Modern photovoltaic technologies
PHYS-609

Part 1.4 III-V solar cells

- III-V solar cells
- multi-junction solar cells
- solar cells for space applications
- concentrated photovoltaics (CPV)

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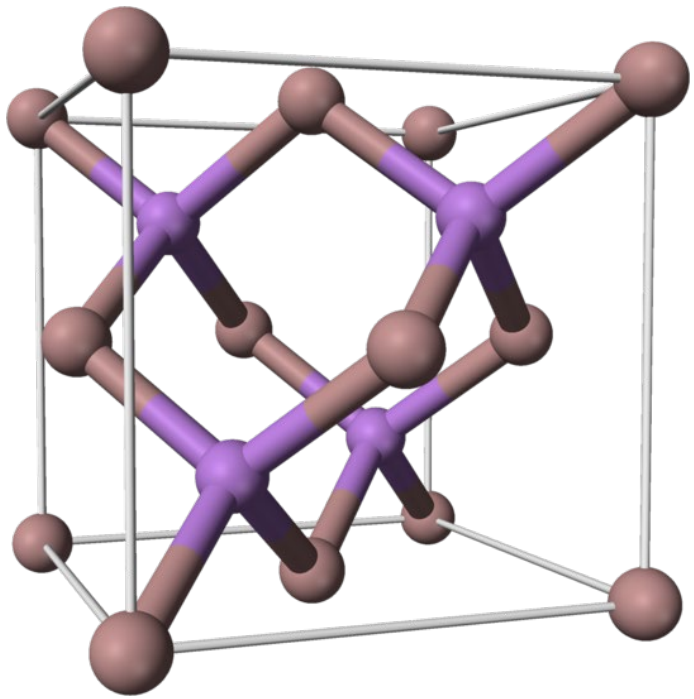
Empa
Materials Science and Technology

III-V semiconductors



Cubic crystal structure of GaAs
www.wikipedia.com

GaAs (*Eg* = 1.42 eV)

GaP

InP

InAs

GaInAs

GaInP

AlGaInAs

AlGaInP

Growth methods: Metalorganic Vapor Phase Epitaxy (MOVPE)
Molecular beam epitaxy (MBE)

III-V semiconductor bandgaps

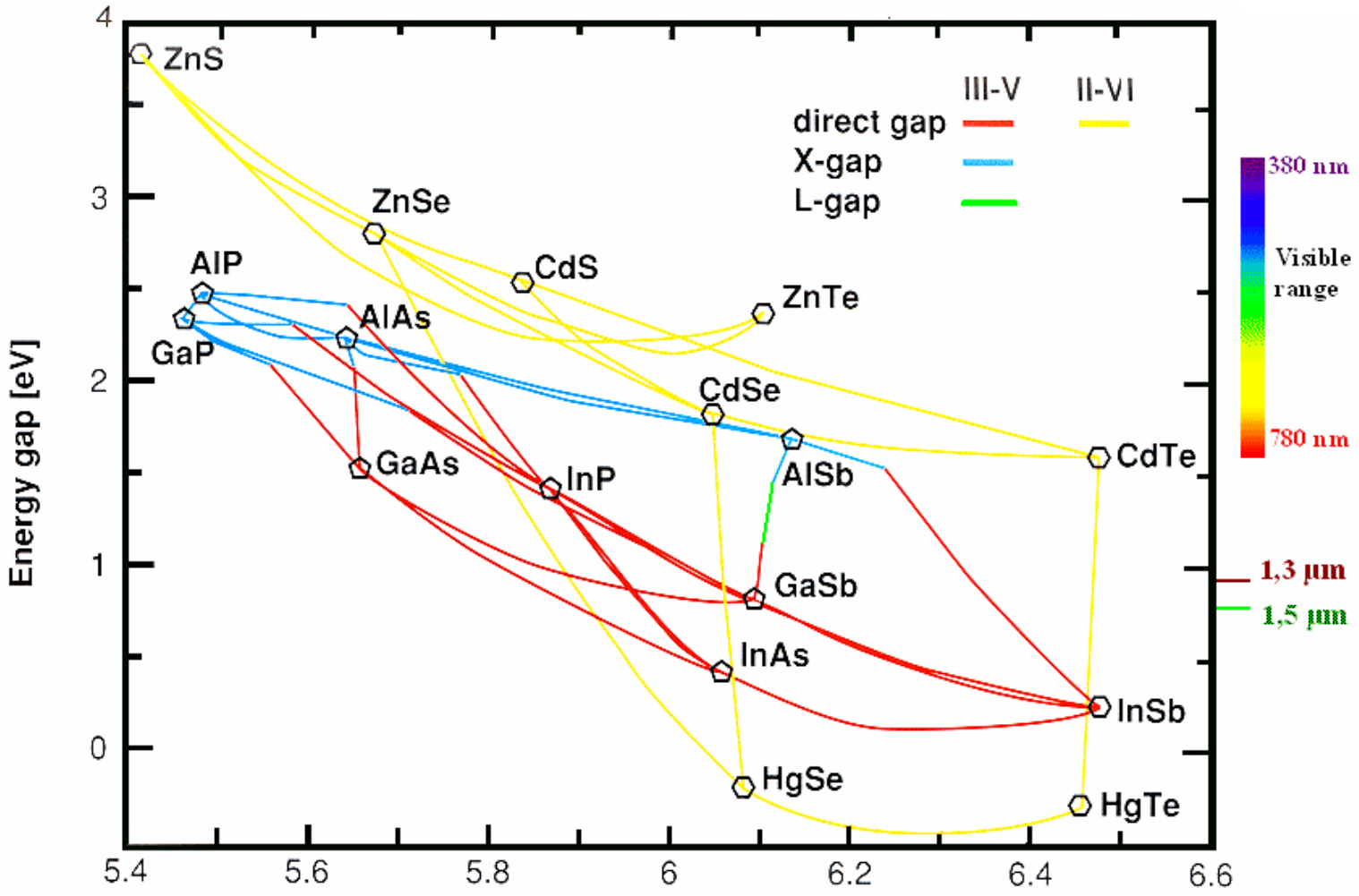
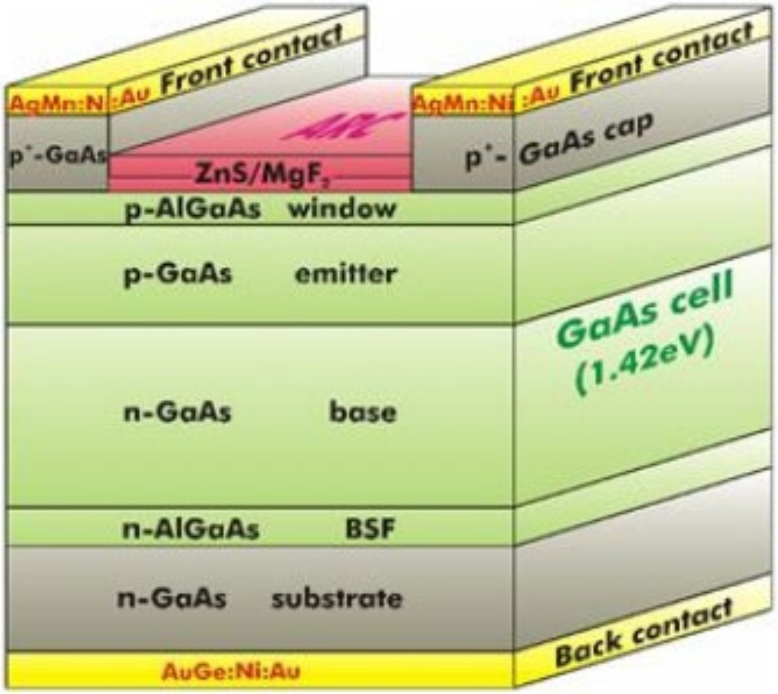
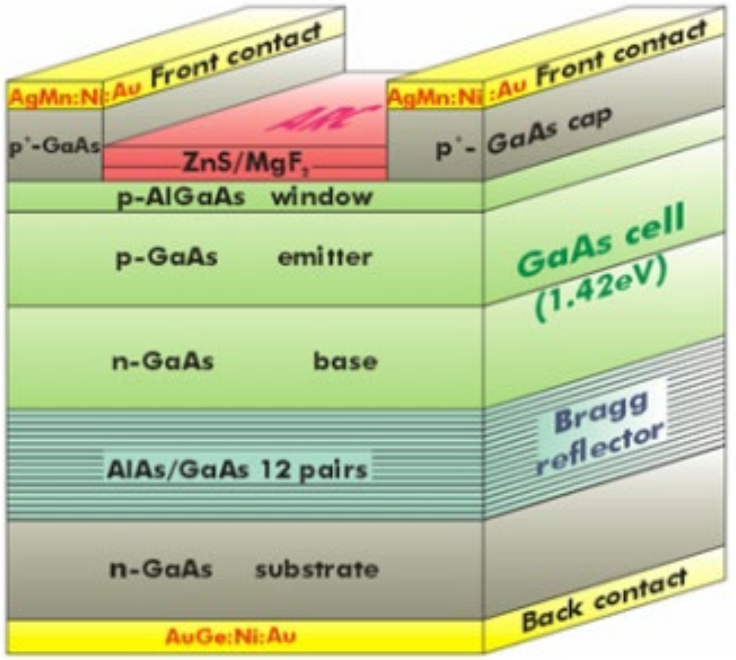


