The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA International Atomic Energy Agency

2132-1

Winter College on Optics and Energy

8 - 19 February 2010

Third generation photovoltaics

J. Nelson
*Imperial College
London
U.K.*

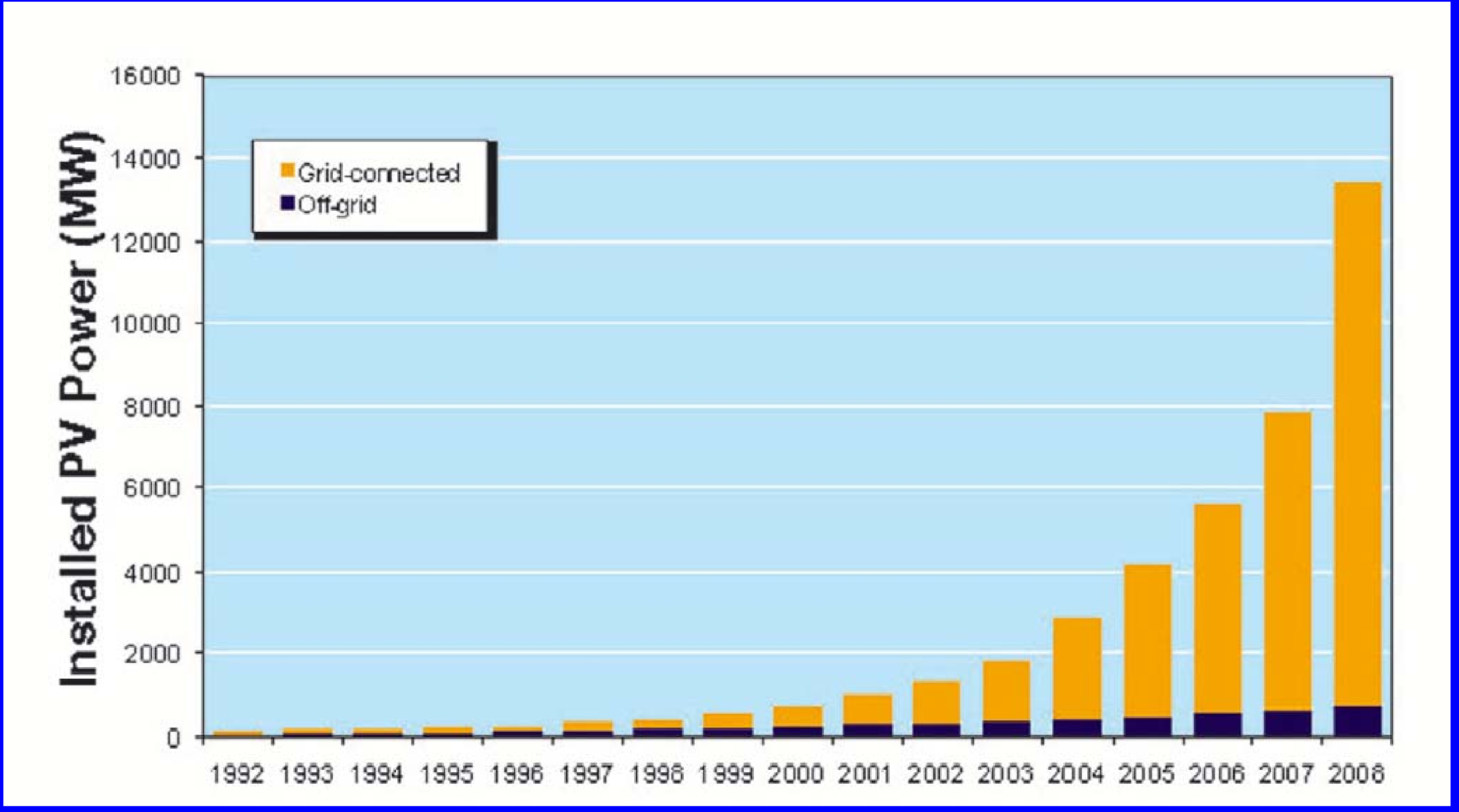
Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

ICTP Winter College on Optics and Energy
8 – 19 February 2010

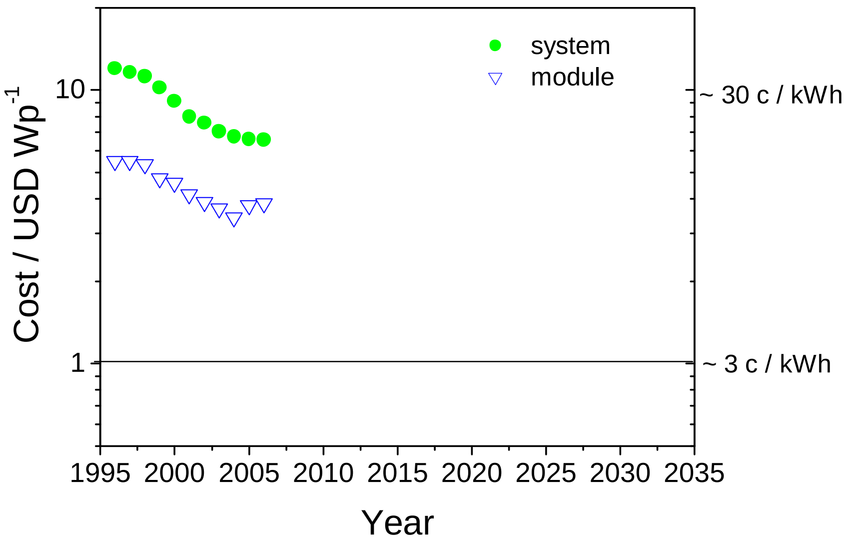
Third generation photovoltaics

Jenny Nelson
Department of Physics
Imperial College London
(jenny.nelson@imperial.ac.uk)

THE FUTURE FOR PV



Strategies to cost reduction



Barrier to implementation is the capital cost of the module

Dominated by the cost of silicon

Report IEA-PVPS T1-16:2007

Use cheaper photovoltaic material?

More work per photon?

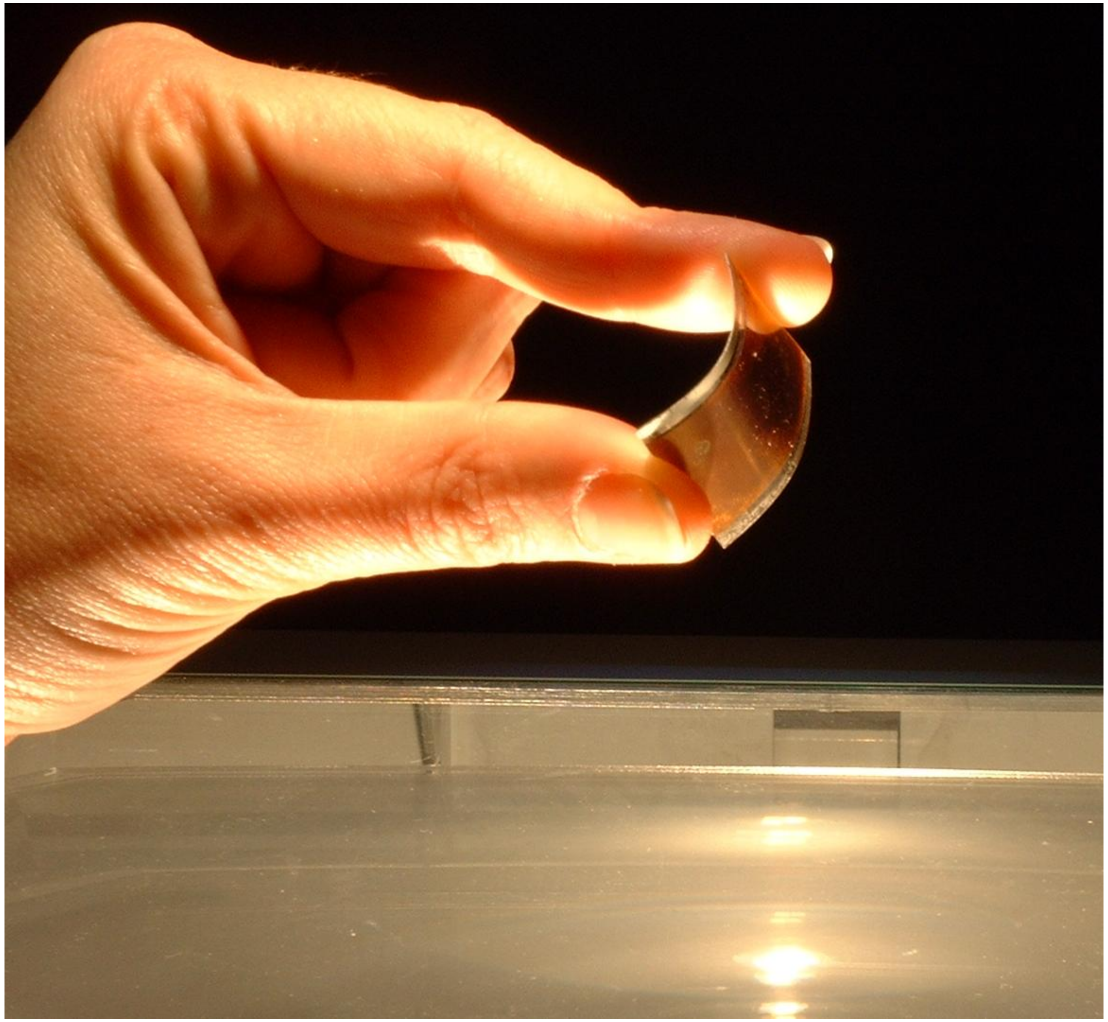
Use less photovoltaic material?

