

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)

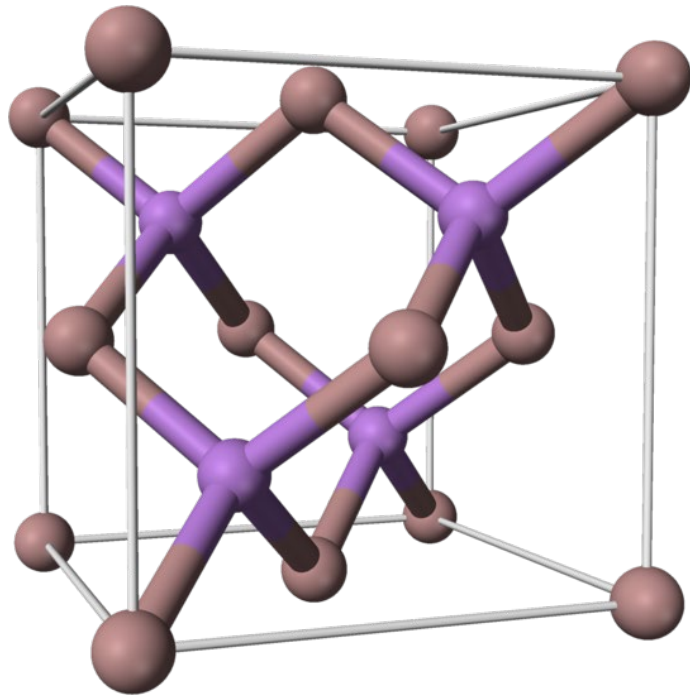
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Empa – Swiss Federal Laboratories for Materials Science and Technology
yaroslav.romanyuk@empa.ch



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

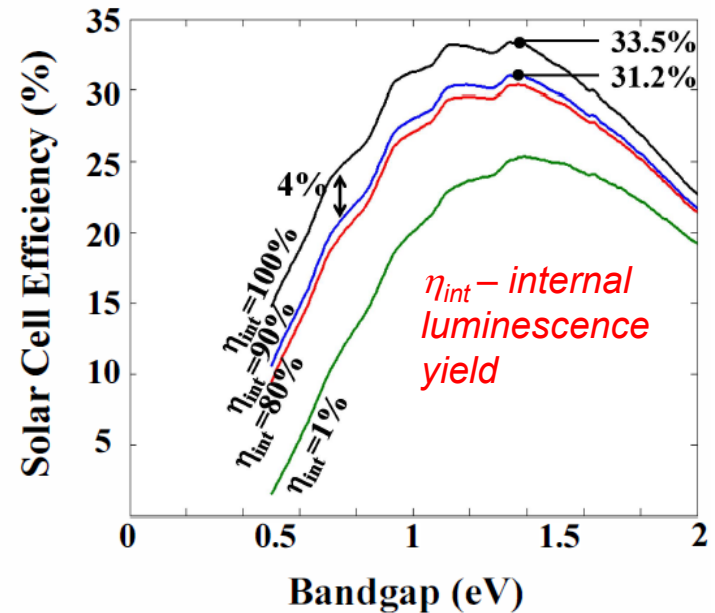
Growth methods:

Metalorganic Vapor Phase Epitaxy (MOVPE)
Molecular beam epitaxy (MBE)

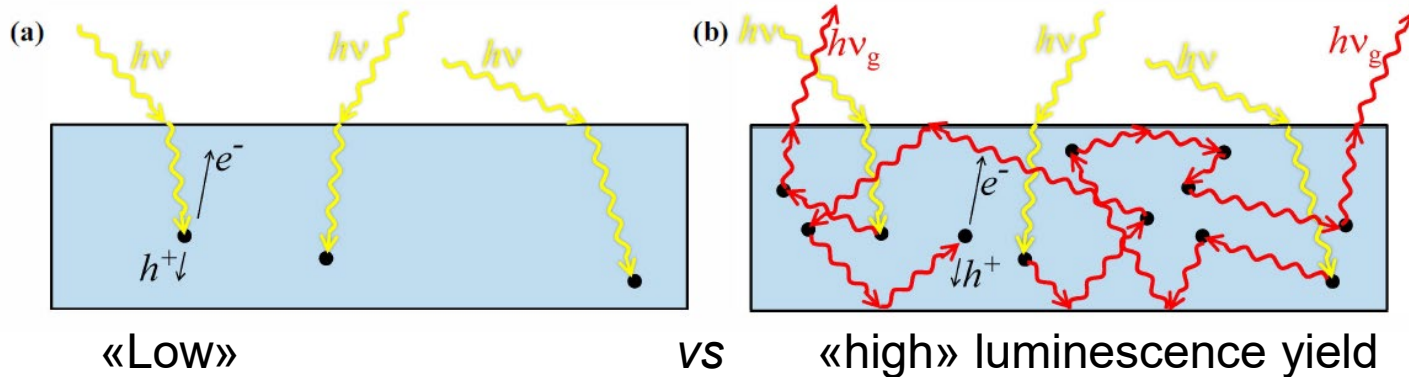
Why GaAs is a good PV material

- High carrier mobility up to 8500 cm²/Vs
- Suitable bandgap 1.42 eV
- High absorption coeff. > 10⁵ cm⁻¹
- High luminescence yield (>99%)

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



Concept of «photon recycling»



III-V semiconductor bandgaps

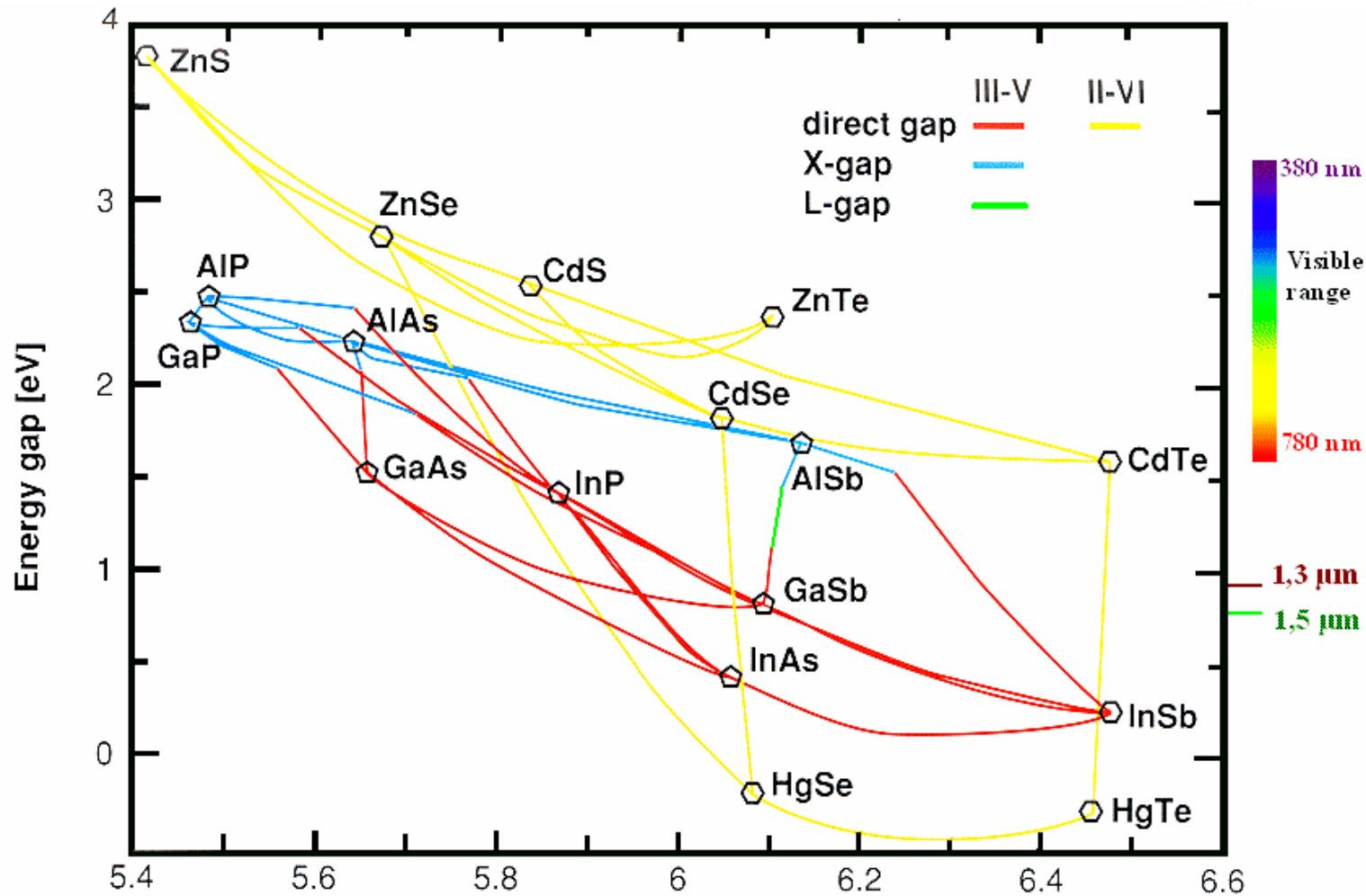
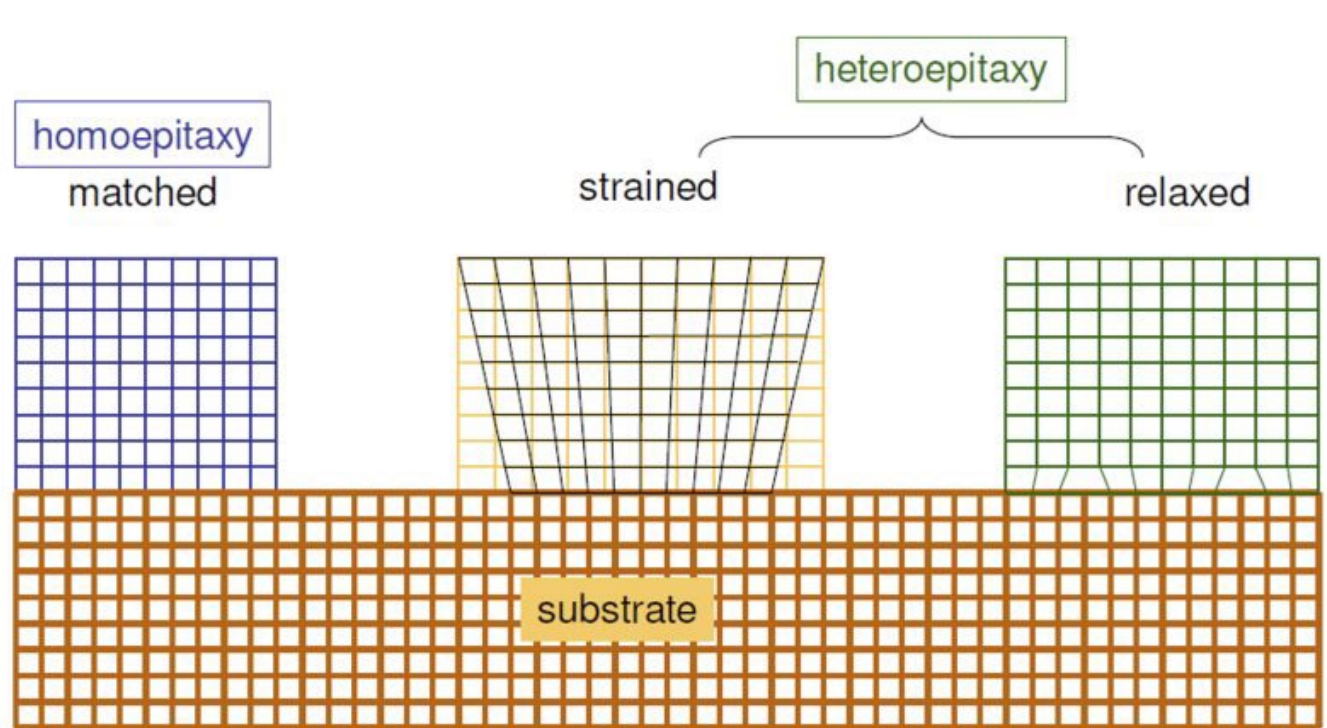


