Faculty of Engineering, Solar & Renewable Energy Engineering

Solar Energy System Efficiencies of 70%, fact or fiction?

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Part I: Solar Power Conversion above 40%

- Efficiency limits for PV,
- Multi-junction solar cells,
- Intermediate band solar cells,
- Hot carrier solar cells.

https://www.youtube.com/watch?v=femL4hatRBc

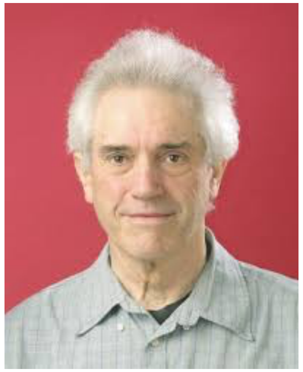
Part II:

- Quantum Well solar cells
- Molecular up-conversion & IB solar cell
- Hybrid PV-Thermal systems:
    - Emissivity control

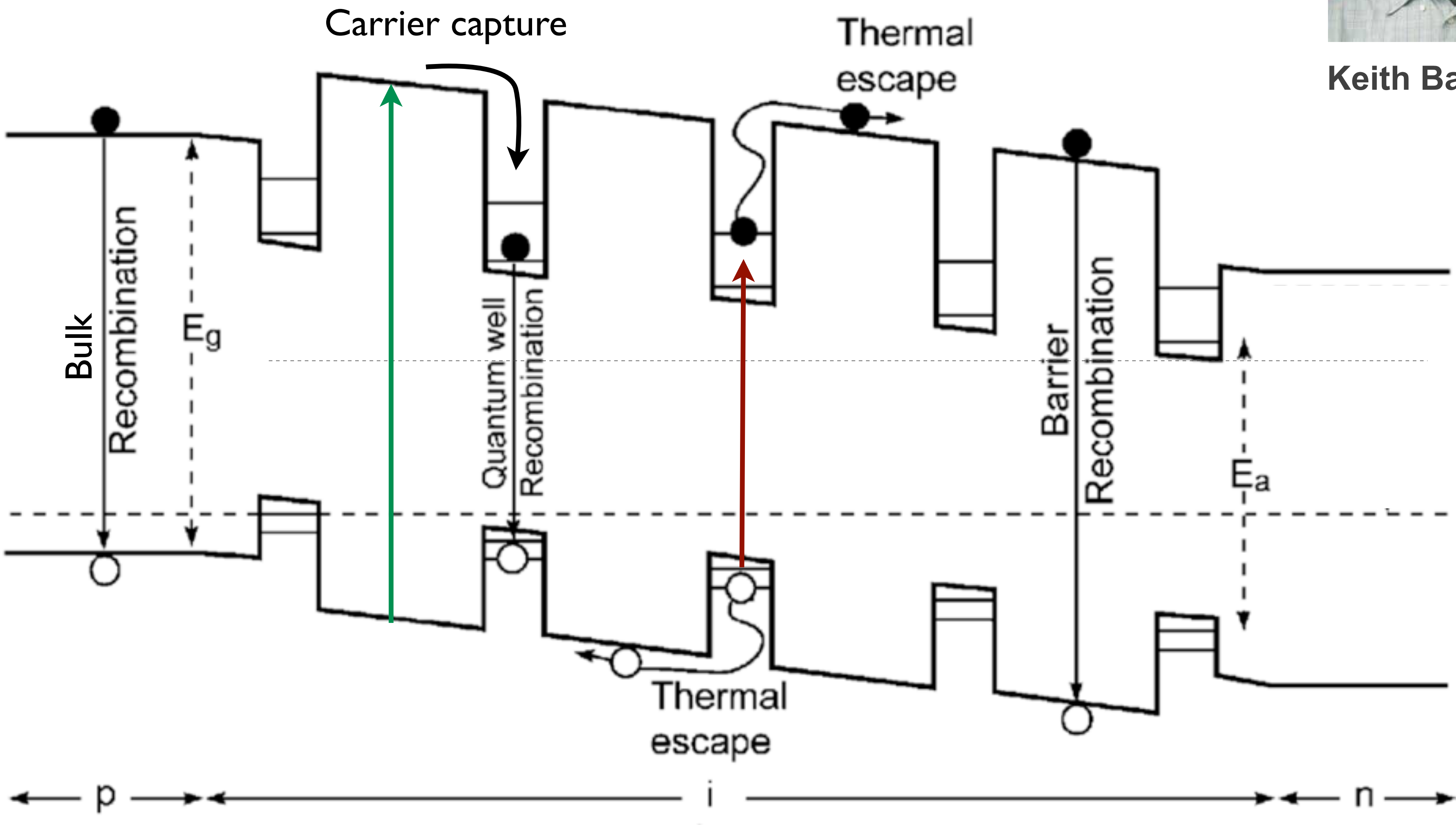
PhD opportunities available - please contact Ned by email if interested in working in this field.

An early influence:

Quantum Well Solar Cell

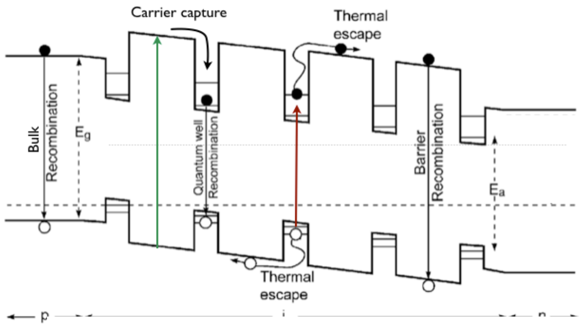


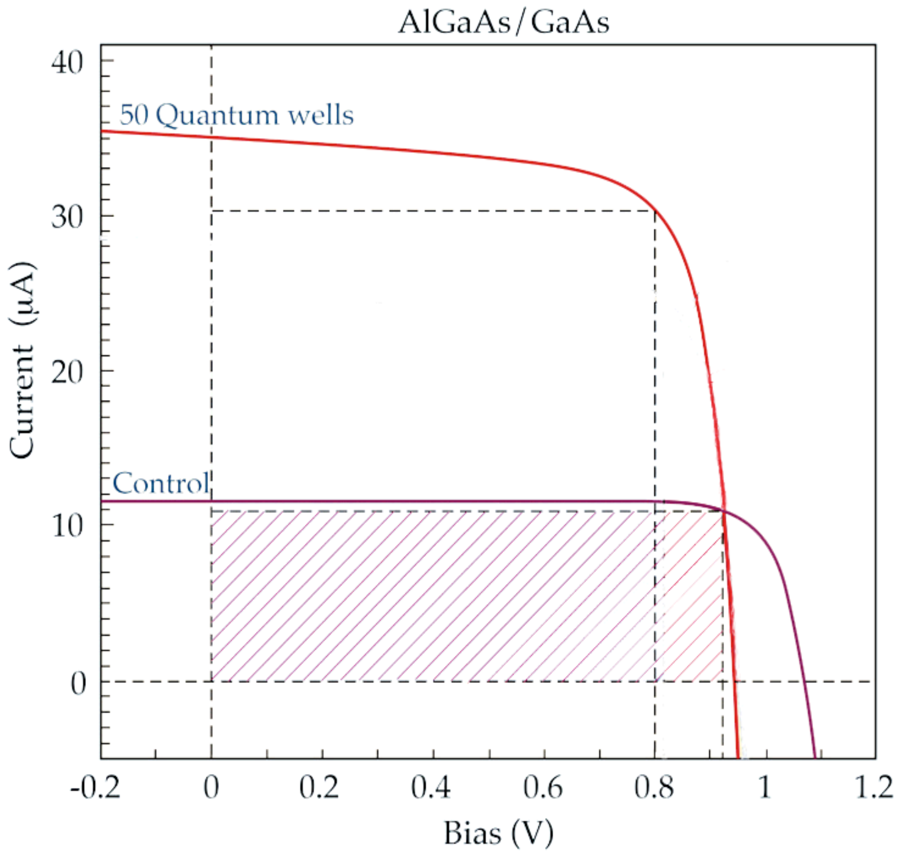
Keith Barnham

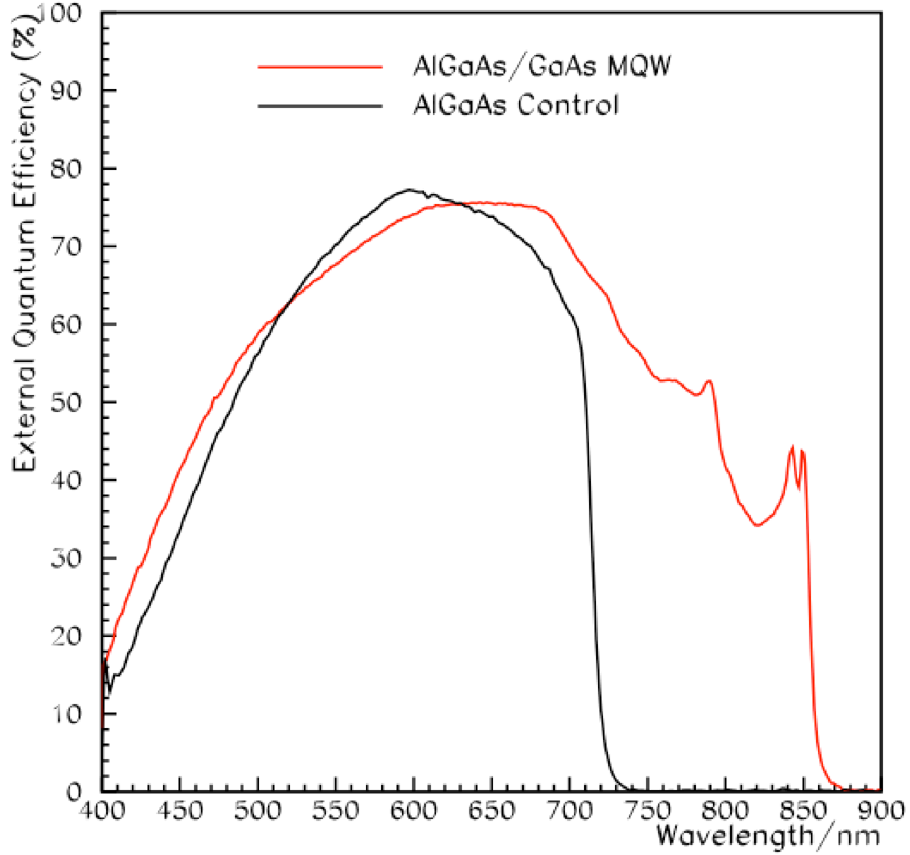


K. Barnham & G.Duggan. Journal of Applied Physics (1990) vol. 67 (7) pp. 3490

Quantum Well Solar Cell







K.Barnham et al., Appl.Phys.Lett. 59, 135 (1991)

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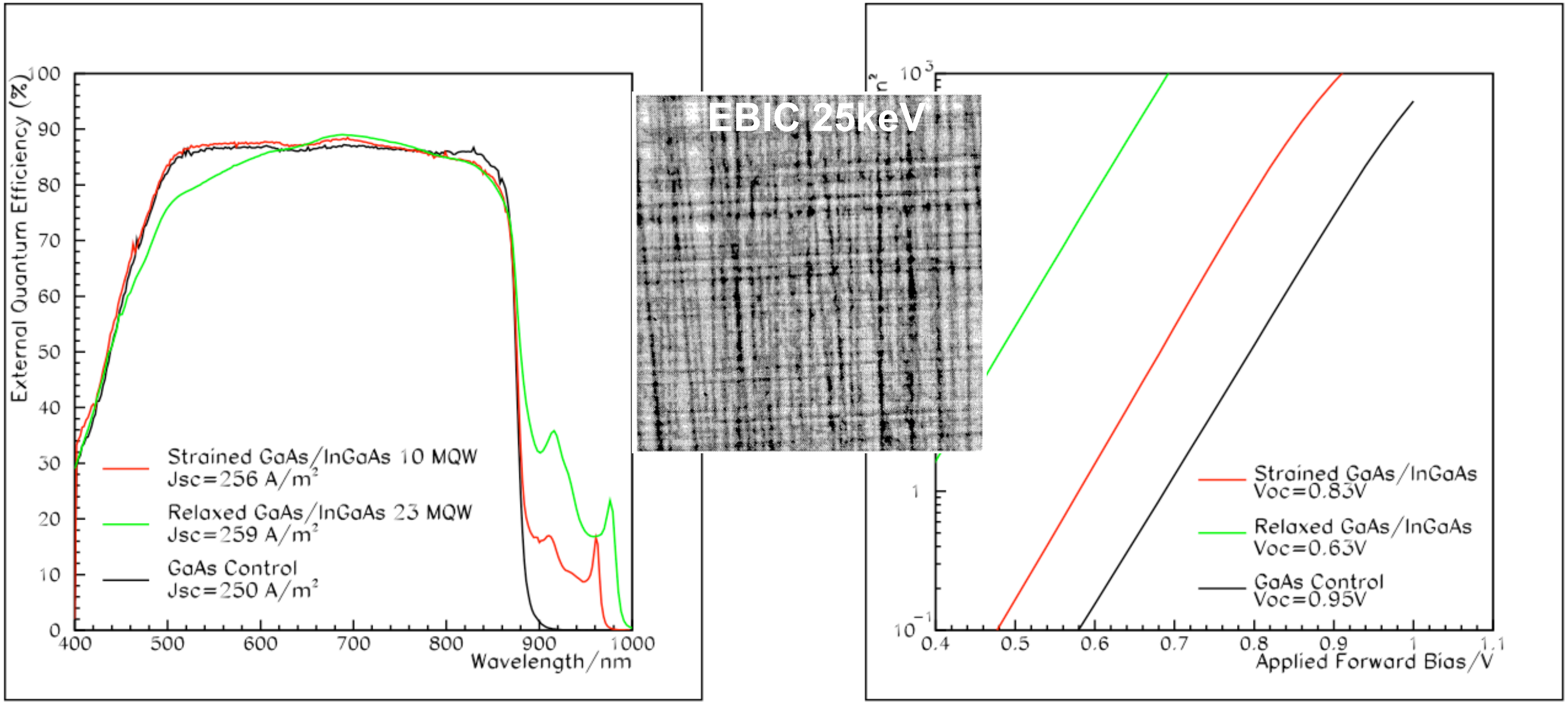
GaAs/InGaAs MQW Solar Cells



GaAs Control **19%**

10 MQW **17%**

23 MQW **12%**

J.Barnes et al., J. Appl. Phys, 79, 7775-7779 (1996)

