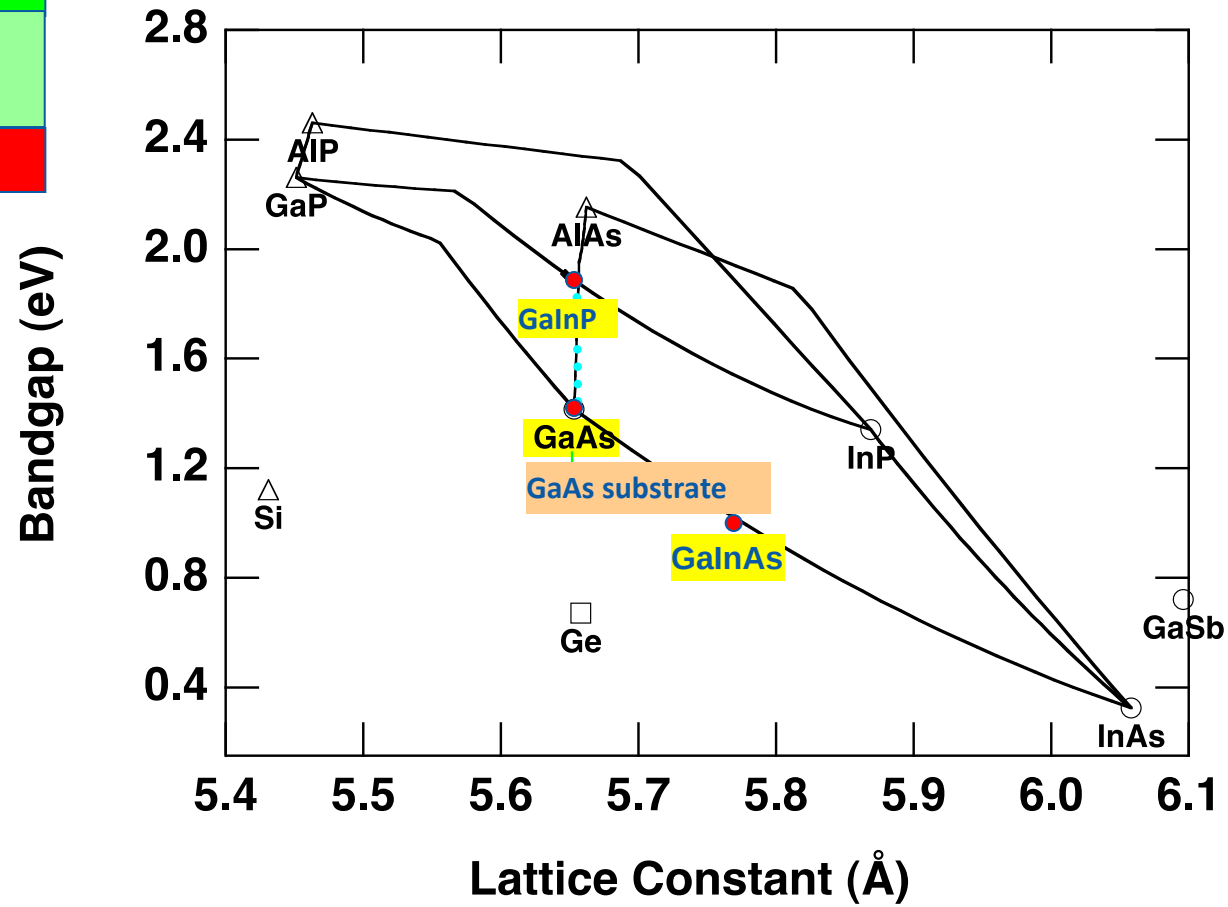




Two-sided triple junction (GaInP/GaAs/GaInAs)



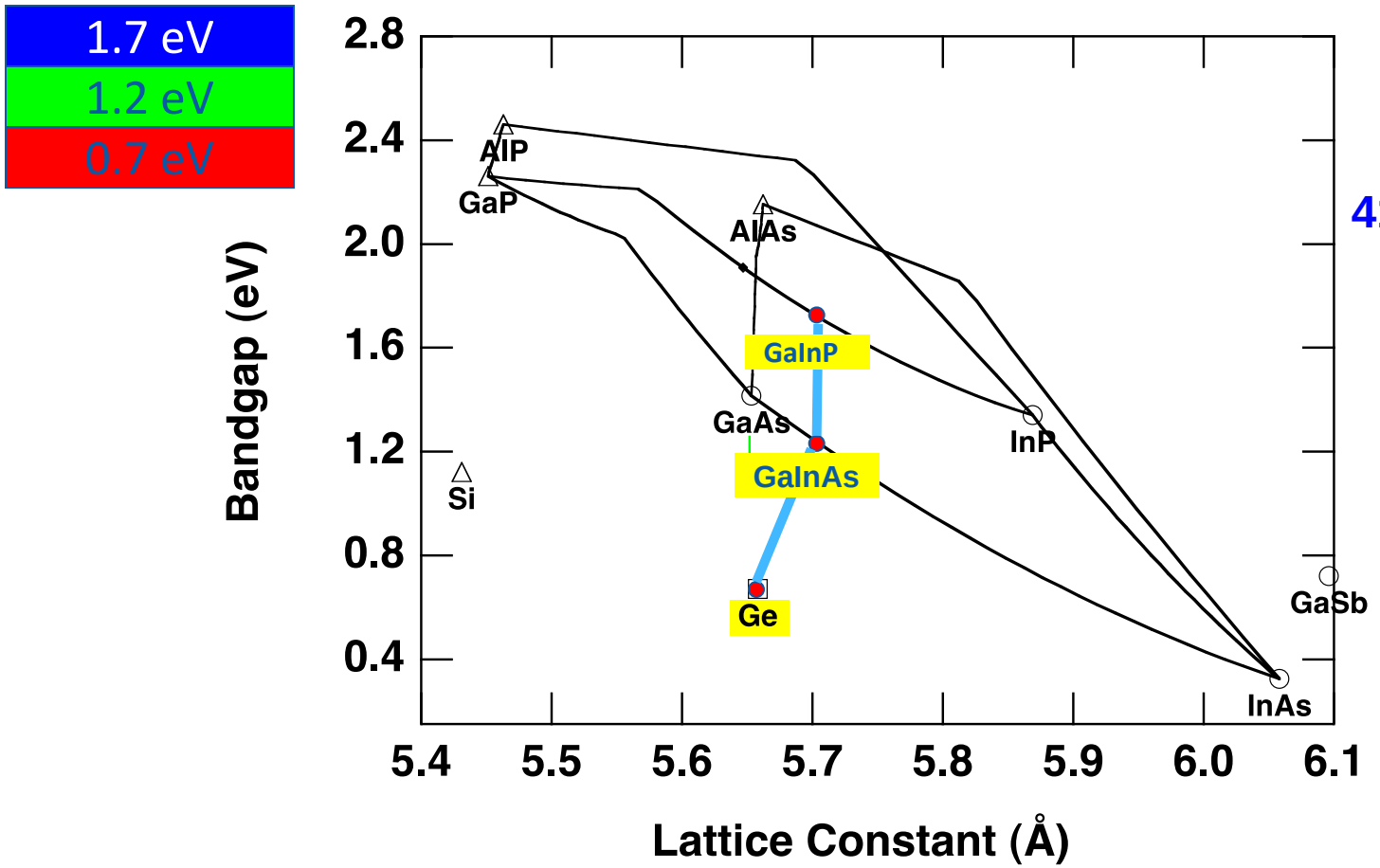
(estimated, since details of the cell have not been published)



42.3% @ 406 suns
Spire - 2010

Growth on both sides of wafer gives flexibility
First explored by Varian in the 1990s

