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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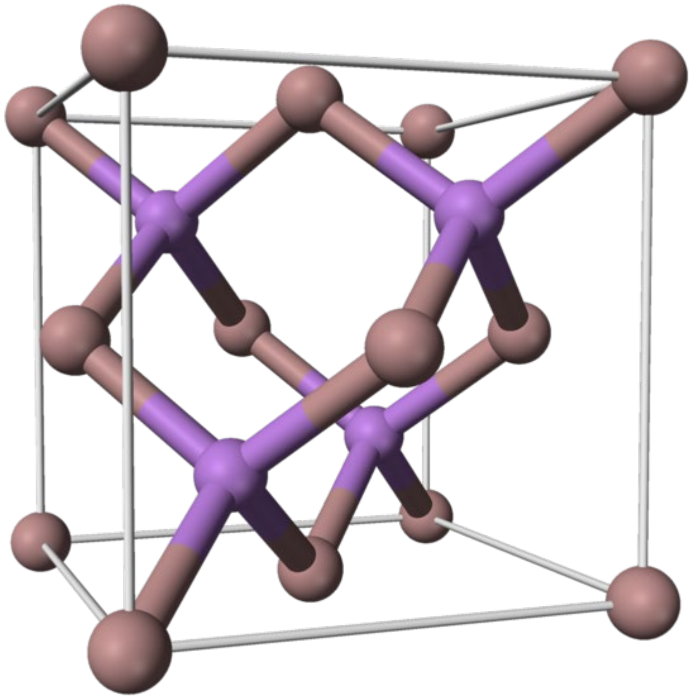
Empa
Materials Science and Technology

III-V semiconductors



Cubic crystal structure of GaAs
www.wikipedia.com

GaAs (E_g = 1.42 eV)

GaP

InP

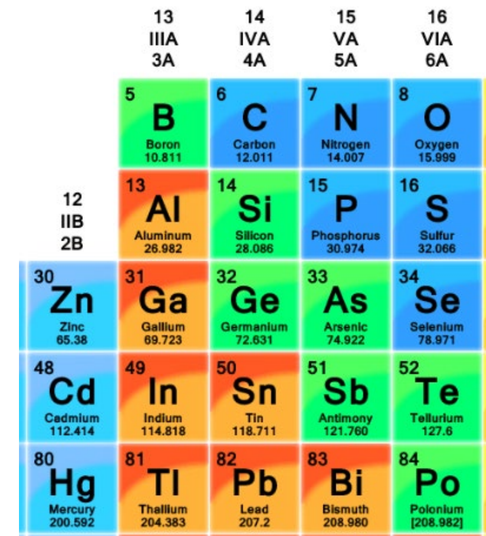
InAs

GaInAs

GaInP

AlGaInAs

AlGaInP



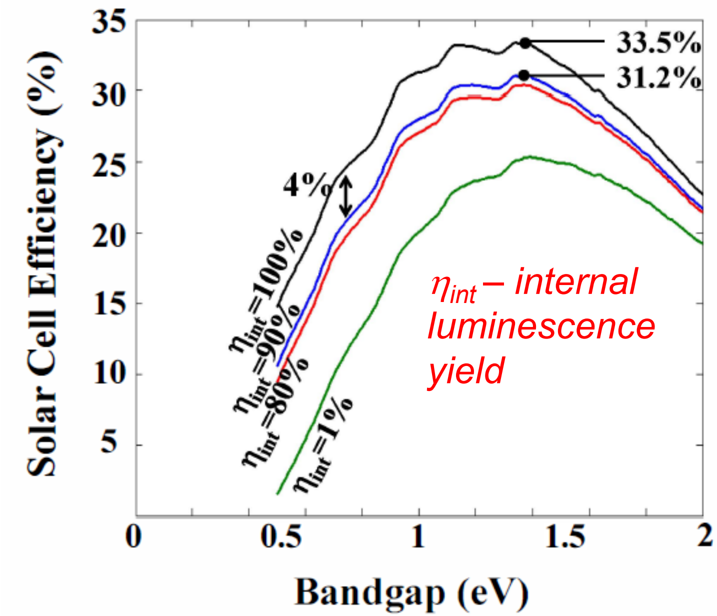
https://sciencenotes.org/use-periodic-table/

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

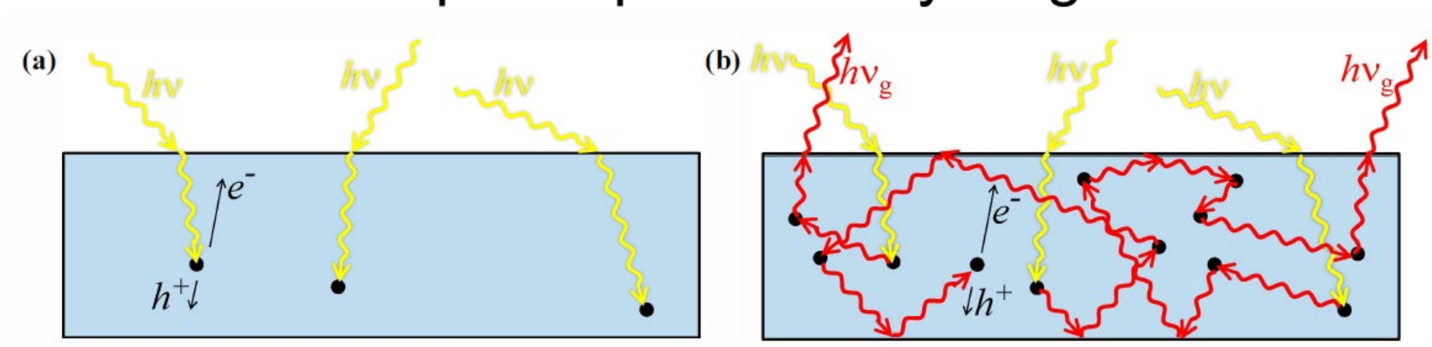
Why GaAs is a good PV material

- High carrier mobility up to 8500 cm^2/Vs
- Suitable bandgap 1.42 eV
- High absorption coeff. > 10^5 cm^{-1}
- High luminescence yield (>99%)

⇒ Good PV material is a good LED!
(and vice versa)



Concept of «photon recycling»



«Low» *vs* «high» luminescence yield

E. Yablonovich et al, IEEE (2016) 001556

III-V semiconductor bandgaps

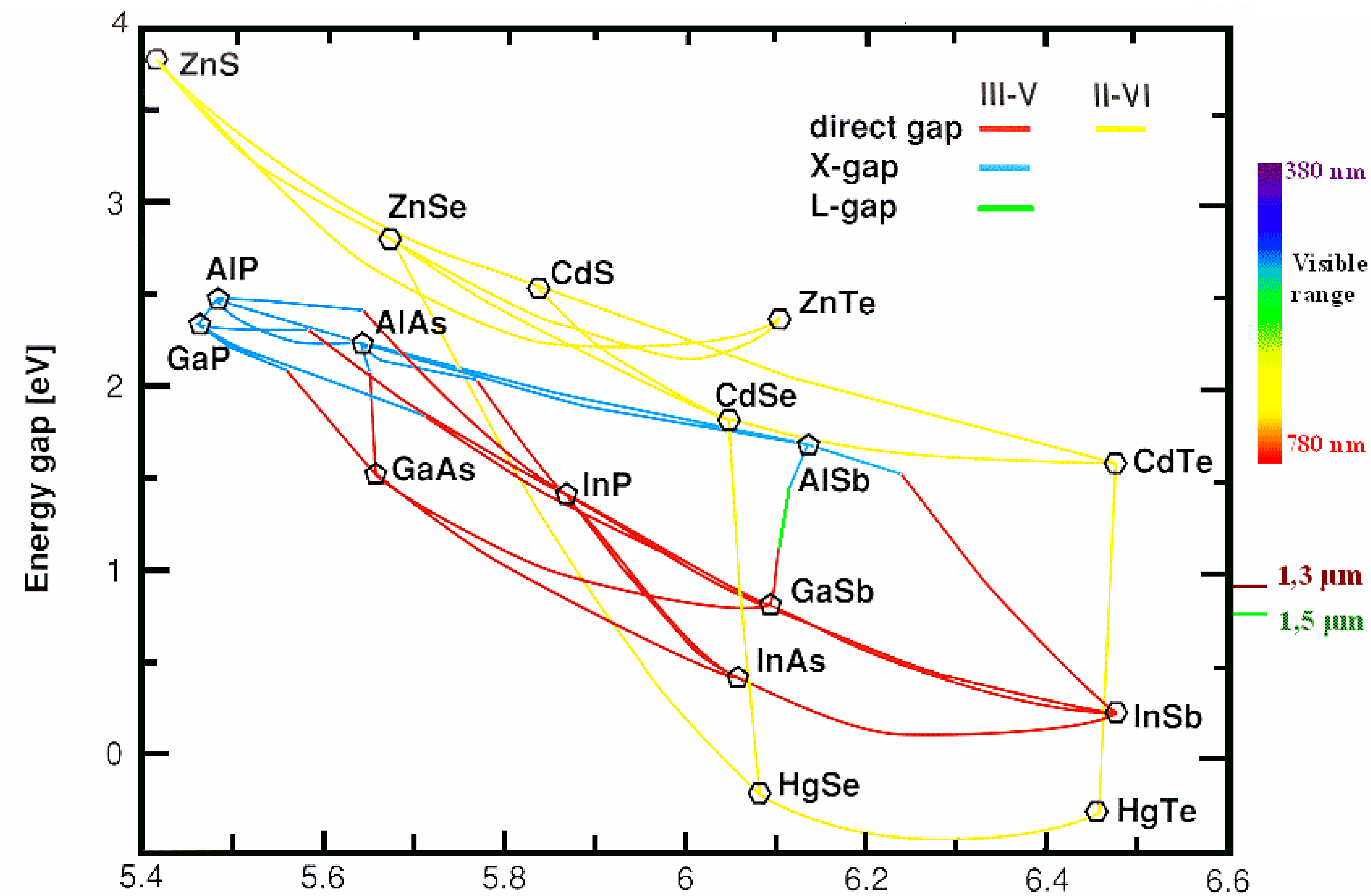
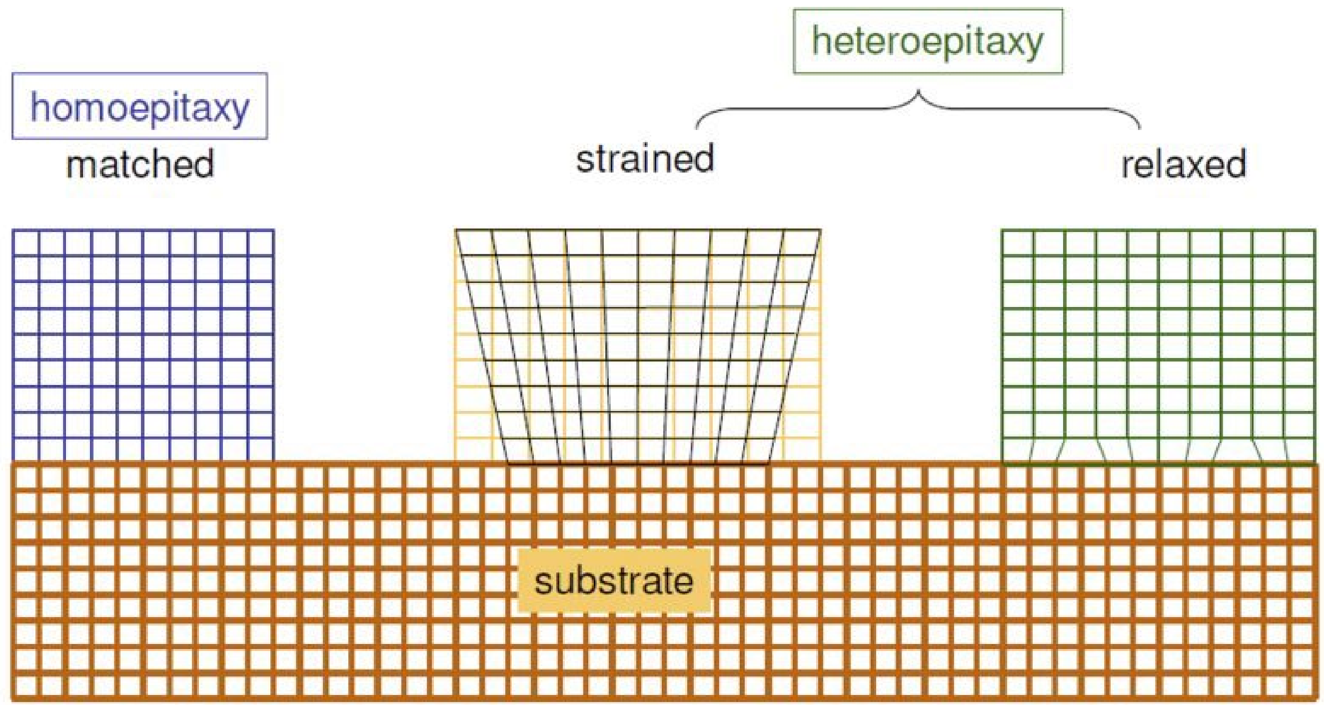