Image from https://www.tf.uni-kiel.de

GaAs single junction cells



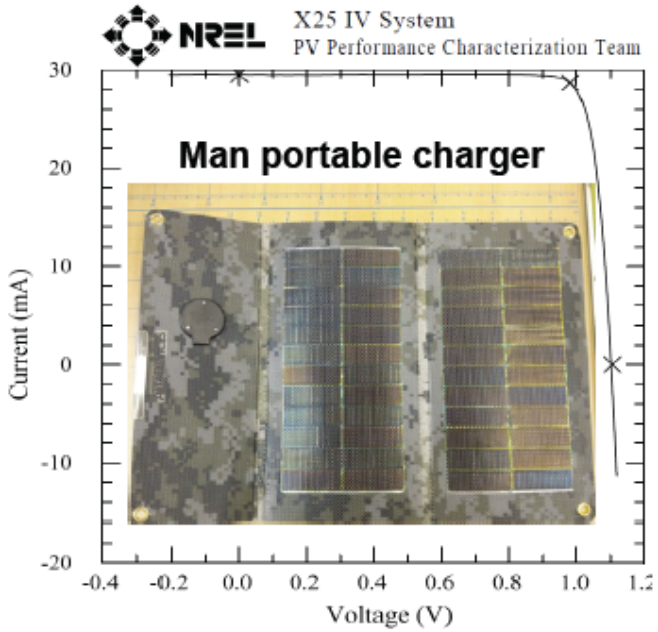


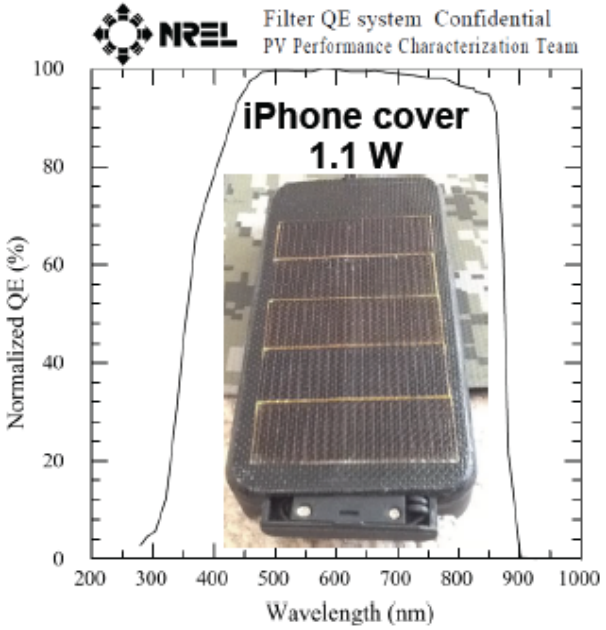
w/ Bragg reflector

Source: http://pvlab.ioffe.ru/about/solar_cells.html

GaAs cells from Alta Devices

Single crystal thin film GaAs solar cells and modules



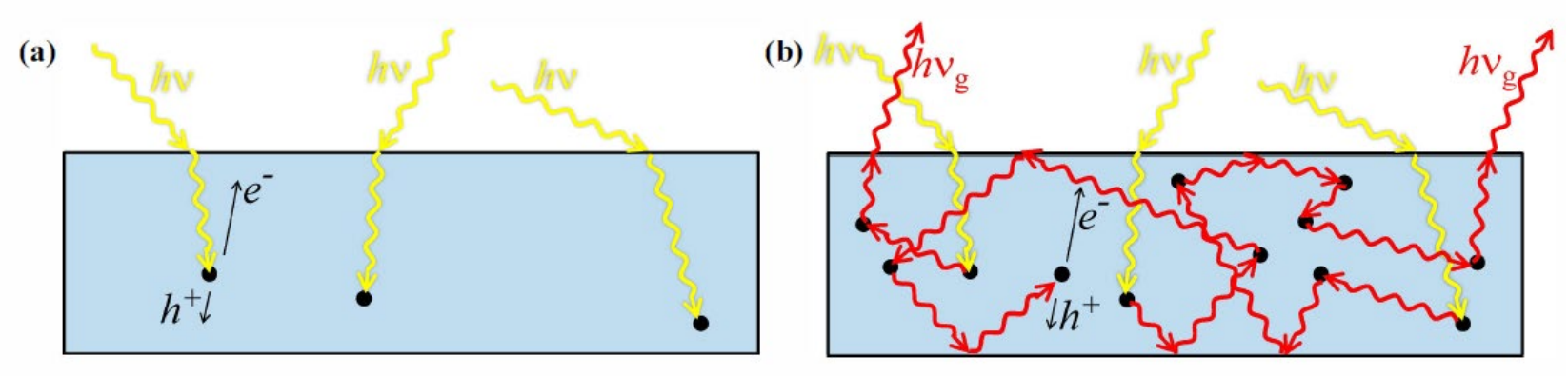


- **Cell efficiency η = 28.8% @ 1 Sun AM 1.5G** — **ERE = 48%**
- **Module efficiency of 23.2%**
- **IQE > 0.96**
- **Economical III-V flat plate ($1/Wp) PV System)**

ALTADEVICES

Source: Prof. H. Atwater, Intersolar 2013

Concept of «photon recycling»

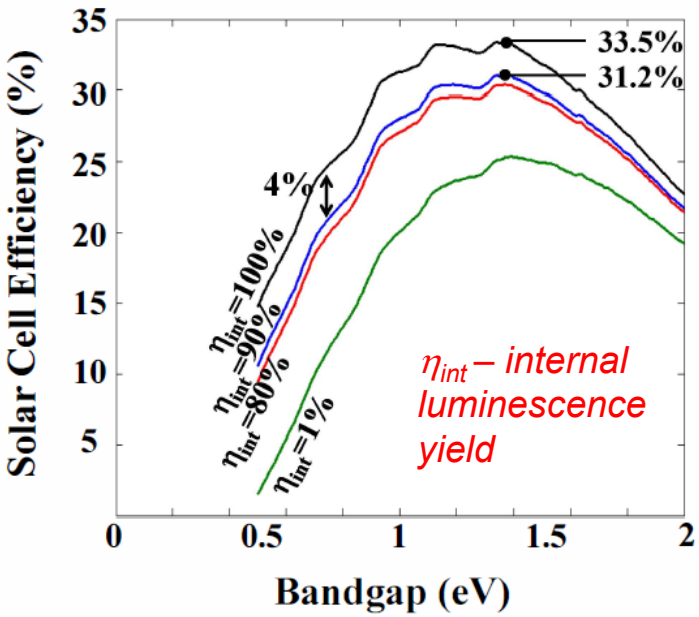


«Low» *vs* «high» luminescence yield

Reasons for high efficiency in GaAs:

- Optimum bandgap 1.45 eV
- Excellent electronic properties
- High luminescence yield (>99%)

⇒ Good PV material if good LED
(and vice versa)



E. Yablonovich et al, IEEE (2016) 001556

Multi-junction III-V cells

Spectral mismatch for single-junction cells

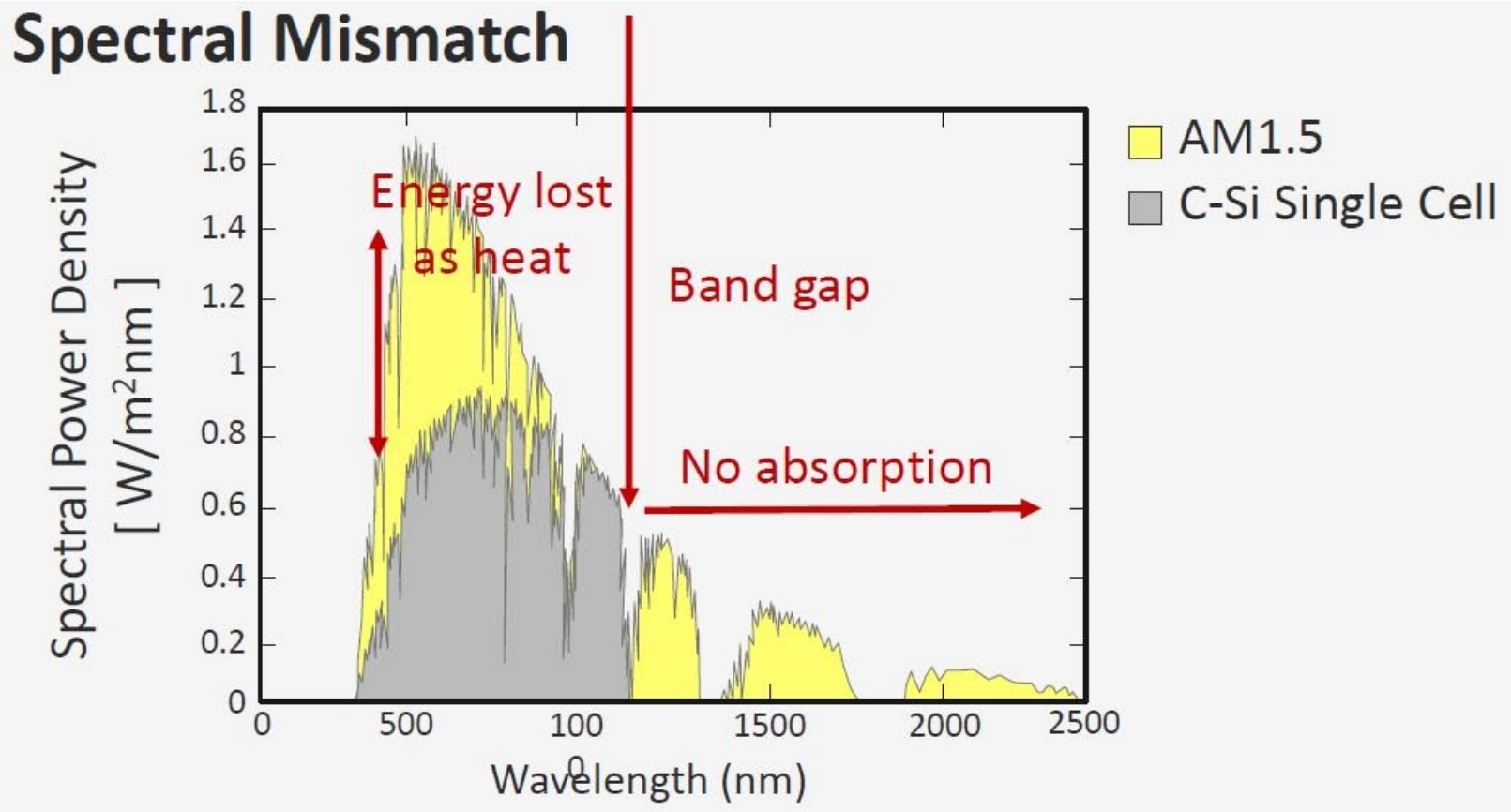
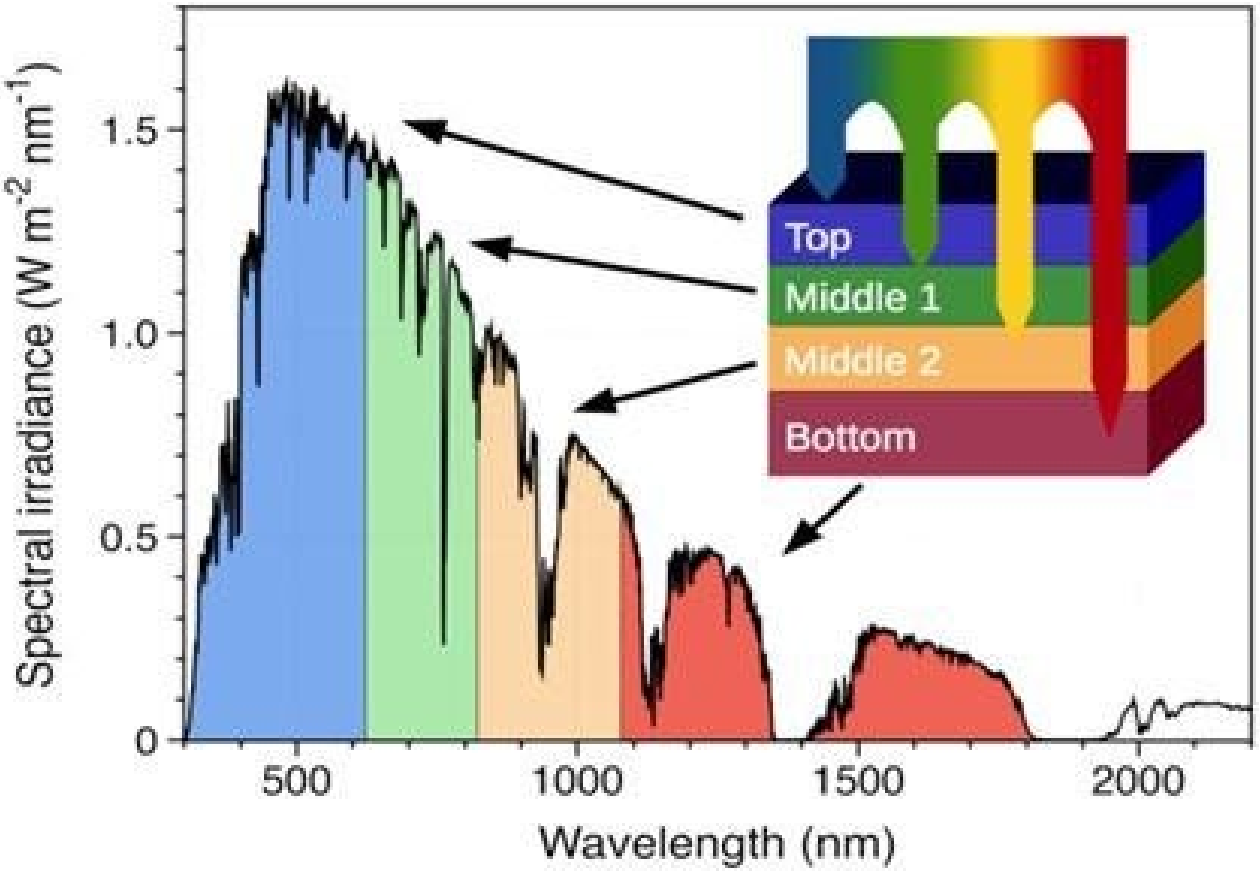


Image from : http://maxloosolarenergy.blogspot.com/2016/12/spectral-utilization-ii-shockley.html