Mazzer et al. Mat Sci Eng B-Solid (1996) vol. 42 pp. 43-51

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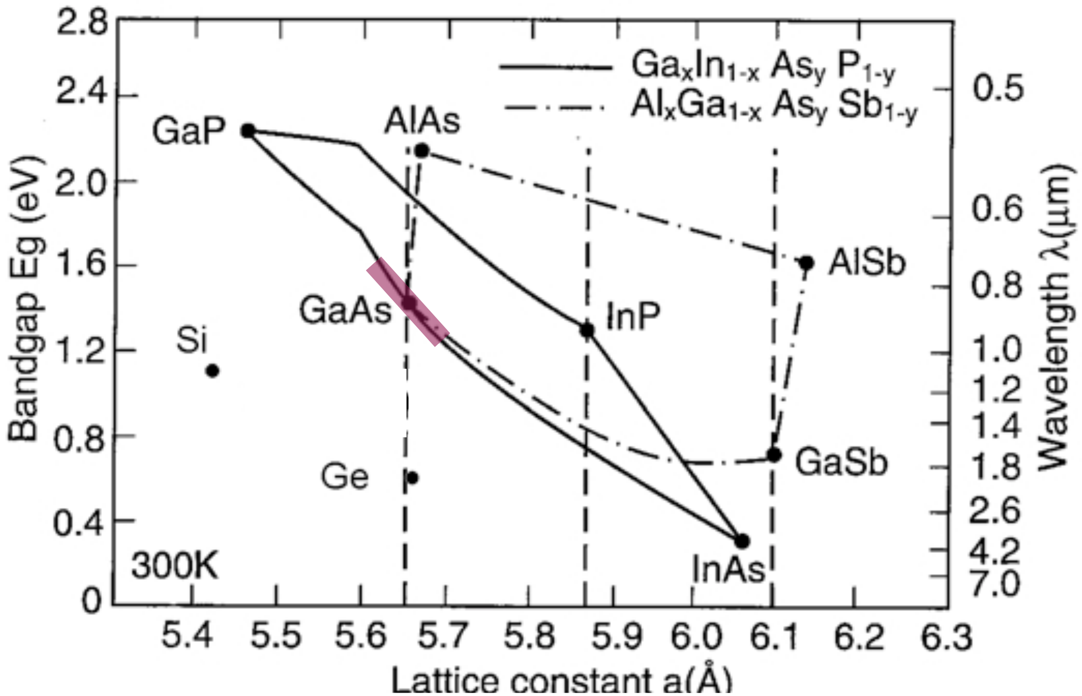
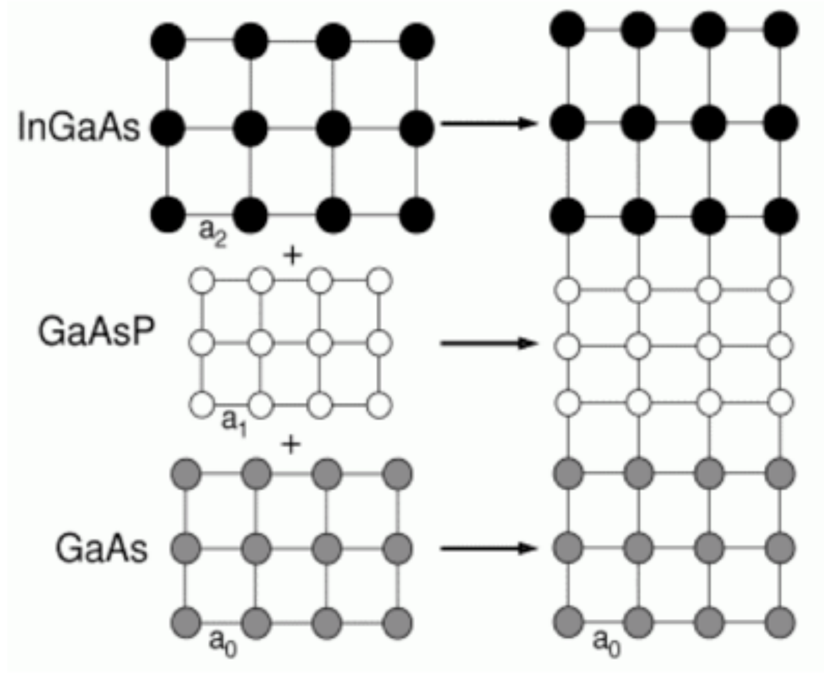
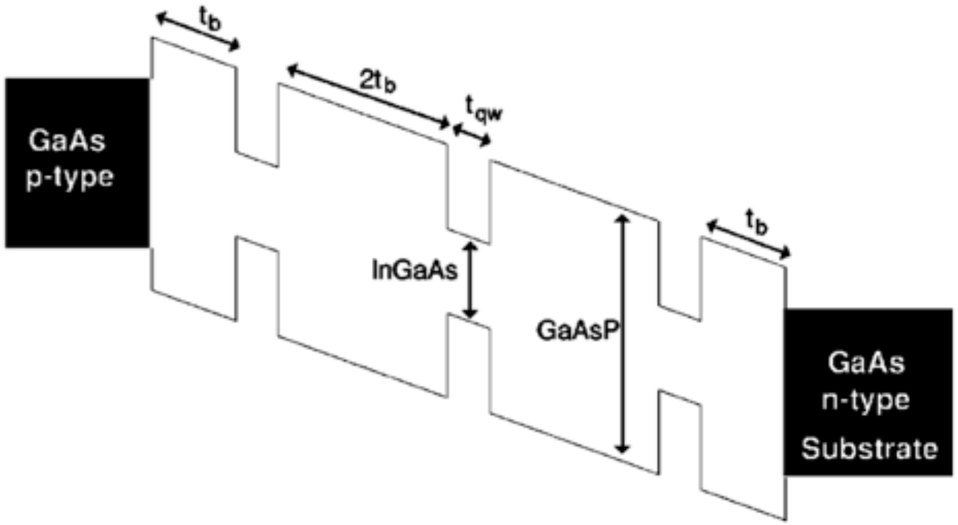
Strain-Balanced Multi-Junction Solar Cell

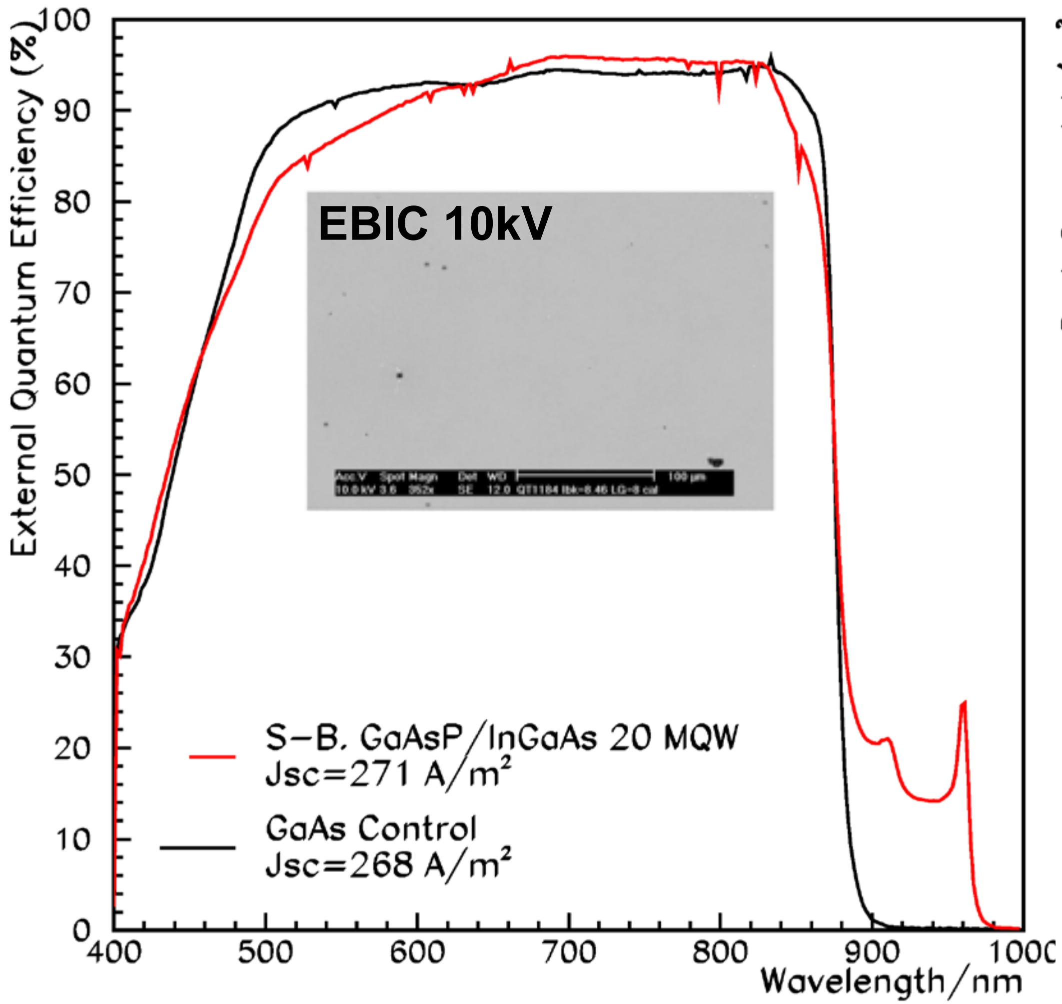


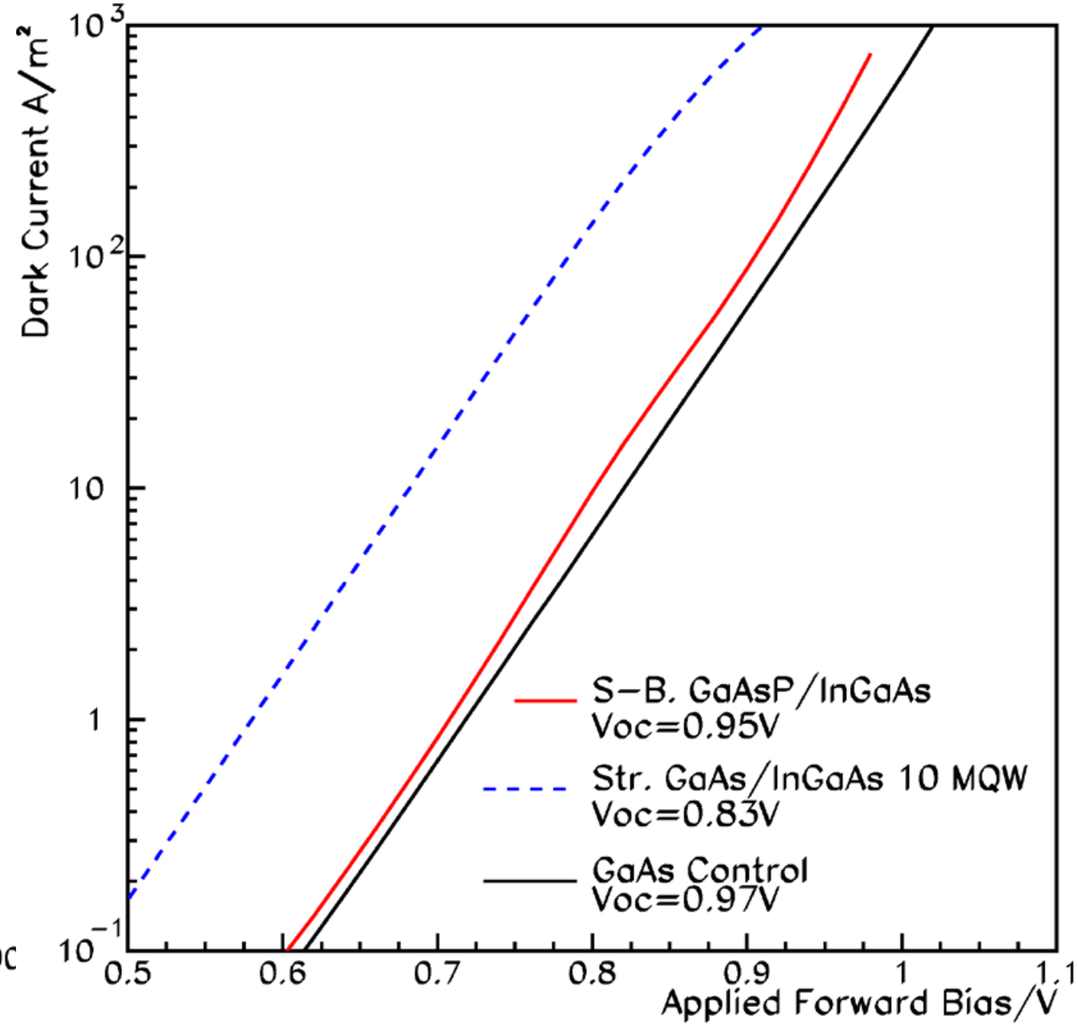




Dr John Roberts,
University of Sheffield.

GaAsP / InGaAs Strain-Balance Cell

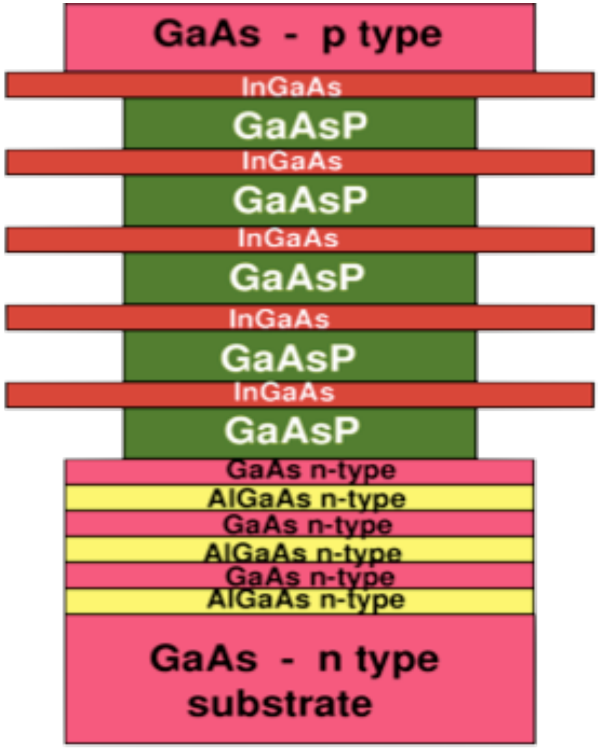


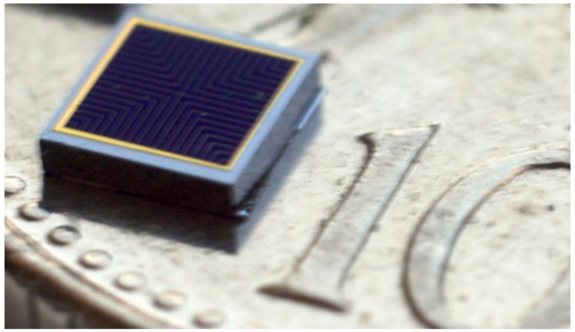


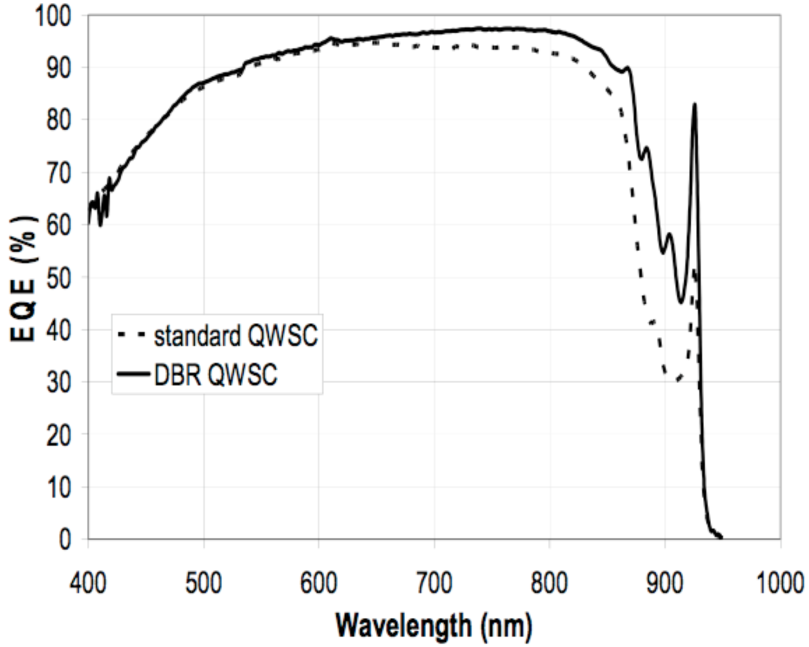
N. J. Ekins-Daukes, et. al., Appl. Phys. Lett., 75, p 4195, (1999)