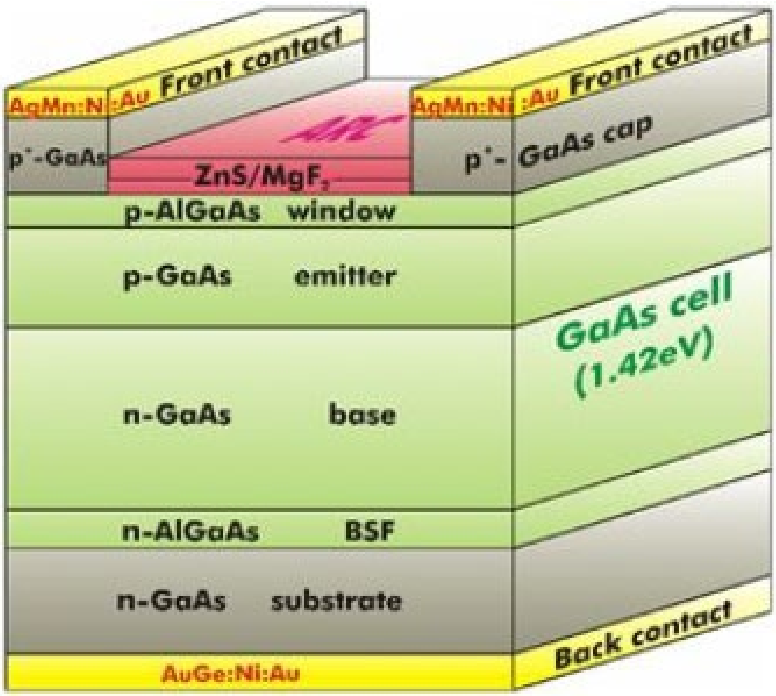
Image from https://www.tf.uni-kiel.de

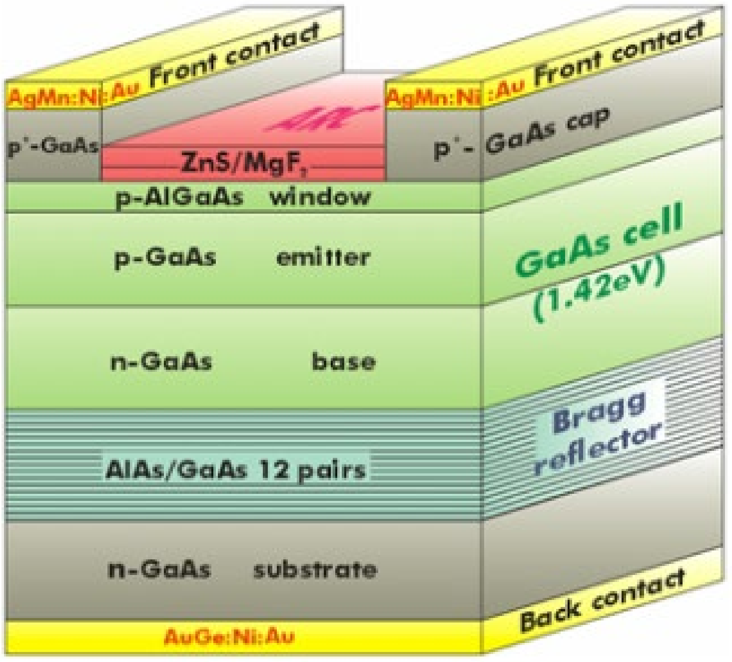
Epitaxial growth



- Deposition (growth) of layer on a single crystal substrate where atoms of the grown layer accommodate/follow the same crystalline order as the substrate
- Epitaxy yields single-crystalline layers with low defect concentration
- Important keywords: lattice mismatch, strained/relaxed, dislocations
- Growth methods: Metalorganic Vapor Phase Epitaxy (MOVPE), Molecular beam epitaxy (MBE), Dynamic Hybrid Vapor Phase Epitaxy (D-HVPE)

GaAs single junction cells



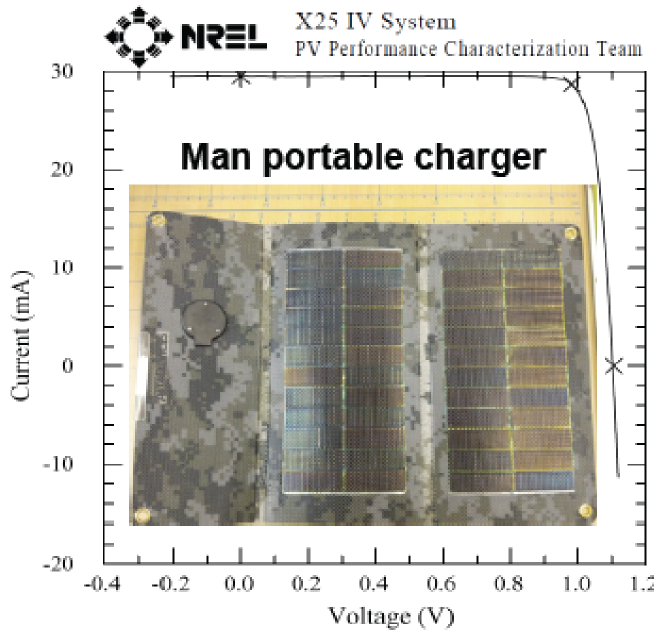


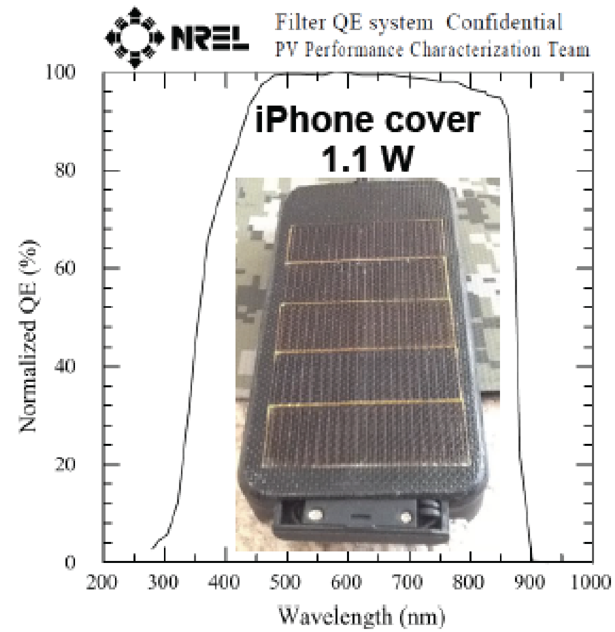
w/ Bragg reflector

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%

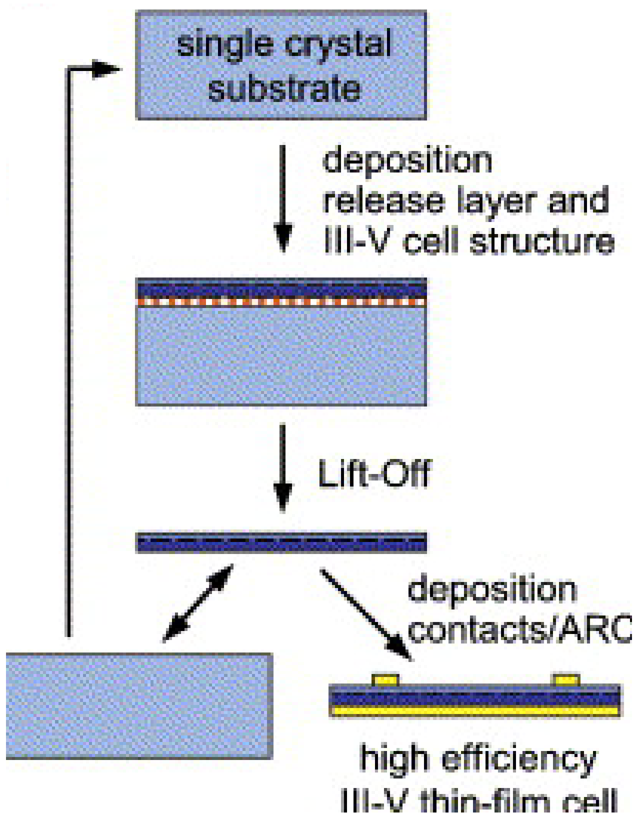
- **Module efficiency of 23.2%**

ALTADEVICES

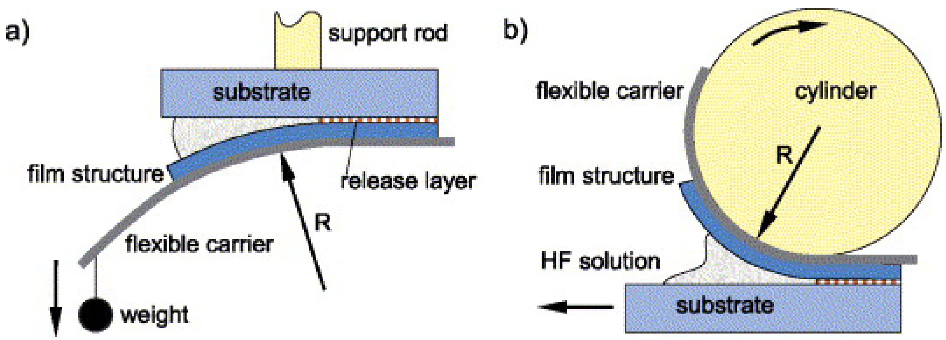
- **IQE > 0.96**
- **Economical III-V flat plate ($1/Wp) PV System)**

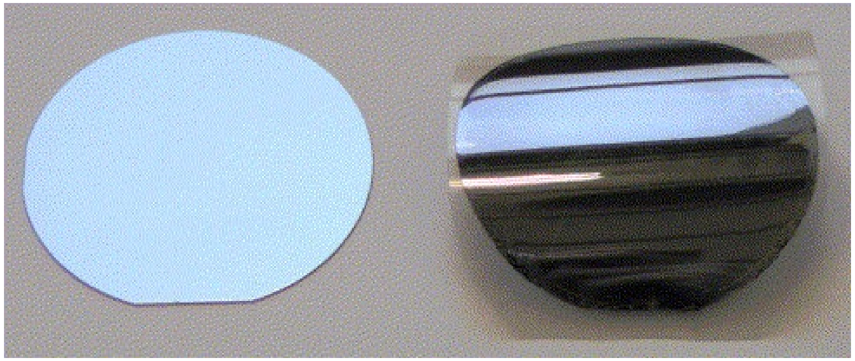
Source: Prof. H. Atwater, Intersolar 2013

GaAs production by ELO process



J.J. Schermer et al, Thin Solid Films, Volumes 511–512, 2006, 645





A 1-μm-thick GaAs film of 2 in. in diameter on a flexible plastic carrier (right-hand side) after epitaxial lift-off from its substrate (left-hand side).

- Highest efficiency GaAs cells are prepared with Epitaxial Lift-Off (ELO) process that has potential of significant cost reduction.

Multi-junction III-V cells

Spectral mismatch for single-junction cells

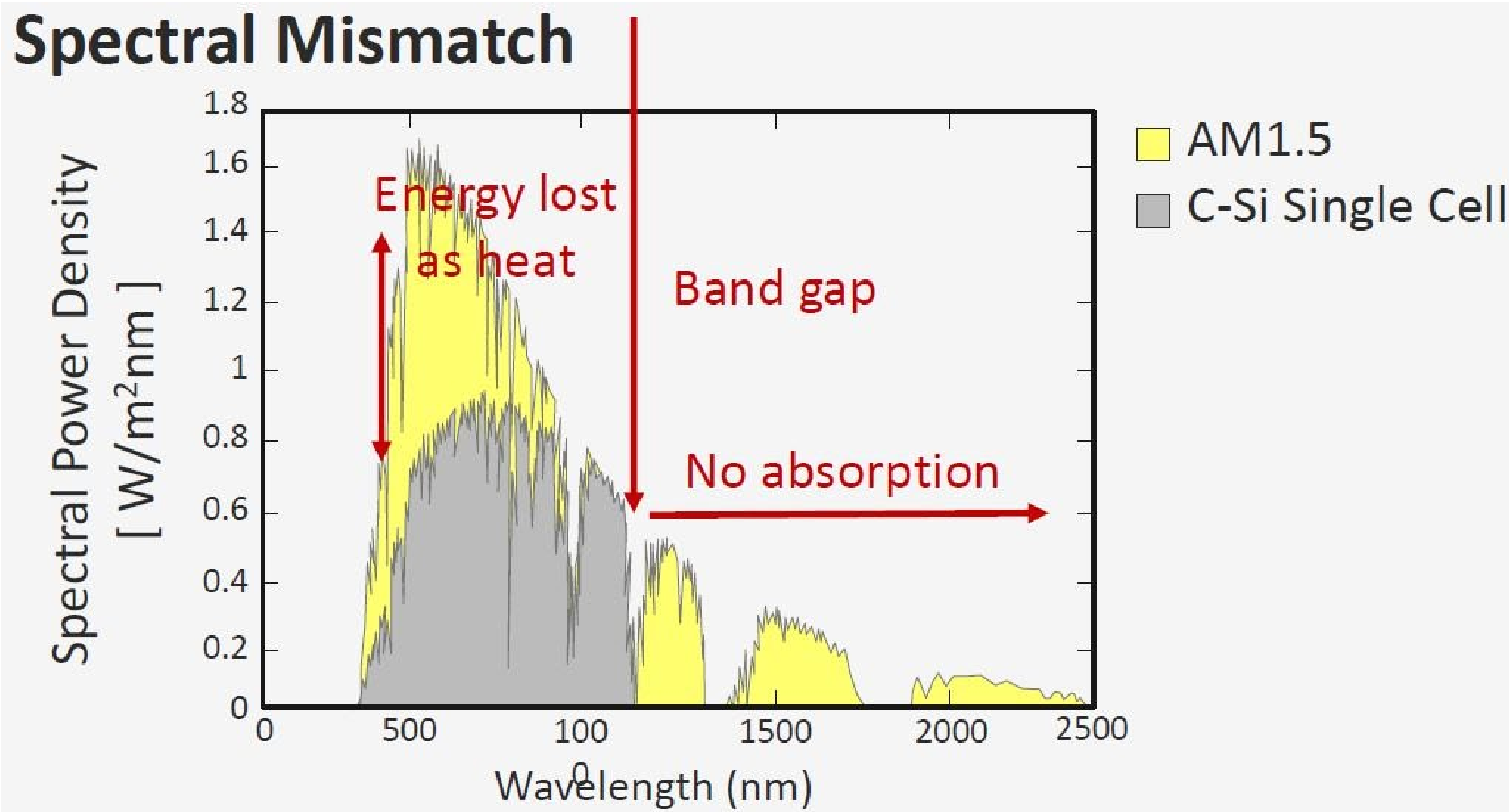
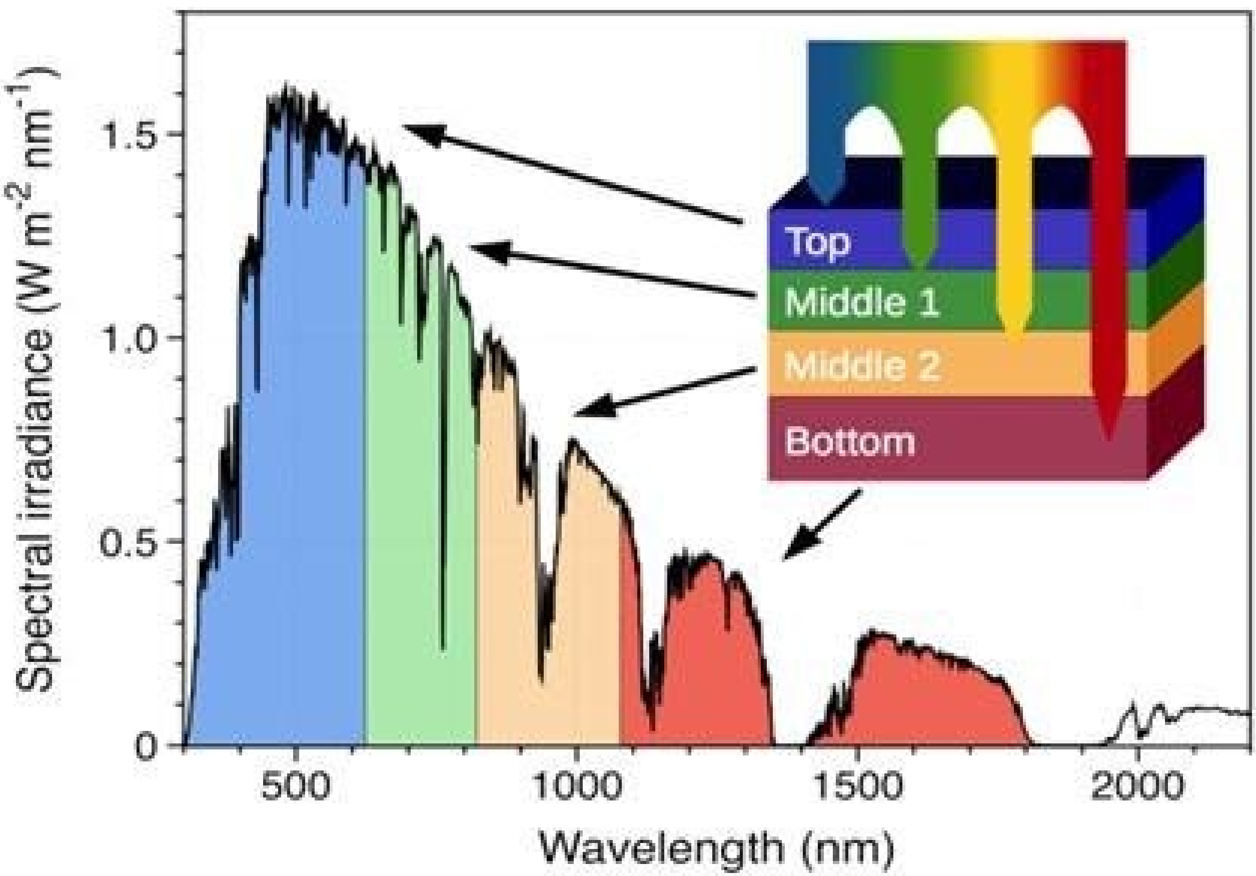