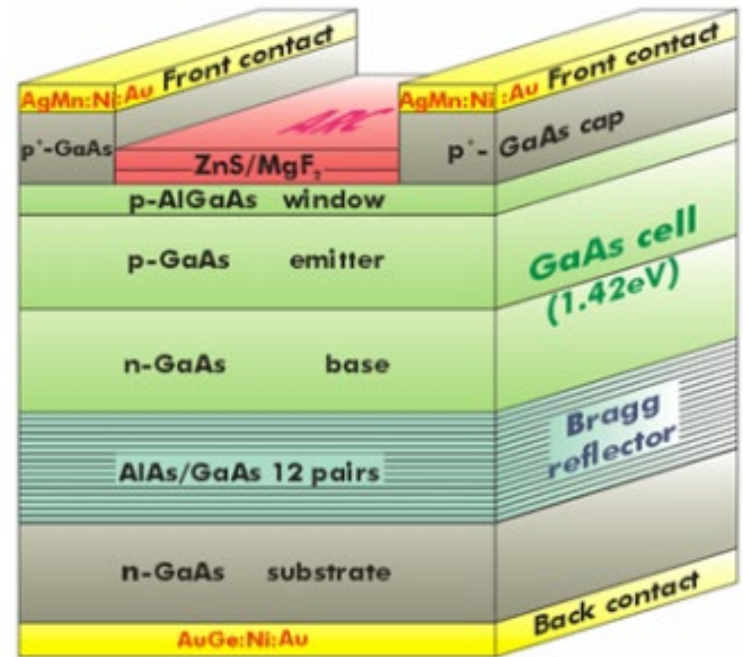
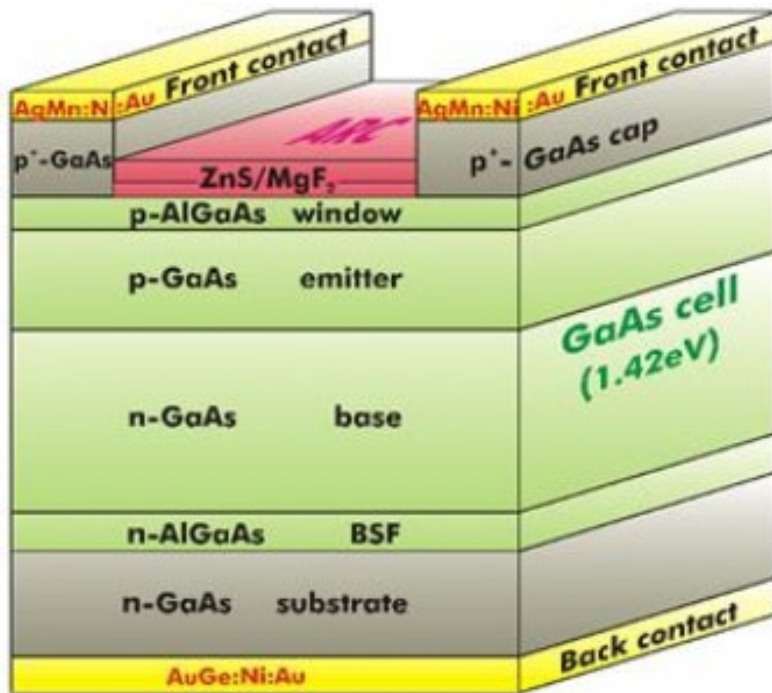
Image from <https://www.tf.uni-kiel.de>

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)

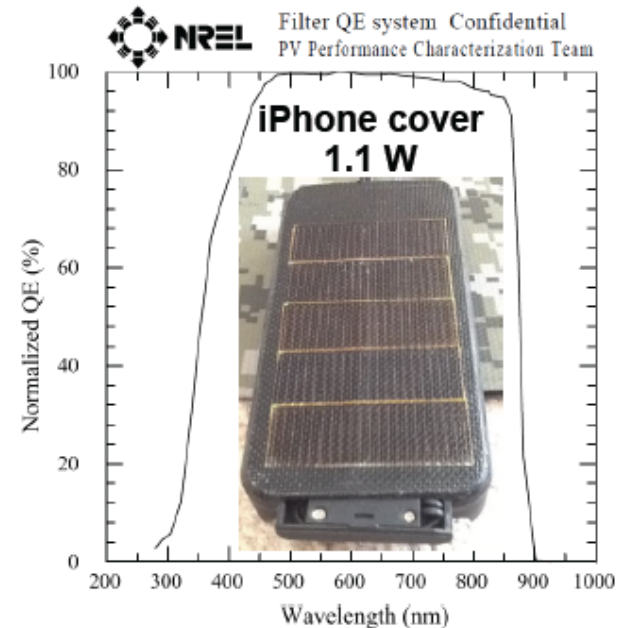
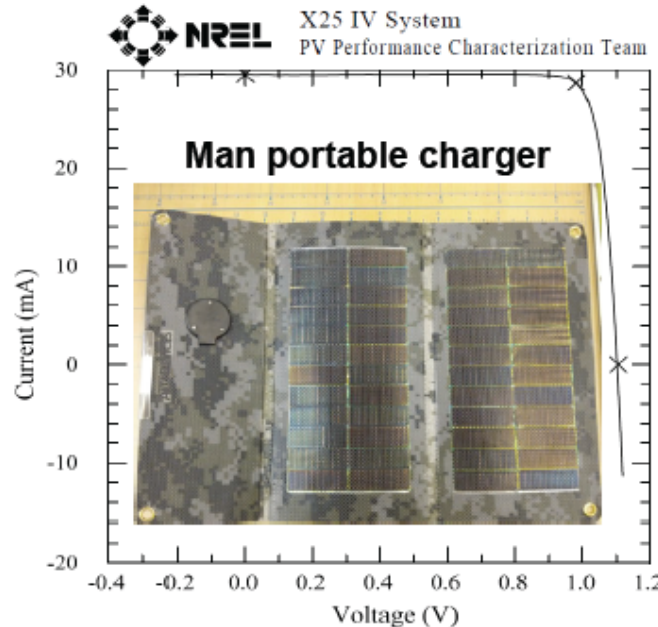
GaAs single junction cells



w/ Bragg reflector

GaAs cells from Alta Devices

Single crystal thin film GaAs solar cells and modules



• Cell efficiency $\eta = 28.8\%$ @ 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

Multi-junction III-V cells

Spectral mismatch for single-junction cells

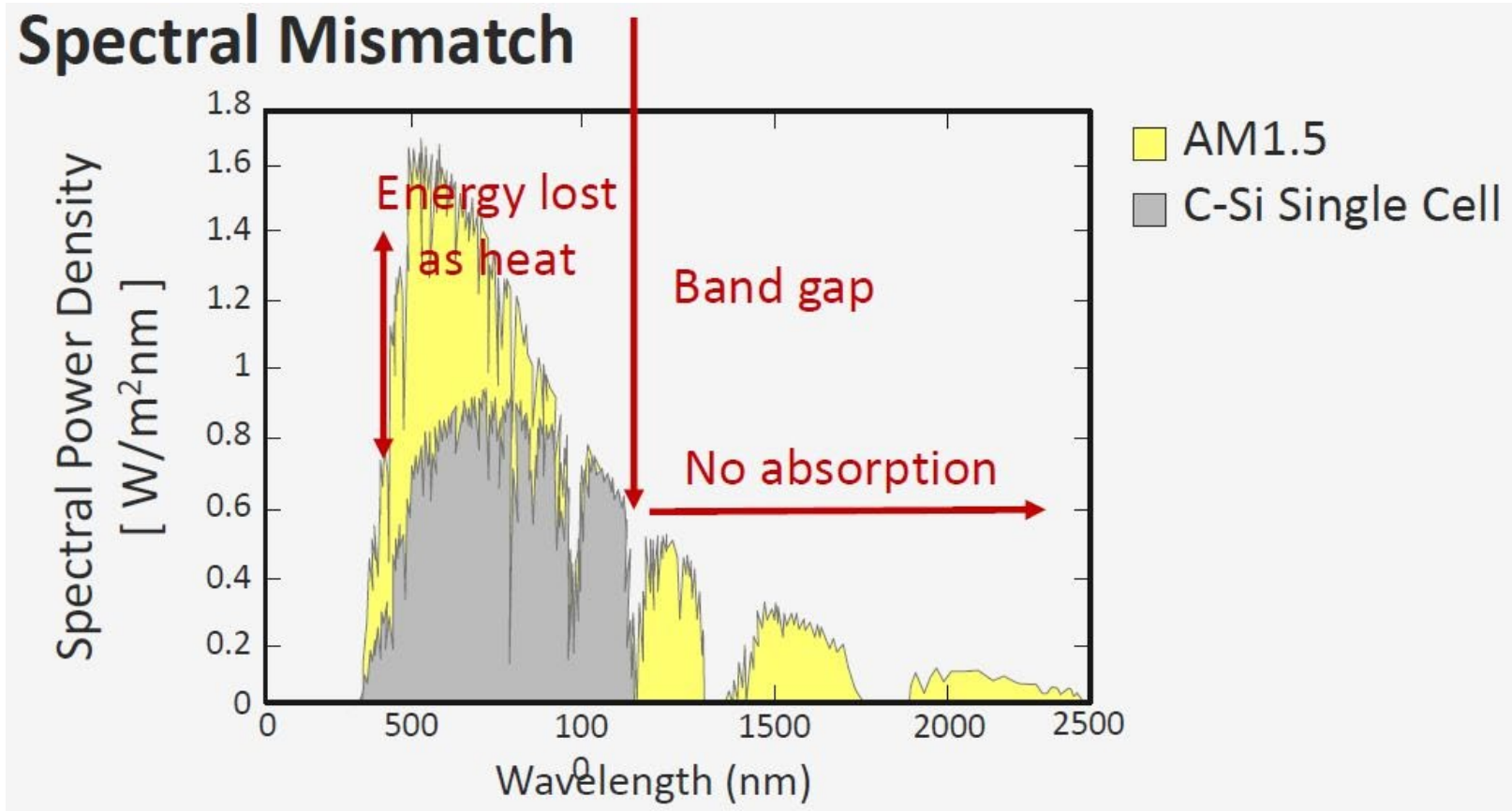
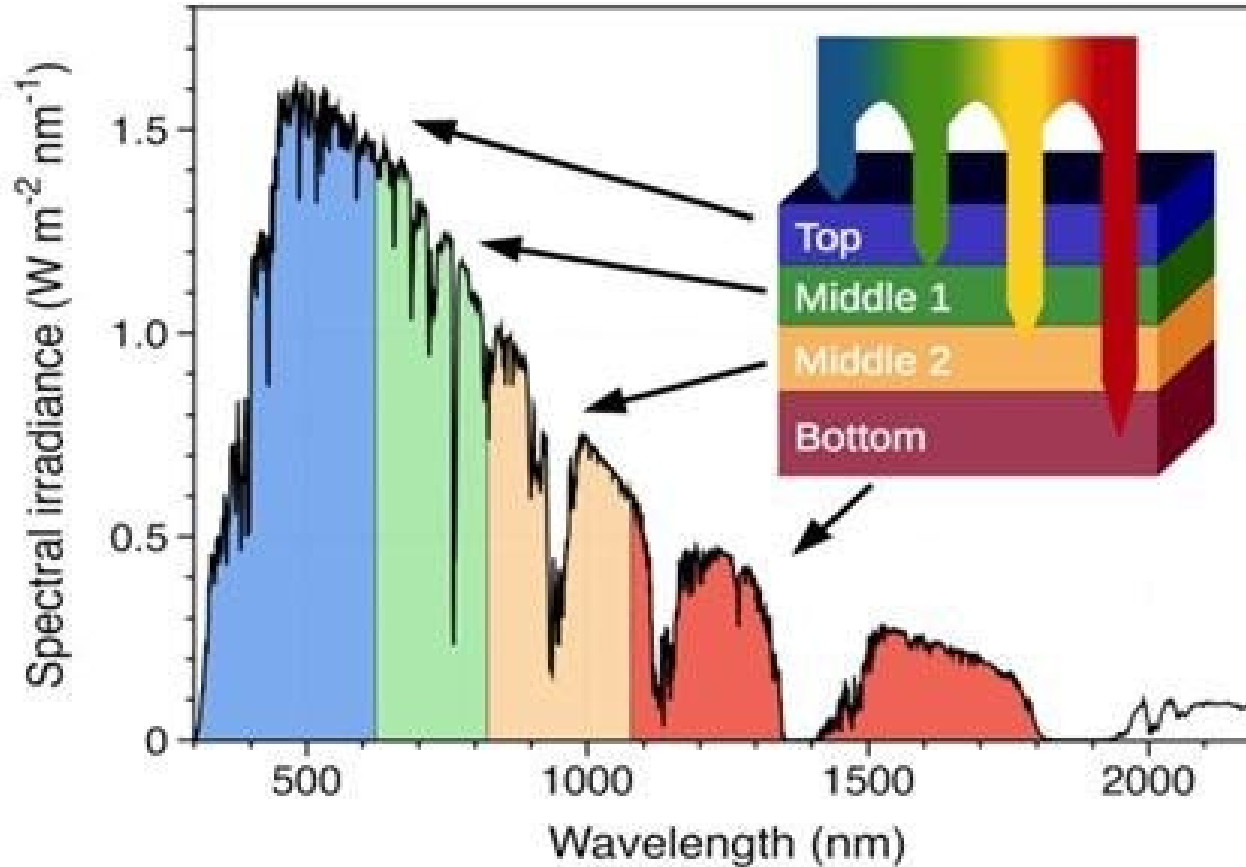


Image from : <http://maxloosolarenergy.blogspot.com/2016/12/spectral-utilization-ii-shockley.html>

