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High-efficiency multijunction solar cells for Concentrator PV applications

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Contents

- High-efficiency multijunction solar cells
- CPV system
- Commercial status and challenges

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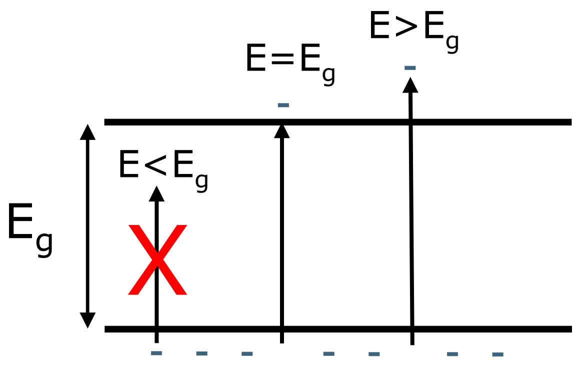
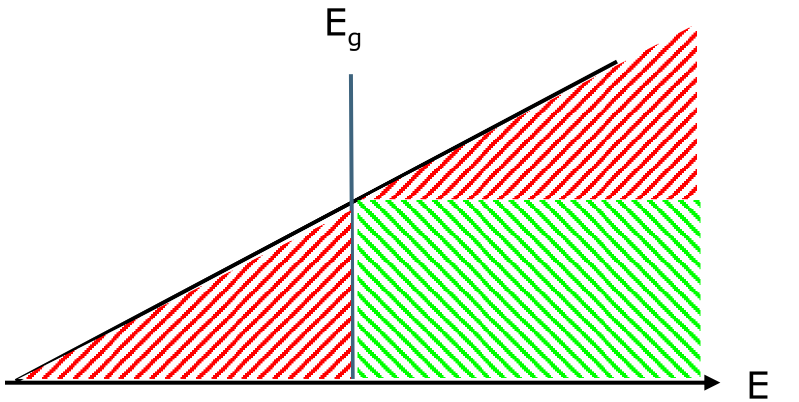
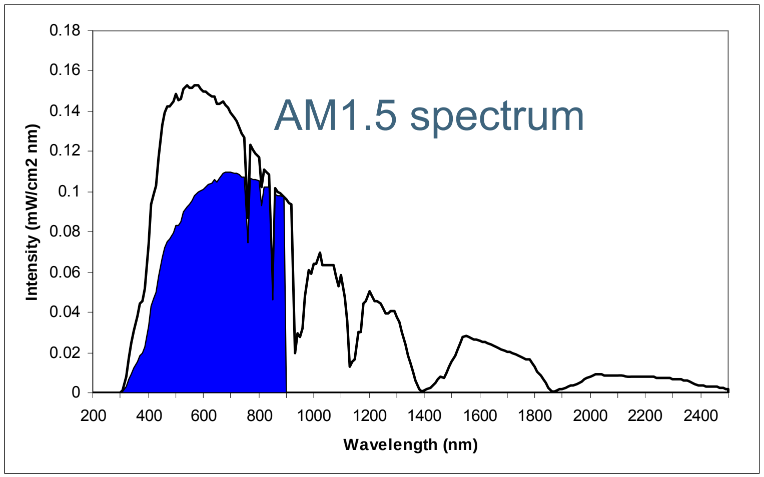
Multijunction solar cell basics

- Fundamental solar cell efficiency limits
  - Incomplete absorption
  - Thermalization



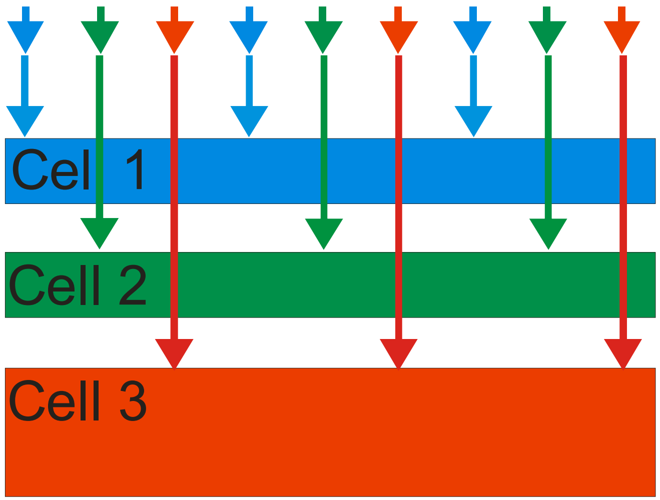


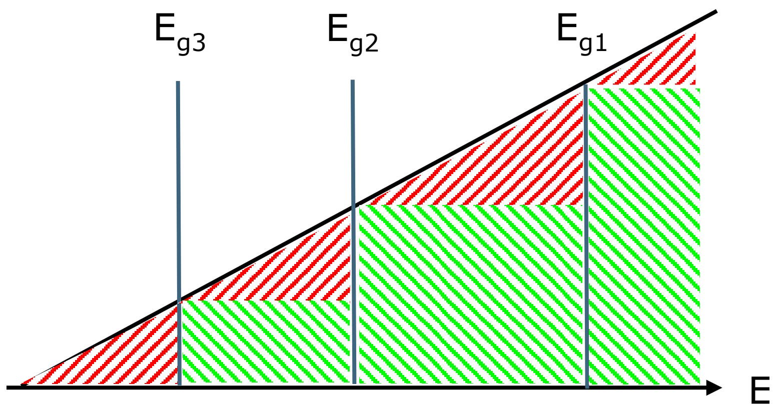


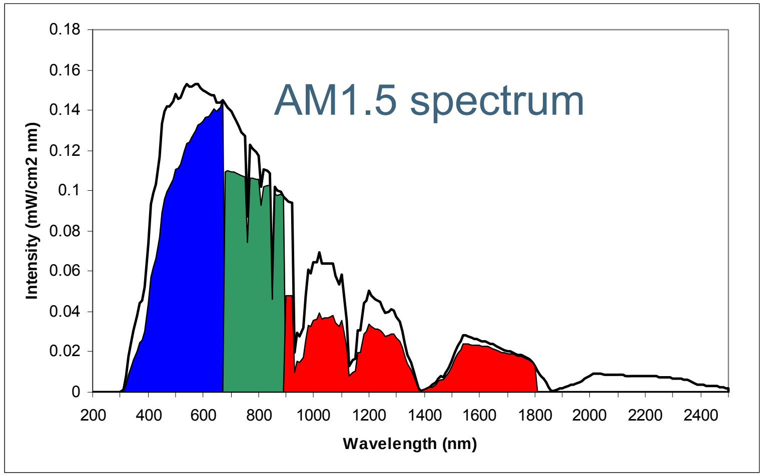
- Single-junction cell efficiency is limited to ≈ 30%

Multijunction solar cell basics

- Multijunction cells: combine different cells (different E_g) to minimize absorption and thermalization losses







Multijunction solar cell basics

- Practical implementation?