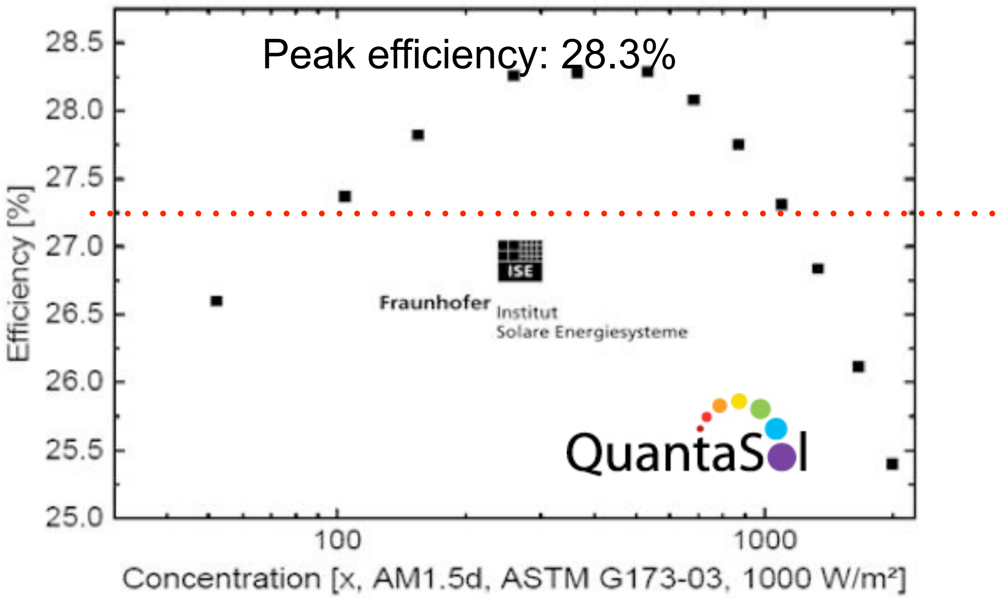
& Cryst Growth Des, vol. 2, no. 4, pp. 287–292, (2002).

Record Single Junction Quantum Well Solar Cell









K.Barnham, M.Mazzer, J.S. Roberts, T.Tibbits, D.Bushnell and Quantasol team… (2009)

J.Nelson & N.Ekins-Daukes "Clean Electricity from Photovoltaics", 2nd Ed. Imperial College Press 2014.

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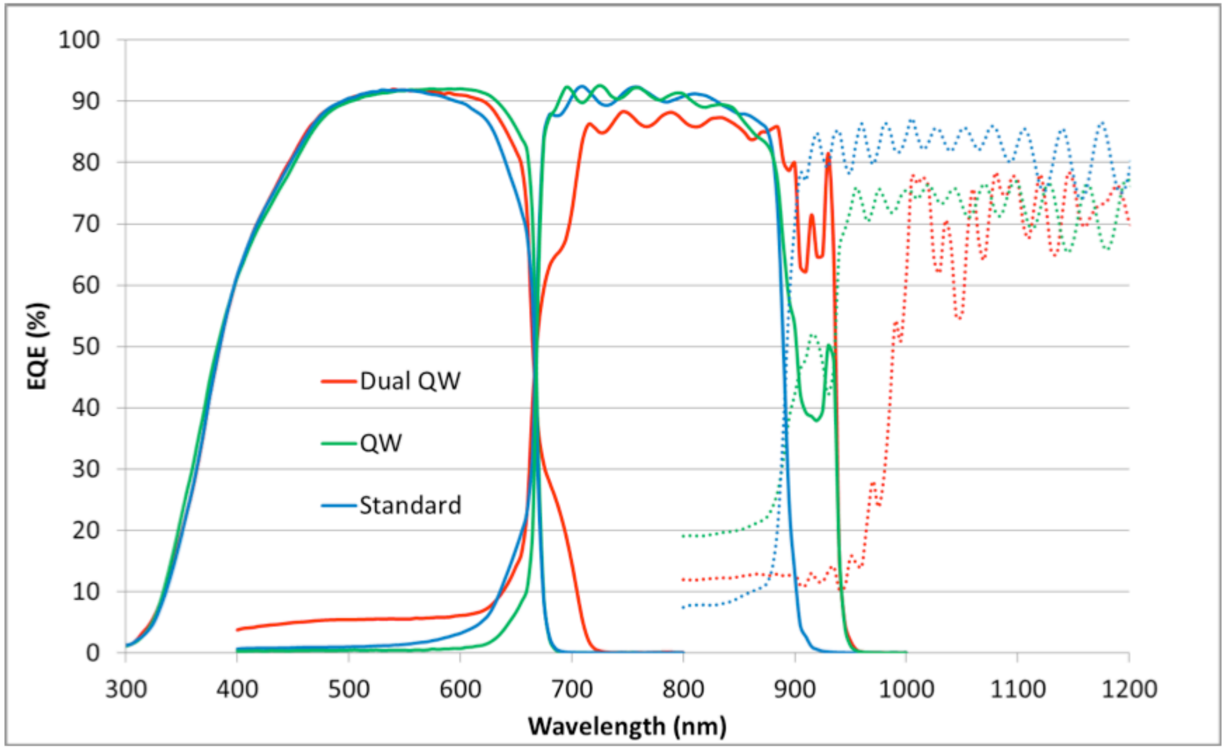
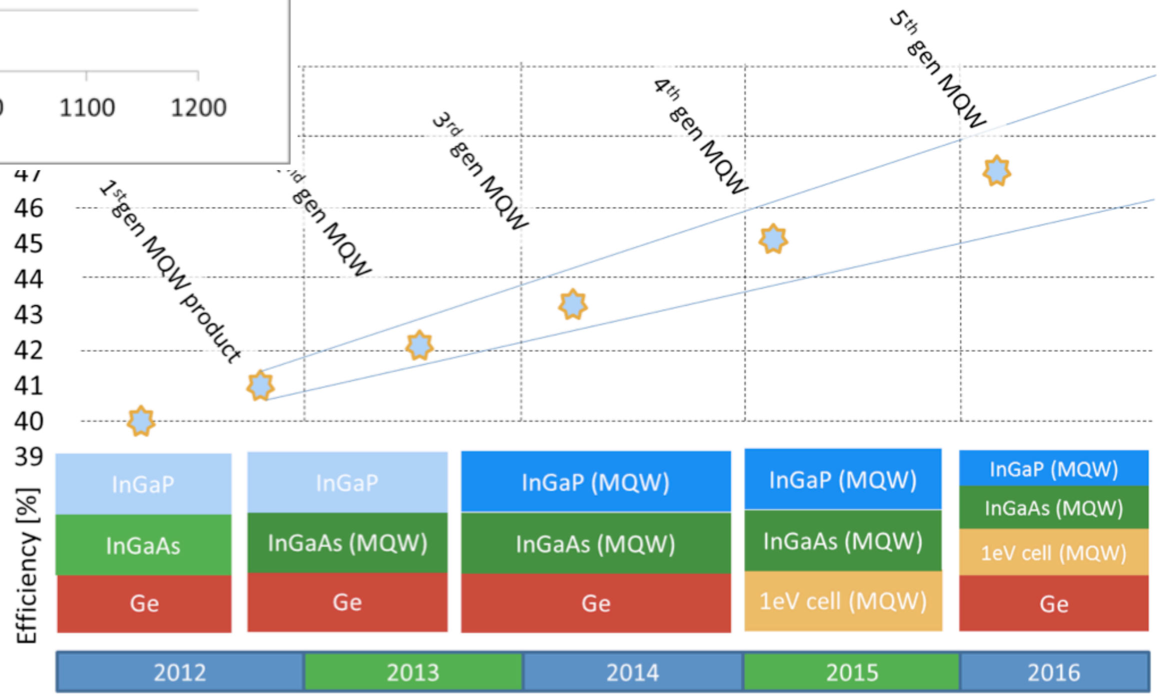
Dual (InGaP/InGaAsP)/(GaAsP/InGaAs)/Ge MQW 3J solar cell



B. Browne, 9th International Conference on Concentrator Photovoltaic Systems: CPV-9, 2013, vol. 1556, no. 1, pp. 3–5.

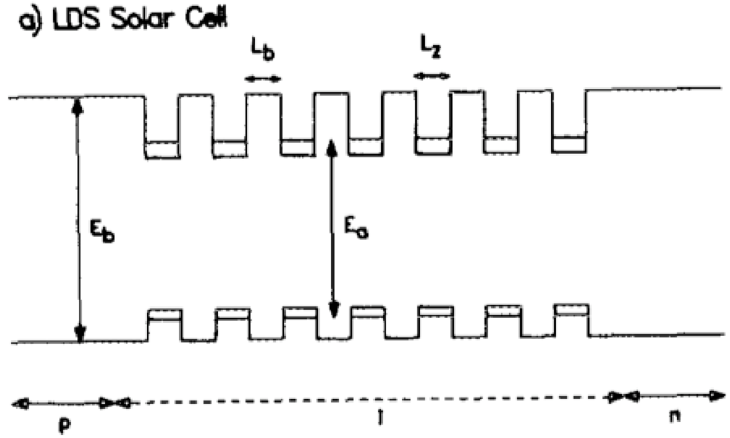


A new approach to high-efficiency multi-band-gap solar cells

K. W. J. Barnham
Blackett Laboratory, Imperial College of Science, Technology, and Medicine, London SW7 2BZ, United Kingdom
G. Duggan
Philips Research Laboratories, Redhill RH1 5HA, United Kingdom

(Received 12 June 1989; accepted for publication 8 December 1989)

The advantages of using multi-quantum-well or superlattice systems as the absorbers in concentrator solar cells are discussed. By adjusting the quantum-well width, an effective band-gap variation that covers the high-efficiency region of the solar spectrum can be obtained. Higher efficiencies should result from the ability to optimize separately current and voltage generating factors. Suitable structures to ensure good carrier separation and collection and to obtain higher open-circuit voltages are presented using the (AlGa)As/GaAs/(InGa)As system. Efficiencies above existing single-band-gap limits should be achievable, with upper limits in excess of 40%.

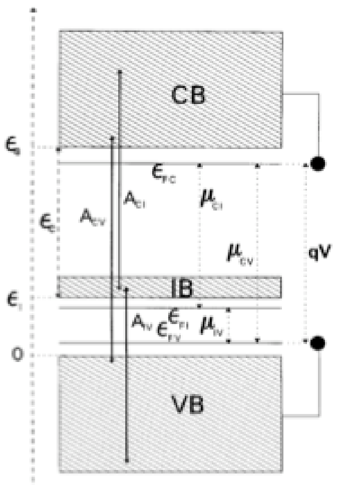


RECOMBINATION OF CARRIERS IN QUANTUM WELL SOLAR CELLS

Proc. IEEE, 1993

Richard Corkish and Martin A. Green
Centre for Photovoltaic Devices and Systems
University of New South Wales
P.O. Box 1 Kensington, NSW 2033 Australia

VOLUME 78, NUMBER 26 PHYSICAL REVIEW LETTERS 30 JUNE 1997

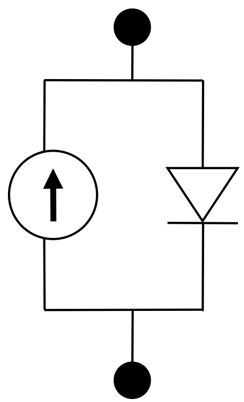


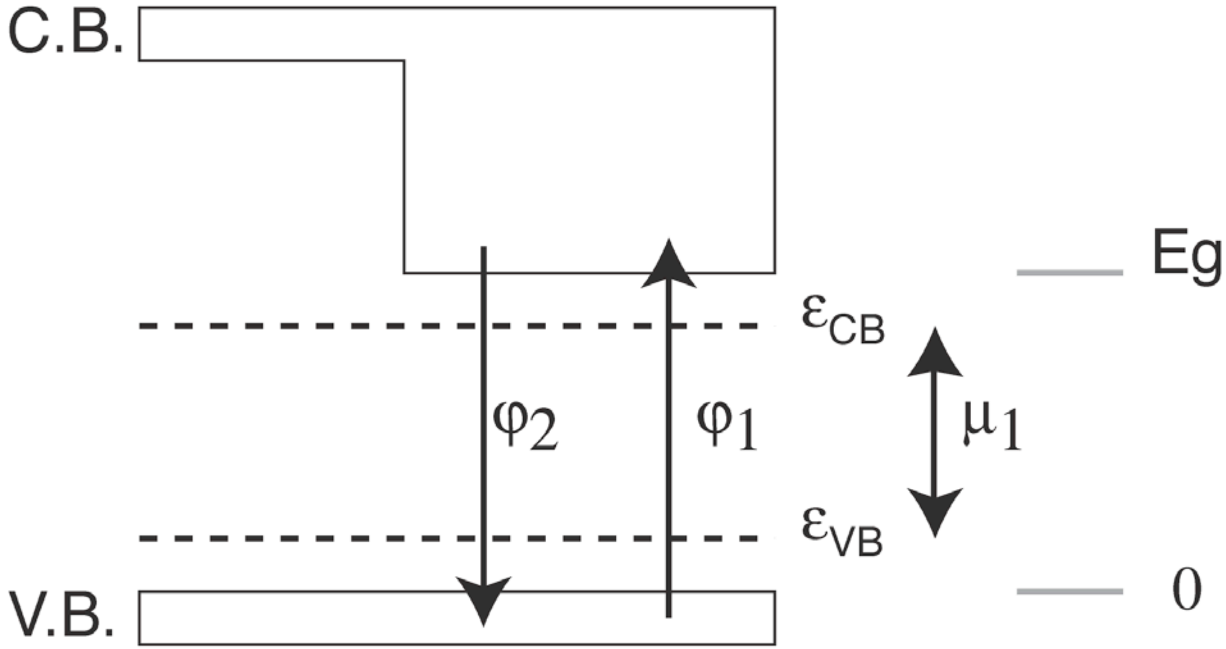
Increasing the Efficiency of Ideal Solar Cells by Photon Induced Transitions at Intermediate Levels

Antonio Luque and Antonio Martí
Instituto de Energía Solar, Universidad Politécnica de Madrid, 28040 Madrid, Spain
(Received 7 February 1997)

Recent attempts have been made to increase the efficiency of solar cells by introducing an impurity level in the semiconductor band gap. We present an analysis of such a structure under ideal conditions. We prove that its efficiency can exceed not only the Shockley and Queisser efficiency for ideal solar cells but also that for ideal two-terminal tandem cells which use two semiconductors, as well as that predicted for ideal cells with quantum efficiency above one but less than two. [S0031-9007(97)03454-6]

