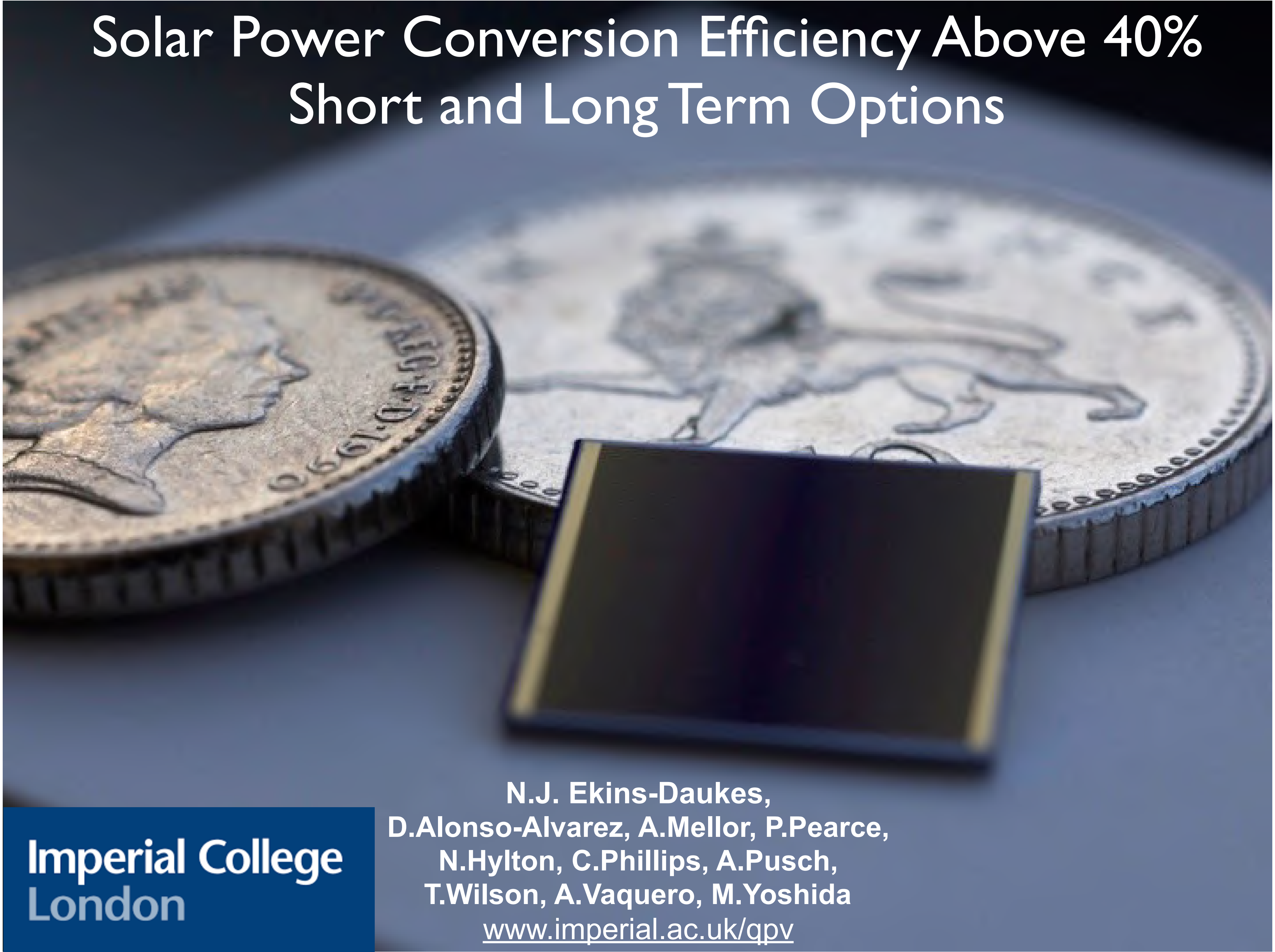
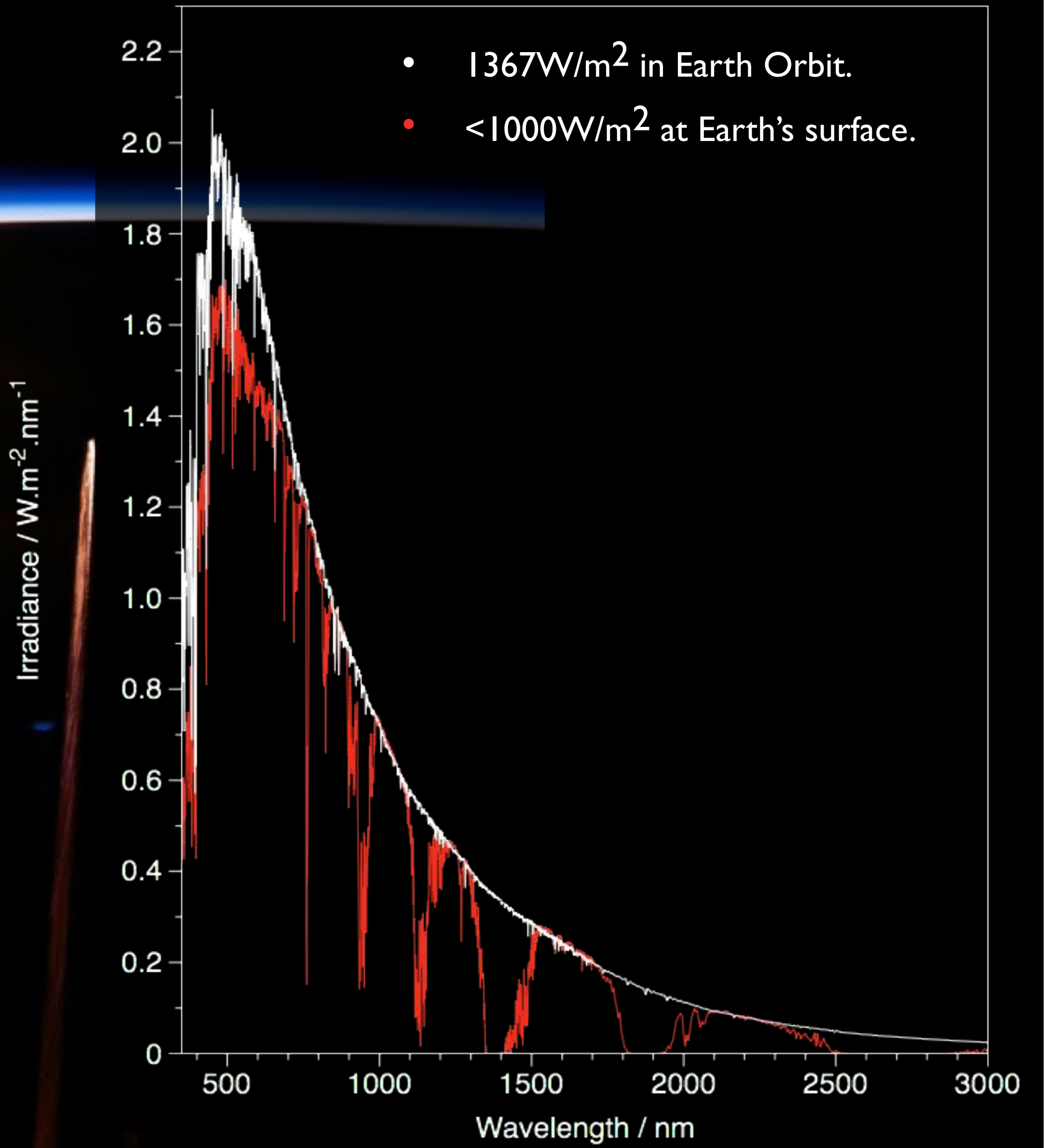
Solar Power Conversion Efficiency Above 40%
Short and Long Term Options



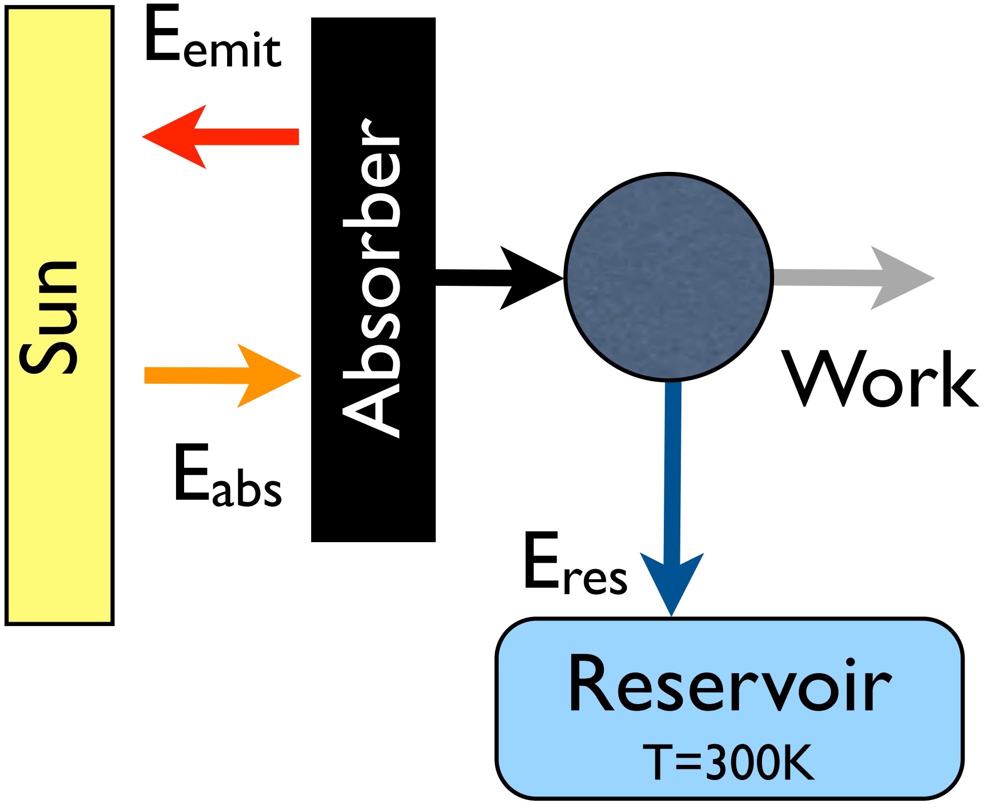
N.J. Ekins-Daukes,
D.Alonso-Alvarez, A.Mellor, P.Pearce,
N.Hylton, C.Phillips, A.Pusch,
T.Wilson, A.Vaquero, M.Yoshida
www.imperial.ac.uk/qpv

Imperial College
London



- 1367W/m^2 in Earth Orbit.
- <1000W/m^2 at Earth's surface.

General Solar Collector



Sun

E_{emit}

E_{abs}

Absorber

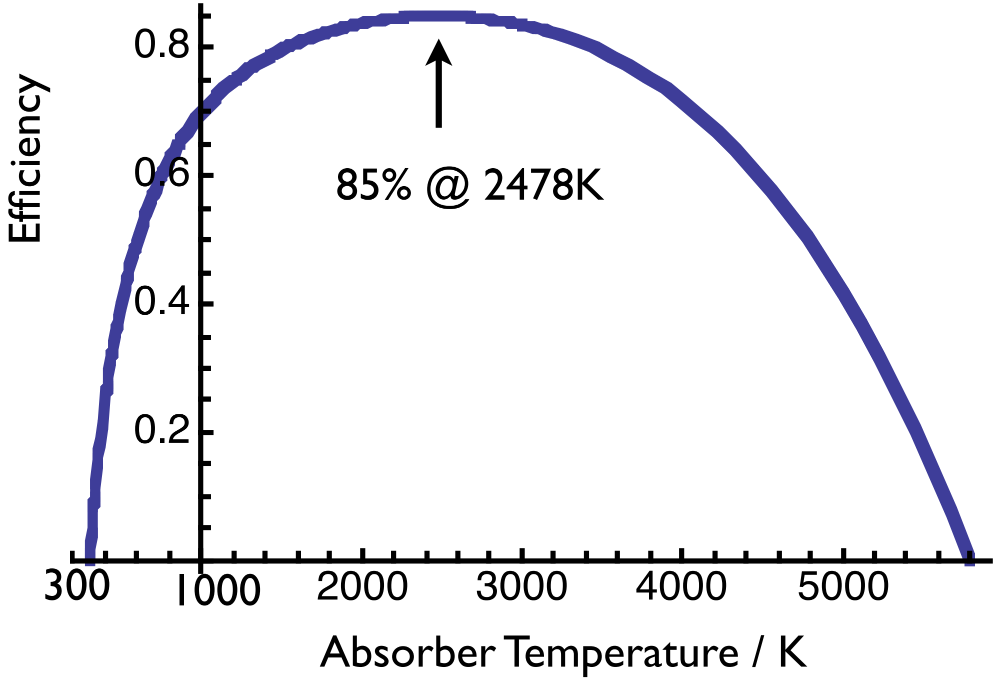
Work

E_{res}

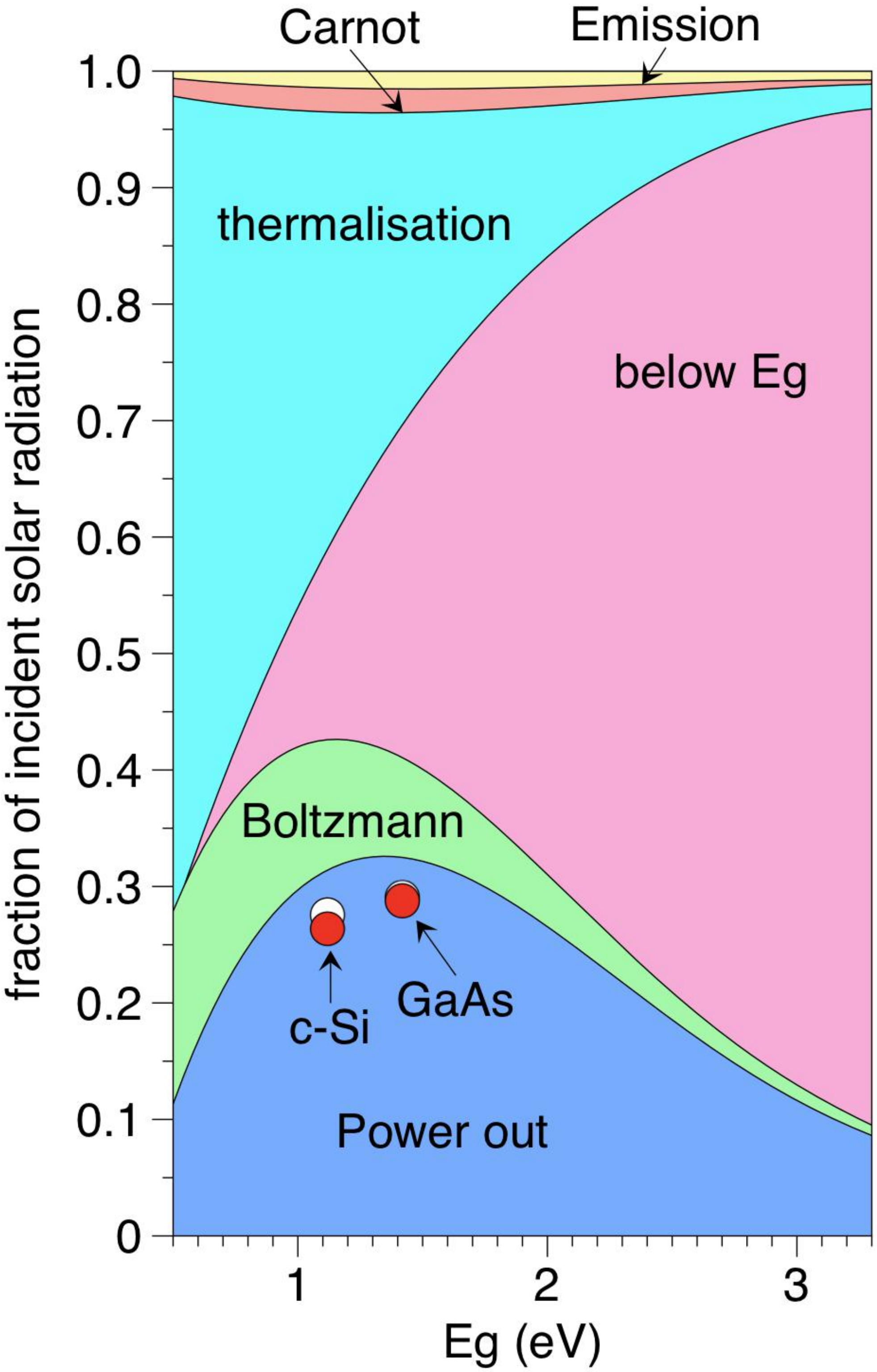
Reservoir

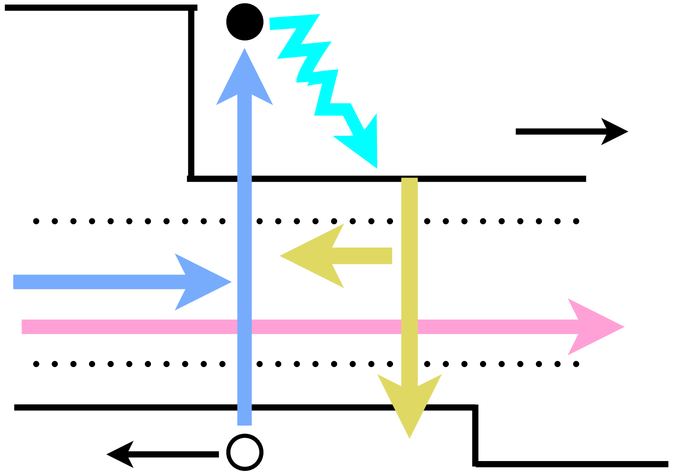
T=300K

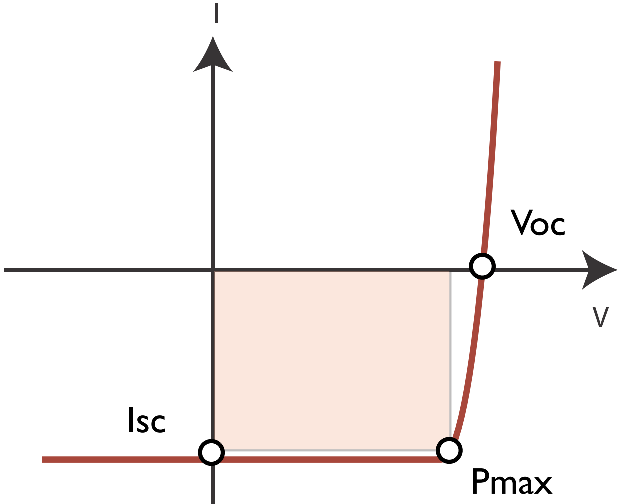
SEGS - Mojave Desert, California



The Shockley-Queisser Efficiency limit.

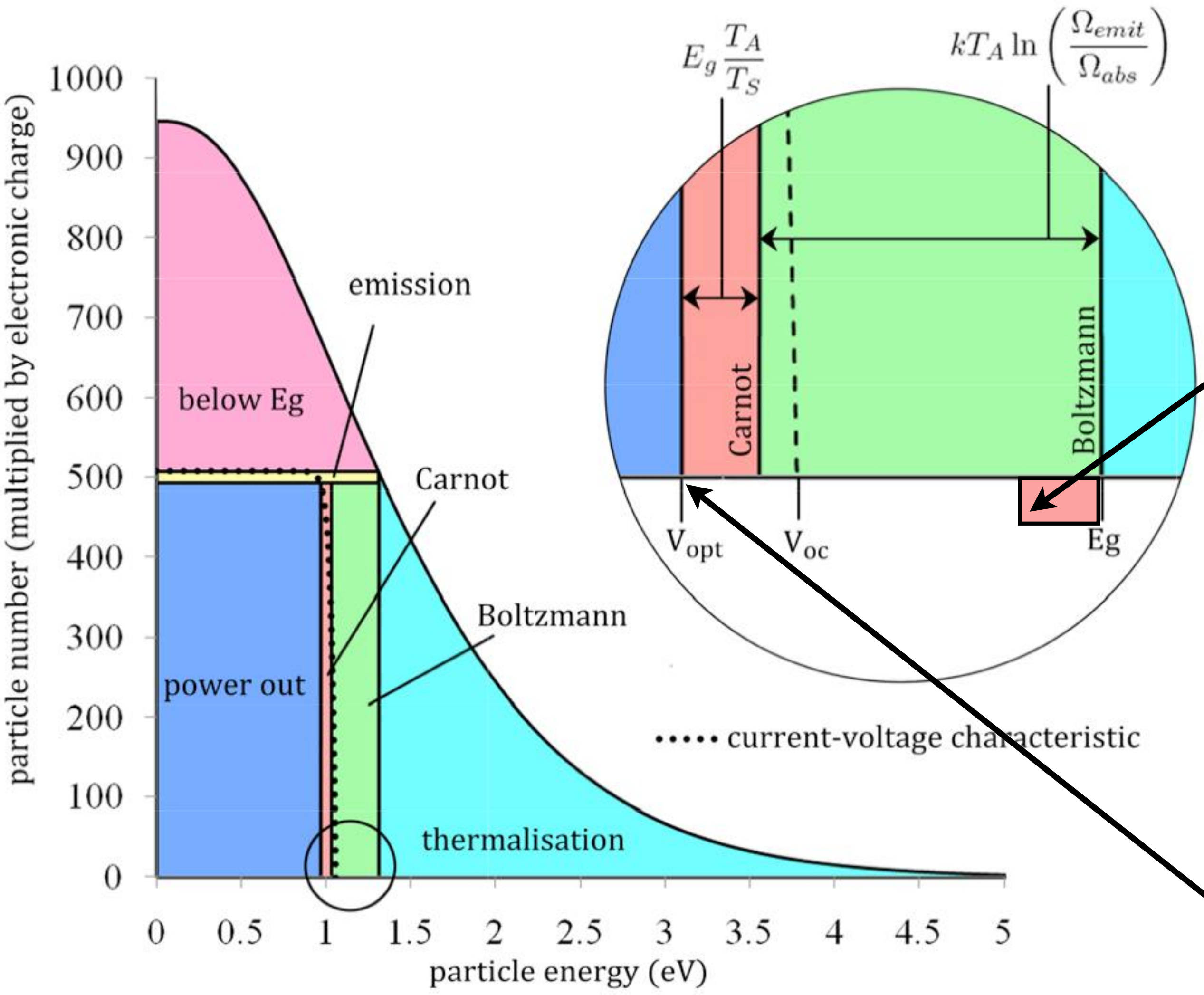


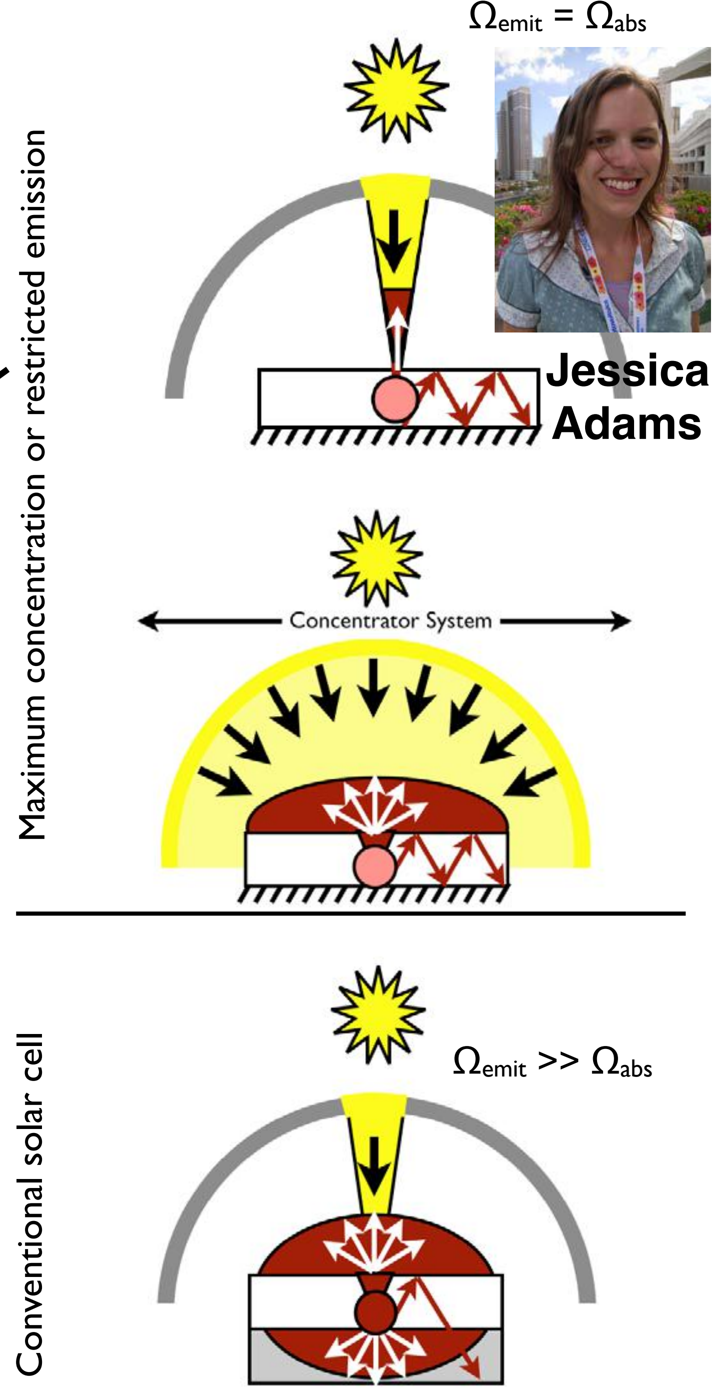




Louise Hirst & N.J.Ekins-Daukes, “Fundamental Losses in Solar Cells” Progress in Photovoltaics, (2011) 19: p286