Imperial College London

Outline

1. Future directions for PV
2. Using cheaper photovoltaic materials
3. Limiting efficiency of solar cells
4. Routes to more work per photon
5. More efficient light harvesting

Cheaper photovoltaic materials



To be treated in detail in future lectures

Device structures

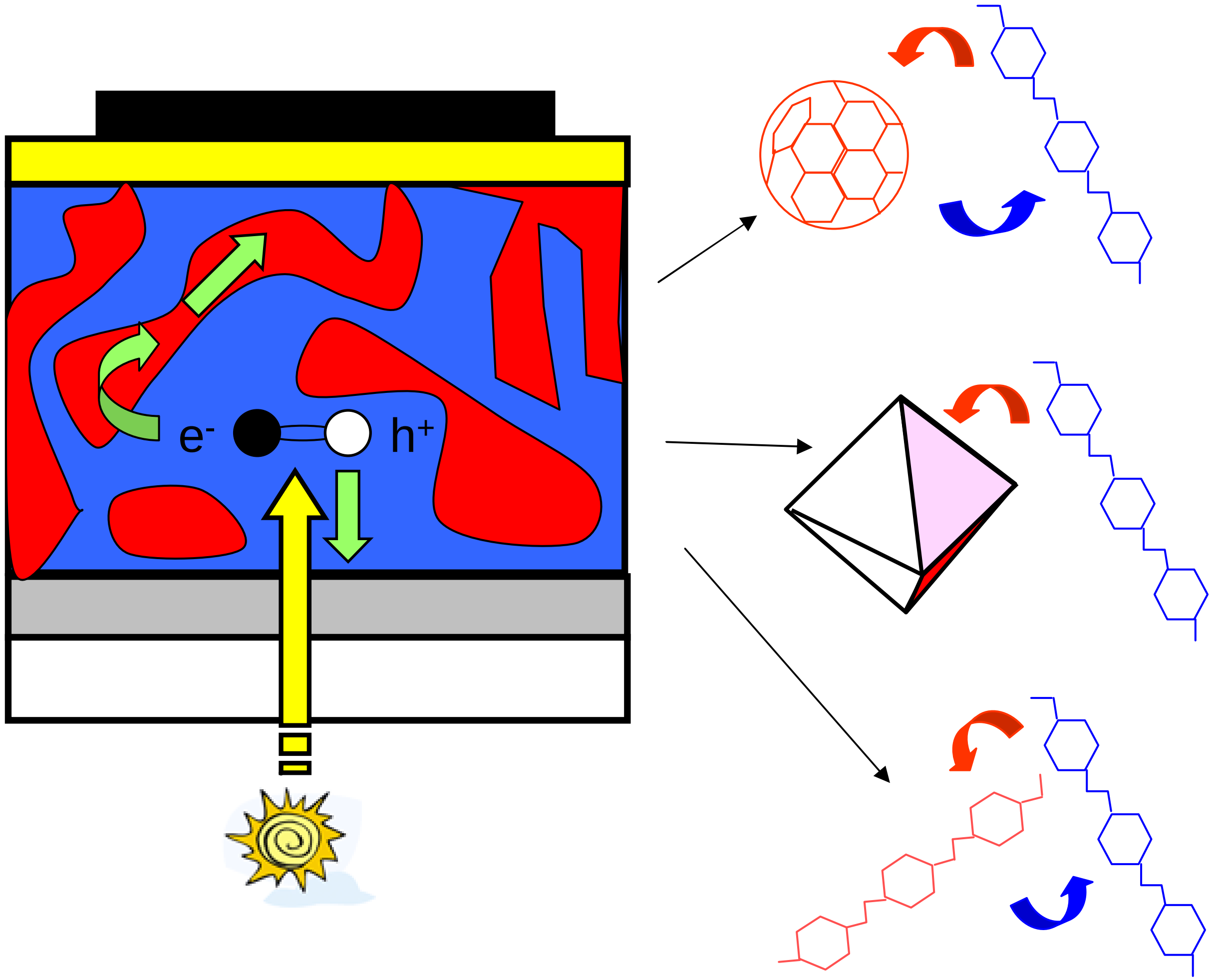
- Donor-acceptor bulk heterojunction devices

Al cathode

Donor-Acceptor blend:
e.g. polymer / fullerene,
polymer / nanocrystal,
polymer / polymer