- Spectral splitting
- Mechanical stack
- Monolithic stack

Multijunction solar cell basics

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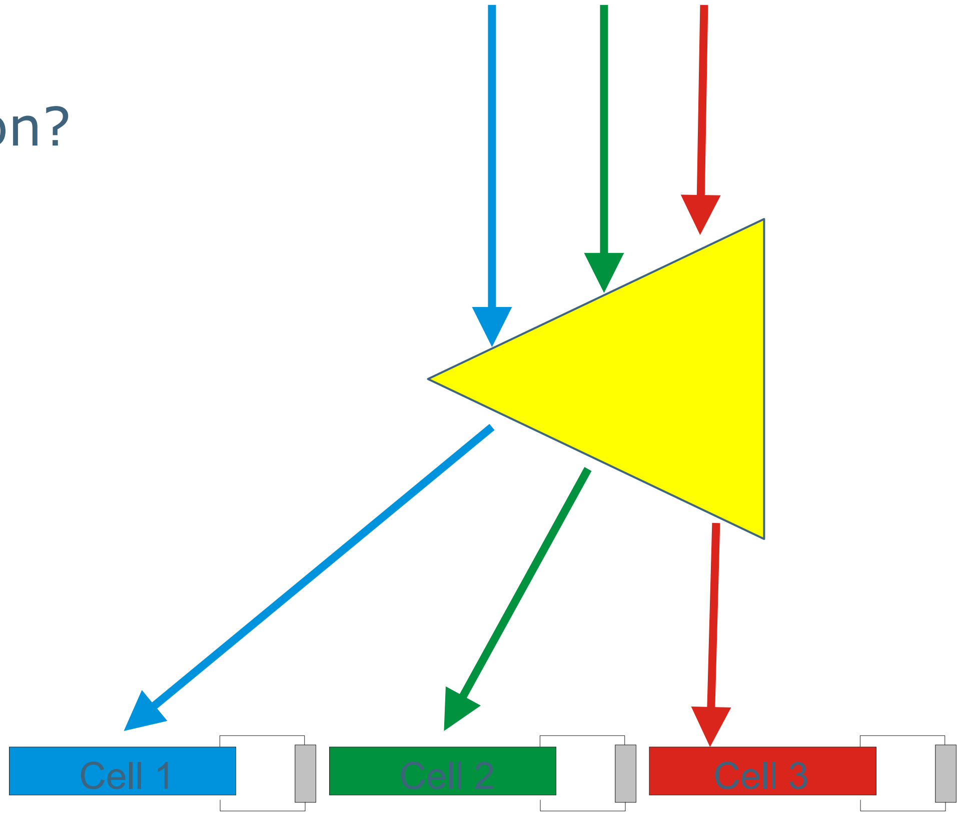


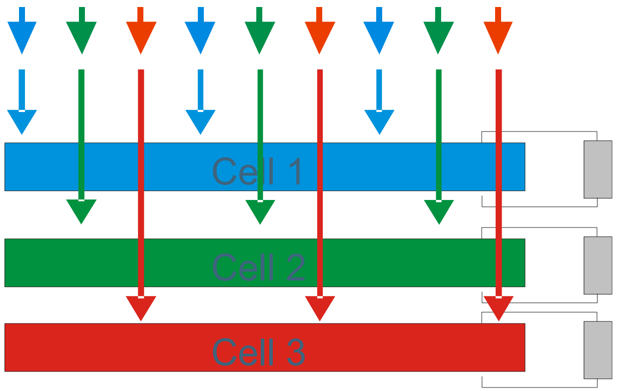
Main challenges:

- bulky
- mechanical architecture
- electrical architecture
- limited by optical system

Multijunction solar cell basics

- Practical implementation?

- Spectral splitting
- Mechanical stack
- Monolithic stack



Main challenges:

- electrical architecture
- optical coupling
- interconnect/stacking complexity
- heat dissipation

Multijunction solar cell basics

- Practical implementation?

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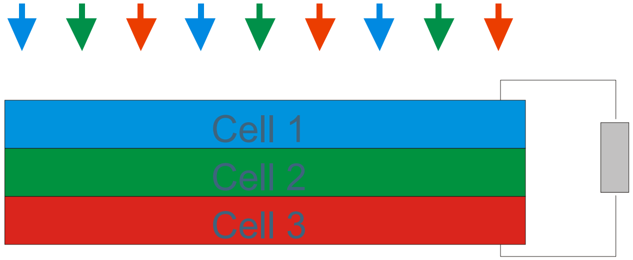
- Monolithic stack

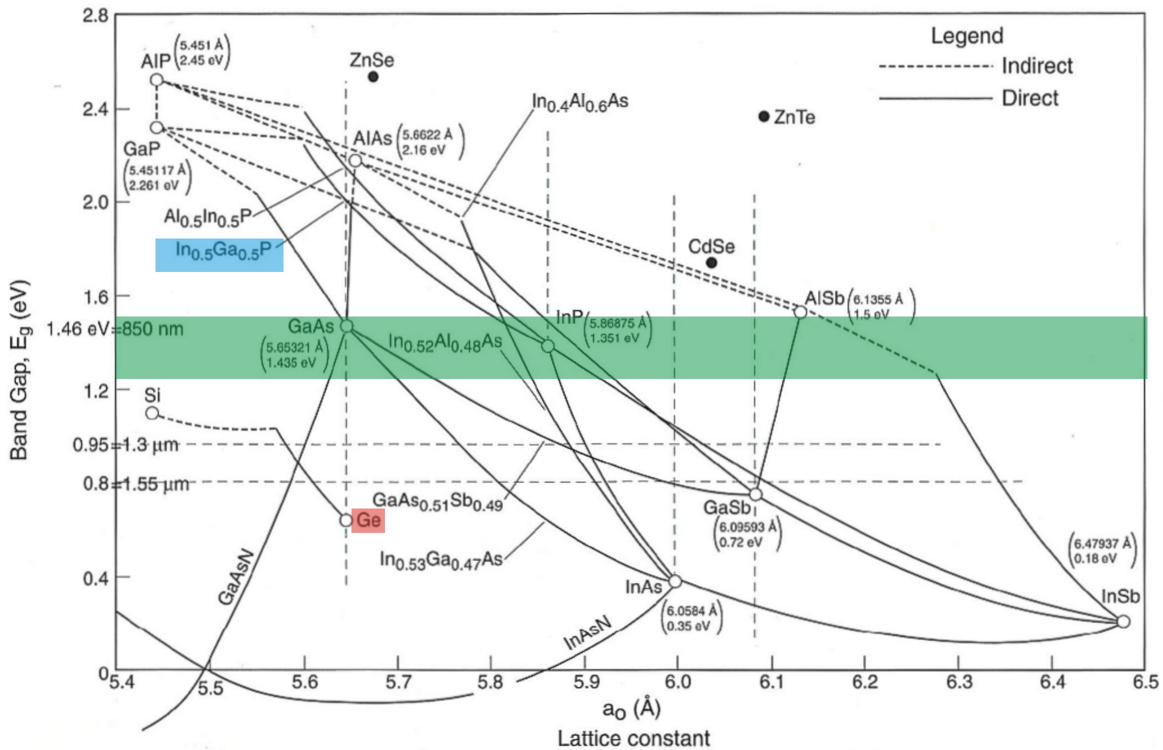


Main challenges:

- series connection
- current matching requirement
- limited choice of materials (lattice matching)