Image from : http://maxloosolarenergy.blogspot.com/2016/12/spectral-utilization-ii-shockley.html

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

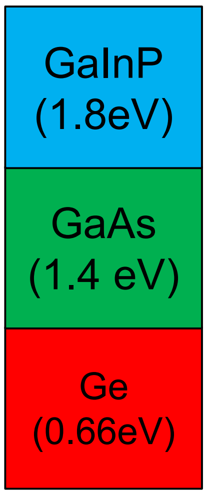
Multi-junction solar cells



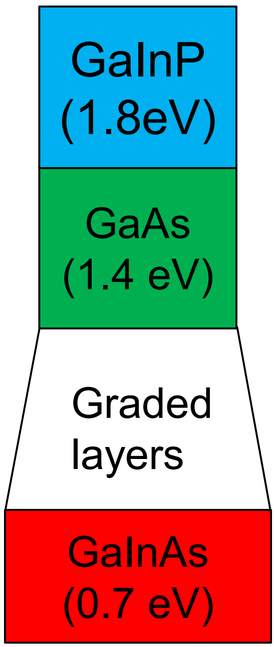
- Better utilization of the solar spectrum in multi-junction cells

Multi-junction approaches

Monolithic

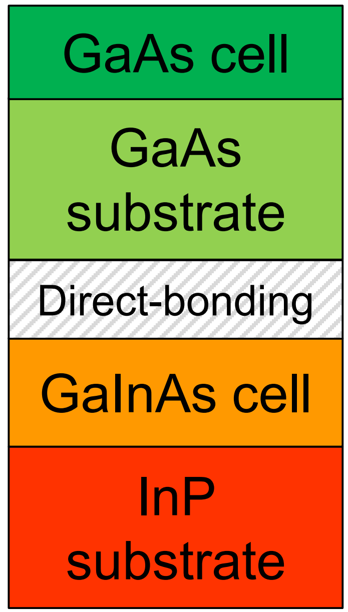


Lattice matched



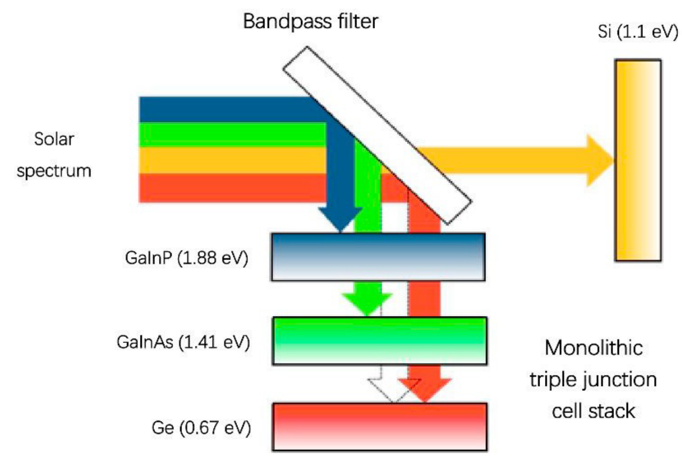
Metamorphic (lattice mismatched)

Mechanical stack



Tanabe et al., APL 89, 102106, 2006

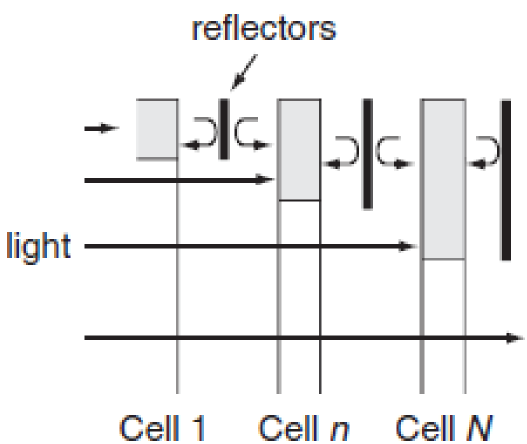
Spectrum splitting



D. Lan, M. Green, SNEC 2018

https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119313021.ch5

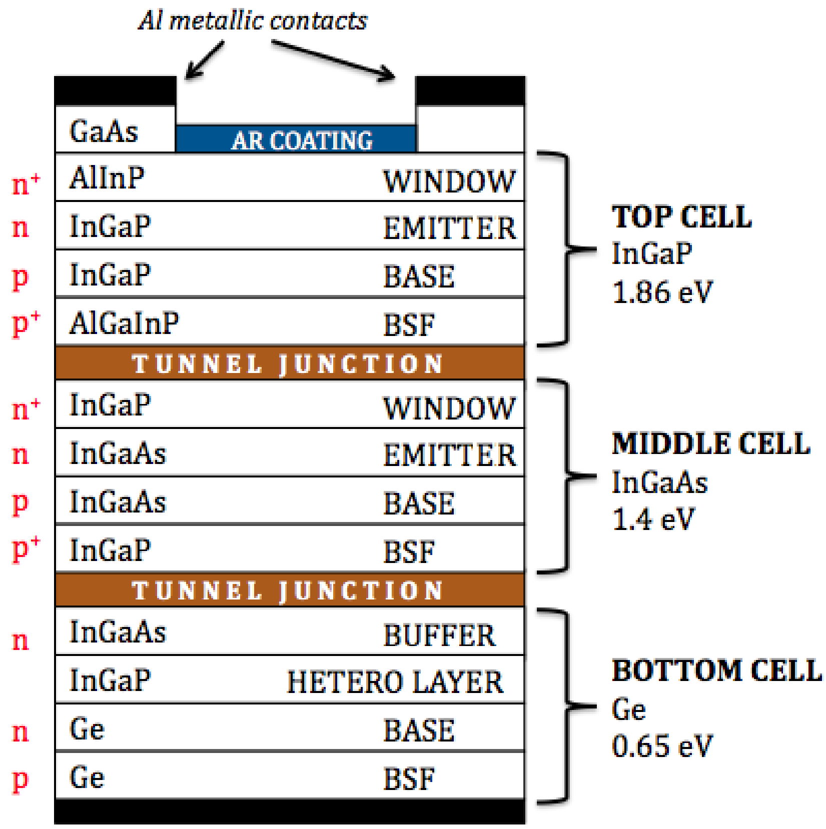
Maximum efficiency for multi-junction cells



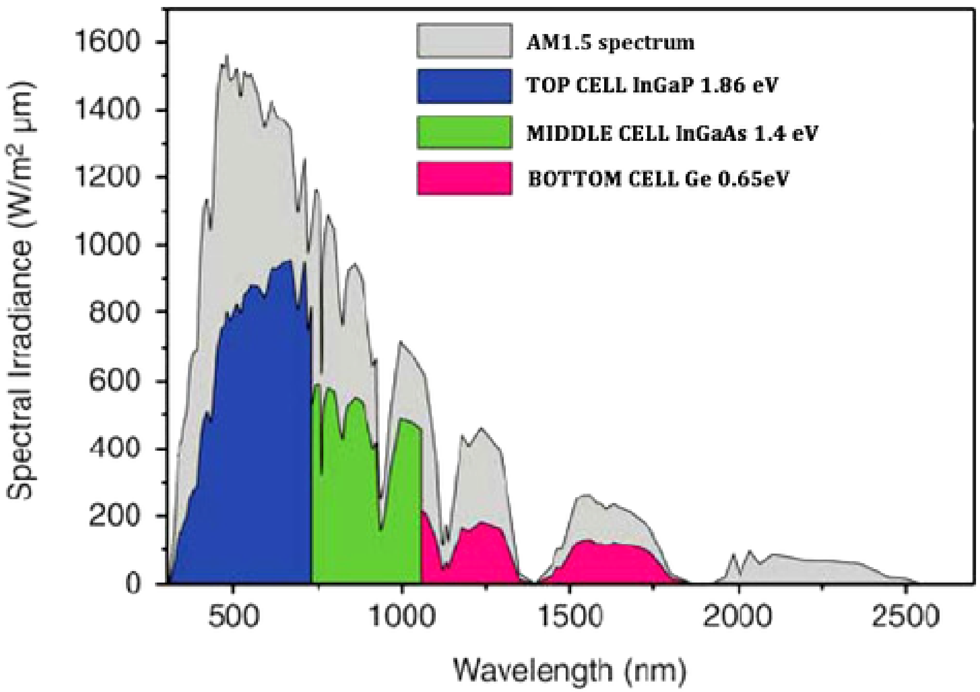
N. cells	Description	Reflectors?	Optimum gaps (eV)				Eff (%)
			$E1$	$E2$	$E3$	$E4$	
(AM1.5 direct normal irradiance)							
	1 sun, no angular restriction	Yes	1.13	–	–	–	32.5
1	1 sun no angular restiction	No	1.13	–	–	–	32.5
	Maximum concentration	Yes	0.94	–	–	–	44.6
	Maximum concentration	No	0.94	–	–	–	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)

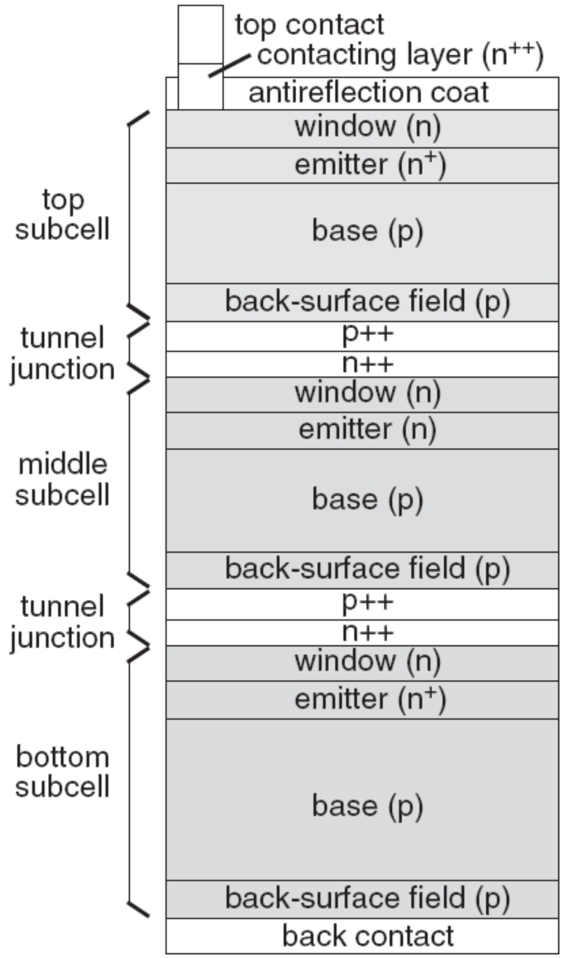
Image: www.Wikipedia.com

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
$Ti0_2/Al_20_3$		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