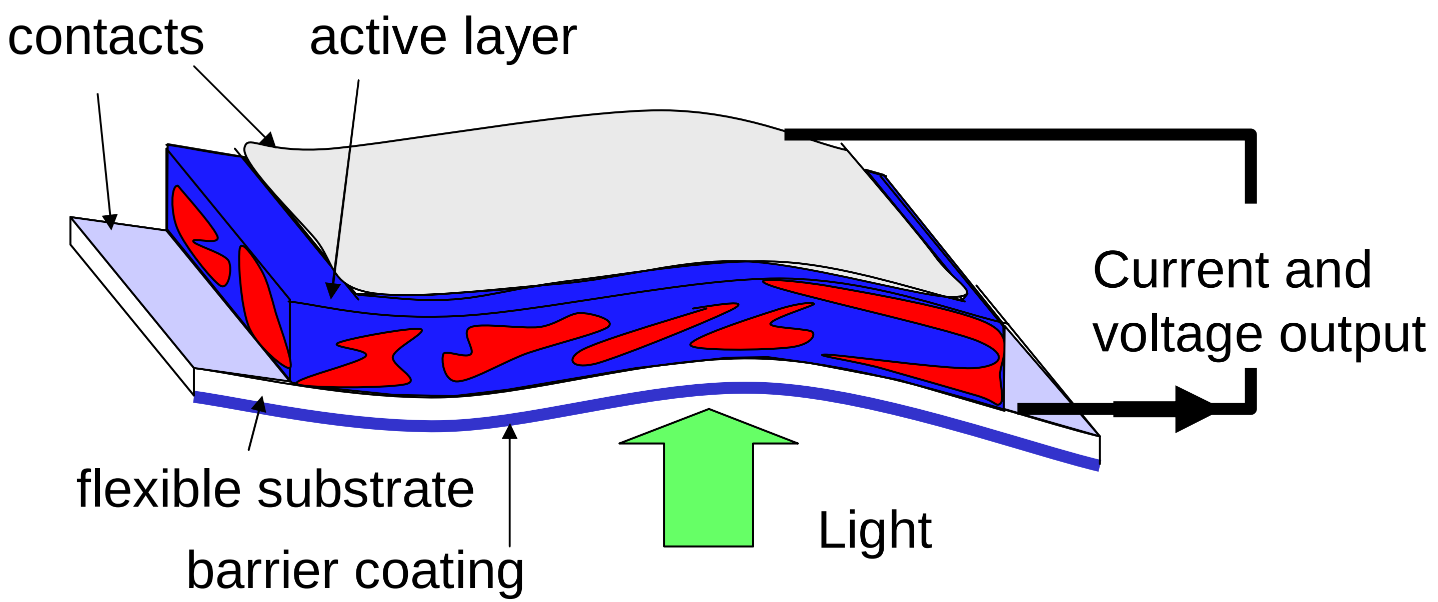
ITO anode

Glass substrate



- Both components deposited from same solution

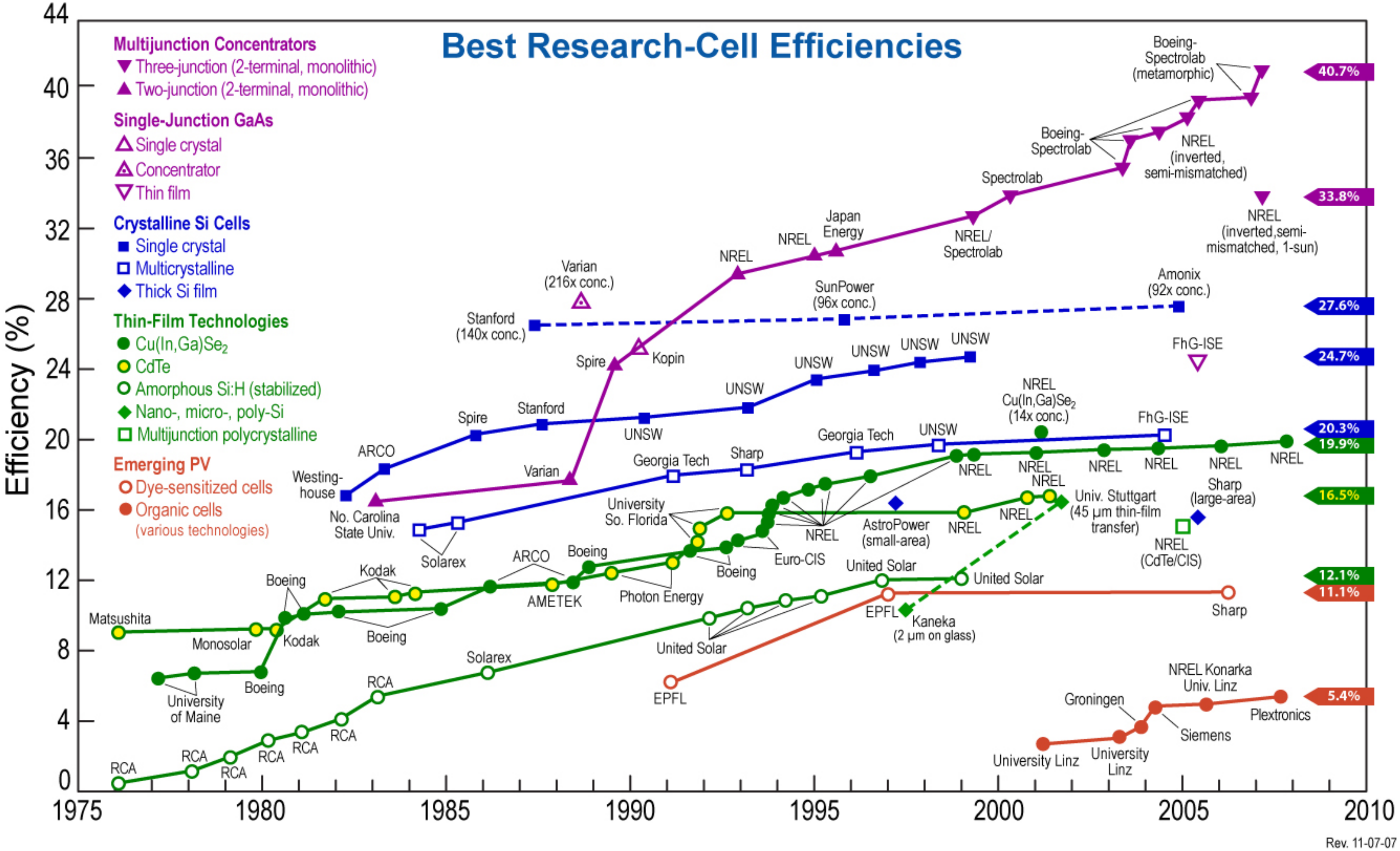
Generic device structure



- Active layer ~100 nm thick
- Low temperature processing enables use of flexible substrates

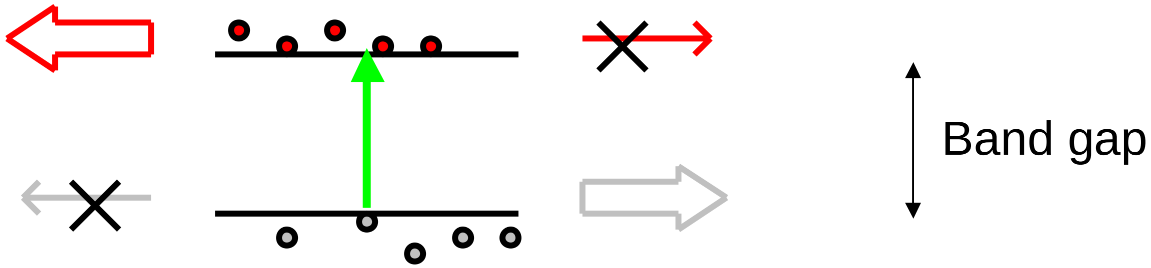
Outline

1. **Future directions for PV**
2. **Using cheaper photovoltaic materials**
3. **Limiting efficiency of solar cells**
4. **Routes to more work per photon**
5. **More efficient light harvesting**



National Renewable Energy Laboratory

Detailed balance limit



(i) One electron hole pair per photon with $h\nu > E_g$,

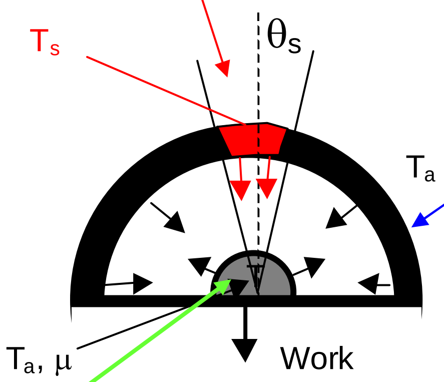
(ii) Carriers relax to form separate Fermi distributions at lattice temperature $T_{ambient}$ with quasi Fermi levels separated by $\Delta\mu$.

(iii) All electrons extracted with same electrochemical potential $\Delta\mu = eV$

(iv) Only loss process is spontaneous emission

Limiting power conversion efficiency

A fraction Xβ of the "sky" emits solar radiation at a black body temperature of T_{sun}



A fraction (1 - Xβ) of the "sky" emits ambient radiation at a black body temperature of $T_{ambient}$

The photovoltaic energy converter emits ambient radiation at a black body temperature of $T_{ambient}$ and a chemical potential of Δμ

The remaining charge pairs provide a current of electrons with chemical potential of Δμ

Calculation of limiting efficiency

Photon flux density from sun ($T = T_{sun}$) or ambient ($T = T_{ambient}$)

$$N(E_{\min}, E_{\max}, T, \Delta\mu) = \frac{2\pi}{h^3 c^2} \int_{E_{\min}}^{E_{\max}} \frac{E^2}{e^{(E-\Delta\mu)/k_B T} - 1} dE$$

Irradiance from sun ($T = T_{sun}$)

$$L(E_{\min}, E_{\max}, T, \Delta\mu) = \frac{2\pi}{h^3 c^2} \int_{E_{\min}}^{E_{\max}} \frac{E^3}{e^{(E-\Delta\mu)/k_B T} - 1} dE$$

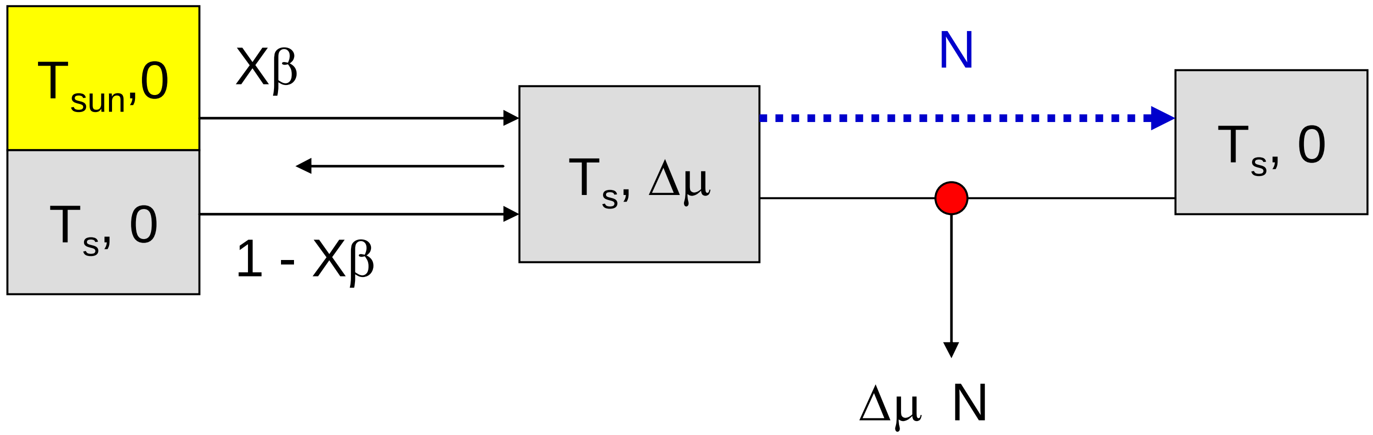
Balance fluxes to obtain current

$$J(V) = q\left\{Xf_s N(E_g, \infty, T_s, 0) + (1 - Xf_s) N(E_g, \infty, T_a, 0) - N(E_g, \infty, T_a, qV)\right\}$$

Power conversion efficiency

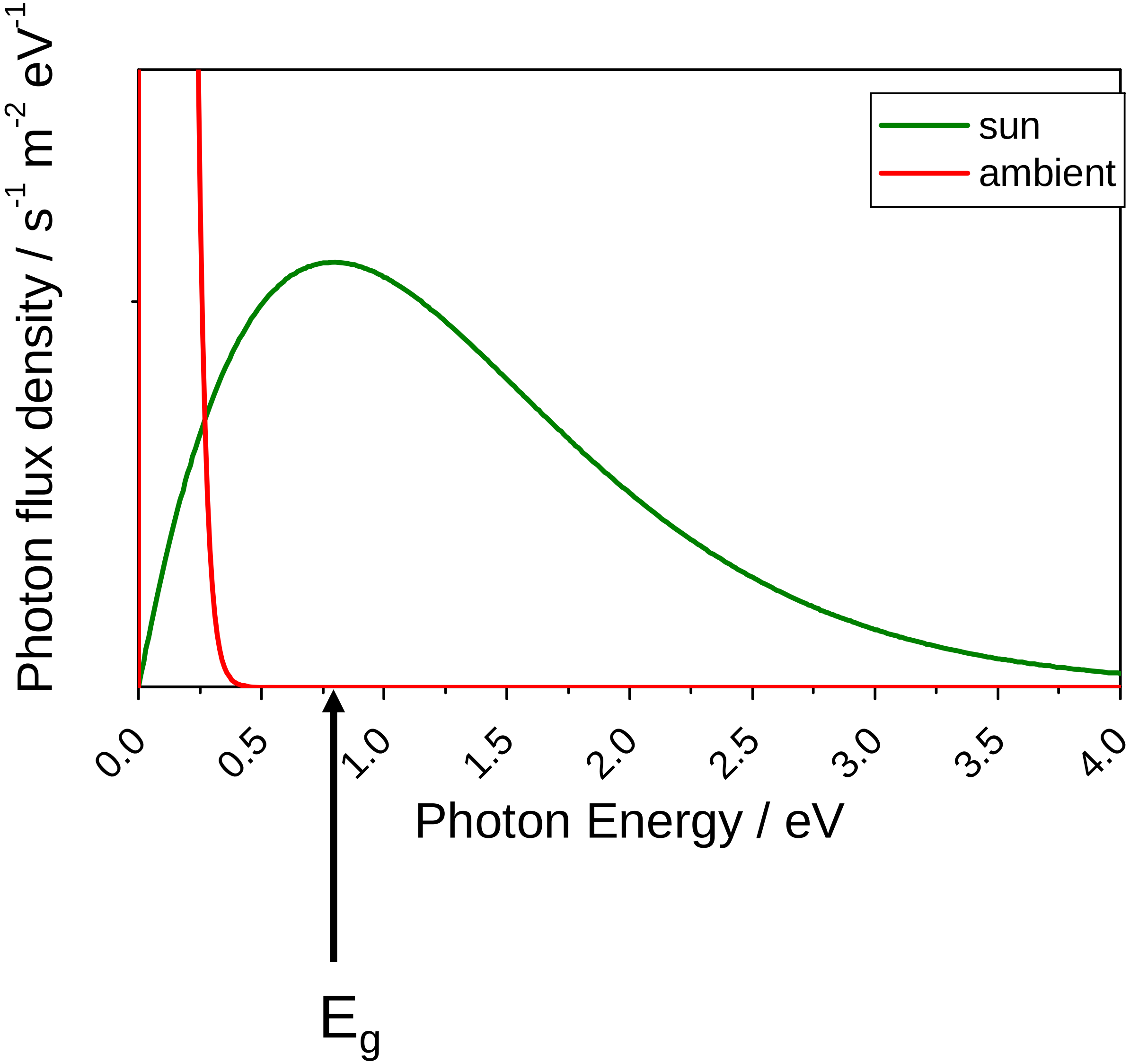
$$\eta = \frac{J(V)V}{P_s} \qquad P_s = Xf_s L(0, \infty, T_s, 0)$$