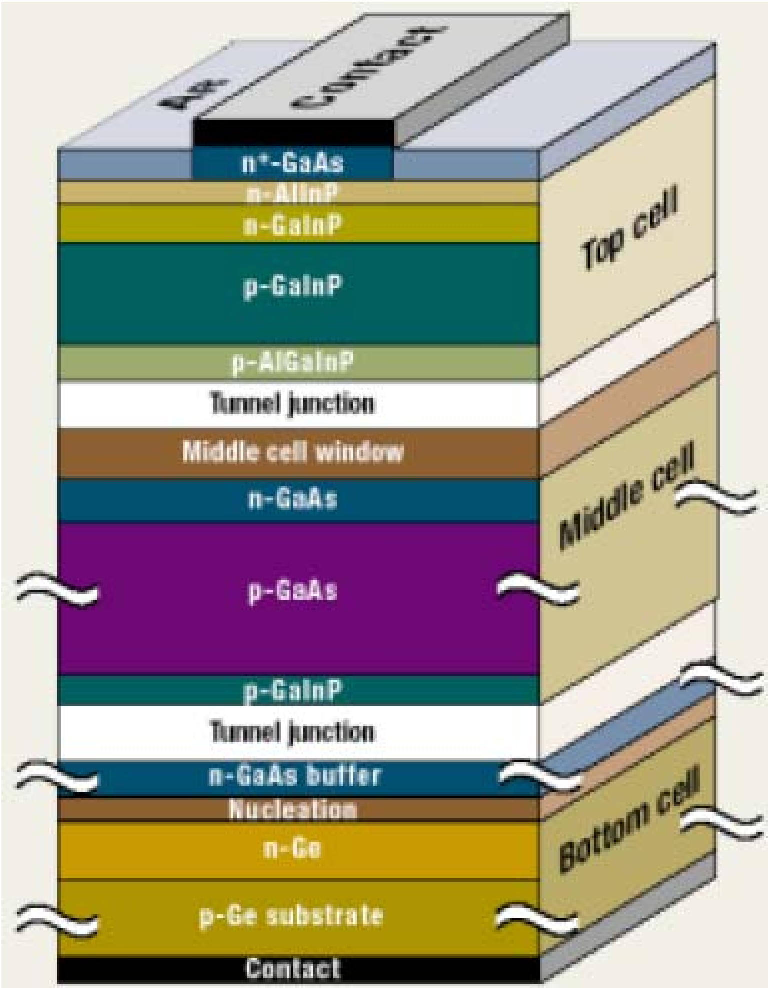
State-of-the-art

- $In_{0.5}Ga_{0.5}P$/GaAs/Ge monolithic triple-junction



- Optimal single-junction: GaAs (25.1 %)
- Addition of lattice-matched $In_{0.5}Ga_{0.5}P$ top cell (30.3 %)
- Addition of Ge bottom cell in high-quality Ge substrate (32.0 %)

State-of-the-art



Record conversion efficiencies obtained (32% under 1 sun, 40.1% under concentration)

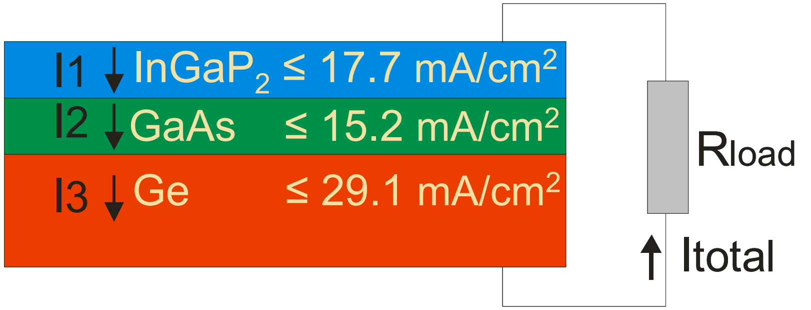
Key technologies:

- current matching of top and middle cell
- wide-gap tunnel junction
- exact lattice matching (1% Indium added in GaAs cell)
- InGaP disordering
- Ge junction formation

Further optimization of triple-junction design

- $In_{0.5}Ga_{0.5}P$/GaAs/Ge monolithic triple-junction

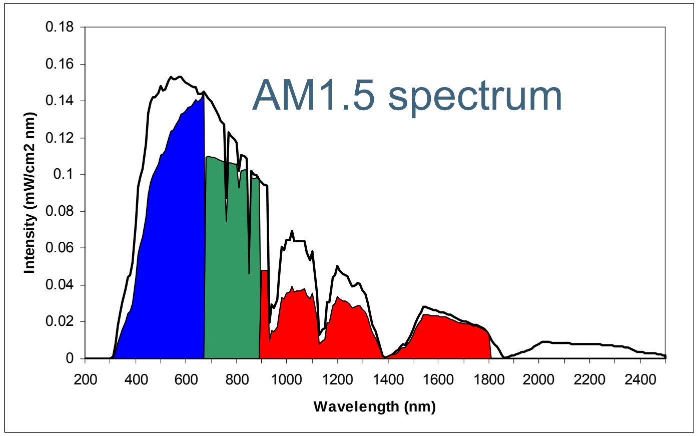
Important limitation: Ge photocurrent is used inefficiently because of current matching requirement

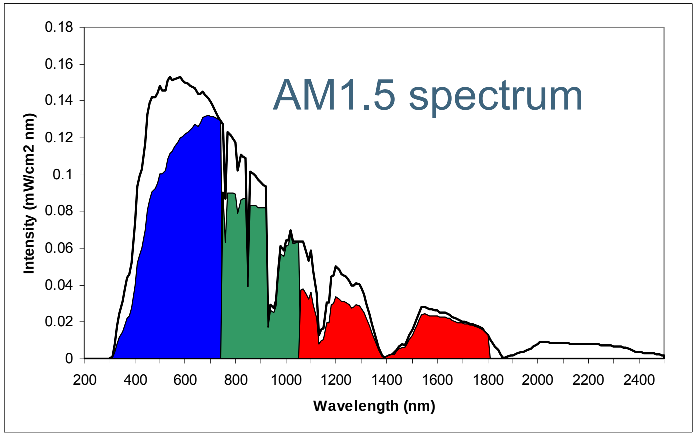


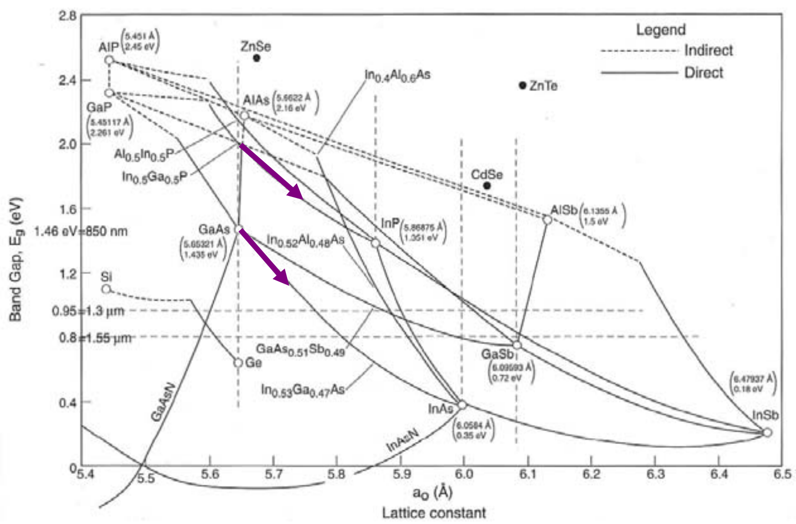
→ Room for improvement !

Metamorphic InGaP/InGaAs/Ge

→ Decrease top and middle cell bandgap



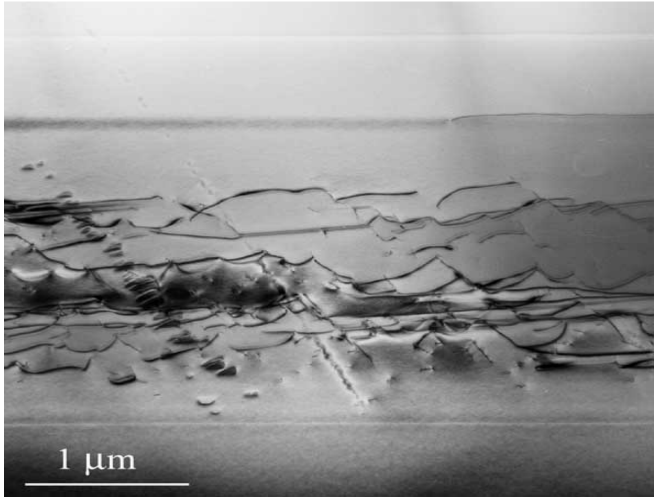




Optimal combination: lattice matched $In_{0.65}Ga_{0.35}P$ top and $In_{0.17}Ga_{0.83}As$ middle cell, 1.1% lattice-mismatched to Ge bottom cell (metamorphic cell)