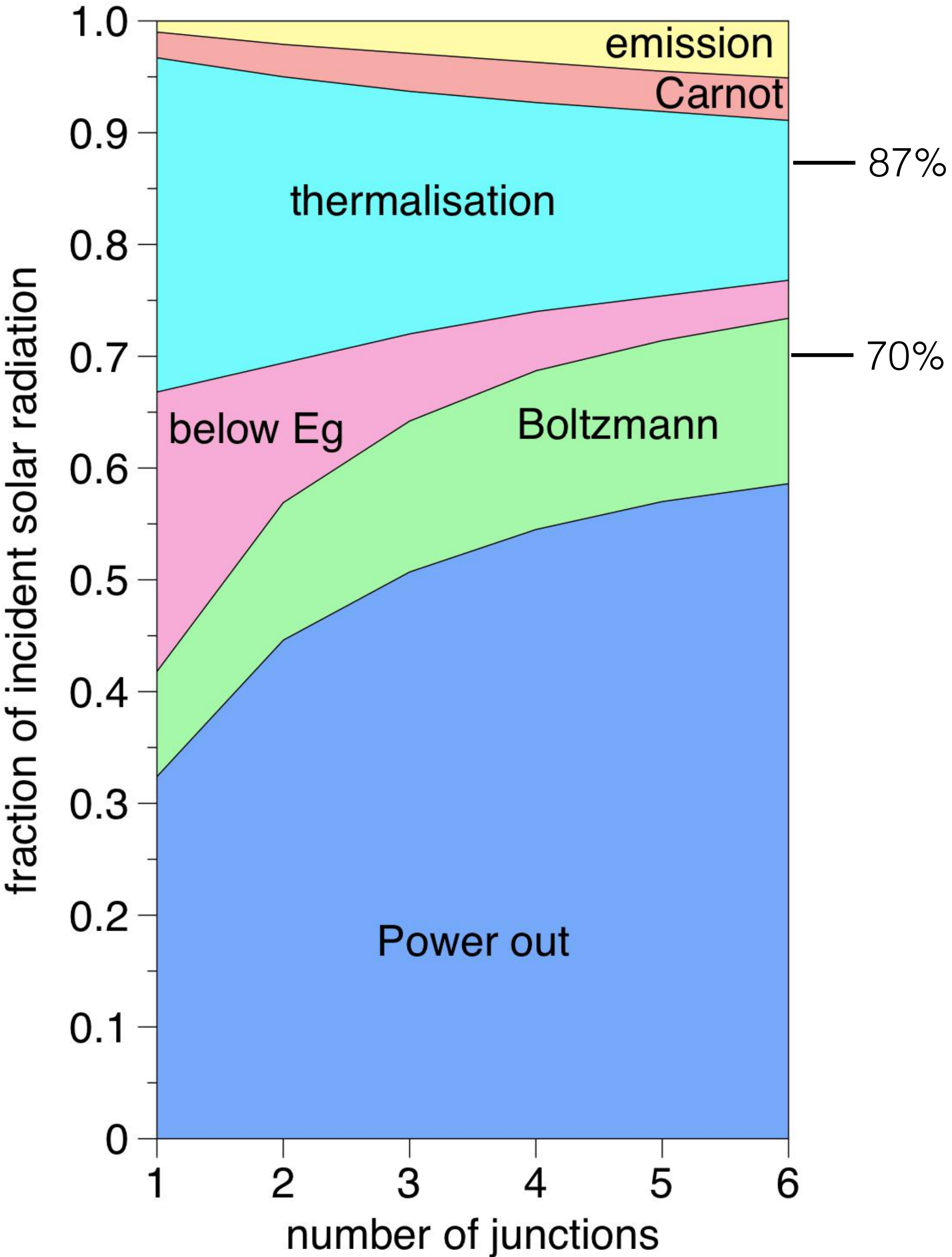
Origin of the Boltzmann Loss

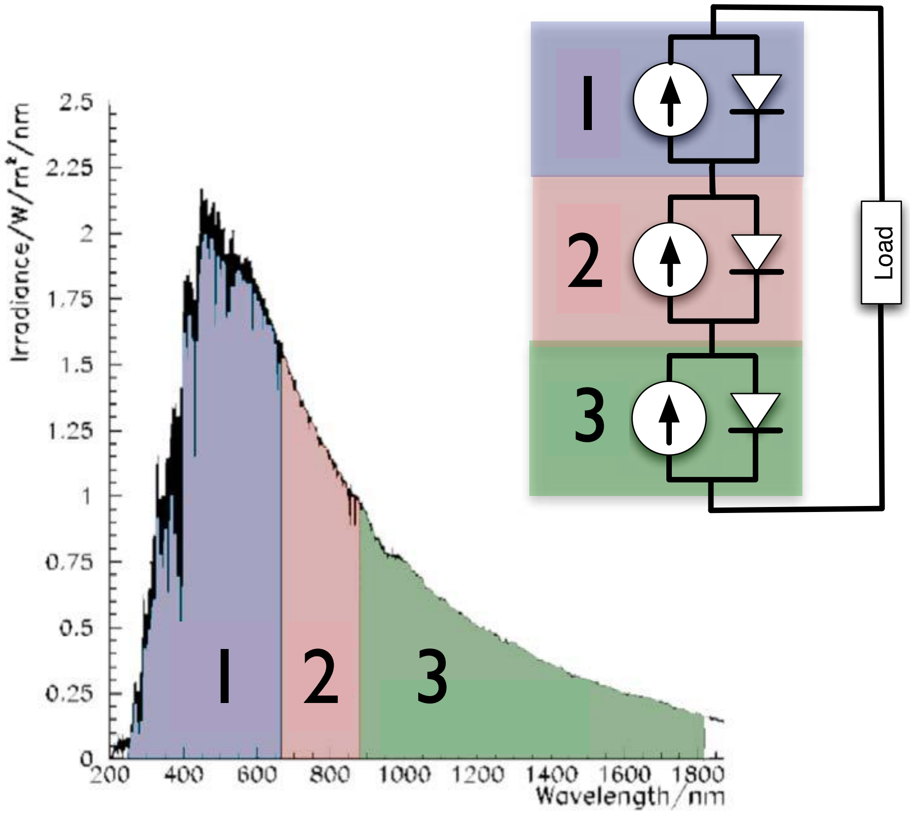




T. Markvart. J Opt A-Pure Appl. Opt (2008) vol. 10 pp. 015008
L. Hirst , Progress in Photovoltaics, (2011) 19: p286

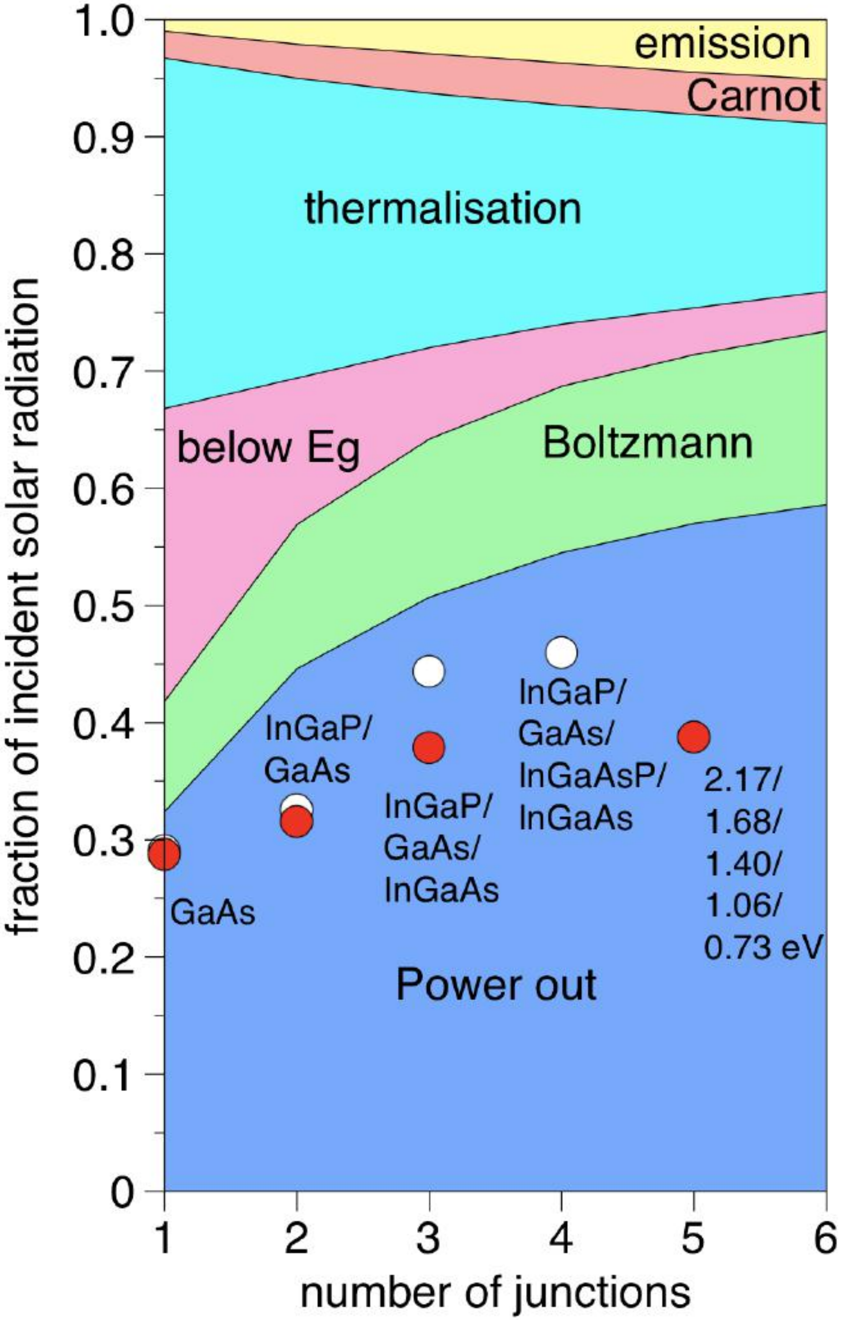
Multi-Junction Cell Limiting Efficiency

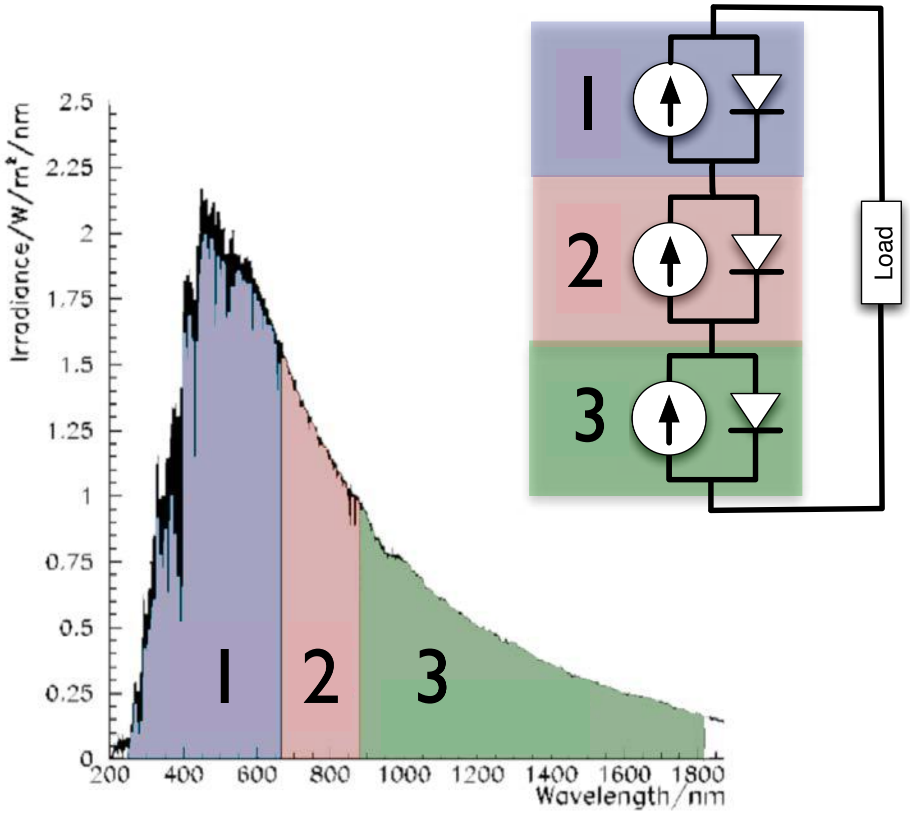




Louise Hirst & N.J.Ekins-Daukes,
“Fundamental Losses in Solar Cells”
Progress in Photovoltaics, (2011) 19: p286

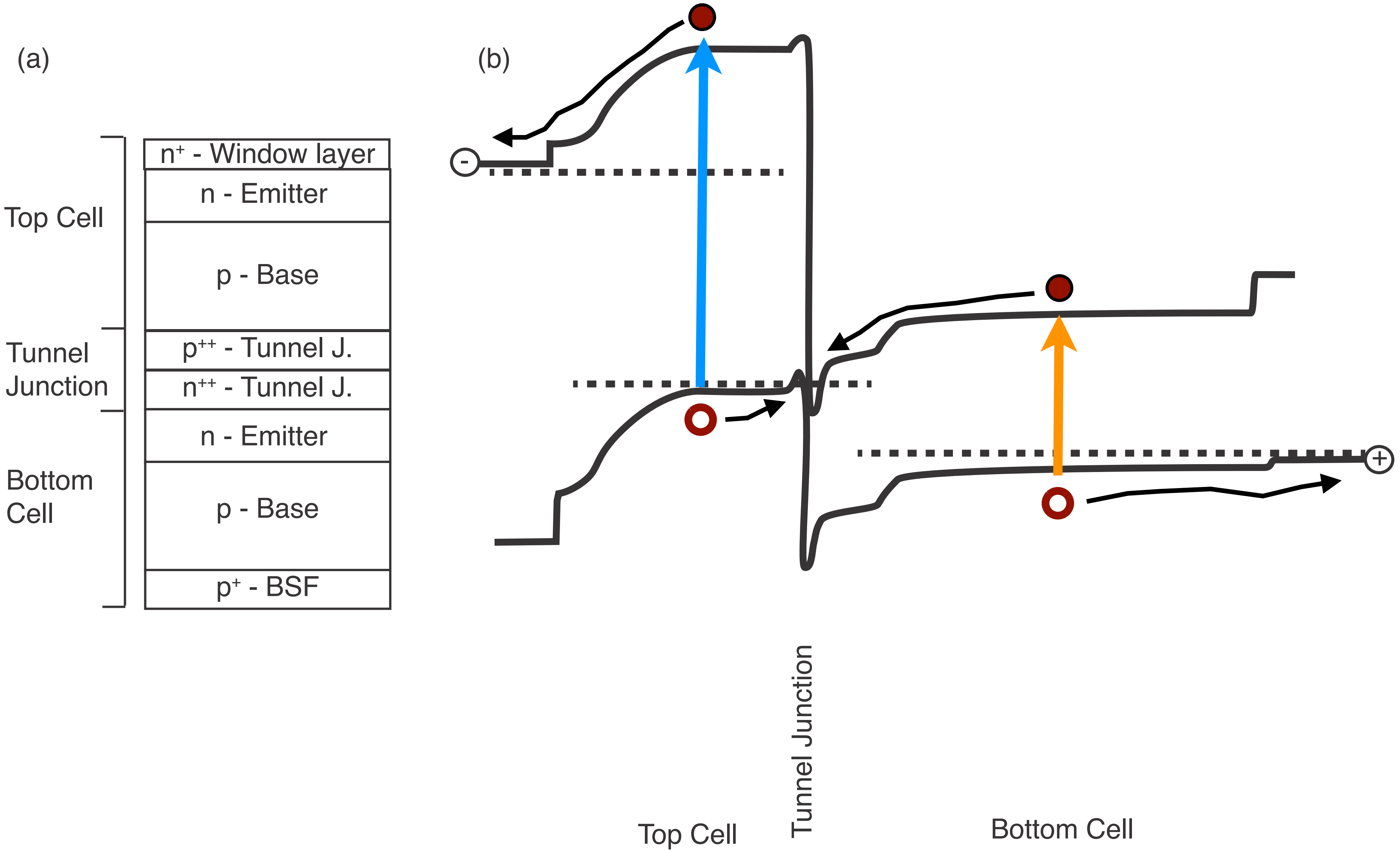
Multi-Junction Cell Summary





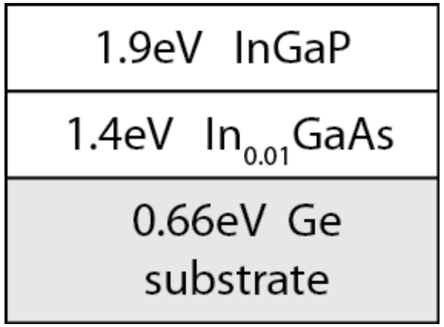
Louise Hirst & N.J.Ekins-Daukes,
"Fundamental Losses in Solar Cells"
Progress in Photovoltaics, (2011) 19: p286

Typical n/p InGaP/GaAs 2J Solar Cell



Lattice Matched MJ Cells

InGaP/InGaAs/Ge 3J



1.9eV InGaP

1.4eV $In_{0.01}GaAs$

0.66eV Ge substrate

CPV ~40%
(AM1.5d)

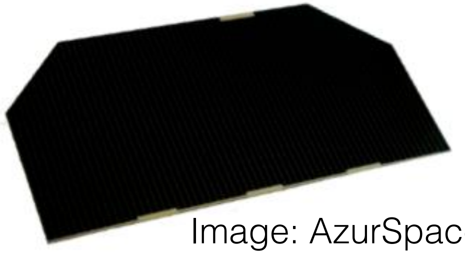
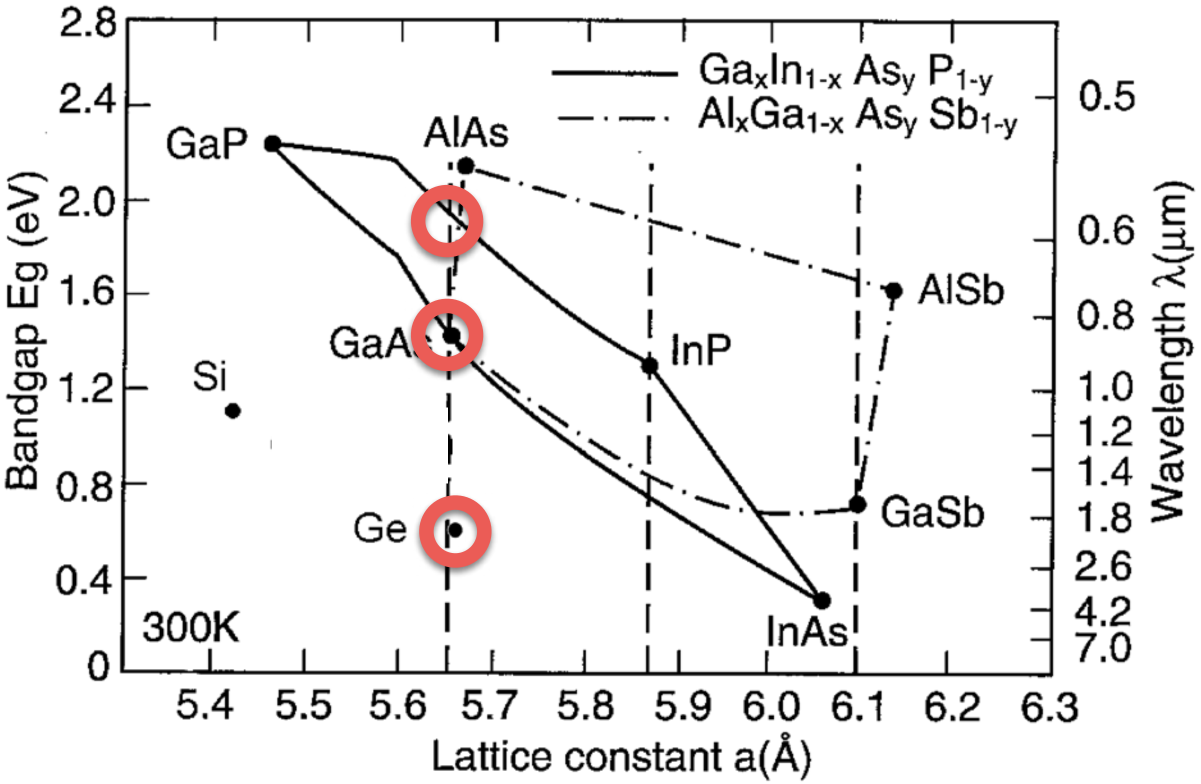


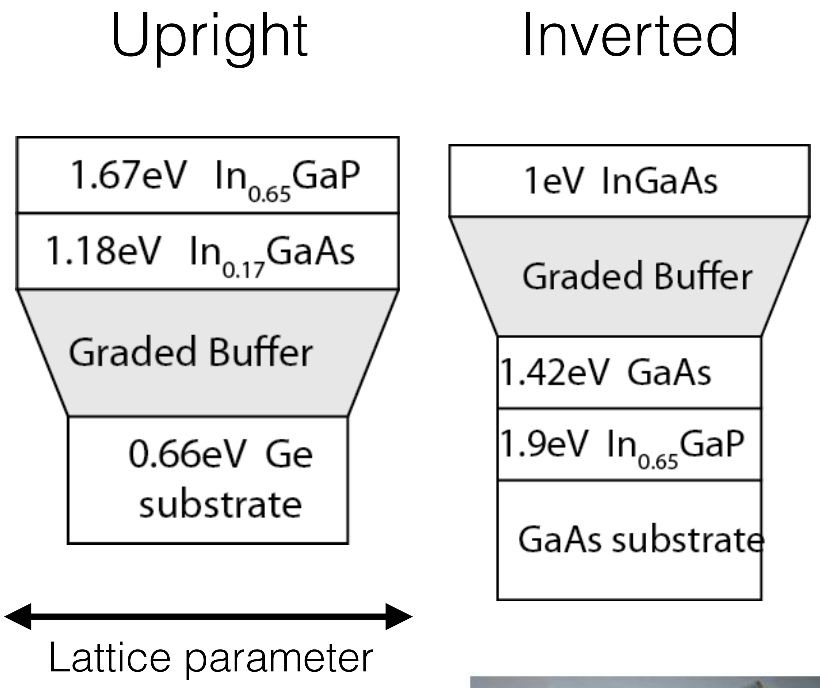
Image: AzurSpace.