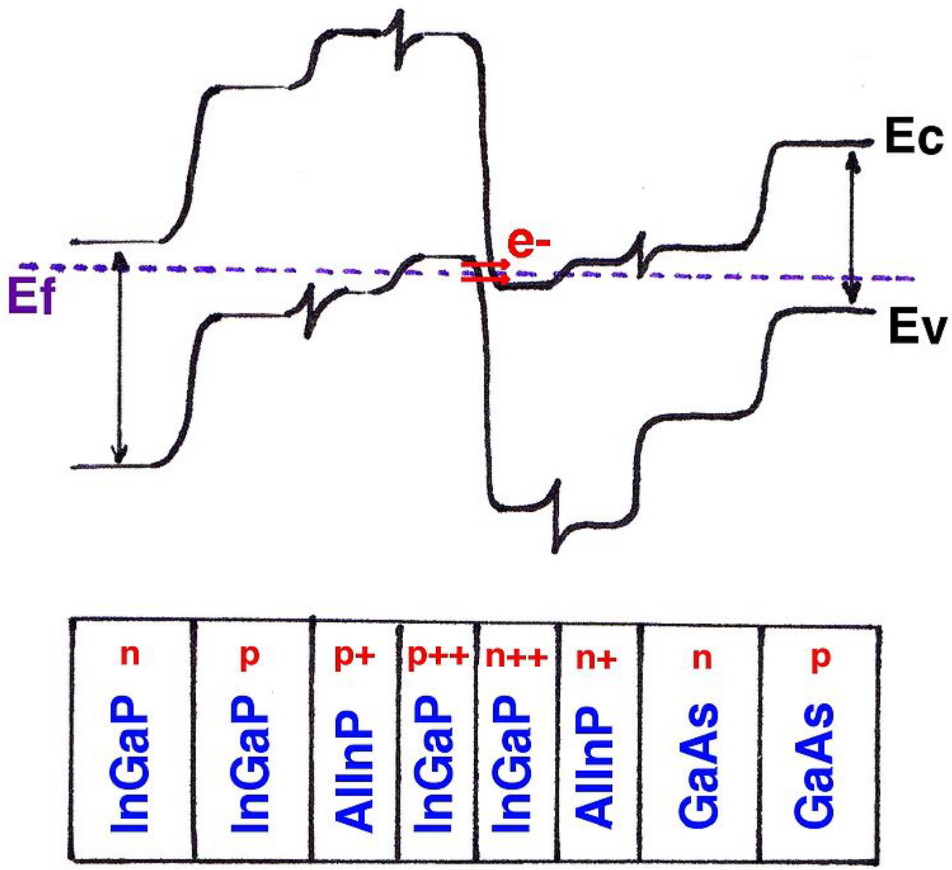
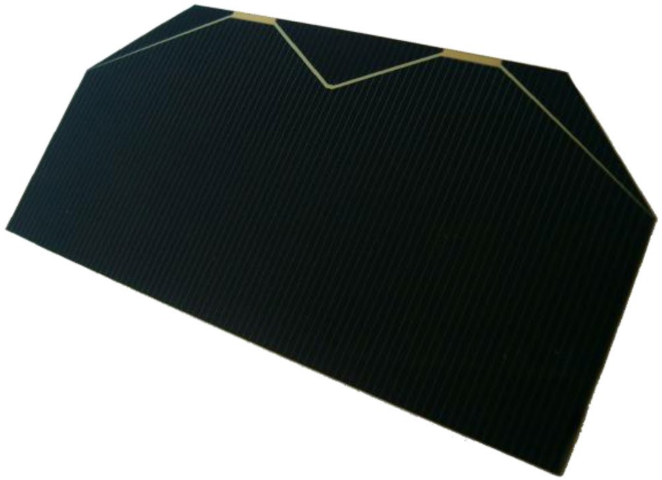
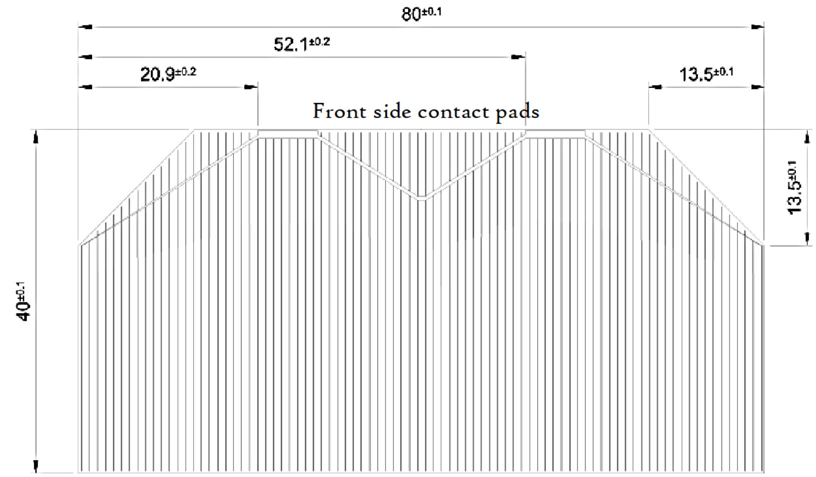


Image: www.Wikipedia.com

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

3J space cell from Azur Space





Design and Mechanical Data

Base Material	GaInP/GaAs/Ge on Ge substrate
AR-coating	TiO_x/Al_2O_3
Dimensions	40 x 80 mm ± 0.1 mm
Cell Area	30.18 cm^2
Average Weight	≤ 50 mg/cm^2
Thickness (without contacts)	80 ± 20 µm
Contact Metallization Thickness (Ag/Au)	3 – 10 µm
Grid Design	Grid system with 2 contact pads

Electrical Data

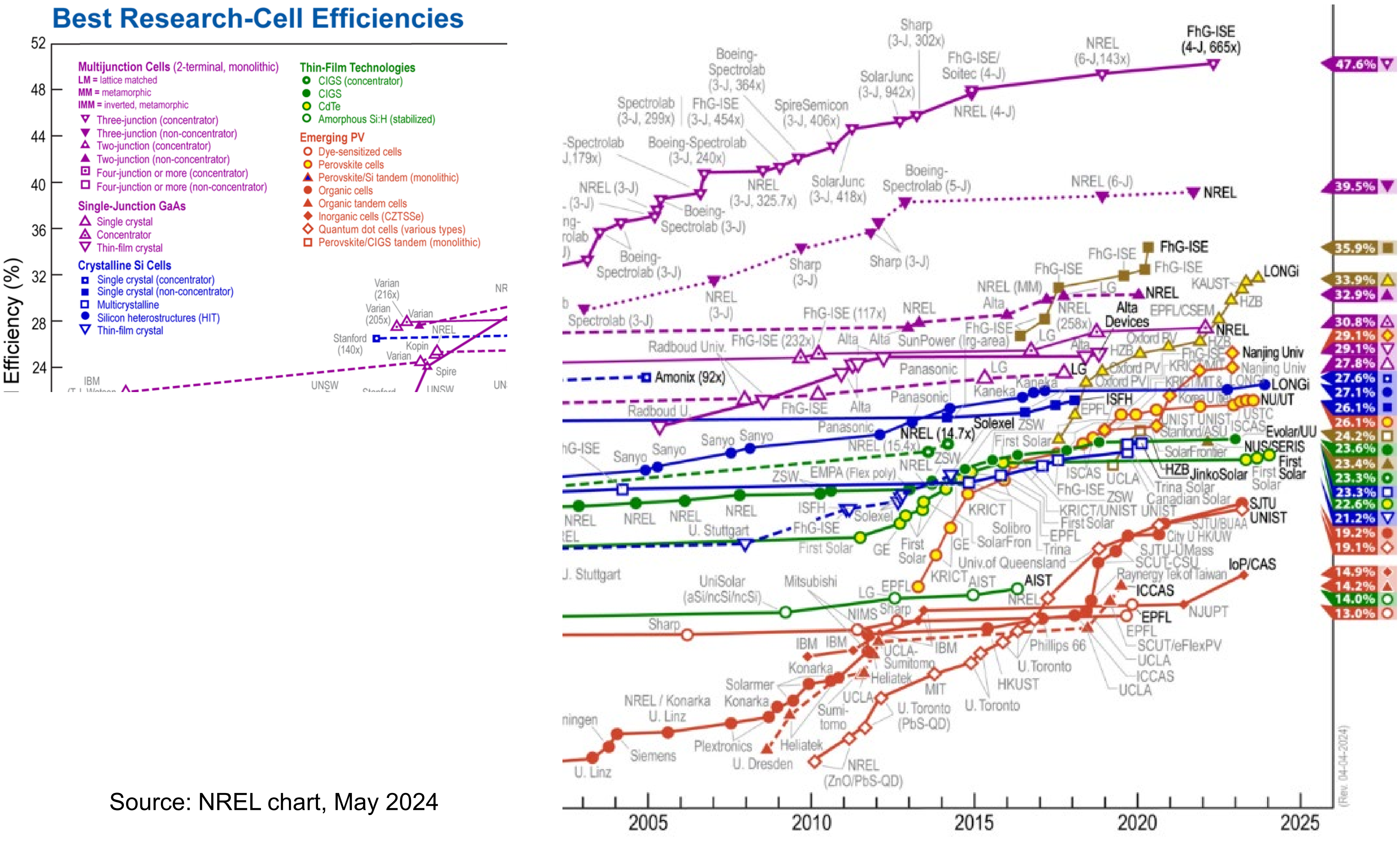
		BOL	2,5E14	5E14	1E15
Average Open Circuit V_{oc}	[mV]	2700	2616	2564	2522
Average Short Circuit I_{sc}	[mA]	520.2	518.5	514.0	501.9
Voltage at max. Power V_{mp}	[mV]	2411	2345	2290	2246
Current at max. Power I_{mp}	[mA]	504.4	503.2	500.6	486.6
Average Efficiency η_{bare} (1367 W/m^2)	[%]	29.5	28.6	27.8	26.5
Average Efficiency η_{bare} (1353 W/m^2)	[%]	29.8	28.9	28.1	26.8

Standard: CASOLBA 2005 (05-20MV1, etc); Spectrum: AMO WRC = 1367 W/m^2; T = 28 °C @fluence 1MeV [e/cm^2]

Parameters given for Begin of life (BOL) and End of life (EOL) after different electron fluence

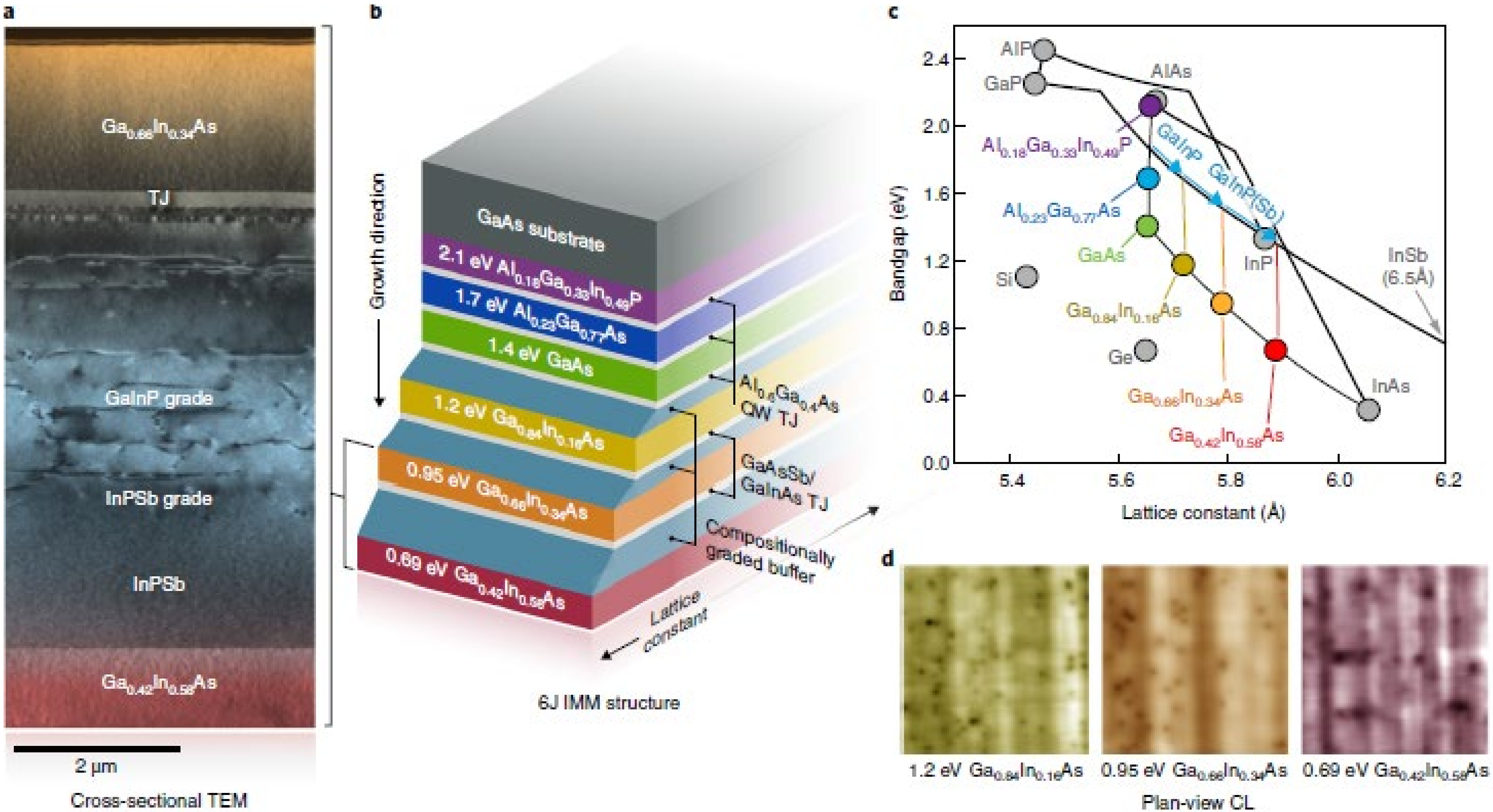
Source: http://www.azurspace.com/images/products/0004148-00-01_DB_GBK_80µm.pdf