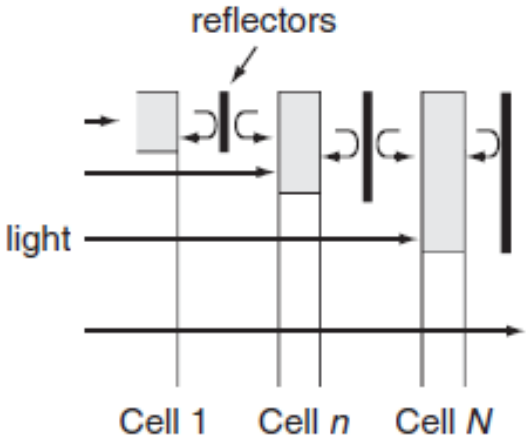
- Incomplete utilization of the solar spectrum in single-junction cells limits the maximum efficiency to 33% (S-Q limit)

Multi-junction solar cells



- Better utilization of the solar spectrum in multi-junction cells

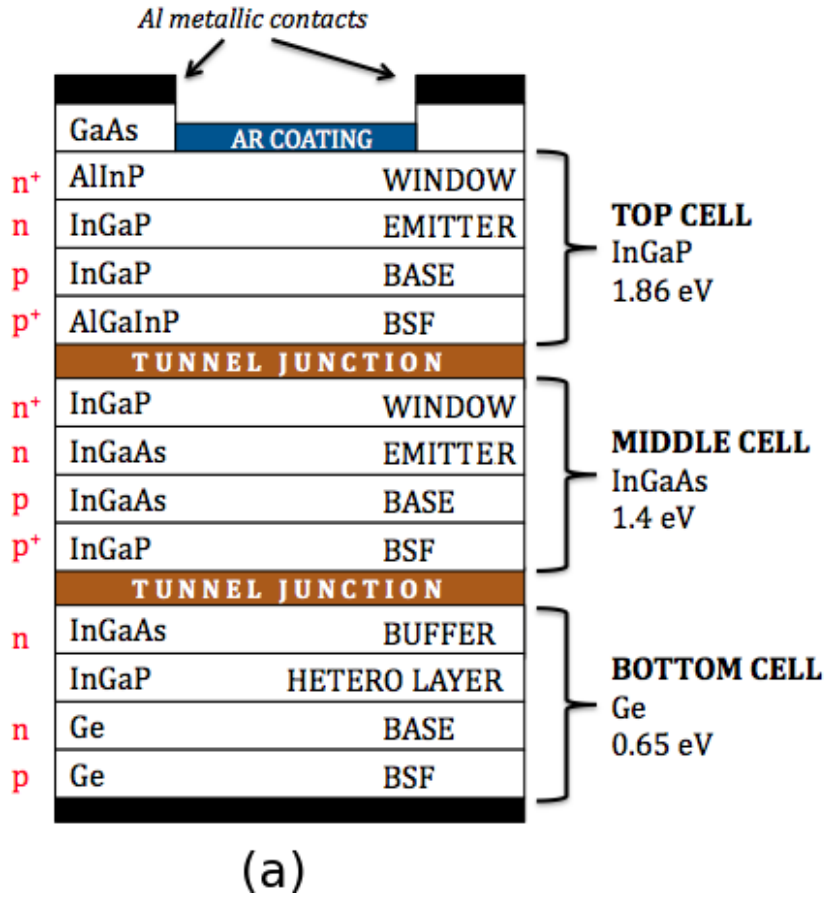
Maximum efficiency for multi-junction cells



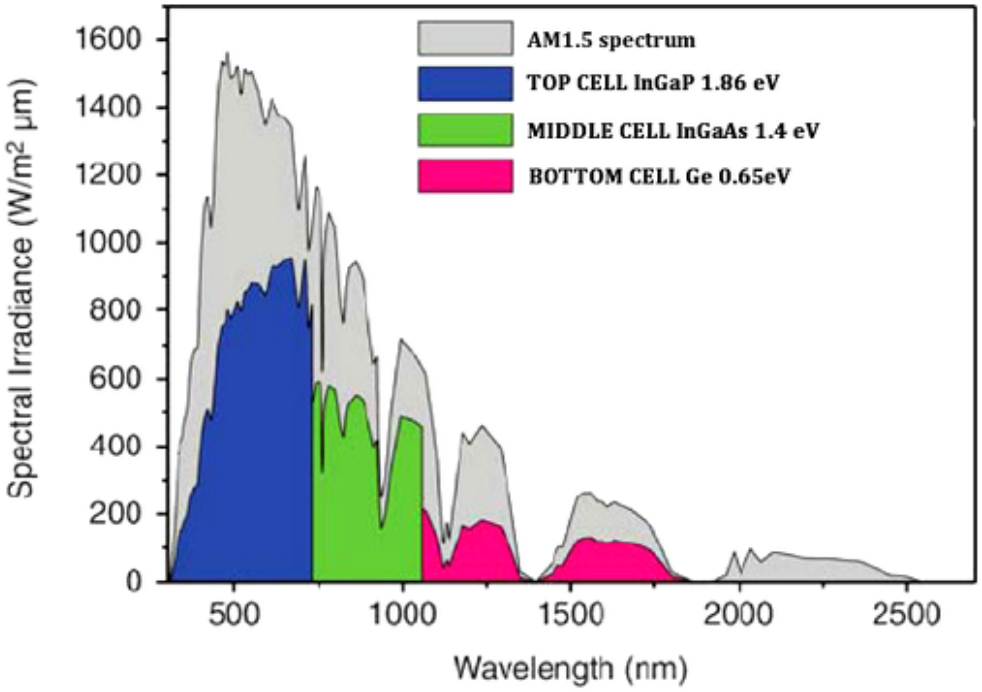
N. cells	Description	Reflectors?	Optimum gaps (eV)				Eff (%)
			*E*1	*E*2	*E*3	*E*4	
(AM1.5 direct normal irradiance)							
	1 sun, no angular restriction	Yes	1.13	–	–	–	32.5
1	1 sun no angular restiction	No	1.13	–	–	–	32.5
	Maximum concentration	Yes	0.94	–	–	–	44.6
	Maximum concentration	No	0.94	–	–	–	44.6
	1 sun, no angular restriction	Yes	0.94	1.64	–	–	44.3
2	1 sun no angular restiction	No	0.94	1.64	–	–	44.1
	Maximum concentration	Yes	0.71	1.41	–	–	59.7
	Maximum concentration	No	0.71	1.41	–	–	59.4
	1 sun, no angular restriction	Yes	0.71	1.16	1.83	–	50.1
3	1 sun no angular restiction	No	0.71	1.16	1.83	–	49.7
	Maximum concentration	Yes	0.69	1.16	1.84	–	67.0
	Maximum concentration	No	0.69	1.16	1.83	–	66.6
	1 sun, no angular restriction	Yes	0.71	1.13	1.55	2.13	54.0
4	1 sun no angular restiction	No	0.71	1.13	1.55	2.13	53.6
	Maximum concentration	Yes	0.53	1.13	1.55	2.13	71.0
	Maximum concentration	No	0.53	1.13	1.55	2.13	70.7
	1 sun, no angular restriction	Yes	–	–	–	–	65.4
∞	1 sun no angular restiction	No	–	–	–	–	65.4
	Maximum concentration	Yes	–	–	–	–	85.0
	Maximum concentration	No	–	–	–	–	85.0

Marti & Araujo, SOLMAT 1996

Triple-junction cells based on III-V



(a)

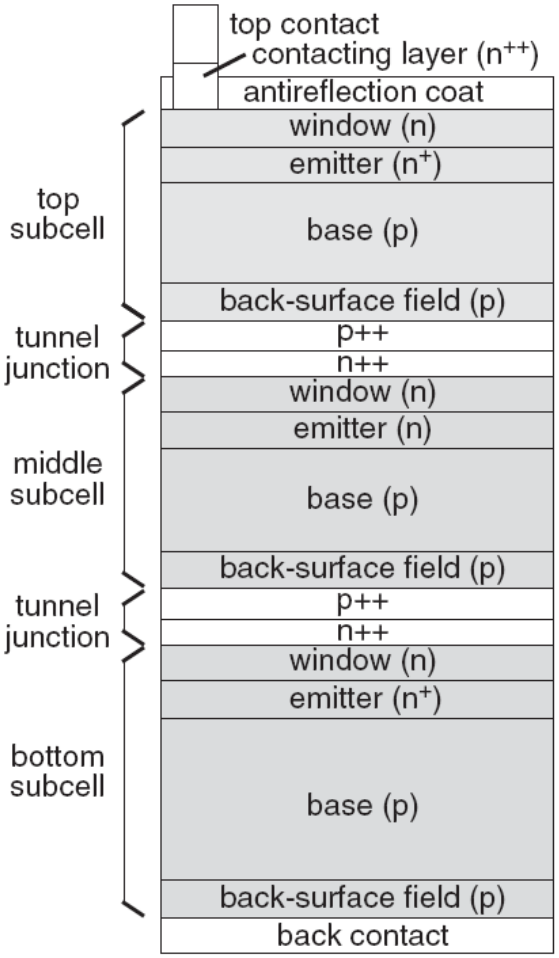


(b)

Image: www.Wikipedia.com

Structure of a triple-junction III-V cell

Monolithic interconnection with tunnel junctions



materials parameters (typical/illustrative):

material	bandgap (eV)	thickness (μm)
Ag		3
Ga(In)As	1.39	0.5
TiO_2/Al_2O_3		0.2
AlInP	2.3	0.03
GaInP	1.85	0.1
GaInP	1.85	0.5 to 1.5
AlGaInP	1.88	0.1
AlGaAs	1.9	0.1
GaInP	1.9	0.1
GaInP	1.85	0.1
Ga(In)As	1.39	0.1
Ga(In)As	1.39	3
GaInP	1.85	0.1
AlGaAs	1.9	0.1
GaInP	1.9	0.1
GaInP	1.85	0.1
Ge (P-diffused)	0.67	0.05
Ge (substrate)	0.67	200
none		
Ag		