Space ~30%
(AM 0)



- InGaP/InGaAs/Ge 3J (40.1% @135X) R.R.King, App.Phys.Lett, 90 183516, (2007)

Metamorphic MJ Cells



Upright

1.67eV $In_{0.65}GaP$

1.18eV $In_{0.17}GaAs$

Graded Buffer

0.66eV Ge substrate

Lattice parameter

Inverted

1eV InGaAs

Graded Buffer

1.42eV GaAs

1.9eV $In_{0.65}GaP$

GaAs substrate

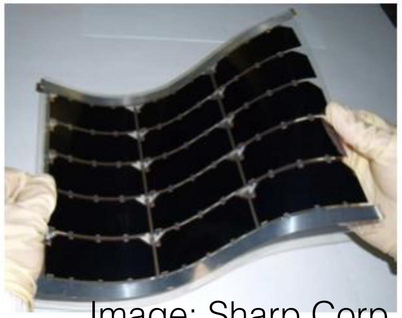
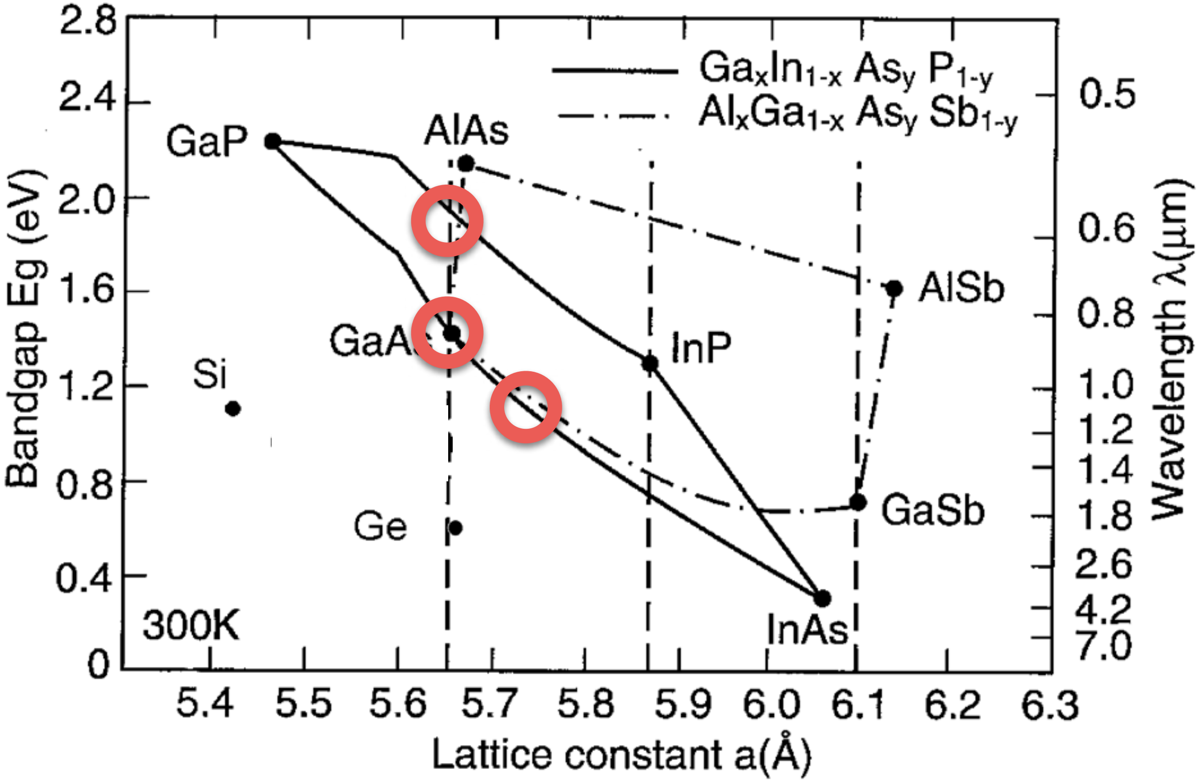
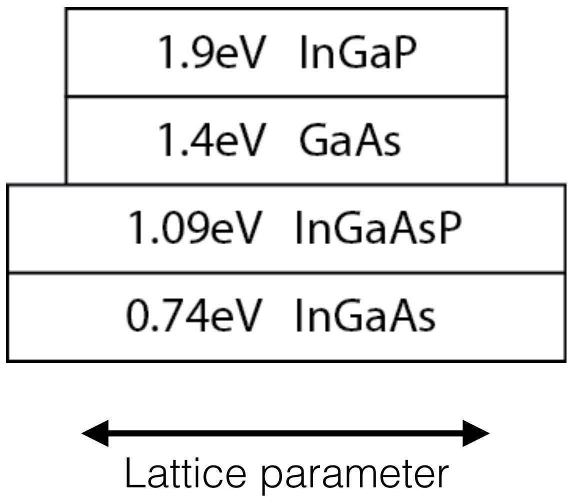


Image: Sharp Corp.



- Upright : W. Guter, Appl. Phys. Lett. 94 (2009) 223504.
- Inverted : T. Takamoto et al. Proc. 35th IEEE PVSC (2010) p.412.

Wafer Bonded Solar Cells



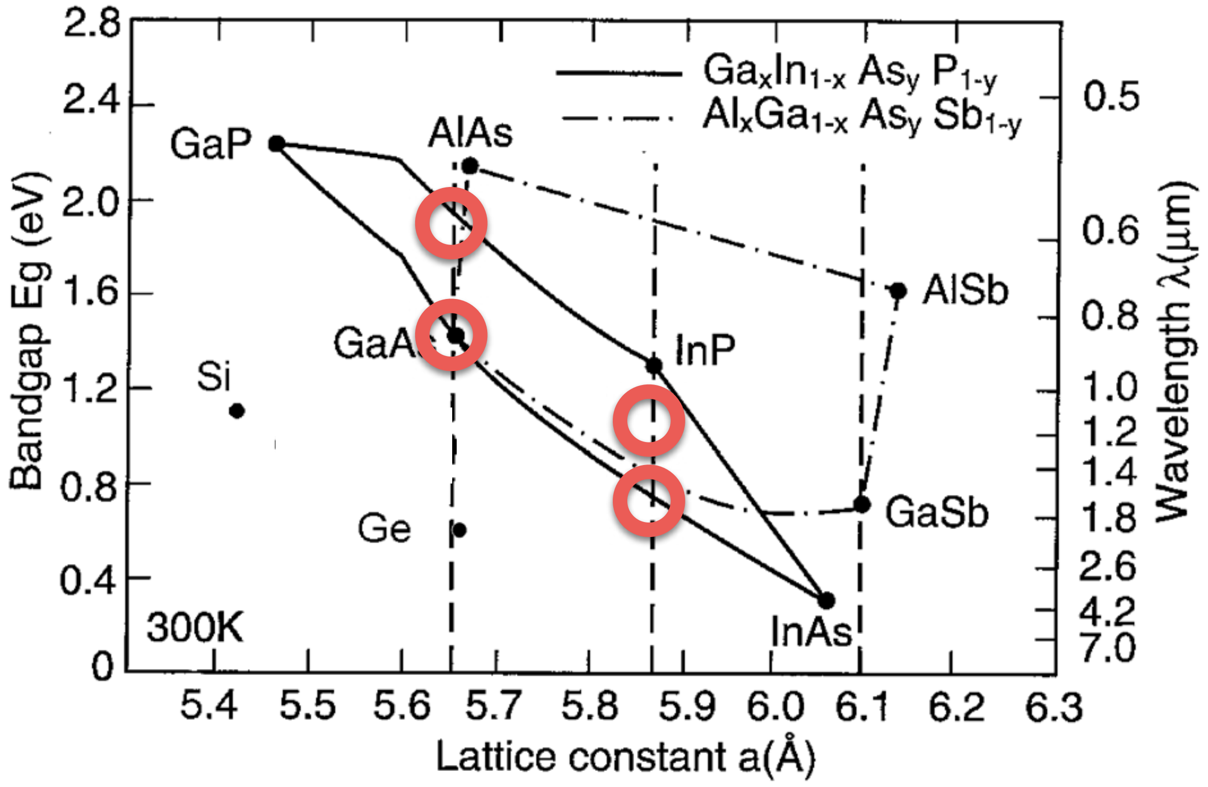
1.9eV InGaP

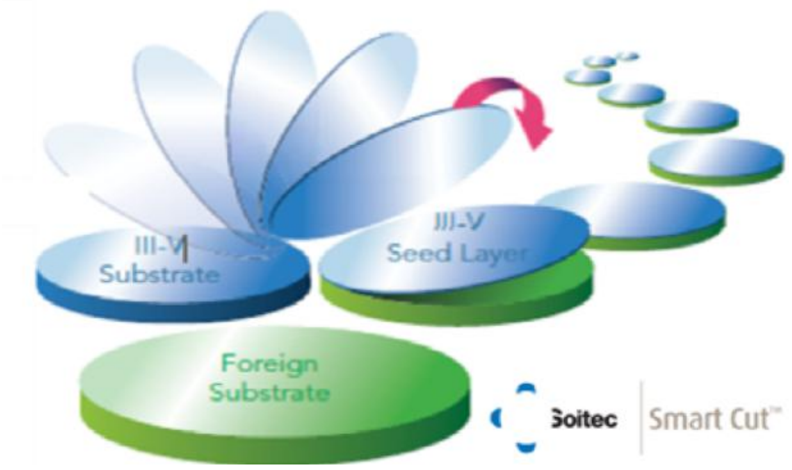
1.4eV GaAs

1.09eV InGaAsP

0.74eV InGaAs

Lattice parameter





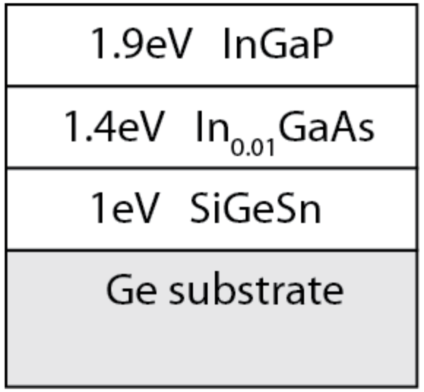
- 508X AM1.5D 46.5% T.Tibbits, et al. Proc. EU PVSEC, (2014)
- AM1.5G 5J 38.8% Chiu PT, et al., Proc. 40th IEEE PVSC (2014) 11–13.

Lattice Matched SiGeSn MJ Cells


Phoebe Pearce


Tom Wilson

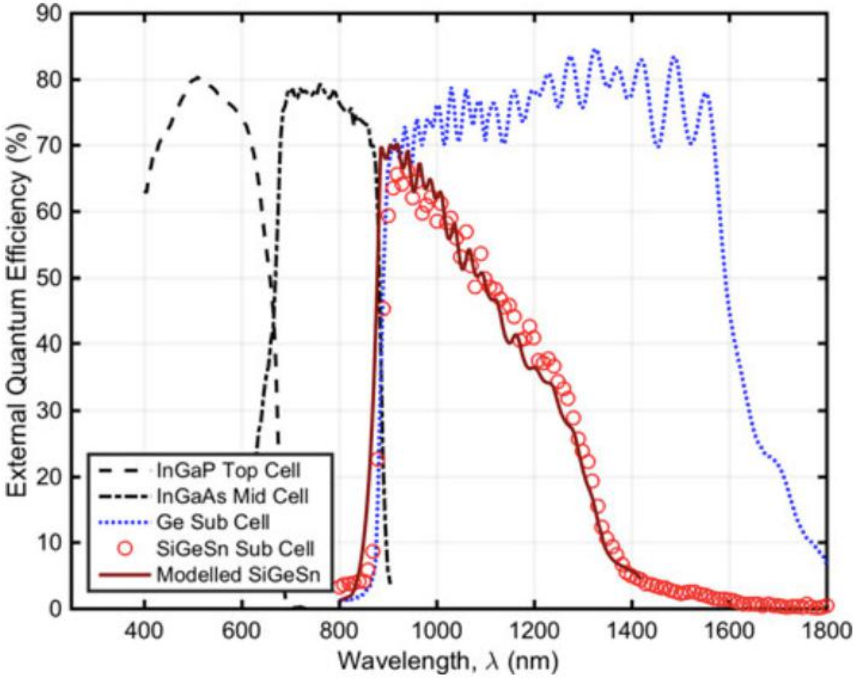
InGaP/InGaAs/Ge 3J

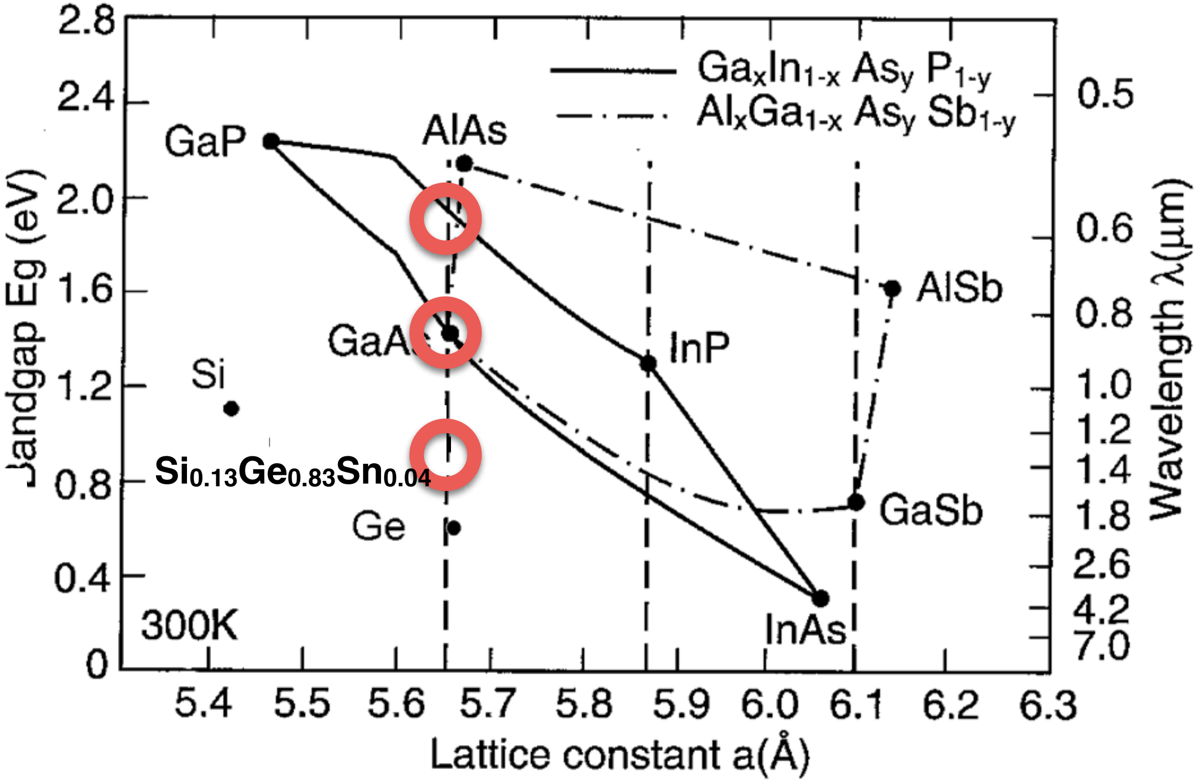

1.9eV InGaP

1.4eV $In_{0.01}GaAs$

1eV SiGeSn

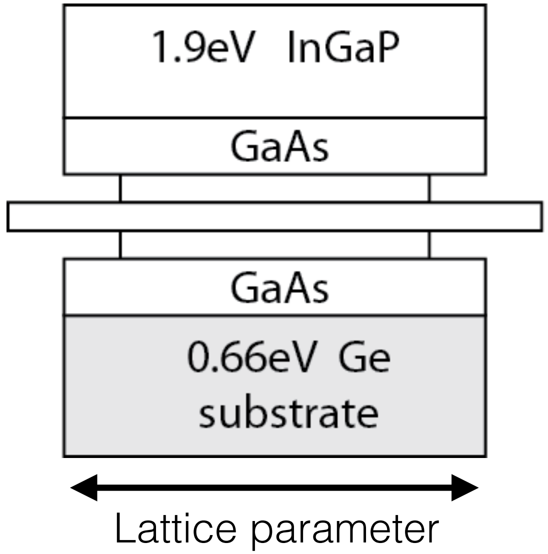
Ge substrate





- InGaP/GaAs/**SiGeSn** 3J, R.Rouka et al, IEEE-JPV,6(4) p1025 (2016)