Lattice-mismatched triple junction on Ge

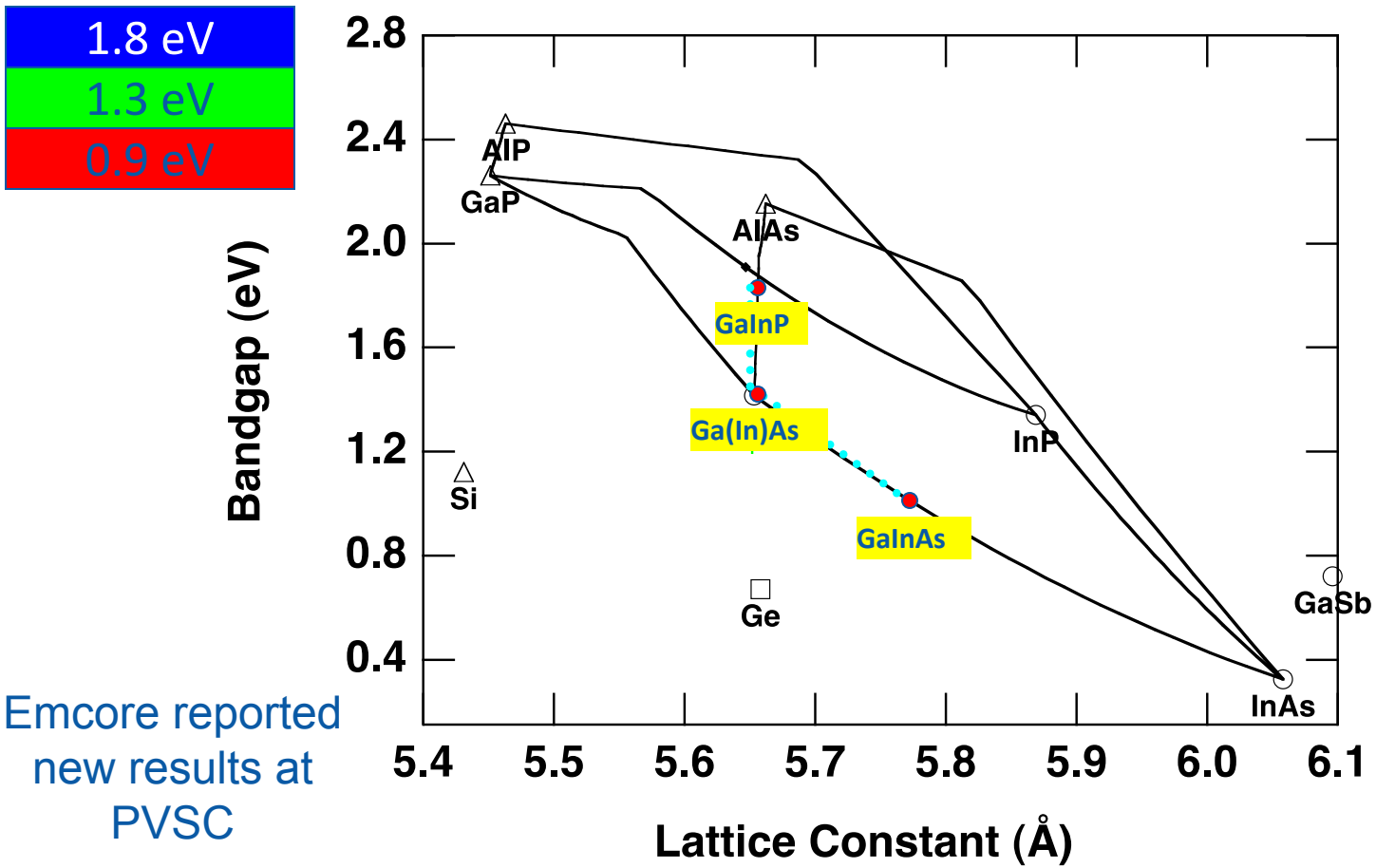


41.1% @ 454 suns
Guter 2009, APL
Fraunhofer

Spectrolab now sells mismatched cells

Lattice mismatched materials give close to optimal band gap combination, but are more difficult to grow with high yield

Inverted lattice-mismatched (IMM)



Emcore reported new results at PVSC

40.8% @ 326 suns

Geisz APL 2008 (NREL)

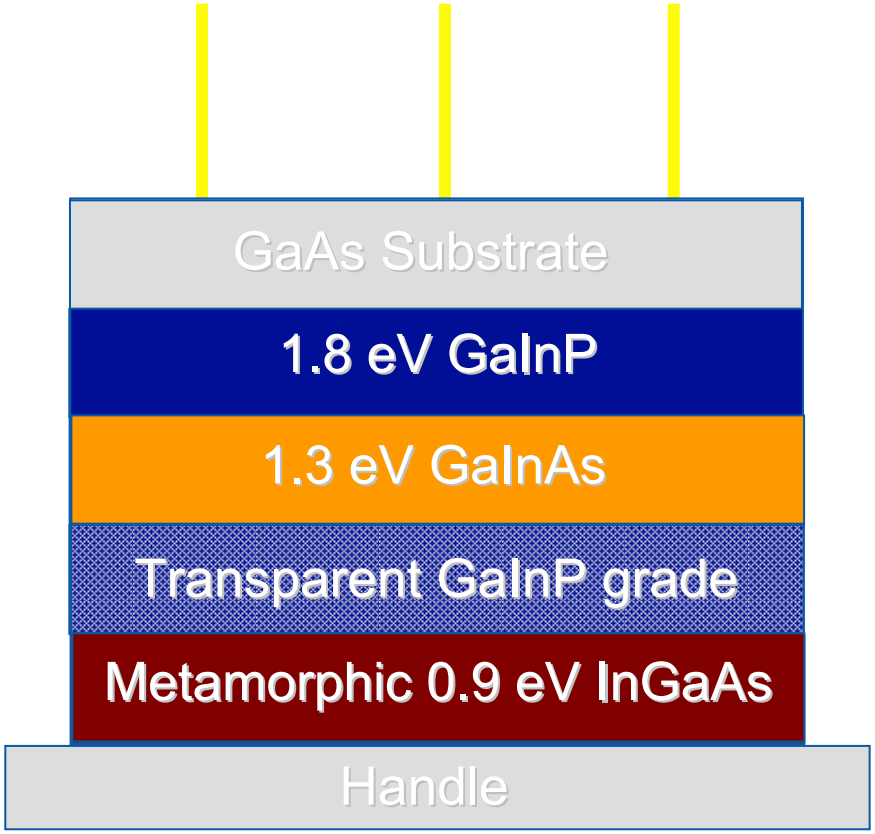
Lattice matched materials are grown first, followed by mismatched – provides pathway to four-junction and higher efficiencies