Handbook for Photovoltaic Science and Engineering, 2011

Tunnel junction

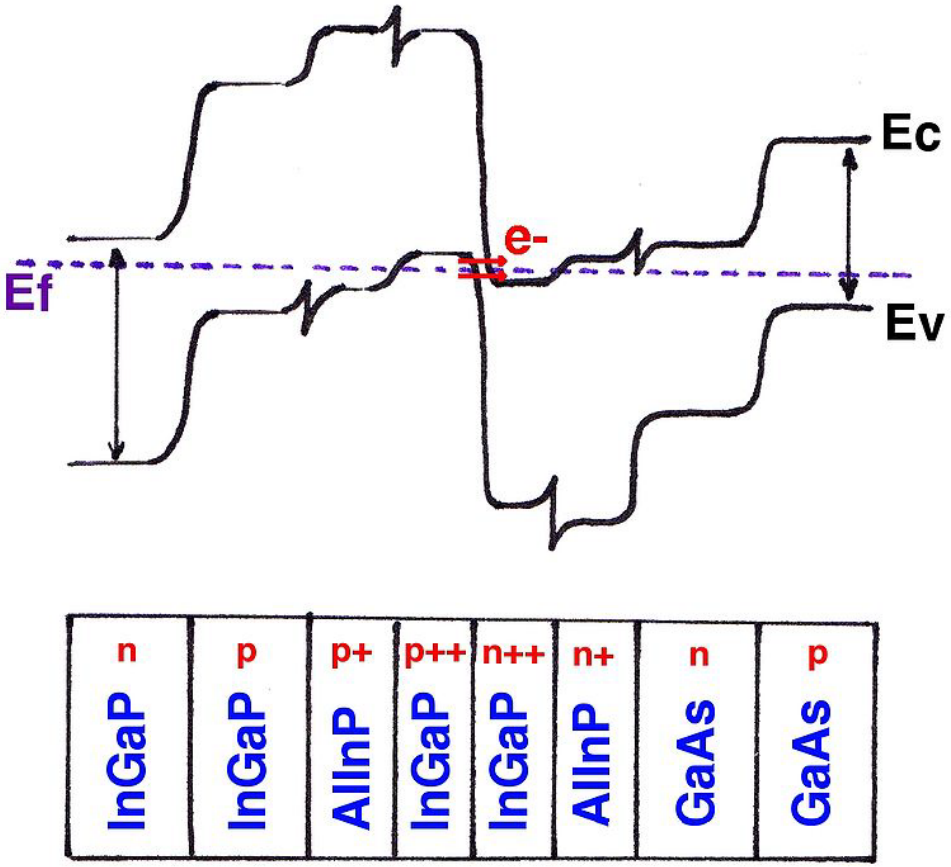
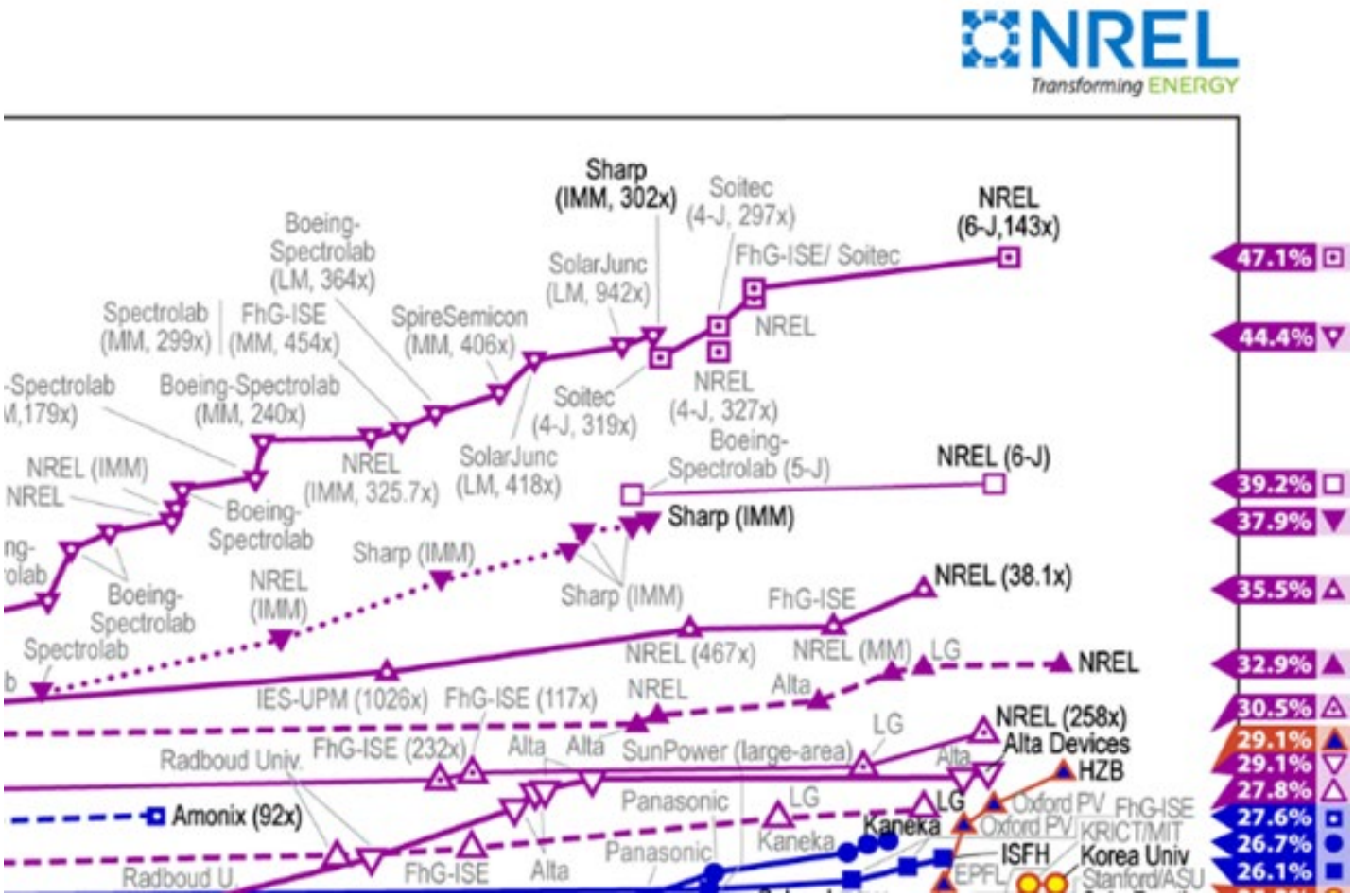


Image: www.Wikipedia.com

- Tunnel junctions provide a low electrical resistance between two subcells
- Must be optically transparent

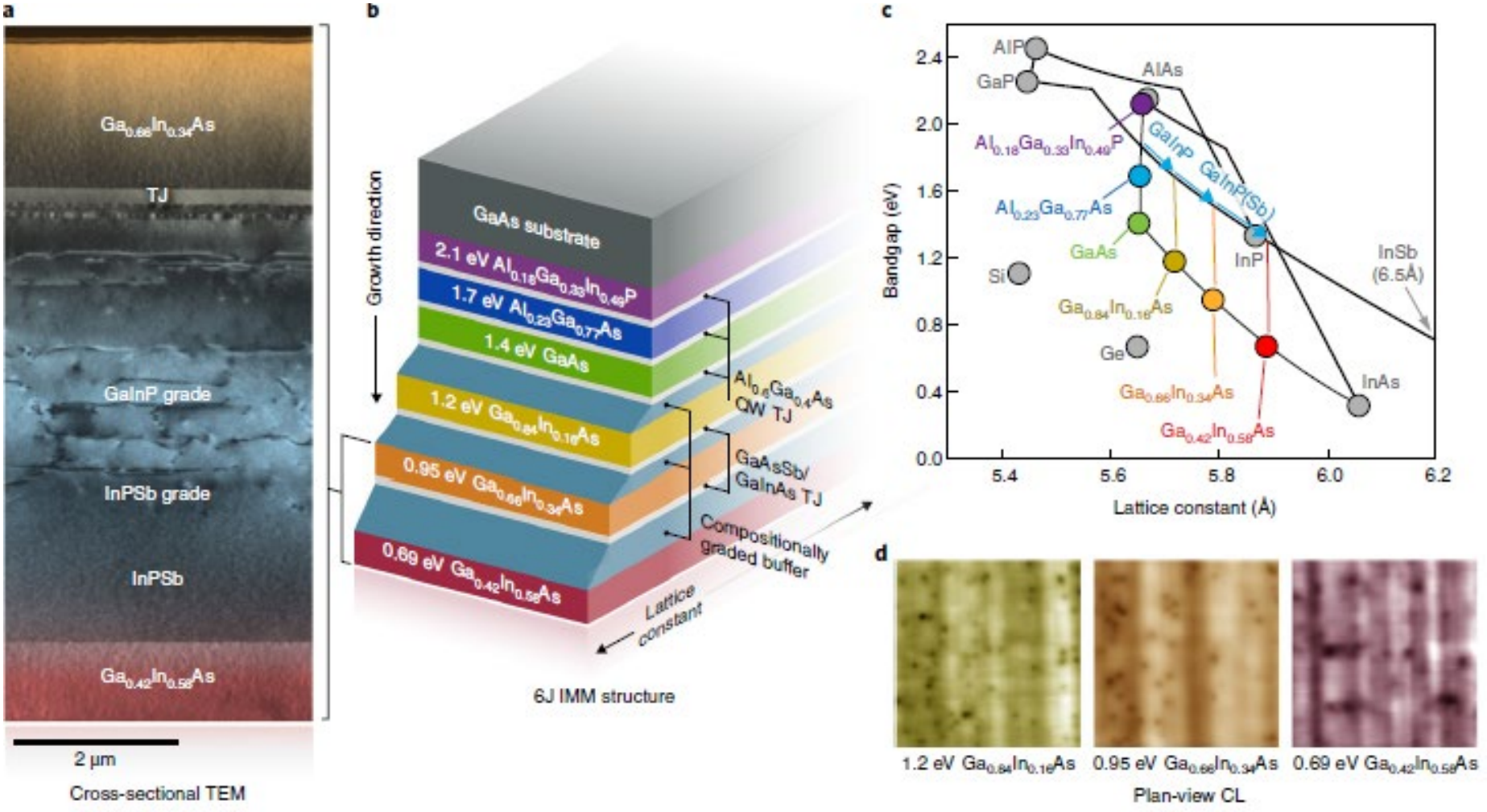
Efficiency of III-V multi-junction cells



- GaAs-based solar cells are the most efficient
- Highest efficiencies up to 47% are measured under concentrated light