Strain-Balanced MJ Solar Cells



1.9eV InGaP

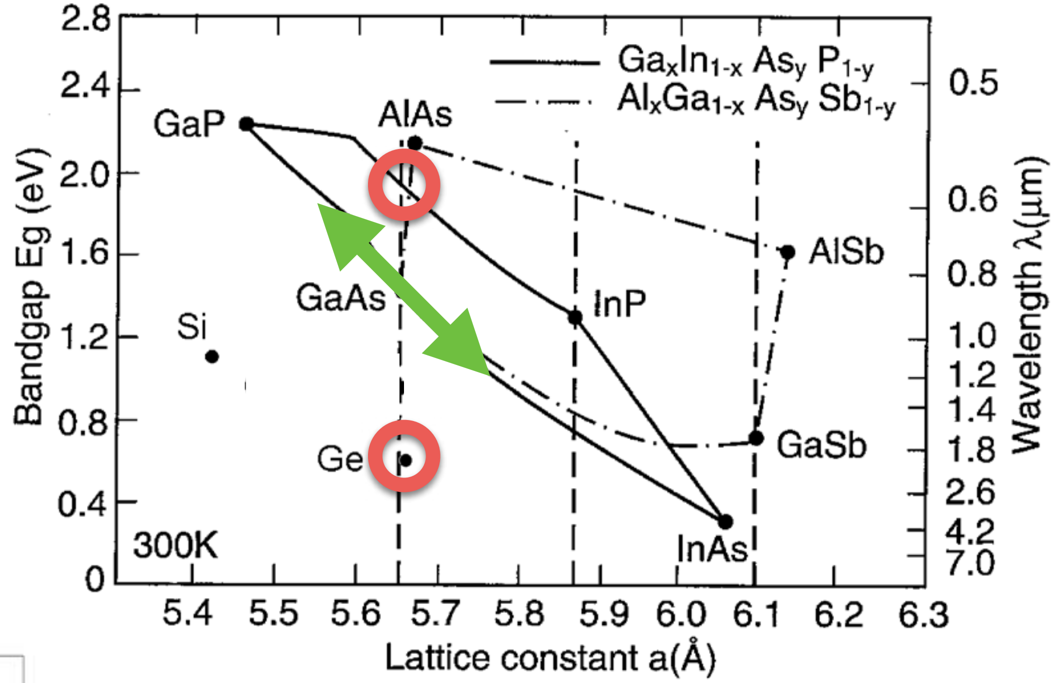
GaAs

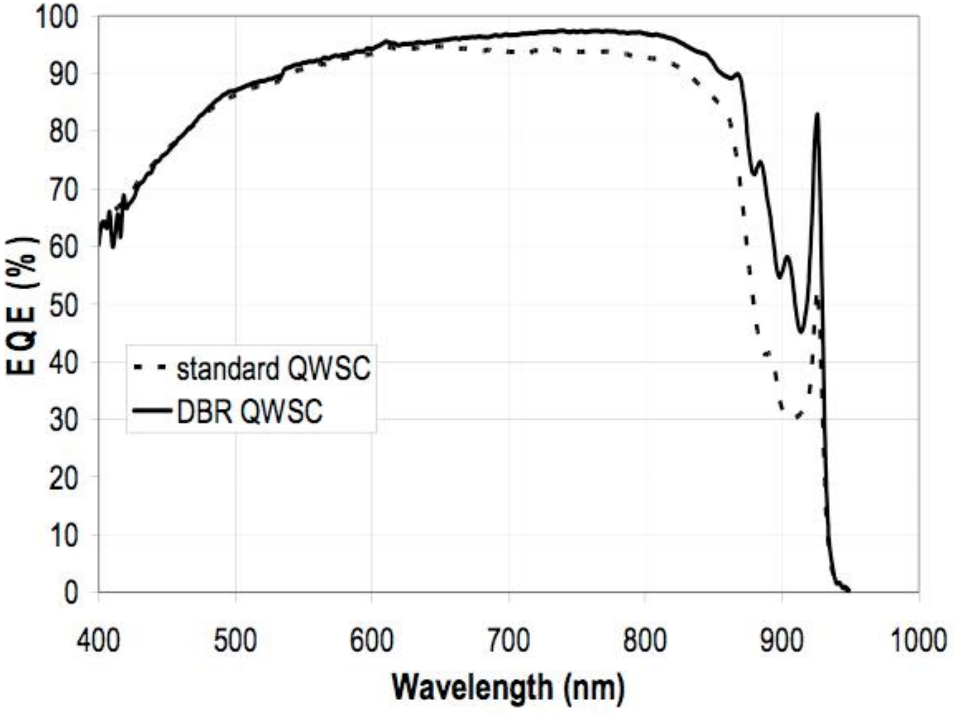
GaAsP/
InGaAs/
GaAsP

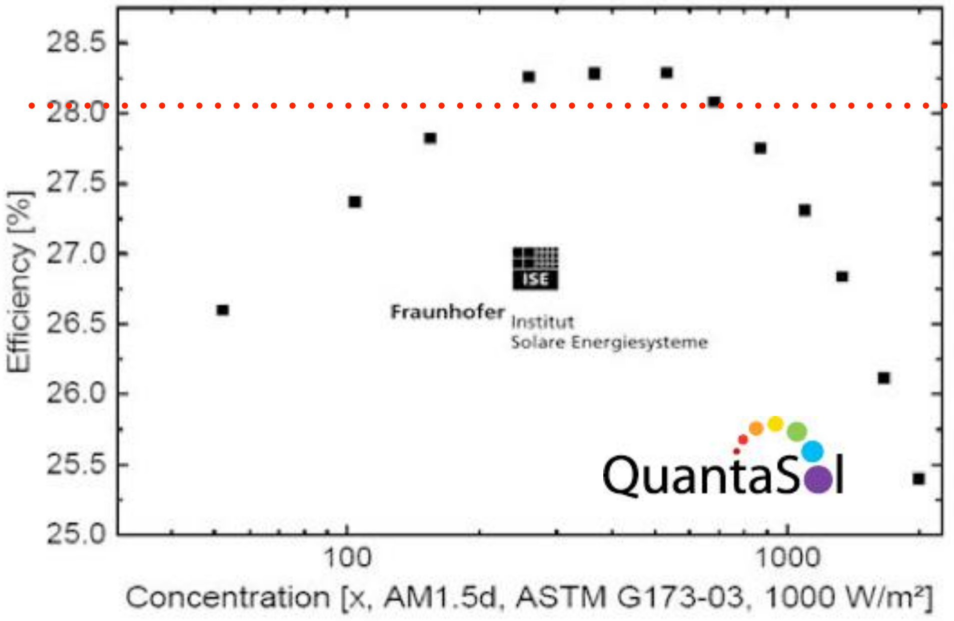
GaAs

0.66eV Ge
substrate

Lattice parameter

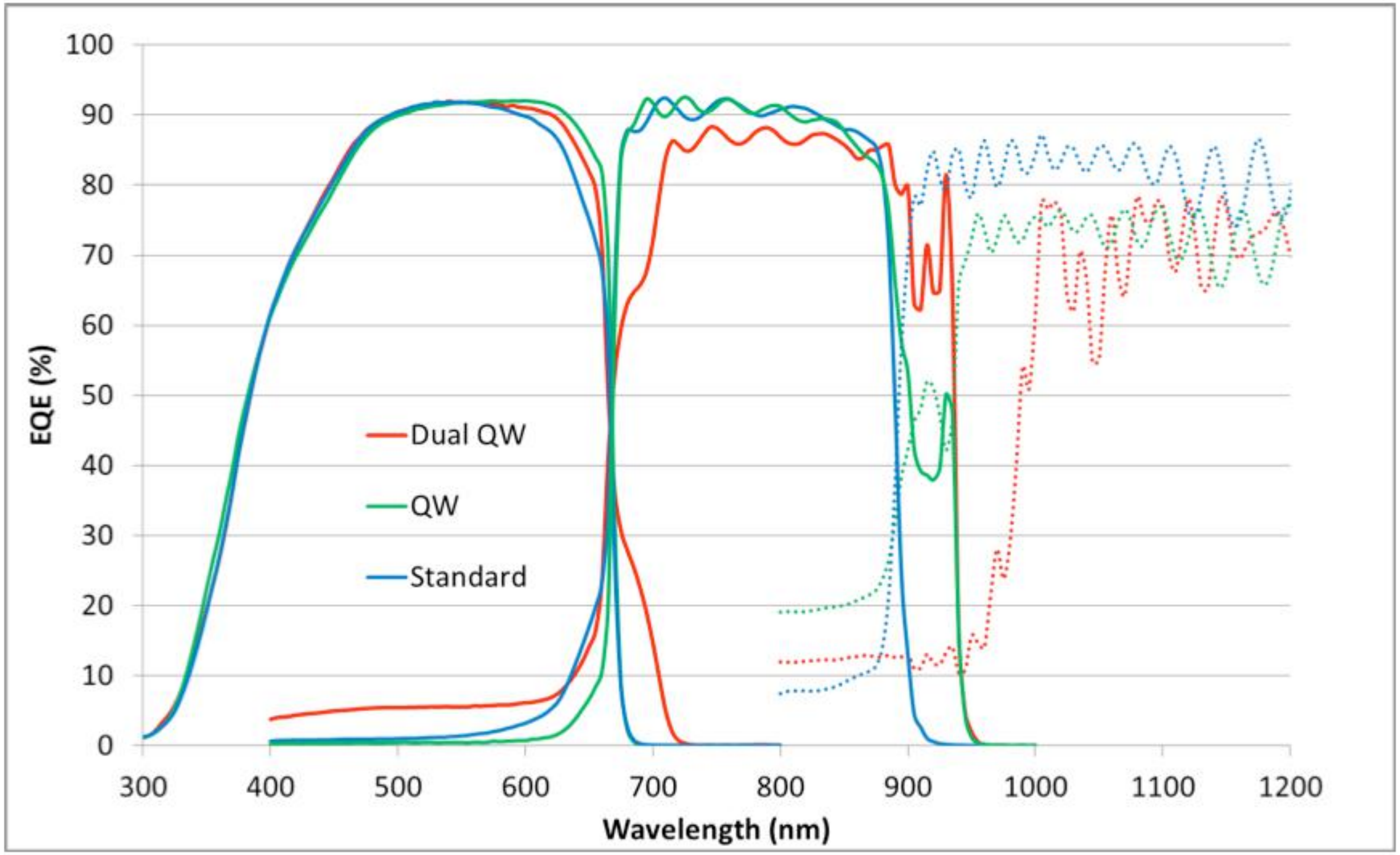


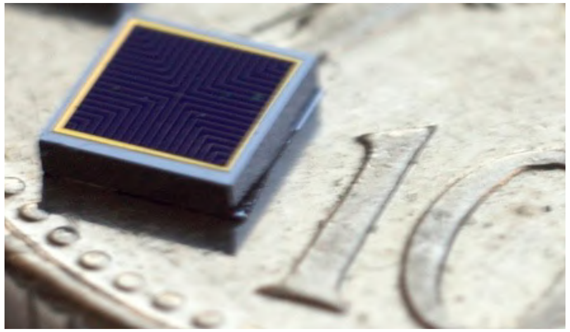




N.J. Ekins-Daukes, App.Phys.Lett. , 75(26), pp.4195 (1999)

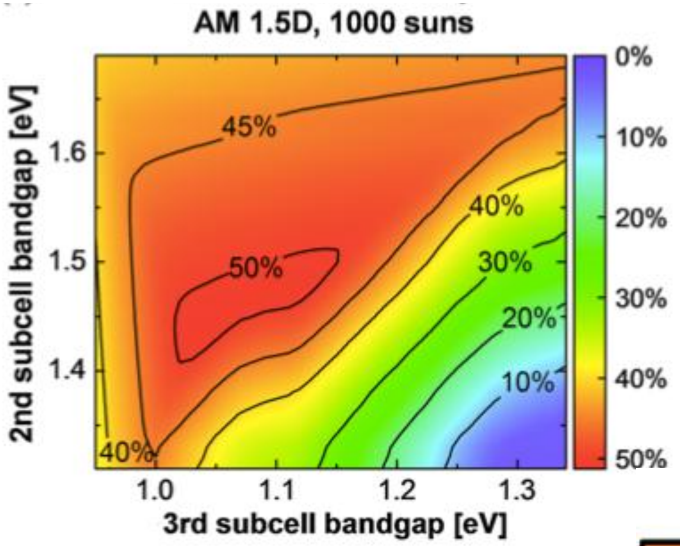
42.5% Dual (InGaP/InGaAsP)/(GaAsP/InGaAs)/Ge MQW 3J solar cell

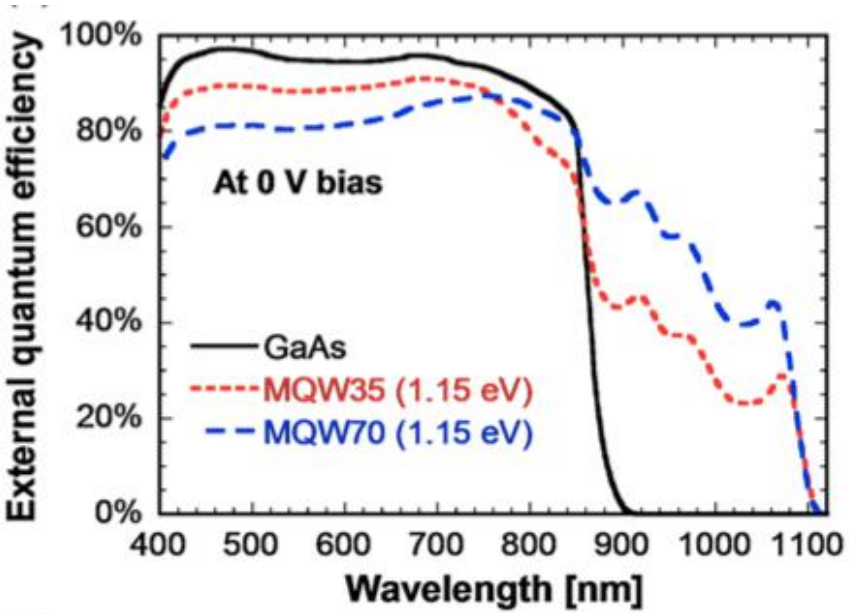


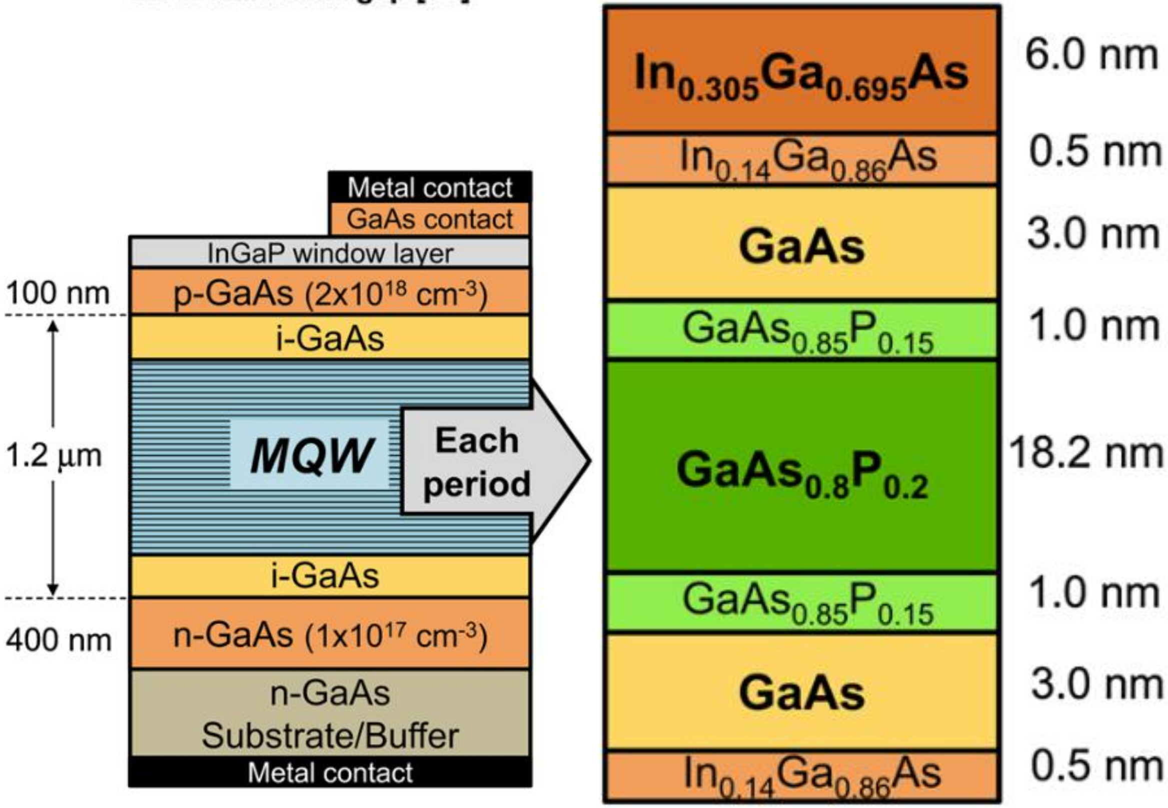


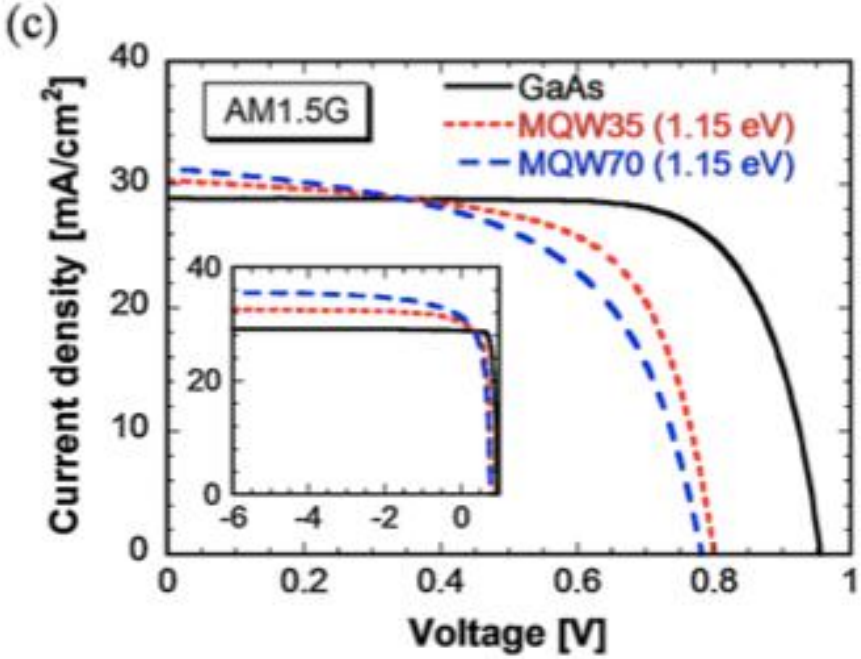
Browne, B. et al., 2013. Triple-junction quantum-well solar cells in commercial production. In 9th International Conference on Concentrator Photovoltaic Systems: CPV-9. AIP, pp. 3–5. (2013)

1.15eV GaAsP/InGaAs MQW



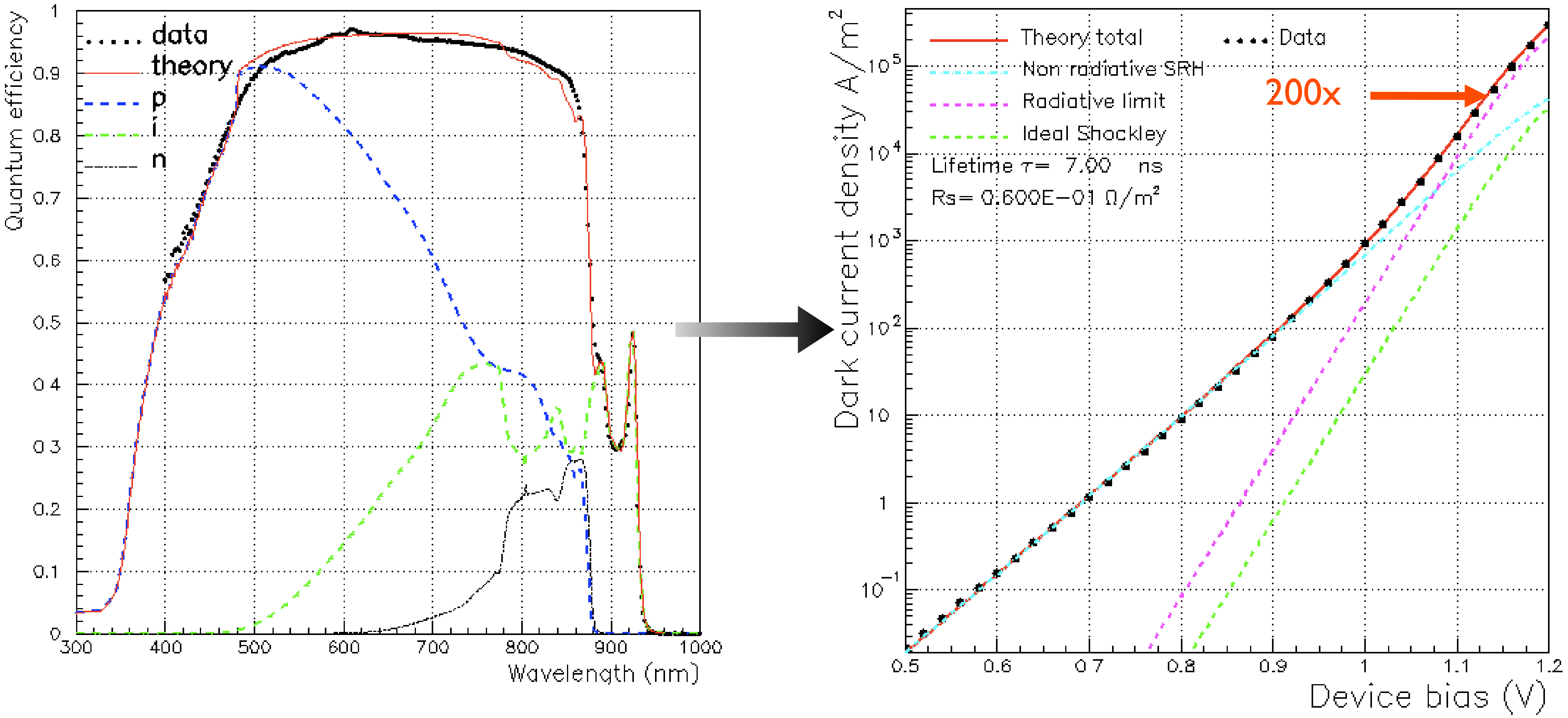






K. Toprasertpong, et al., " Prog. Photovolt: Res. Appl., vol. 24, no. 4, pp. 533–542, 2016.

Drift-Diffusion model for Quantum Efficiency & Dark Current



Model quantum efficiency (left) => predict dark-current (right)

Carrier transport → Shockley injection current

Quantum well absorption → Radiative current

Carrier distributions → SRH current in terms of single non-radiative carrier lifetime

J. Connolly, I. Ballard, K. Barnham, D. Bushnell, T. Tibbits, and J. S. Roberts, Proc EU Photovoltaics Conference (2004), p. 355.

Effect of strain on radiative emission & photovoltaic efficiency

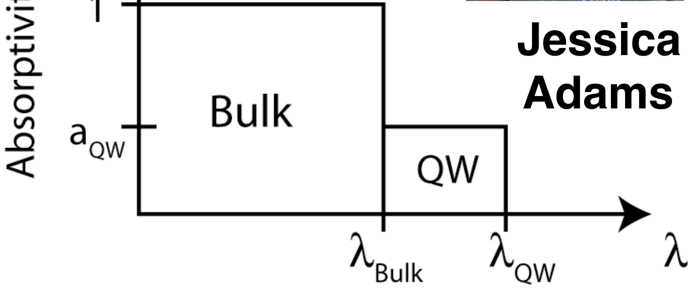
Jessica Adams

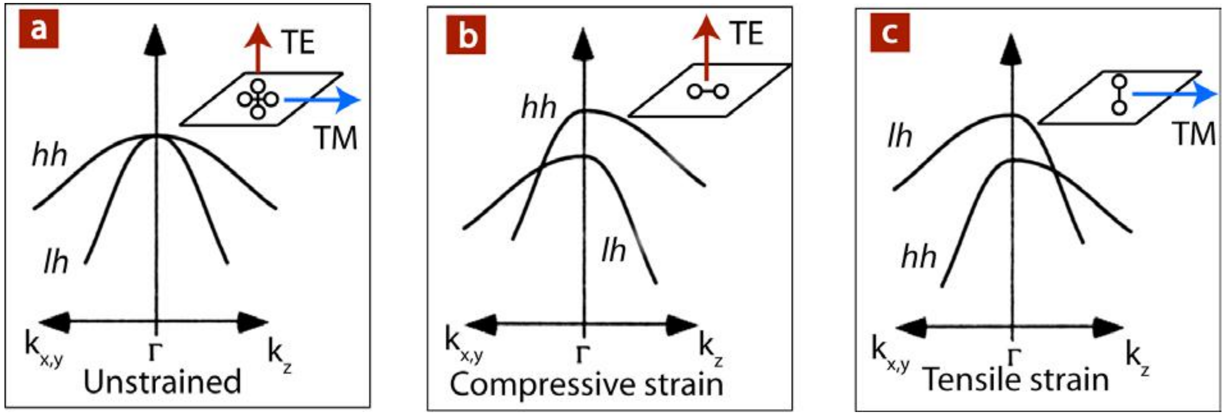
TE: $|M_T|^2 =$

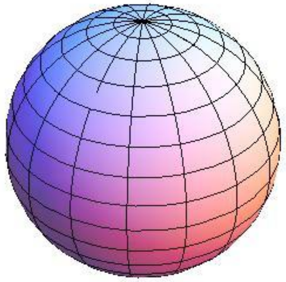
$$|M_T|^2 = \mathbf{P}^2\left(|M_{e-hh,n}|^2 + \frac{1}{3}|M_{e-lh,n}|^2\right)$$

TM : $|M_T|^2 =$

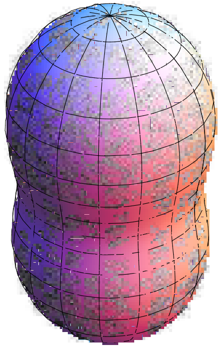
$$\frac{4}{3}\mathbf{P}^2|M_{e-lh,n}|^2$$