Inverted metamorphic approach

GaInP/GaAs/GaInAs Ultra-Thin Tandem Cell

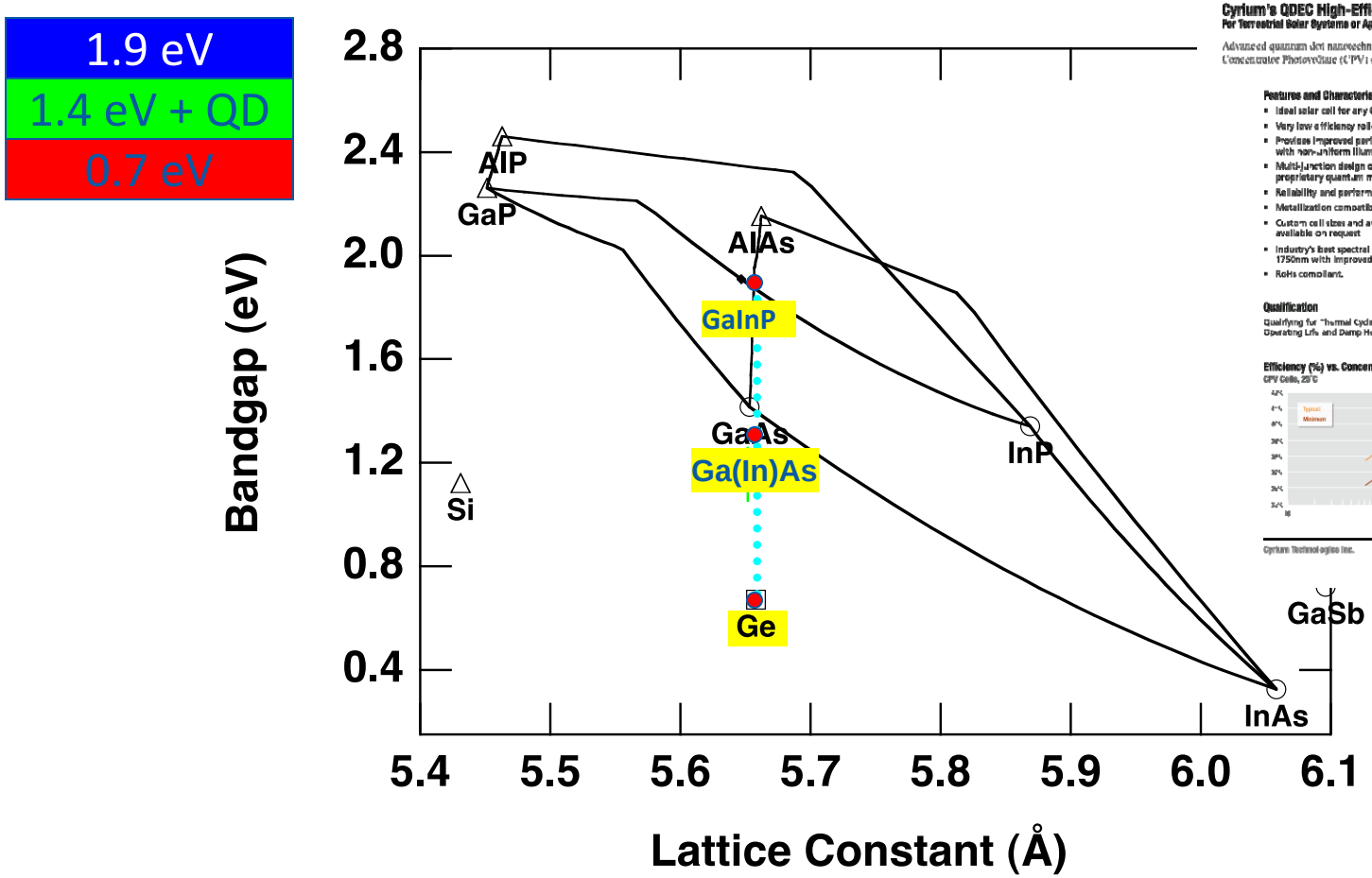
Advantages:

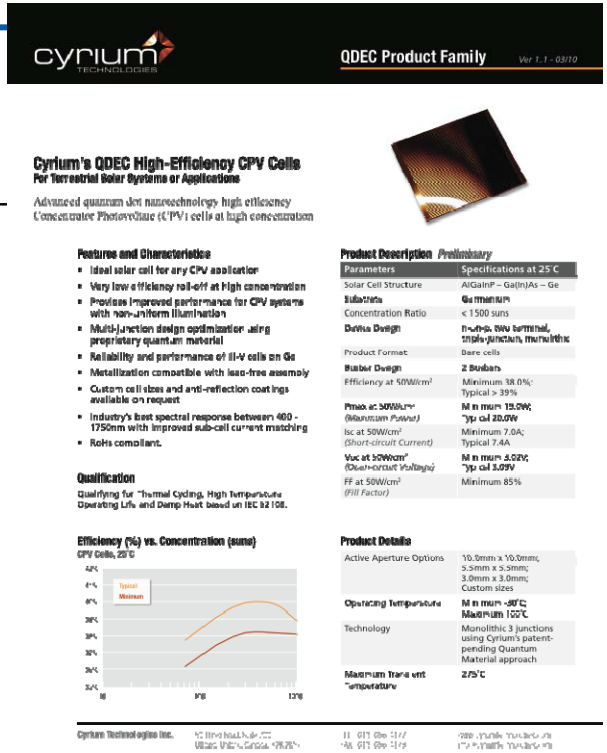
- Path to higher efficiency – 40.8% so far
- Reuse of substrate or use of impure substrate can reduce cost



Invented by Mark Wanlass; 40.8%: Geisz, APL, 2008.

Quantum dot triple junction cells ~40% by Cyrium





Comparison of six ~40% approaches

Design	Efficiency	Efficiency potential	Ease of growth	Thickness	Growth time
Lattice-matched 3-junction	41.6% @ 364 suns	Will be difficult to reach 45%	Lattice matched	No extra layers	Can be grown quickly
Two-sided 3-junction	42.3% @ 406 suns	Could hit 50% with addition of 4th junction	Only low-E part is affected by mismatch	Extra graded layer on back	Requires 2 steps
Mismatched 3-junction	41.1% @ 454 suns	Might reach 45%	Requires excellent control over graded layers	Requires one graded layer	Added time of graded layer
Inverted mismatched 3-junction	40.8% @ 326 suns	Can add more junctions to pass 50%	Requires substrate removal and multiple graded layers	Multiple graded layers	Added time of graded layers
Quantum-dot in GaAs (3-junction)	~40%	Might reach 45% (QD may be used elsewhere)	QD growth requires special skill	No extra layers	QD nucleation takes extra time
Dilute nitride – 3 junction	~40%	Could approach 50% with 4th junction	Probably requires MBE growth – might be a benefit	No extra layers	MBE growth is usually slower

Color coding may be controversial; but conclusion is clear:

We don't have an obvious winner

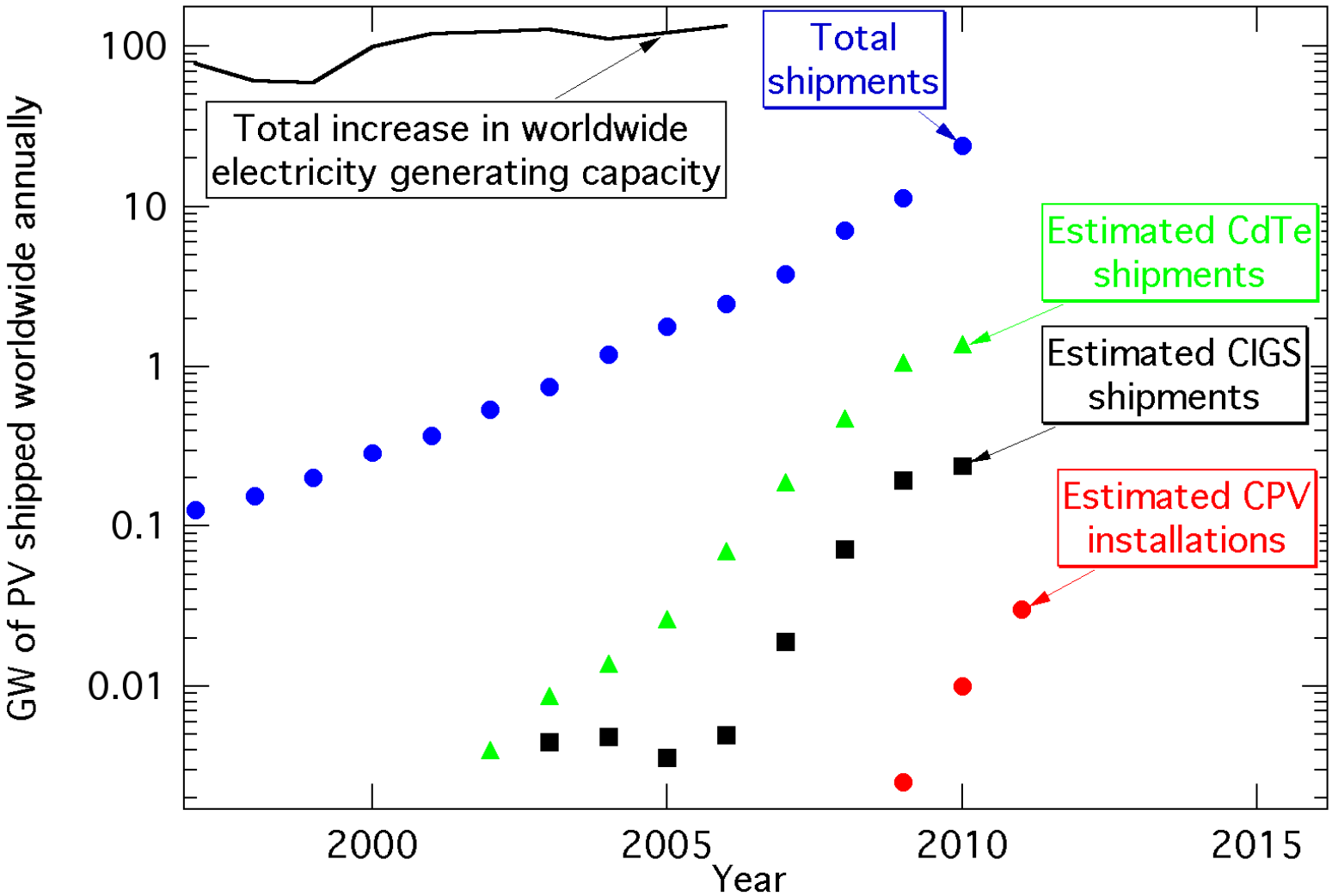
Prioritized research pathways

40%-efficient cells are already available

Challenge is to integrate high-efficiency cells with high-efficiency optics to make a high-efficiency system with low cost and high reliability