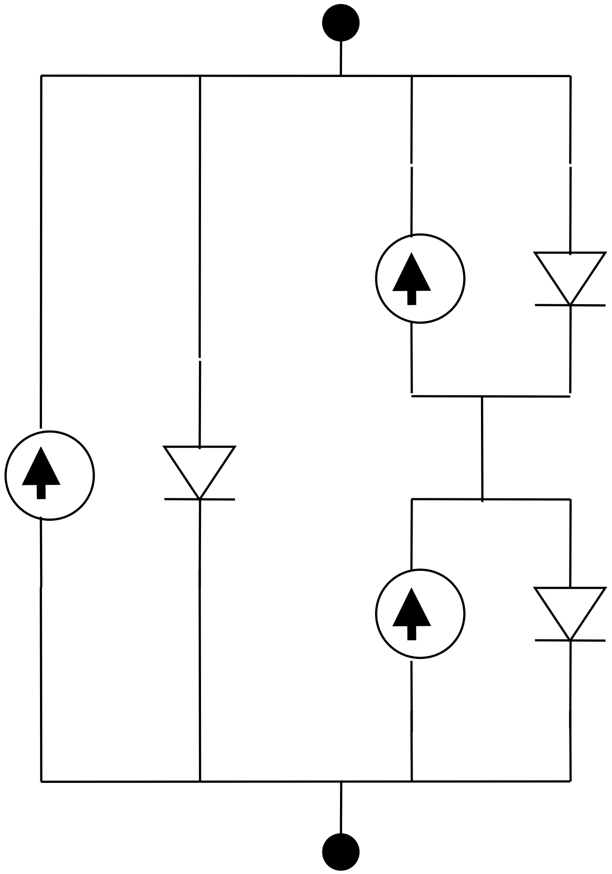
Equivalent Circuit for a Shockley-Queisser Solar Cell

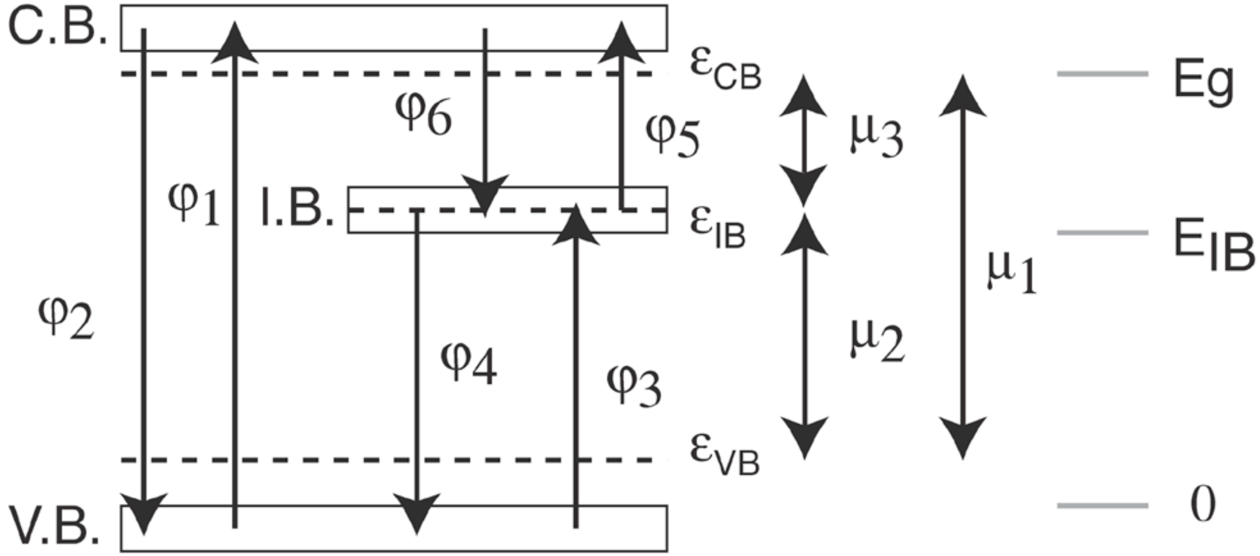




W. Shockley and H.J. Queisser. J Appl Phys (1961) vol. 32 (3) pp. 510

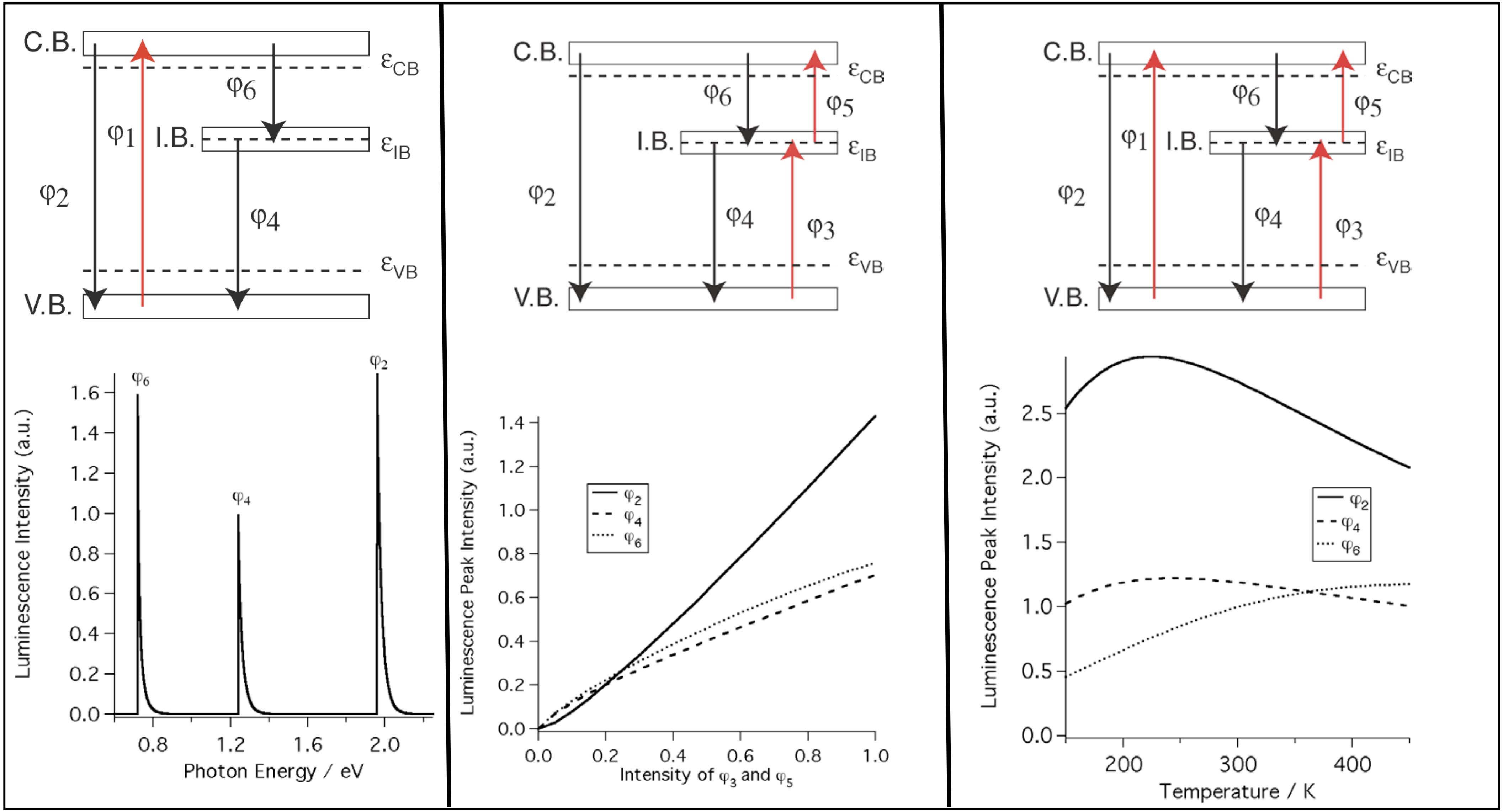
An Equivalent Circuit for the Intermediate Band Solar Cell





Martin Green, Third Generation Photovoltaics, Springer Verlag, 2003

Signature of an intermediate band material:



N. J. Ekins-Daukes, C. B. Honsberg, and M. Yamaguchi,
IEEE Photovoltaic Specialists Conference, 2005. pp. 49–54.

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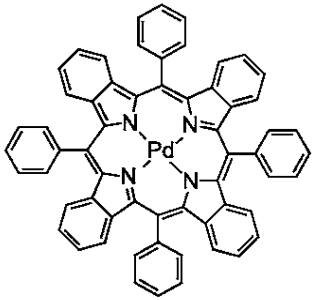
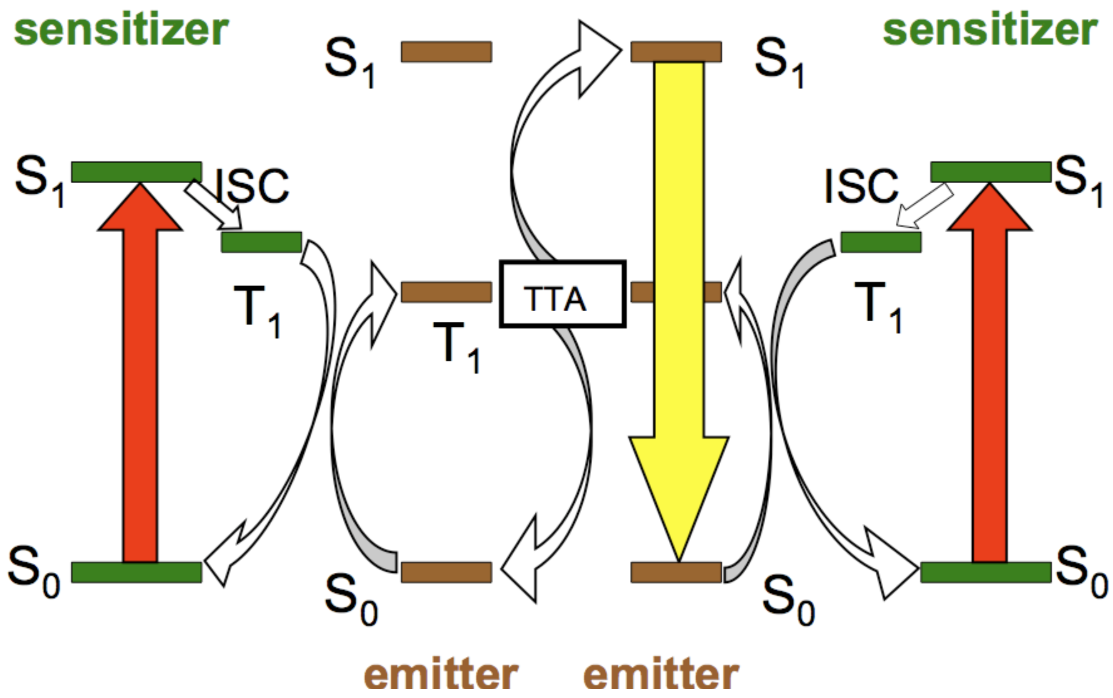
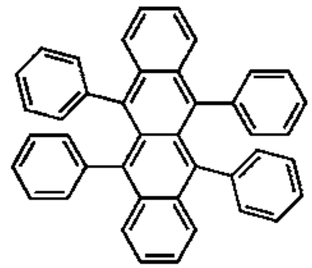
Photochemical up-conversion

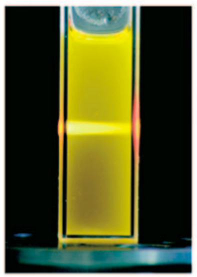


Porphyrin sensitiser

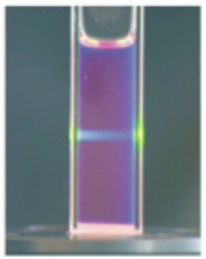




Emitter



$PdPh_4TBP$\
Rubrene



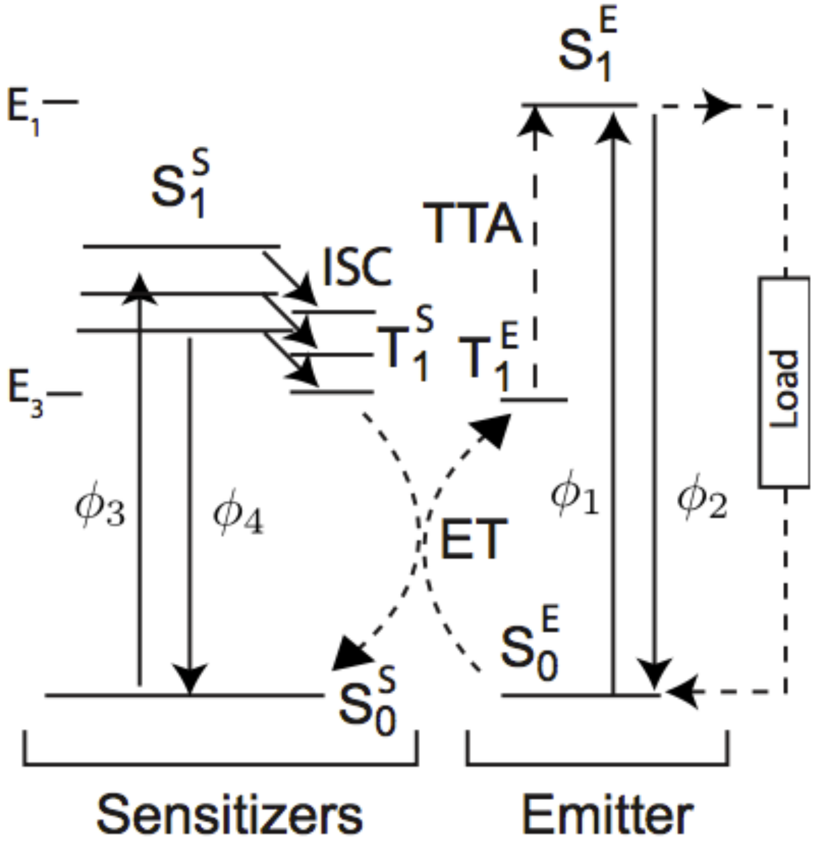
DPA\PdOEP

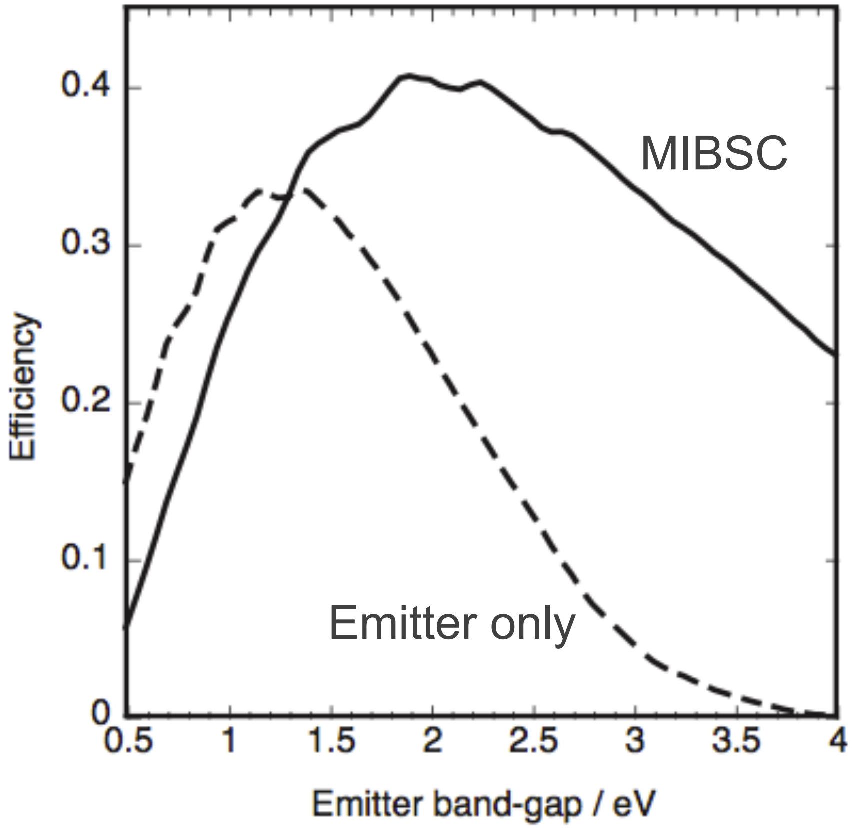
BPEA\$PdPh_4TBP$

BPEN\
$PdPh_4OMe_8TNP$

Baluschev et al. New J. Phys. (2008) vol. 10 (1) pp. 013007
T. F. Schulze Energy Environ. Sci. (2015) vol. 8, no. 1, pp. 103