Particle flux

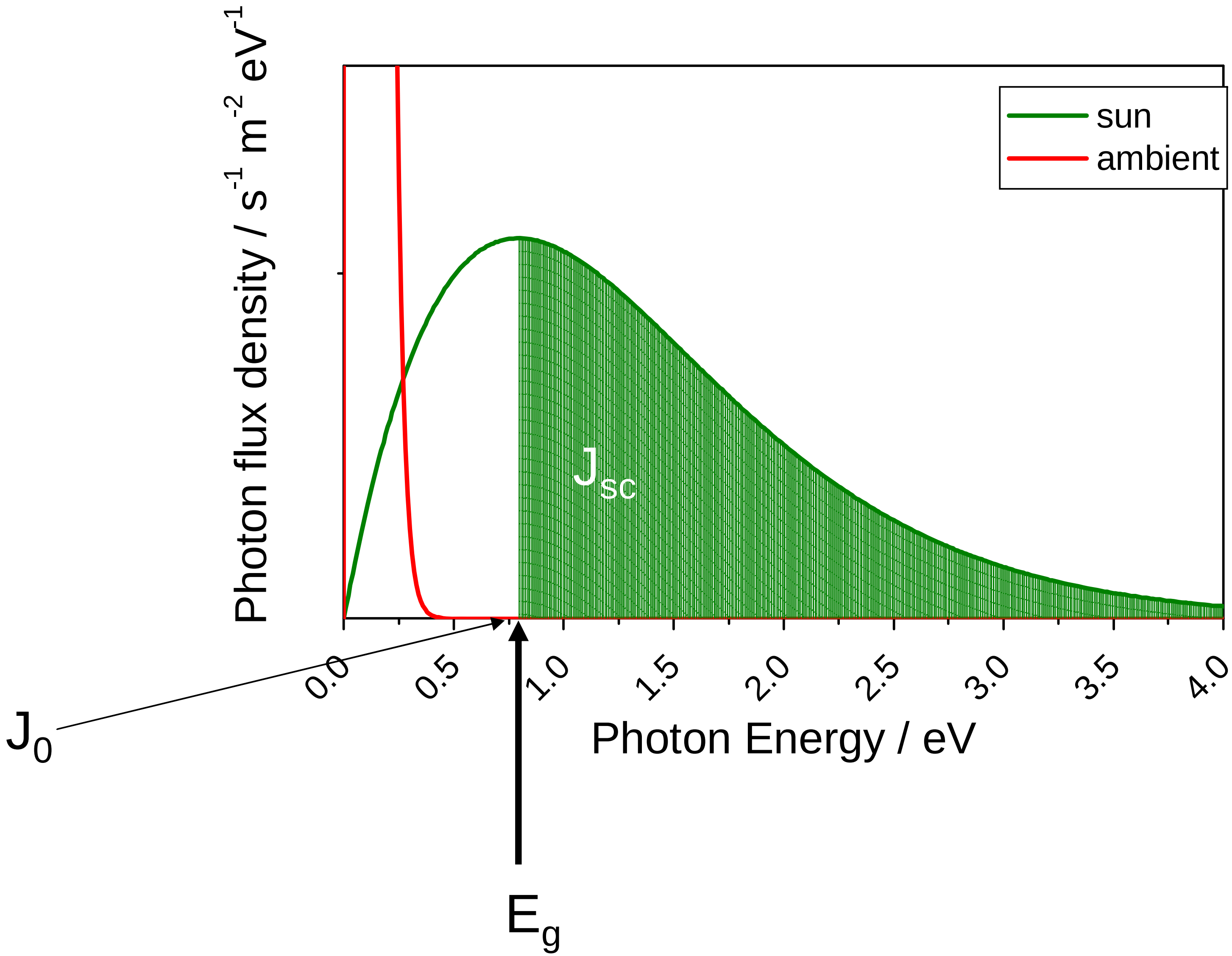


$$\frac{J}{e} = X\beta \int_{E_g}^{\infty} b_{sun}(E)dE + (1 - X\beta)\int_{E_g}^{\infty} b_{ambient}(E)dE - e^{\Delta\mu/kT}\int_{E_g}^{\infty} b_{ambient}(E)dE$$

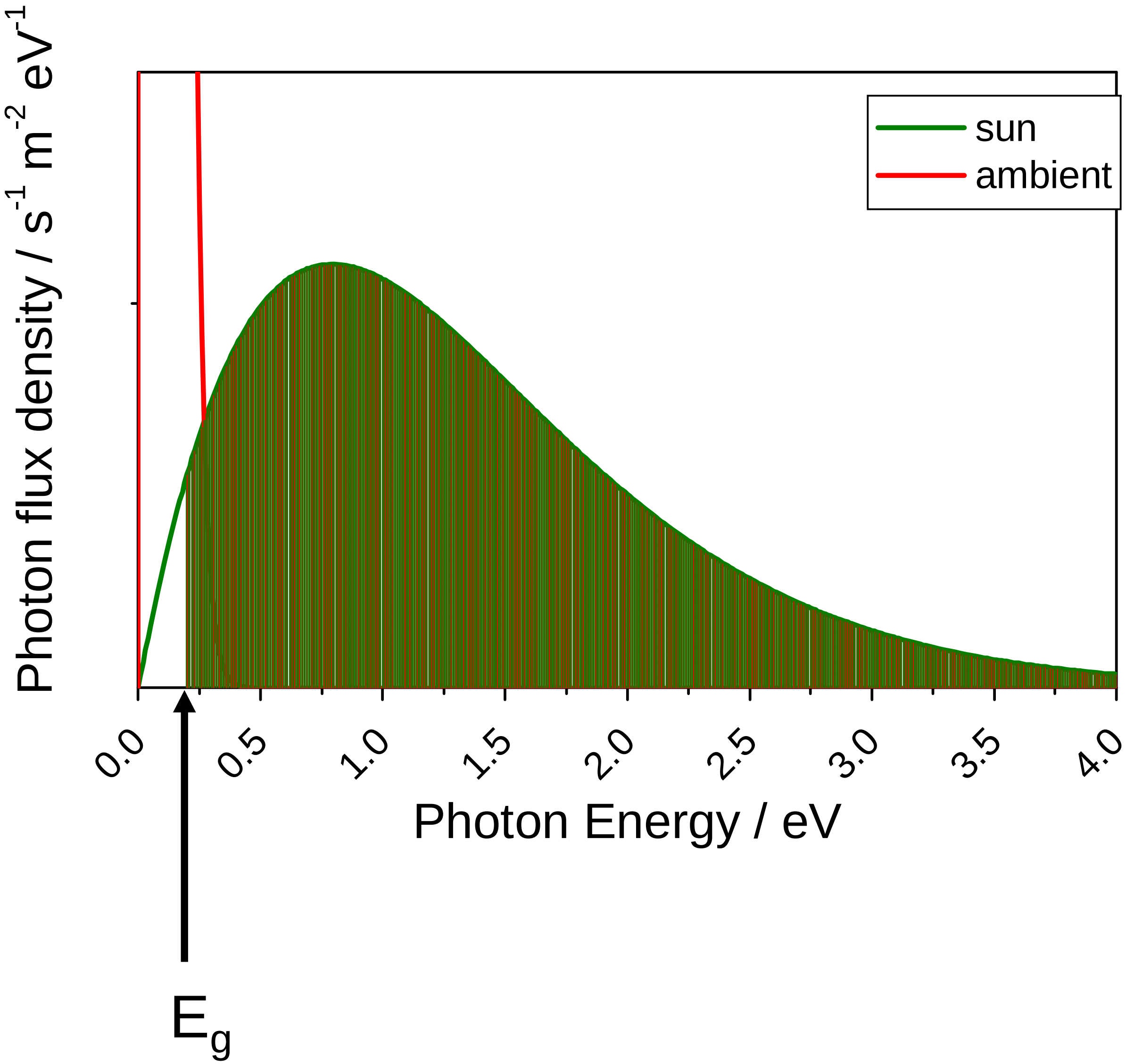
$$J = J_{sc} - J_0\left(e^{eV/kT} - 1\right)$$