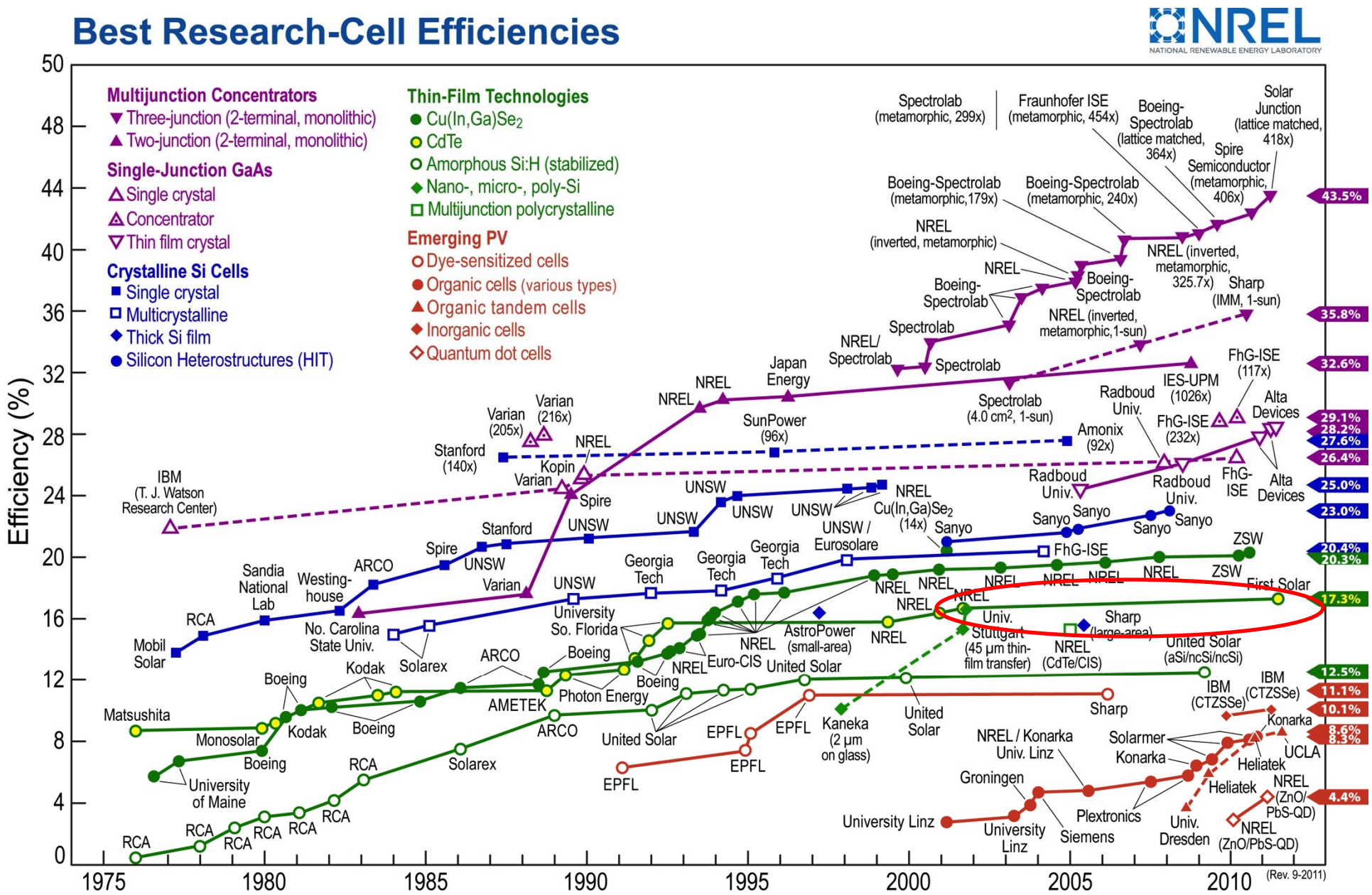
Research Pathways for Thin Films

Growth of PV industry – Technology Trends



CdTe has been a big success under the leadership of First Solar

Champion Solar Cell Efficiencies



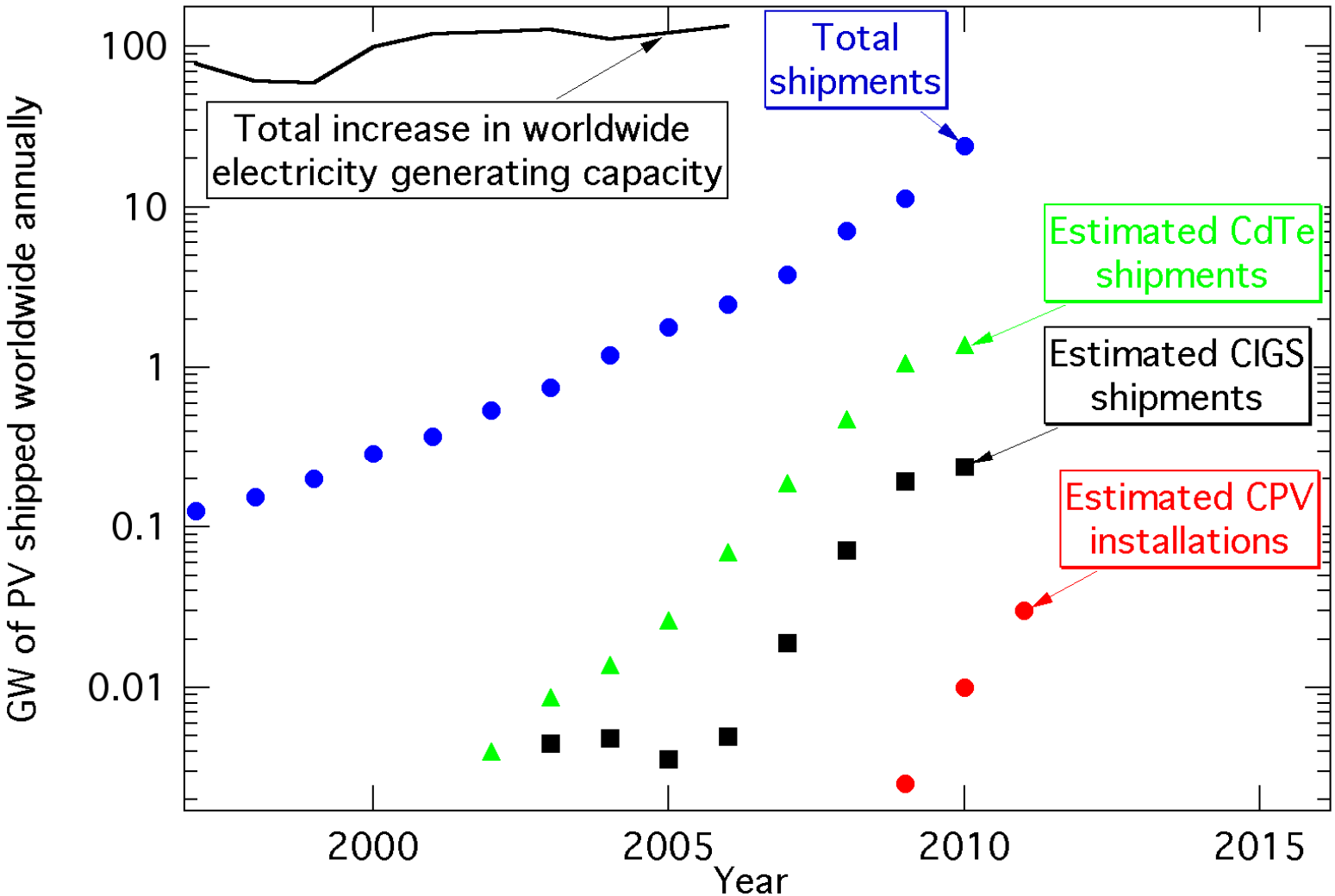
Challenges for CdTe

Can the efficiency reach 20%?

Why is the Voc so low?

Will a shortage of Te be a problem?

Growth of PV industry – Technology Trends



CIGS has achieved higher efficiencies – why is it behind CdTe?
Why no "First Solar" for CIGS? What about Solar Frontier?

Challenges for CIGS

What does it take to reach large-area uniformity consistently?

Can high efficiencies be achieved in large area?

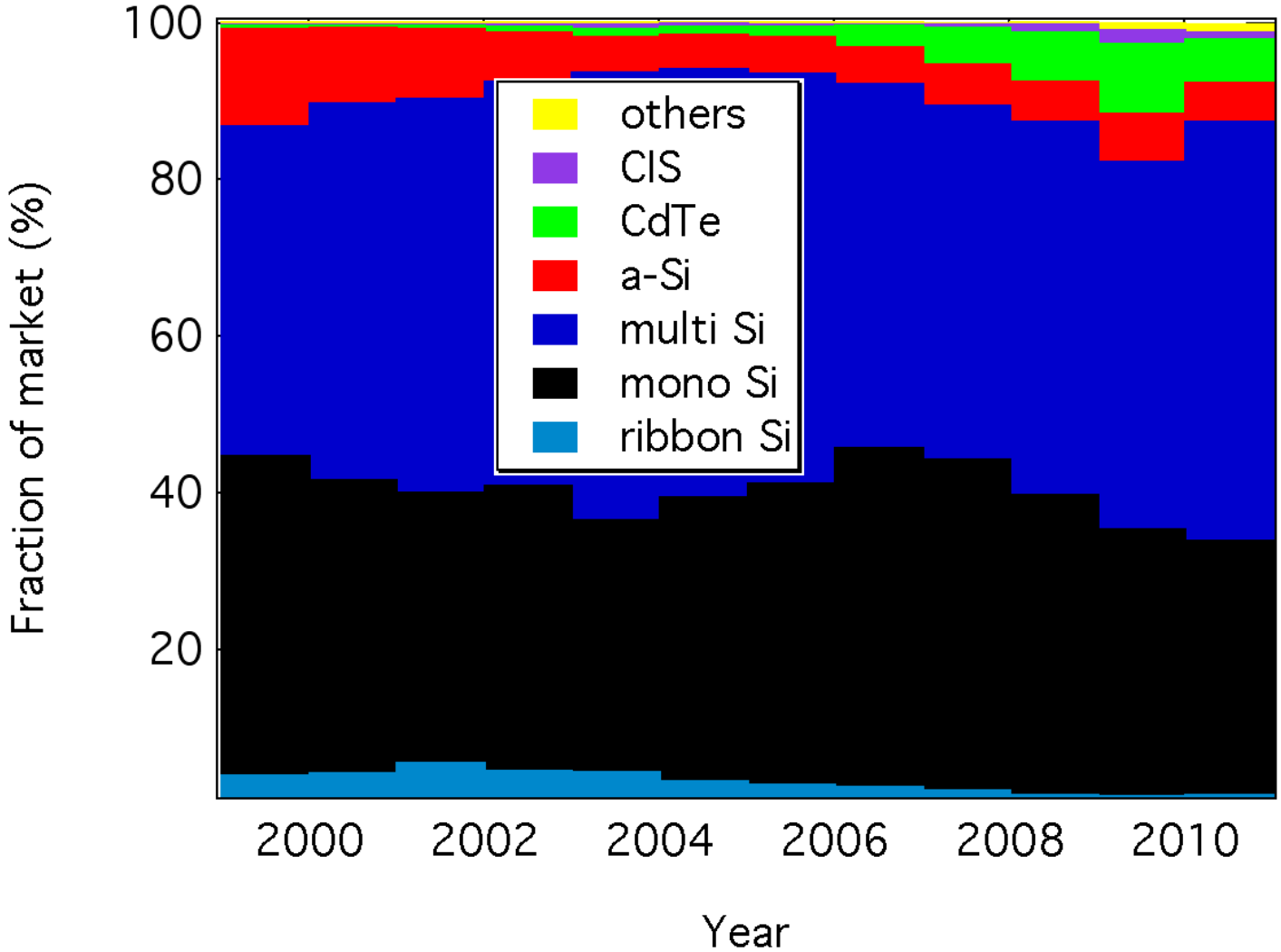
Is it useful to develop an indium-free version?

Can it be successfully deployed in flexible formats?

Will Solar Frontier be the next “First Solar”?