Efficiency chart



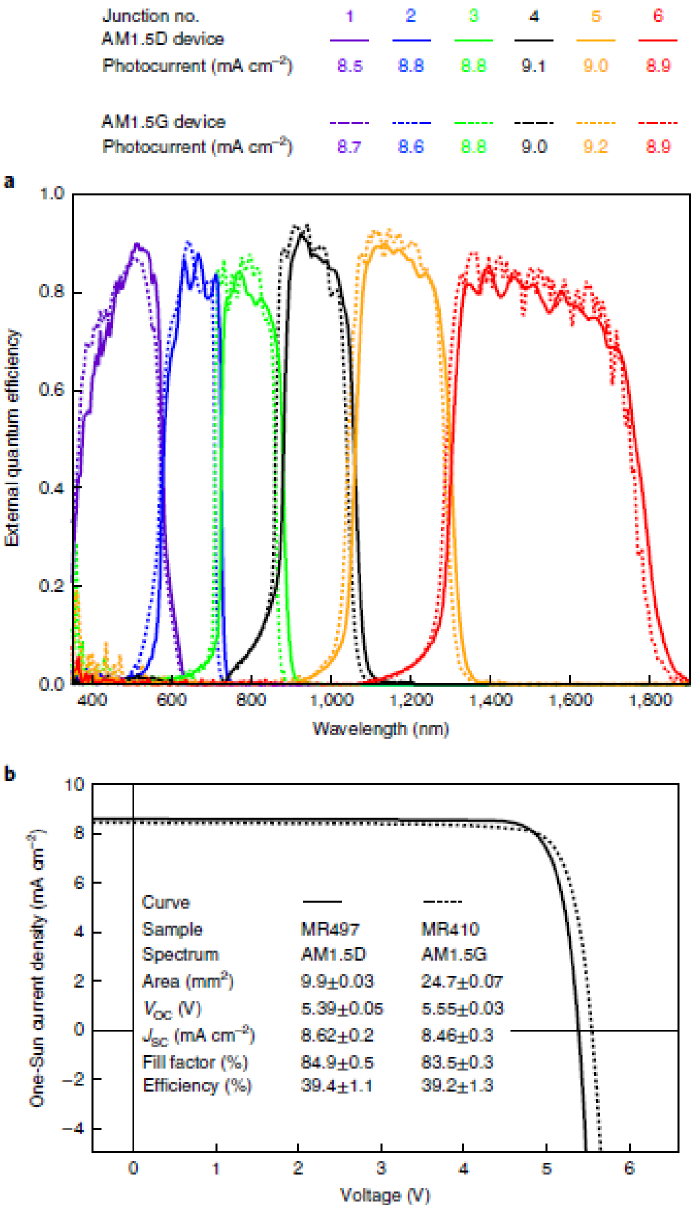
Source: NREL chart, May 2024

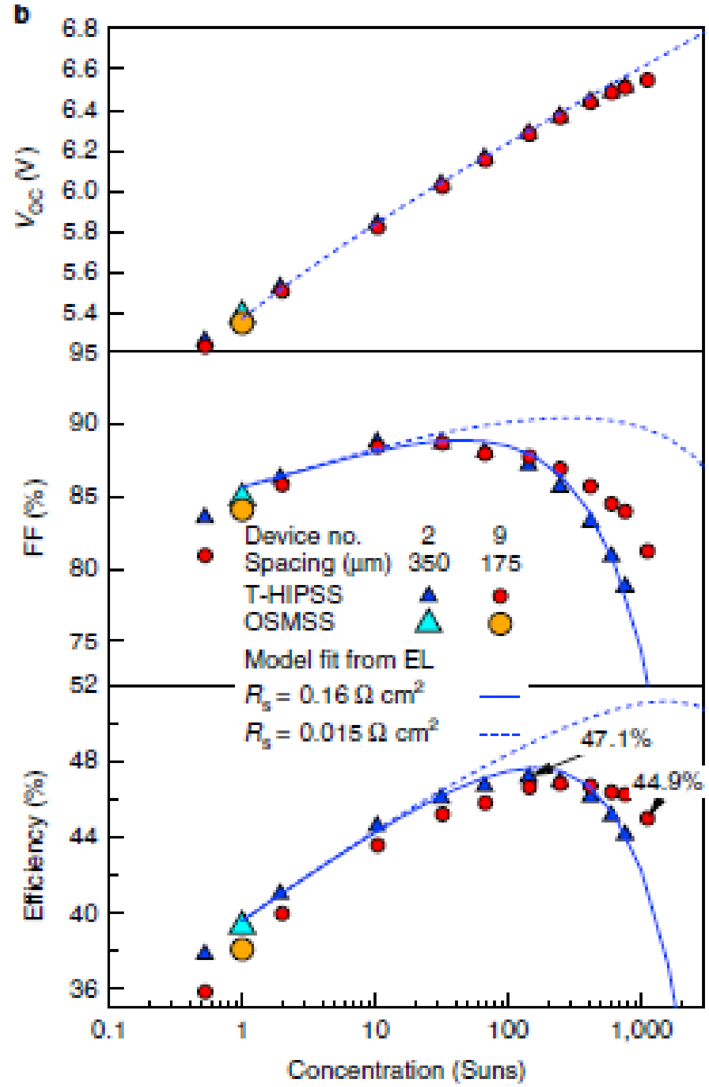
x6 junction solar cell – 47.1% (NREL, 2020)



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

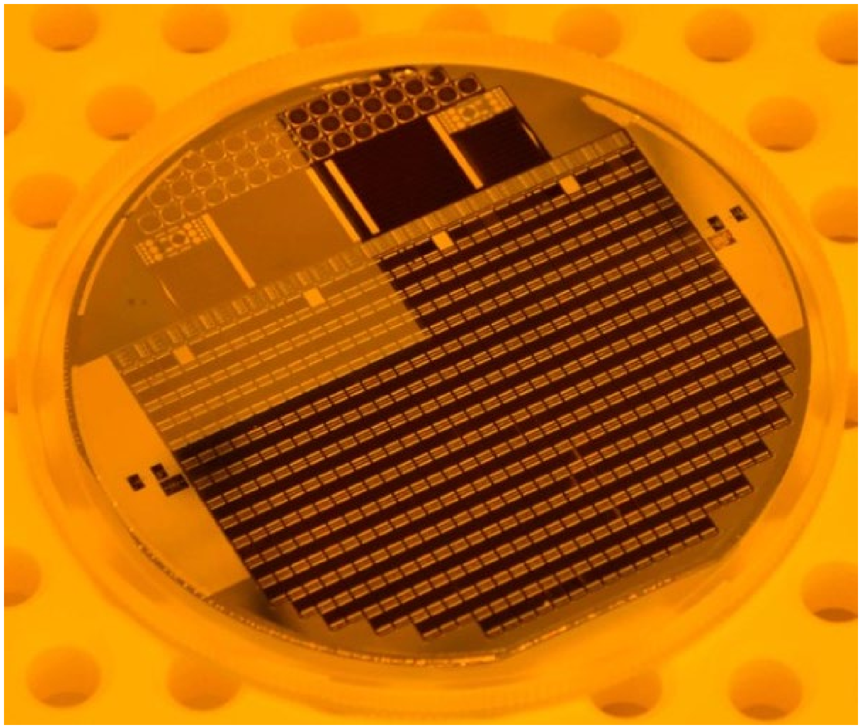
x6 junction with 47.1% efficiency



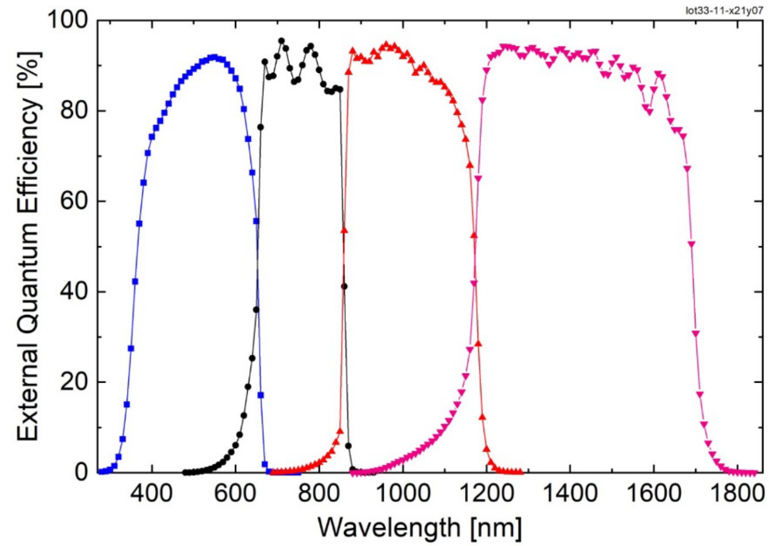


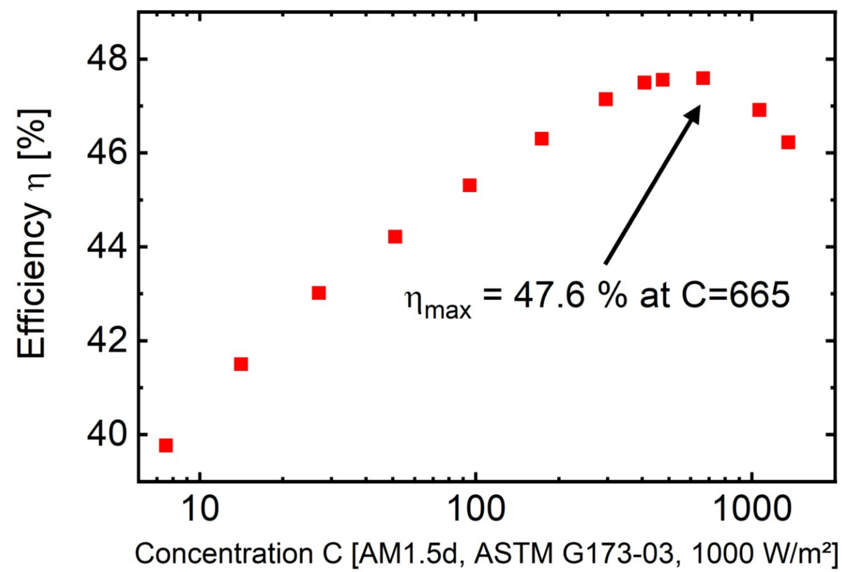
NREL group, *Nature Energy* 5 (2020) 326

Current world record: 47.6% from 4-junction (Fraunhofer ISE, 2022)