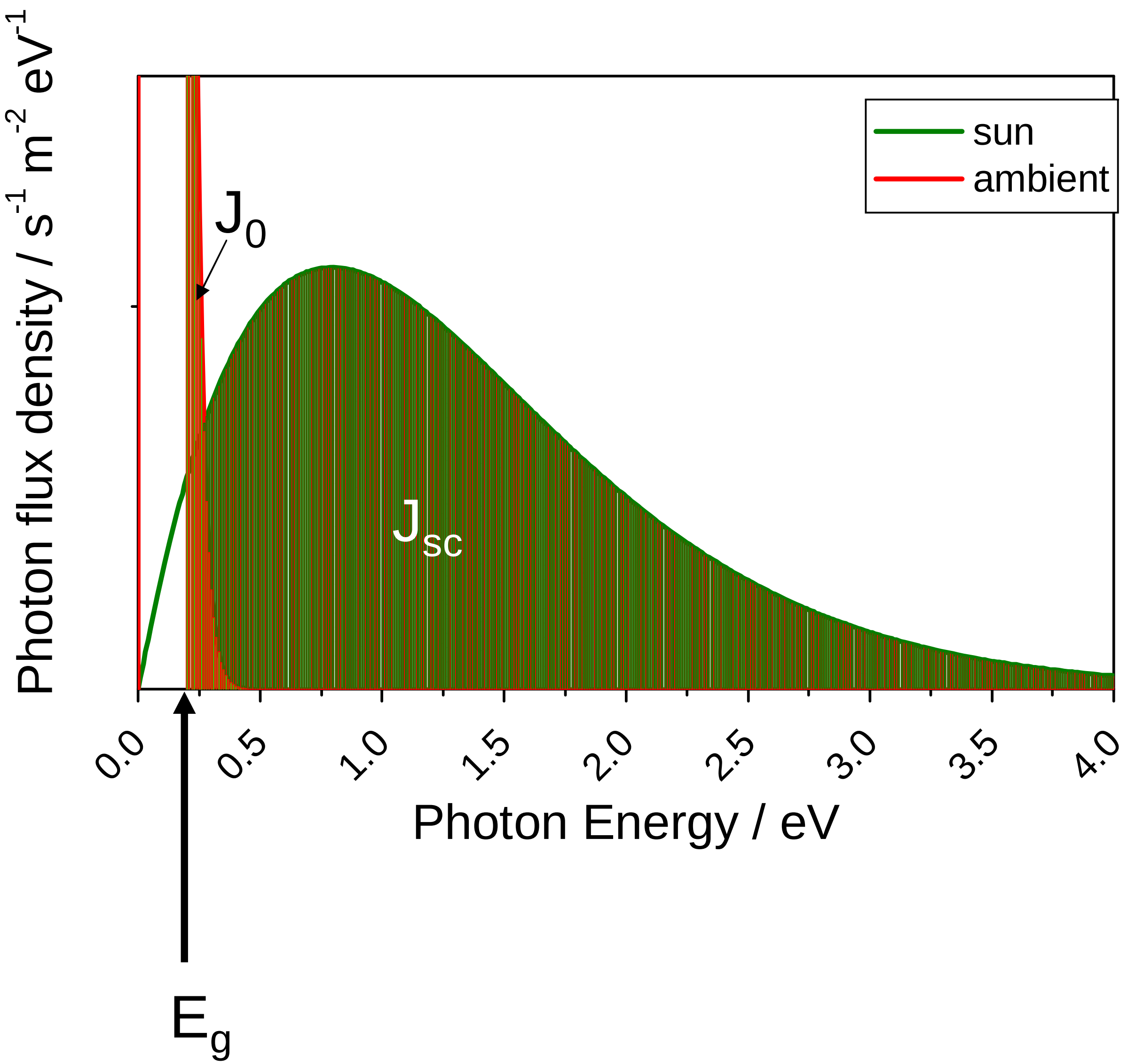
Photon flux density / s^{-1} m^{-2} eV^{-1}
sun
ambient
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Photon Energy / eV
E_g

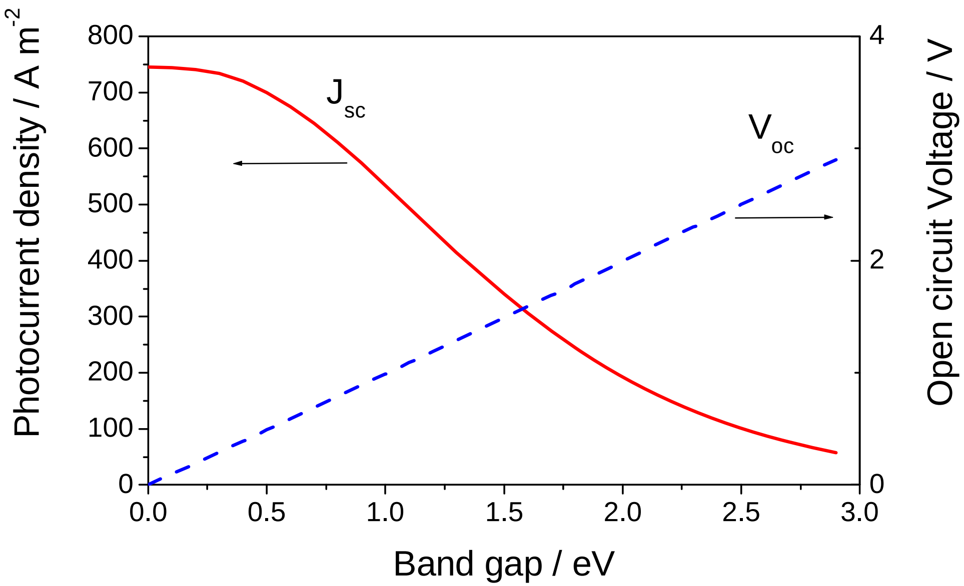


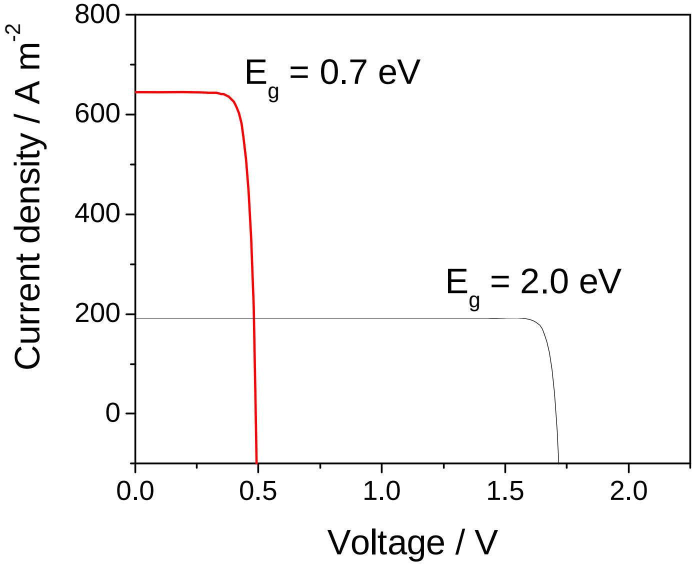
Photon flux density / s-1 m-2 eV-1
sun
ambient
Jsc
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Photon Energy / eV
J0
Eg

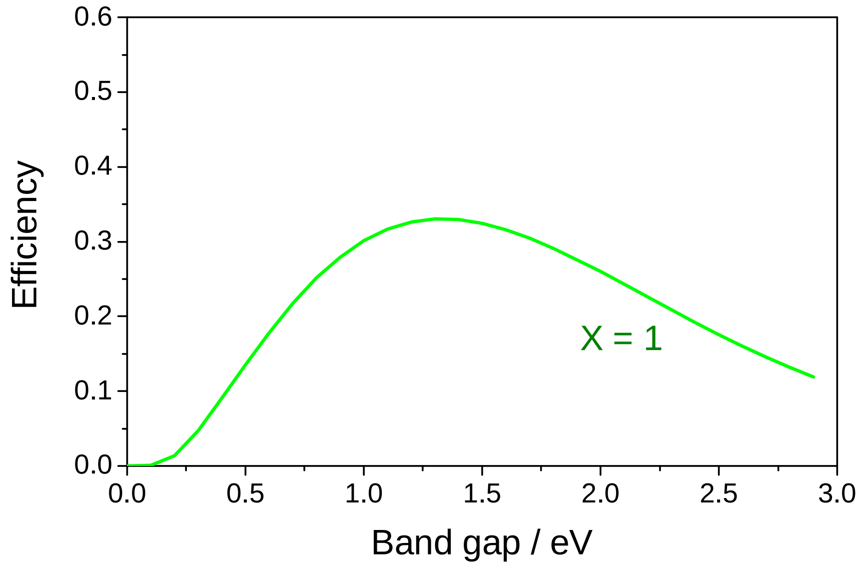


Imperial College London


Photon flux density / s-1 m-2 eV-1
sun
ambient
J0
Jsc
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Photon Energy / eV
Eg