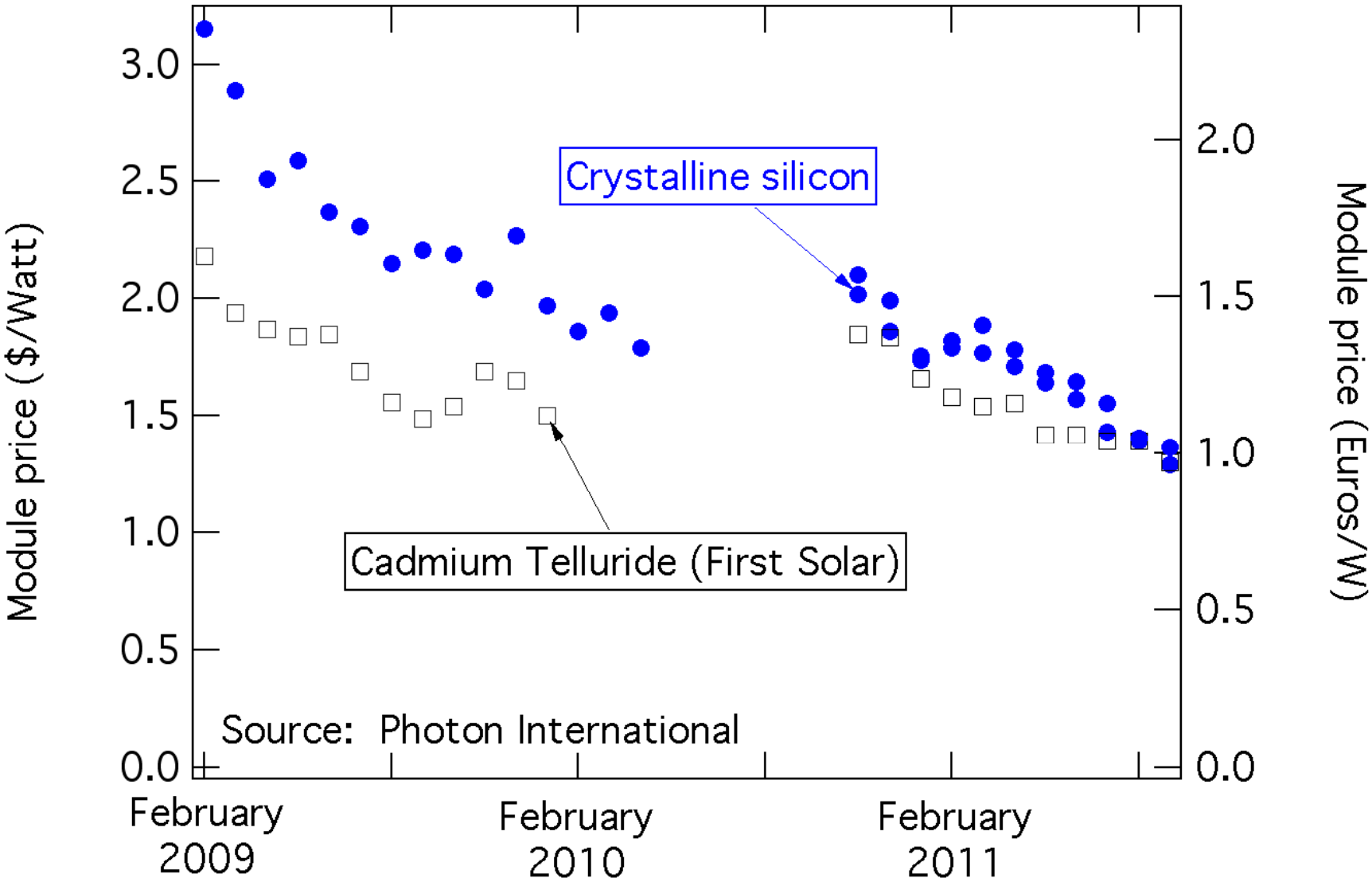
Research Pathways for Silicon

PV Technology trends:



Si dominates the PV industry – Will it always dominate?

PV module prices are coming down



Si module prices have dropped more than a factor of two in last 3 years!

Where will silicon lead to?

Silicon has already achieved what many said it would never achieve. Where will it go next?

Opportunities for more cost reduction:

-Low purified Si prices

-Economies of scale

-Many improvements and tweaks

-Radically new approaches as you'll hear later today

Biggest opportunities now may be with other aspects:

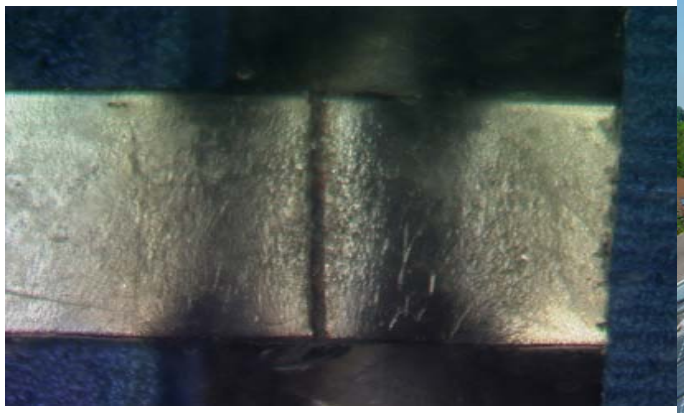
-Soft costs (Recent DOE opportunity)

-Reliability

Research Pathways related to PV Reliability

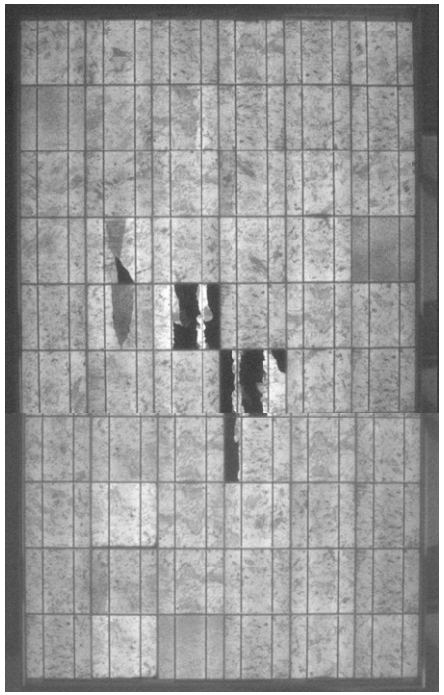
Examples of Field Failures

Broken Interconnects



Ground Fault

Broken Cells



Delamination

Corrosion

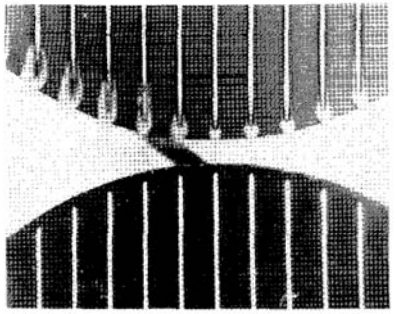


Figure 2. Solar-Cell Electrochemical Corrosion

John Wohlgemuth

Additional Field Failures

Electro-Chemical Corrosion of TF Module

Broken Glass Leading to Corrosion

John Wohlgemuth

Reliability questions – tough to answer

Engineer: How do I decide what warranty to put on my product?

PV customer: How do I know which PV will last the longest?

Investor: How do I convince my board that a $1B PV investment is low risk?

Insurance agent: How do I set the rates for insuring PV projects?

International PV Module Quality Assurance Forum

The PV QA Task Force was formed last July and consists of six Task Groups;

Task Group 1: PV QA Guideline for Manufacturing Consistency (leader Ivan Sinicco)

~200 volunteers

Task Group 2: PV QA Testing for Thermal and mechanical fatigue including vibration (leader Chris Flueckiger)

Task Group 3: PV QA Testing for Humidity, temperature, and voltage (leaders John Wohlgemuth and Neelkanth Dhere)

Task Group 4: PV QA Testing for Diodes, shading and reverse bias (leaders Vivek Gade and Paul Robusto)

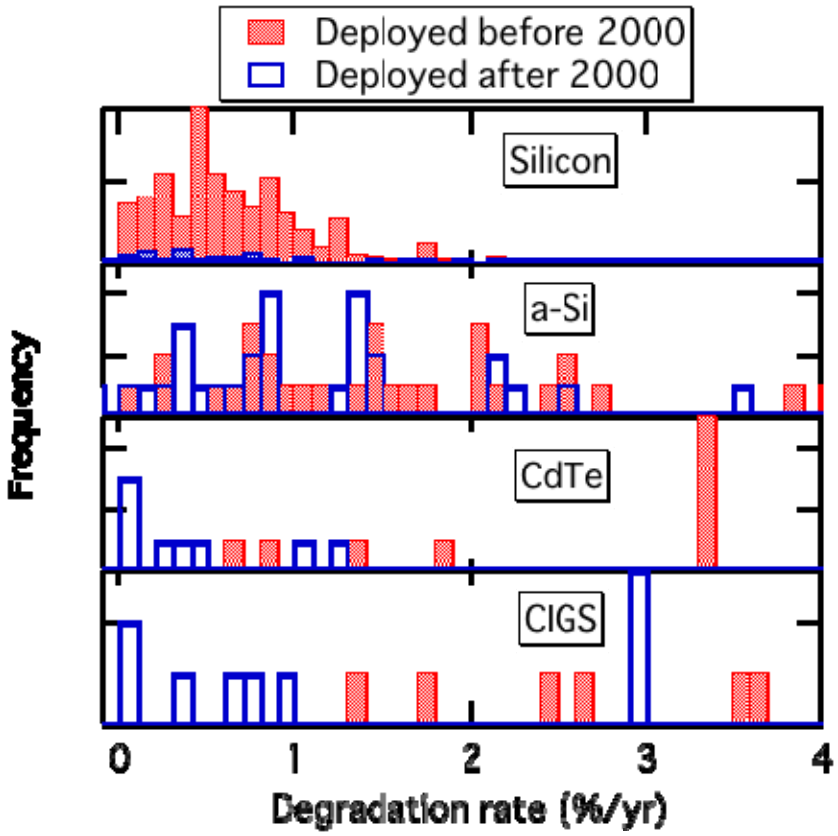
Task Group 5: PV QA Testing for UV, temperature and humidity (leader Michael Köhl)