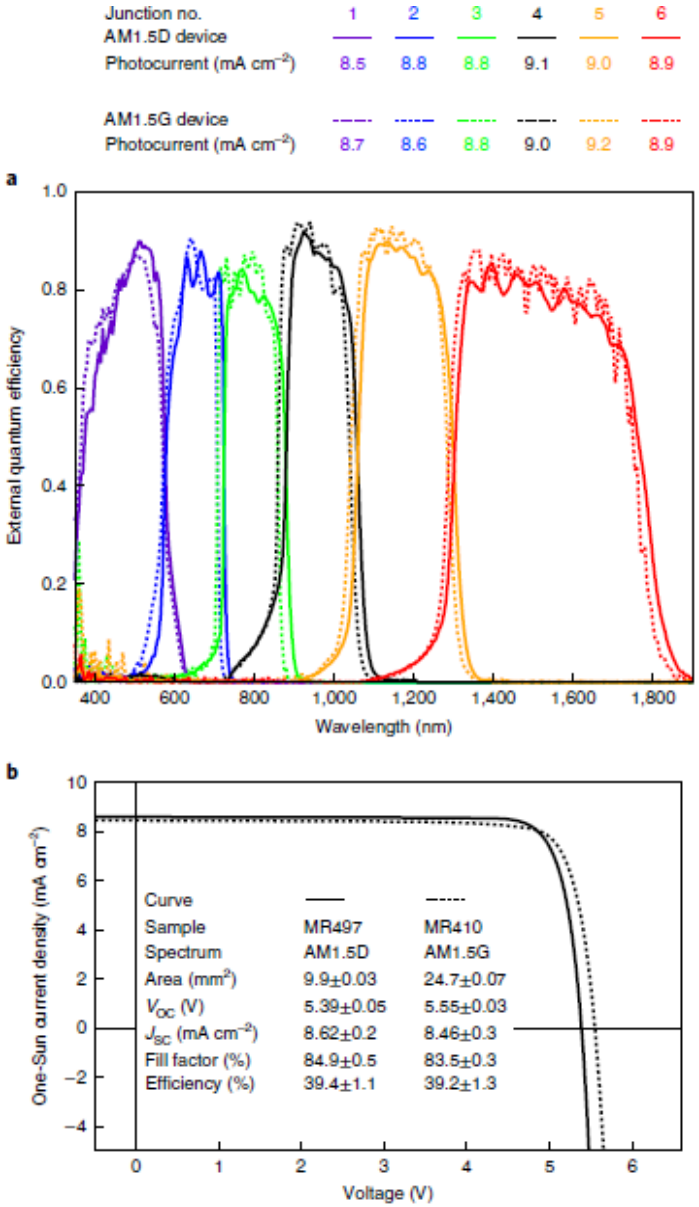
Source: NREL, June 2022

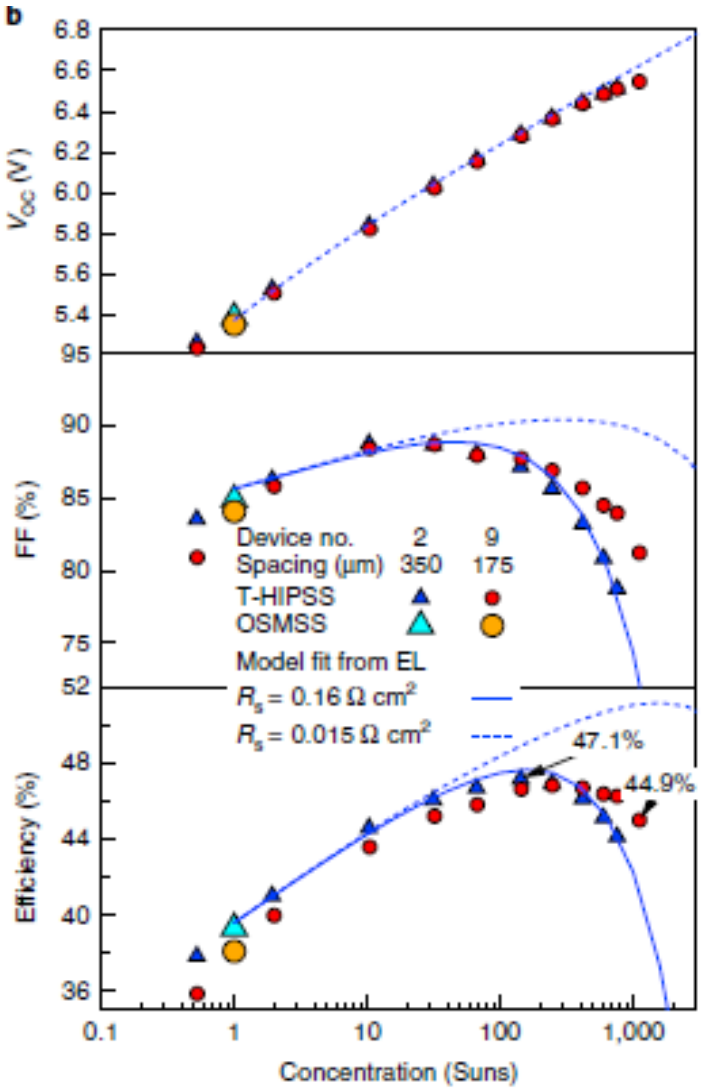
World record solar cell x6 junction cell



NREL group, *Nature Energy* 5 (2020) 326

World record 47.1% efficiency under 143 Suns concentration



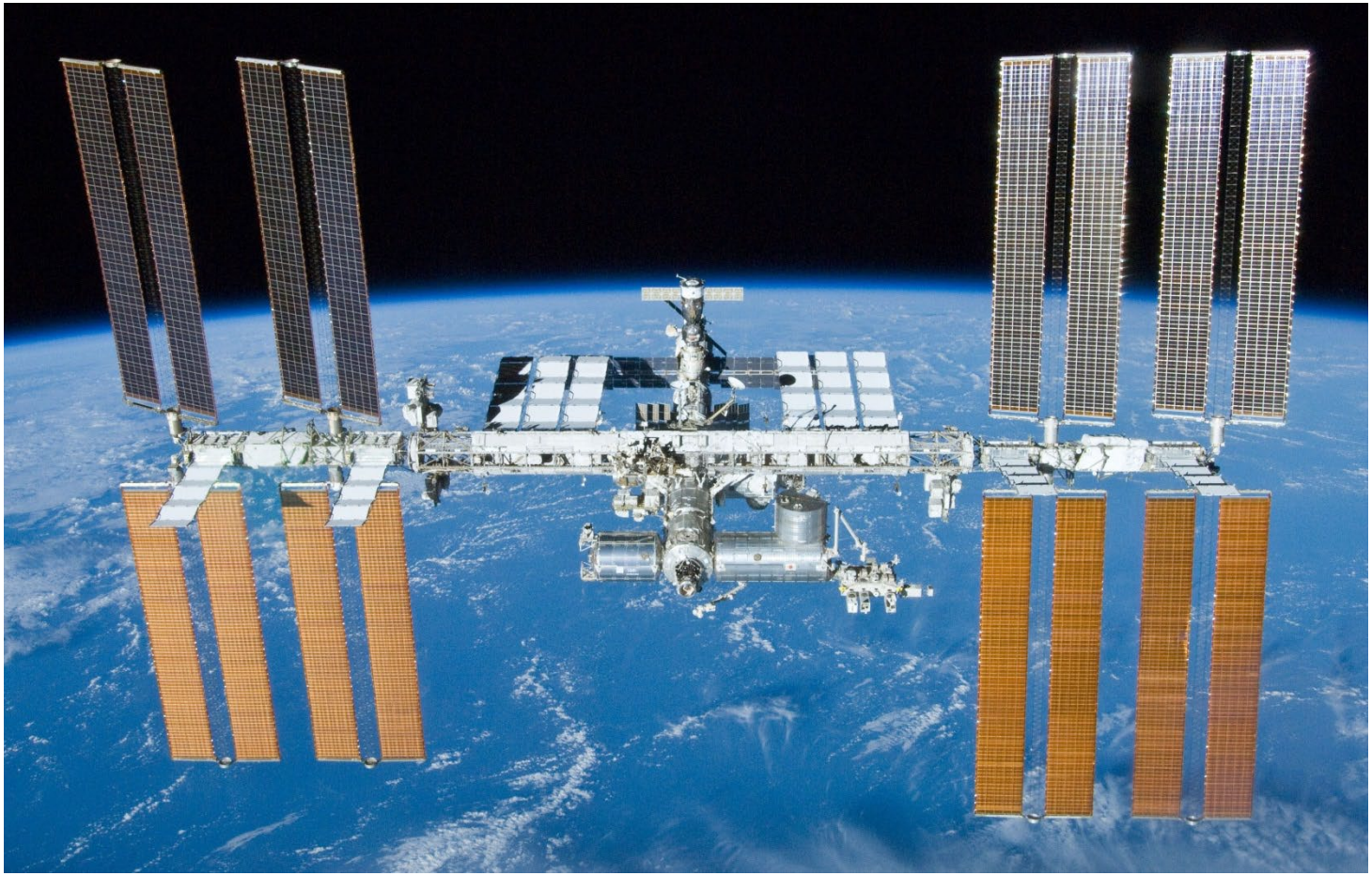


NREL group, *Nature Energy* 5 (2020) 326

Solar cells for space

Solar Power Generation in Space

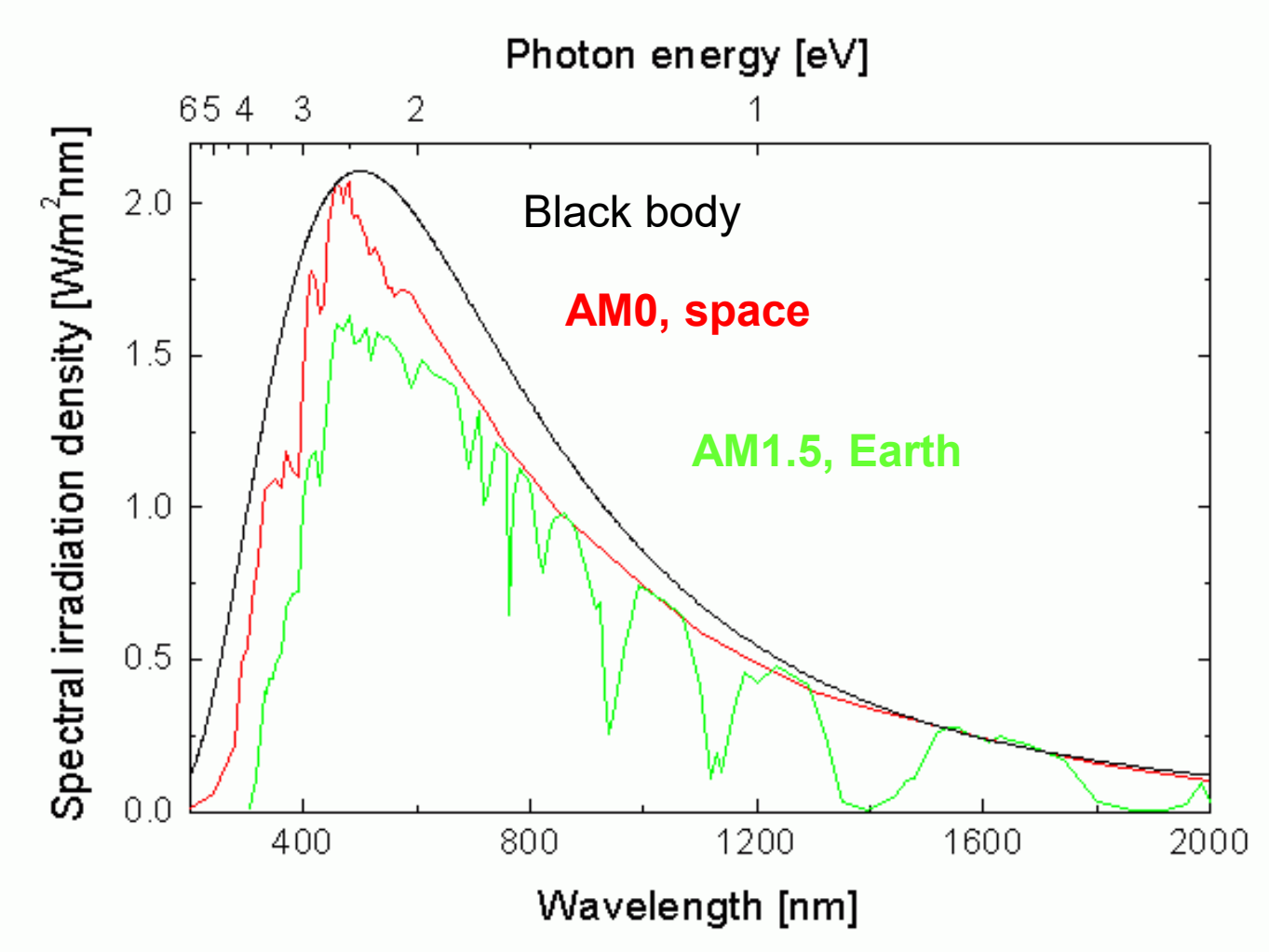
Vanguard 1
(USA, 1958 - 1964)



International Space Station (ISS), 1998-

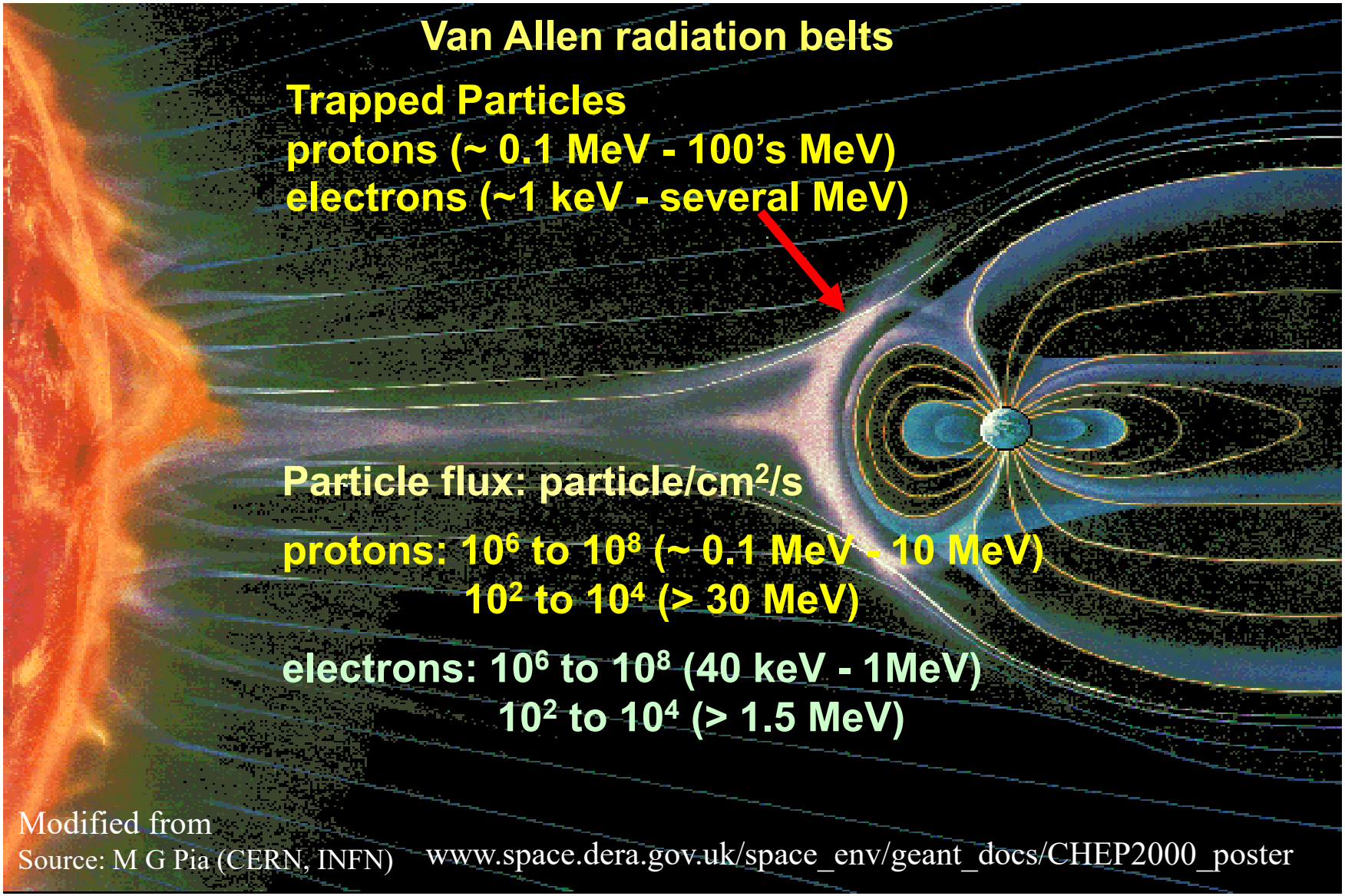
By NASA - http://spaceflight.nasa.gov/gallery/images/shuttle/sts-106/html/s106e5116.html