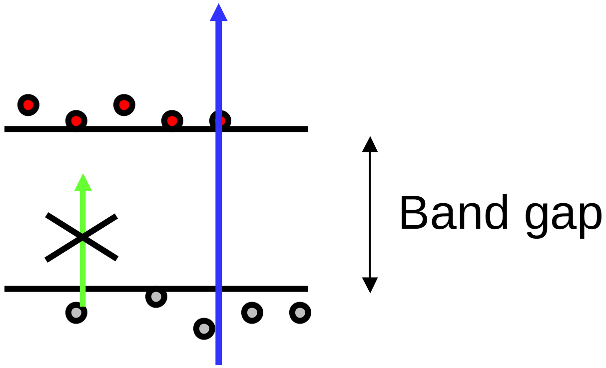


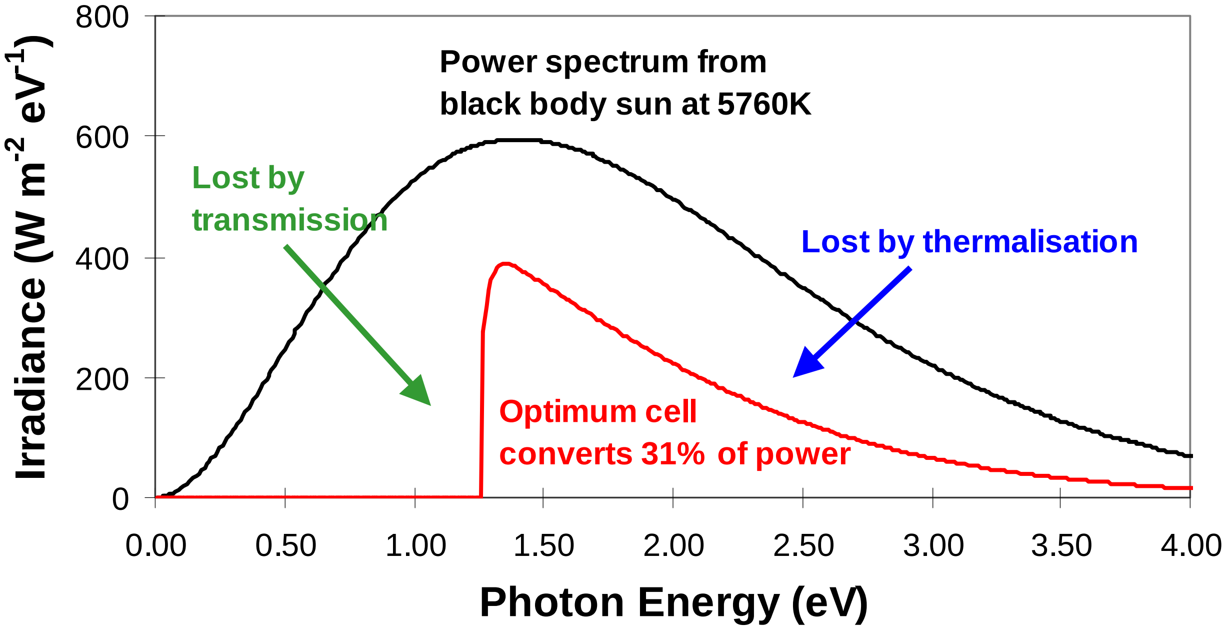




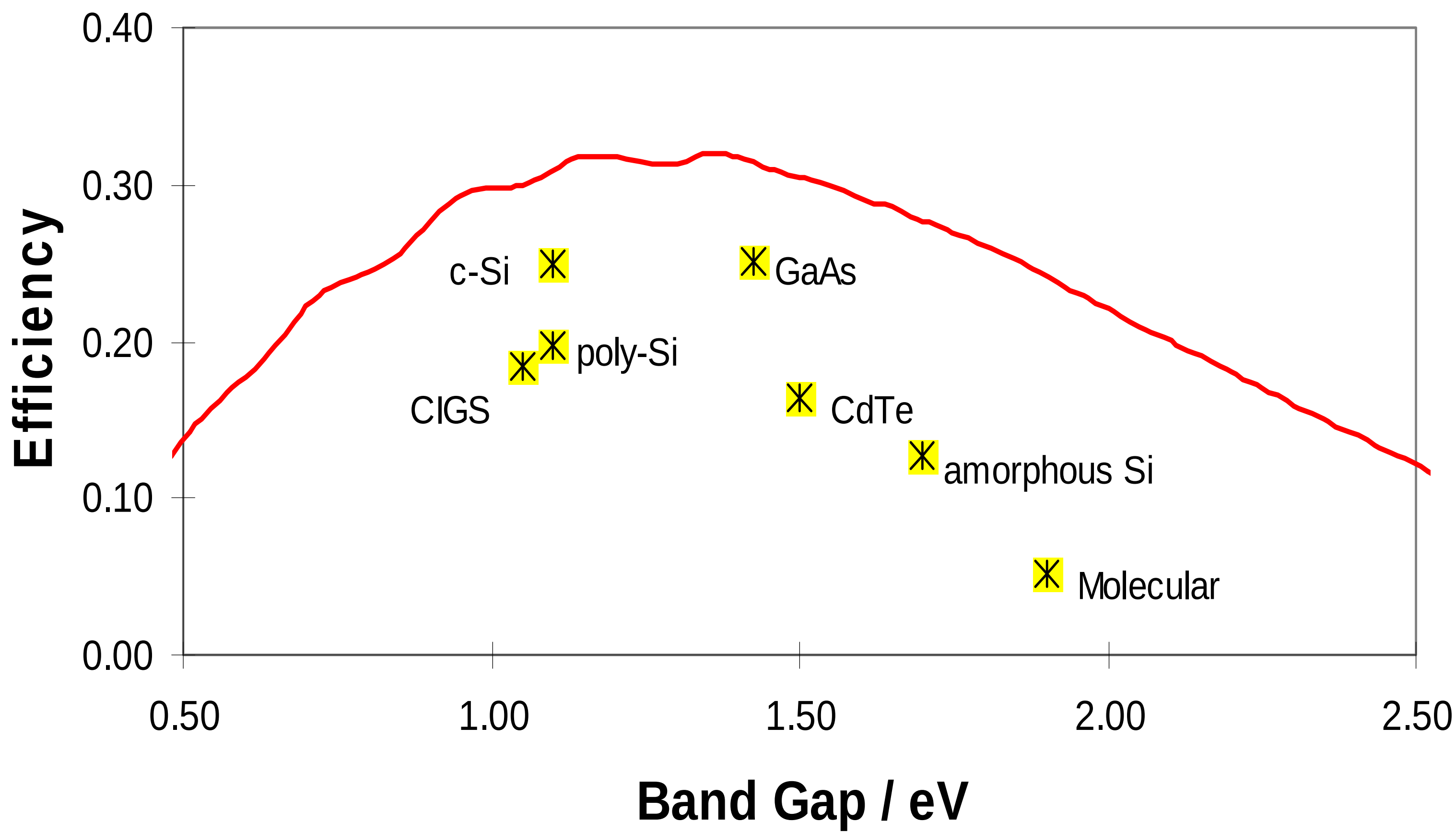
Imperial College London

Limiting efficiency of single band gap cell

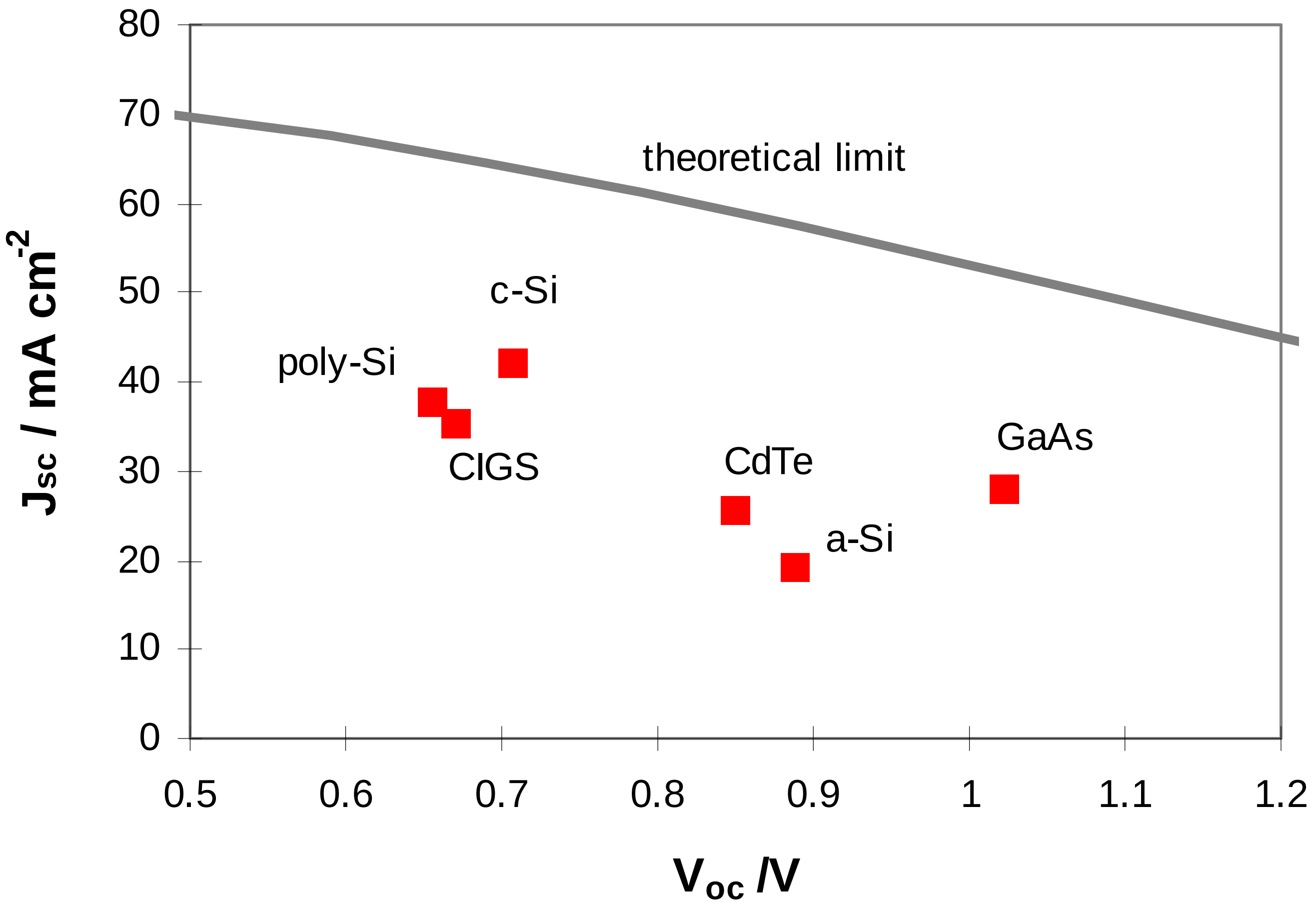




Actual versus ideal PV performance



Actual versus ideal PV performance



Limiting efficiency under full concentration

Photon flux density from sun ($T = T_{sun}$) or ambient ($T = T_{ambient}$)

$$N(E_{\min}, E_{\max}, T, \Delta\mu) = \frac{2\pi}{h^3c^2}\int_{E_{\min}}^{E_{\max}} \frac{E^2}{e^{(E-\Delta\mu)/k_BT} - 1} dE$$

Irradiance from sun ($T = T_{sun}$)

$$L(E_{\min}, E_{\max}, T, \Delta\mu) = \frac{2\pi}{h^3c^2}\int_{E_{\min}}^{E_{\max}} \frac{E^3}{e^{(E-\Delta\mu)/k_BT} - 1} dE$$