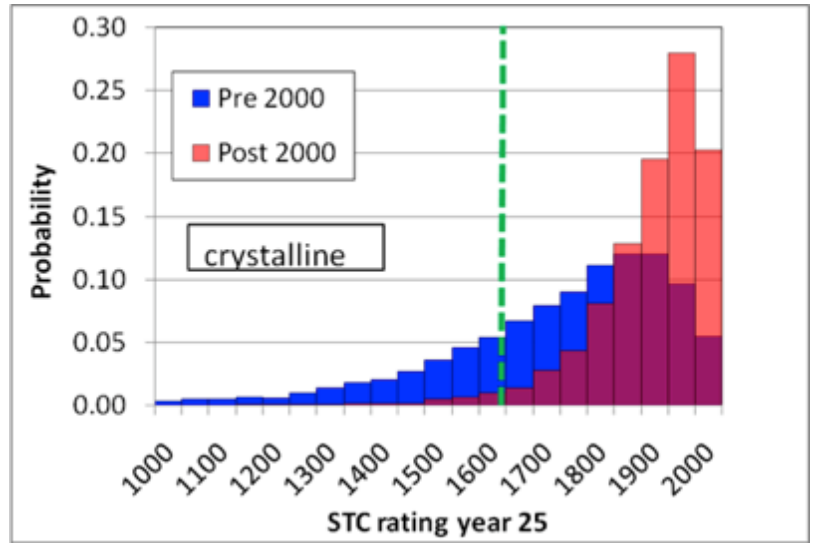
Task Group 6: Communication of PV QA ratings to the community (leader David Williams)

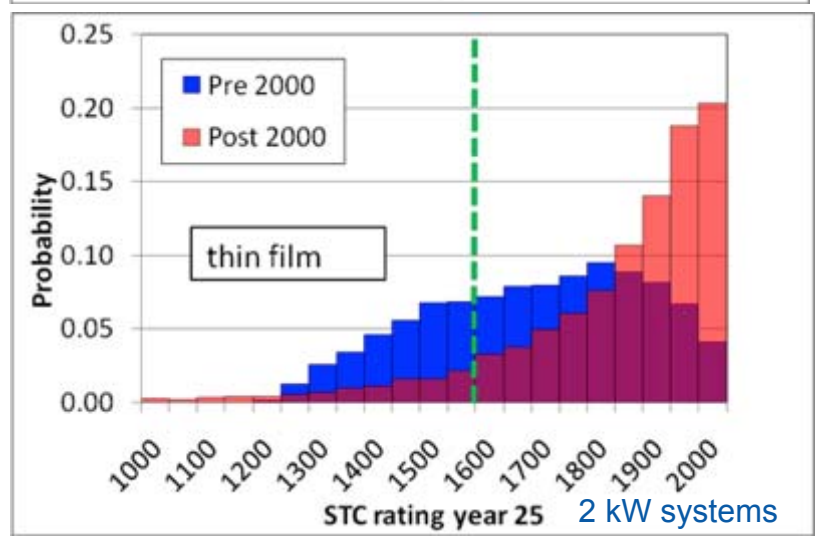
http://www.nrel.gov/ce/ipvmqa_forum/index.cfm

Survey of degradation rates – assess risk

Historical Degradation Rates from Literature





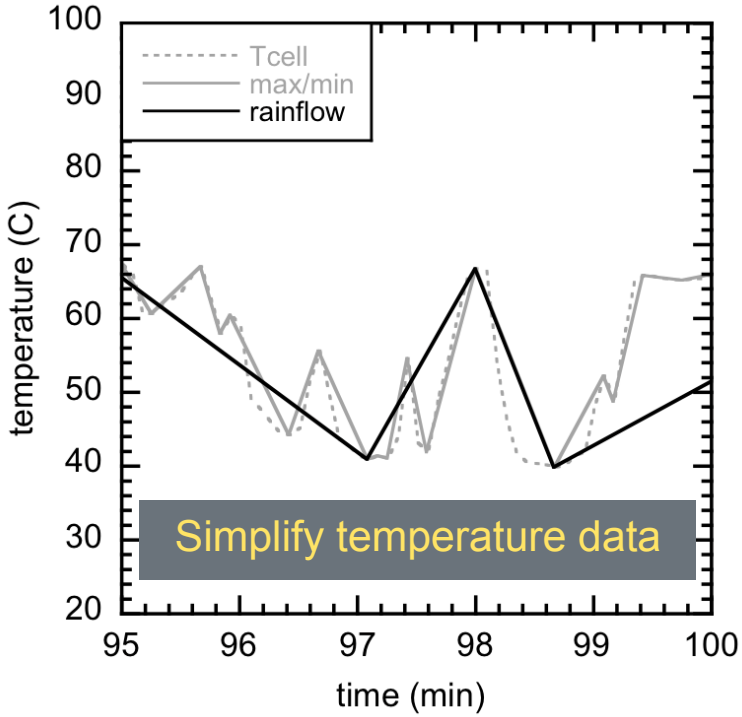


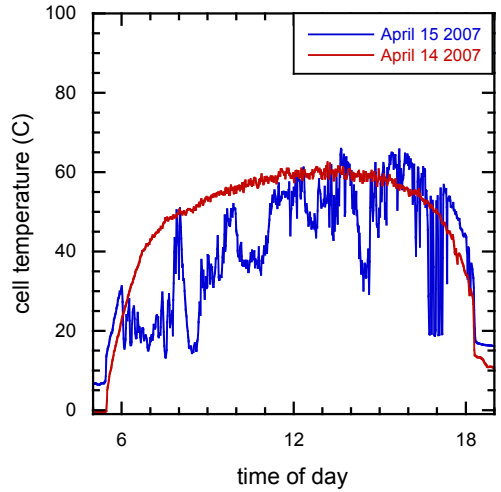
Literature data shows statistical distribution of degradation rates
These can be used to calculate risk
Web based data base will assemble and quantify these as a function of location

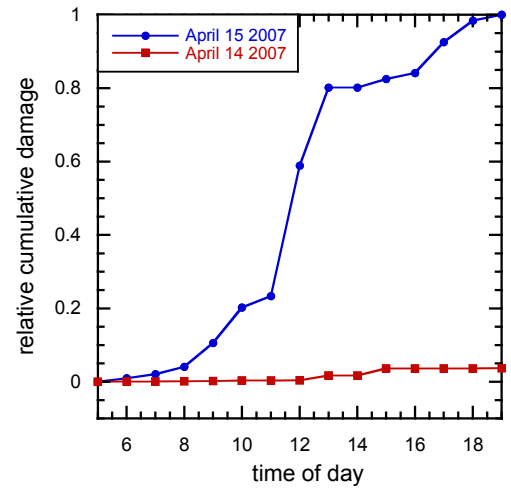
Dirk Jordan

Model to correlate weather with damage

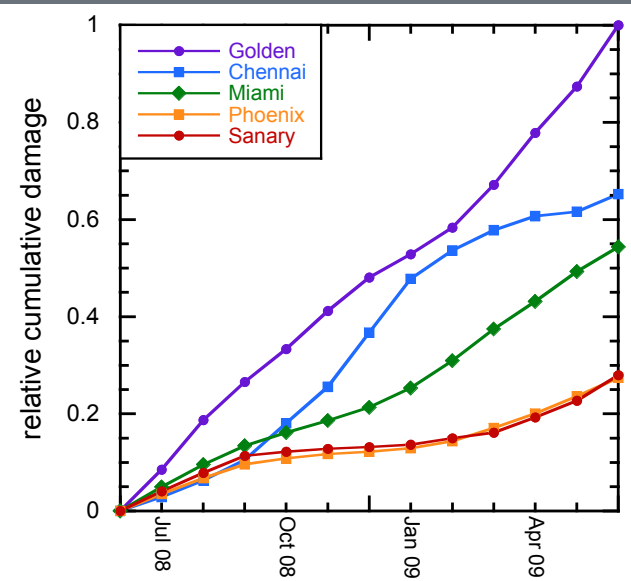
Objective: Quantify relationship between weather-induced damage and accelerated thermal cycling test