Solar radiation in space



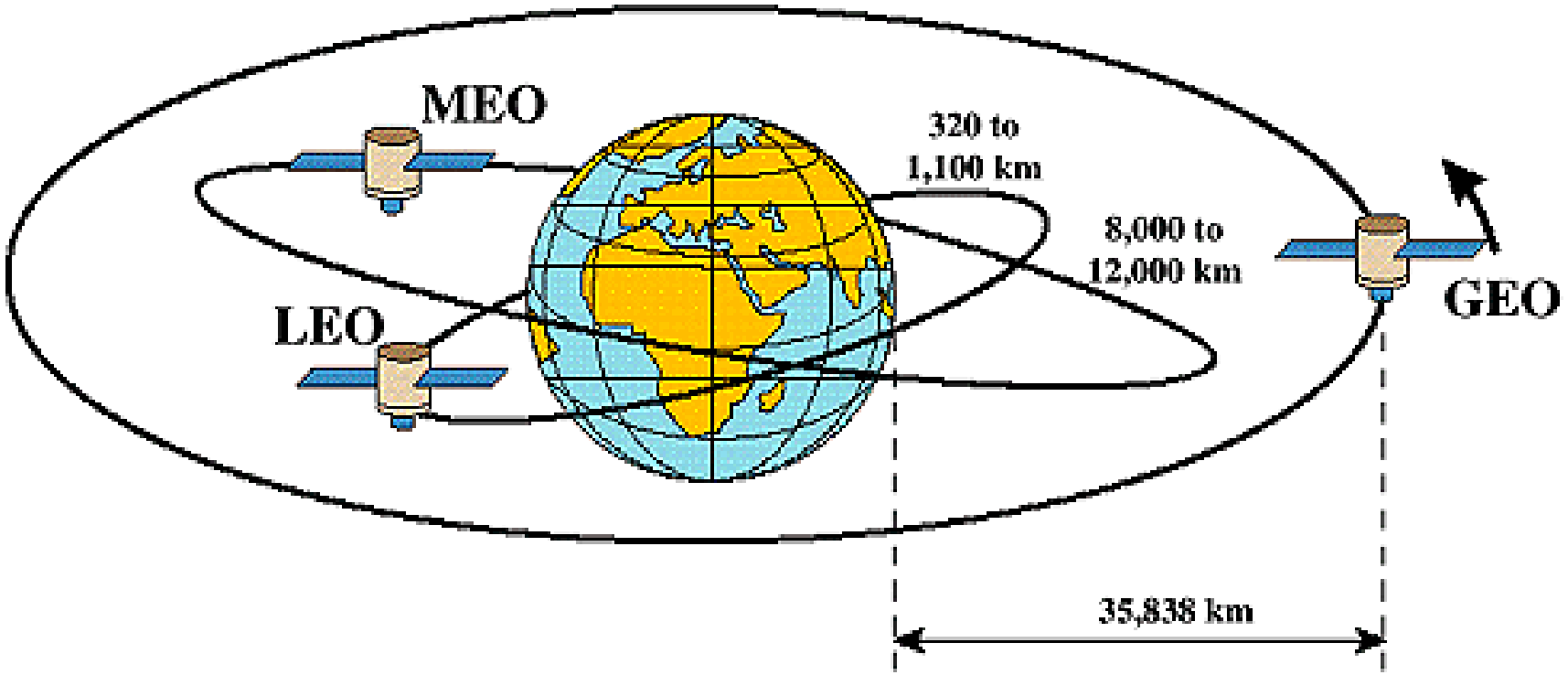
AM0 solar spectrum in space (outside Earth‘s atmosphere): 1353 W/m^2

Particle fluxes near the Earth



Modified from
Source: M G Pia (CERN, INFN) www.space.dera.gov.uk/space_env/geant_docs/CHEP2000_poster

Satelite orbits



http://www.informit.com

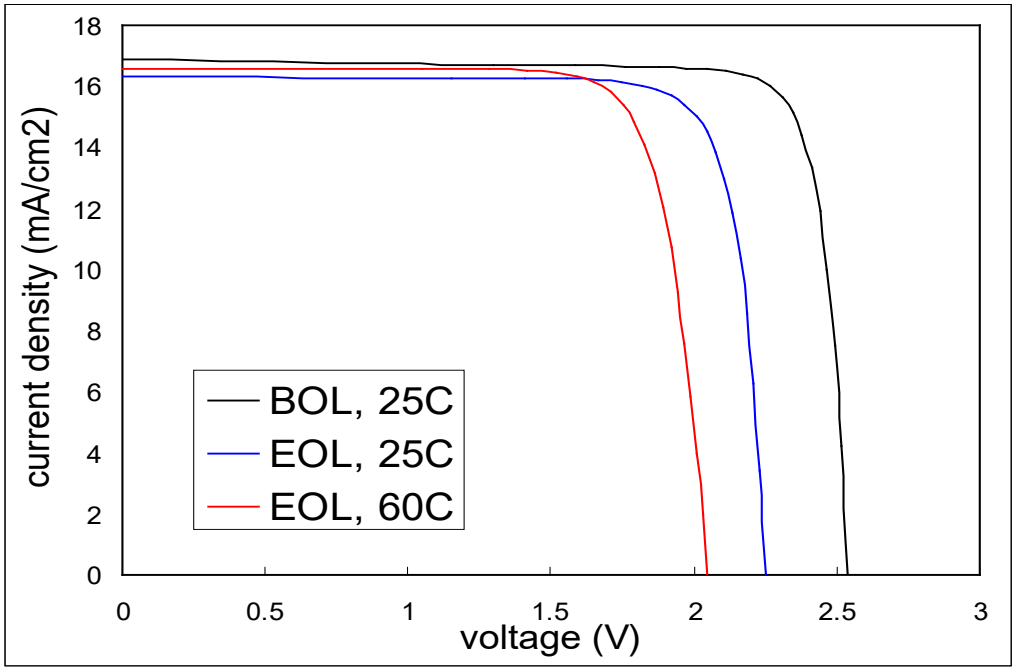
- PV power requirement for a telecom satellite~ 10kW
- Weight 20…200 kg (array specific power 45W/kg)
- can add $1….10 Mio$ to the launch cost for GEO

*-http://www.daystartech.com/applications/space.htm

Cell degradation in space

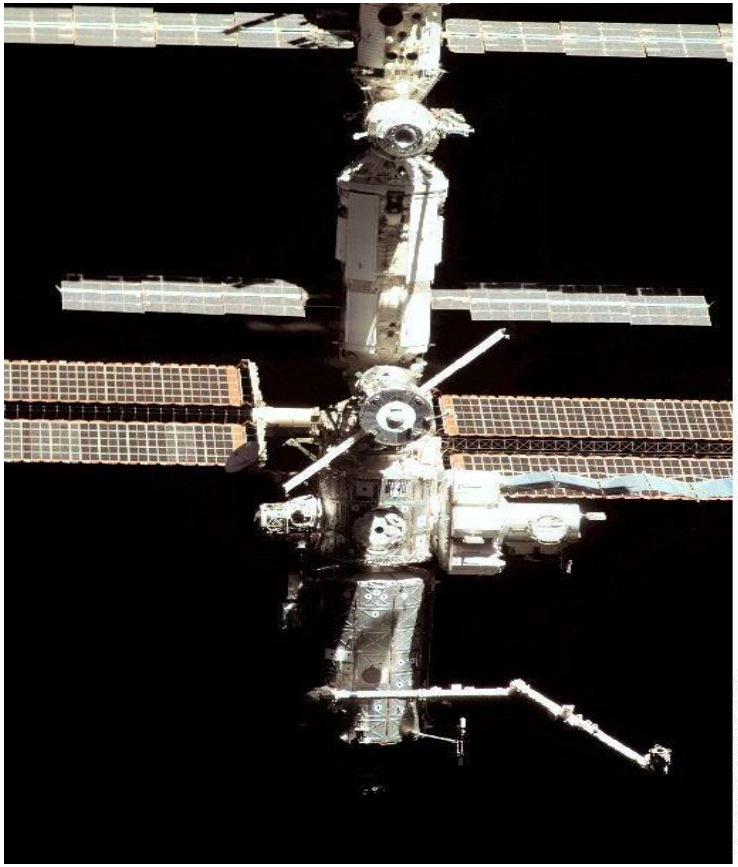
Efficiency degradation in space due to electron and proton irradiation

- Degradation of solar cell performance due to defect generation in the semiconducting layers.
- Elevated temperatures reduce the voltage, FF and increase the current.