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

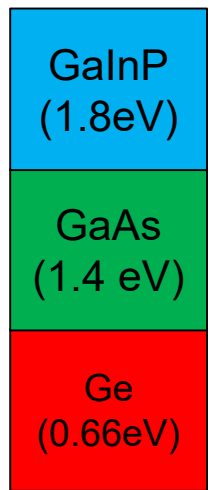
Multi-junction solar cells



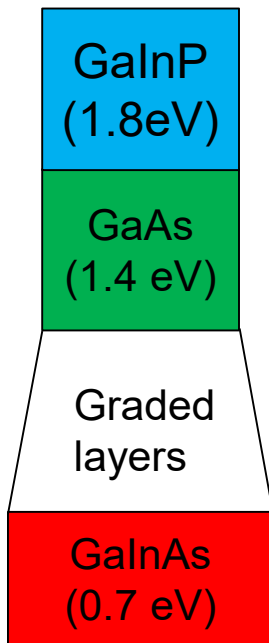
- Better utilization of the solar spectrum in multi-junction cells

Multi-junction approaches

Monolithic

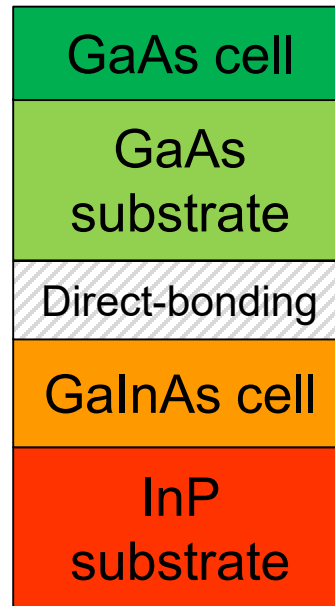


Lattice
matched



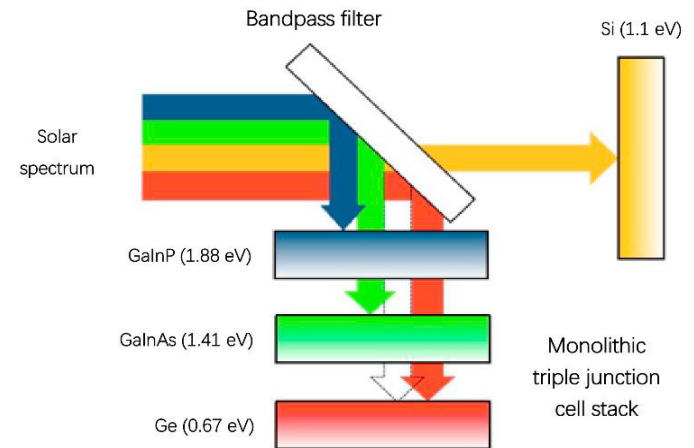
Metamorphic
(lattice mismatched)

Mechanical stack



Tanabe et al., APL 89, 102106, 2006

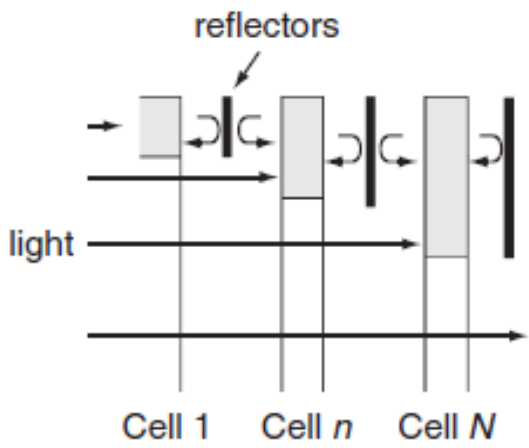
Spectrum splitting



D. Lan, M. Green, SNEC 2018

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

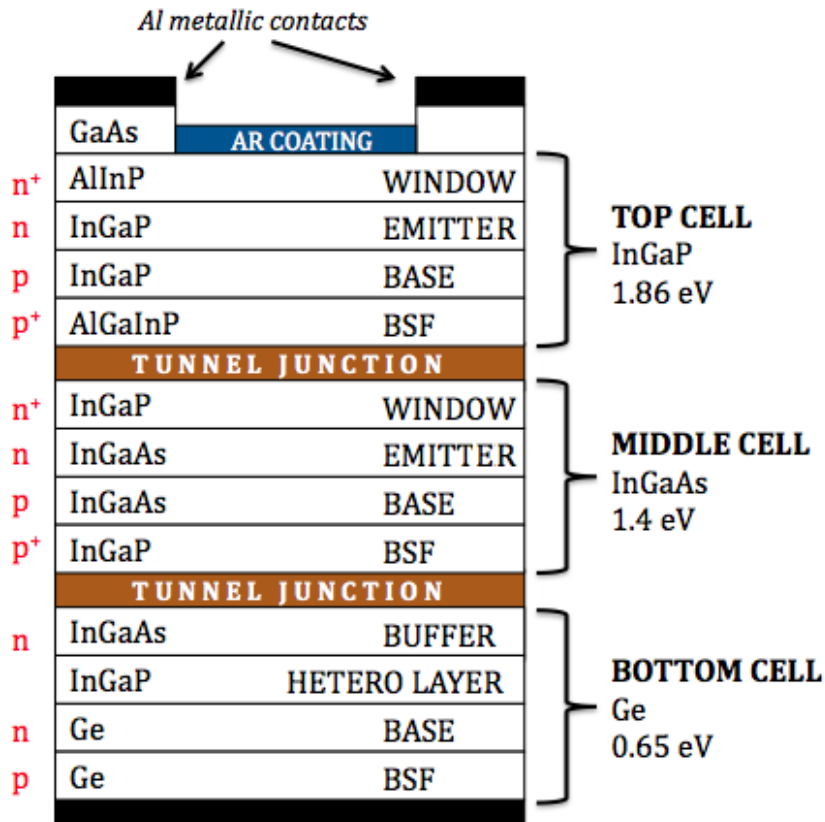
Maximum efficiency for multi-junction cells



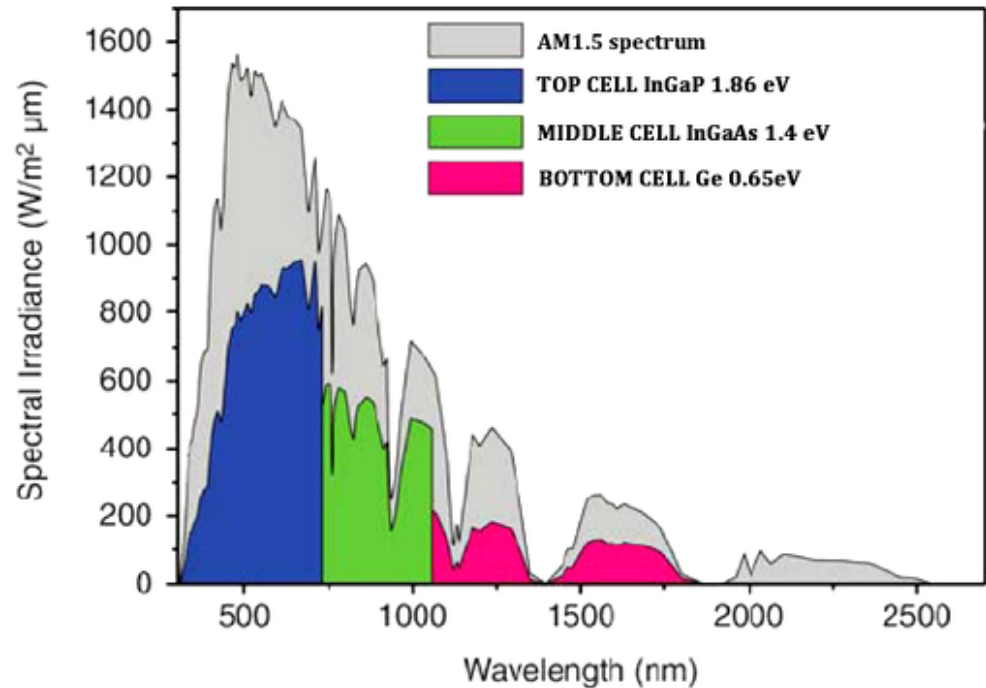
N. cells	Description	Reflectors?	Optimum gaps (eV)				Eff (%)
			<i>E1</i>	<i>E2</i>	<i>E3</i>	<i>E4</i>	
(AM1.5 direct normal irradiance)							
1	1 sun, no angular restriction	Yes	1.13	-	-	-	32.5
	1 sun no angular restriction	No	1.13	-	-	-	32.5
	Maximum concentration	Yes	0.94	-	-	-	44.6
	Maximum concentration	No	0.94	-	-	-	44.6
2	1 sun, no angular restriction	Yes	0.94	1.64	-	-	44.3
	1 sun no angular restriction	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
3	1 sun, no angular restriction	Yes	0.71	1.16	1.83	-	50.1
	1 sun no angular restriction	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
4	1 sun, no angular restriction	Yes	0.71	1.13	1.55	2.13	54.0
	1 sun no angular restriction	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 restriction	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)
top subcell	top contact	Ag		3
	contacting layer (n^{++})	Ga(In)As	1.39	0.5
	antireflection coat	$\text{TiO}_2/\text{Al}_2\text{O}_3$		0.2
	window (n)	AlInP	2.3	0.03
	emitter (n^+)	GaInP	1.85	0.1
tunnel junction	base (p)	GaInP	1.85	0.5 to 1.5
	back-surface field (p)	AlGaInP	1.88	0.1
middle subcell	p^{++}	AlGaAs	1.9	0.1
	n^{++}	GaInP	1.9	0.1
	window (n)	GaInP	1.85	0.1
	emitter (n)	Ga(In)As	1.39	0.1
	base (p)	Ga(In)As	1.39	3
tunnel junction	back-surface field (p)	GaInP	1.85	0.1
	p^{++}	AlGaAs	1.9	0.1
	n^{++}	GaInP	1.9	0.1
	window (n)	GaInP	1.85	0.1
	emitter (n^+)	Ge (P-diffused)	0.67	0.05
bottom subcell	base (p)	Ge (substrate)	0.67	200
	back-surface field (p)	none		
	back contact	Ag		

Tunnel junction

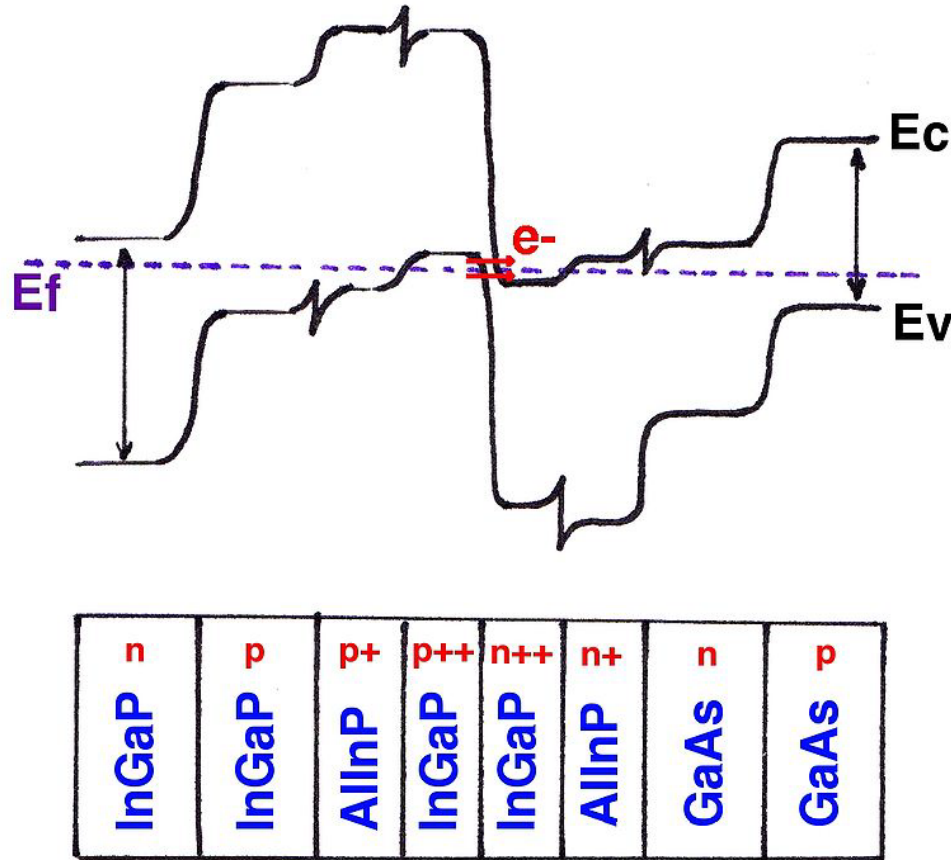
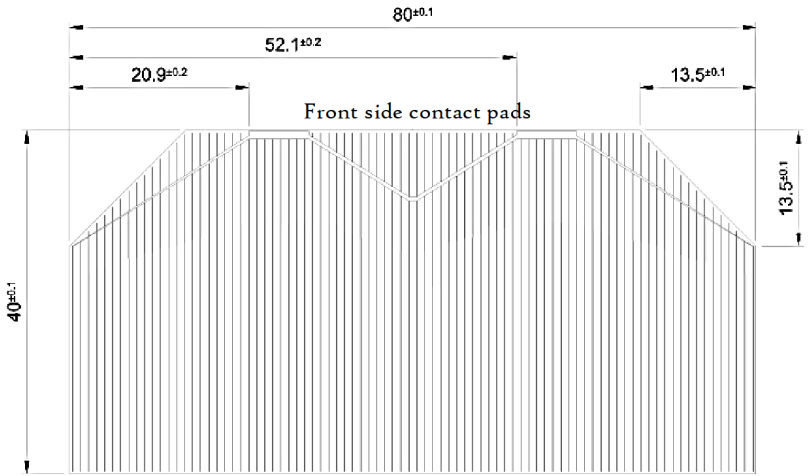
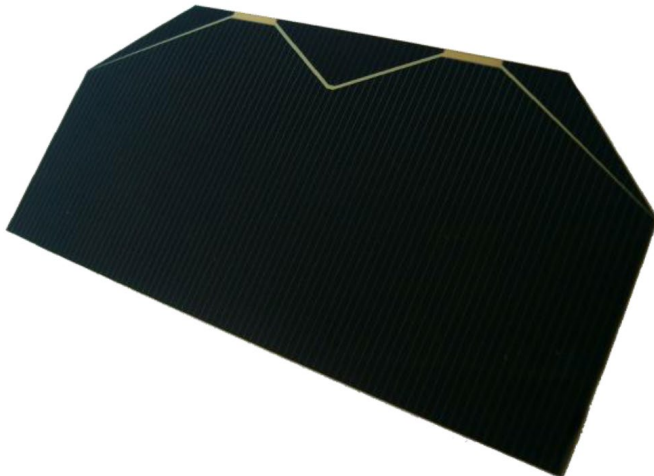


