NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Technology Overview

Solar Power International 2010
Los Angeles, CA

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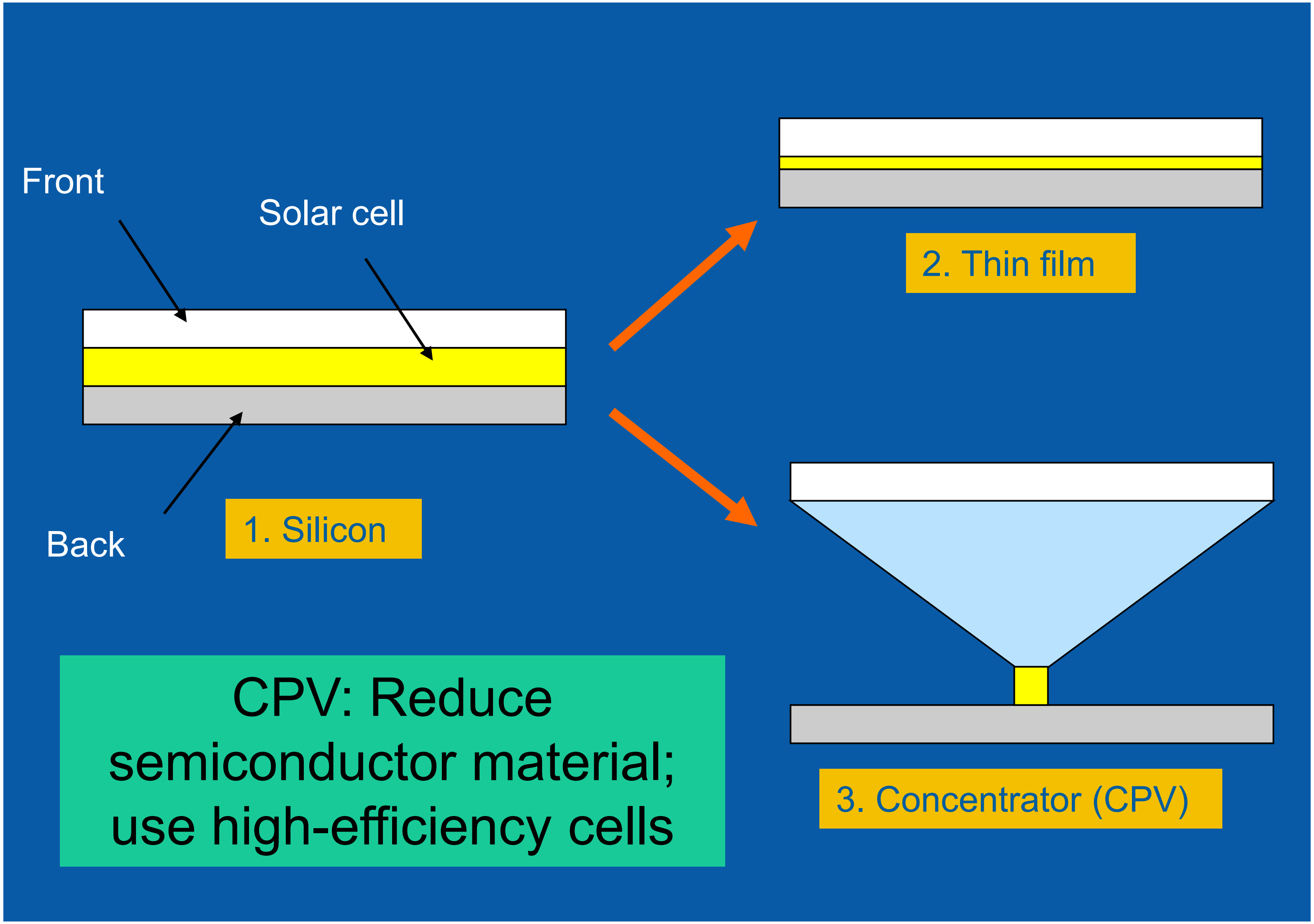
Outline

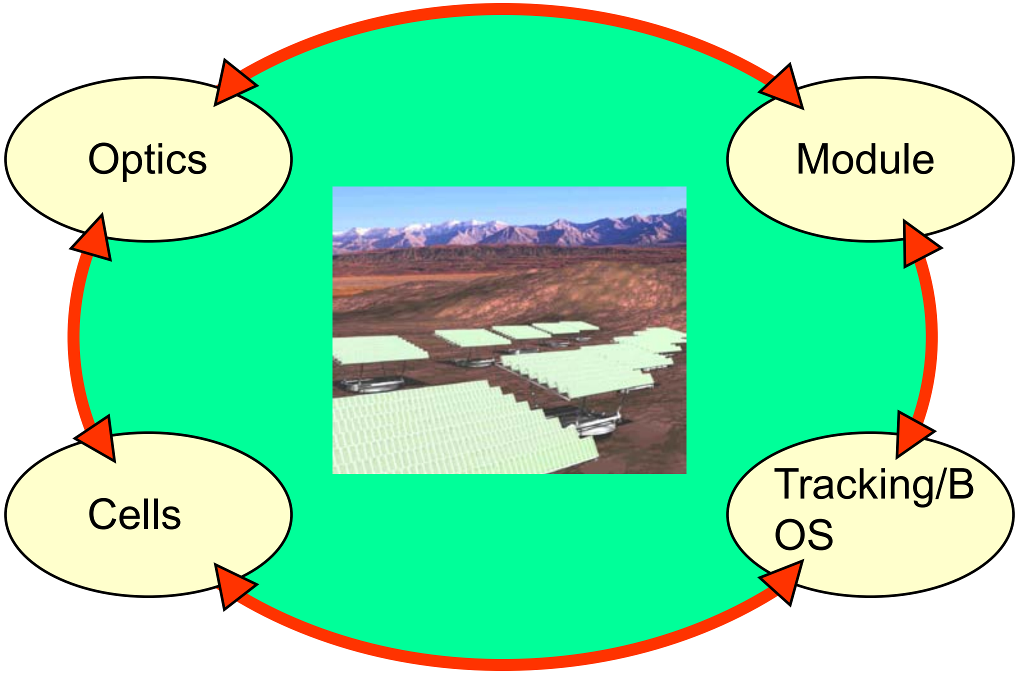
- CPV systems – optimize the system
- Two primary approaches: multijunction or Si
- Multijunction cells
  - Multiple companies/technologies >40%
  - Strong technology/Strong business
- Optics: creativity could lead to new things
- Tracking: many designs, but still biggest reliability concern
- Standards:
  - Power rating: creating order from chaos
- Slow start, but bright future for CPV

Three approaches to PV (and lower cost)



The Challenge of Concentrator PV

Simultaneously consider the whole system!



Optimize the whole concentrator system !!!

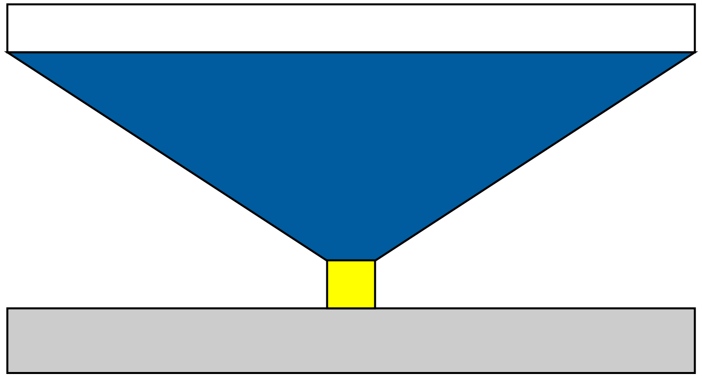
Optimize:

- Performance
- Cost
- Reliability
- Manufacturability
- Ease of shipping, installation, alignment, maintenance

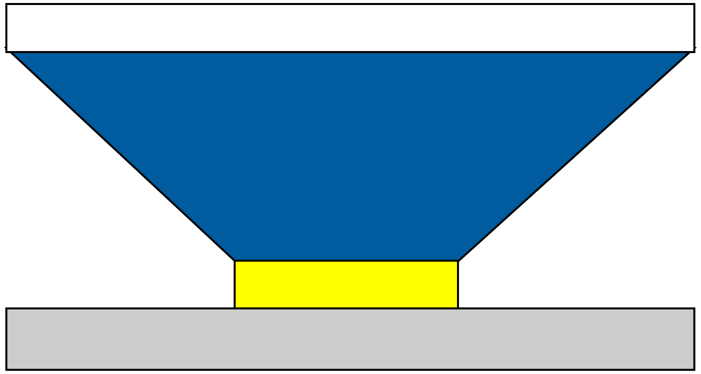
Two primary concentrator approaches

Amonix

Skyline Solar



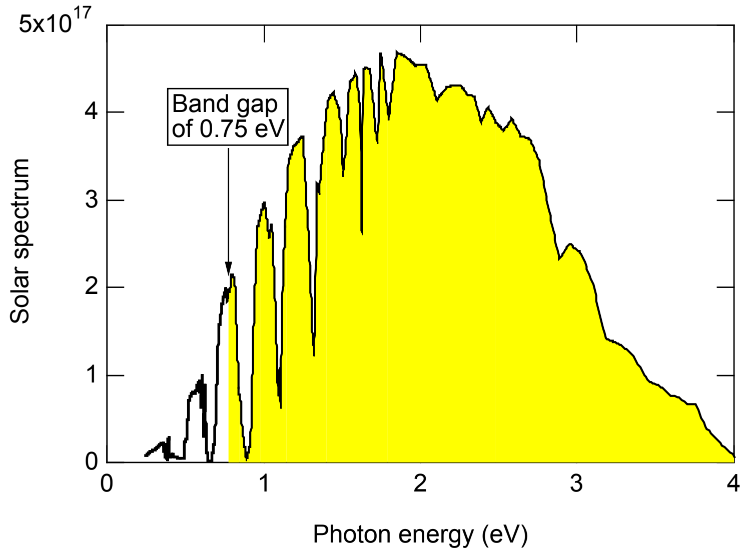
High concentration
- 35% - 40% III-V cells
- 400X – 1500 X



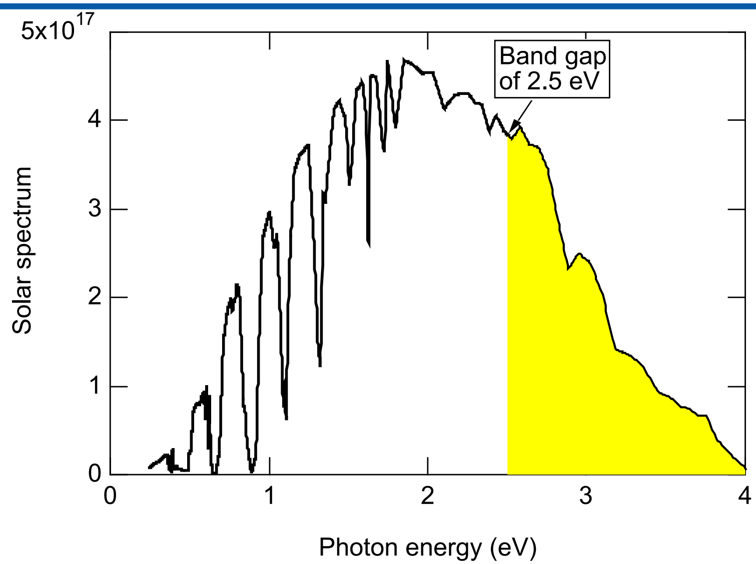
Low concentration
- 15% - 25% Silicon cells
- 2X – 100 X