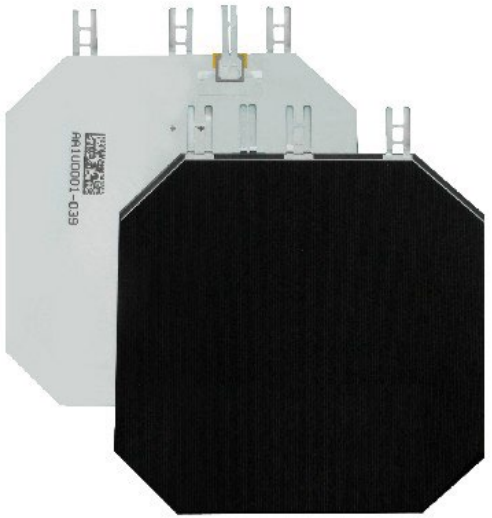


Spectrolab 3J GaAs

III-V multi-junction cells for space



Spectrolab NeXt Triple Junction (XTJ) cells
Efficiency: 29.5%



Radiation Degradation

(Fluence 1MeV Electrons/cm²)

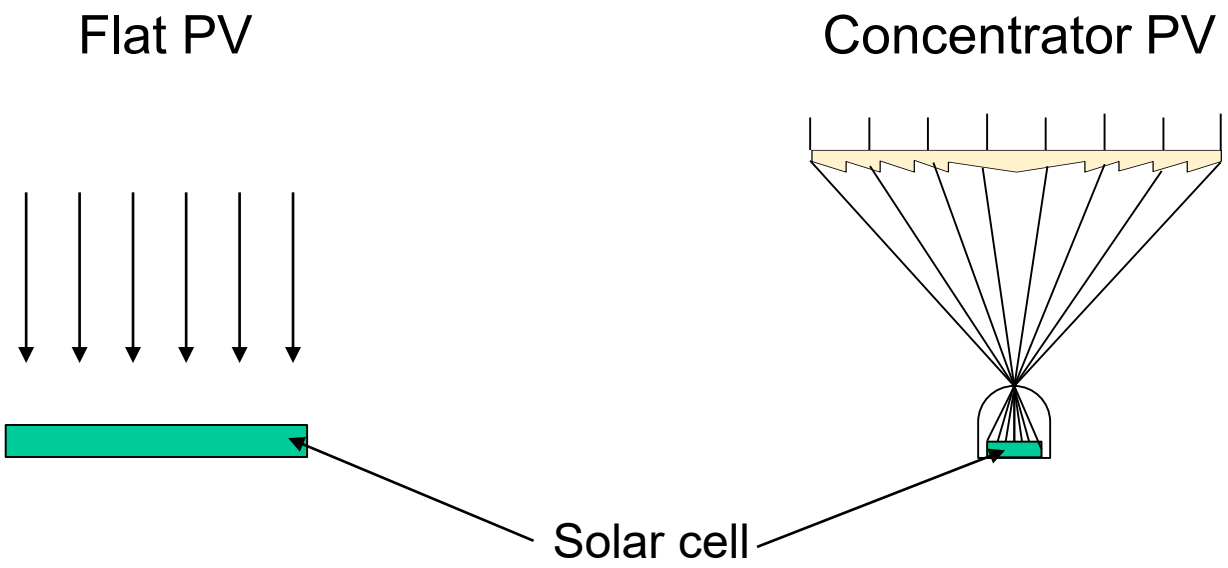
Parameters	$1x10^{14}$	$5x10^{14}$	$1x10^{15}$
Imp/Imp_0	1.00	0.99	0.95
Vmp/Vmp_0	0.94	0.91	0.89
Pmp/Pmp_0	0.95	0.90	0.85

Concentrator PV (CPV)

(not to be confused with concentrator solar power CSP)

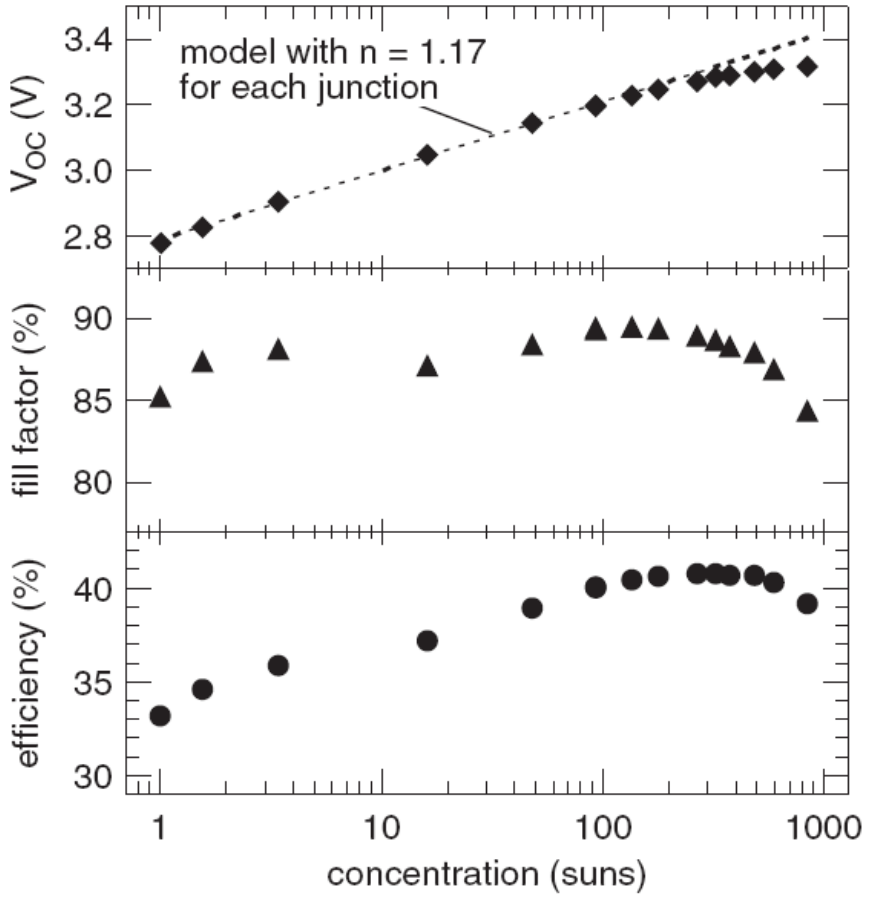
Why concentrator photovoltaics?

Reduce solar cell area by using optical concentration: up to ~1000 suns



Replace solar cell material (expensive) by optics (cheaper?)

Solar parameters under concentrated light



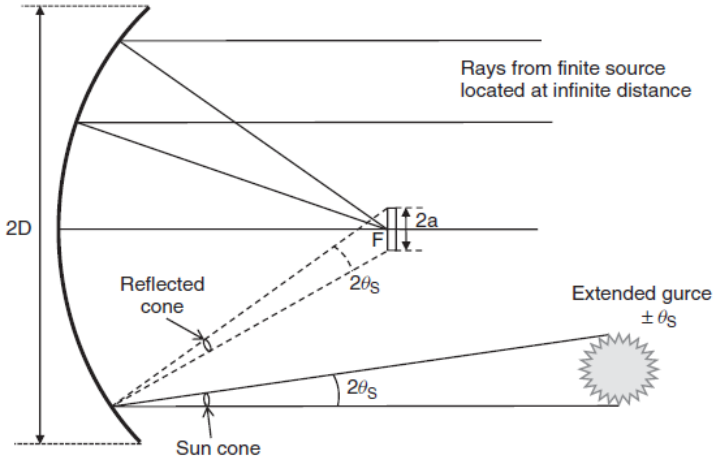
$$V_{oc} \approx \frac{kT}{q} \ln\left(\frac{I_L}{I_0}\right)$$

Figure 8.12 Efficiency, V_{OC}, and fill factor of state-of-the-art GaInP/$Ga_{0.96}In_{0.04}As$/$Ga_{0.63}In_{0.37}As$ three-junction cell as a function of concentration. J_{SC}, not shown, is assumed to increase proportionally to concentration

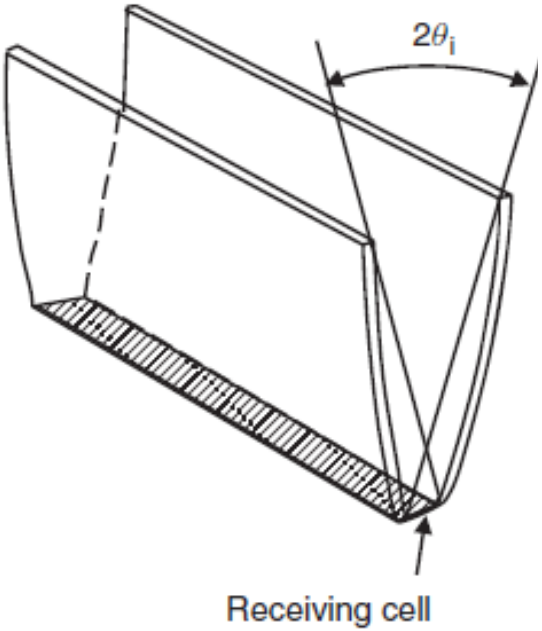
Handbook of photovoltaic science and engineering, 2011

Light concentrators

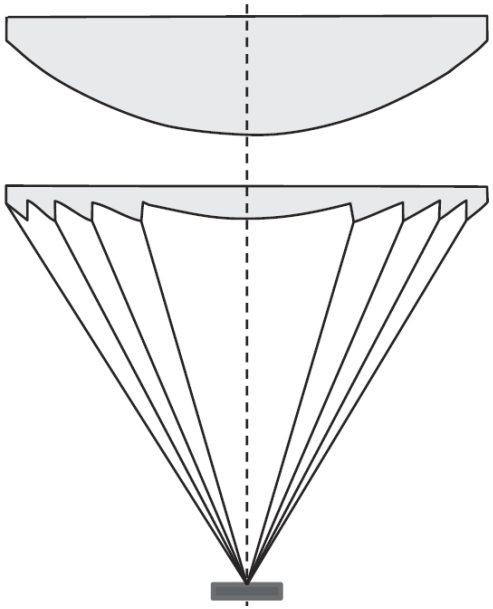
Parabollic
mirror concentrator



Compound
parabolic
concentrator

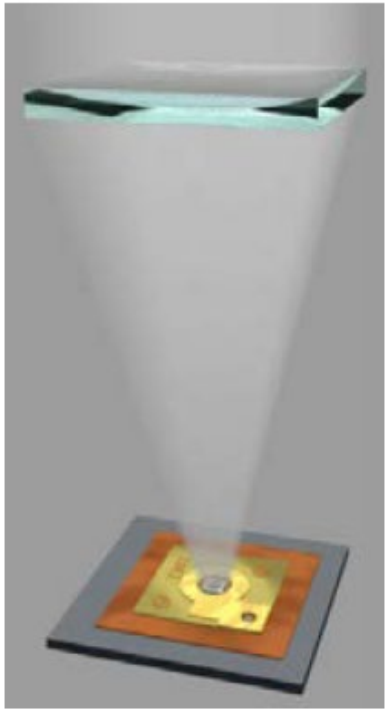


Fresnel lenses



Handbook of photovoltaic science and engineering, 2011

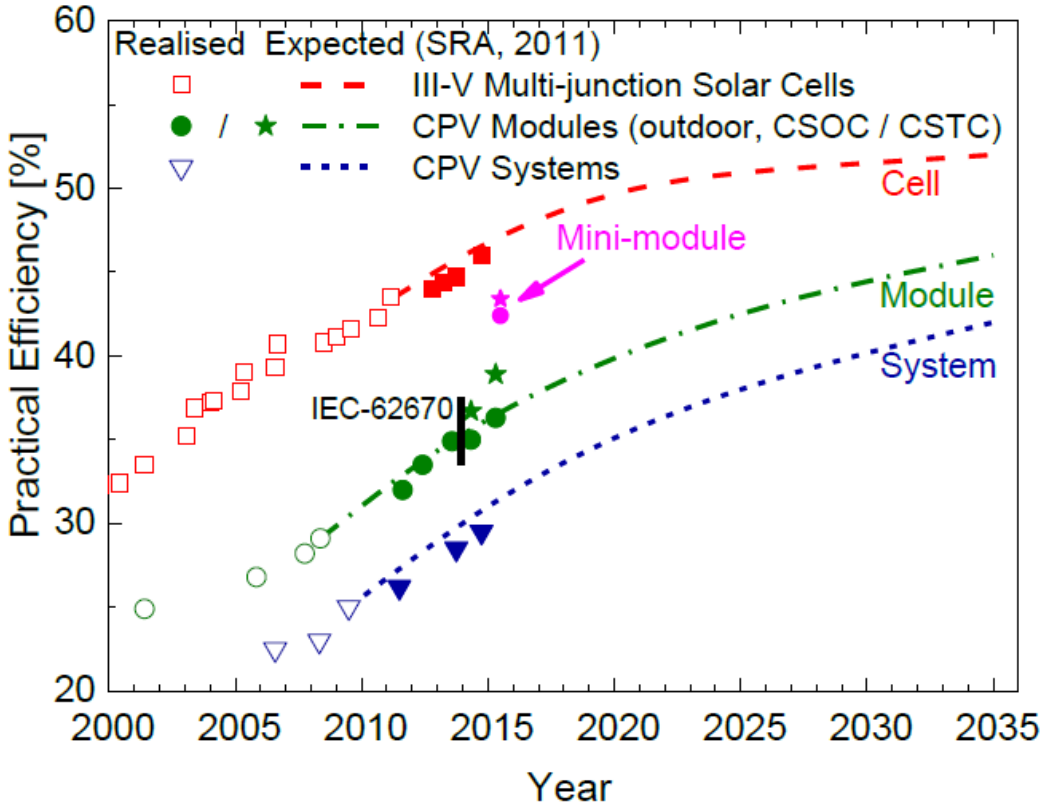
Light concentrating systems



Class of CPV	Typical concentration ratio	Tracking	Type of converter
High Concentration PV (HCPV)	300-1000	Two-axis	III-V multi-junction solar cells
Low Concentration PV (LCPV)	< 100	One or two-axis	c-Si or other cells