Fraunhofer ISE, May 2022

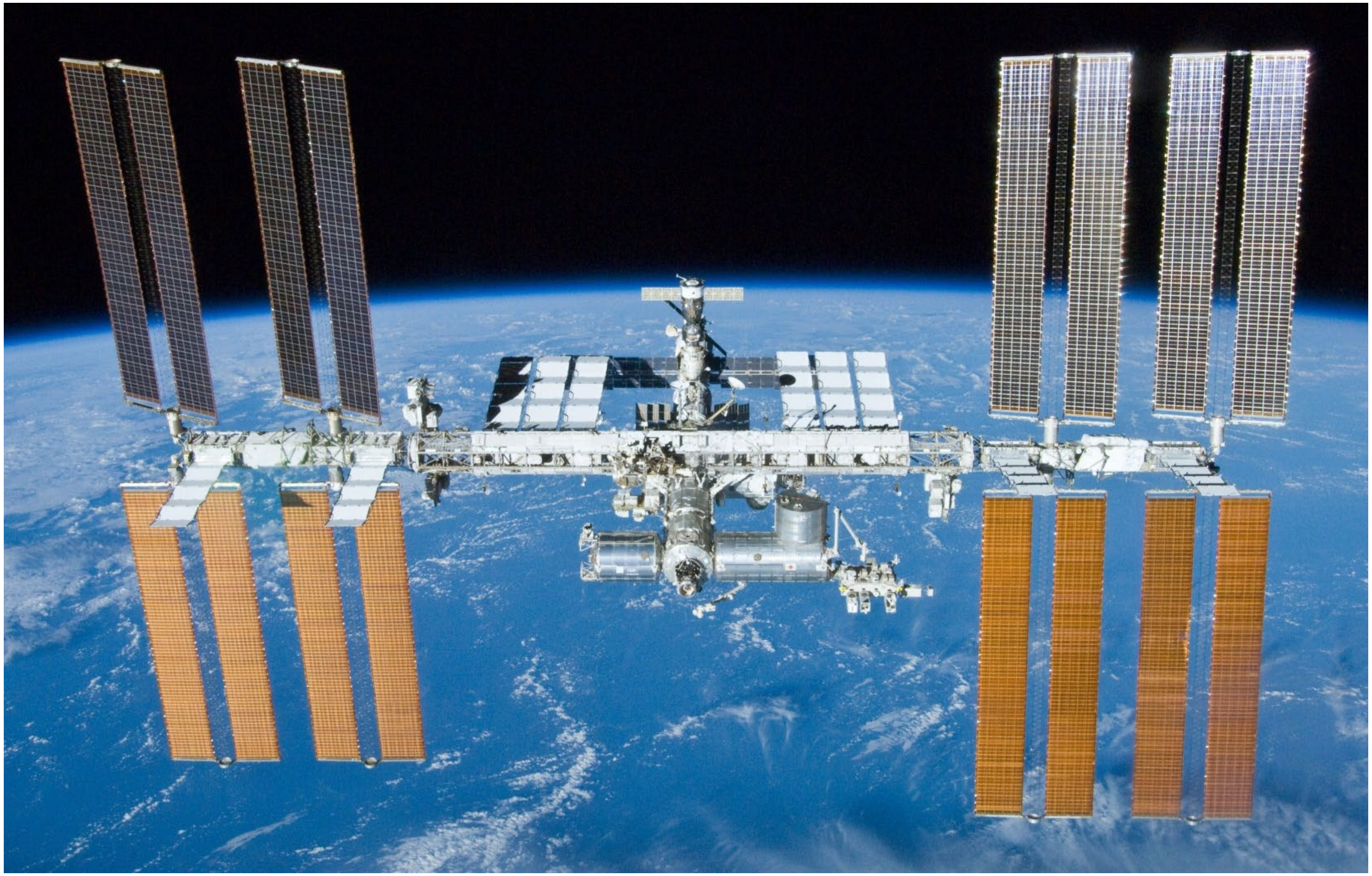




Solar cells for space

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 Power Array for Envisat

Largest European satellite
Mission: 4 years
Launched in February 2002

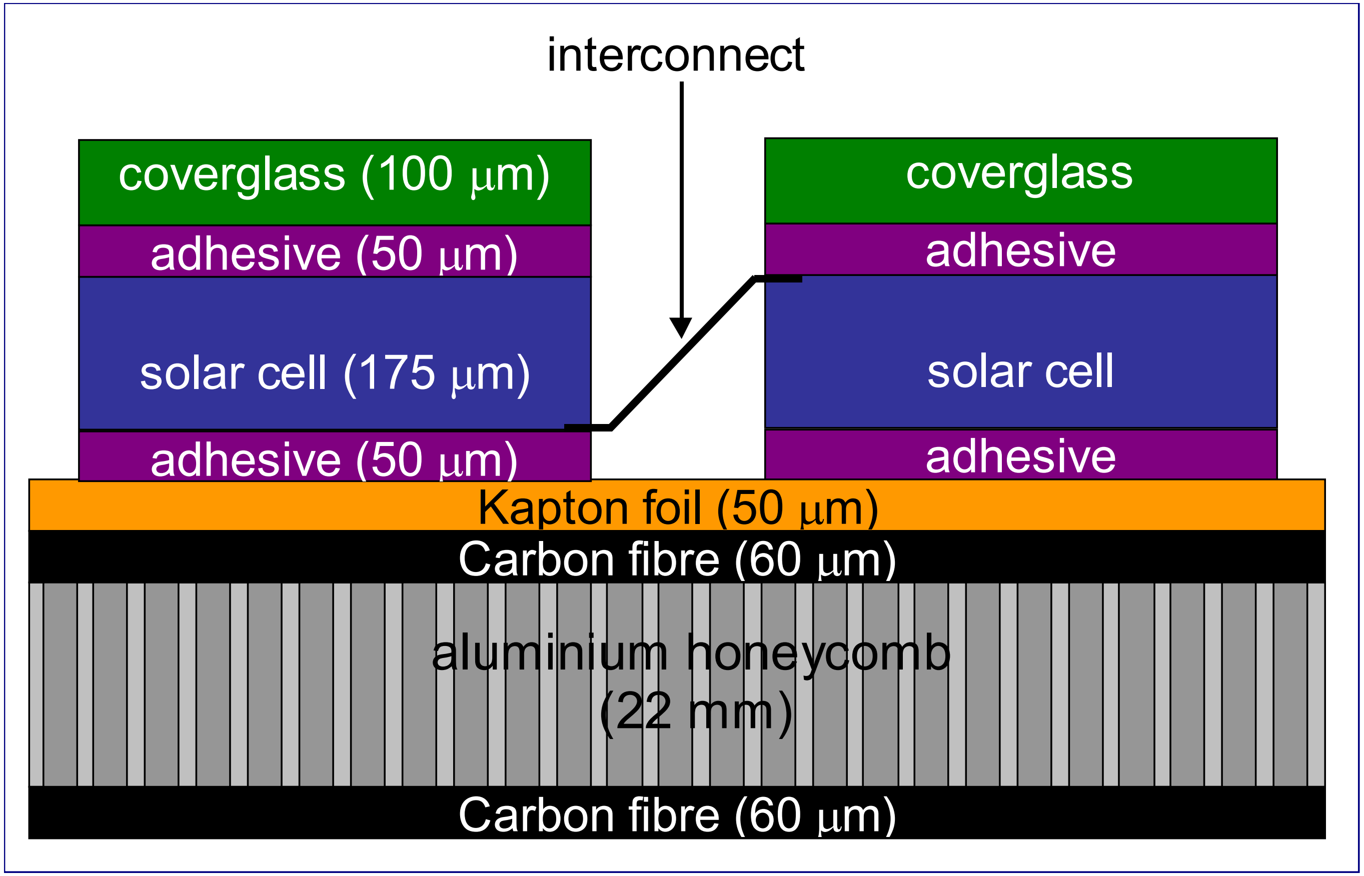
Power: 6.55 kW (EOL)
Size: 5x14 m^2

Silicon cells

Rigid (foldable) structure

Dutch Space

Space solar module assembly



Dutch space

- Thermal stresses relieved by thick adhesives.
- Interconnects equipped with stress relieve.

Starlink

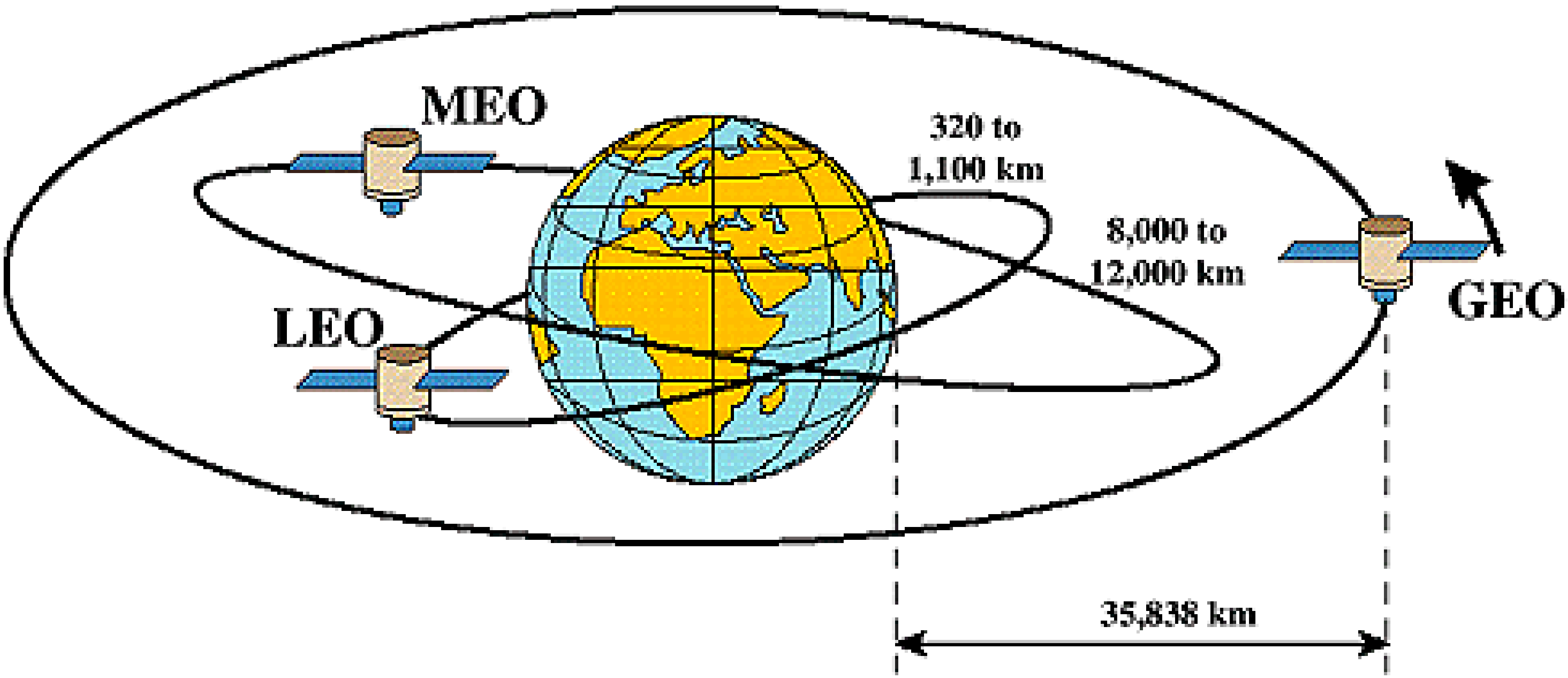
- 12 segments of 3.2 m long, total area 30 m2
- Probably Si cells

https://space.stackexchange.com/questions/64729/who-is-manufacturing-the-solar-panels-for-starlink-satellites

- Assuming 18% efficiency and 1250 W/m2 gives 6 kW of total power

https://lilibots.blogspot.com/2020/04/starlink-satellite-dimension-estimates.html

Satelite orbits

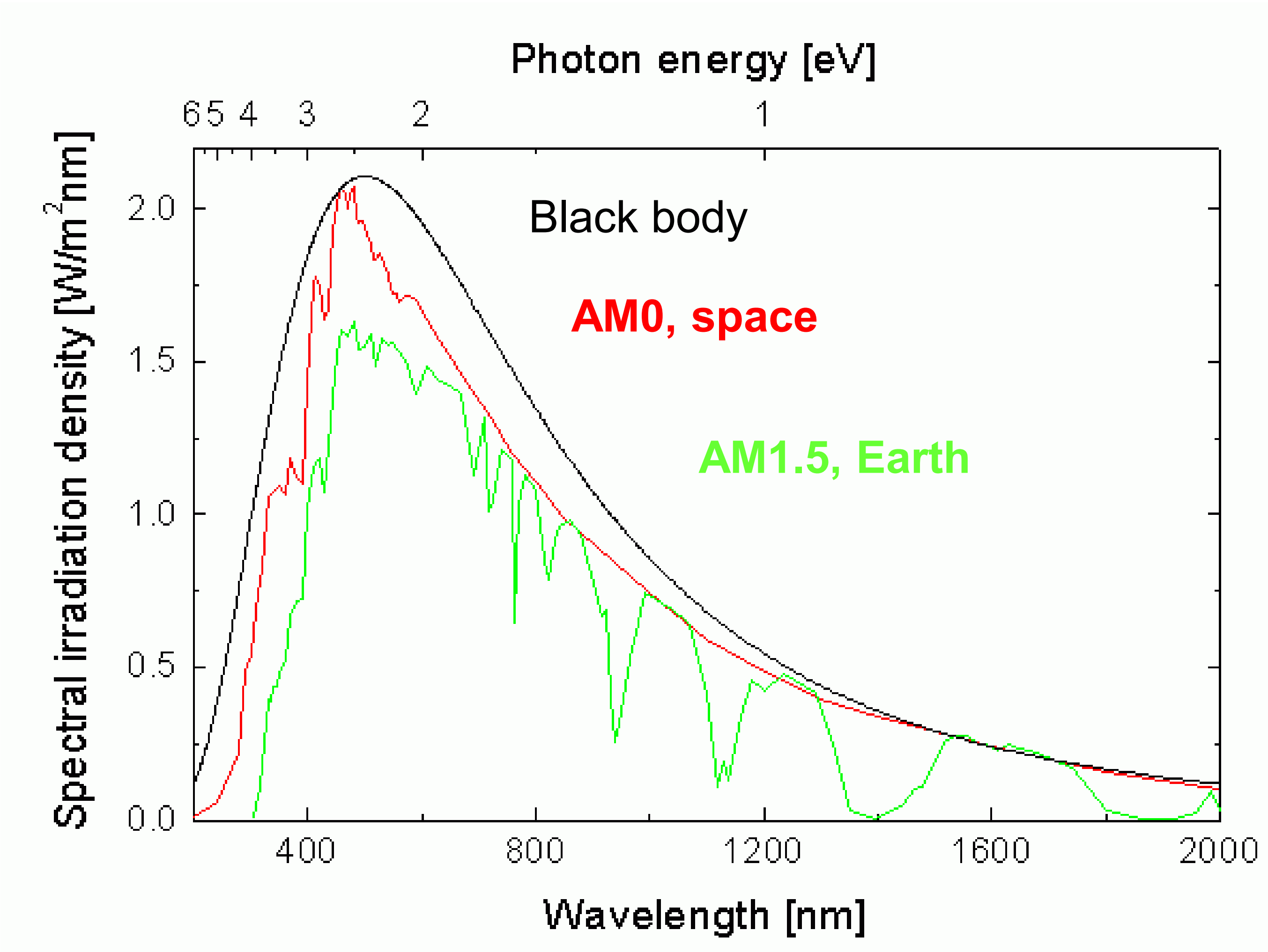


http://www.informit.com

- 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

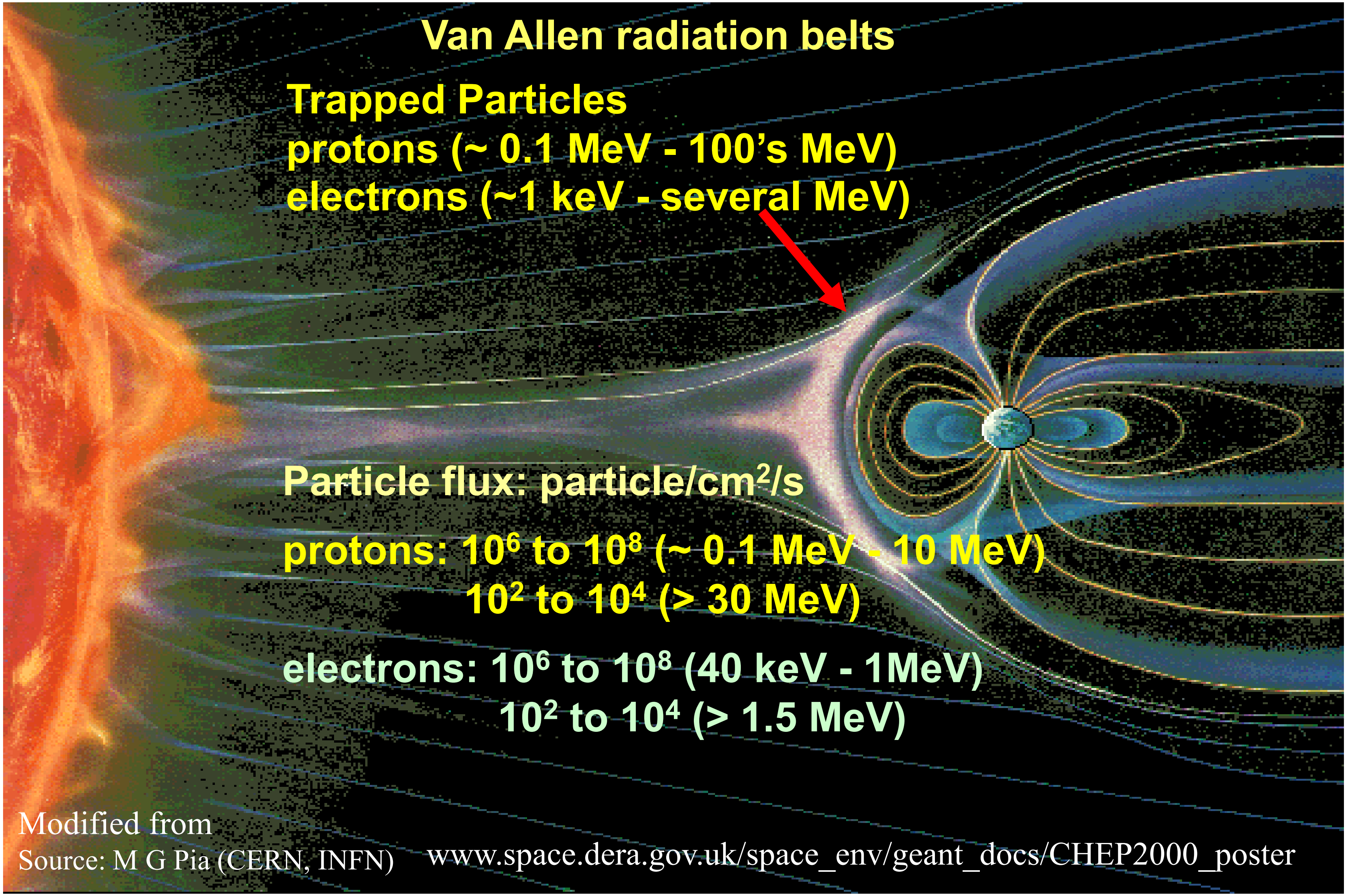
*-http://www.daystartech.com/applications/space.htm