Molecular intermediate ‘band’ solar cell



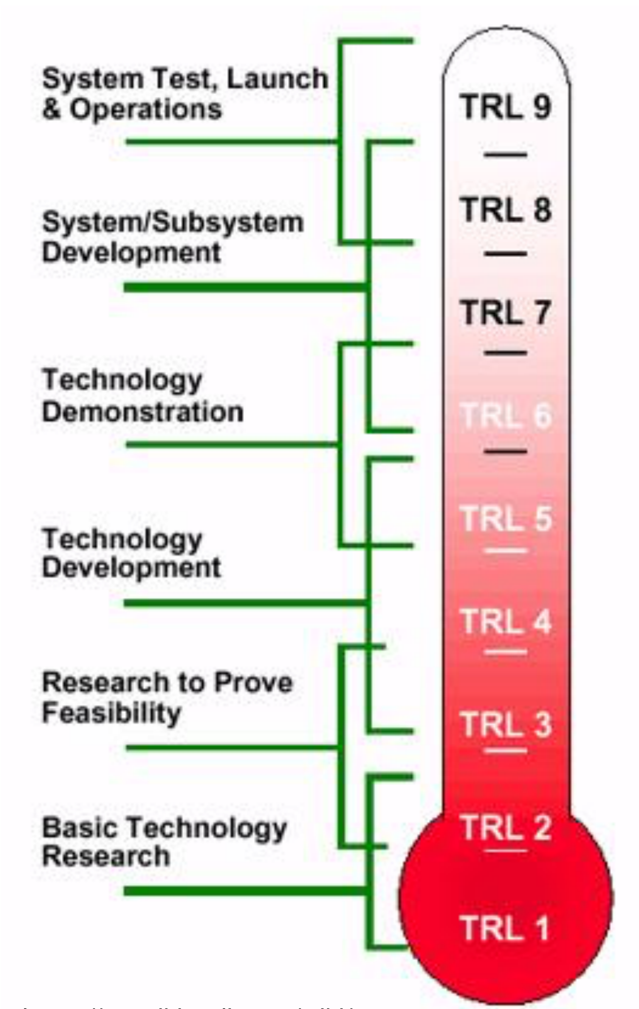


N. J. Ekins-Daukes and T. Schmidt, Applied Physics Letters (2008) vol. 93, no. 6, pp. 063507

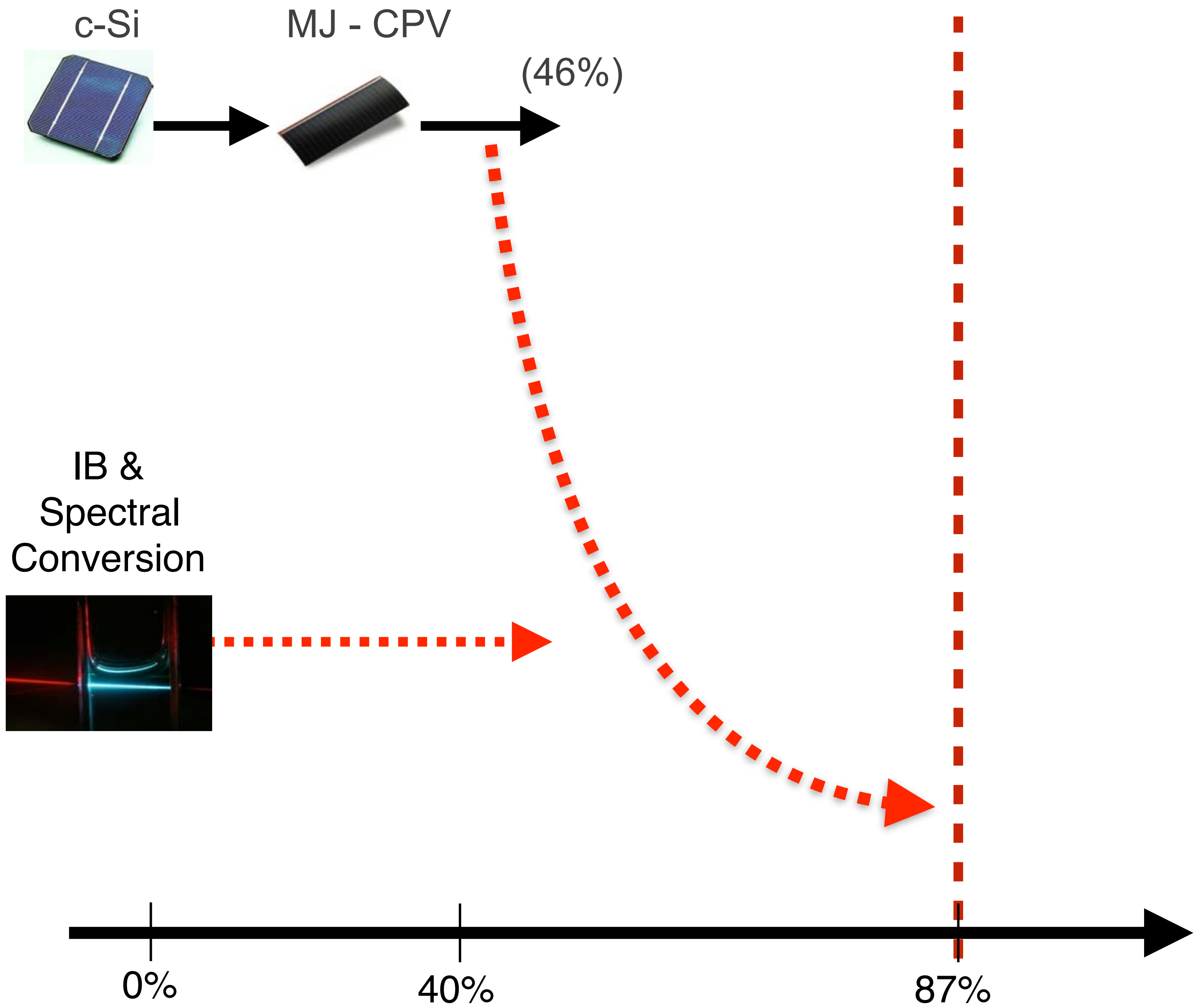
C. Simpson, Phys Chem Chem Phys (2015) vol. 17, no. 38, pp. 24826

PV Technologies on a TRL scale

Technology readiness level:



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



The Virtu PV-Thermal Module

- Up to 80% system efficiency measured at 2 pilot installations
  - Large supermarket in Southern England
  - Hotel in Malta.

http://www.nakedenergy.co.uk

naked energy®

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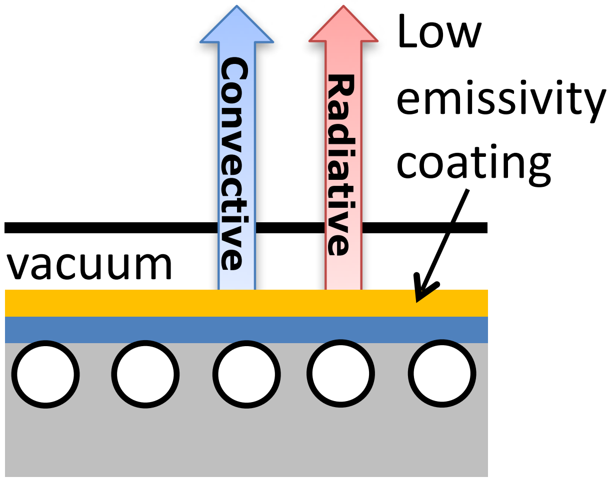
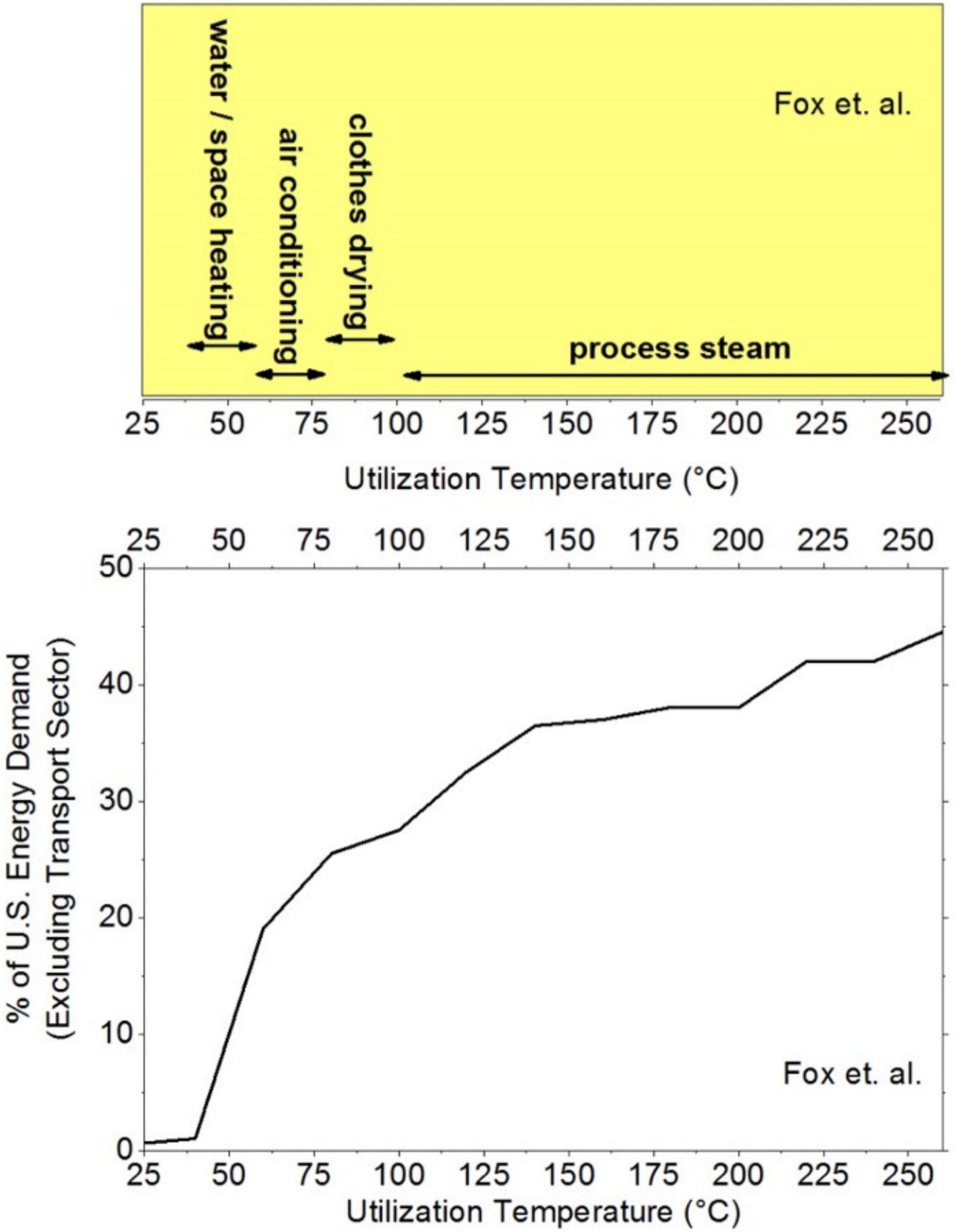
Application for low-grade heat