"Current status of concentrator photovoltaic (CPV) technology" report, ISE and NREL, 2016

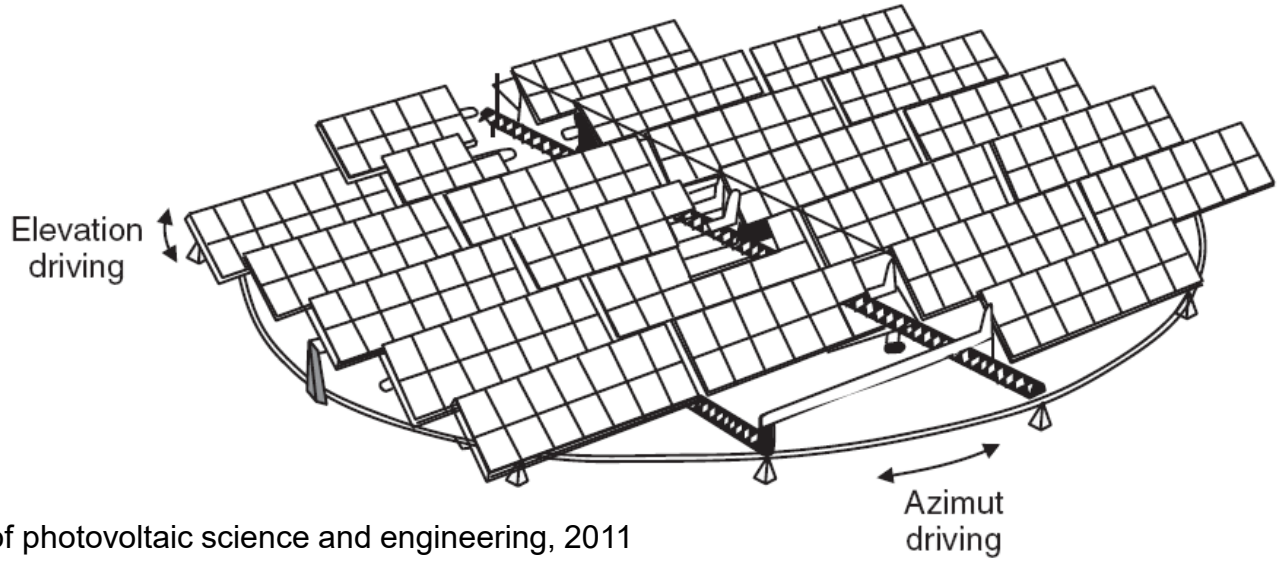
CPV efficiency



- Certified record value for solar cell efficiency of 47.1% (NREL, 2020)
- 38.9% module efficiency of 38.9 % (Soitec)

Report «Current status of CPV technology», ISE-NREL, 2017

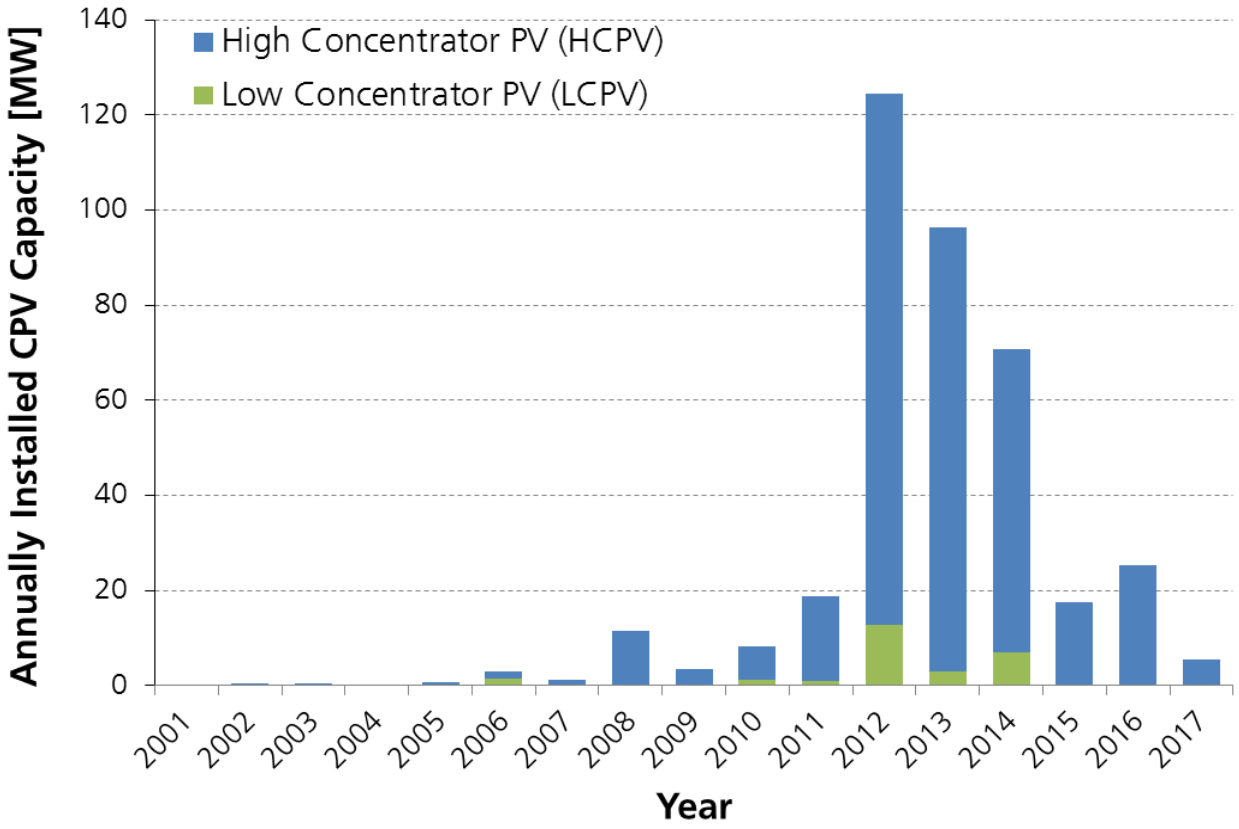
Light-tracking systems



Handbook of photovoltaic science and engineering, 2011

30 MW plant in Alamosa, Colorado, USA (© Amonix)

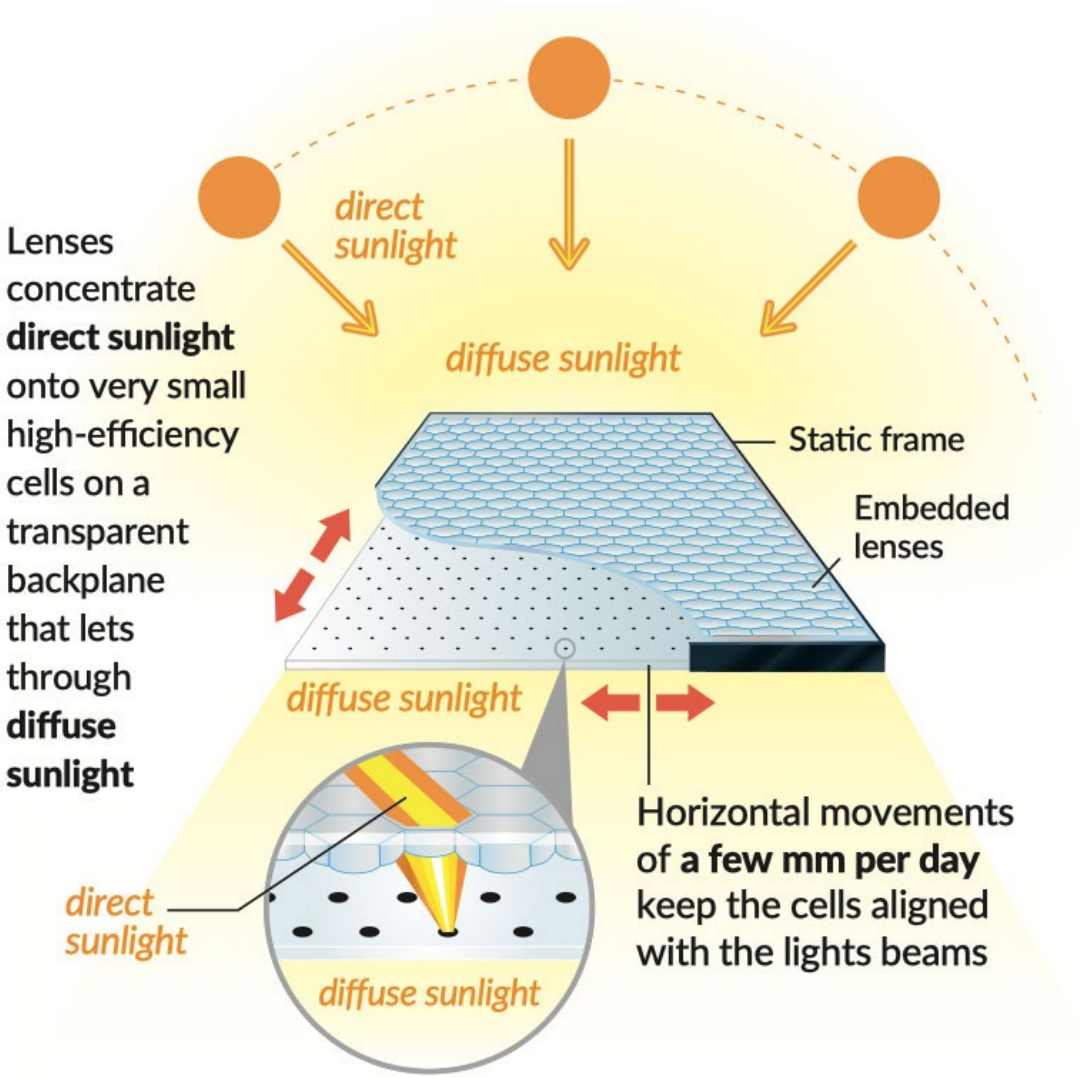
CPV installations

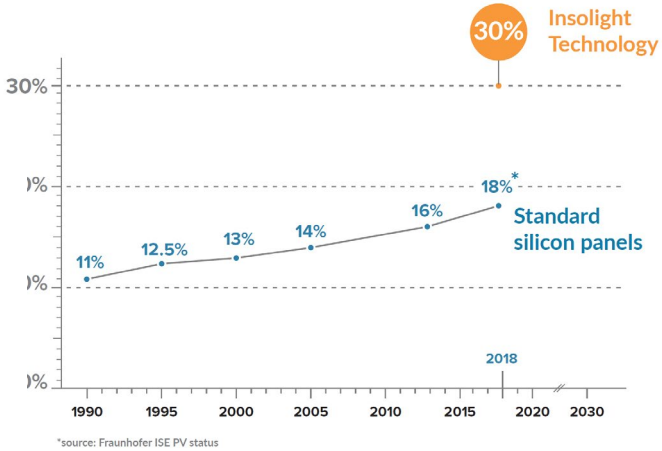


"Current status of concentrator photovoltaic (CPV) technology" report, ISE and NREL, 2018

- Cumulative worlds installations: 360 MW (only 0.1% of total PV)
- Worldwide manufacturing capacities have strongly decreased in 2015 due to the closure of Soitec's and Suncore's manufacturing facilities.

Insolight (Swiss made)





https://insolight.ch/technology/