Image: www.Wikipedia.com

- 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	GaNP/GaAs/Ge on Ge substrate
AR-coating	TiO _x /Al ₂ O 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

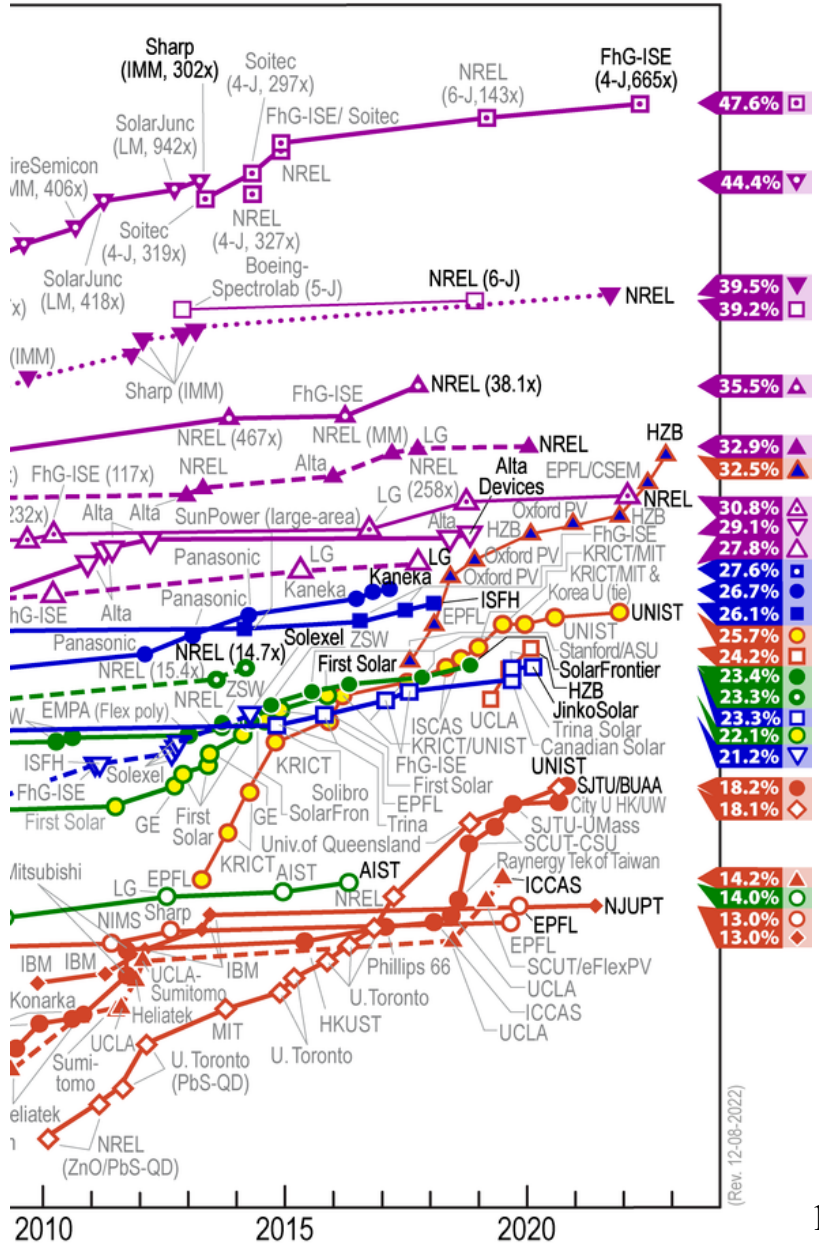
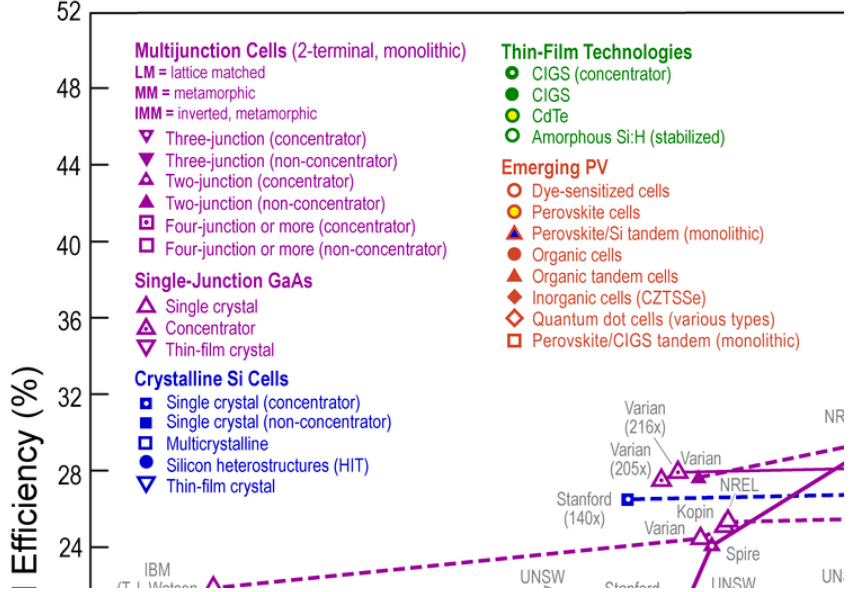
Parameters given for Begin of life (BOL) and End of life (EOL) after different electron fluence

Standard: CASOLBA 2005 (05-20MV1, etc); Spectrum: AMO WRC = 1367 W/m²; T = 28 °C @fluence 1MeV [e/cm²]