Multijunction (MJ) solar cells

Why MJ? Power = Current X Voltage



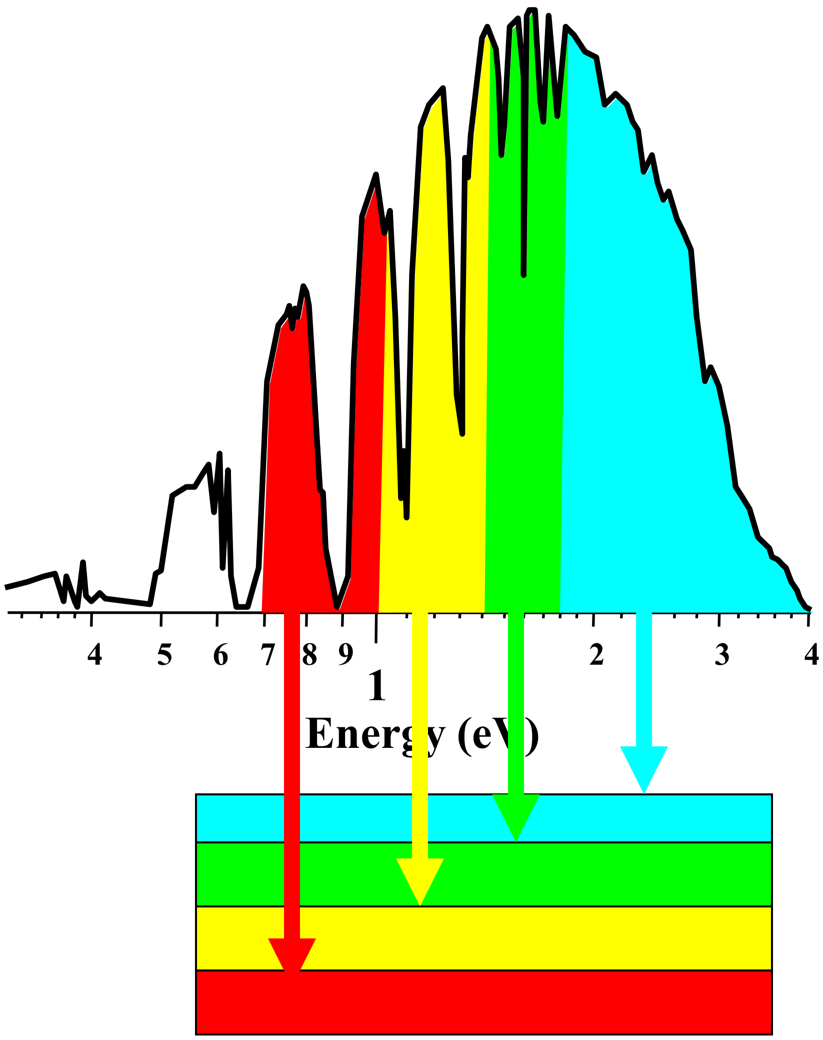
High current, but low voltage
Excess energy lost to heat



High voltage, but low current
Subbandgap light is lost

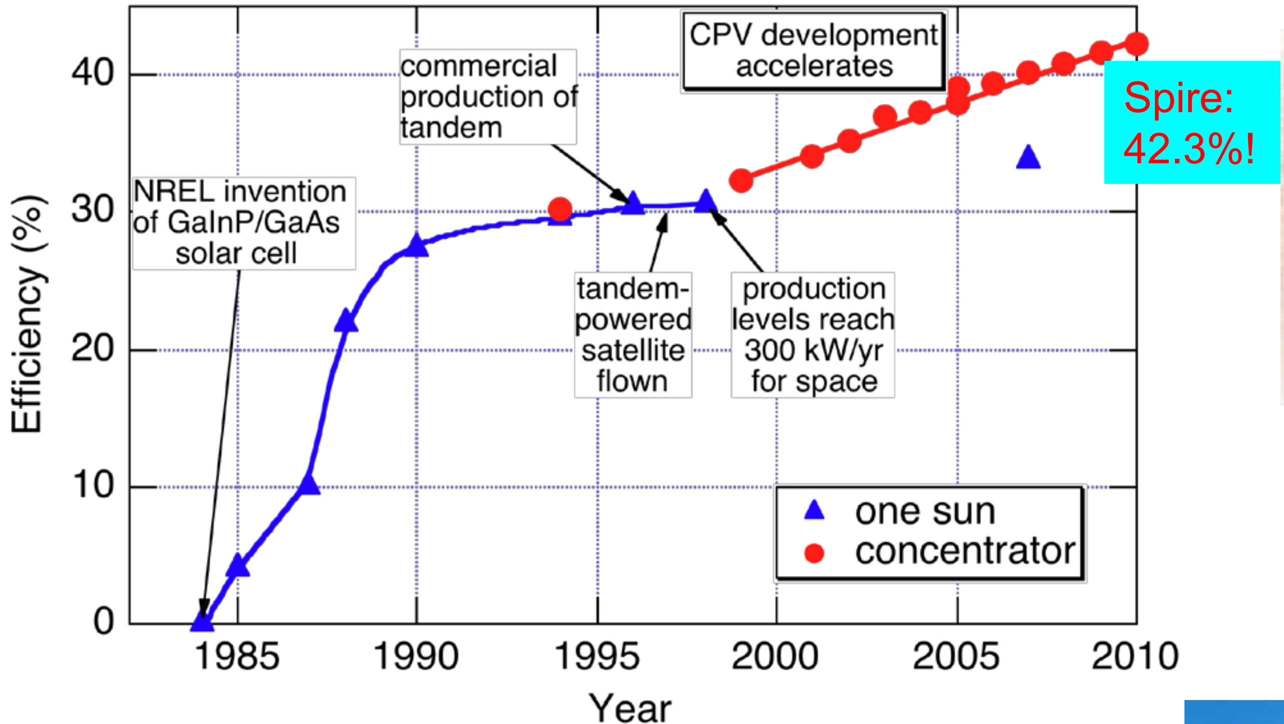
White light can be converted most efficiently by multiple materials

Choose materials with band gaps that span the solar spectrum



Multiple junctions – currently 3 junctions in champion cells

Success of GaInP/GaAs/Ge (or ?) 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

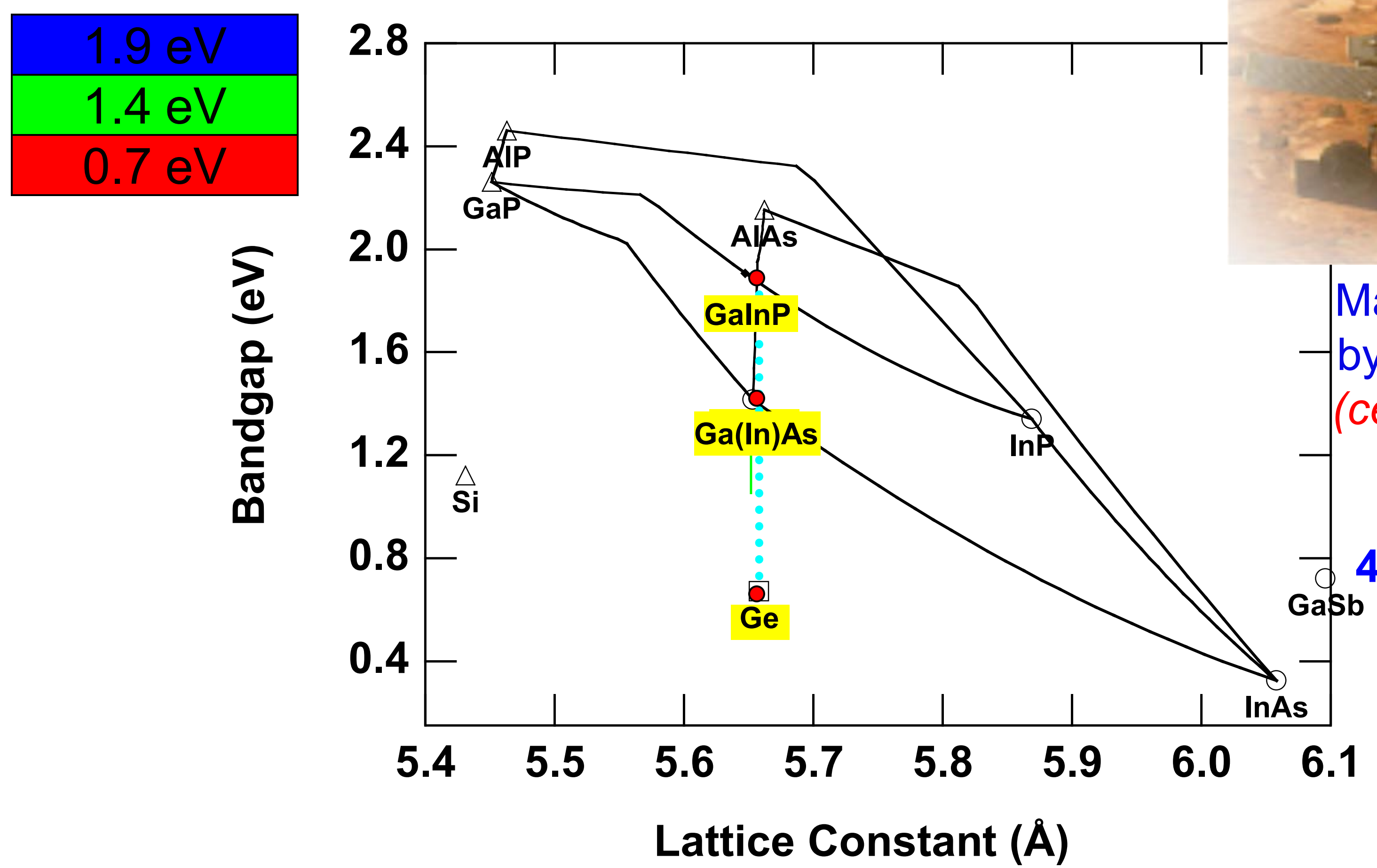
Four cell architectures have achieved > 40%