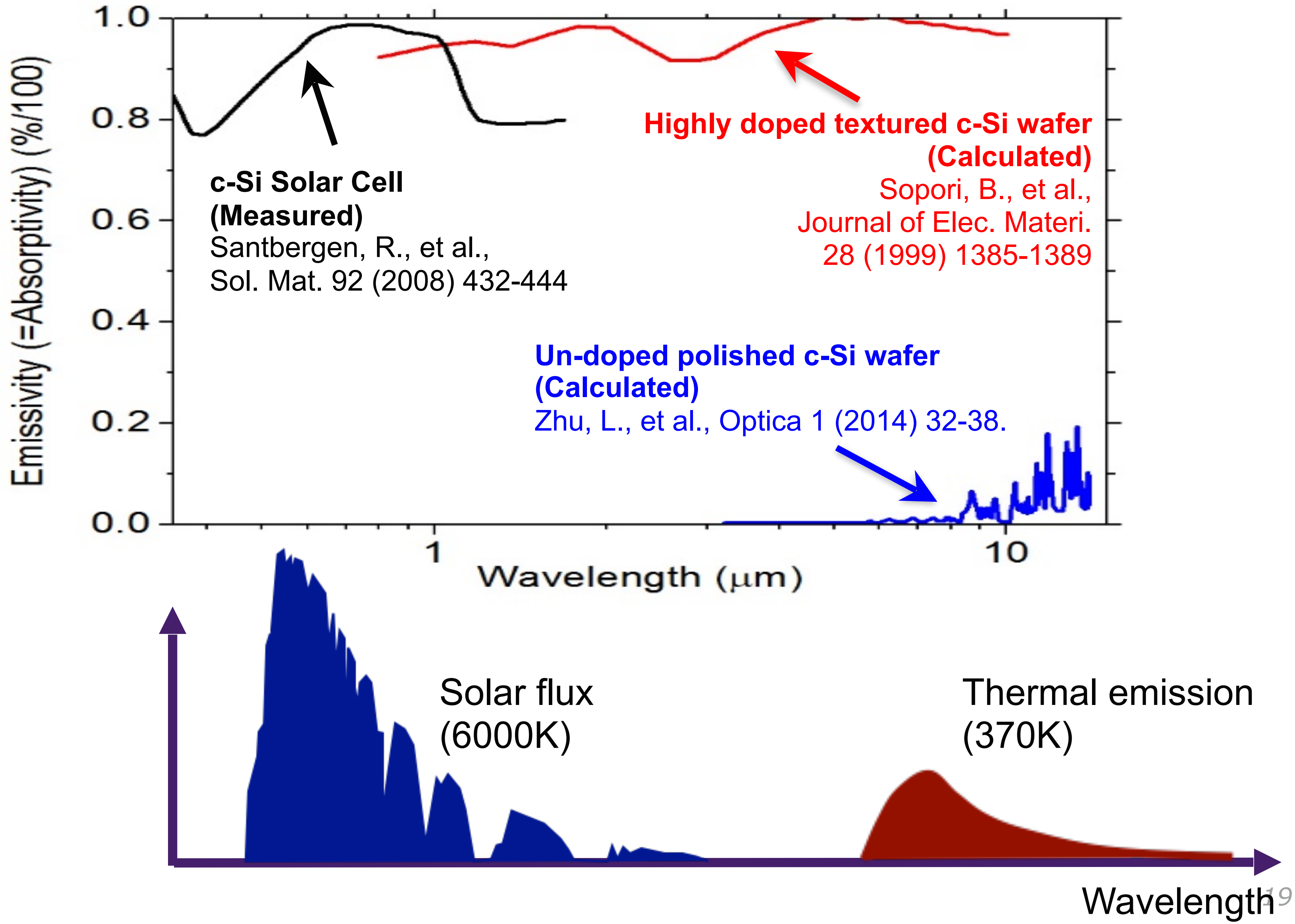




Fox, D. B., et al., Energy & Environmental Science 4 (2011) 3731-3740

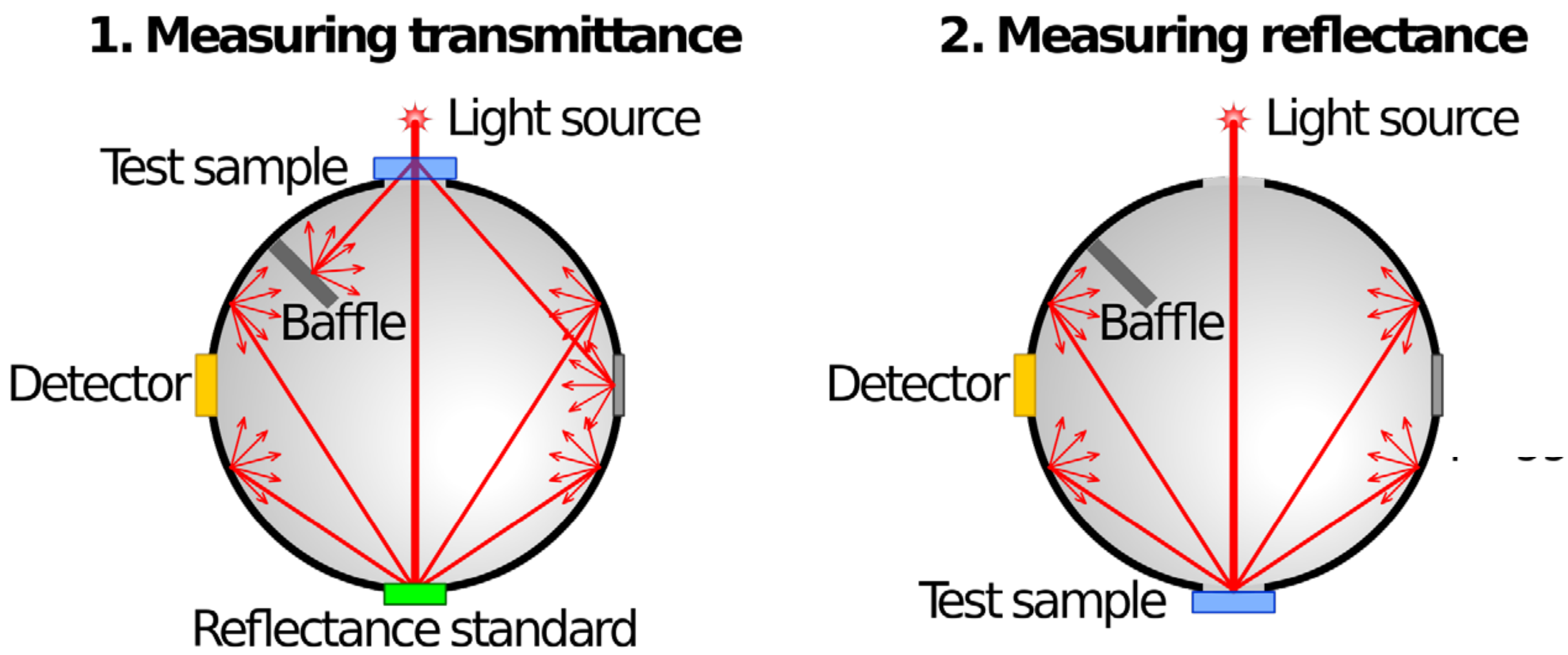
What is the emissivity of c-Si PV ?

Imperial College London



Measuring Emissivity

Emissivity of an unencapsulated silicon solar cell

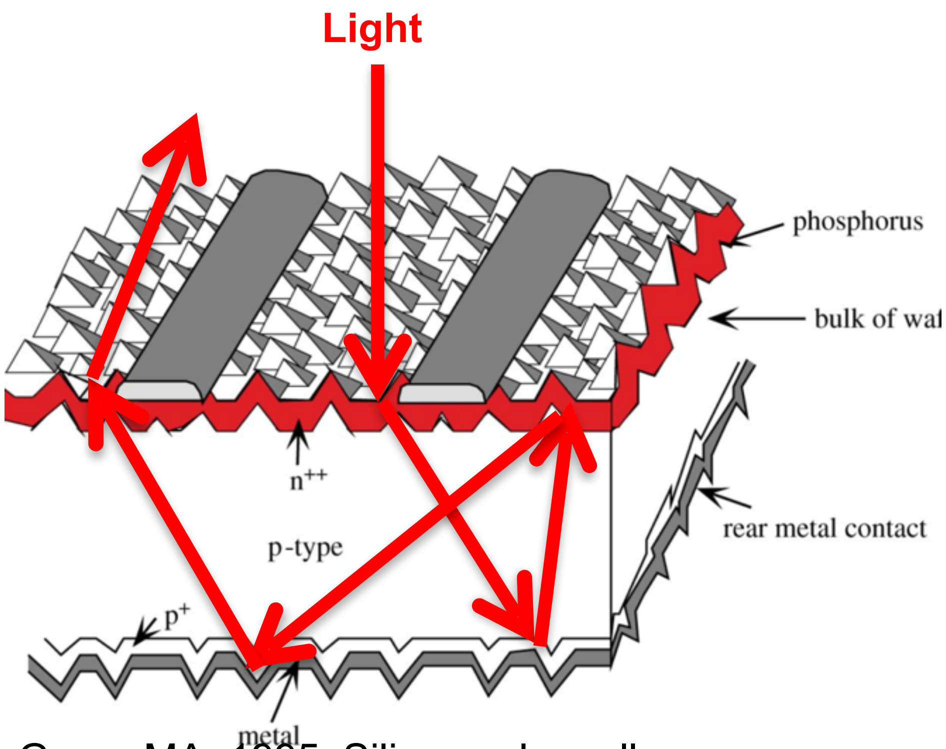


Emissivity (E) = Absorptivity (A) = 1 – Reflectance (R) – Transmittance (T)

***Wikipedia:** *https://en.wikipedia.org/wiki/Integrating_sphere*

Calculating Emissivity

Optical Modelling of silicon solar cells



Green MA, 1995, Silicon solar cells: advanced principles and practice

Range of dimensions:

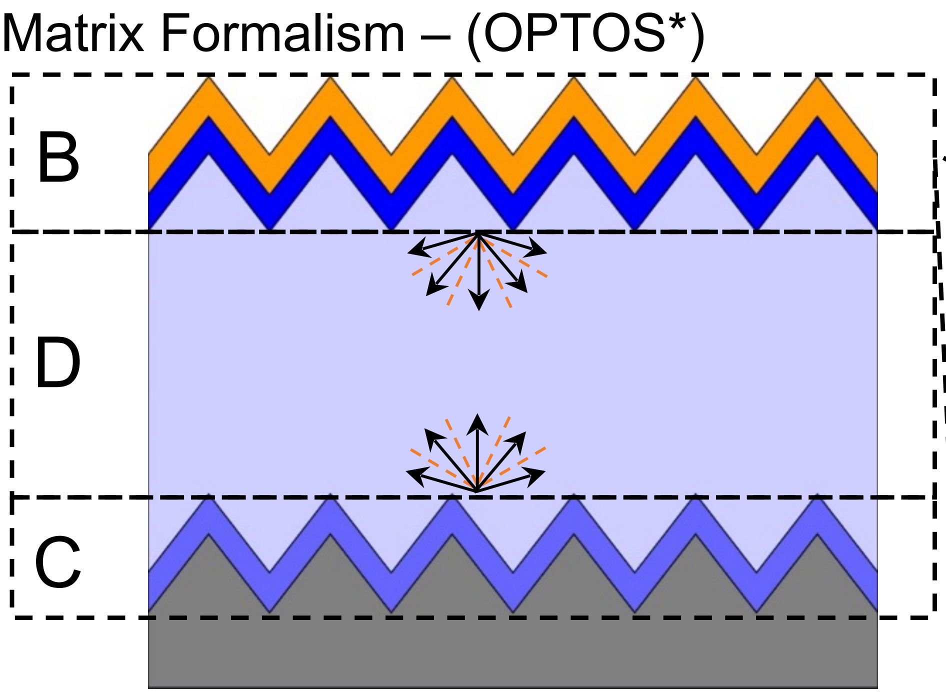
- Wafer thickness ~ 200 µm
- Texture features ~ 4 µm
- Coatings ~ 50 nm

Simulation Method?

- Ray tracing / Monte-Carlo – computationally costly
- Full wave optical – computationally prohibitive

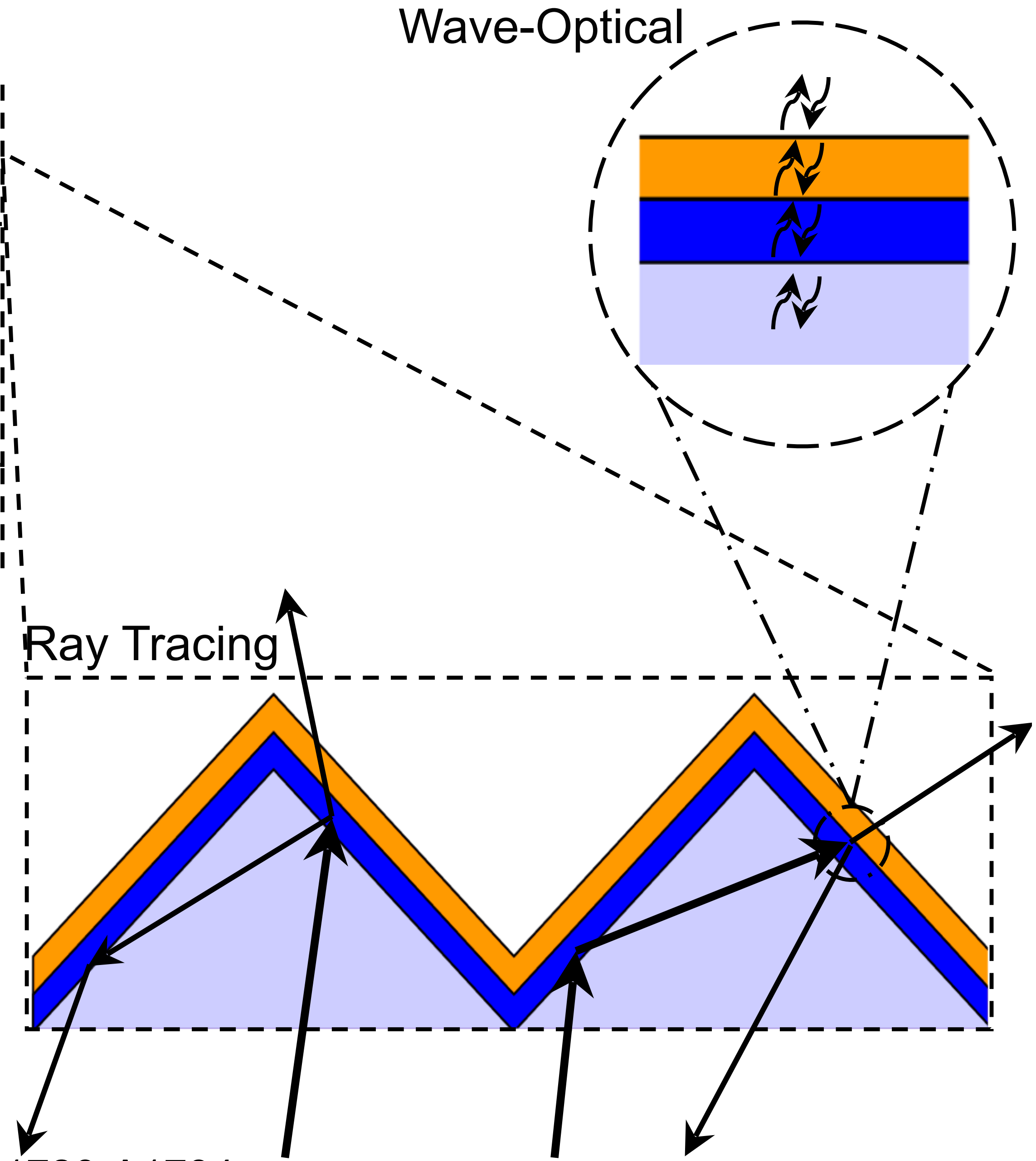
Calculating Emissivity

Optical Modelling of silicon solar cells



$$B,C=\begin{pmatrix} \theta_1\rightarrow\theta_1 & \cdots & \theta_n\rightarrow\theta_1 \\ \theta_1\rightarrow\theta_2 & \cdots & \theta_n\rightarrow\theta_2 \\ \vdots & \ddots & \vdots \\ \theta_1\rightarrow\theta_n & \cdots & \theta_n\rightarrow\theta_n \end{pmatrix}$$

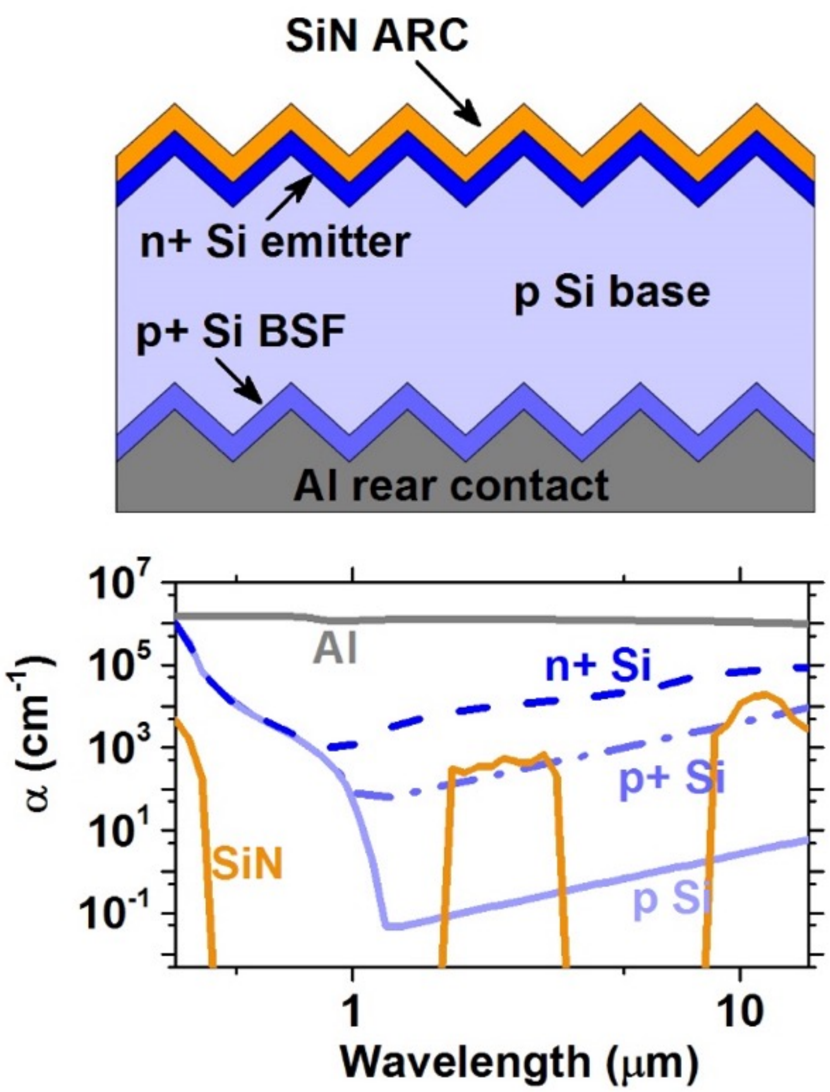
$$D=\begin{pmatrix} e^{-\alpha d/\cos\theta_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & e^{-\alpha d/\cos\theta_n} \end{pmatrix}$$