Efficiency chart

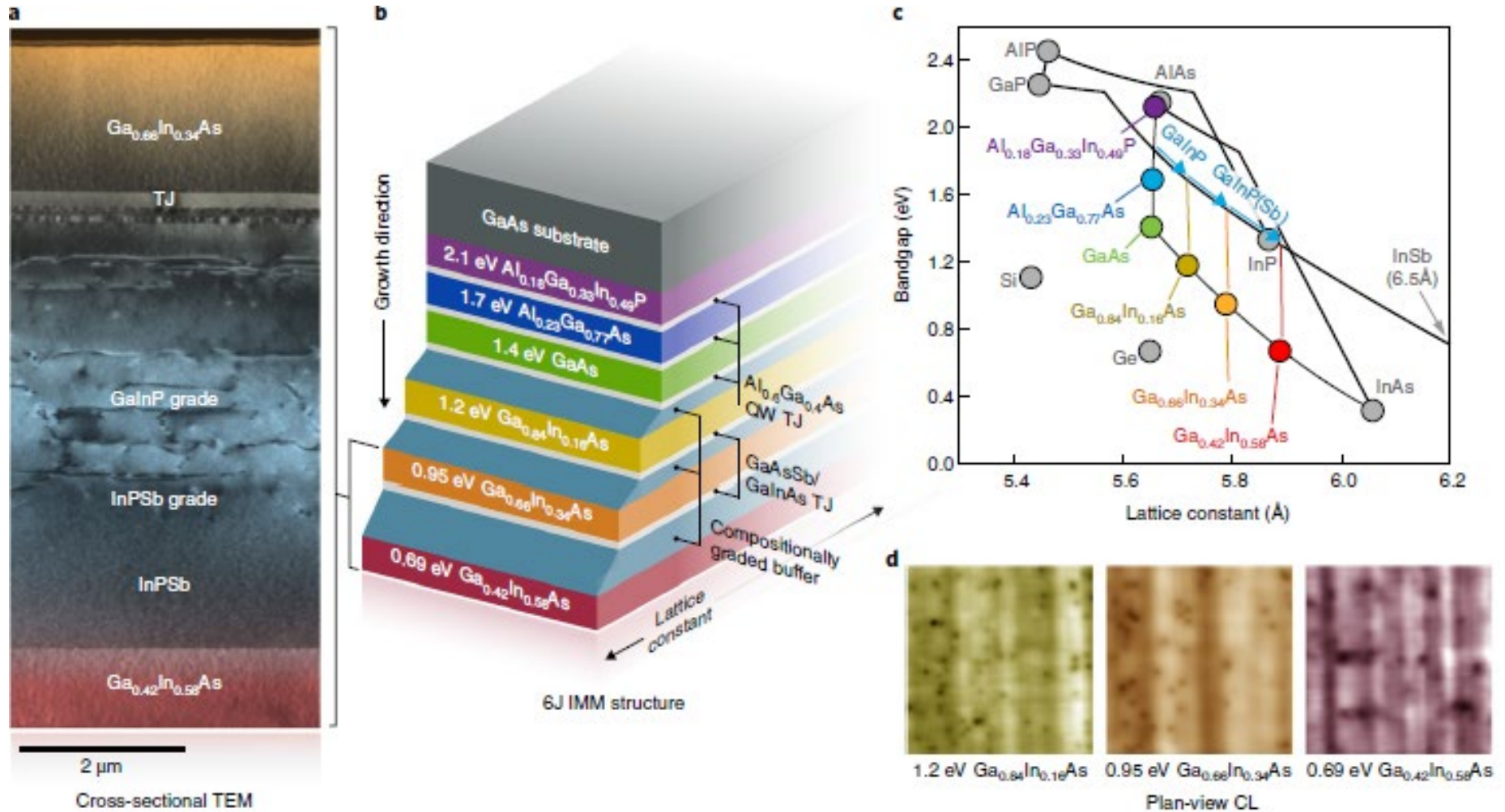


Best Research-Cell Efficiencies

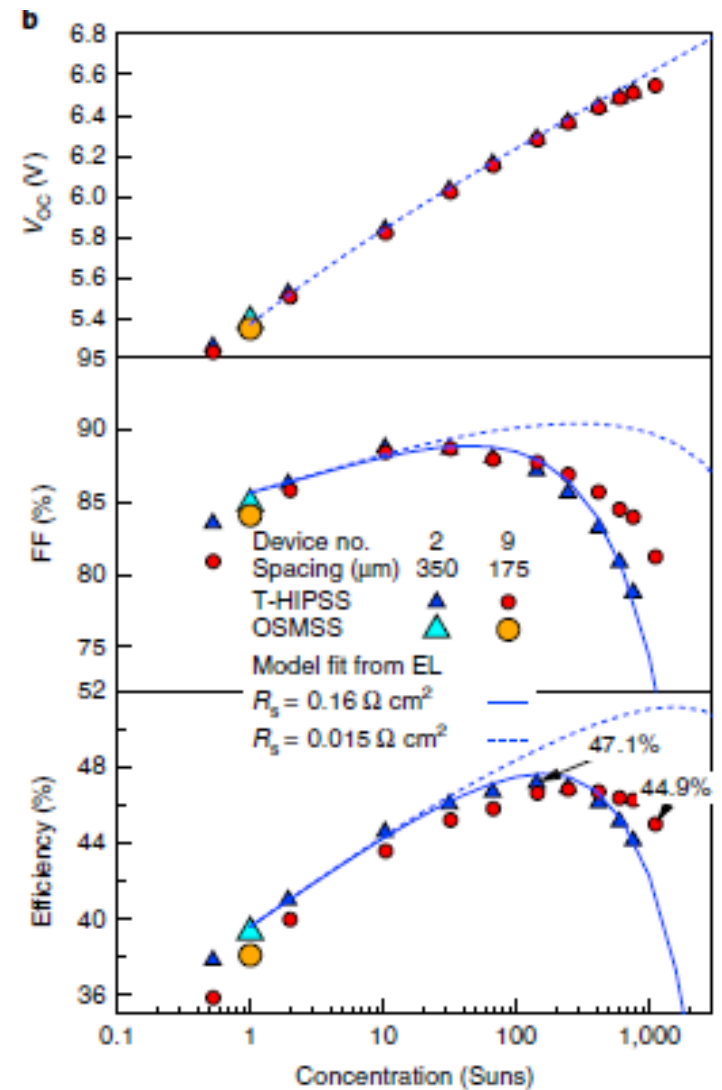
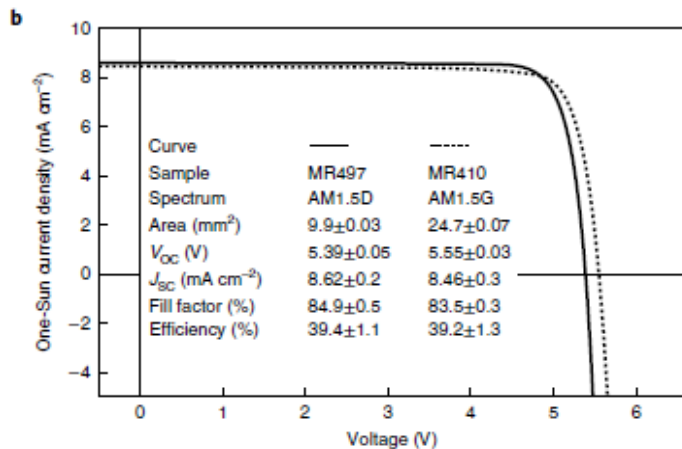
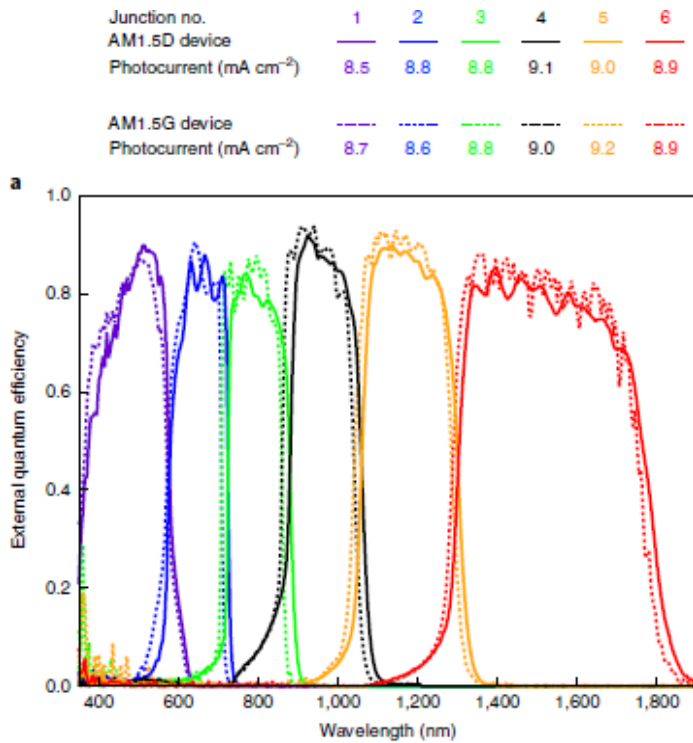


Source: NREL chart, November 2022

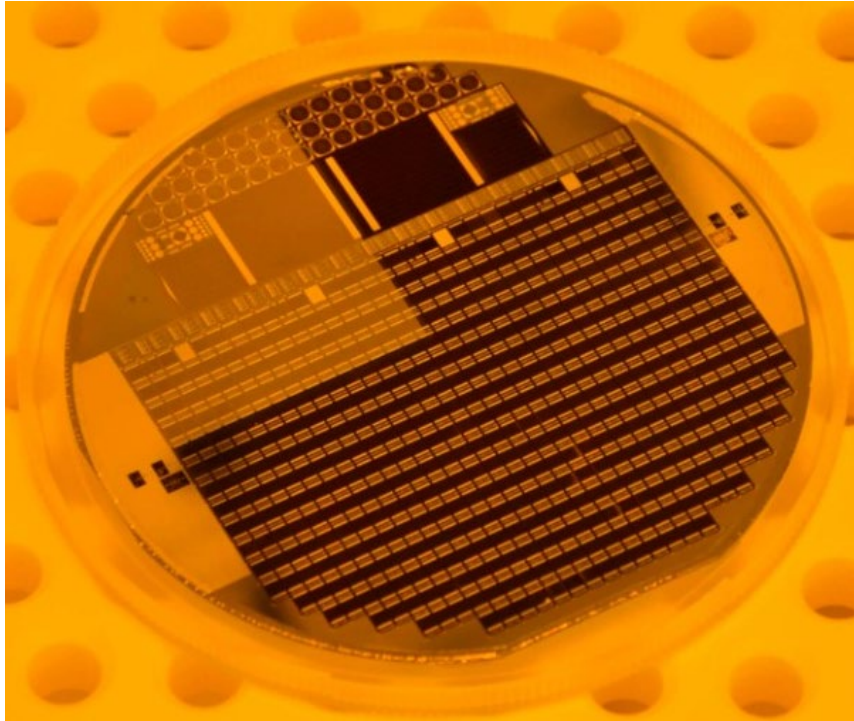
x6 junction solar cell – 47.1% (NREL, 2020)



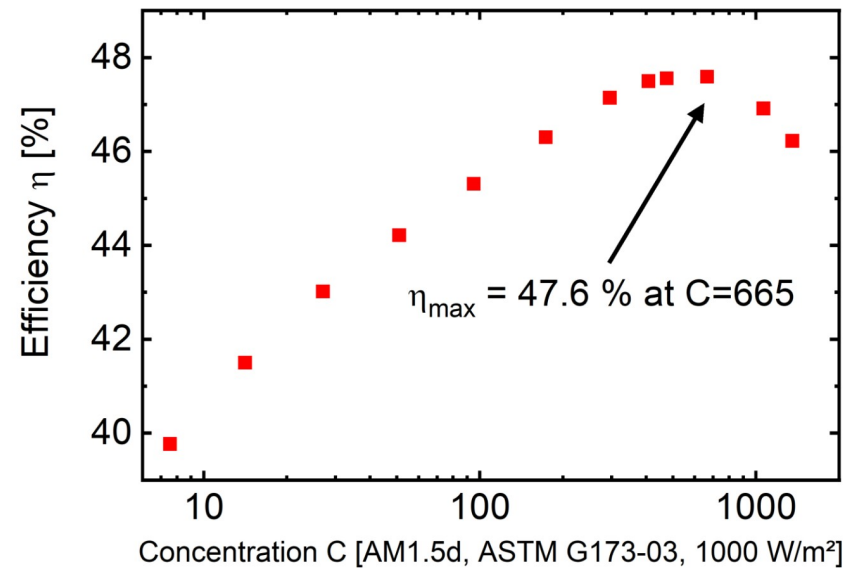
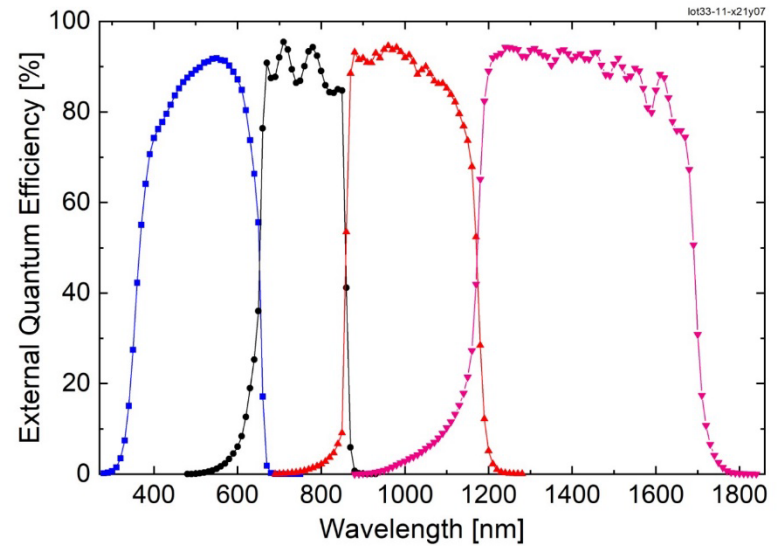
X6 junction with 47.1% efficiency