Cells have been well tested for space applications

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

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

Lattice-matched 3 junction is commercially available

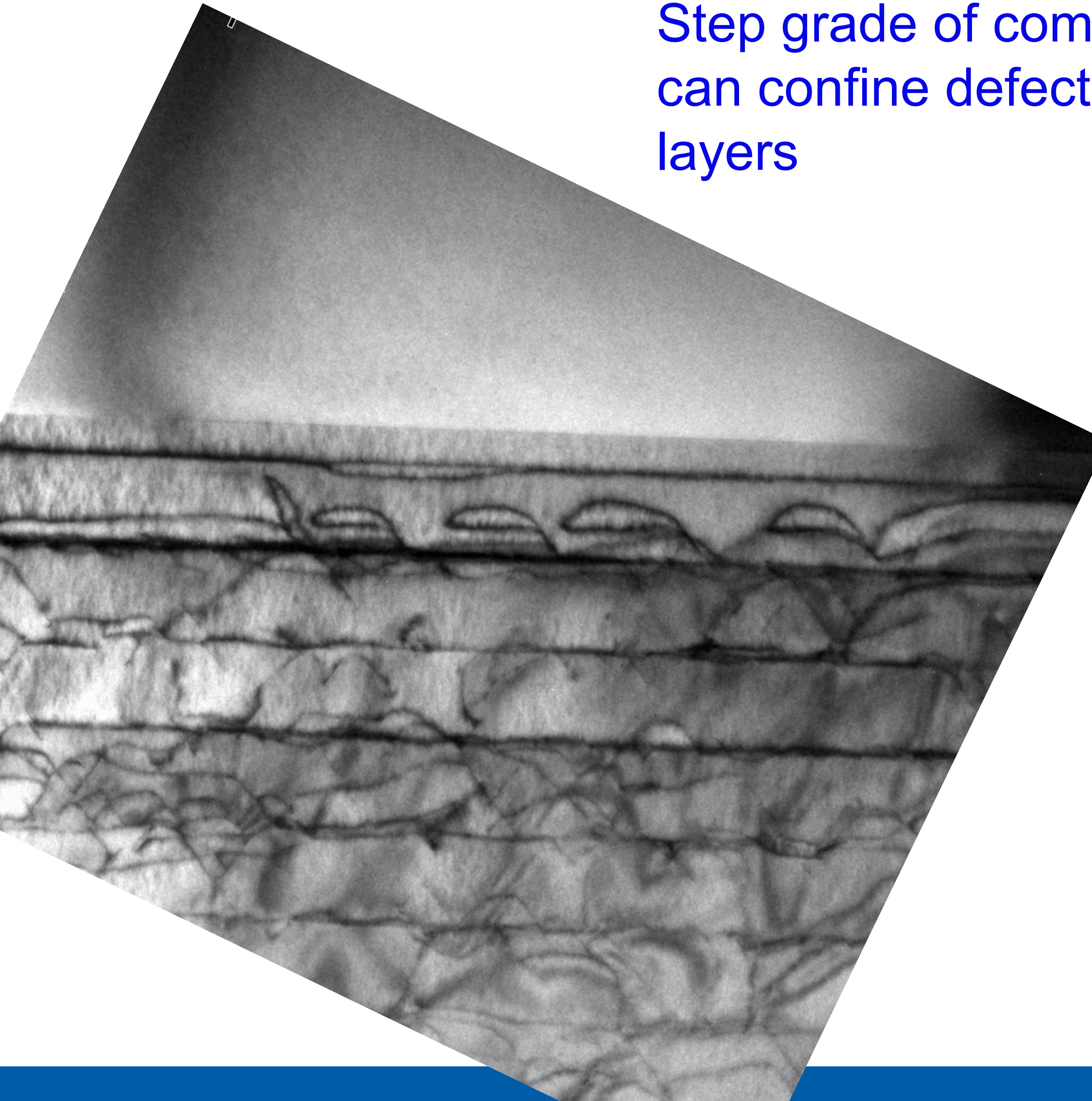


Mars Rover powered by multijunction cells *(cells are well tested)*

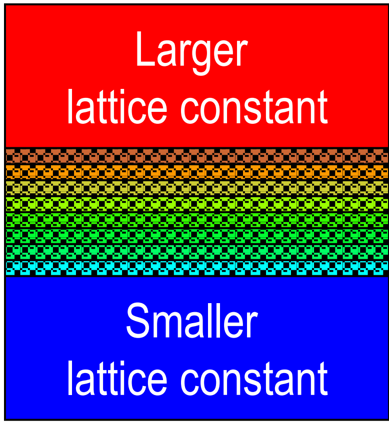
41.6% @ 364 suns
King 2009;
24th PVSEC
Spectrolab

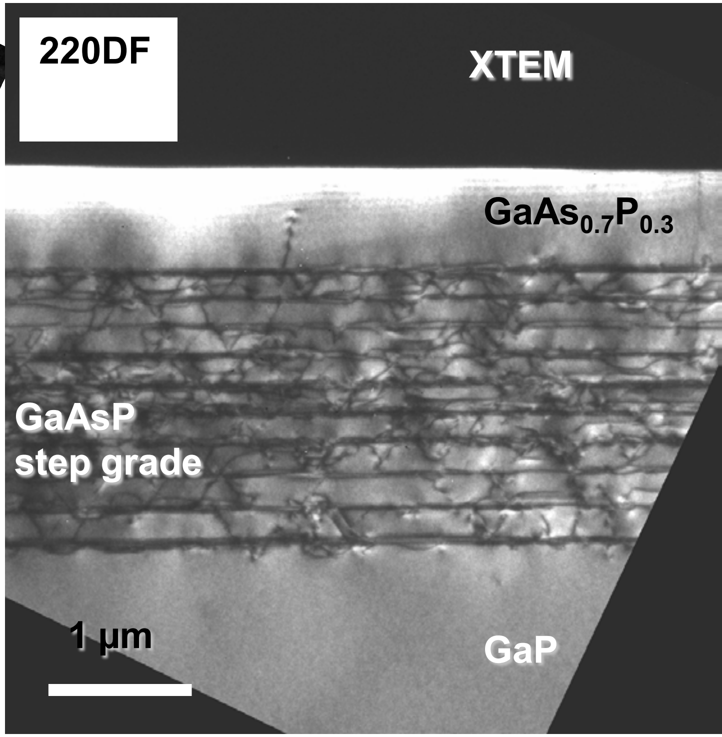
Lattice matched materials give high crystal quality though they do not provide optimal band gap combination