Metamorphic InGaP/InGaAs/Ge

Lattice-mismatch causes dislocations and subsequent recombination



$In_{0.15}Ga_{0.85}As$ layer

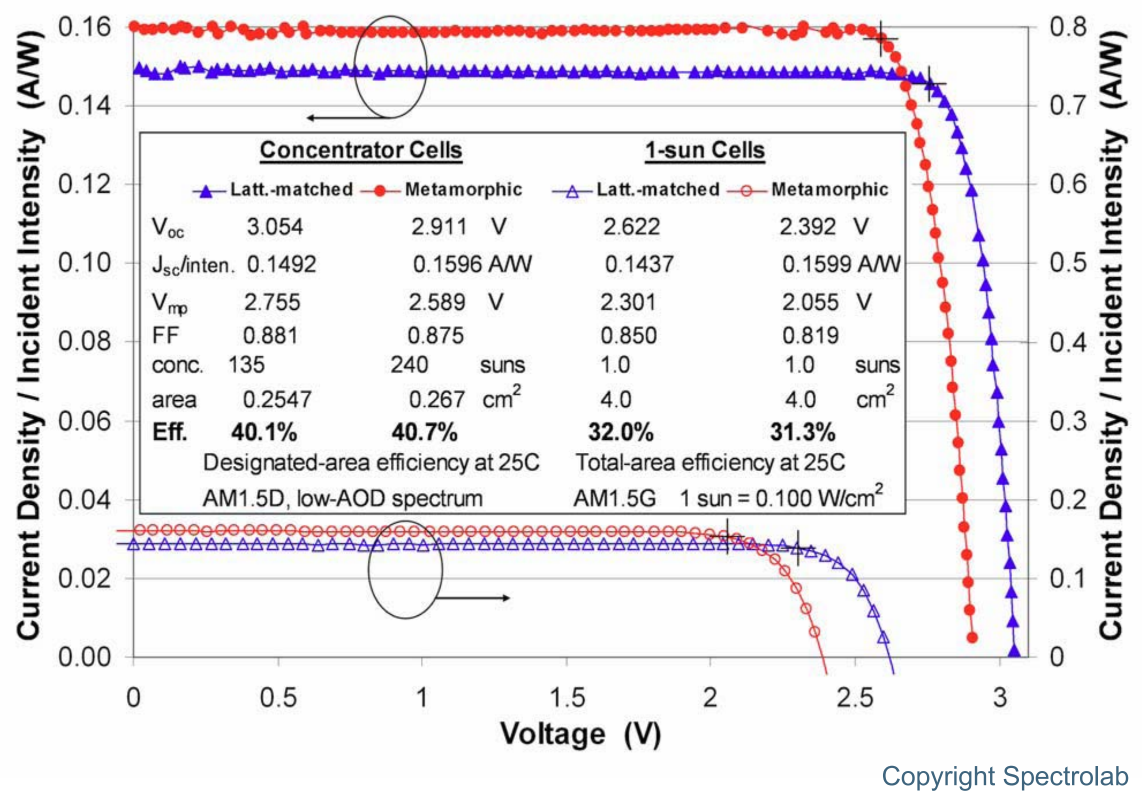
graded buffer
efficiently stops
threading dislocations

Ge substrate

Buffer structures are used to accommodate dislocations and allow growth of relaxed active layers

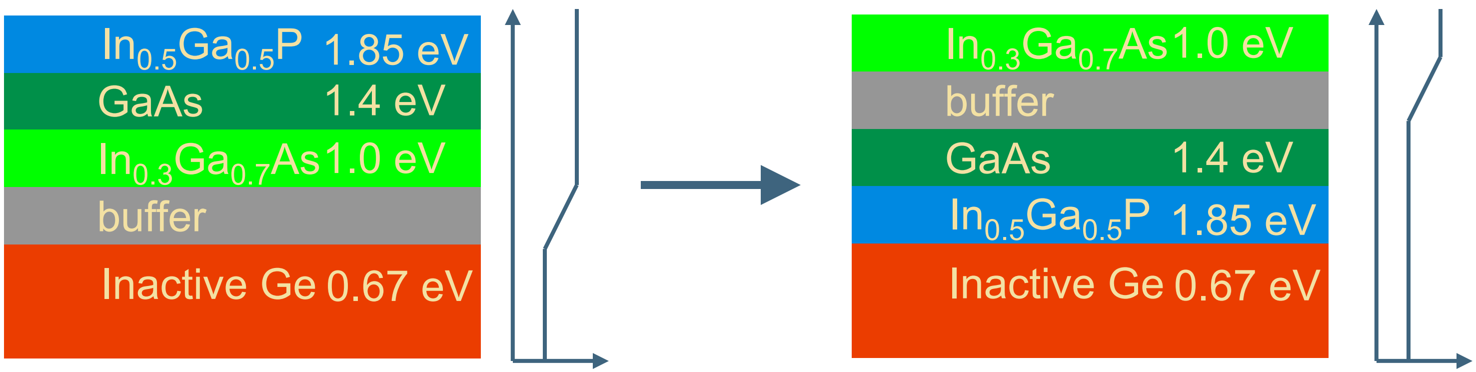
Metamorphic InGaP/InGaAs/Ge

Best results obtained using $In_{0.56}Ga_{0.44}P/In_{0.08}Ga_{0.92}As/Ge$ cell (0.5% MM): 40.7% at C=240



Inverted metamorphic InGaP/(In)GaAs/InGaAs

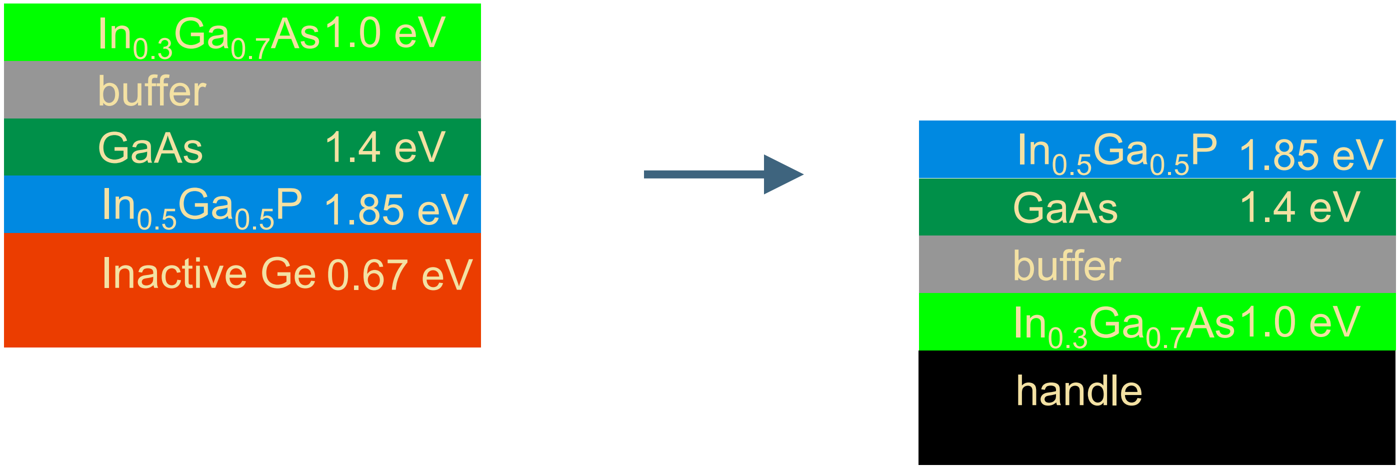
Further optimization of bandgap combinations
→ InGaP/GaAs/InGaAs(1 eV), or
InGaP/InGaAs(1.34eV)/InGaAs(0.9 eV) triple-junction cell



1.9% mismatch

- Dislocations degrade high bandgap cells
- Inverting the structure limits dislocations to InGaAs cell