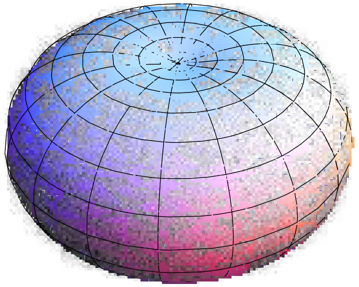




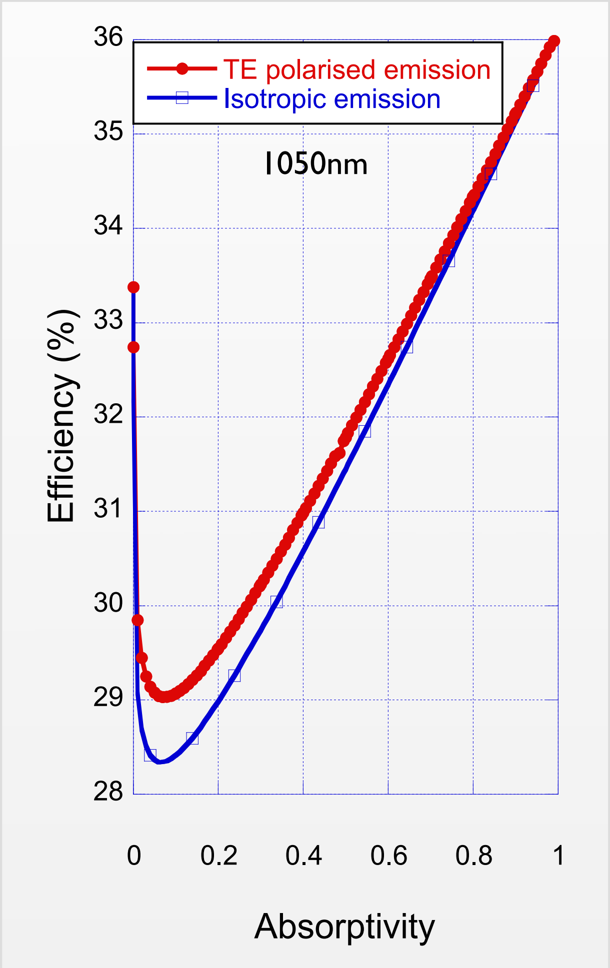
Isotropic emission



Directional emission perpendicular to QW

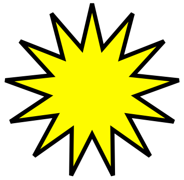


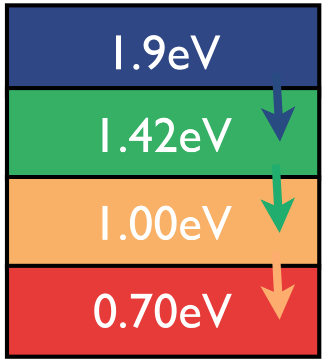
Directional emission parallel to QW

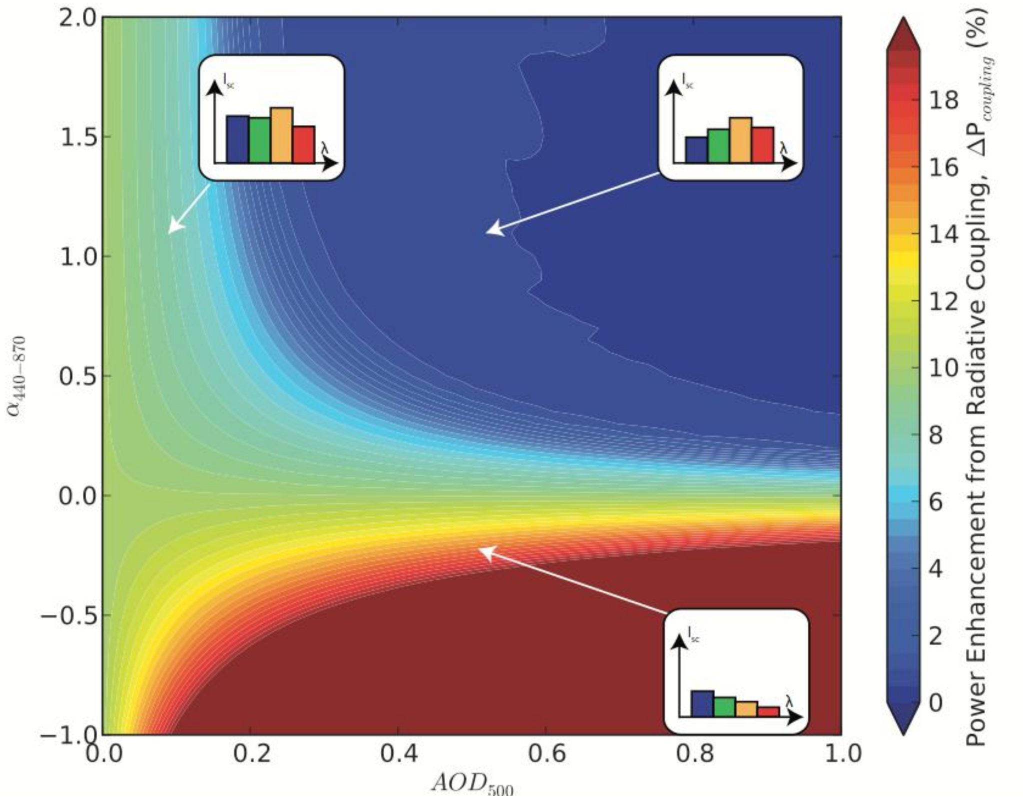


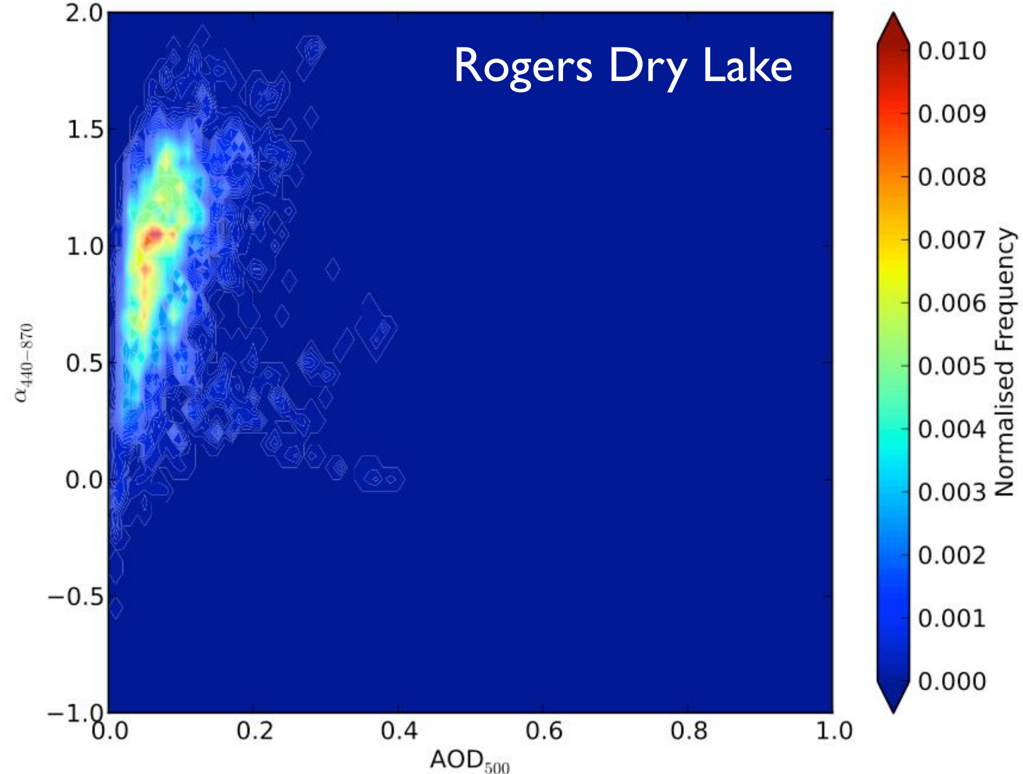
J.Adams et al., Progress in Photovoltaics (2011), pp. 865–877.

Quad cell radiative coupling



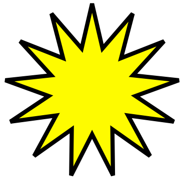


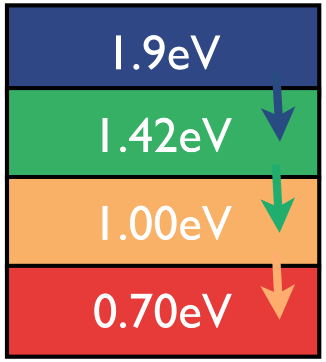




Chan, N.L.A. et al., 2014.. Photovoltaics, IEEE Journal of, 4(5), pp.1306–1313.

Quad cell radiative coupling



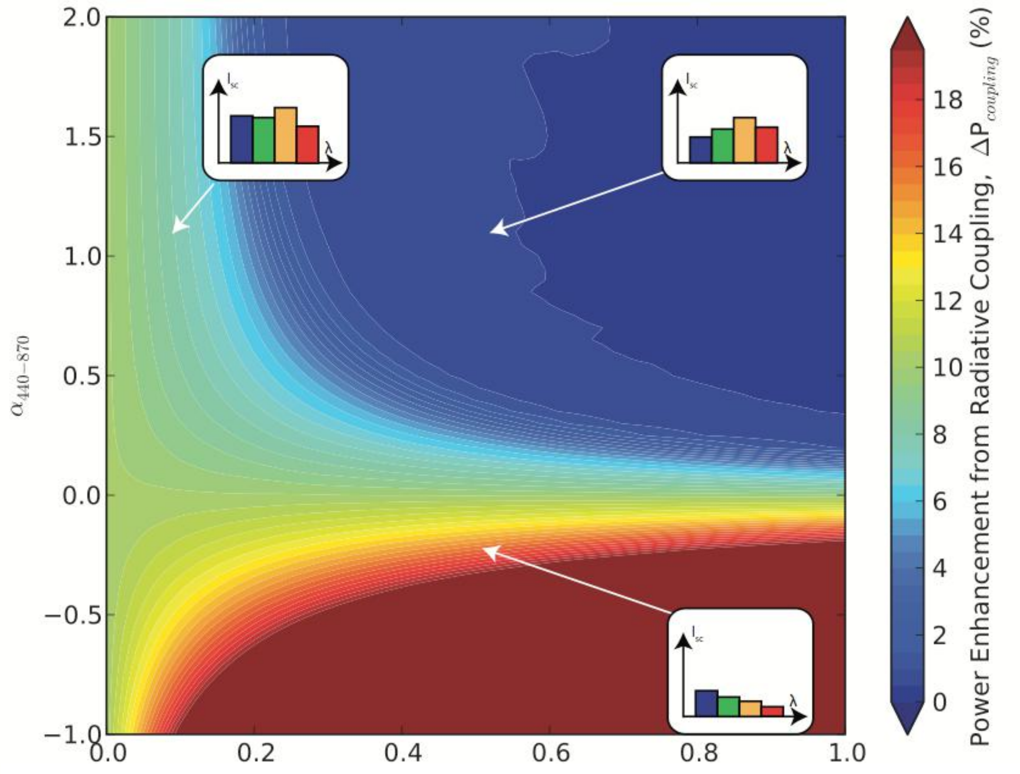


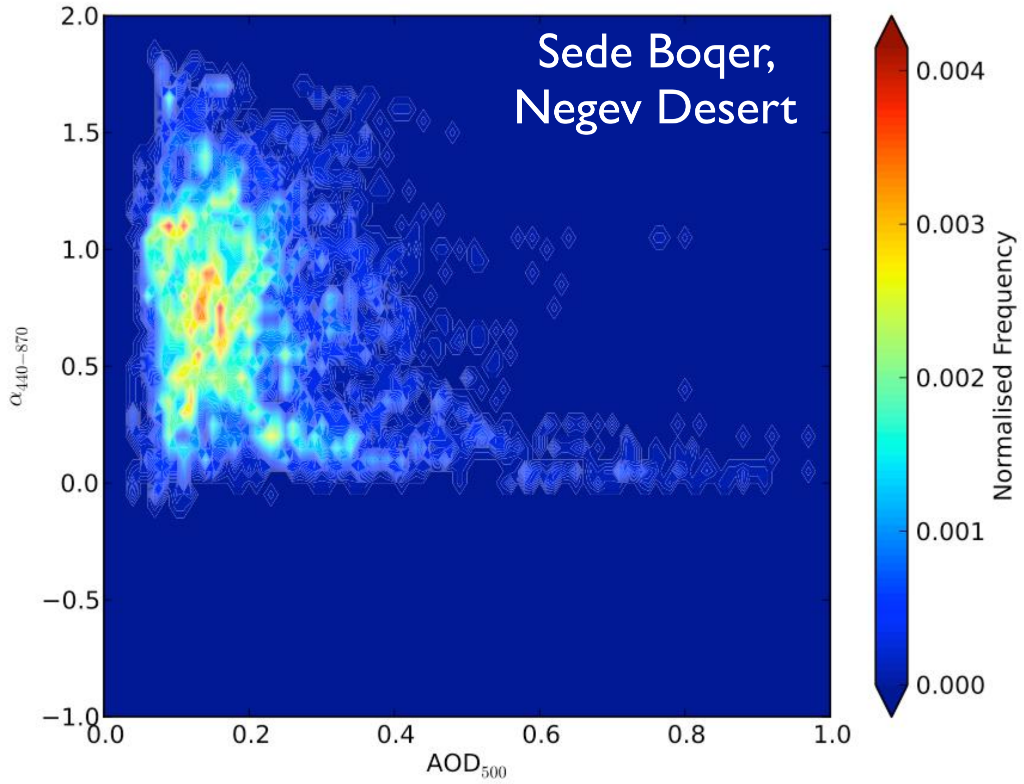
1.9eV

1.42eV

1.00eV

0.70eV

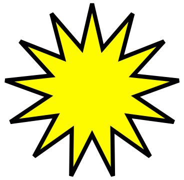


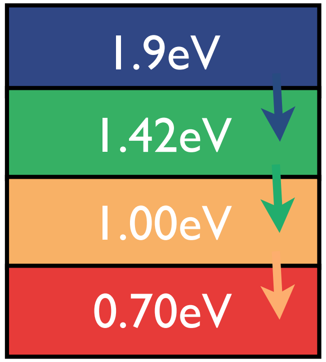


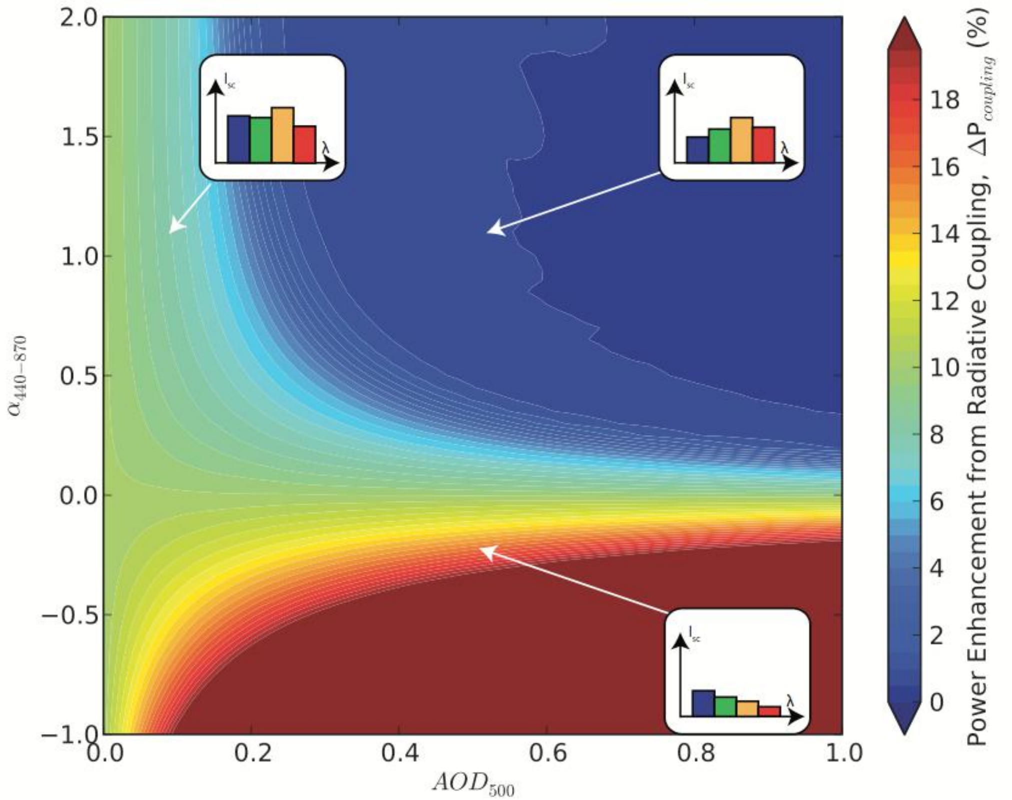
Sede Boqer,
Negev Desert

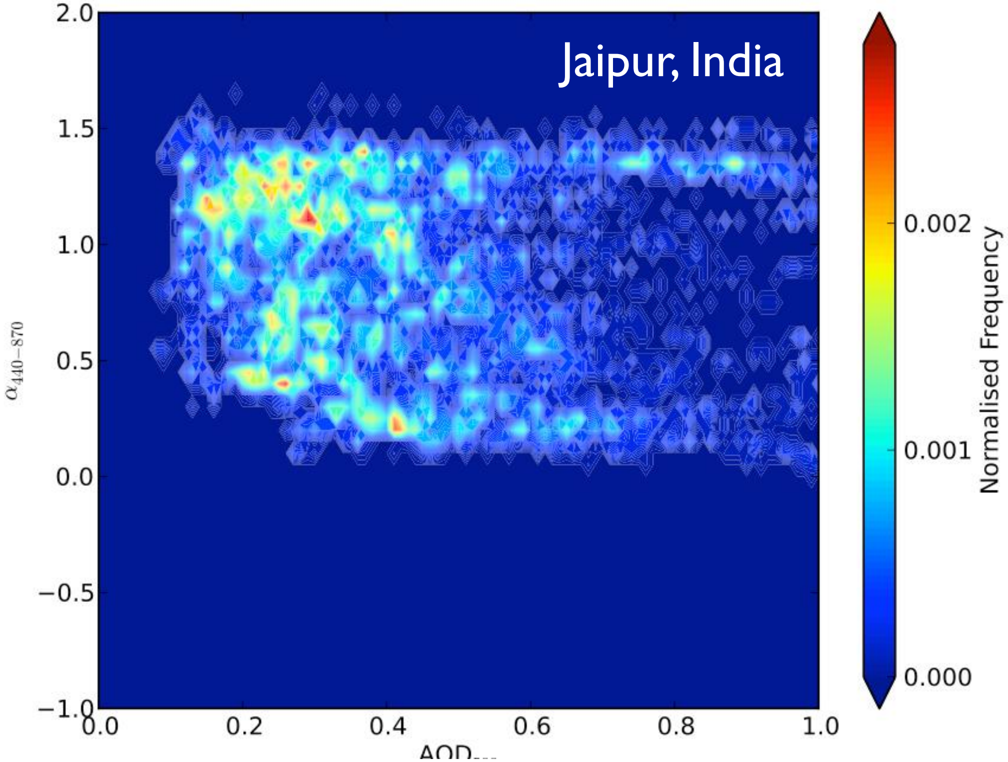
Chan, N.L.A. et al., 2014.. Photovoltaics, IEEE
Journal of, 4(5), pp.1306–1313.

Quad cell radiative coupling





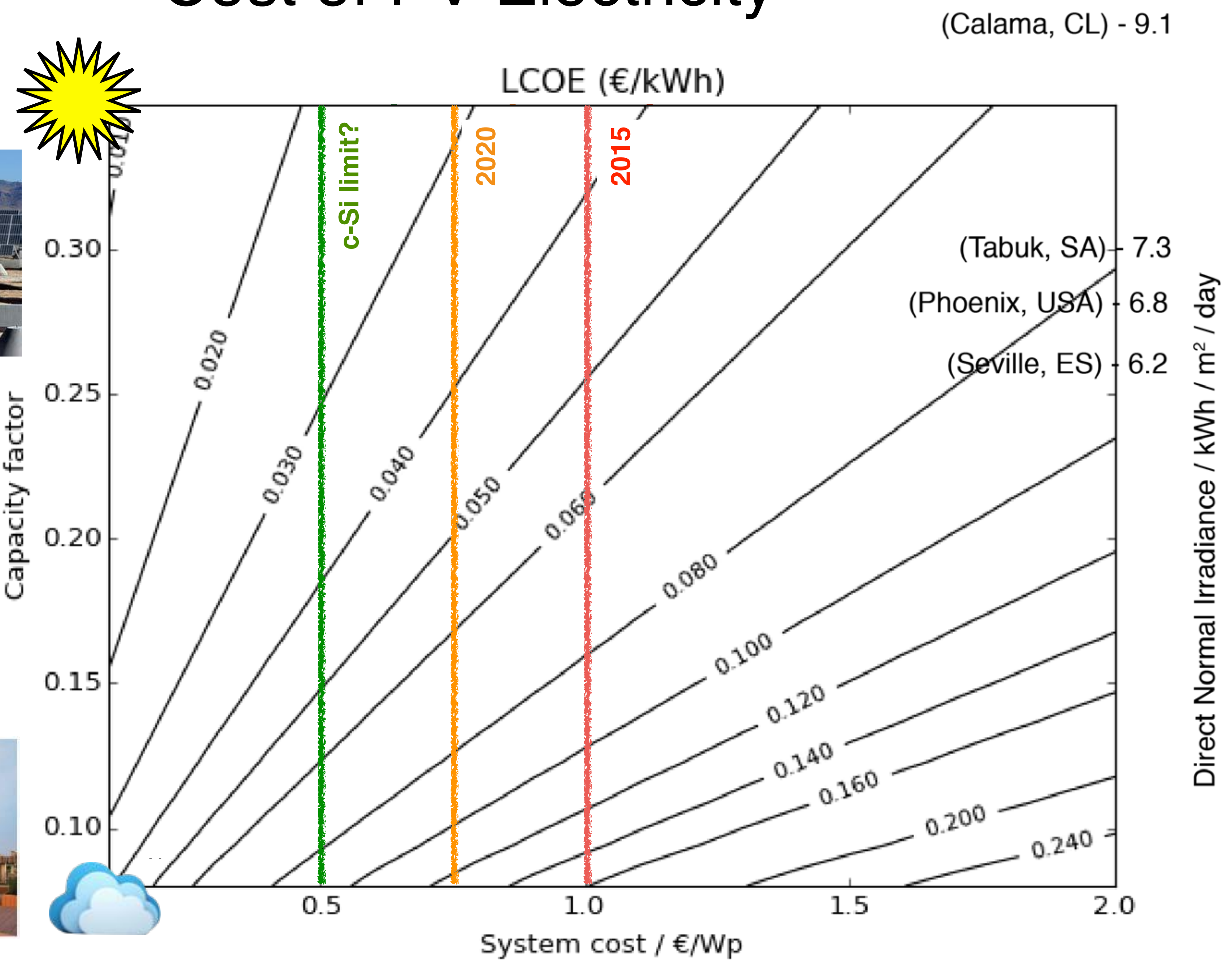




Chan, N.L.A. et al., 2014.. Photovoltaics, IEEE Journal of, 4(5), pp.1306–1313.