Lattice mismatched growth gives new opportunities

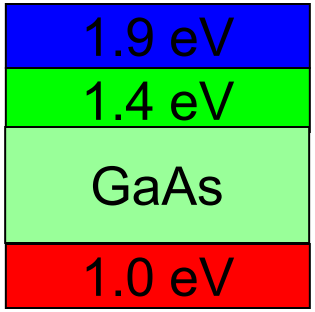


Step grade of composition can confine defects to graded layers

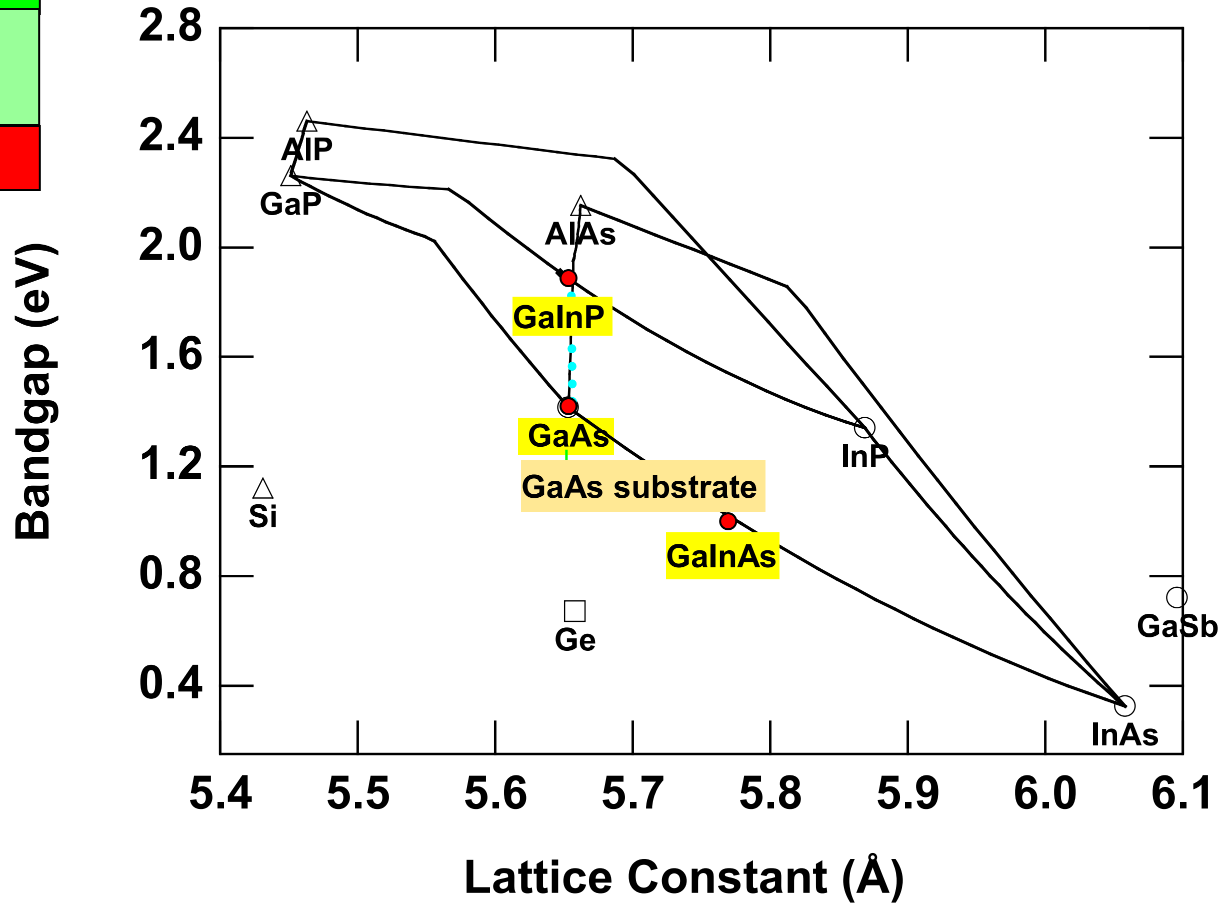




New World Record – triple junction grown on 2 sides



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



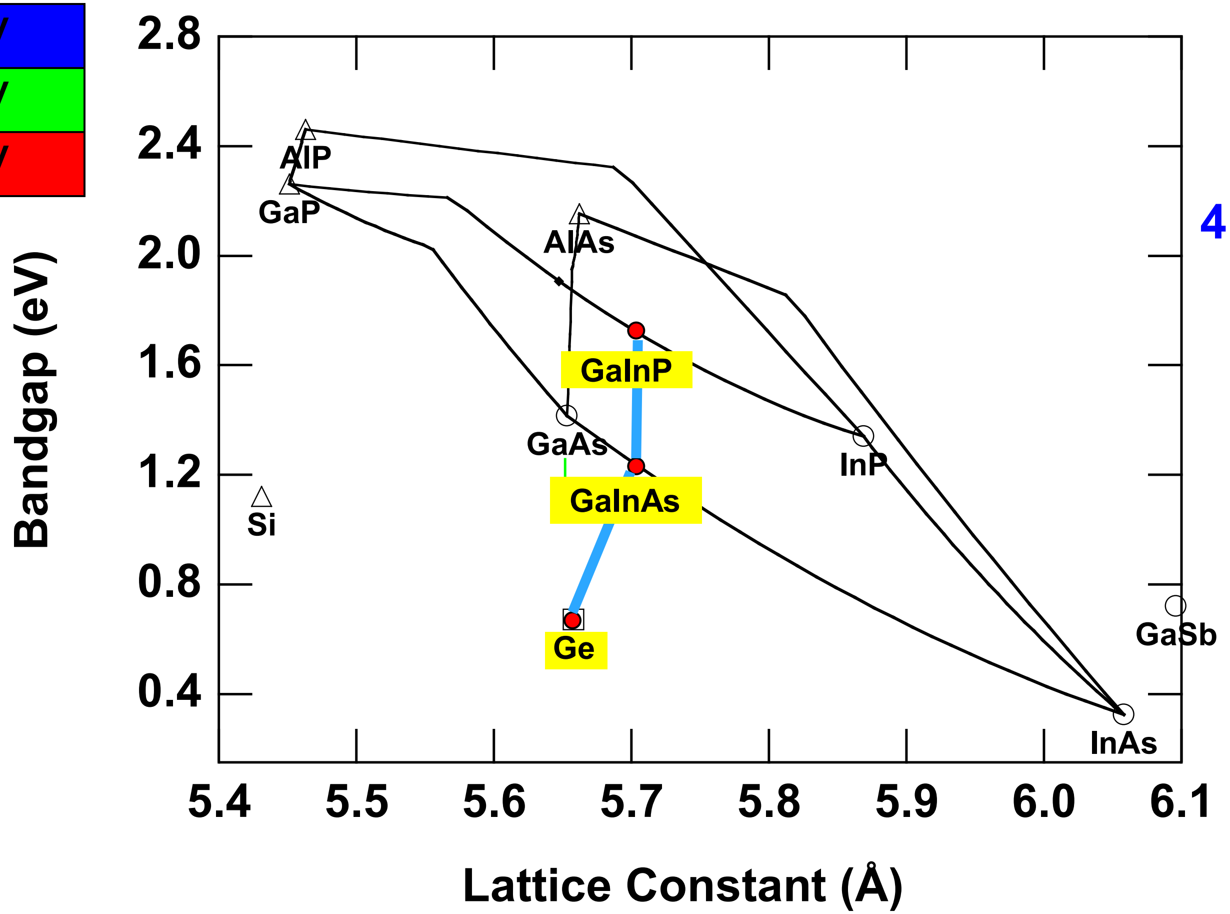
42.3% @ 406 suns

Spire – just announced

Growth on both sides of wafer gives flexibility

Lattice-mismatched triple junction on Ge

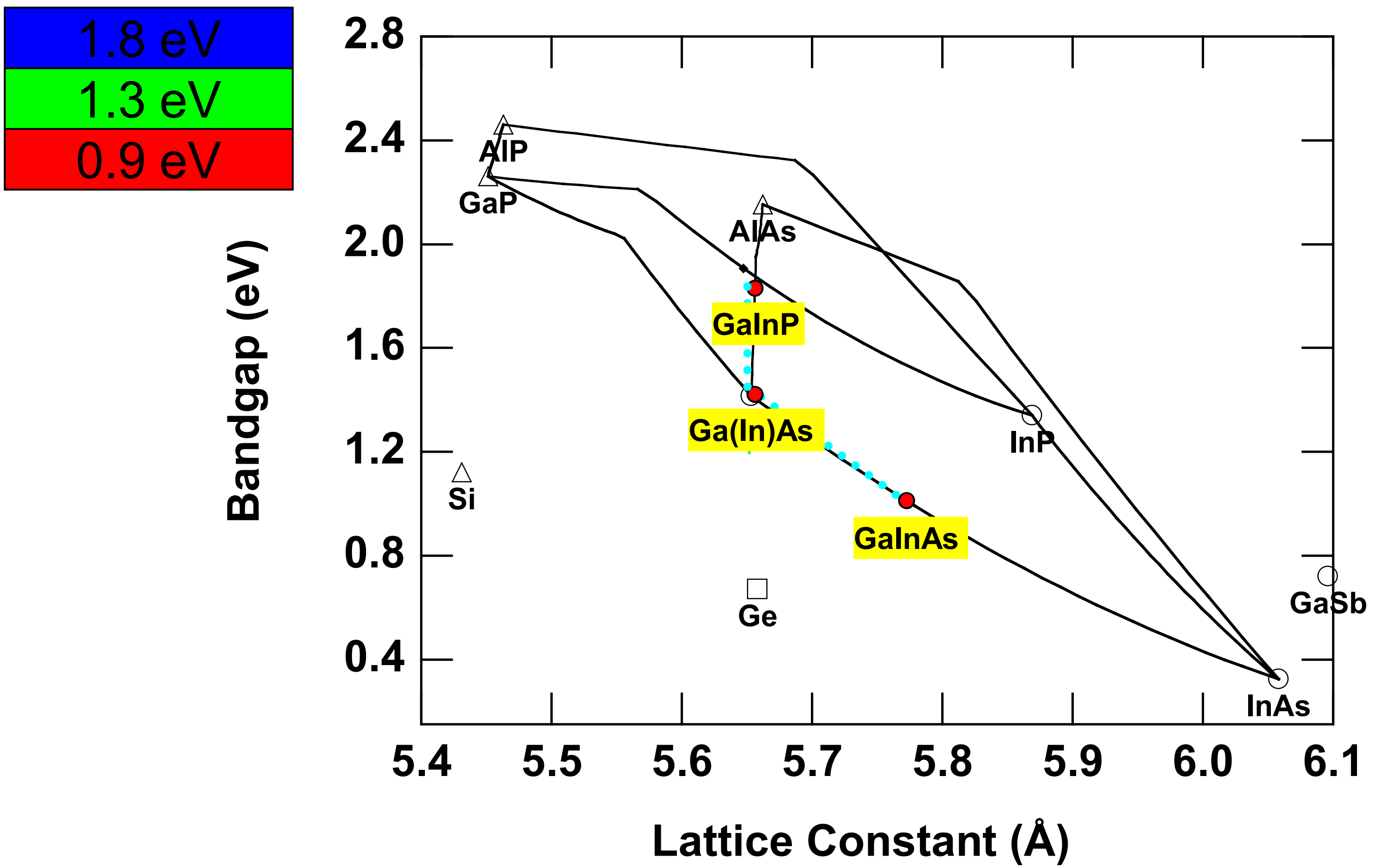
1.7 eV
1.2 eV
0.7 eV



41.1% @ 454 suns
Guter 2009, APL
Fraunhofer

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

Inverted lattice-mismatched (IMM)



40.8%
Geisz
APL
2008
(NREL)

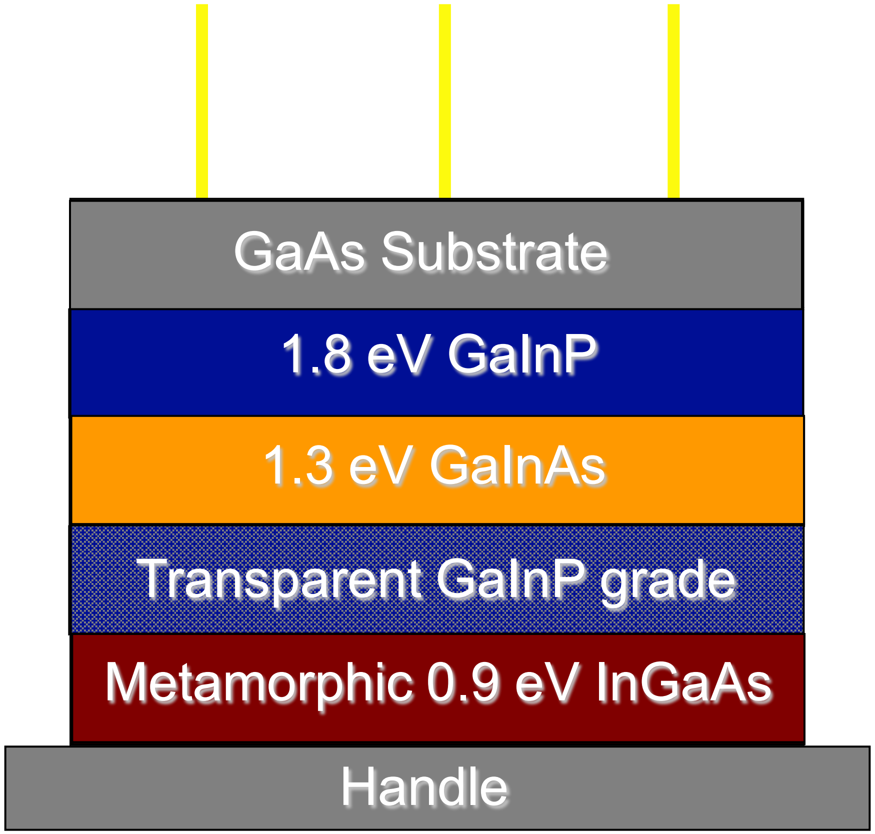
Lattice matched materials are grown first followed by mismatched – provides pathway to four-junction and higher efficiencies

Inverted metamorphic approach

GaInP/GaAs/GaInAs Ultra-Thin Tandem Cell

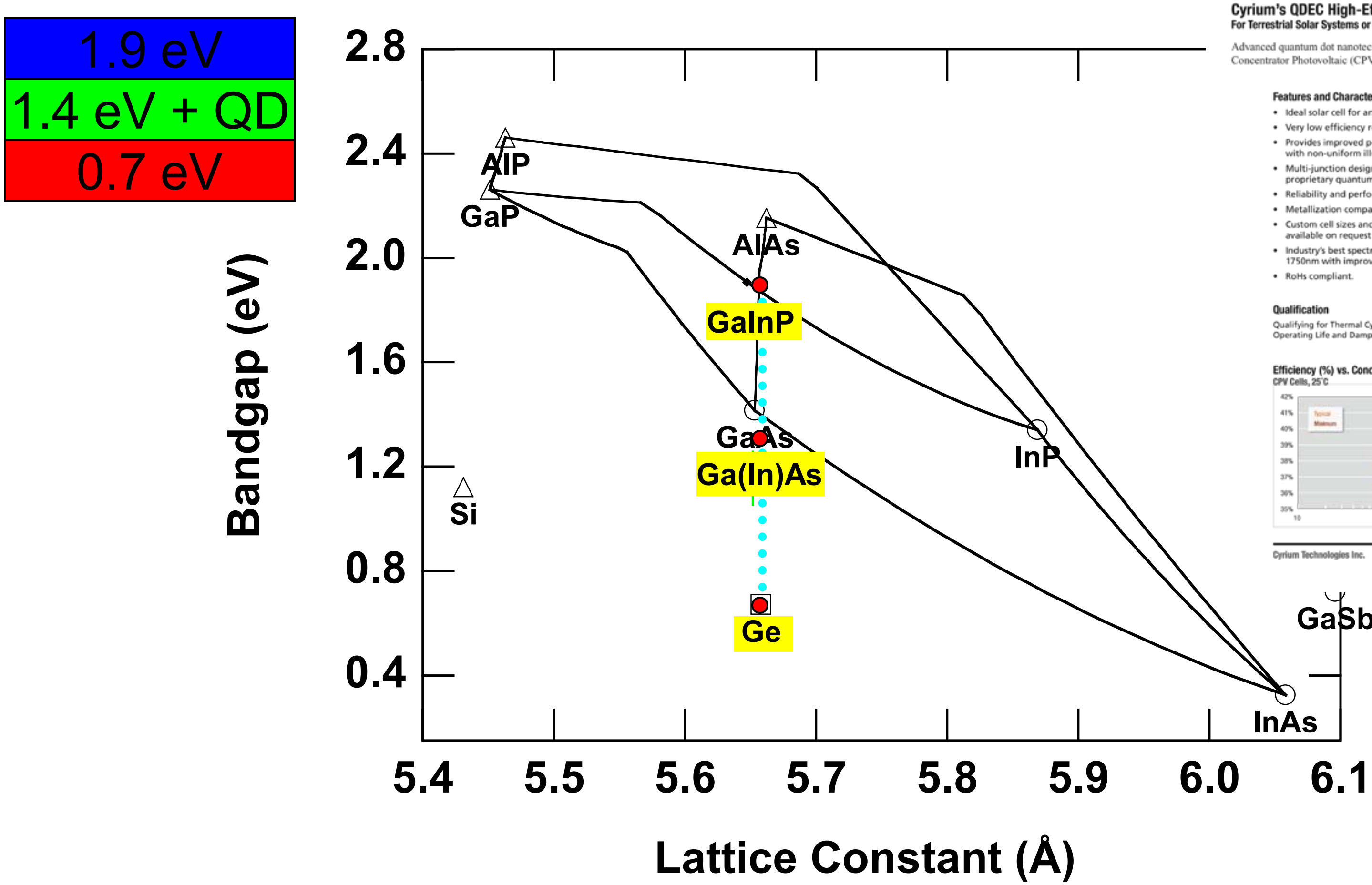
Advantages:

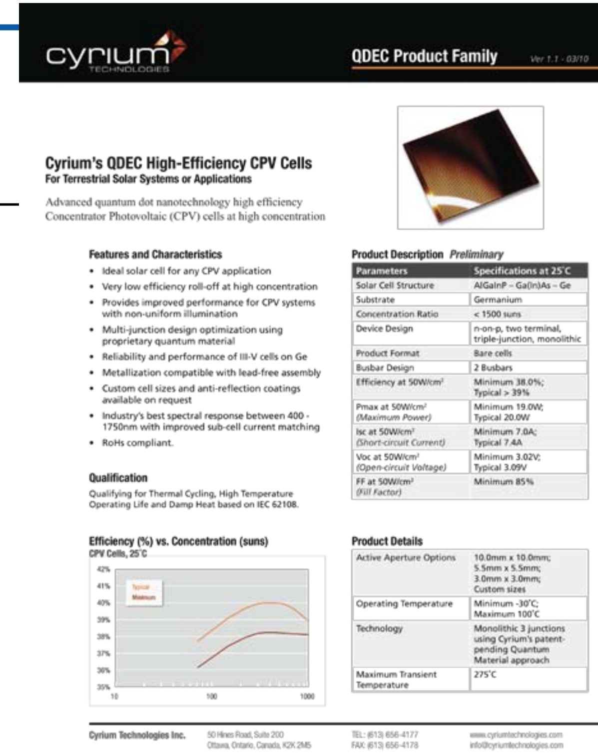
- Path to higher efficiency – 40.8% so far
- Reuse of substrate or use of impure substrate can reduce cost



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

Quantum dot triple junction cells ~40% by Cyrium





cyrium TECHNOLOGIES

QDEC Product Family *Ver 1.1 - 03/10*

Cyrium's QDEC High-Efficiency CPV Cells

For Terrestrial Solar Systems or Applications

Advanced quantum dot nanotechnology high efficiency Concentrator Photovoltaic (CPV) cells at high concentration

Features and Characteristics

- Ideal solar cell for any CPV application
- Very low efficiency roll-off at high concentration
- Provides improved performance for CPV systems with non-uniform illumination
- Multi-junction design optimization using proprietary quantum material
- Reliability and performance of III-V cells on Ge
- Metallization compatible with lead-free assembly
- Custom cell sizes and anti-reflection coatings available on request
- Industry's best spectral response between 400 - 1750nm with improved sub-cell current matching
- RoHs compliant.

Qualification

Qualifying for Thermal Cycling, High Temperature Operating Life and Damp Heat based on IEC 62108.

Efficiency (%) vs. Concentration (suns)

CPV Cells, 25°C

42%, 41%, 40%, 39%, 38%, 37%, 36%, 35%

10, 100, 1000

Product Description *Preliminary*

Parameters	Specifications at 25°C
Solar Cell Structure	AlGaInP – Ga(In)As – Ge
Substrate	Germanium
Concentration Ratio	< 1500 suns
Device Design	n-on-p, two terminal, triple-junction, monolithic
Product Format	Bare cells
Busbar Design	2 Busbars
Efficiency at 50W/cm²	Minimum 38.0%; Typical > 39%
Pmax at 50W/cm² *(Maximum Power)*	Minimum 19.0W; Typical 20.0W
Isc at 50W/cm² *(Short-circuit Current)*	Minimum 7.0A; Typical 7.4A
Voc at 50W/cm² *(Open-circuit Voltage)*	Minimum 3.02V; Typical 3.09V
FF at 50W/cm² *(Fill Factor)*	Minimum 85%

Product Details

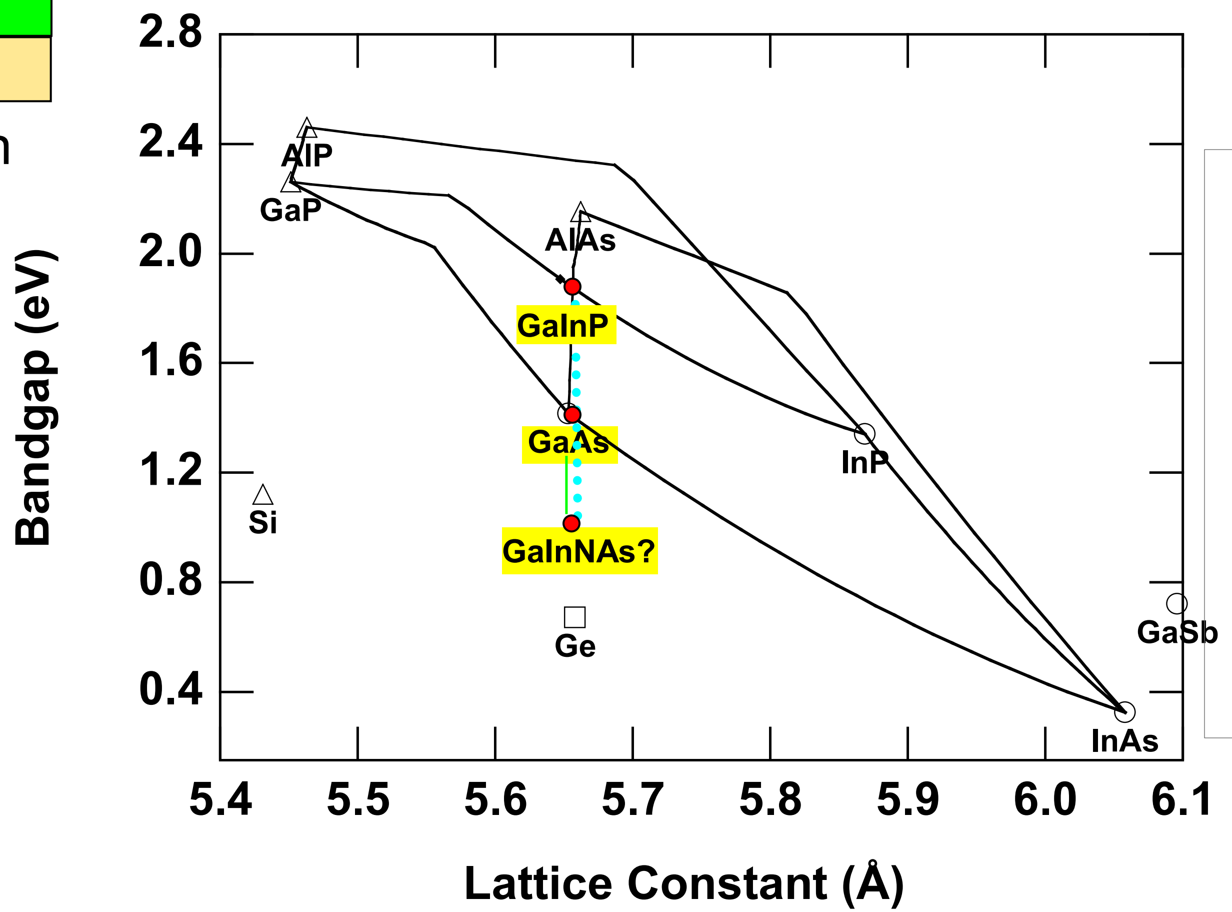
Active Aperture Options	10.0mm x 10.0mm; 5.5mm x 5.5mm; 3.0mm x 3.0mm; Custom sizes
Operating Temperature	Minimum -30°C; Maximum 100°C
Technology	Monolithic 3 junctions using Cyrium's patent-pending Quantum Material approach
Maximum Transient Temperature	275°C

Cyrium Technologies Inc. 50 Hines Road, Suite 200 Ottawa, Ontario, Canada, K2K 2M5 TEL: (613) 656-4177 FAX: (613) 656-4178 www.cyriumtechnologies.com info@cyriumtechnologies.com

Dilute nitride unique to Solar Junction

1.9 eV
1.4 eV
1.0 eV

3-junction lattice matched



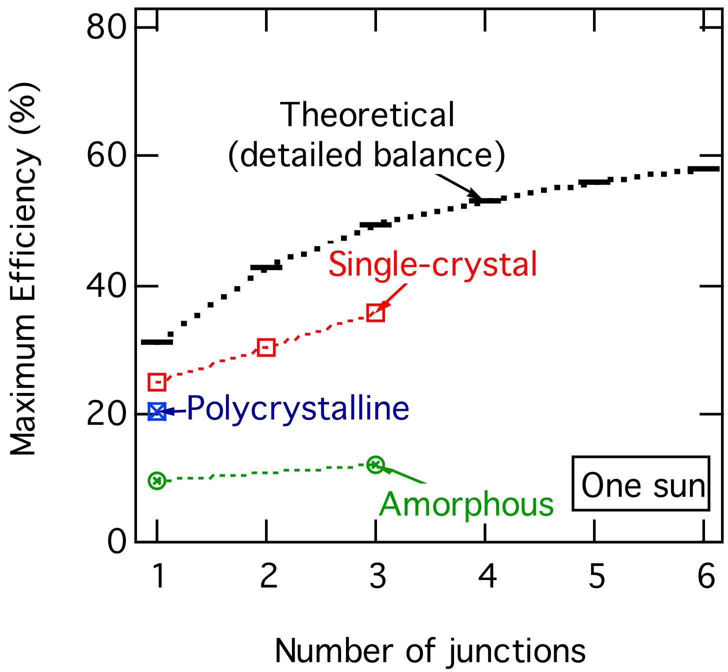
~40% @ 1000 suns

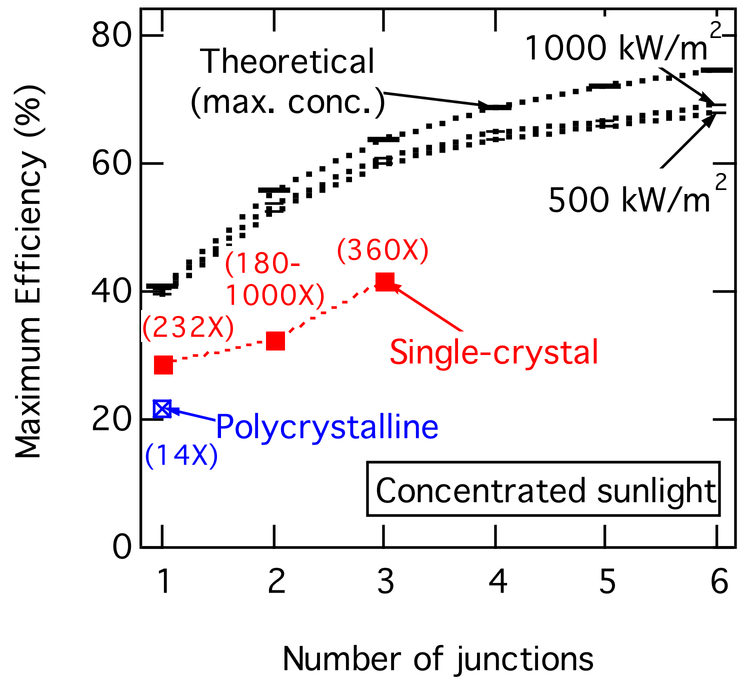
Dilute nitride bottom junction with Eg of 0.8 -1.4 eV

Platform for future generations of higher efficiency cells built on a high reliability lattice-matched architecture.

This makes six different multijunction structures that could be viable for moving past 40%

Efficiency limit for multijunction cells





Kurtz, Prog. In PV, 2008.