Partly cloudy day causes more damage than clear day

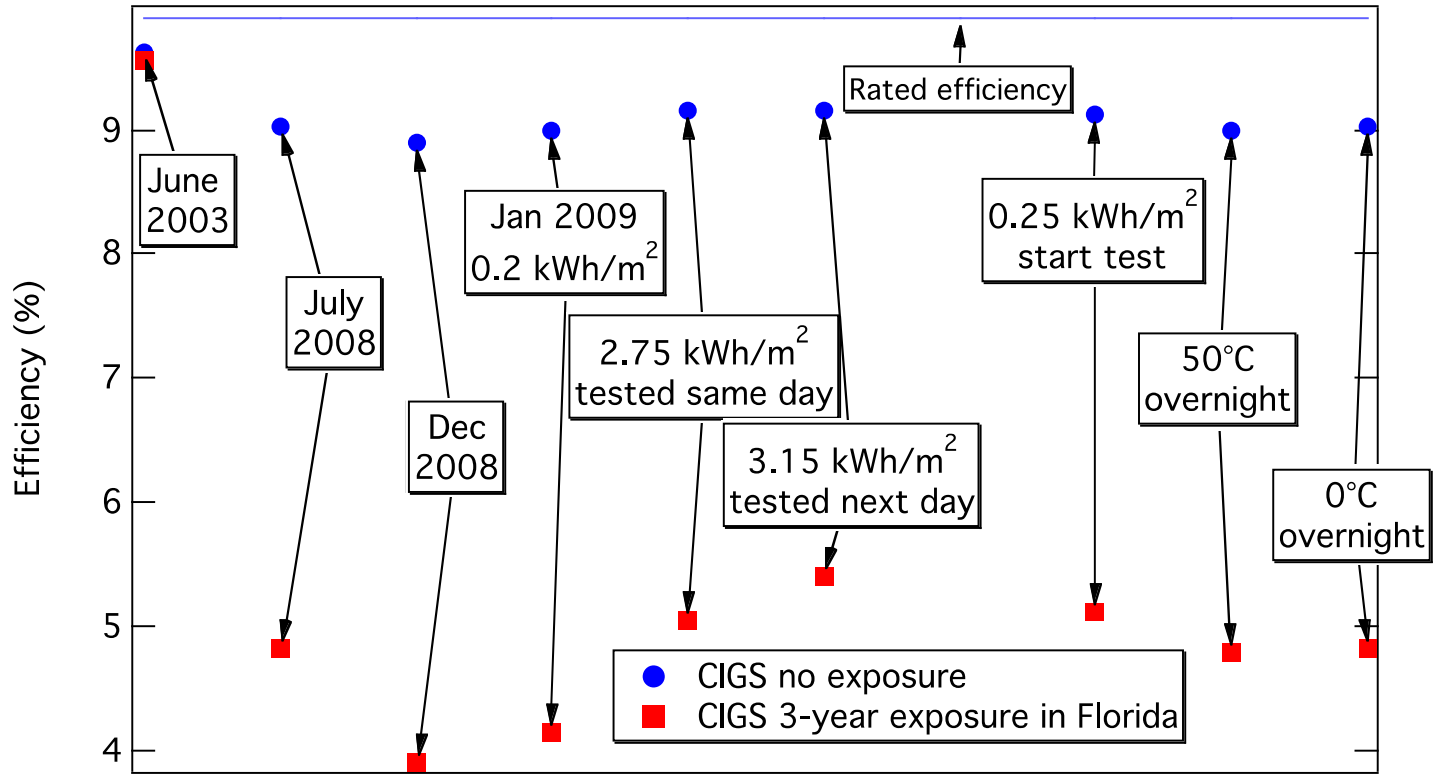


Damage is non linear with temperature change; how do we characterize weather data? Rainflow algorithm provides method Need to validate the accuracy of assumptions

Nick Bosco & Tim Silverman

Separate reversible from irreversible changes

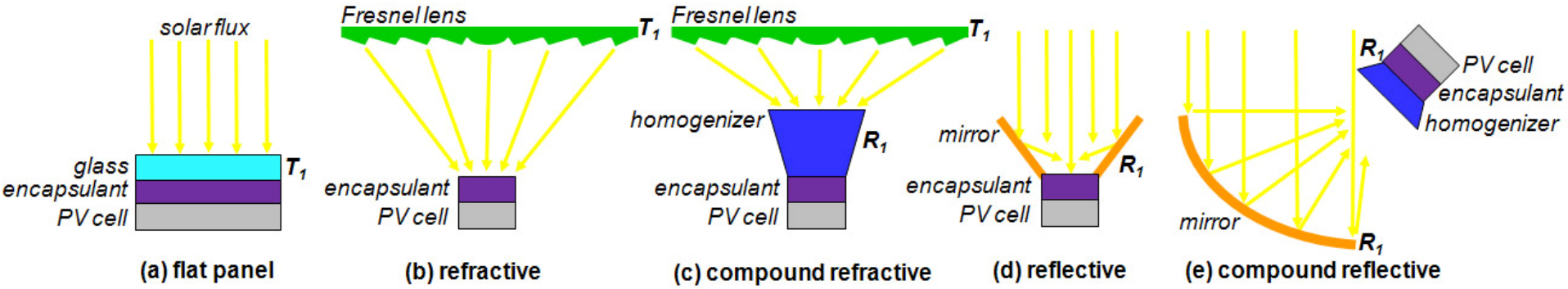
After exposure, thin-film modules show reversible and irreversible changes



One module showed 30% increase

When is concentrated UV a problem for CPV?

Does concentrated sunlight at cell contain damaging UV dose?



Acrylic lenses don't transmit much UV, but some reflective designs do
David Miller

Summary of Research Pathways

System Integration of High-efficiency cells & optics

CPV

Why is the Voc low?

CdTe

How to make it consistently uniform in large area with high efficiency

CIGS

A variety of opportunities

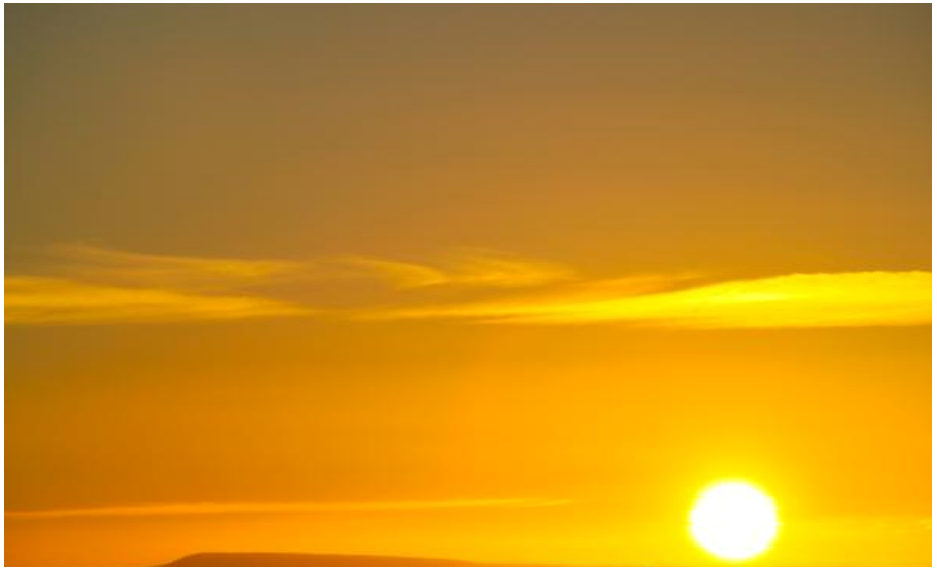
Incremental improvement or radical new approach?

Si

Reliability studies for all technologies

All

What about Alta?



Vision of a planet powered by renewable energy By year 2100 or before?

Thank you to :
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Thank you for your attention!

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