Solar radiation in space



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

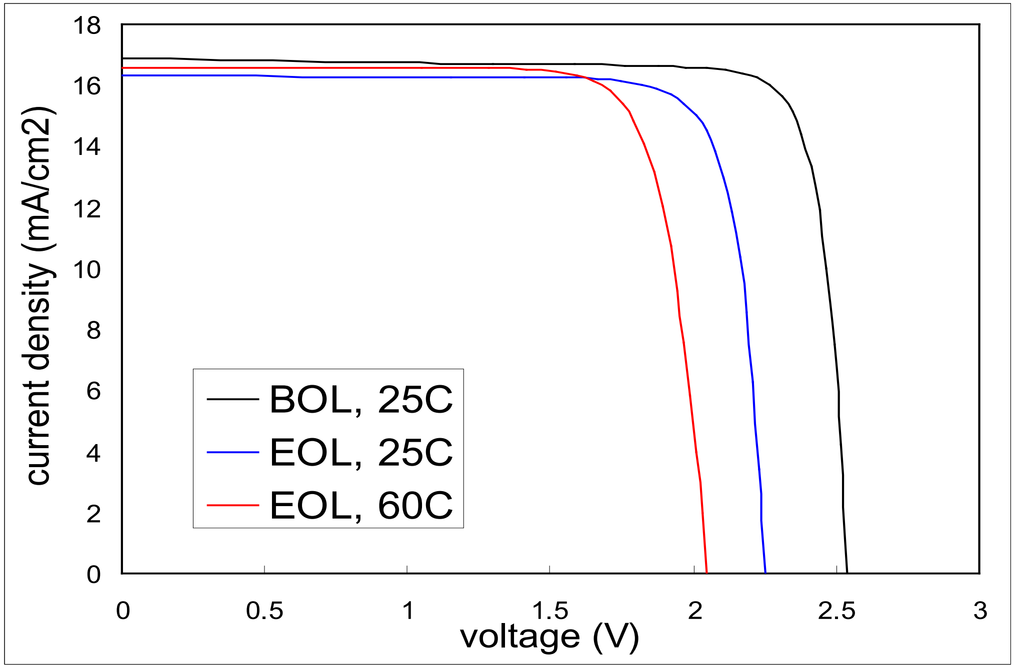
Particle fluxes near the Earth



Cell degradation in space

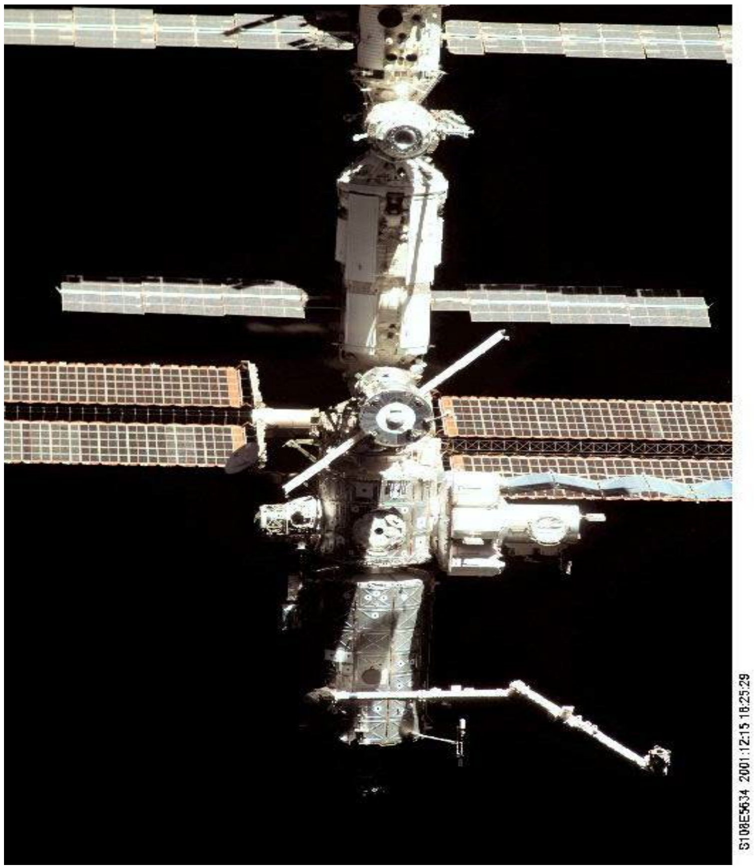
Efficiency degradation in space due to electron and proton irradiation

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

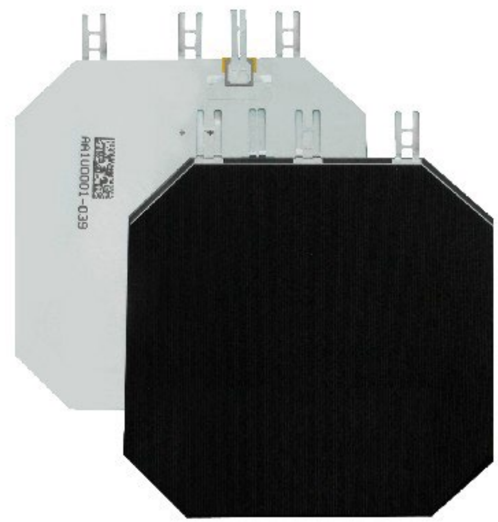


Spectrolab 3J GaAs

III-V multi-junction cells for space



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



Radiation Degradation
(Fluence 1MeV Electrons/cm^2)

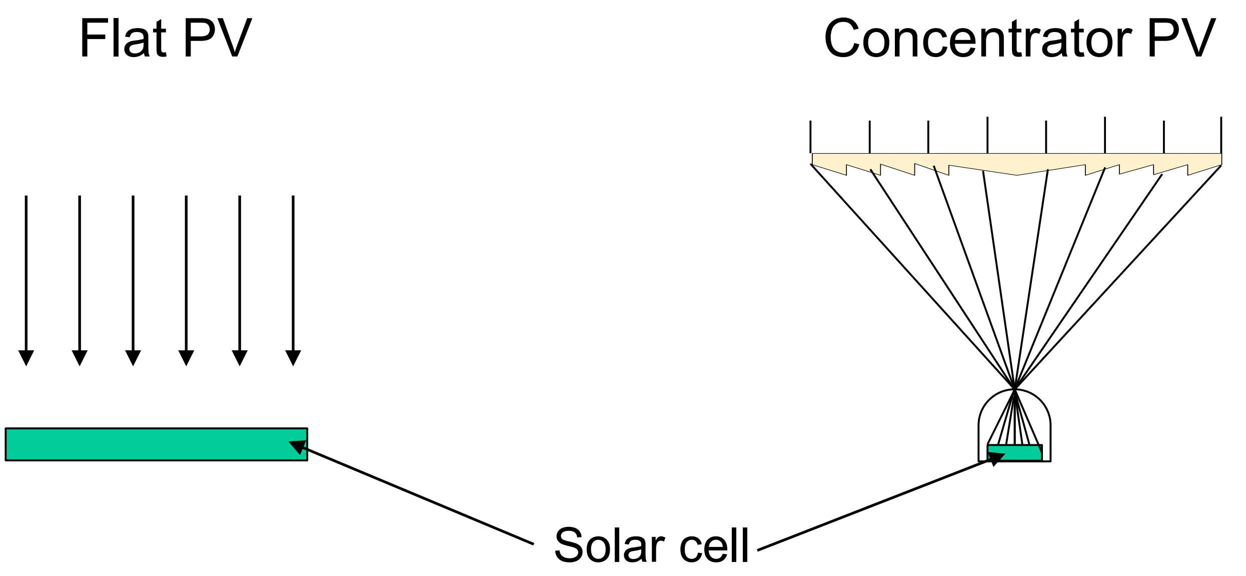
Parameters	1×10^{14}	5×10^{14}	1×10^{15}
I_{mp}/I_{mp0}	1.00	0.99	0.95
V_{mp}/V_{mp0}	0.94	0.91	0.89
P_{mp}/P_{mp0}	0.95	0.90	0.85

Concentrator PV (CPV)

(not to be confused with concentrator solar power CSP)

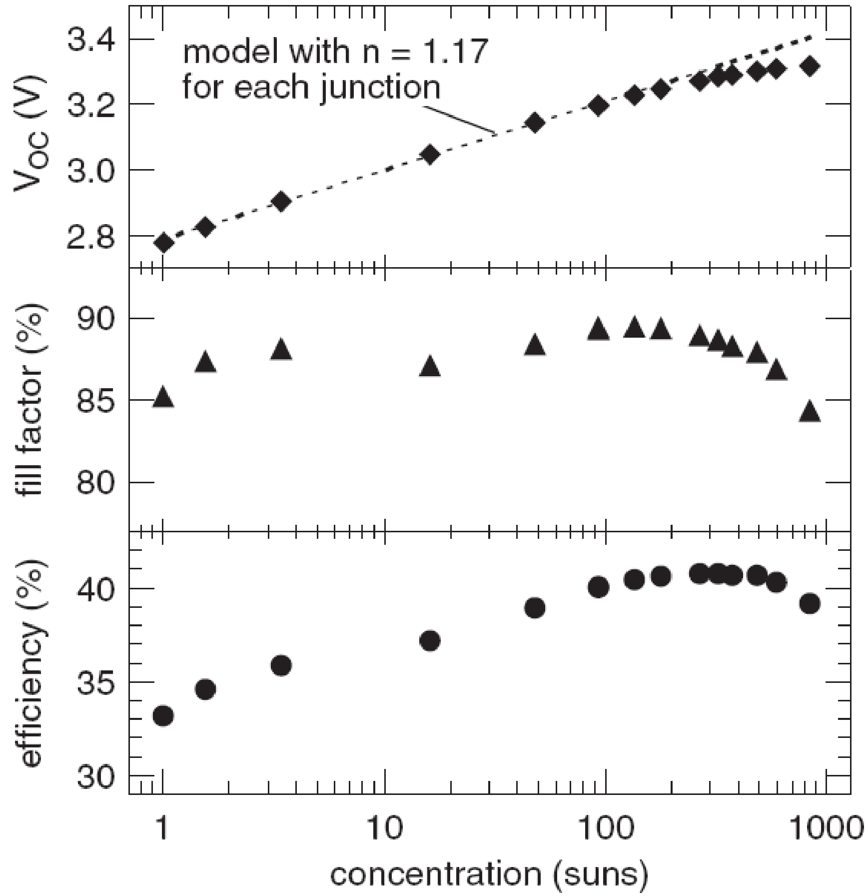
Why concentrator photovoltaics?

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



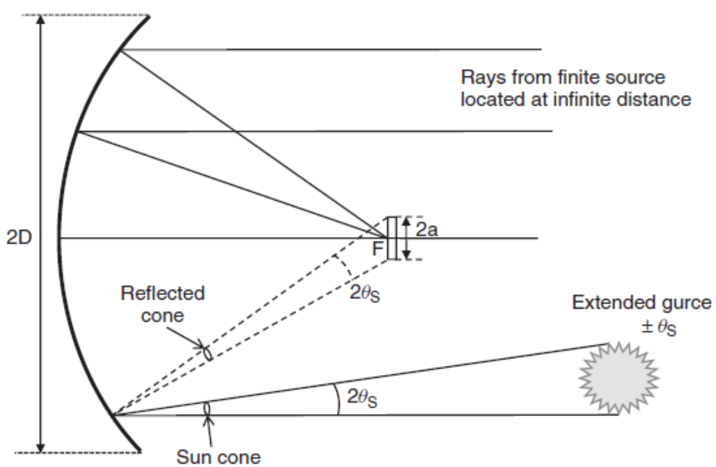
$$V_{oc} \approx \frac{kT}{q} \ln\left(\frac{I_L}{I_0}\right)$$

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

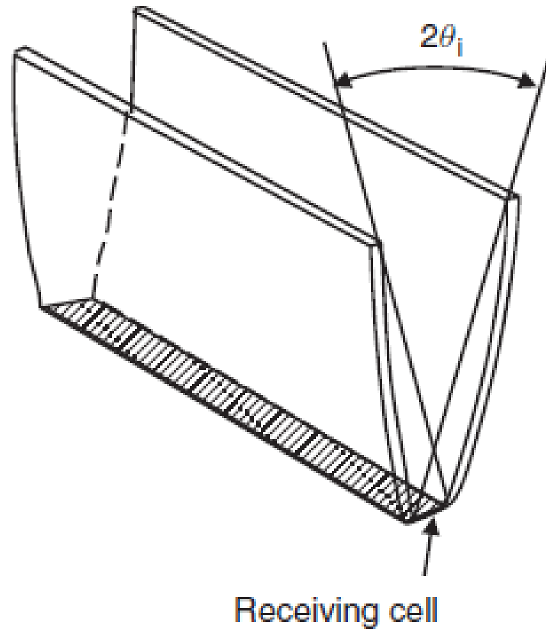
Handbook of photovoltaic science and engineering, 2011