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

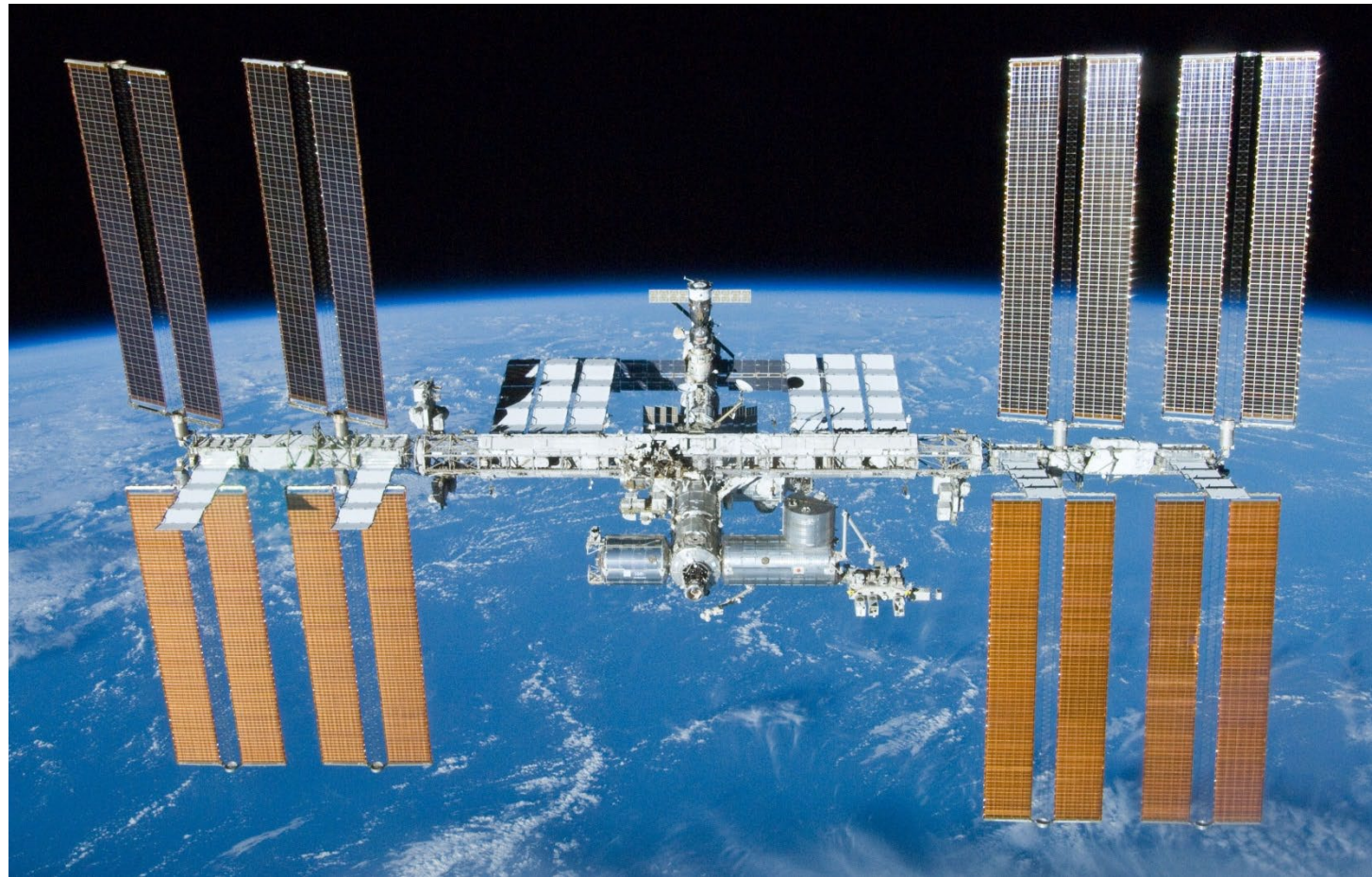


Fraunhofer ISE, May 2022



Solar cells for space

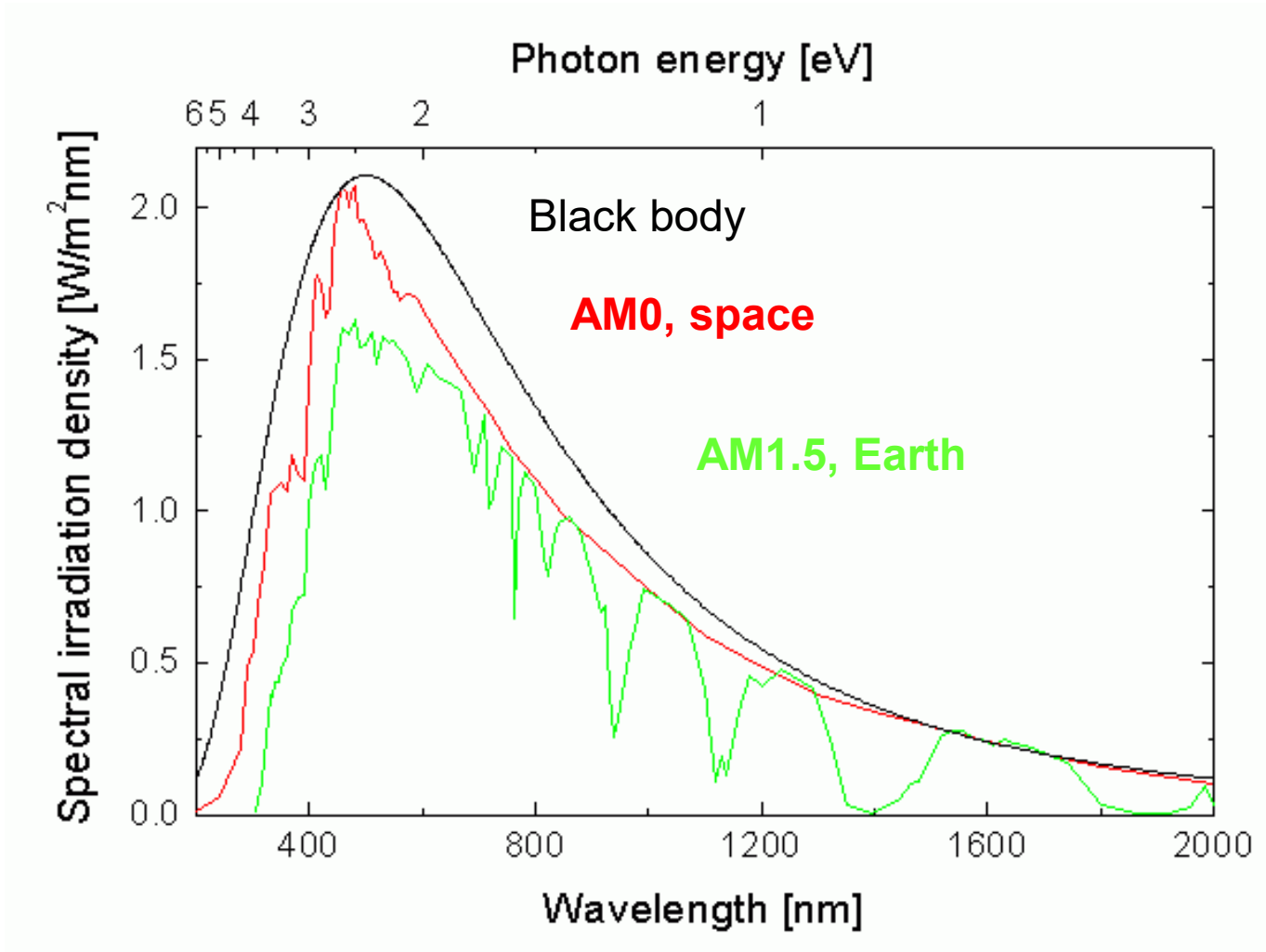
Solar Power Generation in Space



Vanguard 1
(USA, 1958 - 1964)

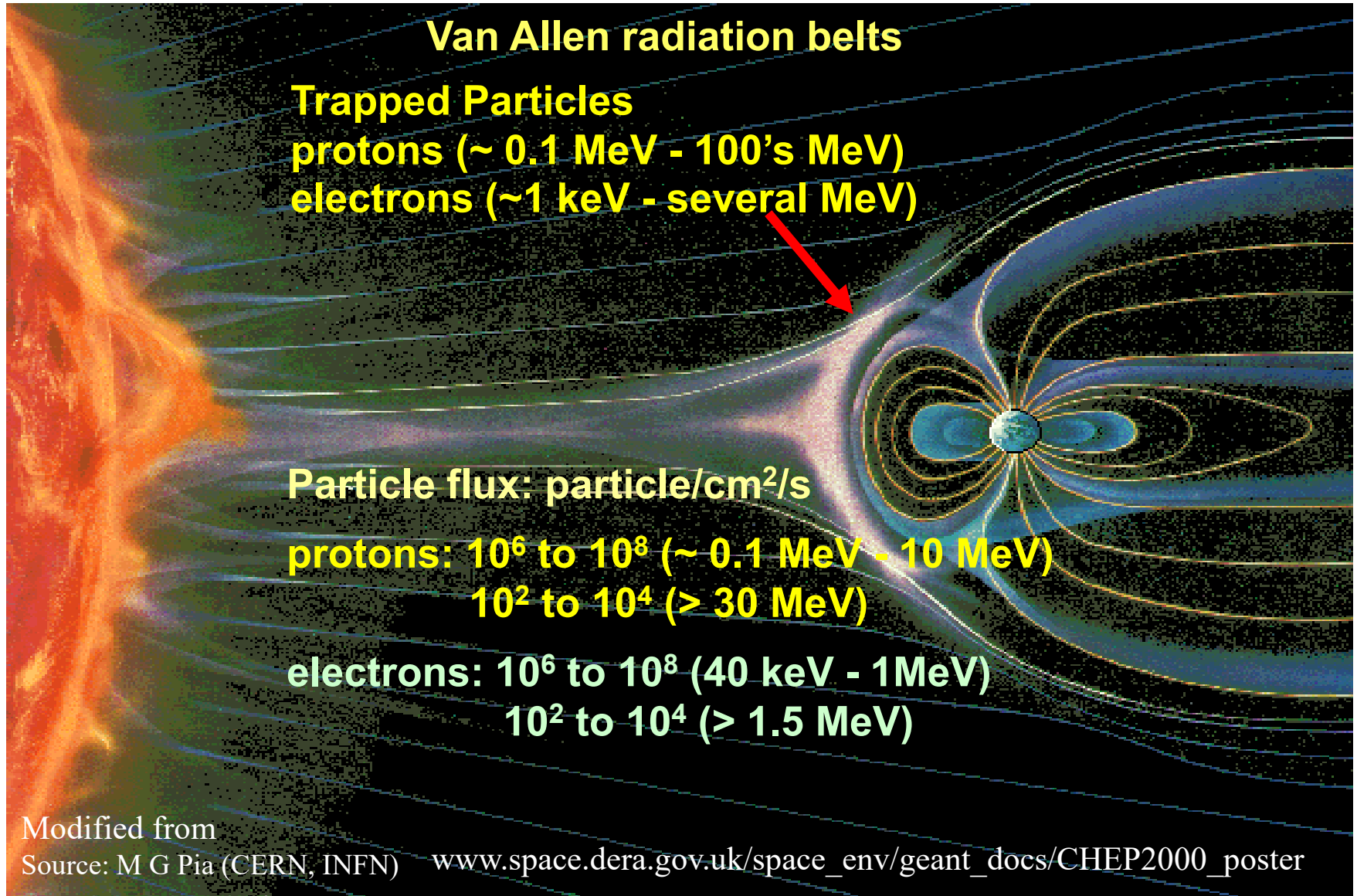
International Space Station (ISS), 1998-

Solar radiation in space

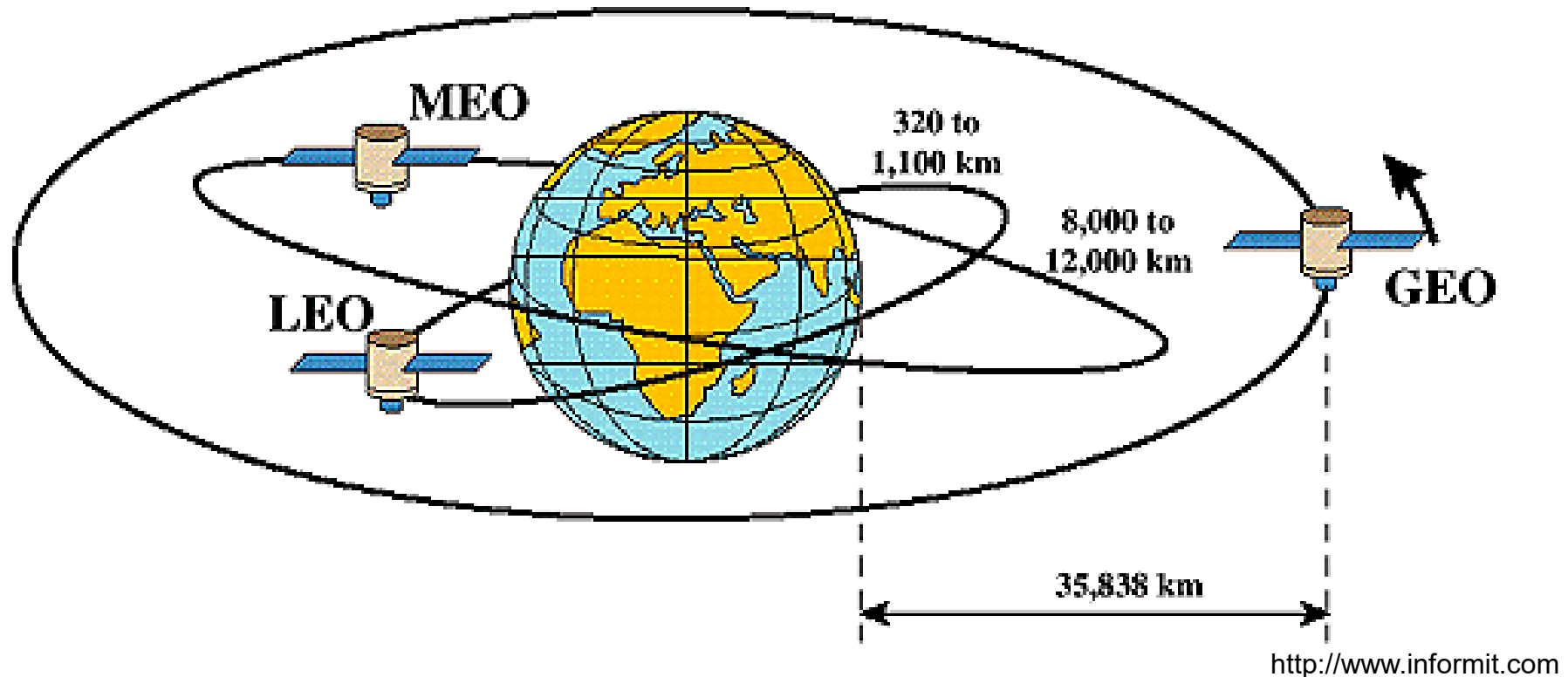


AM0 solar spectrum in space (outside Earth's atmosphere): 1353 W/m²

Particle fluxes near the Earth



Satellite orbits

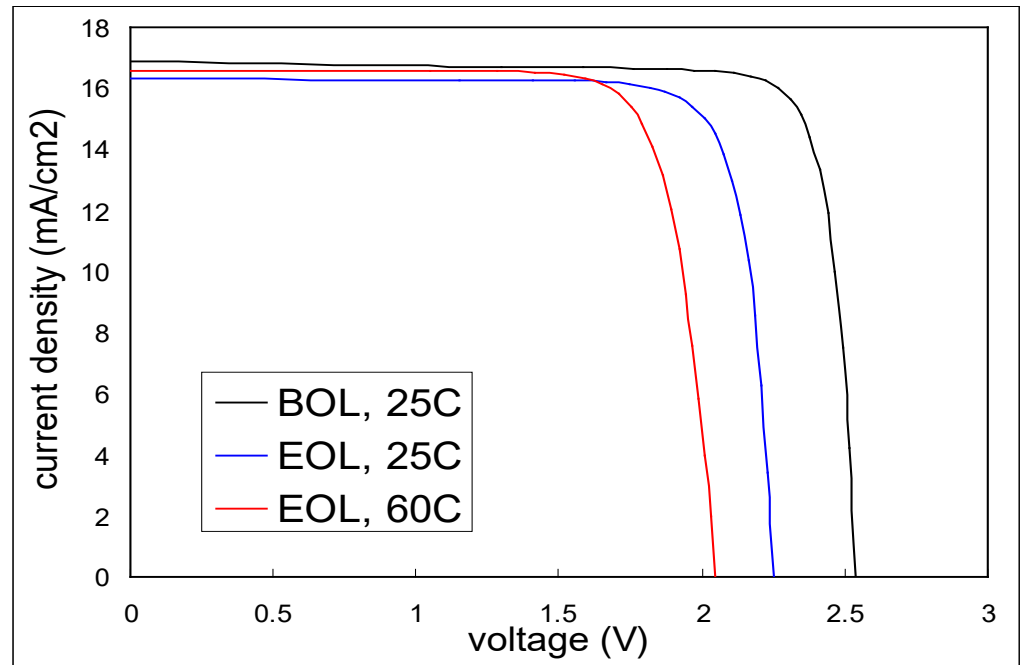


- PV power requirement for a telecom satellite~ 10kW
- Weight 20...200 kg (array specific power 45W/kg)
- can add \$1....10 Mio\$ to the launch cost for GEO