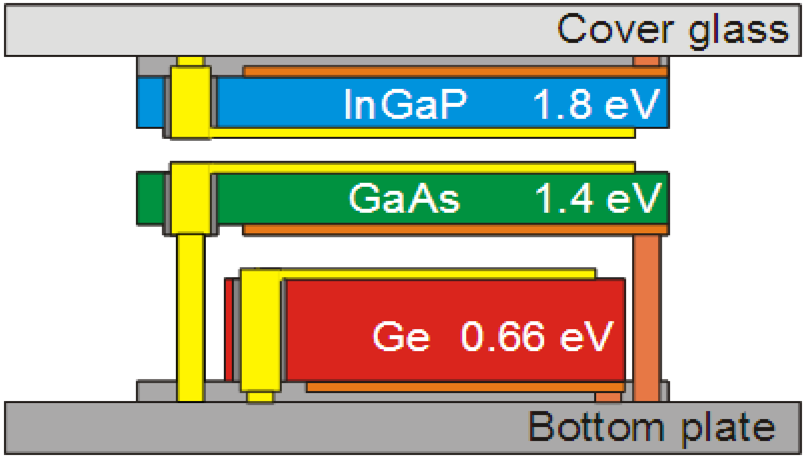
Inverted metamorphic InGaP/(In)GaAs/InGaAs



- Inverted metamorphic (IMM) has achieved record efficiencies of 33.8% (1 sun) and 40.8% (C=326)!
- Additional advantages: flexible and light-weight

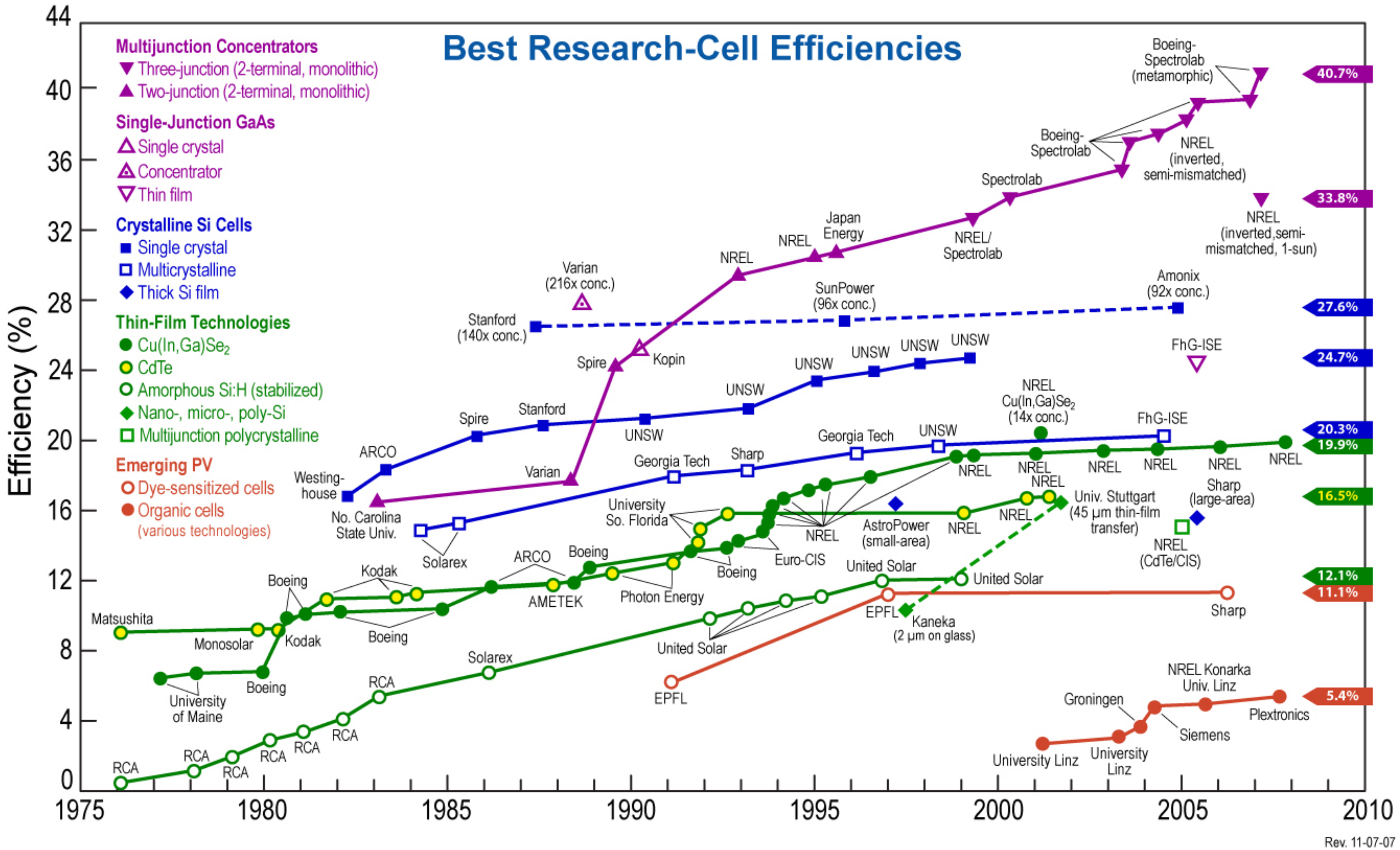
IMEC approach

- Mechanical stack using one-side contacted, thinned-down III-V cells



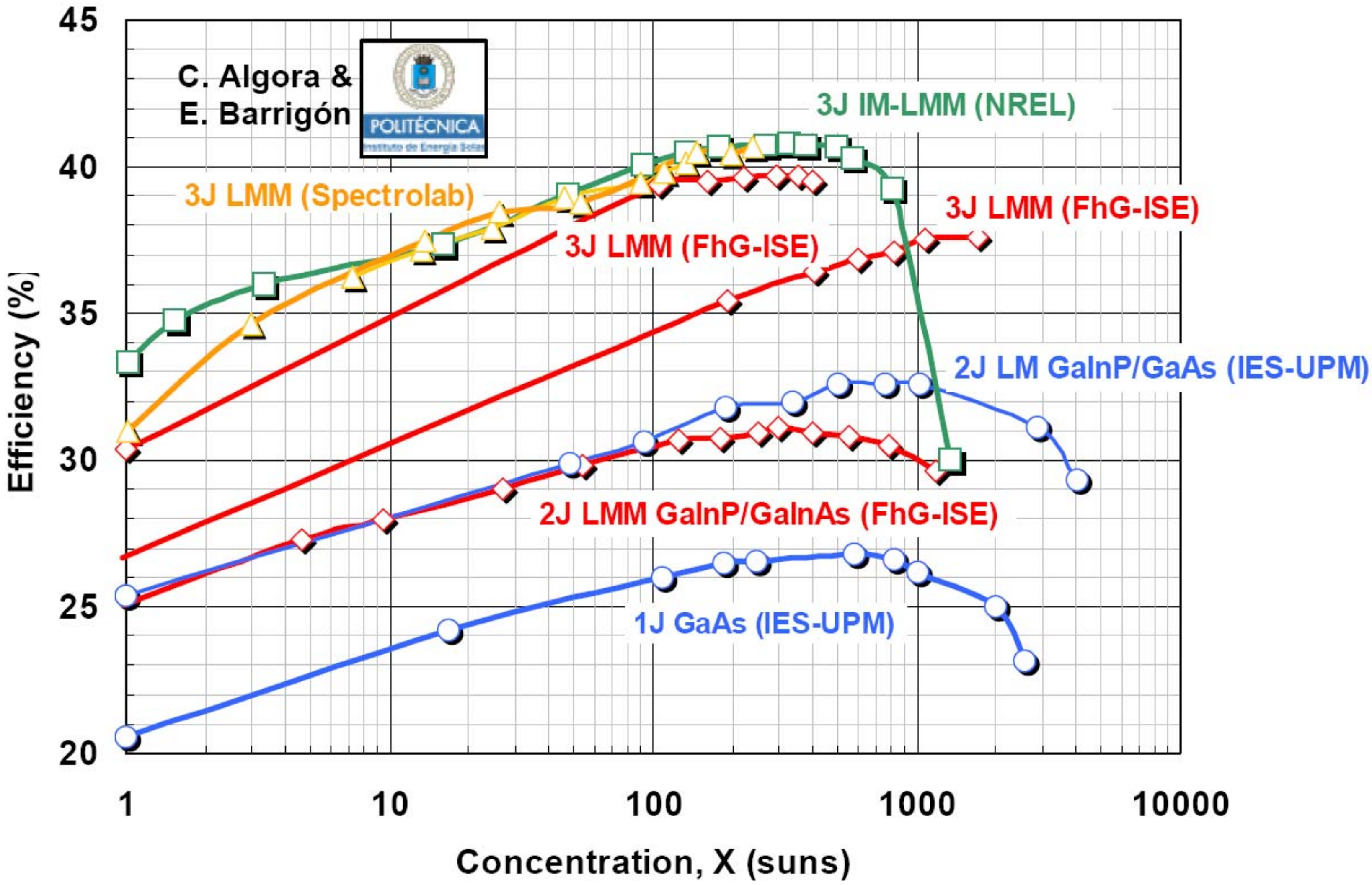
- Full benefit of Ge photocurrent → increased η
- Limited complexity electrical architecture
- No tunnel junctions
- Modular approach
- (re-)use of 3D-stacking technology
- Robust against spectral variations