Cost of PV Electricity

Tracked panels,
Nellis Air Force Base,
Nevada C.F. ~ 22%

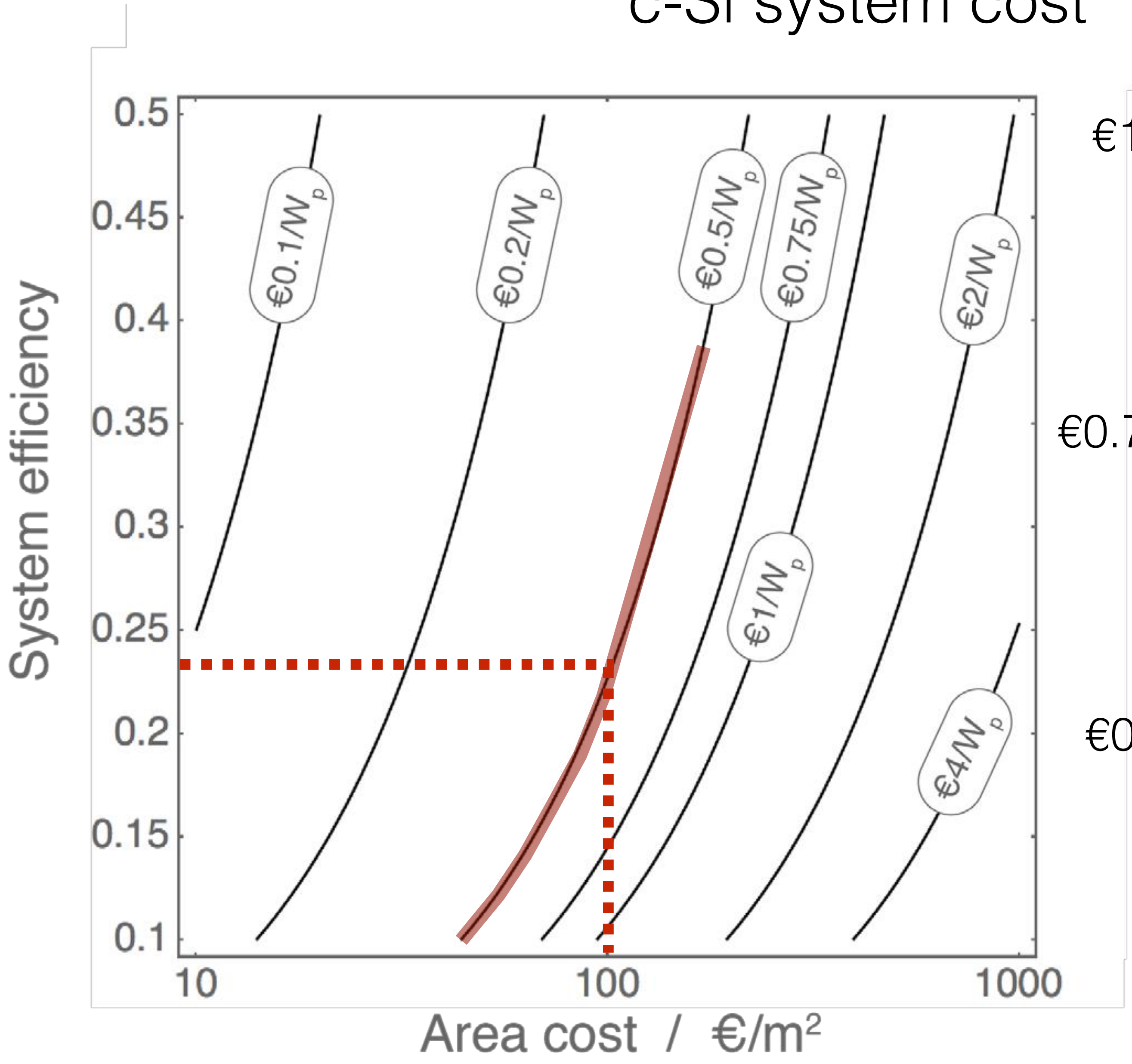


Parameters: r=8%, degradation 0.5%/p,a,, O&M €0.013/Wp/p.a, 30 year operation

N.Ekins-Daukes et al., AIP Conf. Proc. 1766, 020004 (2016)

SolarHaus Darmstadt,
Germany

c-Si system cost



€1/Wp c-Si system cost (2015):

- 15%€system€efficiency€
- €135/m² area cost

€0.75/Wp c-Si system cost (2020):

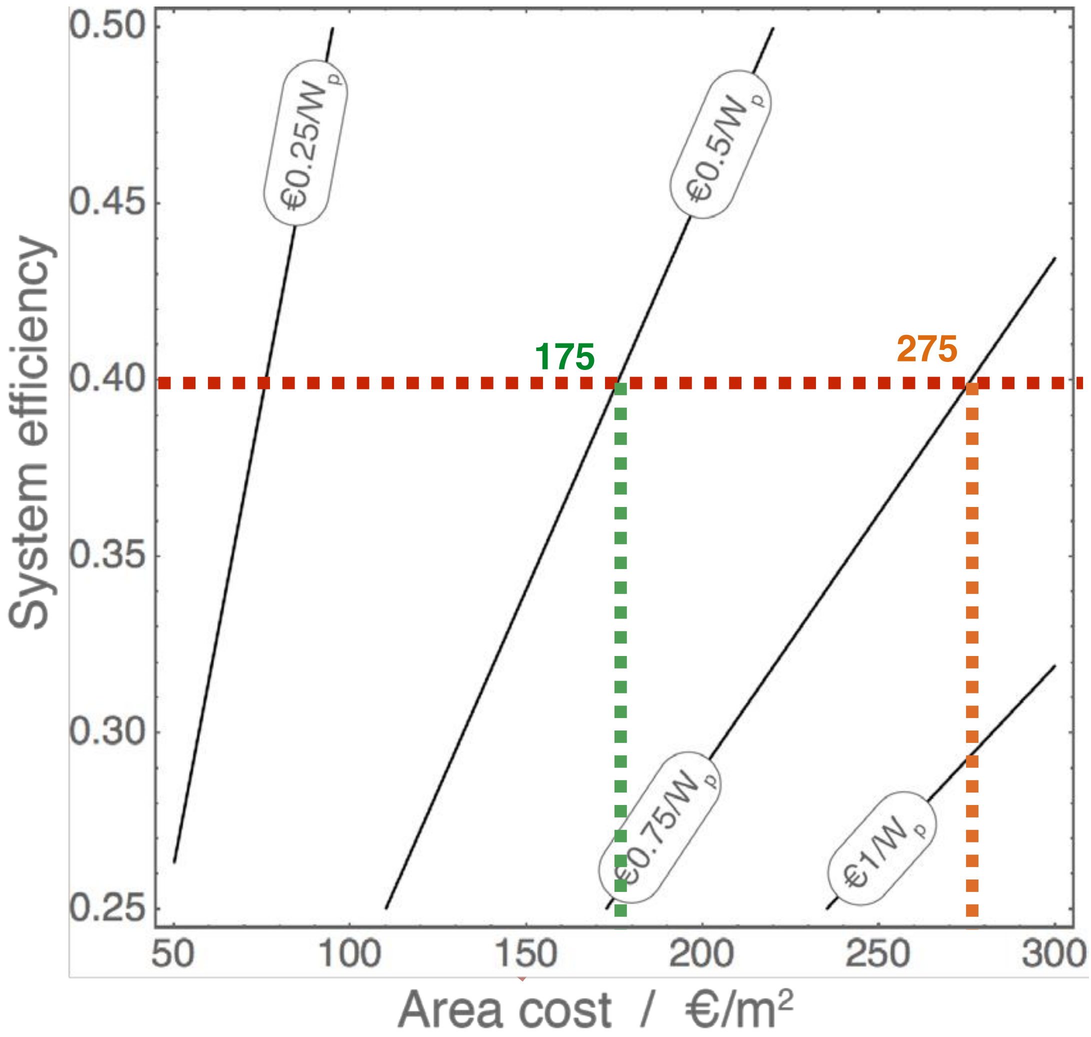
- 17%€system€efficiency€
- €120/m² area cost

€0.5/Wp c-Si system cost (??):

- 23%€system€efficiency€
- €100/m² area cost

$$\text{System cost}[€/W_p] = \frac{\text{Area cost}[€/m^2]}{\text{Std. Irradiance}[W/m^2] \times \text{System Efficiency}} + \text{BOS cost}[€/W_p]$$

CPV system cost



30%€system€efficiency€(2015):€

- €1/Wp implies €275/m² (match c-Si today)
- €0.75/Wp implies €210/m² (match c-Si in 2020)
- €0.5/Wp implies €130/m²

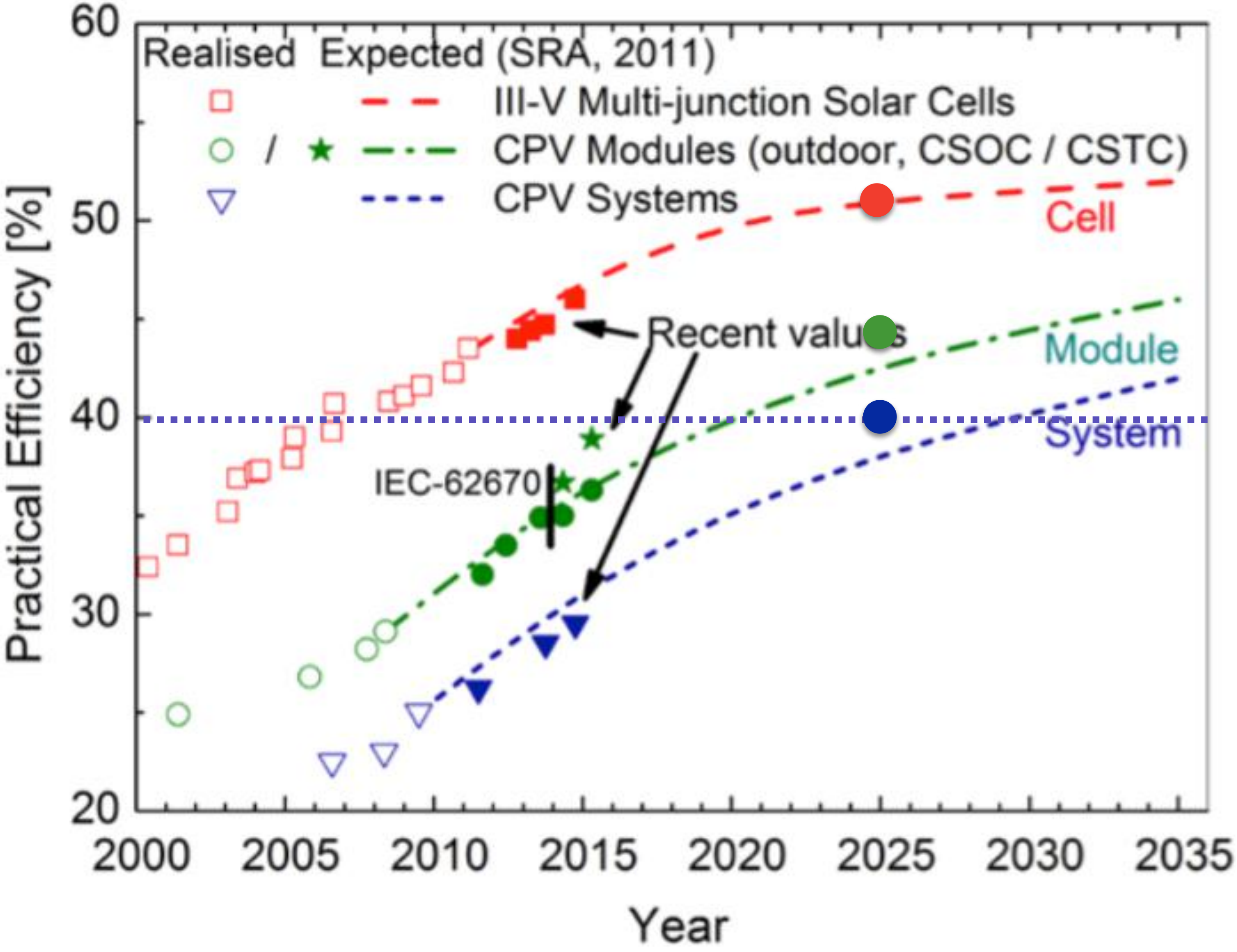
40%€system€efficiency:€

- €0.75/Wp implies €275/m² (match c-Si in 2020)
- €0.5/Wp implies €175/m²

$$\text{System cost}[€/W_p] = \frac{\text{Area cost}[€/m^2]}{\text{Std. Irradiance}[W/m^2] \times \text{System Efficiency}} + \text{BOS cost}[€/W_p]$$

N.Ekins-Daukes et al., AIP Conf. Proc. 1766, 020004 (2016)

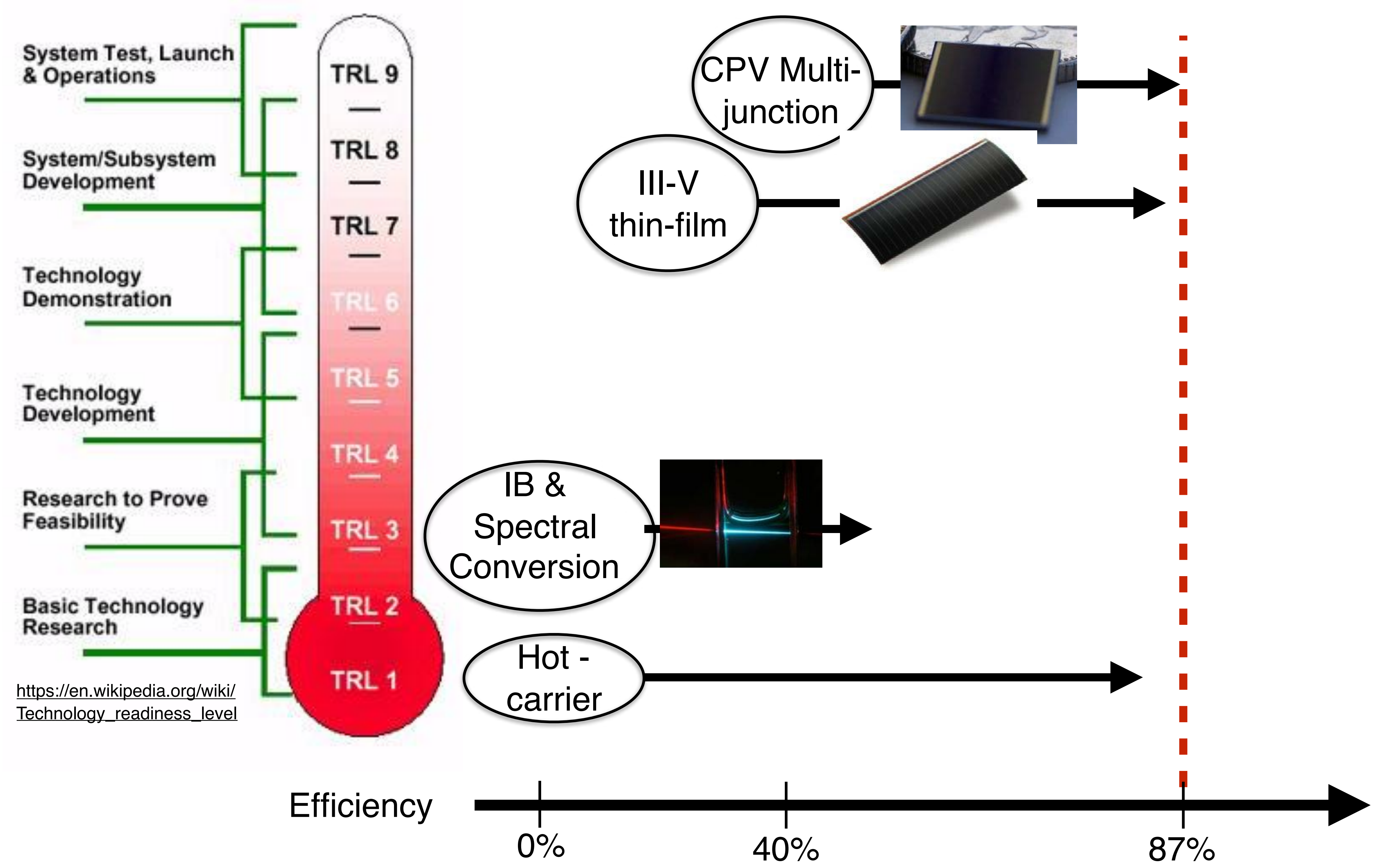
40% system efficiency



Philipps, S.P. et al., 2016. Current Status of Concentrator Photovoltaic (CPV) Technology
TP-6A20-63916

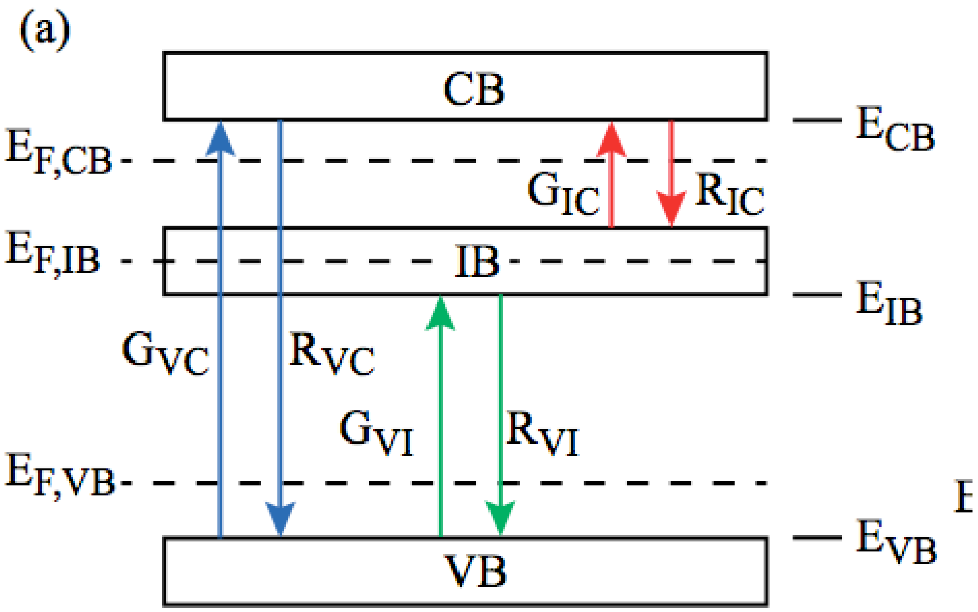
High Efficiency Solar Cell Concepts

Technology readiness level:

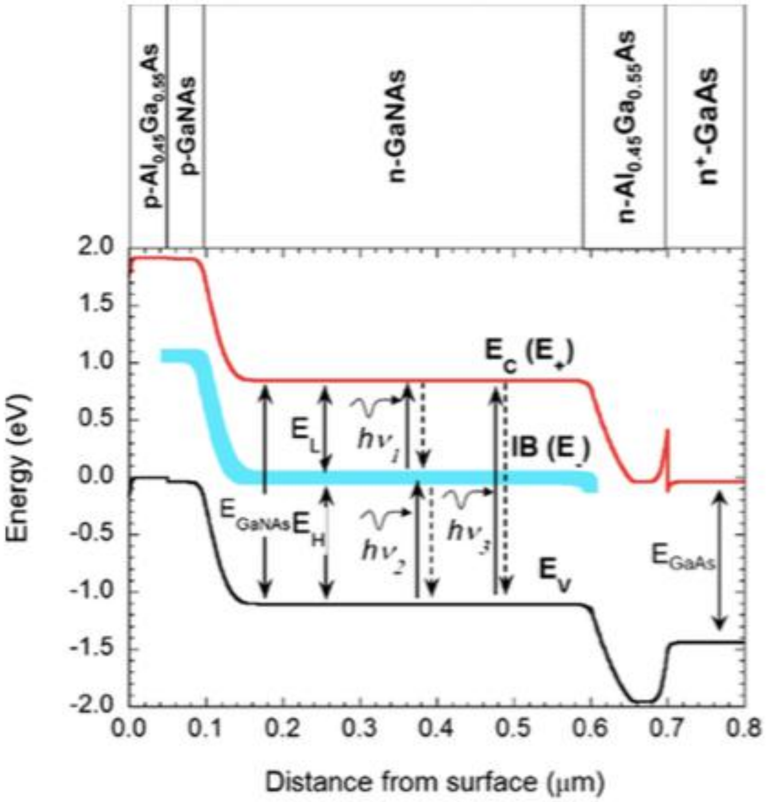


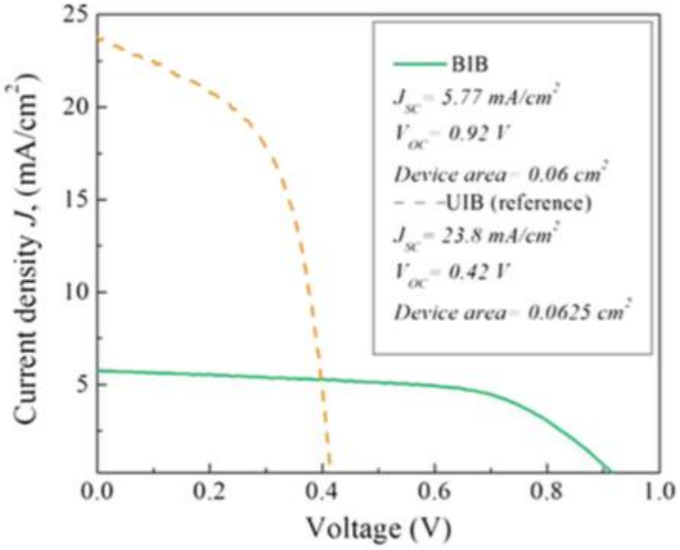
https://en.wikipedia.org/wiki/Technology_readiness_level

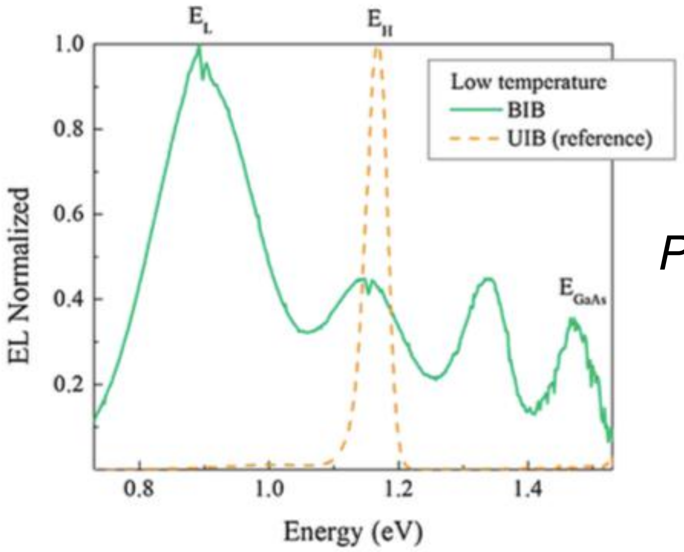
Intermediate Band Solar Cell



A.Luque, A.Marti,
Physical Review Letters, 78, 5014 (1997).