Cell degradation in space

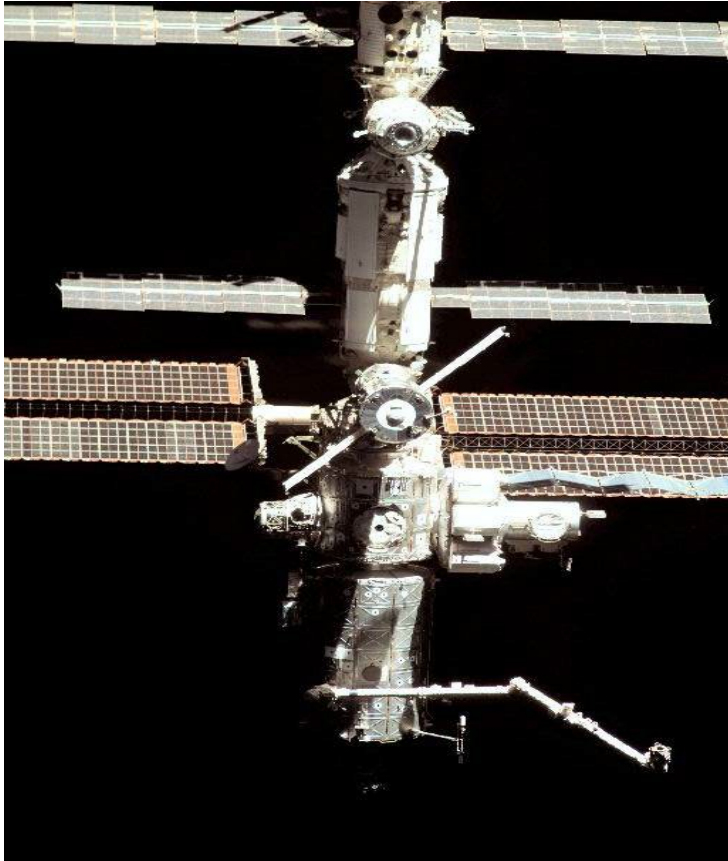
Efficiency degradation in space due to electron and proton irradiation

- 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



S108E9634_2001:12:15 16:25:29

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



Radiation Degradation (Fluence 1MeV Electrons/cm²)

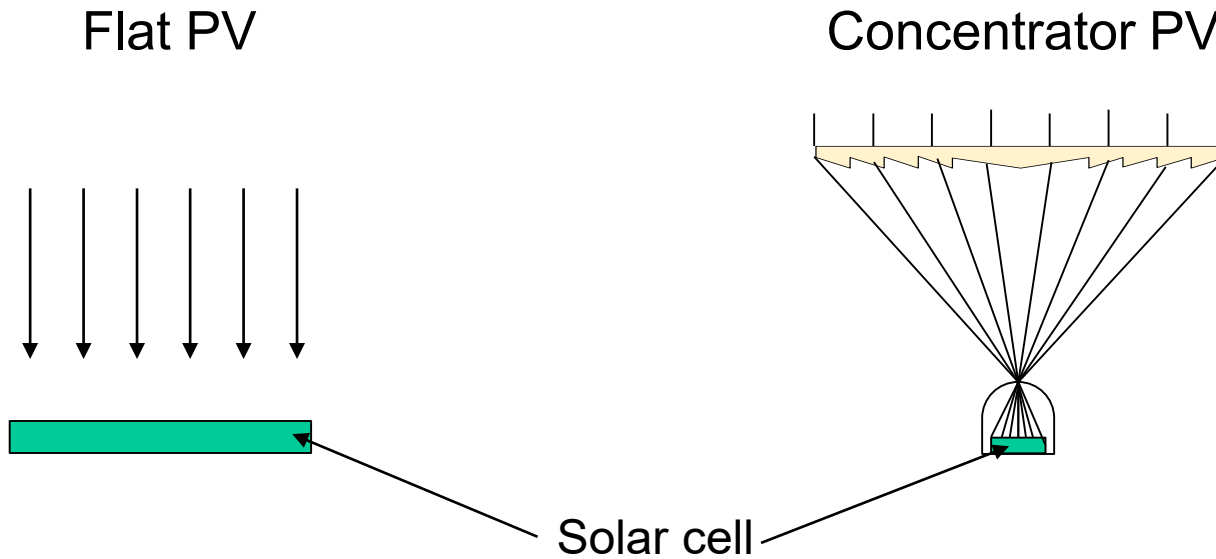
Parameters	1x10 ¹⁴	5x10 ¹⁴	1x10 ¹⁵
I _{mp} /I _{mp0}	1.00	0.99	0.95
V _{mp} /V _{mp0}	0.94	0.91	0.89
P _{mp} /P _{mp0}	0.95	0.90	0.85

Concentrator PV (CPV)

(not to be confused with
concentrator solar power CSP)

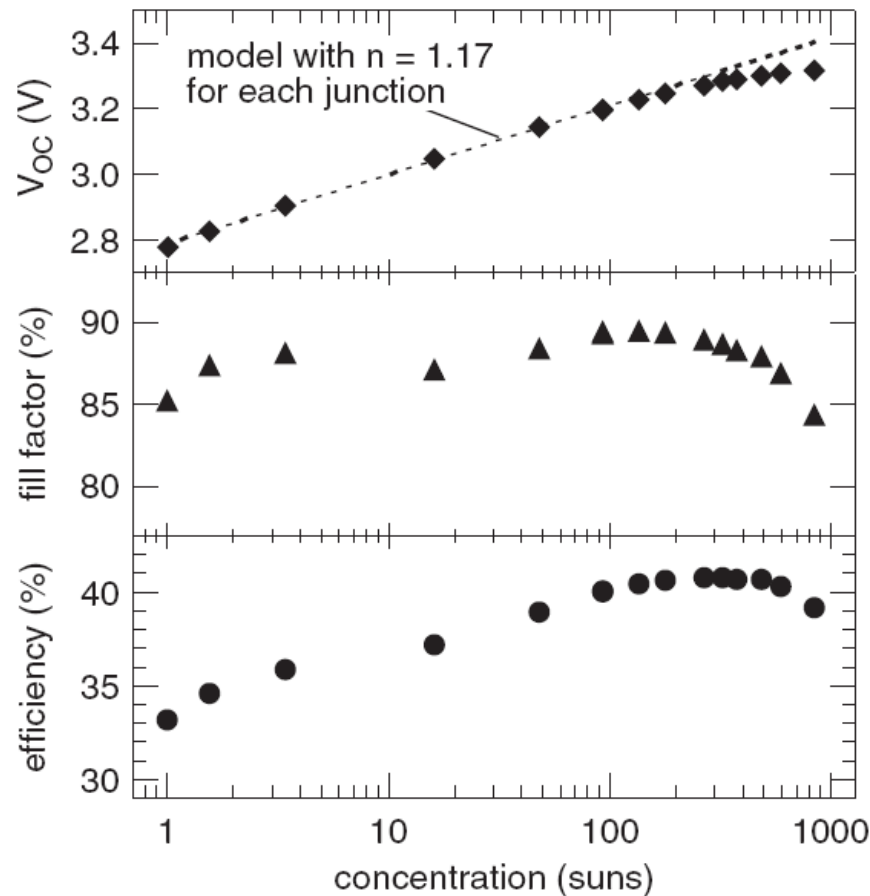
Why concentrator photovoltaics?

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

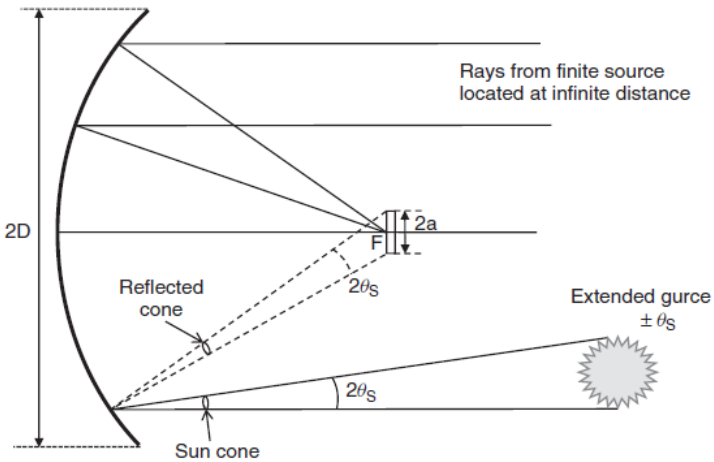


$$V_{oc} \approx \frac{kT}{q} \ln\left(\frac{I_L}{I_0}\right)$$

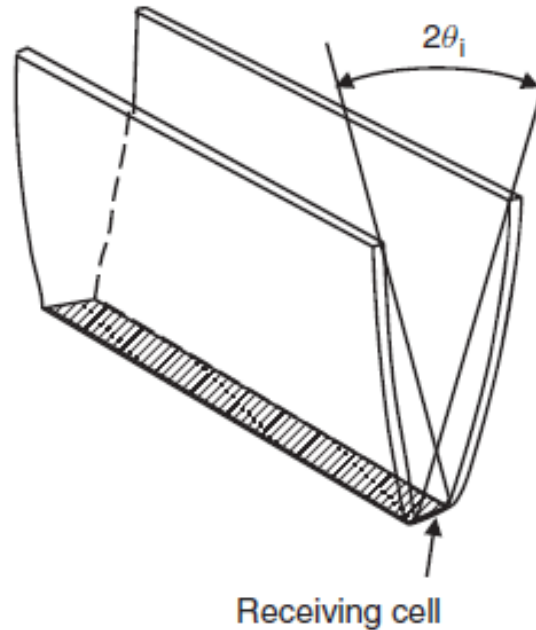
Figure 8.12 Efficiency, V_{oc} , and fill factor of state-of-the-art GaInP/Ga_{0.96}In_{0.04}As/Ga_{0.63}In_{0.37}As three-junction cell as a function of concentration. J_{sc} , not shown, is assumed to increase proportionally to concentration