Record efficiencies



Courtesy NREL

Record efficiencies



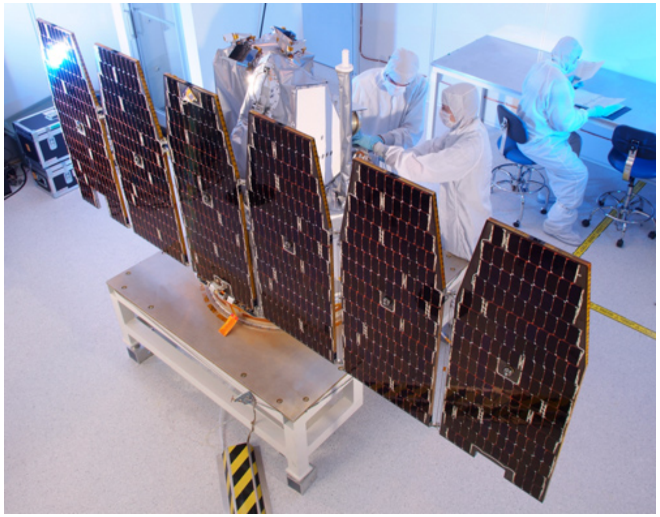
Contents

Space applications

InGaP/GaAs/Ge triple-junction cells have become the unchallenged workhorse for space applications:

- High efficiency allows for reduced solar array area.
- Further weight reduction is achieved by use of thin (140-180 μm) Ge substrates.
- Robustness to cosmic radiation results in high EOL efficiency.

Typical area ≈ 30 cm^2



Terrestrial applications

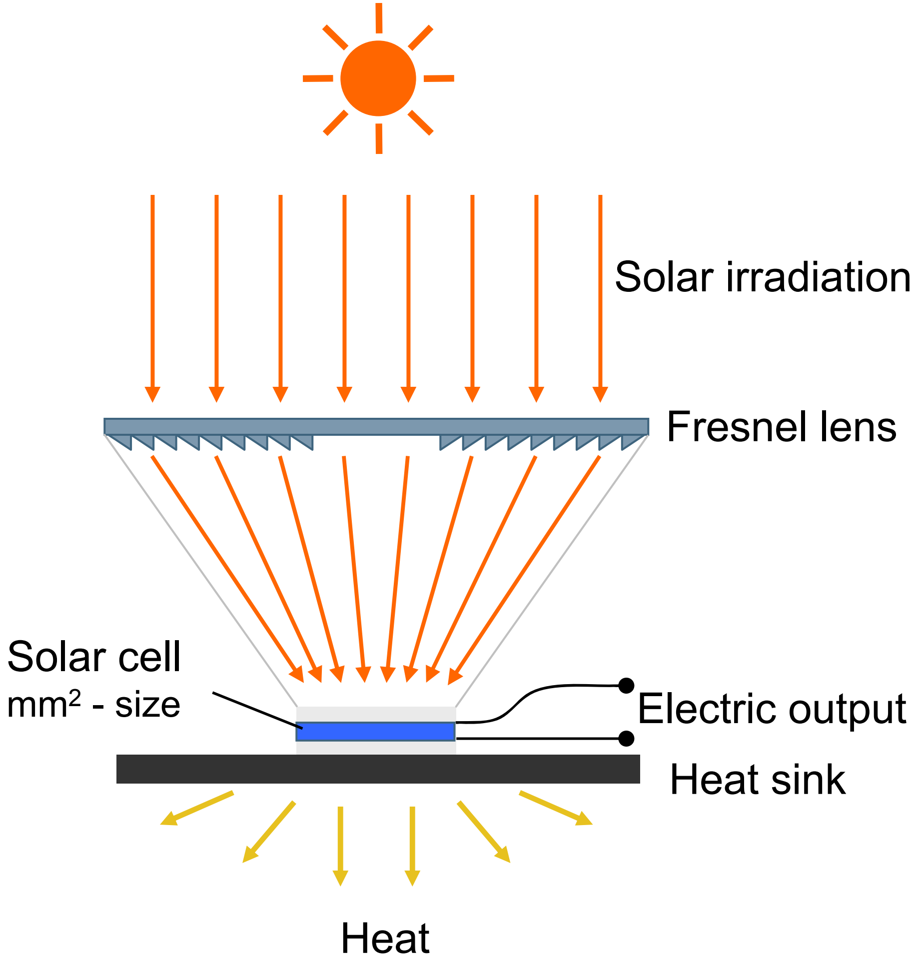
- Can this technology be brought down to earth?
- Current state-of-the-art in terrestrial photovoltaics is flat-plate Si modules, with $\eta \approx 13\%$ (15-16% at cell level) at a module cost of 2-2.5 €/W (cell cost 1-1.5 €/W).
- State-of-the-art InGaP/GaAs/Ge cell cost ≈ 200-250 $/W
- Solution: apply InGaP/GaAs/Ge cells in concentrator (CPV) systems.

CPV system

- Replace expensive solar cells with cheaper optical elements
- Make full use of high η offered by multijunction cells ($V_{oc} \sim \ln(J_{sc})$)
- High concentration (500-1000) effectively offsets cell cost

CPV system components:

- Solar cell
- Optics
- Tracker



CPV system: optics

Basically two options: refractive vs. reflective

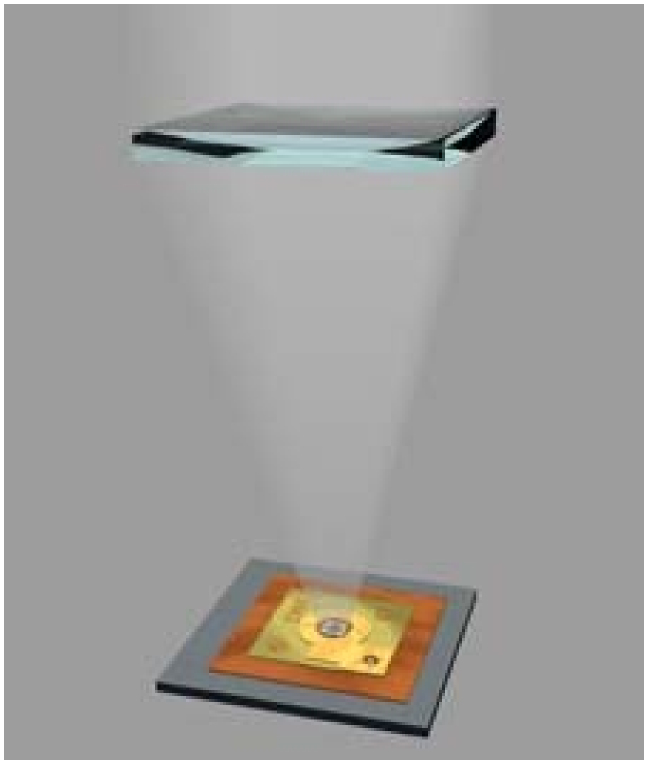


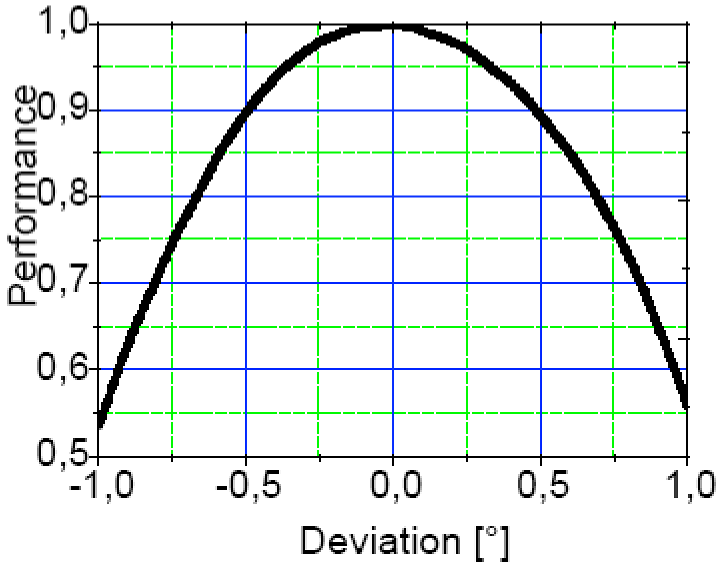
Photo Credit Concentrix Solar

Photo Credit Solar systems

Currently, as many solutions for optic system as CPV companies around
Typical optical efficiency ≈ 85%

CPV system: tracker

Because of high concentration factor, CPV system needs to be pointed accurately at the sun (typical CPV acceptance angle = 0.1^0-1^0)



No proven best general solution → room for improvement

Significant component of system cost (~20%) → avoid overdesign!

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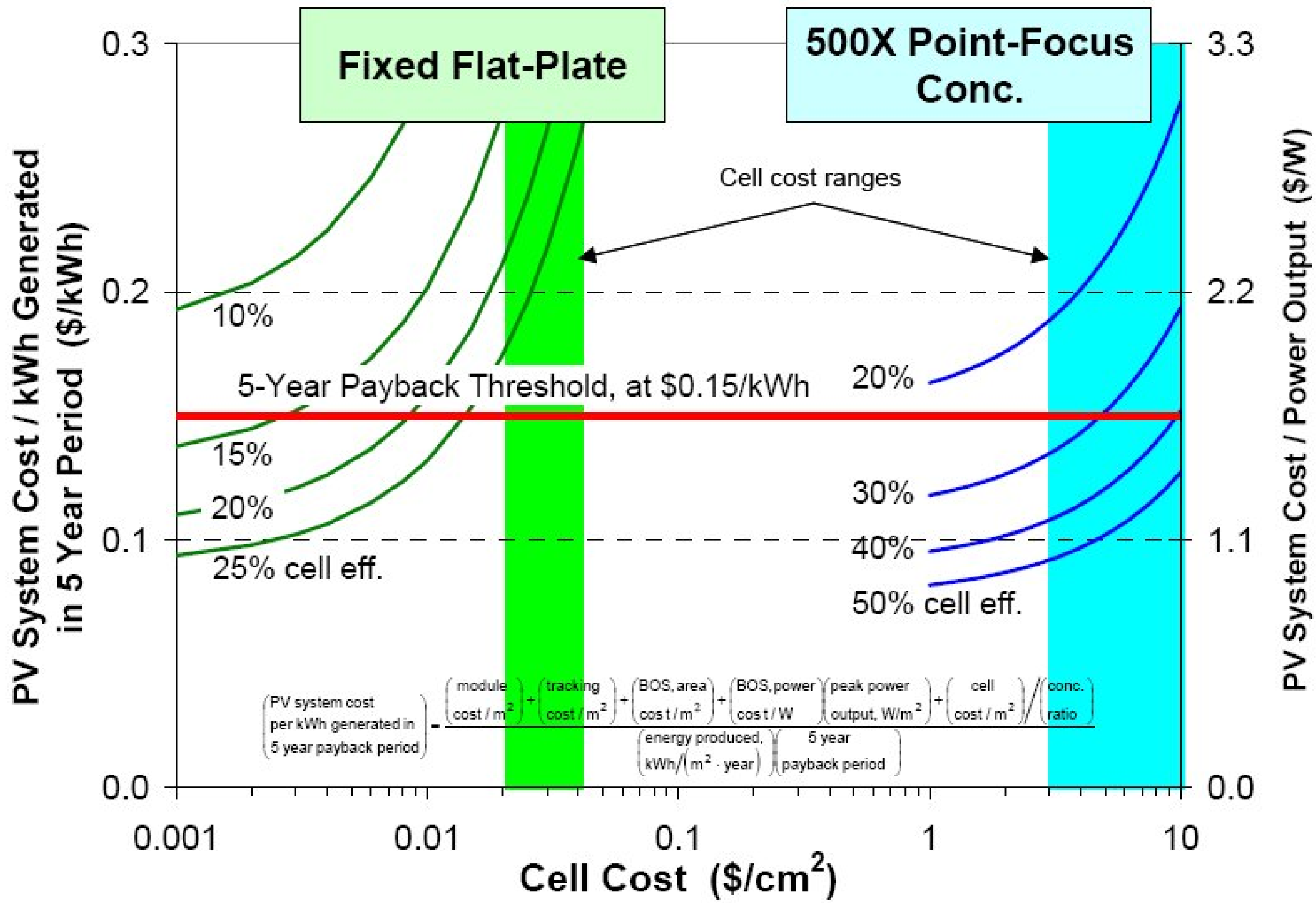
Is CPV cost competitive?