Balance fluxes to obtain current

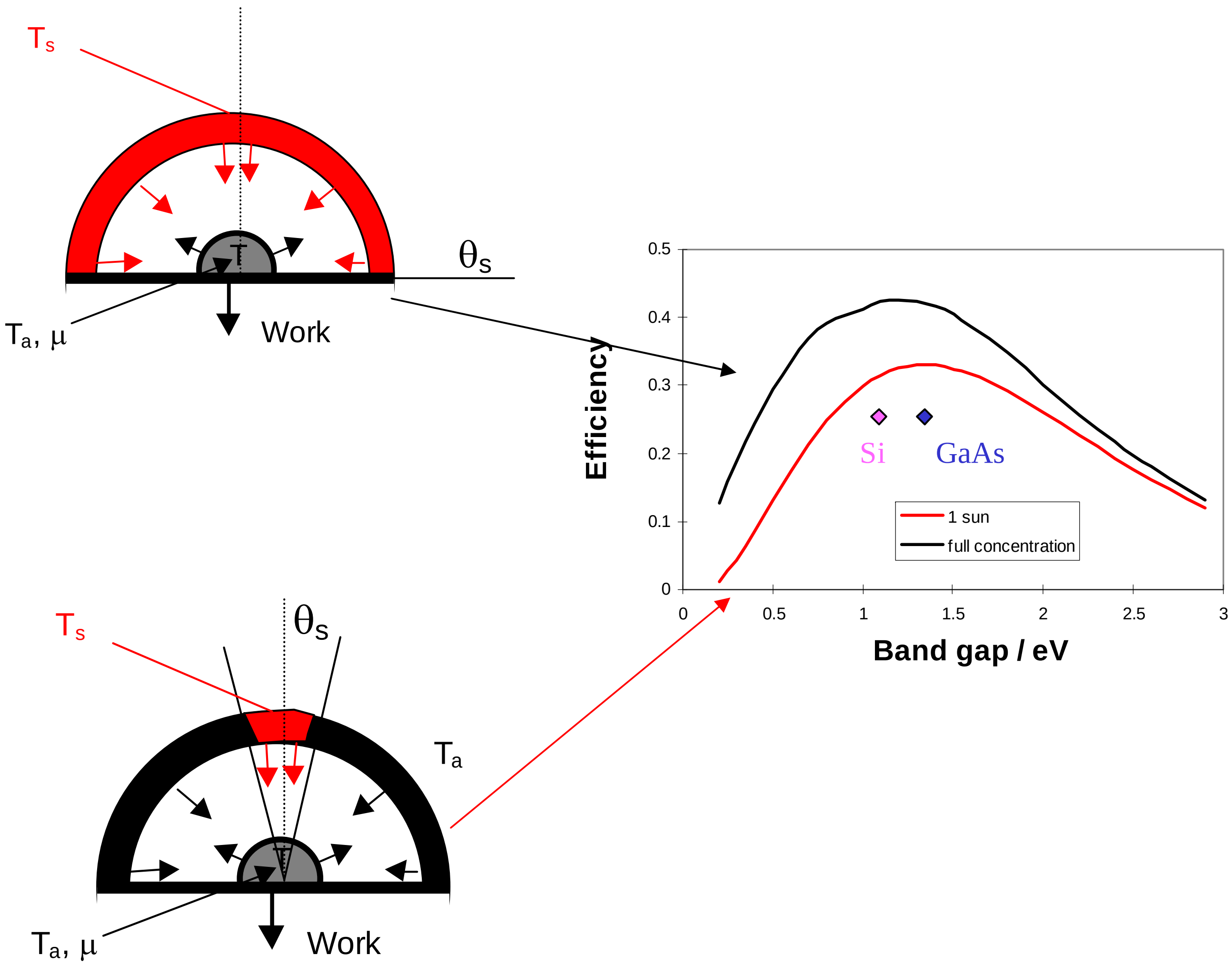
At full concentration

$$J(V) = q\{N(E_g, \infty, T_s, 0) - N(E_g, \infty, T_a, qV)\}$$

Power conversion efficiency

$$\eta = \frac{J(V)V}{P_s} \qquad P_s = Xf_sL(0, \infty, T_s, 0)$$

Limiting efficiency under full concentration



Outline

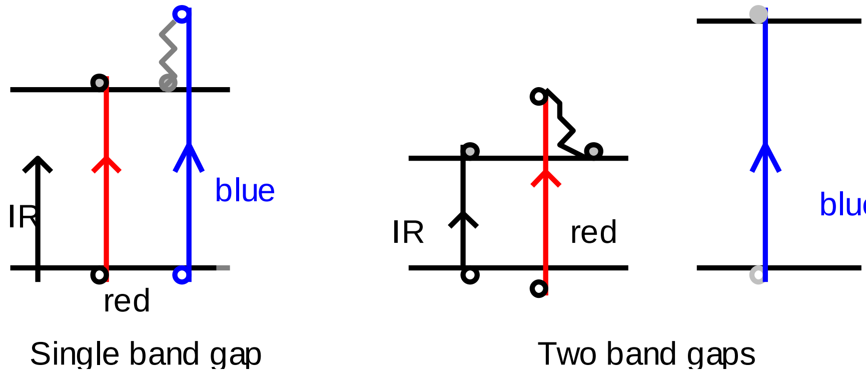
1. **Future directions for PV**
2. **Using cheaper photovoltaic materials**
3. **Limiting efficiency of solar cells**
4. **Routes to more work per photon**
5. **More efficient light harvesting**

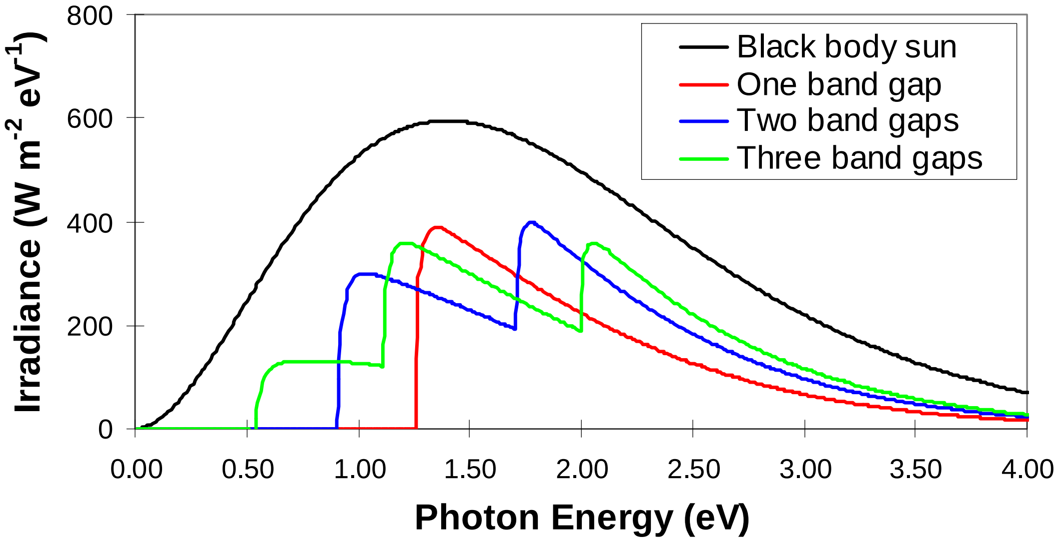
Imperial College London

How to get more ...