Light concentrators

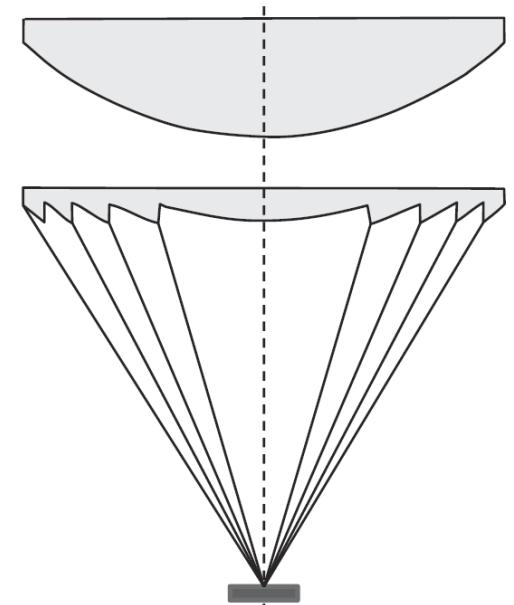
Parabolic mirror concentrator



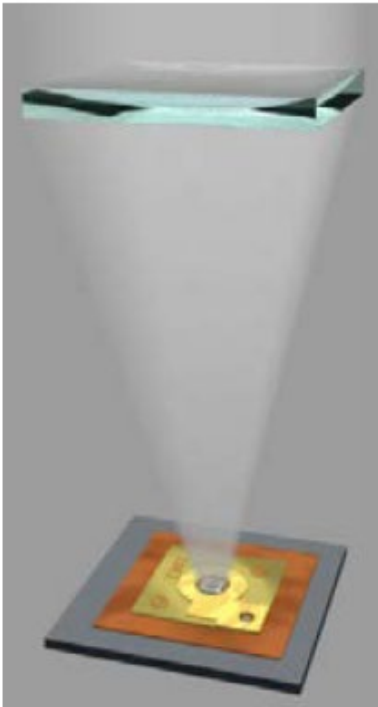
Compound parabolic concentrator



Fresnel lenses

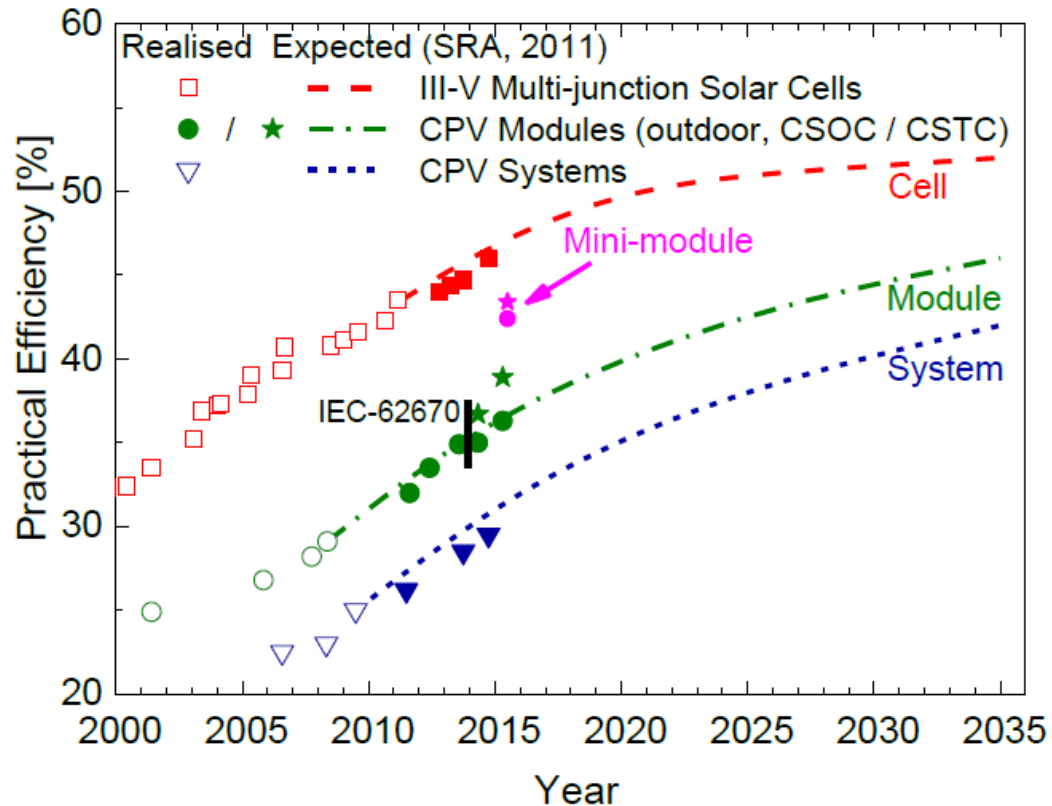


Light concentrating systems



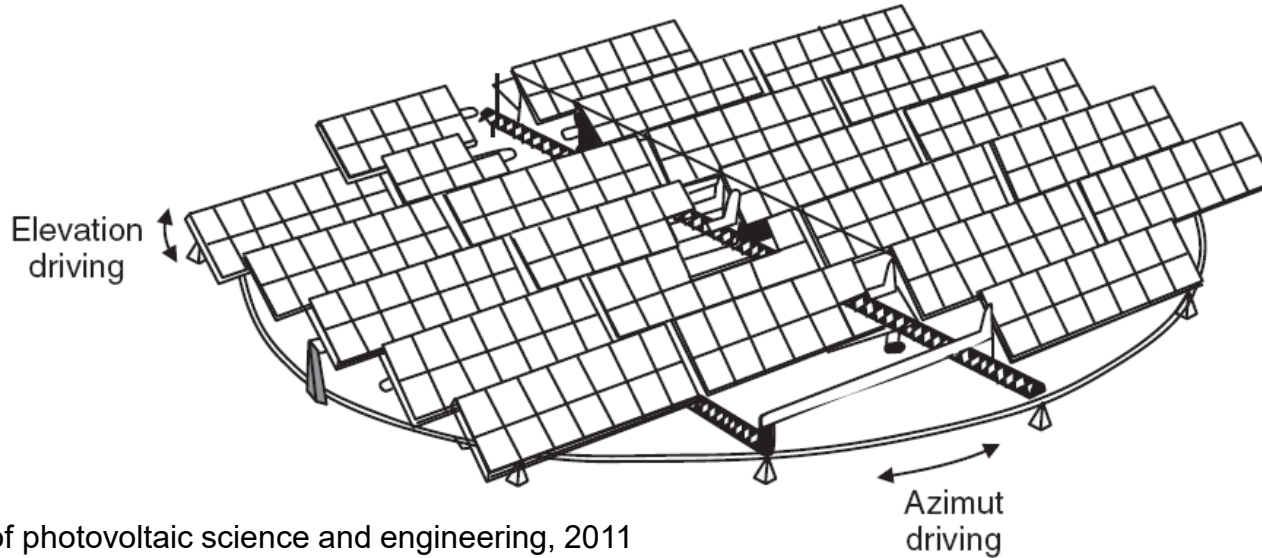
Class of CPV	Typical concentration ratio	Tracking	Type of converter
High Concentration PV (HCPV)	300-1000	Two-axis	III-V multi-junction solar cells
Low Concentration PV (LCPV)	< 100	One or two-axis	c-Si or other cells

CPV efficiency



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

Light-tracking systems

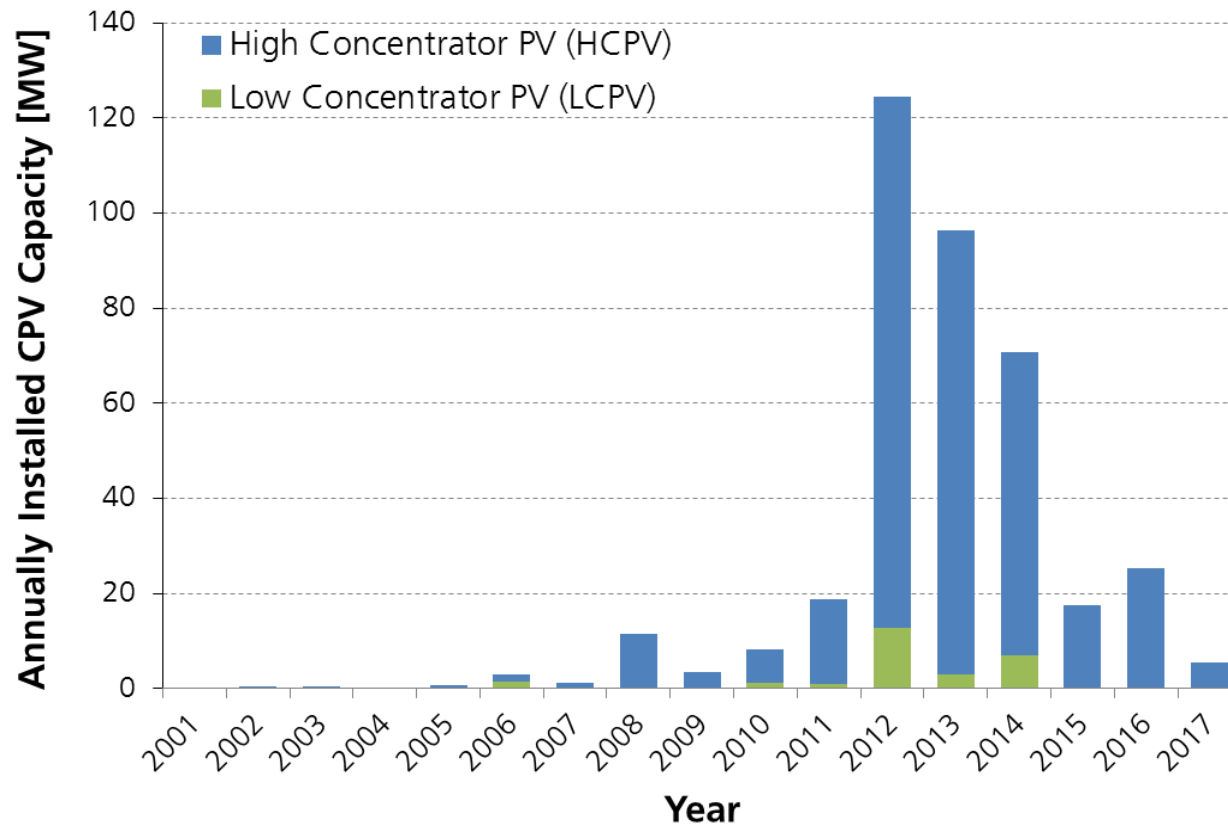


Handbook of photovoltaic science and engineering, 2011



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

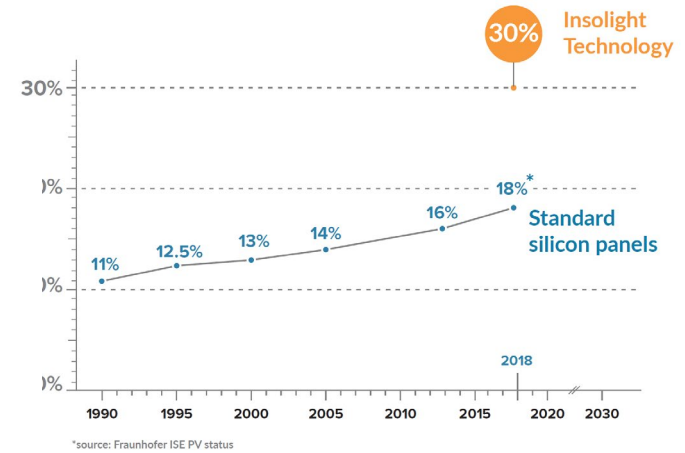
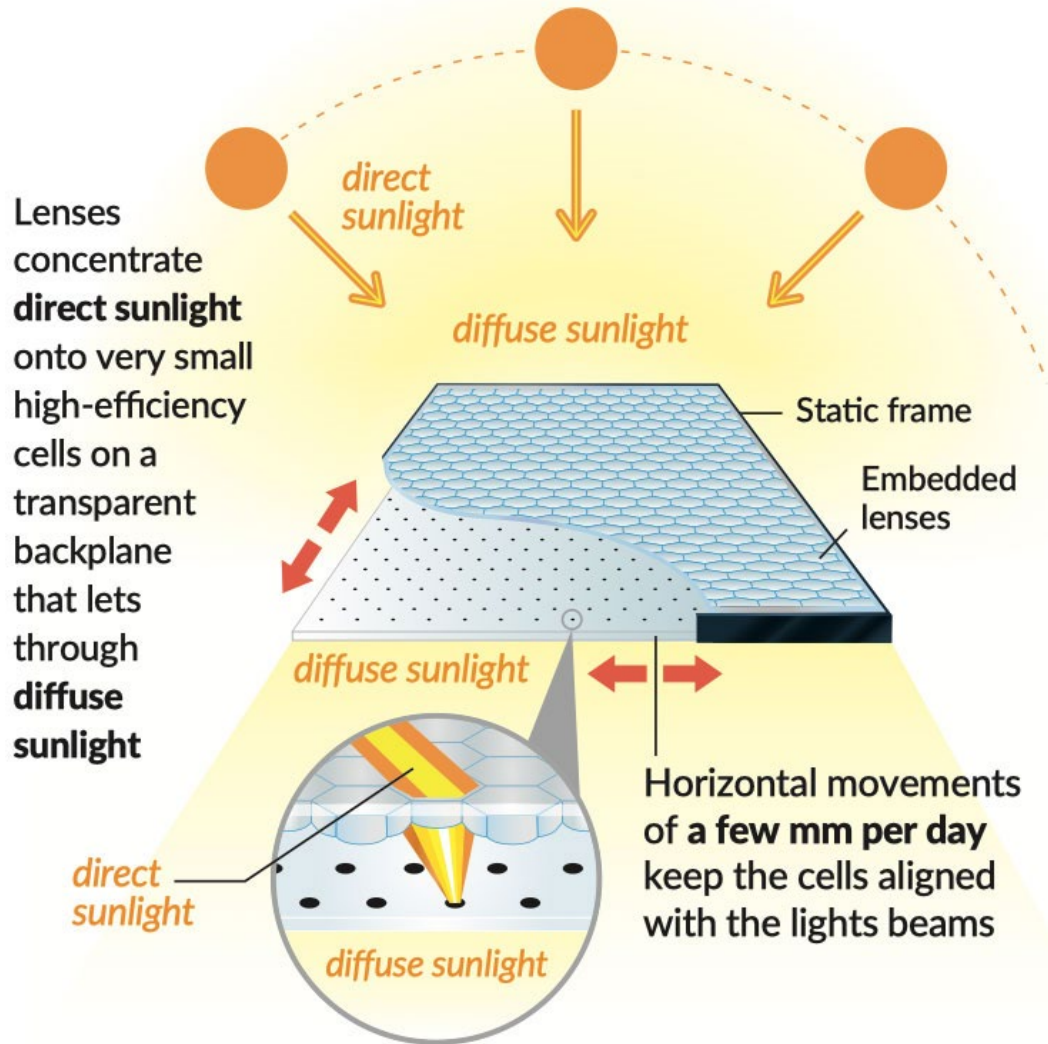
CPV installations



“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/>