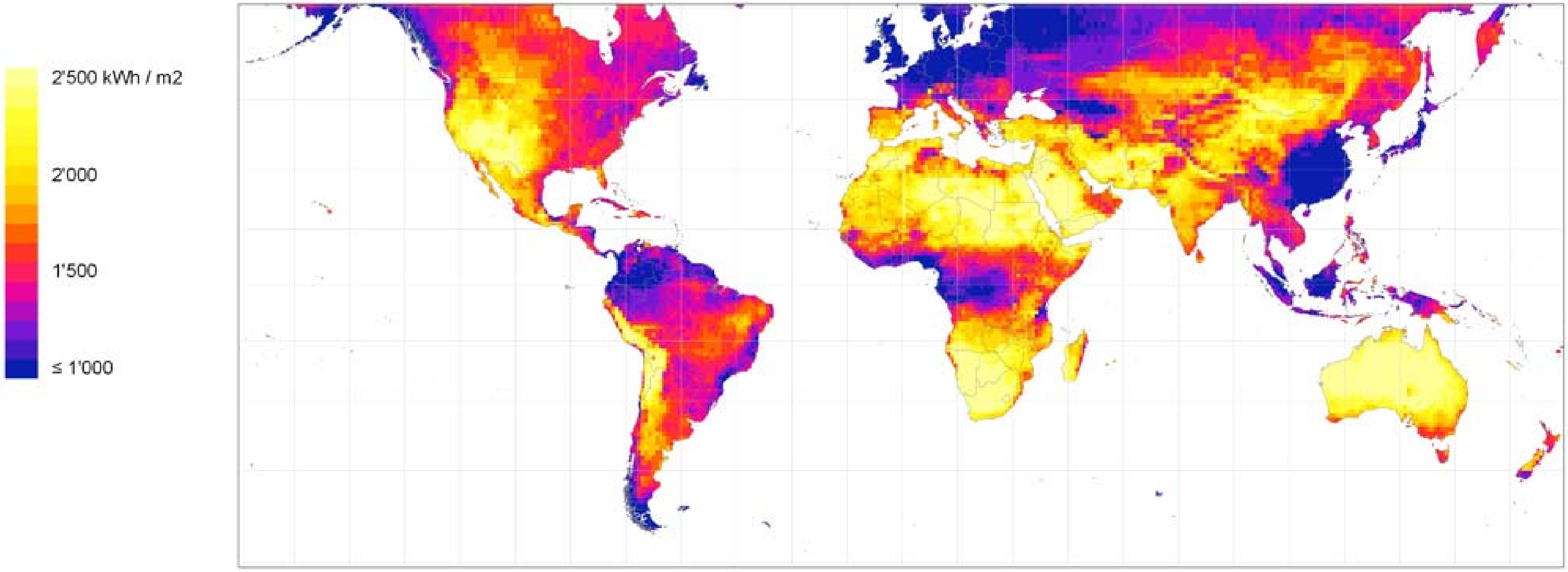
$$\left(\begin{array}{c}\text{PV system cost}\\ \text{per kWh generated in}\\ \text{5 year payback period}\end{array}\right) = \frac{\left(\begin{array}{c}\text{module}\\ \text{cost / m}^2\end{array}\right) + \left(\begin{array}{c}\text{tracking}\\ \text{cost / m}^2\end{array}\right) + \left(\begin{array}{c}\text{BOS, area}\\ \text{cost / m}^2\end{array}\right) + \left(\begin{array}{c}\text{BOS, power}\\ \text{cost / W}\end{array}\right)\left(\begin{array}{c}\text{peak power}\\ \text{output, W/m}^2\end{array}\right) + \left(\begin{array}{c}\text{cell}\\ \text{cost / m}^2\end{array}\right) \Big/ \left(\begin{array}{c}\text{conc.}\\ \text{ratio}\end{array}\right)}{\left(\begin{array}{c}\text{energy produced,}\\ \text{kWh/(m}^2\cdot\text{year)}\end{array}\right)\left(\begin{array}{c}\text{5 year}\\ \text{payback period}\end{array}\right)}$$

Cell cost ranges, module and BOS costs from: Swanson, Prog. Photovolt. Res. Appl. ***8****, 93-111 (2000).*

Is CPV cost competitive?

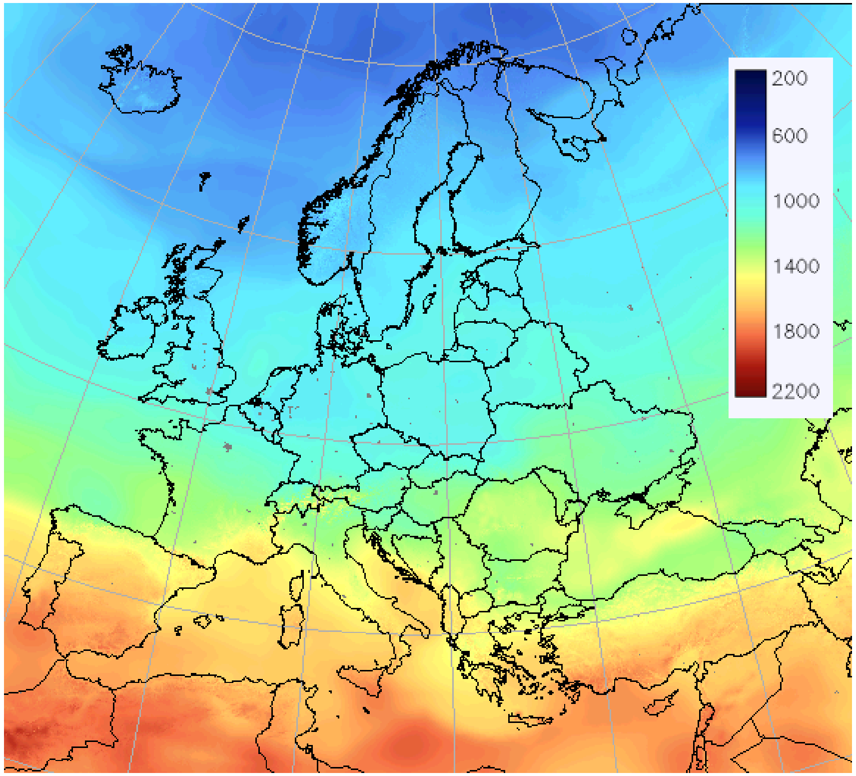
Yes!

but…

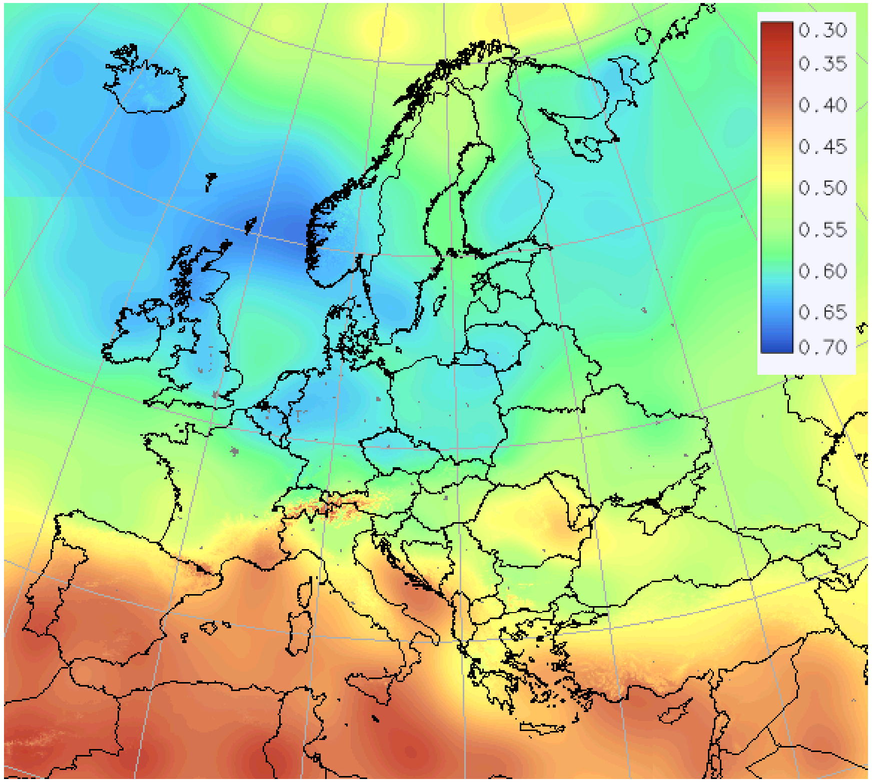


Is CPV cost competitive?

Yearly global irradiation (kWh/m²)



Diffuse/Global irradiation light



Commercialization

- First commercial systems are appearing.

© by Concentrix

Commercialization

- First commercial systems are appearing.

© by Solar Systems

Challenges

In order to move from demonstrator/prototype phase to commercial application, CPV industry requires:

- Assembly automation (Microelectronics/LED like)
- System integration
- Relevant DNI data
- Standards: testing, power/energy rating, certification (IEC 62108)

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