45% may be practical; 50% may be achievable

Companies making multijunction CPV cells

Company Name/Web Link	Location	Comment
Arima	Taipei, Taiwan	Reported achieving >40% cells.
Azur Space (RWE)	Heilbronn, Germany	Reported 36% efficiency; custom designs available.
CESI	Milano, Italy	Datasheet reports efficiency >30%.
Compound Solar Technology	Hsinchu Science Park, Taiwan	Website shows I-V curve with 33.4% efficiency
Cyrium	Ottawa, Canada	Datasheet describes typical > 39% cells
Emcore	Albuquerque, NM, USA	Datasheet describes typical 39% cells and receivers at ~500 X.
Epistar	Hsinchu, Taiwan	Multijunction cells in development
IQE	Cardiff, Wales, UK	Has demonstrated state-of-the-art efficiencies
JDSU	Milpitas, CA, USA	Advertises multijunction concentrator cells on website
Microlink Devices	Niles, IL, USA	Multijunction cells removed from substrate in development
Quantasol	Kingston upon Thames, Surrey, UK	Multijunction cells with quantum wells
RFMD	Greensboro, NC, USA	Multijunction cells in development
Sharp	Japan	Has demonstrated high efficiencies; has not indicated plans for external commercialization.
Solar Junction	San Jose, CA, USA	“Approaching 40%”
Spectrolab (Boeing)	Sylmar, CA, USA	Datasheet describes minimum average 36% cells and cell assemblies at 50 W/cm^2. Will ship 35 MW in 2009, and plan to ship 100 MW in 2010 (@500X).
Spire	Boston, MA, USA	Announced achievement of 42.3% efficiency.
VPEC	Ping-jen city, Taiwan	Multijunction cells in development

Addition of companies like JDSU and RFMD adds financial credibility

Silicon concentrator cells

- Some companies use one-sun silicon cells
- SunPower sold Si CPV cells off the shelf a decade ago, but made a business decision to stop
- NaREC is currently the primary company with this business model
- *Supply of Silicon concentrator cells remains a problem for this segment of the community*

Optics –

Creativity can take us to new worlds

Choices for optics – blessing or curse?

Refractive vs reflective

Add secondary to increase acceptance angle?

Small vs large elements

Planar (Fresnel) vs shaped (domed) elements

Acrylic vs silicone-on-glass vs many other materials

Short vs long focal length (f number)

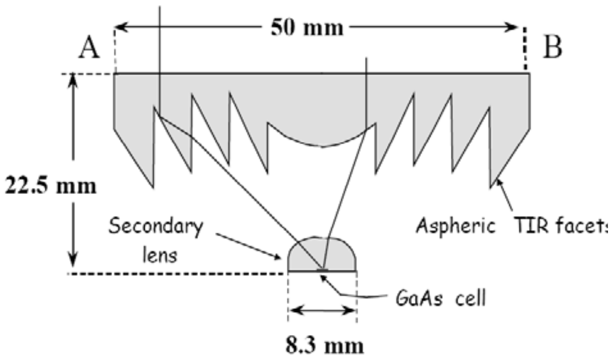
Point focus (MJ CPV?) vs line focus (Si CPV?)

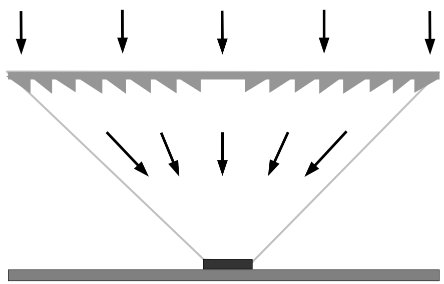
Filled (solid) optics vs transmission through air

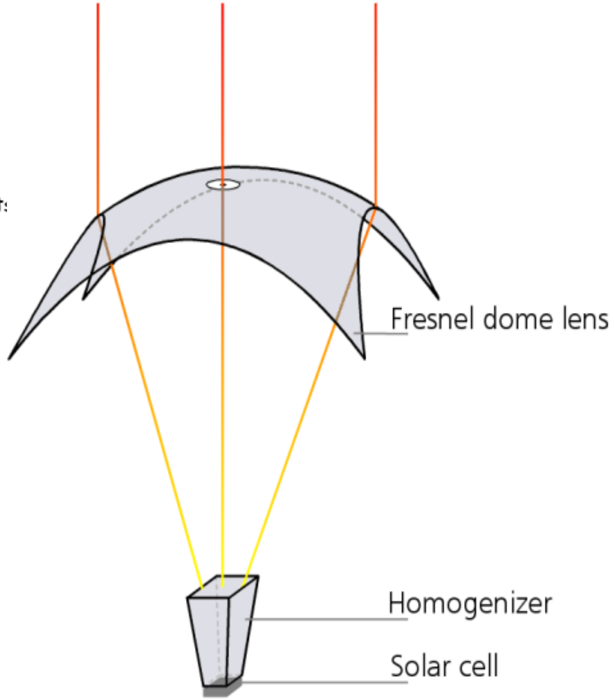
Use of wave guides

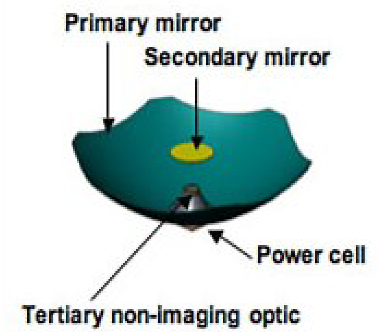
Use of luminescence for concentration

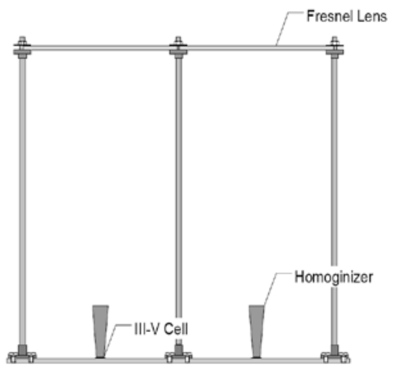
Examples of Concentrating Elements











Trackers –

Choice may depend on application

Choices for trackers

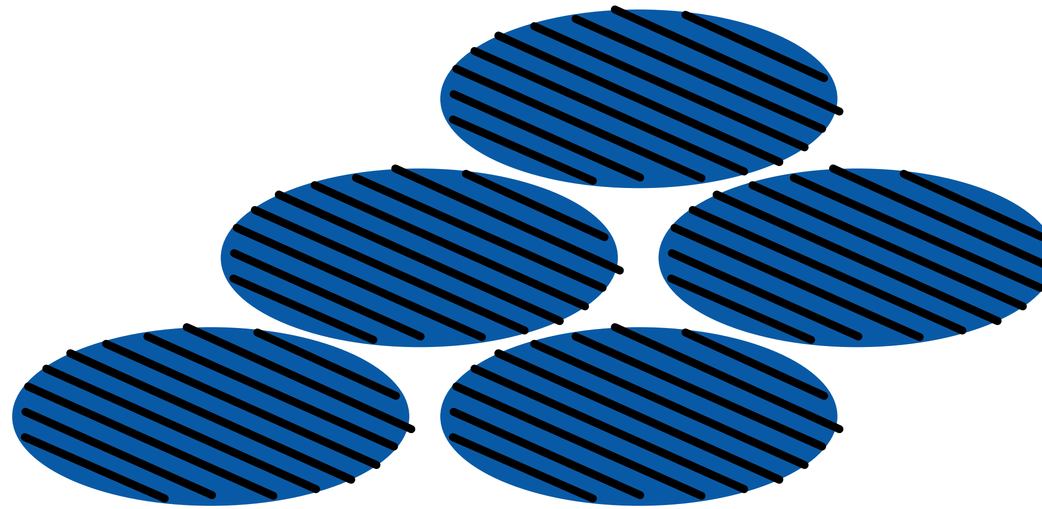
- Pedestal vs distributed support
- One axis (for Si CPV?) vs two axis
- Small (individually tracked) vs large elements
- Height
- Circular (carousel: rotate & roll) vs linear (tilt & roll)
- Planar mounting vs staggered mounting
- Open- vs closed-loop tracking
- Hydraulic vs direct drive
- Stow position (up or down?); stow condition
- Dual use of land

Land use – complicated trade off

High efficiency is often assumed to mean fewer acres/MW

Packing density is trade off between shading and energy production

Pedestal



Carousel

Use of pedestals often results in higher shading losses, but provides opportunity for dual use of land

Carousel or tilt & roll approaches may allow closer packing

Complicated: creativity may minimize shading losses and identify new approaches

Reliability – an important challenge

Reports of reliability issues include:

- Trackers
- Inverters, data acquisition, etc.
- Longevity may be limited by optics, thermal control of cells, dirt getting into the light path
- Only a handful of companies have > 10 y experience in the field
- Most companies are aggressively applying accelerated testing

Most companies are considering “design for reliability” from the start

Convincing banks of long-term reliability is key hurdle to growth

Examples for III-V based Concentrator Systems

Amonix, CA, USA

- C ~ 500x
- Fresnel lens
- Up to 70 kW/pedestal

- $130M new funding this year

- Installed:

~14 MW Si-based

~2 MW MJ

- > 40 MW in progress

- Production capacity 30 MW/y (plans to expand)

Amonix and Solar Systems in Australia have had product in the field for the longest

Examples for III-V based Concentrator Systems

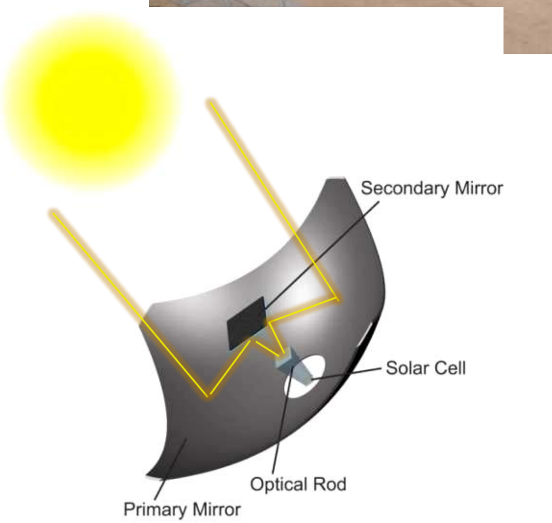
SolFocus, CA USA

- C ~ 650 X
- Multiple reflections within glass
- ~9 kW/pedestal
- Designed for low chromatic aberration and high acceptance angle
- Installed:

~ 2 MW on sun

> 10 MW in progress

- Production capacity 50 MW/y



Examples for III-V based Concentrator Systems

Concentrix Solar, Germany

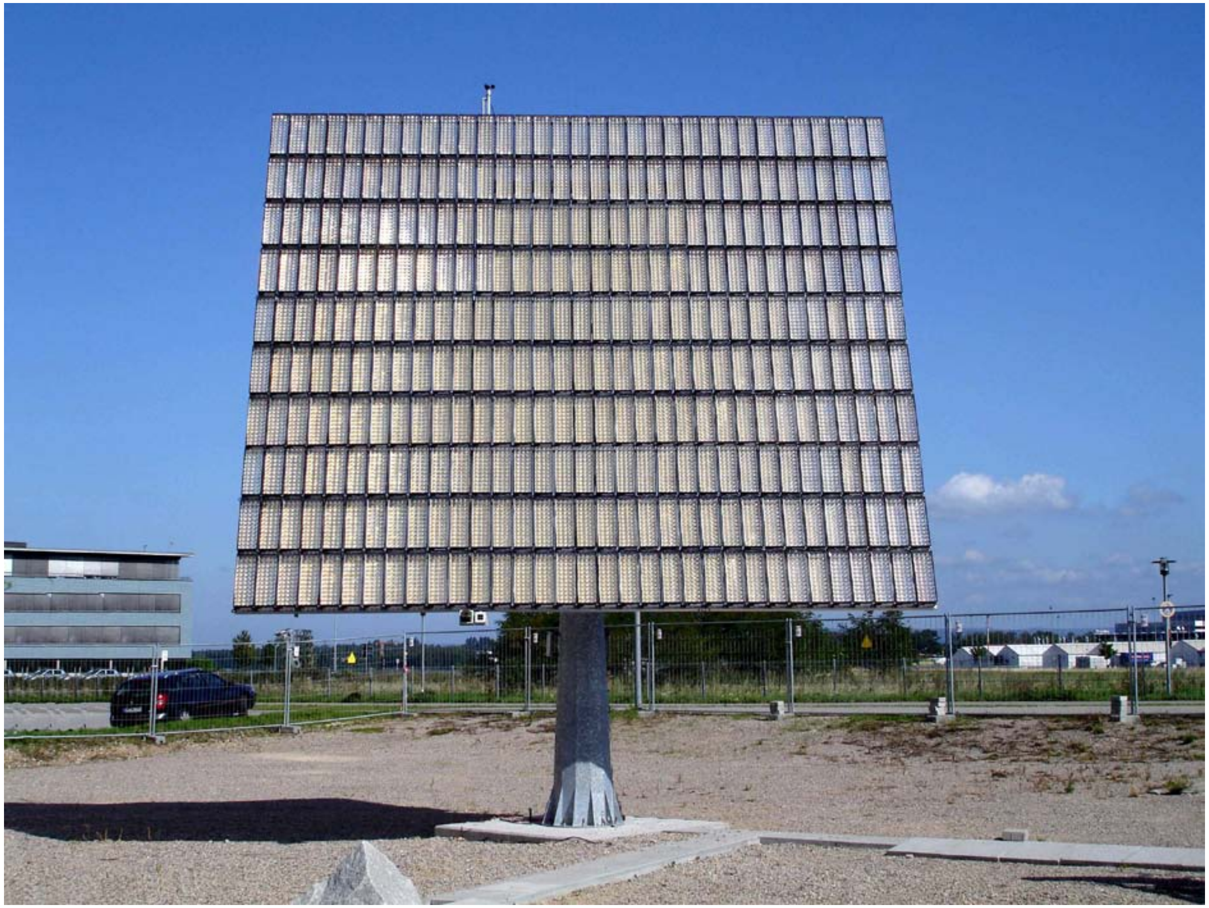
- C ~ 385x
- Fresnel lens
- Up to 70 kW/pedestal
- Glass/glass construction

- Installed:

~ 1 MW on sun

> 1 MW in progress

- Production capacity 25 MW/y



Examples for III-V based Concentrator Systems

Opel, Canada

- C ~ 500x
- Fresnel lens
- ~ 4 kW/pedestal
- Staggered alignment

- Installed:

~ 500 kW

- Scaling up for production

Examples for III-V based Concentrator Systems

Daido Steel, Japan

- C ~ 500x
- Domed Fresnel lens
- ~ 15 kW/pedestal
- Staggered alignment

- Installed:

~ 200 kW

- Advanced prototype development

Examples for III-V based Concentrator Systems

Emcore, NM, USA

- C > 1000x
- Fresnel lens
- Tilt & Roll
- Suggest < 5 acres/MW is possible

- Installed > 1 MW of design on pedestal

Examples for III-V based Concentrator Systems

Soliant Energy, CA, USA

- C ~ 1000x
- Fresnel lens
- Tilt & Roll
- Designed for rooftop installation

- Preparing to start manufacturing

Examples for III-V based Concentrator Systems

Energy Innovations, CA, USA

- C = 1200x
- Fresnel lens
- “Sunflower” uses single-module tracker
- Low-profile, low-weight design for carport, rooftop, or field

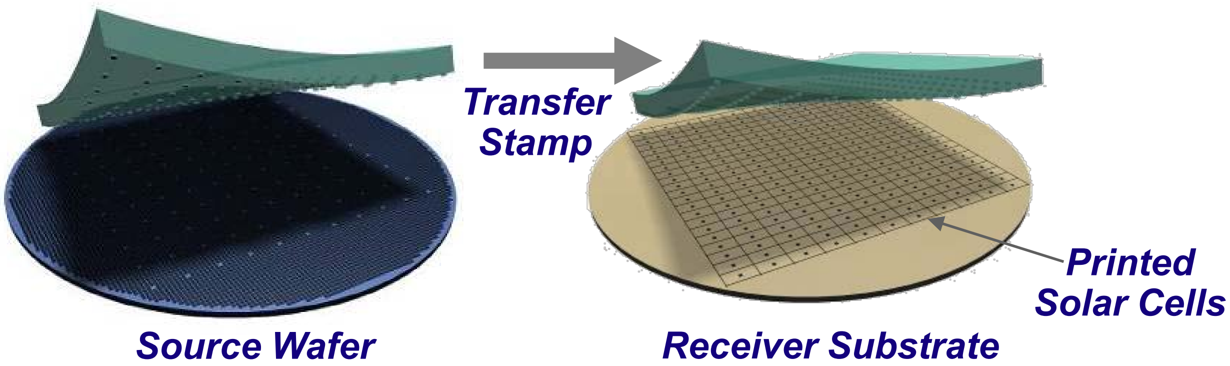
- Installed ~50 kW

Examples for III-V based Concentrator Systems

Semprius, NC, USA

- 0.36 mm^2 microcells assembled with proprietary printing technique
- 31.5% InGaP/GaAs cell efficiency at 800x
- Plano convex silicone-on-glass primary
- Tiny glass ball lens secondary
- RD&D systems under test in NC and AZ
- Advanced prototype development using 3-J cells and 1,111x concentration

RD&D System



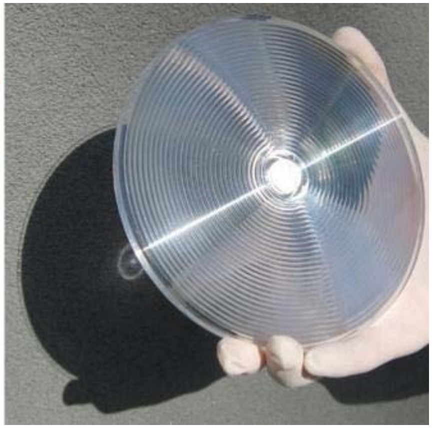
Transfer printing method provides parallel assembly

Examples for III-V based Concentrator Systems

Morgan Solar, Canada

- Light-guide optic
- C ~ 1000X
- Light flows laterally; very thin optic

- Prototype development

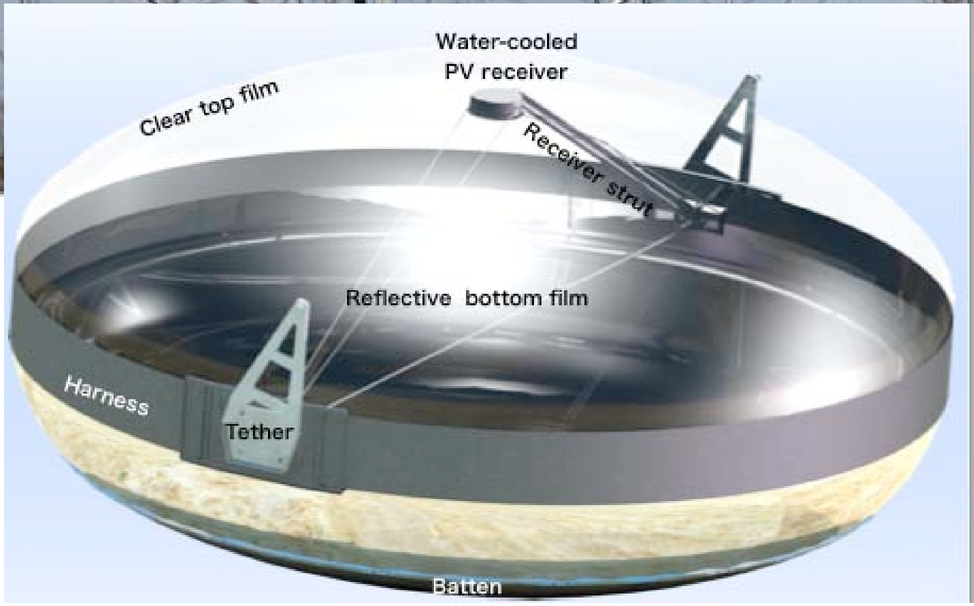


Examples of Concentrator Systems

Cool Earth Solar

- Balloon with back reflector
- Water-cooled cells
- Can use a range of concentrations; either silicon or multijunction cells
- Steel band is used to point at the sun

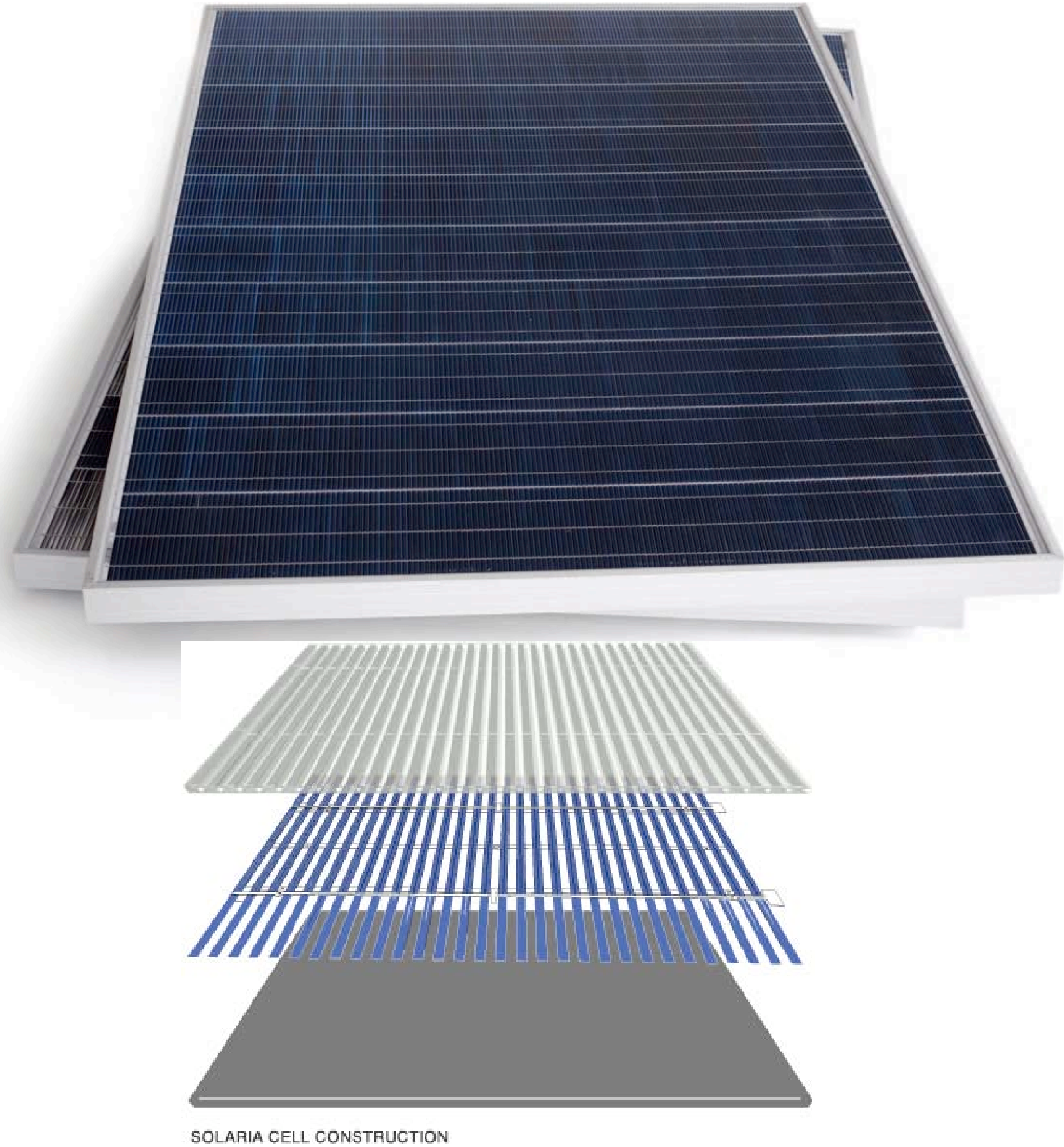
- Advanced prototype development



Examples for Low Concentration Systems

Solaria, CA, USA

- Linear focus
- Thin, refractive optics
- C ~ 2x
- Si cells
- Marketed as a flat-plate module
- Passed certification
- Shipped to a dozen leading companies
- enXco (EDF) has invested in Solaria and will procure several MW in next 6 months (100s of MW planned in future)