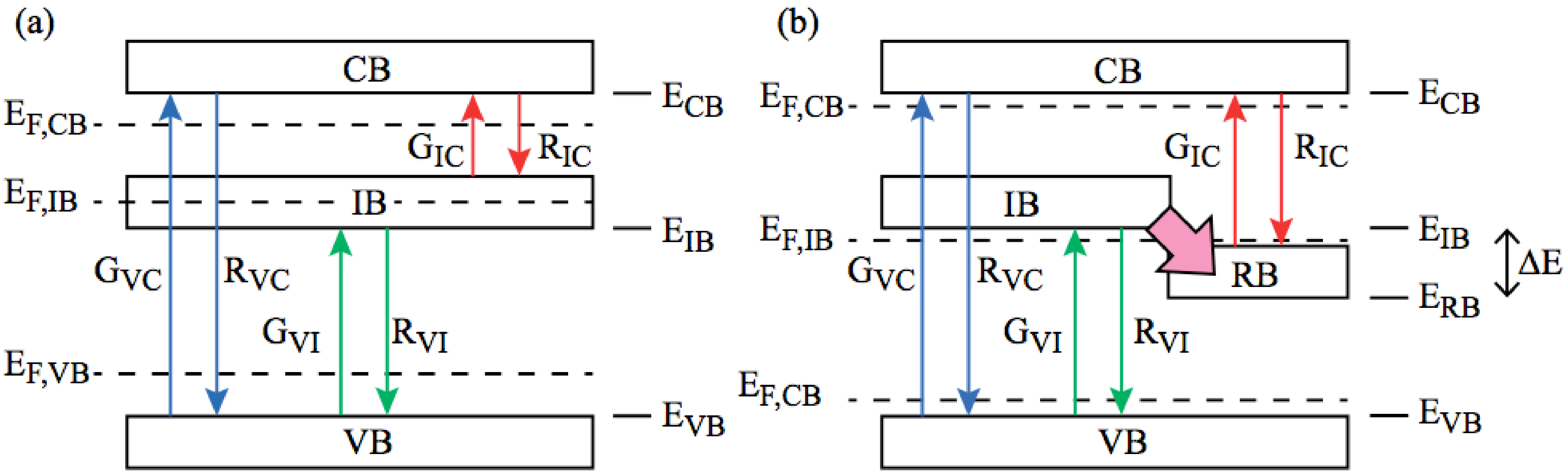


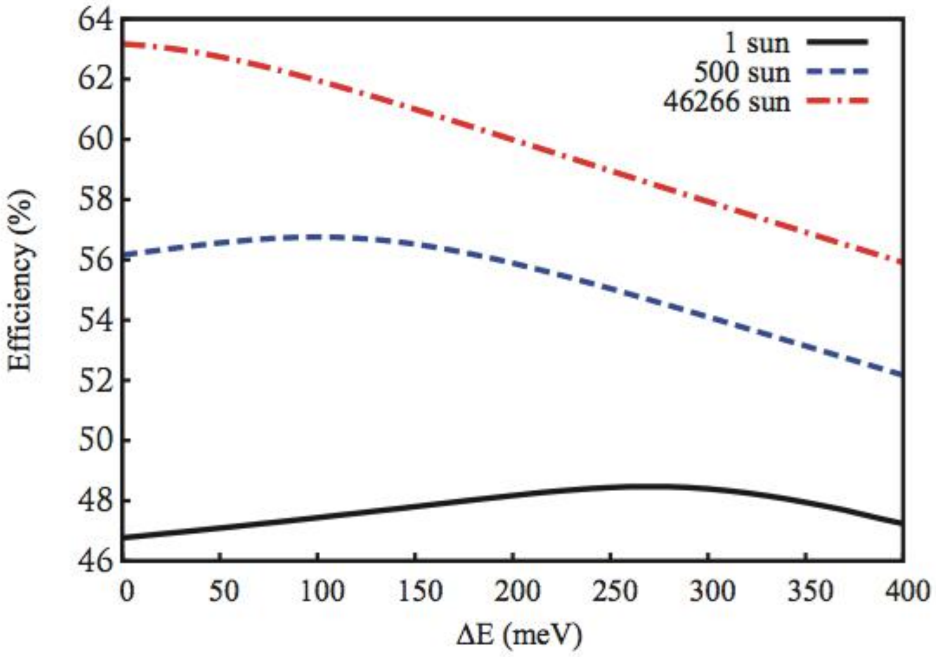
N. López,et al.,

Physical Review Letters,
106(2), p.028701
(2011)

Review paper: Y. Okada, et al., Applied Physics Reviews, 2(2), p.021302 (2015)

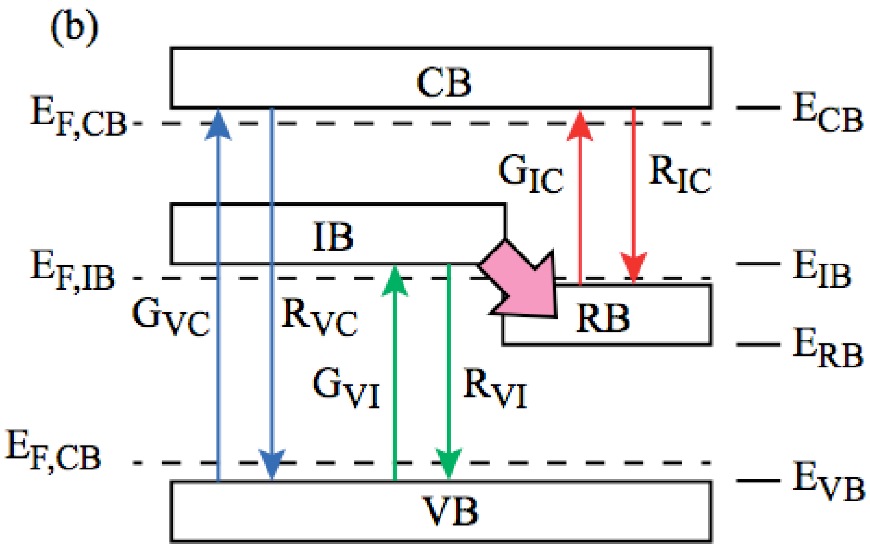
Sequential Absorption via a 'Photon Ratchet'

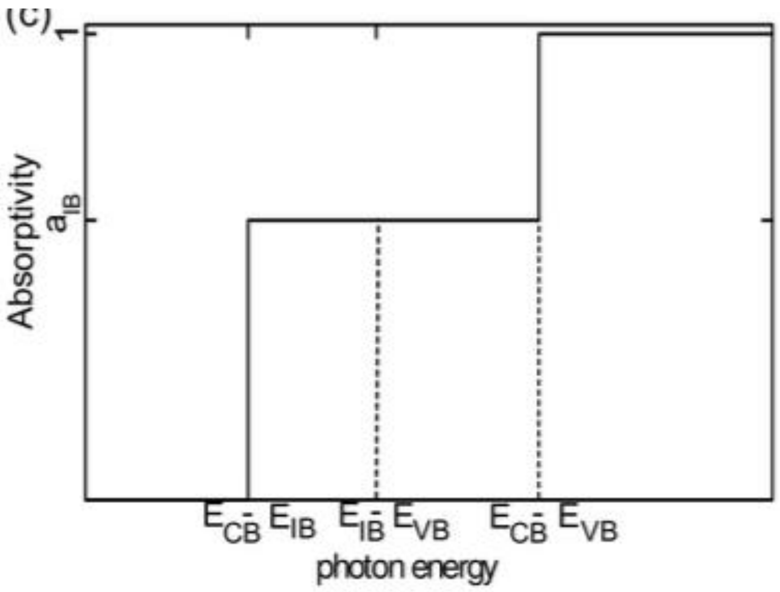


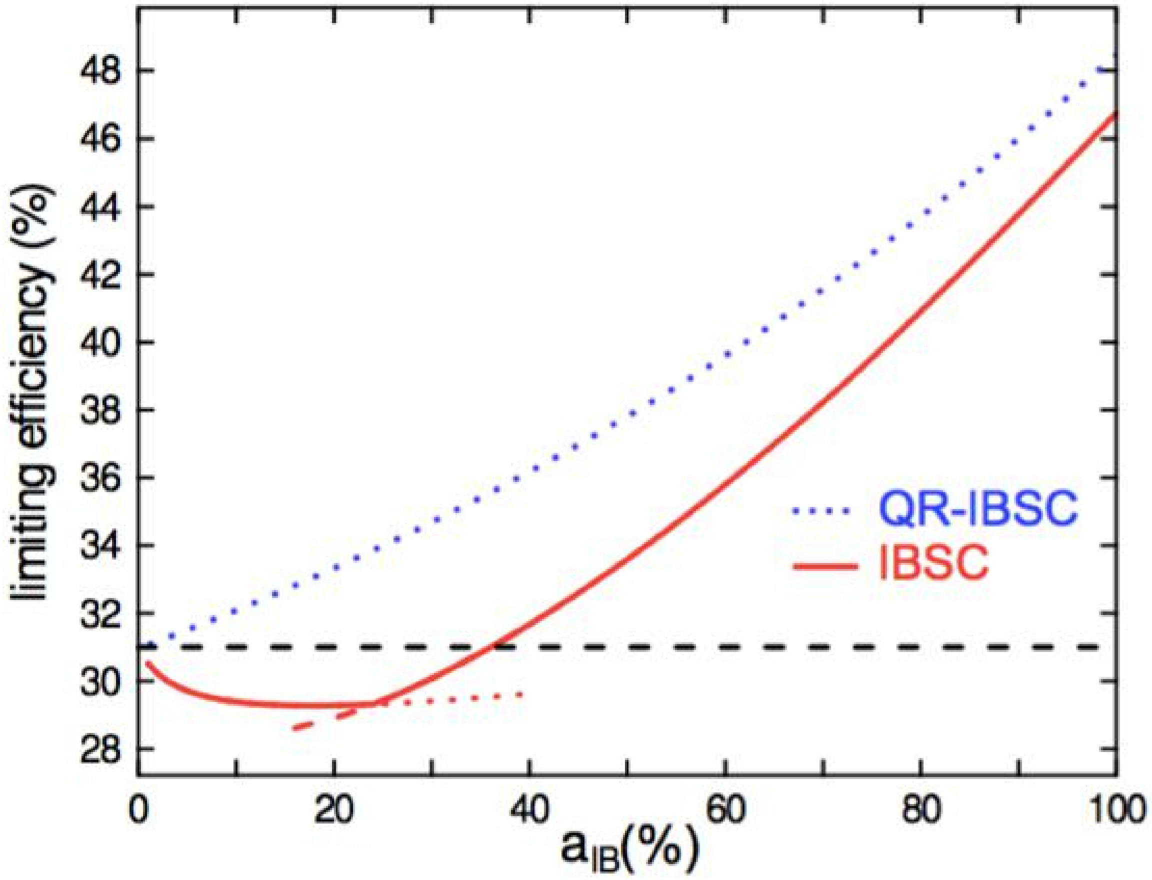


M.Yoshida, et al., Applied Physics Letters 100, 263902 (2012).

The need for absorption and/or relaxation in an IBSC



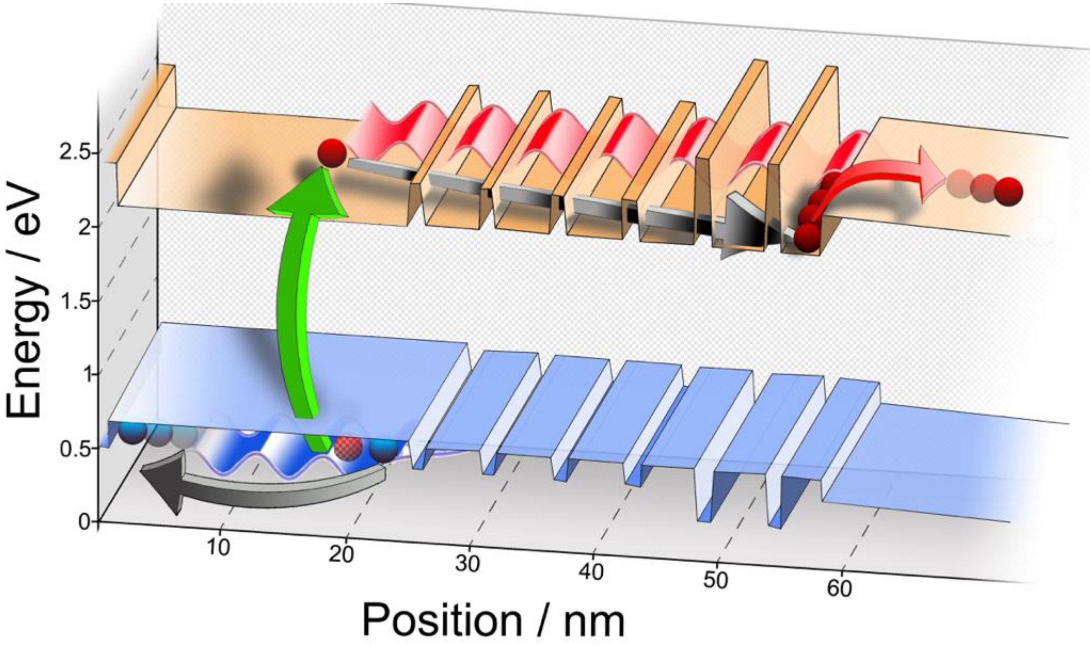




Pusch, A. et al., Progress in Photovoltaics, 24(5), pp.656 (2016).

Examples of two ratchet types:

Spatial Ratchet



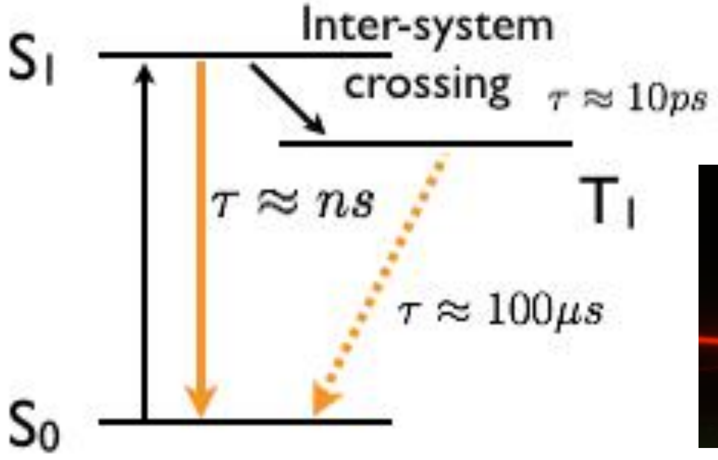
O.J. Curtin, et al., Photovoltaics, IEEE - JPV 6(3), p.673 (2016).

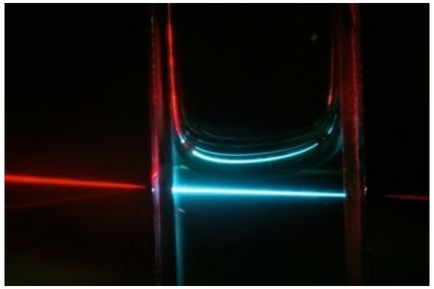
T. Kada, et al., Phys. Rev. B, 91(20), p.201303. (2015)

M.Sugiyama et al., IEEE- JPV, 2(3) p298 (2012)

H.€Lotfi,€App.Phys.Lett.€vol.€102,€ no. 21, p. 211103, (2013).

Spin Ratchet

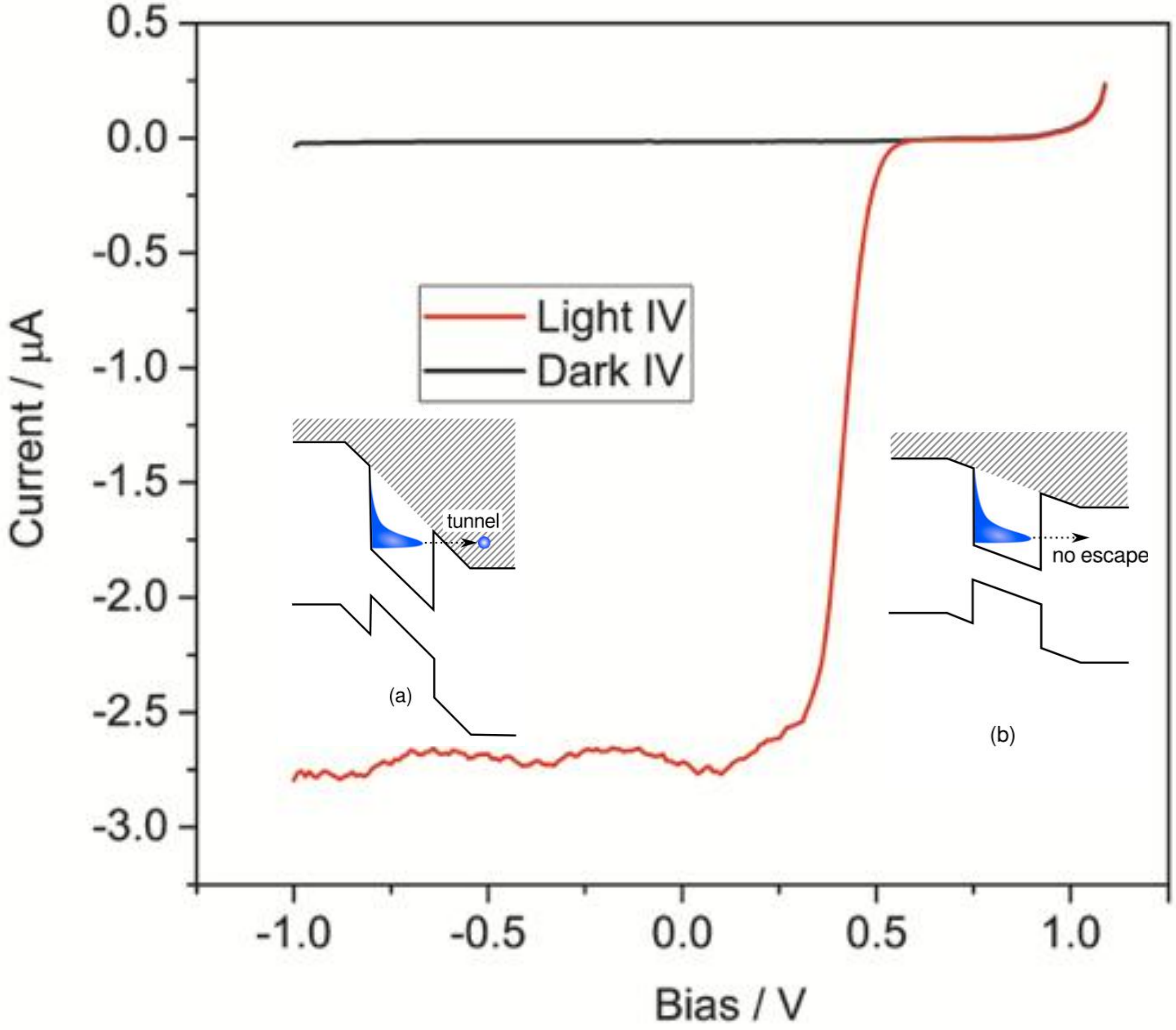




P. Olsson et al., Phys.Rev.Lett 102(22), 227204 (2009)

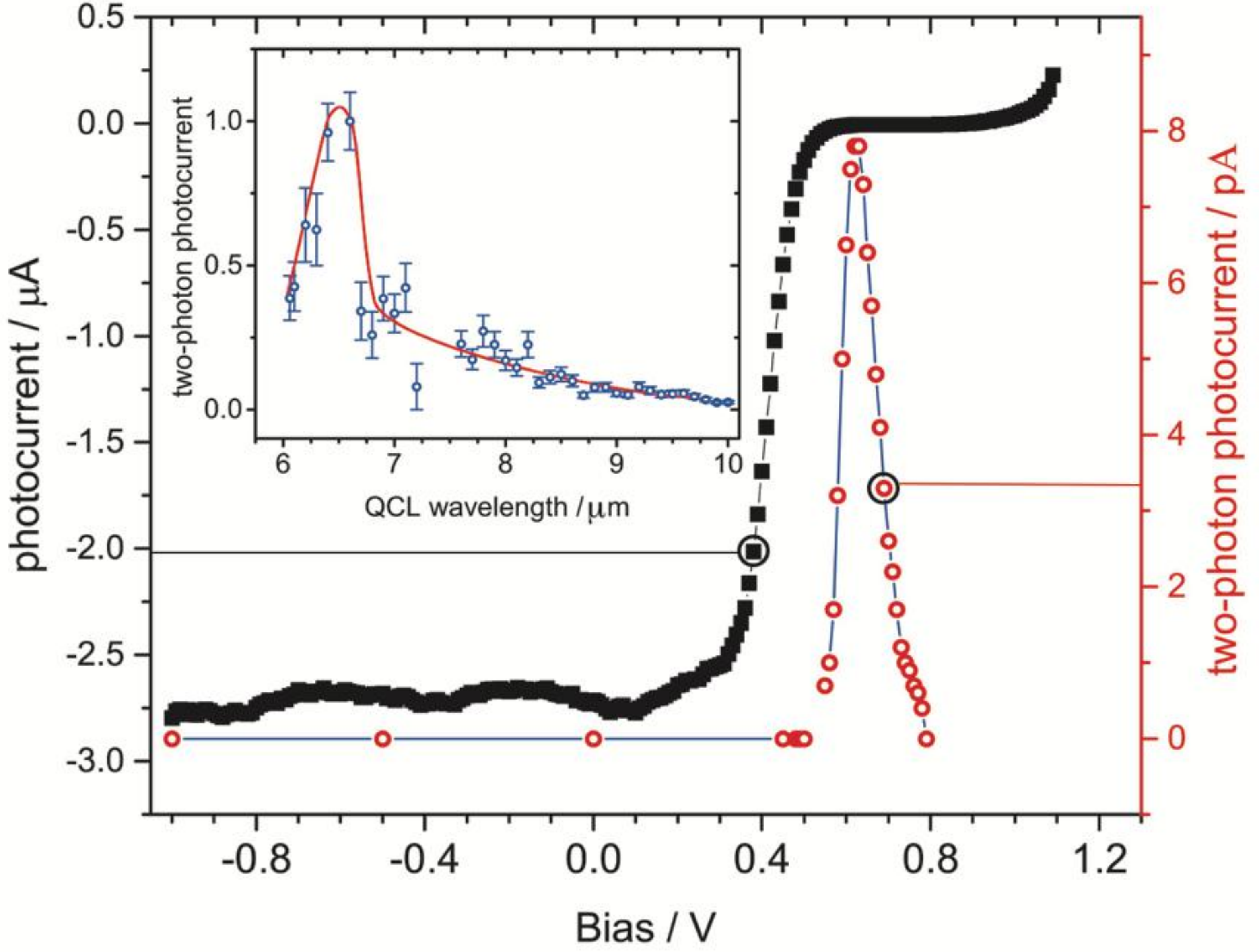
T.F. Schulze, & T.W. Schmidt, Energy Environ. Sci., 8, 103 (2015)

Primary Excitation : (850nm)
Dark & Light IV Characteristics



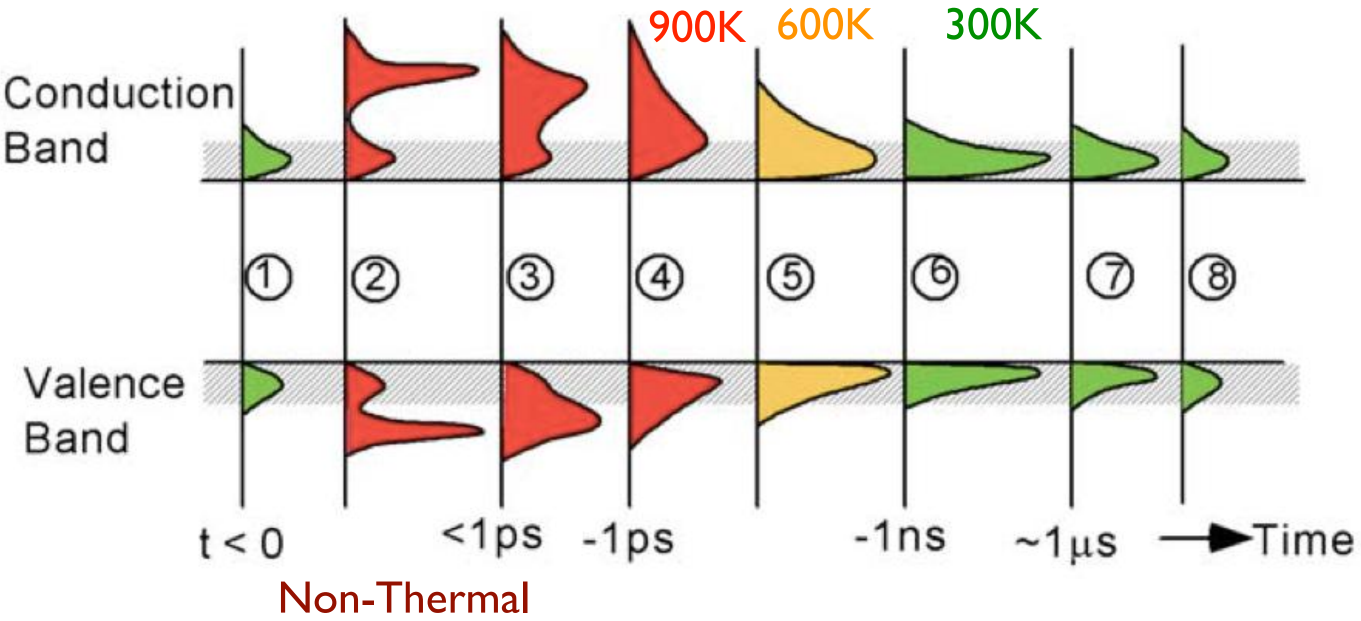
A.Vaquero, submitted for publication (2017)