Light concentrators

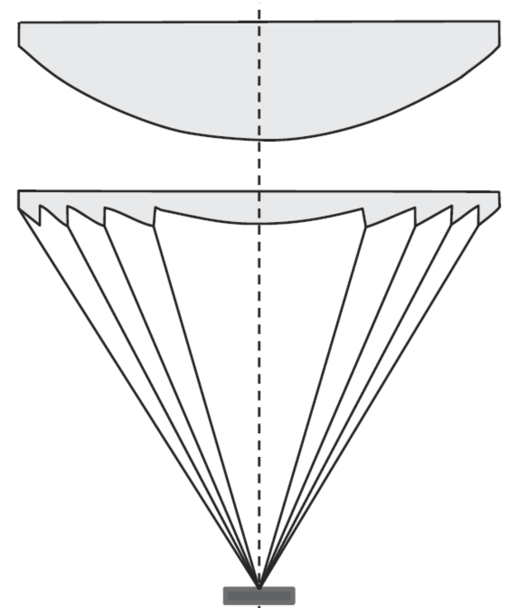
Parabollic
mirror concentrator



Compound
parabolic
concentrator

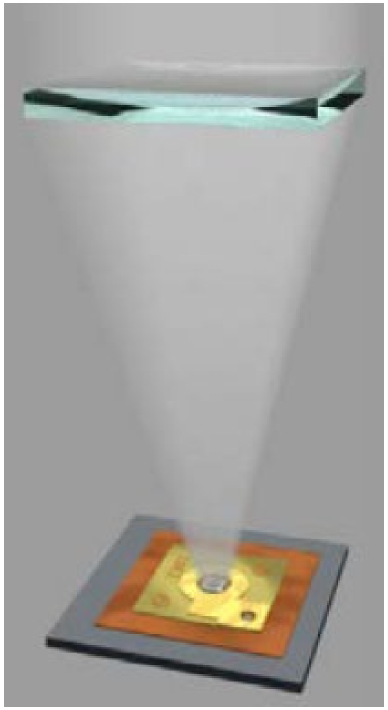


Fresnel lenses



Handbook of photovoltaic science and engineering, 2011

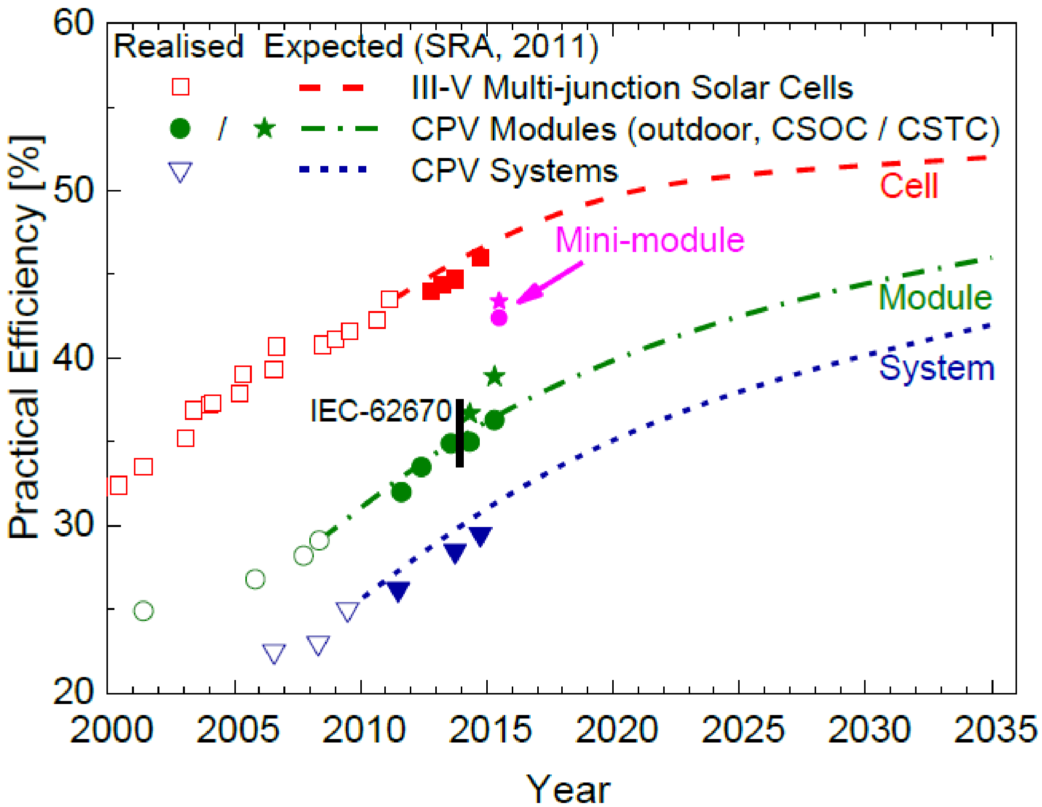
Light concentrating systems



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

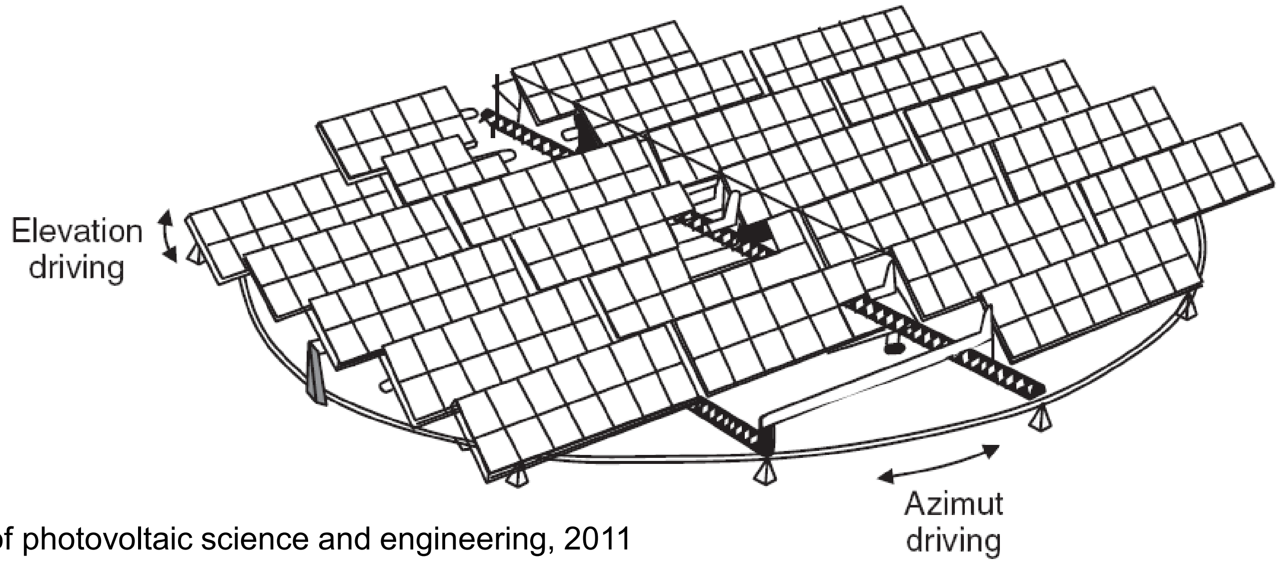
CPV efficiency



- Certified record value for solar cell efficiency of 47.6% (F ISE, 2022)
- Module efficiency of 38.9 % (Soitec)

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

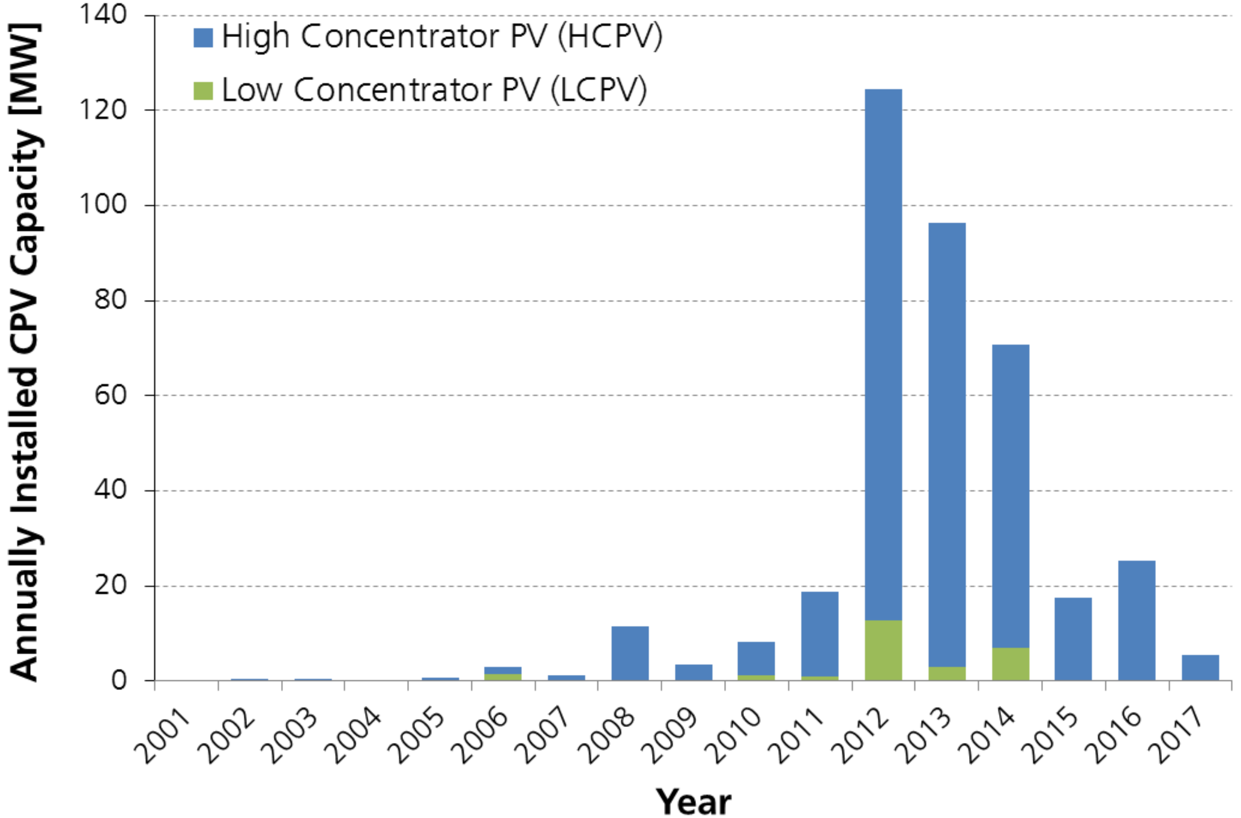
Light-tracking systems



Handbook of photovoltaic science and engineering, 2011

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

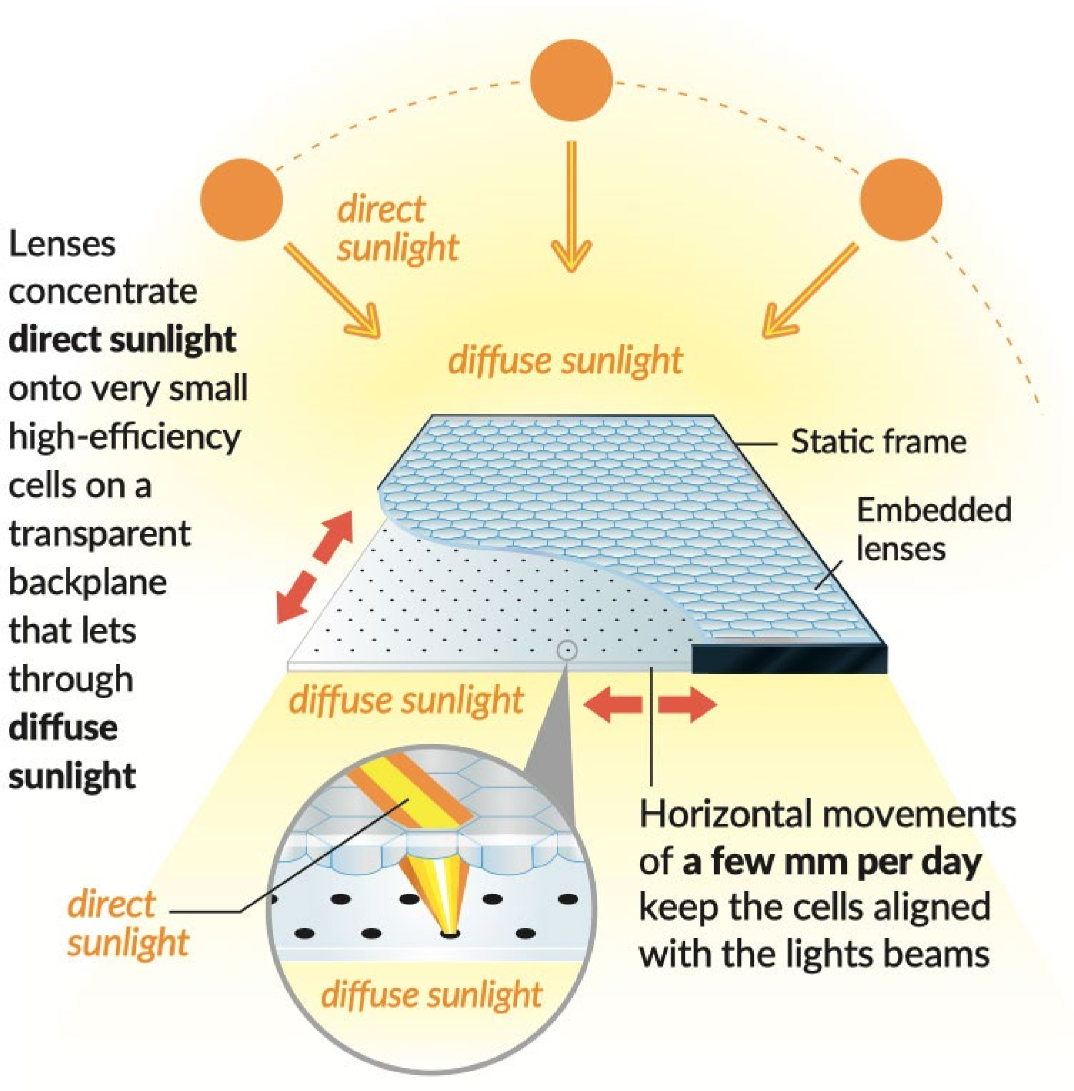
CPV installations

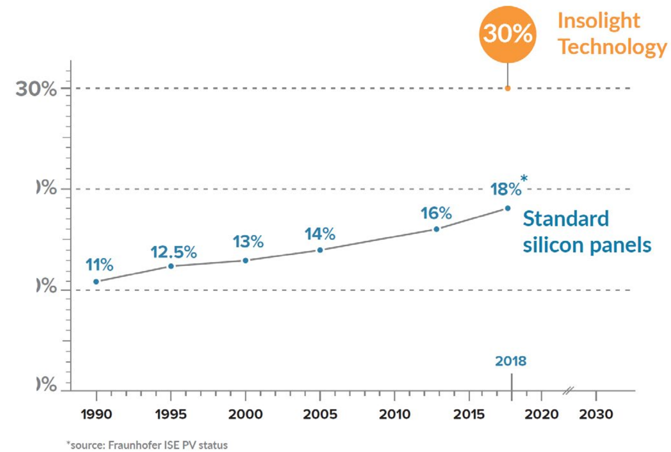


"Current status of concentrator photovoltaic (CPV) technology" report, ISE and NREL, 2018

- 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/