Examples for Low Concentration Systems

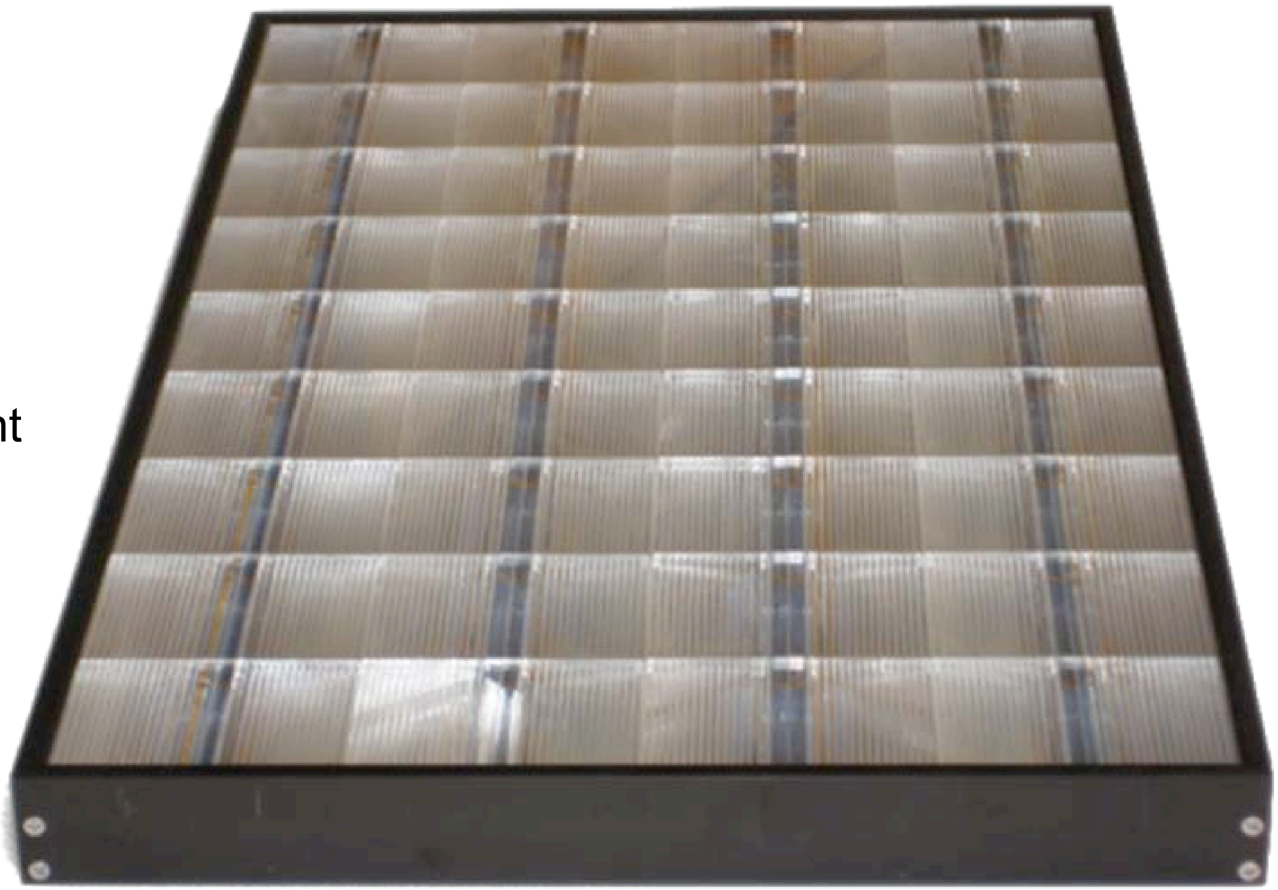
Skyline Solar, CA, USA

- Linear focus
- Reflective optics aimed at opposite side
- C ~ 10x
- Si cells
- Carefully designed heat sink: cells operate at ~ same temperature as flat plate
- “Thin-film” mirrors
- ~ 150 kW on sun
- Mirrors shaped in automotive factory

Examples for Low Concentration Systems

Banyan Energy, CA, USA

- Linear focus
- Aggregated total internal reflection
- C < 10x
- Si cells
- Prototype development



International standards efforts

IEC TC82 WG7 current projects:

- Power Rating
- Safety
- Energy Rating
- Tracker specification
- Acceptance test
- Others

UL:

- Safety

Power rating: order out of chaos

In the past, companies chose rating conditions:

Irradiance: 850, 900, or 1000 W/m^2?

Temperature: 25° C cell or 20° C ambient?

(Affects $/W, performance ratio, and other metrics)

Chaos

IEC WG7 committee has now tentatively chosen:

Irradiance: 900 W/m^2

Test condition:

25° C cell

(same as flat plate)

Operating condition:

20° C ambient

(like California's rating)

This is progress, but be careful (this is too new to be implemented)

Current status & what to expect next

High-concentration CPV Status

> 50 companies are developing prototypes
~ 20 are testing > 2nd generation design

Some companies are moving into production phase

Company	Installed capacity	In progress - other projects at planning stage	Manufacturing capacity
Amonix	~ 2 MW multijunction ~14 MW silicon (Guascor)	30 MW (Xcel, Alamosa, Colorado); 12 MW (Tucson Electric); 2 MW (Tucson Electric/Univ. of Arizona)	30 MW/yr (>100 MW/yr)
Solfocus	~ 2 MW	10 MW in a variety of projects	50 MW/yr
Concentrix	~ 1 MW	1 MW (Chevron, Questa, NM); 100 kW (Abu Dhabi)	25 MW/yr (100 MW/yr)
Solaria (low-X)	Shipments to ~ dozen customers	10s of MWs in next 2Q	40 MW/yr

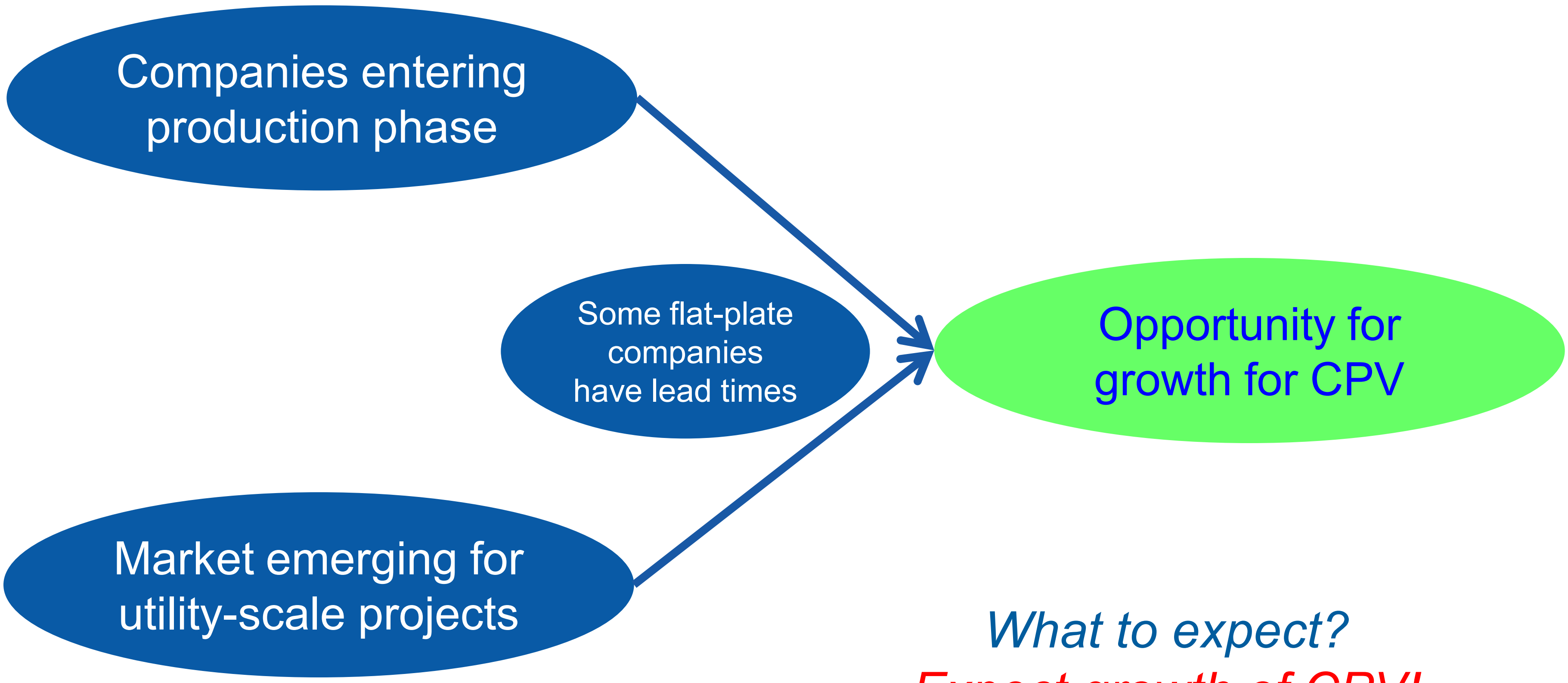
~ 30% efficiencies are being reported

Market is emerging

Utility	Requests for Proposals	Planned capacity
Arizona Public Service	Small Gen RFP – 5-15 MW RFP – 15-50 MW	70 MW 100 MW
Salt River Project	PV-RFP – 12 kV interconnection	50 MW
Southern California Edison	Renewables Standard Offer RFP - ≤ 20 MW RFO for solar PV – 200 kW-2 MW (≤ 20 MW)	500 MW 50 MW
Pacific Gas & Electric	Utility-owned program/RFP - ≤ 20 MW PV PPA Program/RFP - ≤ 20 MW	75 MW 50 MW
Total		**895 MW**

Thank you to Amonix for compilation of data

Convergence provides opportunity



What to expect?

Expect growth of CPV!

Rate of growth will be limited by demonstration of long-term reliability (needed to be "bankable")

Summary

- Many options for optics, trackers, and cells to consider in CPV system development
- High-efficiency multijunction cells enable high-concentration CPV; while low-X CPV reduces use of silicon
- Module efficiencies of 30% are enabling
- Convergence of product development & market emergence provides growth opportunity

For more information:

- Panel tomorrow: “Will 2010 be a Turning Point for CPV?”
- CPV-7 in April, Las Vegas
- http://www.nrel.gov/docs/fy10osti/43208.pdf