2 Beam Excitation : (850nm + Mid-IR)

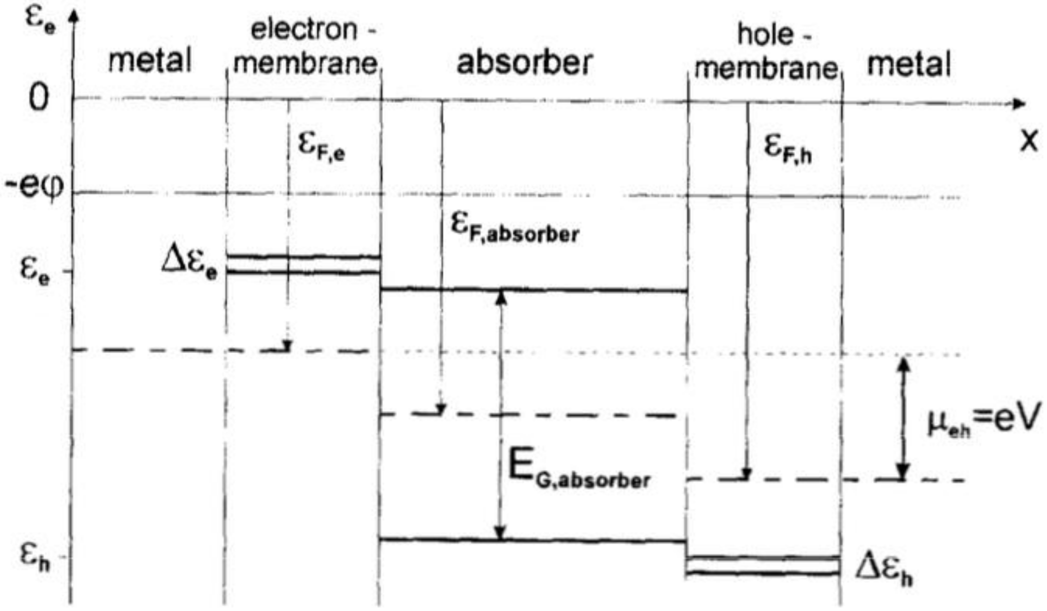


A.Vaquero, submitted for publication (2017)

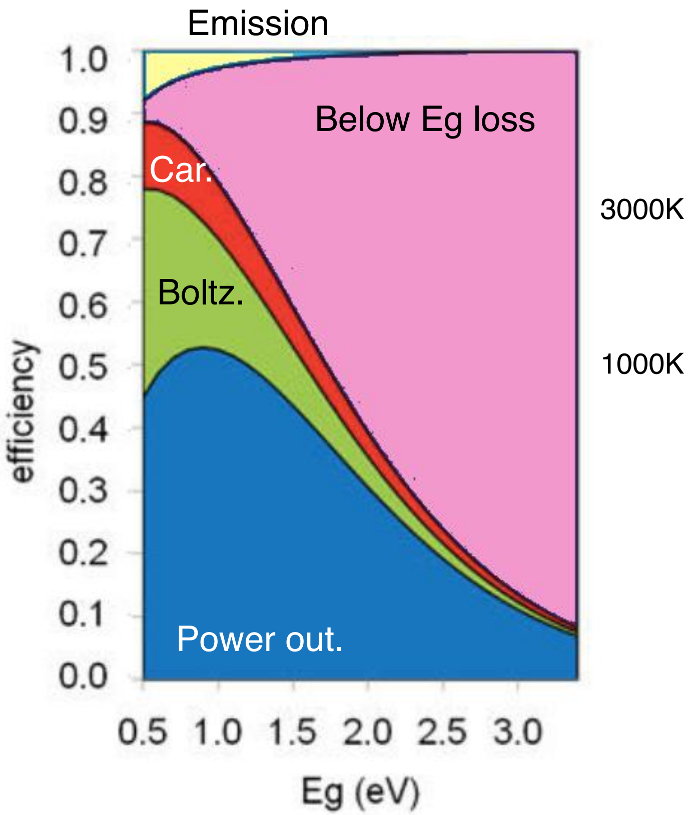
Hot Carrier Solar Cell



Green, M.A., Third Generation Photovoltaics, Springer 2003

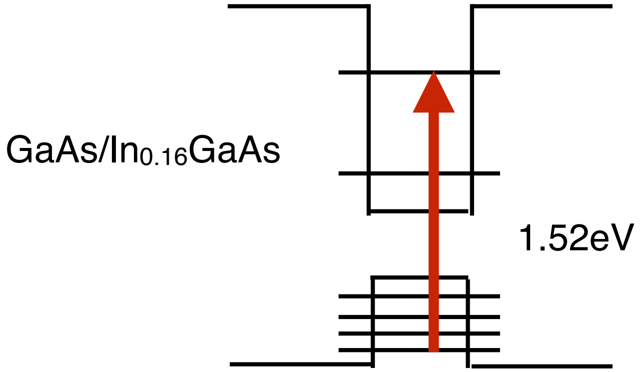


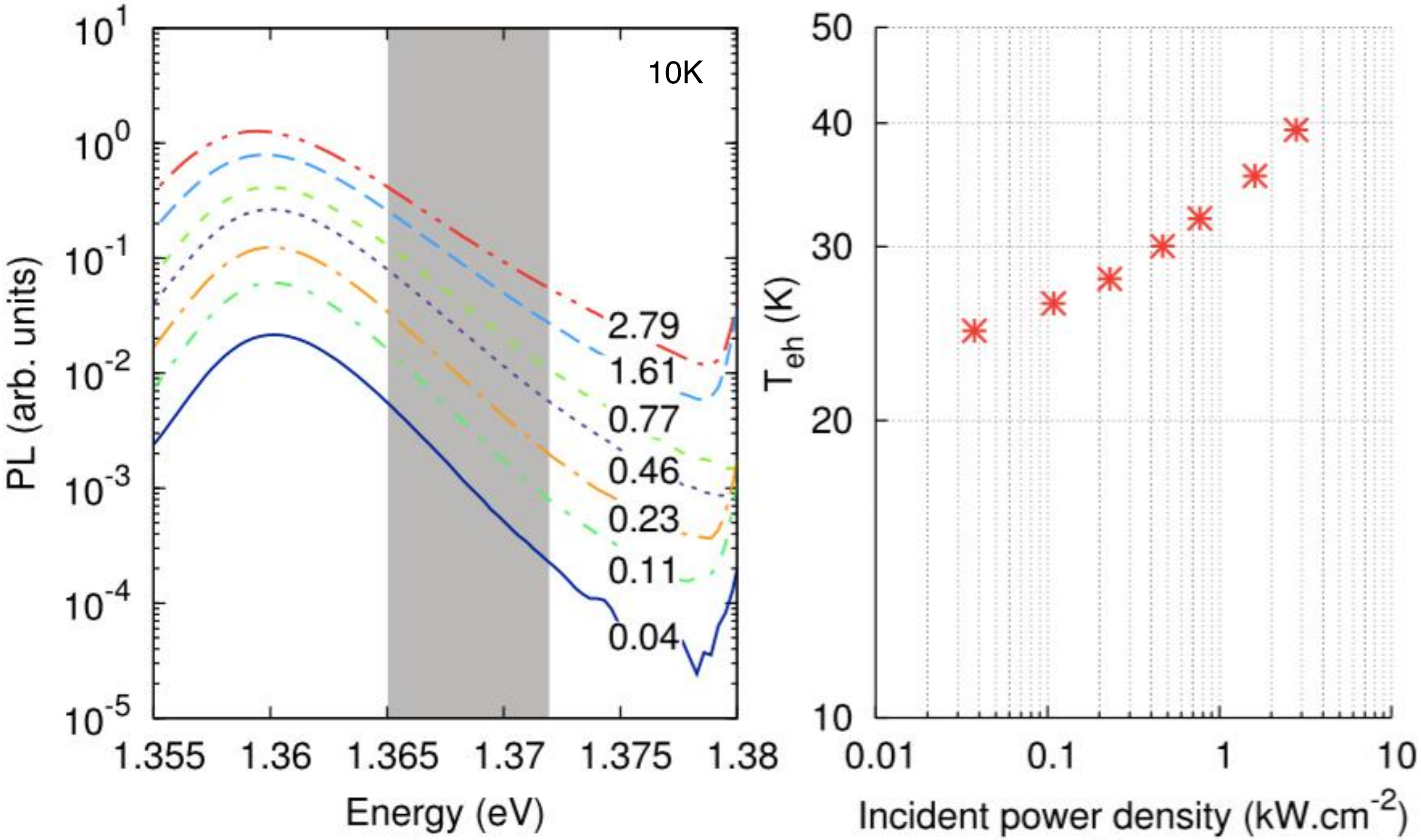
Wurfel, P., *Solar Energy Materials And Solar Cells*, 46(1), pp.43–52. (1997)



Hirst, L.C. et al.,. Proc. 37th IEEE Photovoltaic Specalists Conf.. p. 3302. (2011)

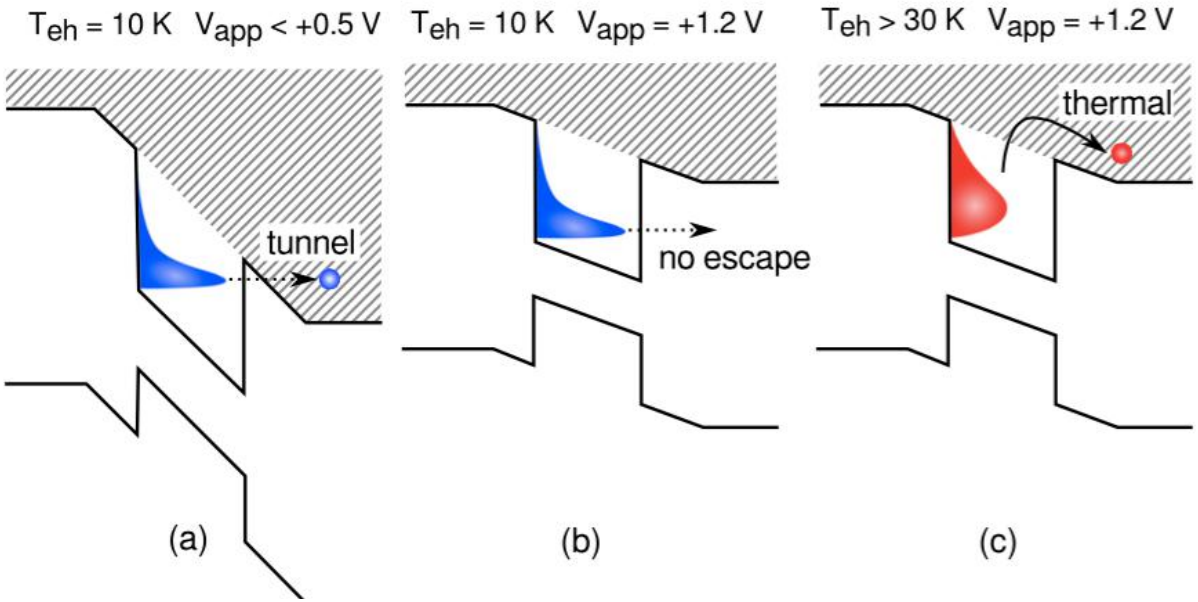
QW Hot-Carrier PV Cell

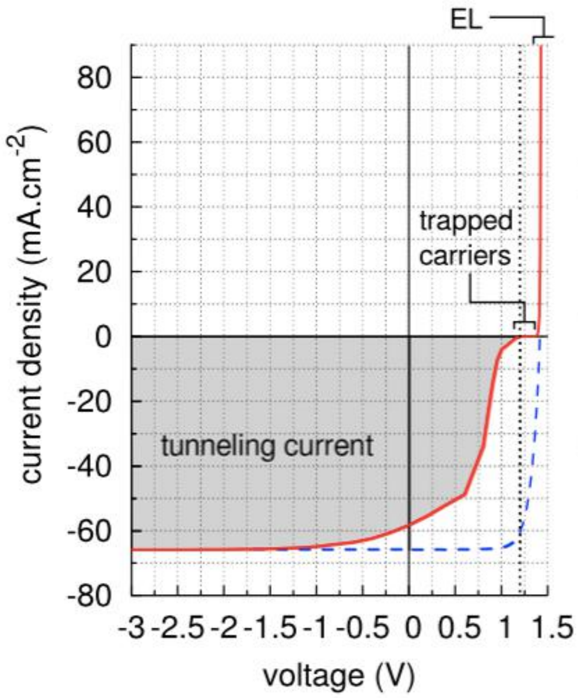


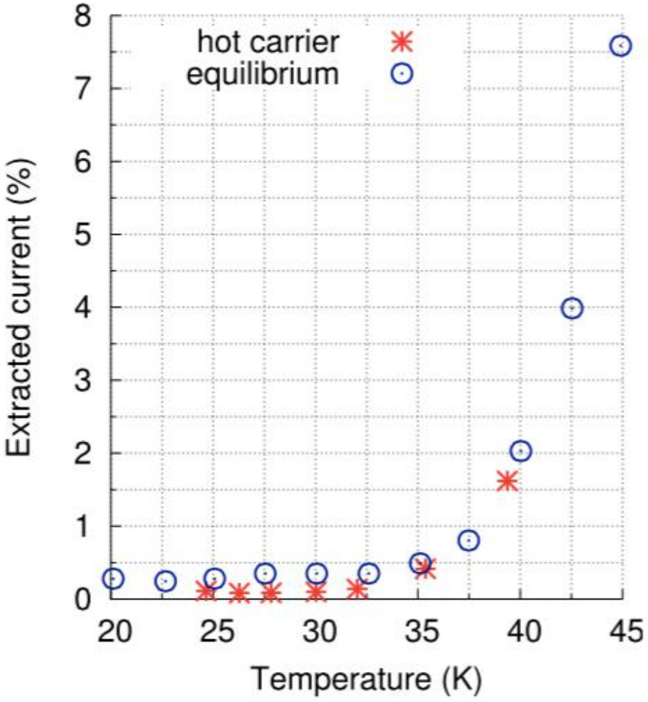


Hirst, L.C. et al. *Applied Physics Letters*, 104(23), p.231115. (2014)

QW Hot-Carrier PV Cell

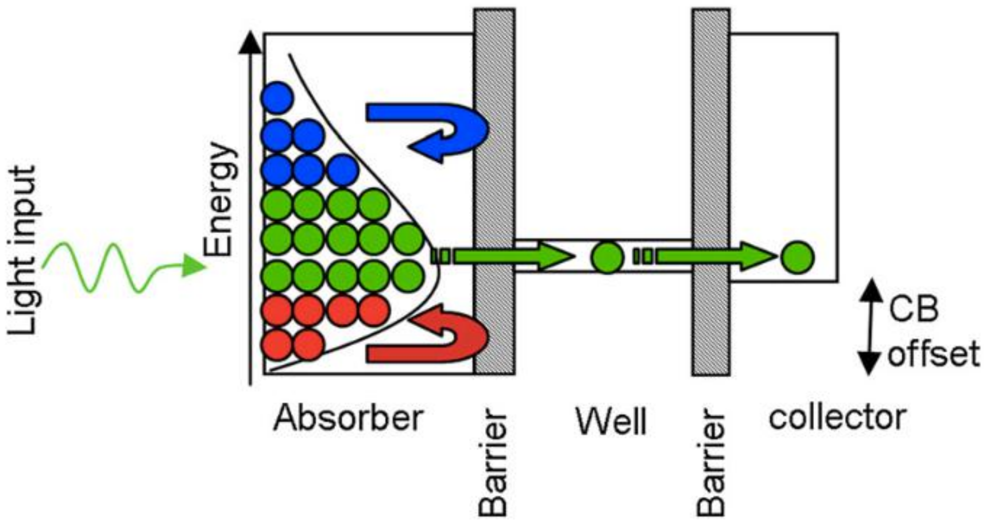


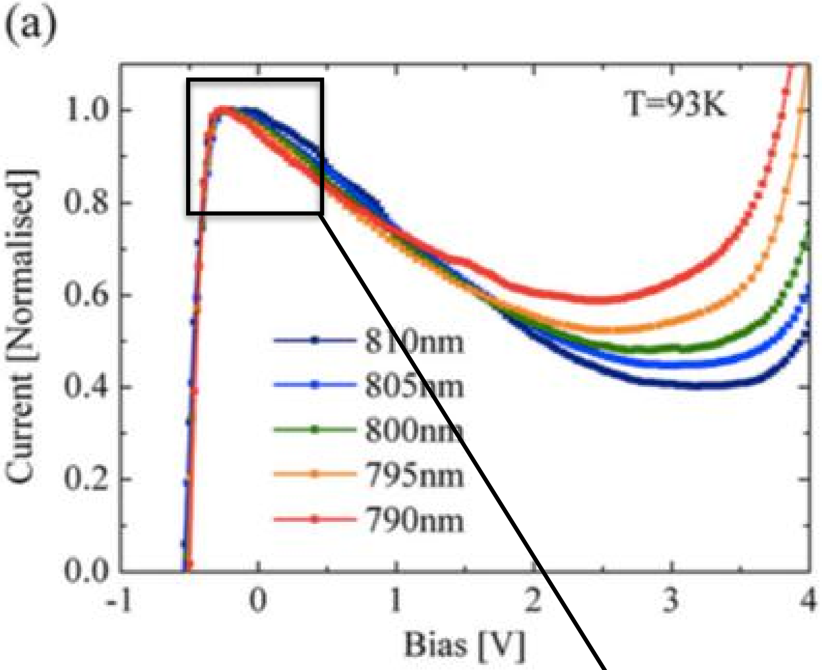


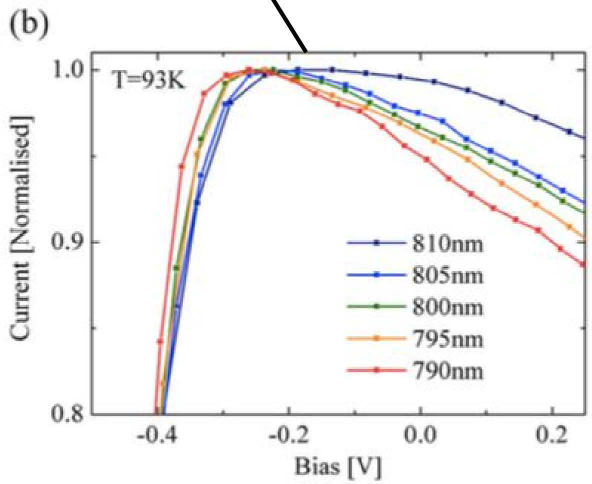


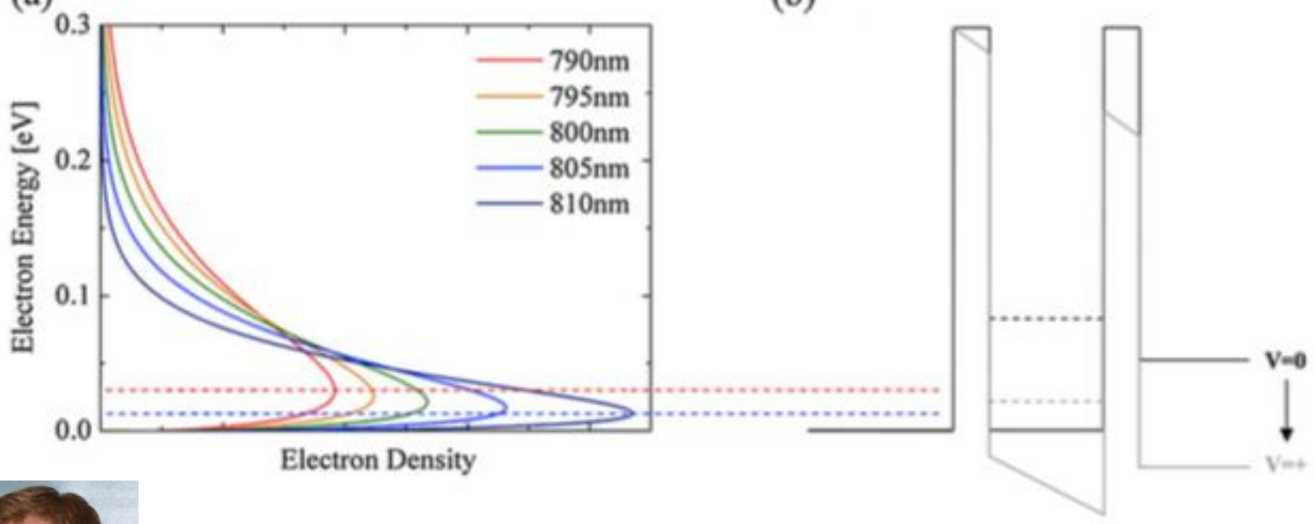
Hirst, L.C. et al. *Applied Physics Letters*, 104(23), p.231115. (2014)

Resonant Tunnel Hot Carrier Solar Cell



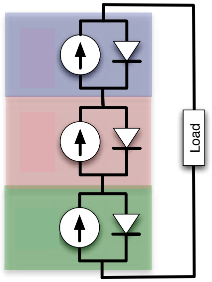






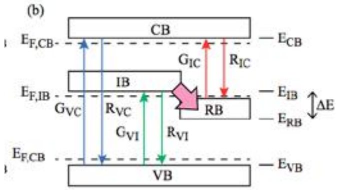
Dimmock, J.A.R. et al., *Progress In Photovoltaics*, 22(2), pp.151–160 (2014).

Conclusions

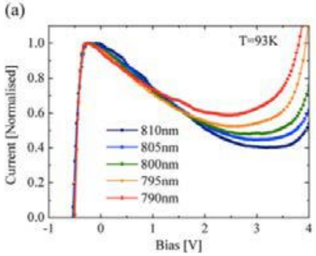


Single junction solar cells now operate close to the Shockley-Queisser limit.

Multi-junction solar cells offer efficiencies >40% today with 50% likely by 2020.



Intermediate band solar cell require strong sequential absorption. A carrier relaxation stage to form a 'ratchet' is likely to aid this process.



Hot carrier solar cells have been demonstrated, under intense, monochromatic illumination at cryogenic temperature.

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