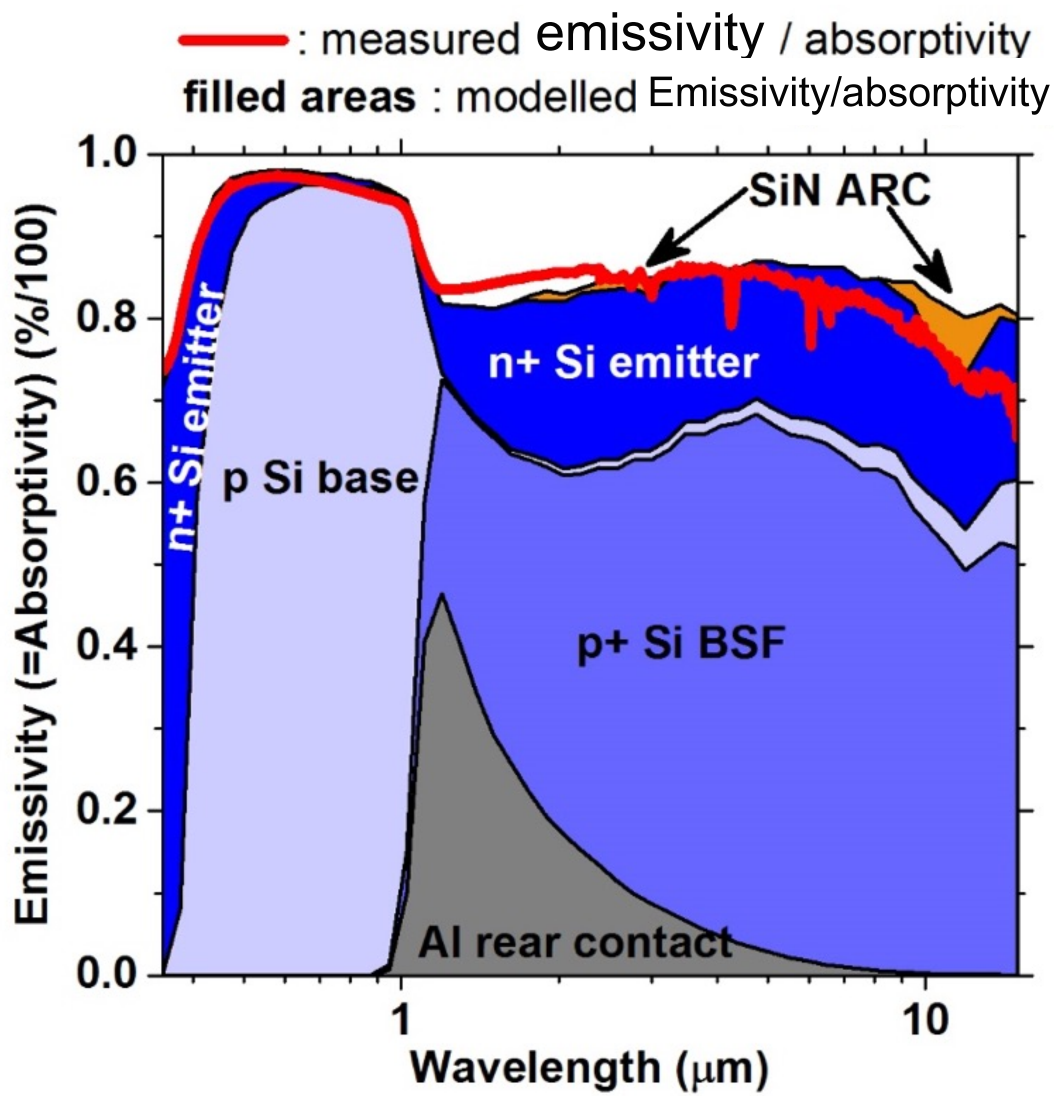


*Tucher, N., et al., Optics Express 23 (2015) A1720-A1734
*Eisenlohr, J., et al., Optics Express 23 (2015) A502-A518

The origin of emissivity

Emissivity of an unencapsulated silicon solar cell

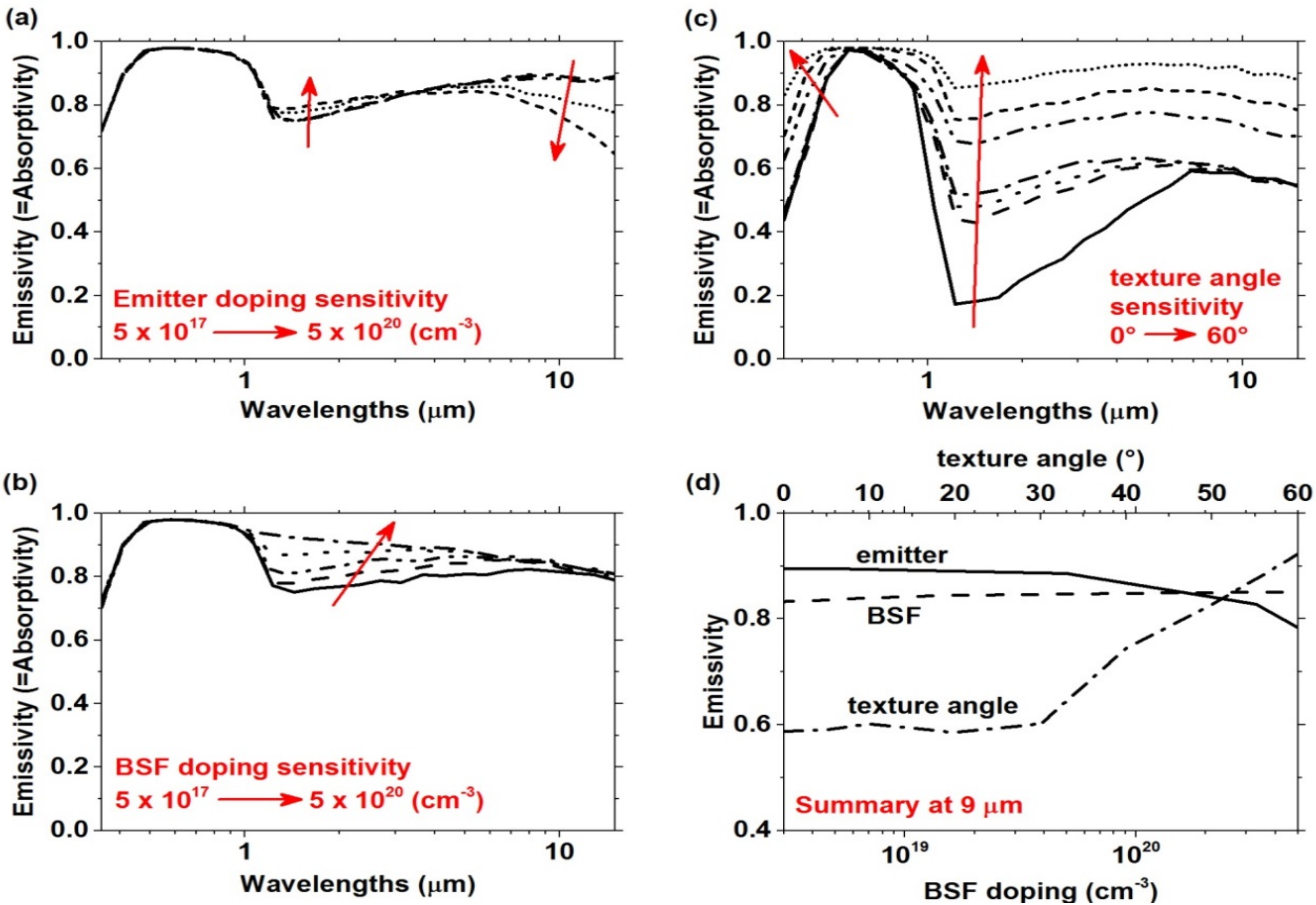




Riverola, A., et. al., Mid-infrared emissivity of crystalline silicon solar cells, submitted

The origin of emissivity

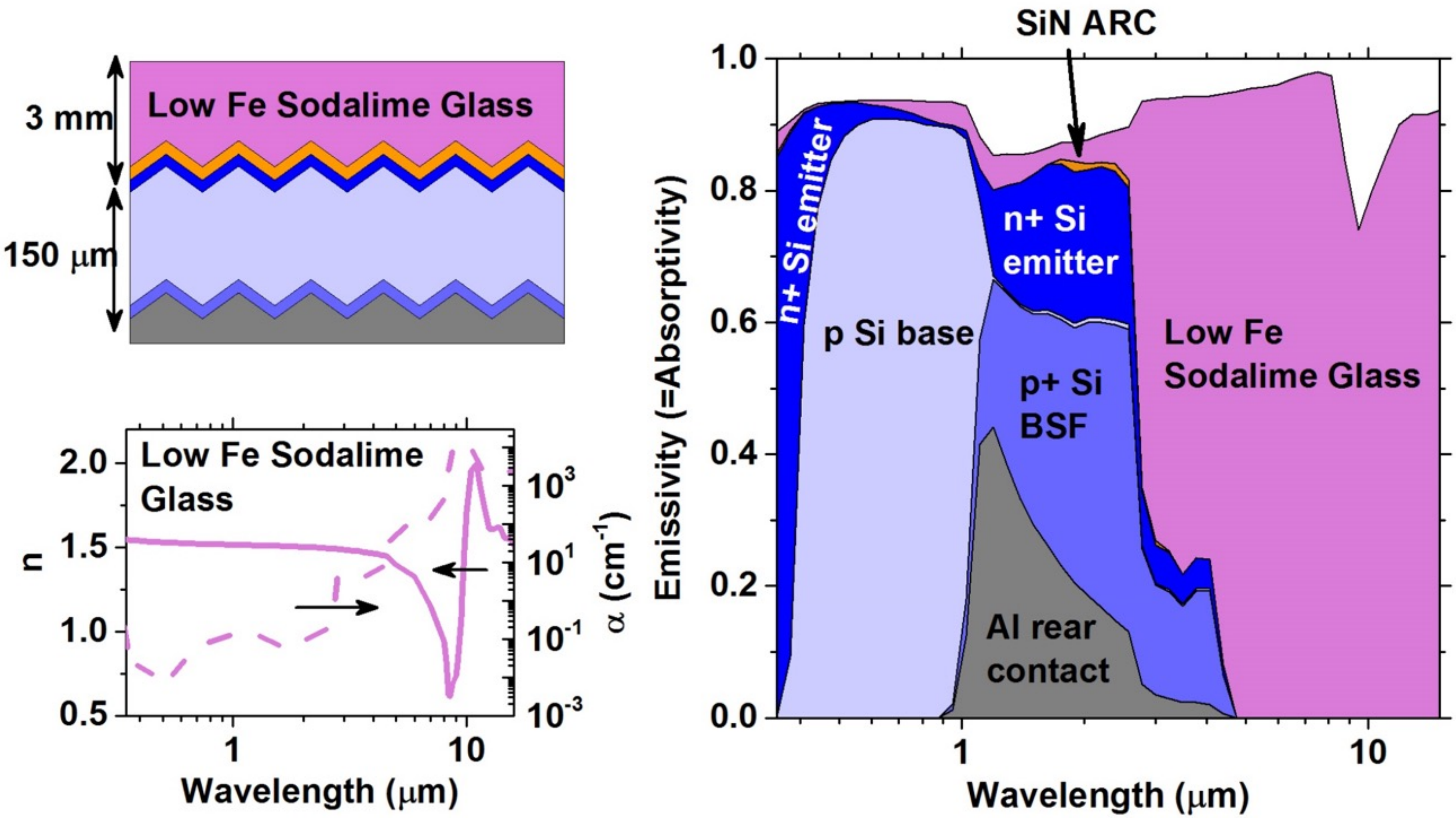
Emissivity of an unencapsulated silicon solar cell



Riverola, A., et. al., Mid-infrared emissivity of crystalline silicon solar cells, submitted

The origin of emissivity

Emissivity of an encapsulated silicon solar cell

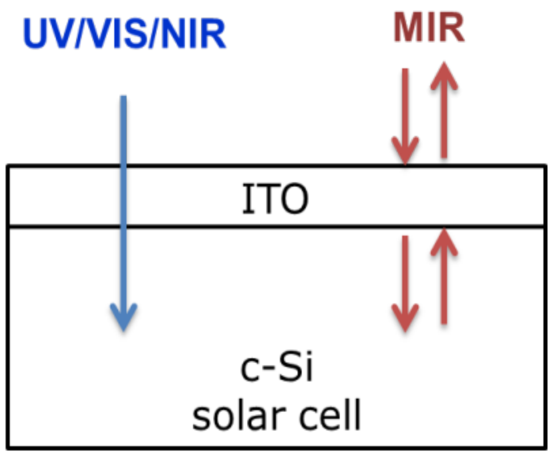


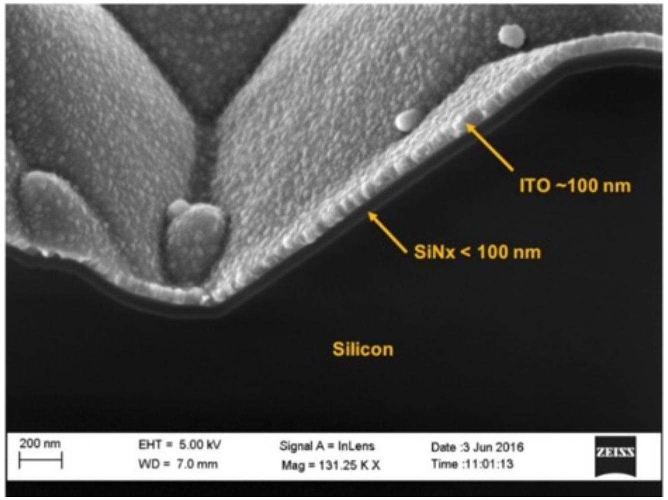
Rubin, M., Solar Energy Materials 12 (1985) 275-288

Riverola, A., et. al., Mid-infrared emissivity of crystalline silicon solar cells, submitted

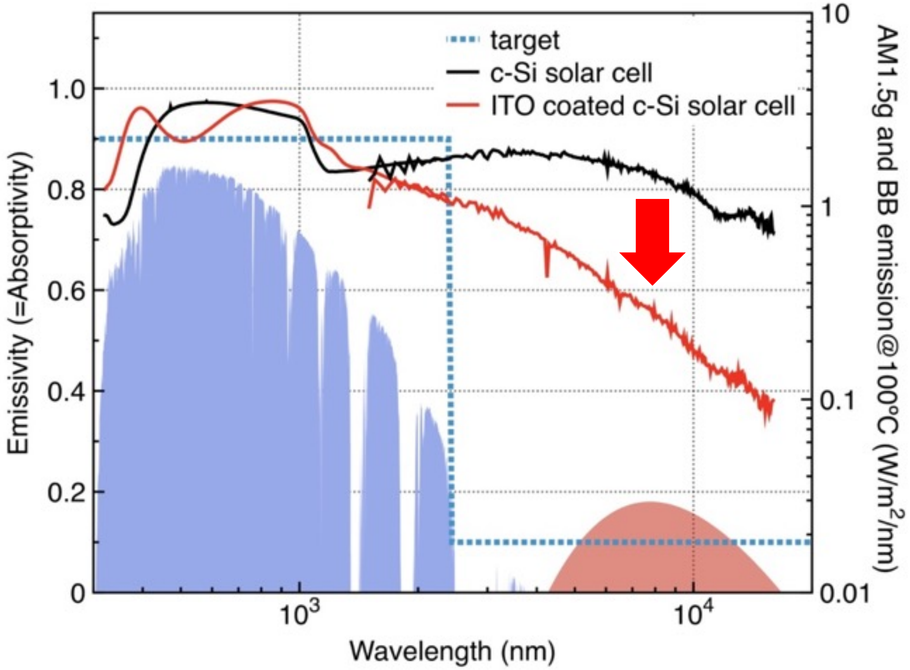
Controlling emissivity

Indium Tin Oxide (ITO) coatings for emissivity suppression

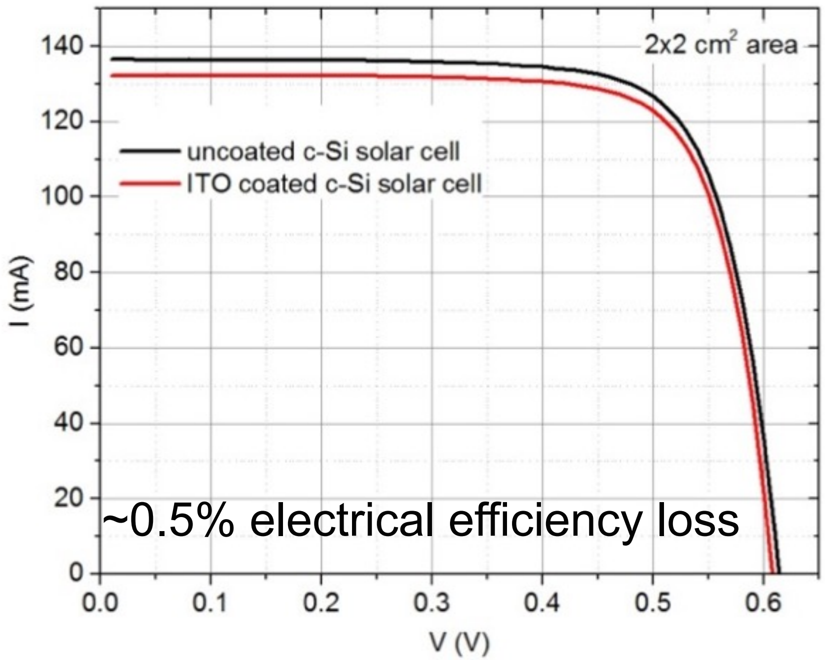




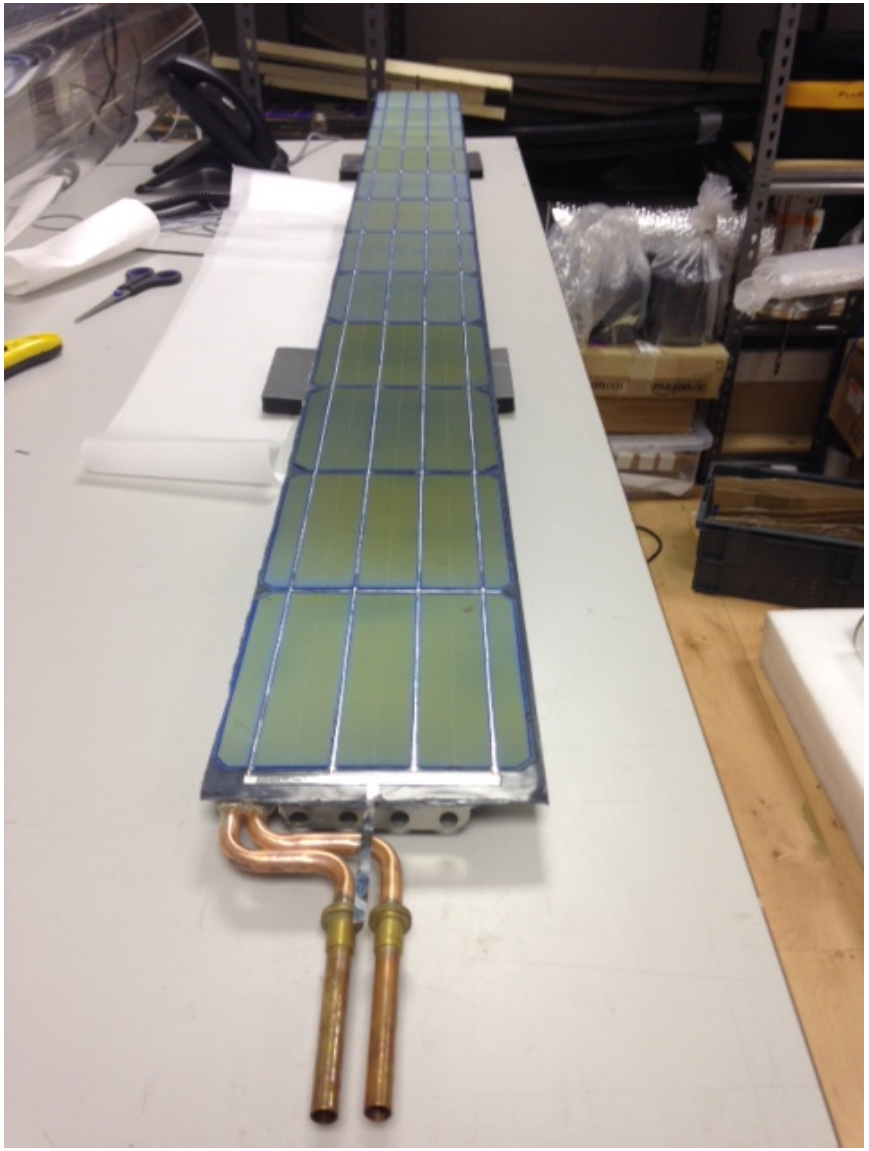
Emissivity Suppression

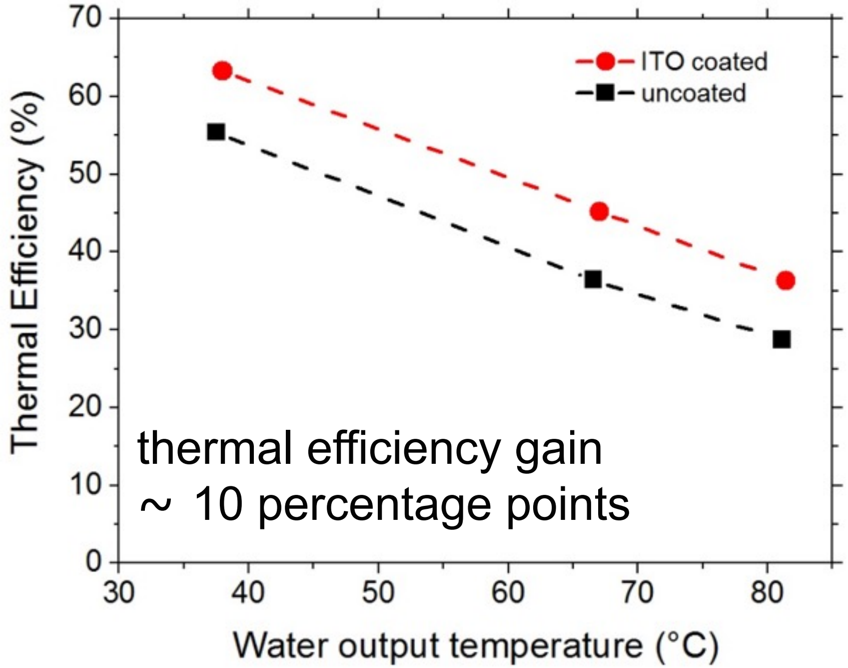


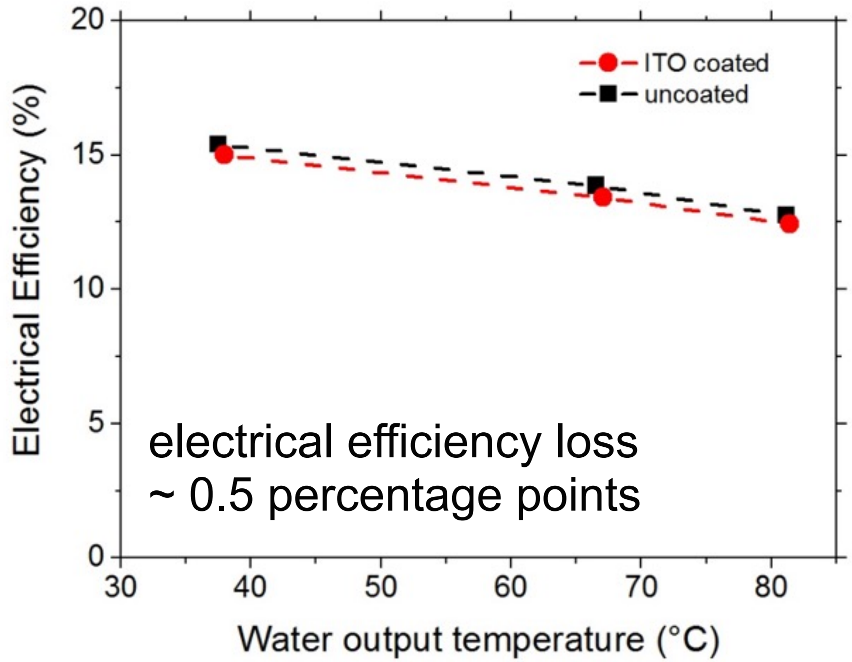
Electrical Losses



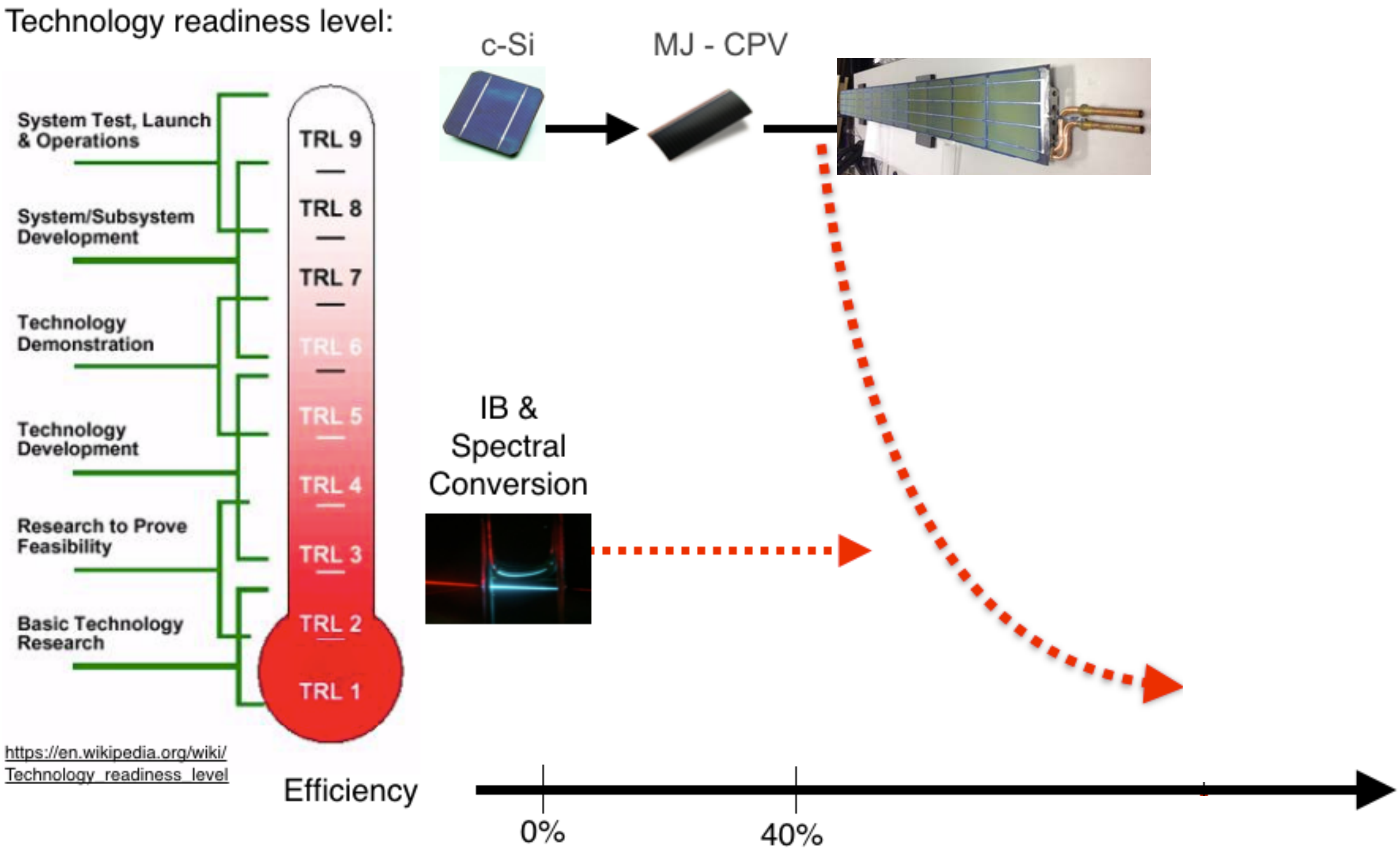
PV-T Collector Results







Conclusion: Solar Energy System Efficiencies of 70%, fact or fiction?



Acknowledgements:

Imperial College London:

Physics

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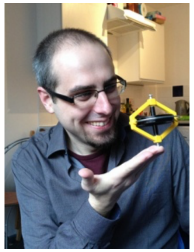
Alex Mellor



Diego Alonso-Alvarez

Christos Markides

Ilaria Guarracino

Tom Wilson

Phoebe Pearce

Alba Ramos Cabal

also Alberto Riverola, Daniel Chemisana, University of Lleida, Spain and Douglas Paul, Lourdes Ferre Lin, University of Glasgow, U.K..

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