- More work per photon with:
  - – more band gaps
    - tandems and intermediate bands
  - – more work per photon
    - prevent carrier thermalisation in “hot carrier” solar cells
  - – more electrons per photon
    - Impact ionisation and up-or down-conversion of light

Route 1: Multiple band gaps

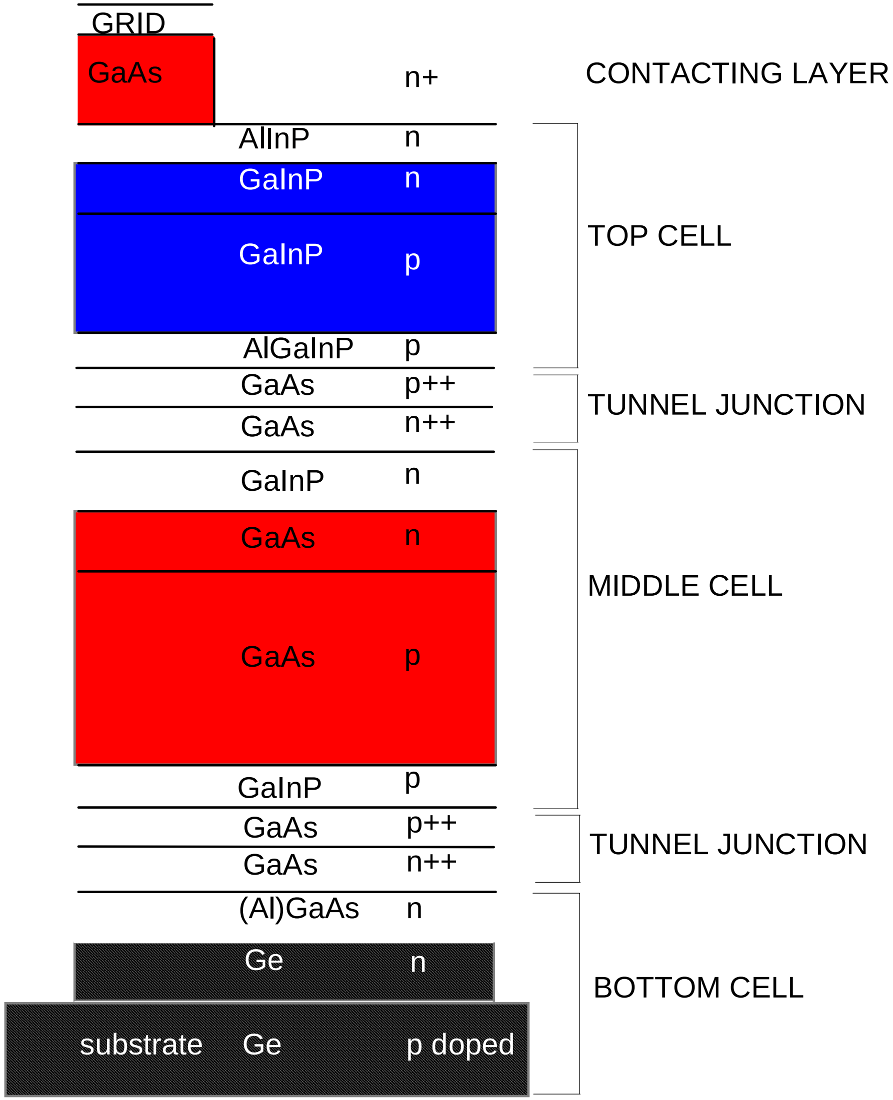


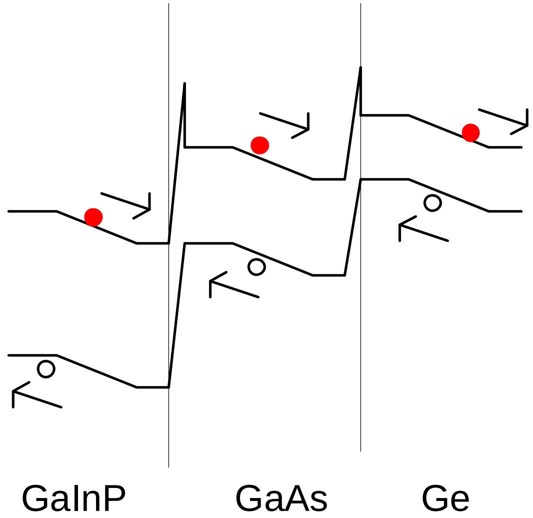


- Approaches using tandem cells, spectral splitting and quantum semiconductor structures

Imperial College London

Triple junction cell

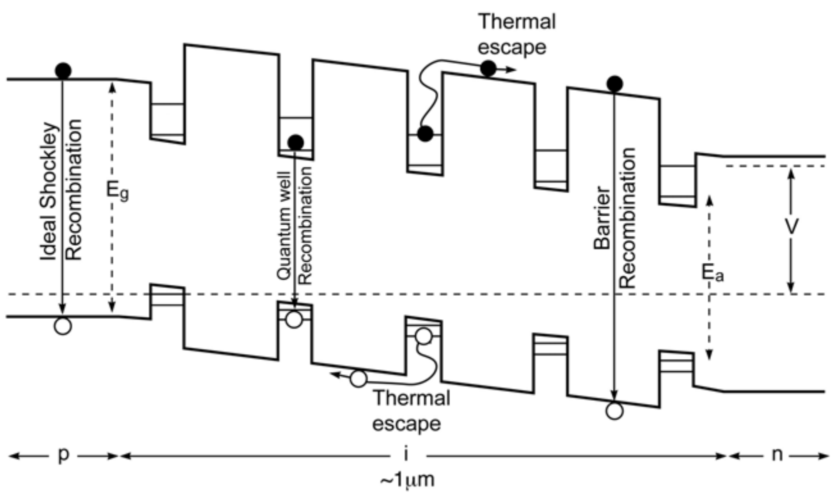




Highest efficiency for a 3 junction tandem:
40.7 % under concentration (Spectrolab, Dec 2006)

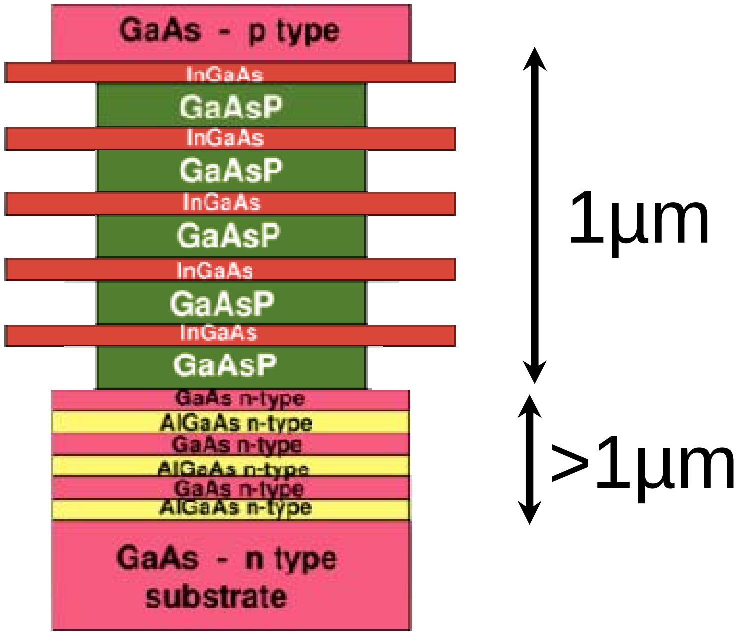
Quantum well structures in solar cells

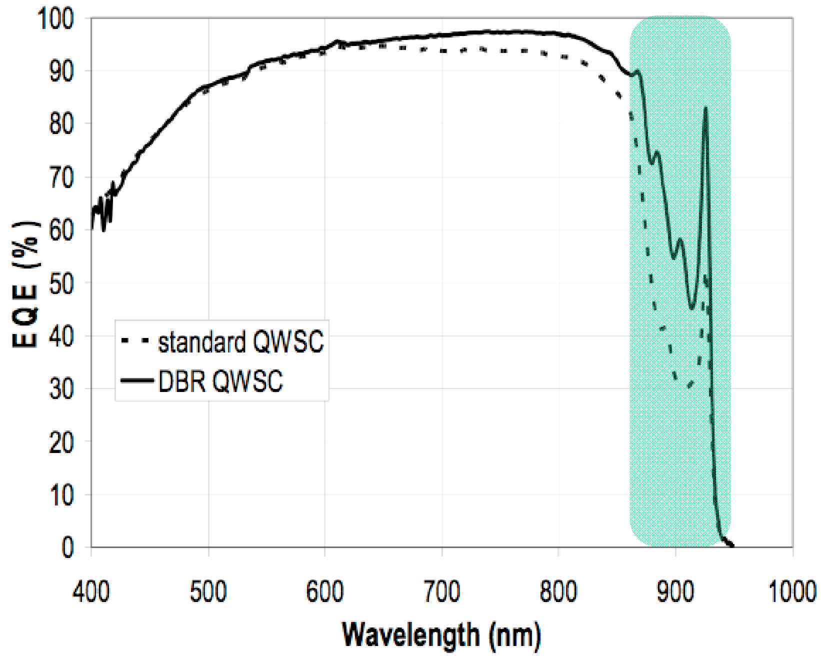
- Additional low energy photons absorbed in QWs in active region
- Charge carriers escape from QWs - less energy lost by thermalisation than in homojunction
- V_{oc} intermediate between values expected for QW and barrier material. Higher efficiency possible.



Imperial College London

Single Junction Quantum Well Solar Cell

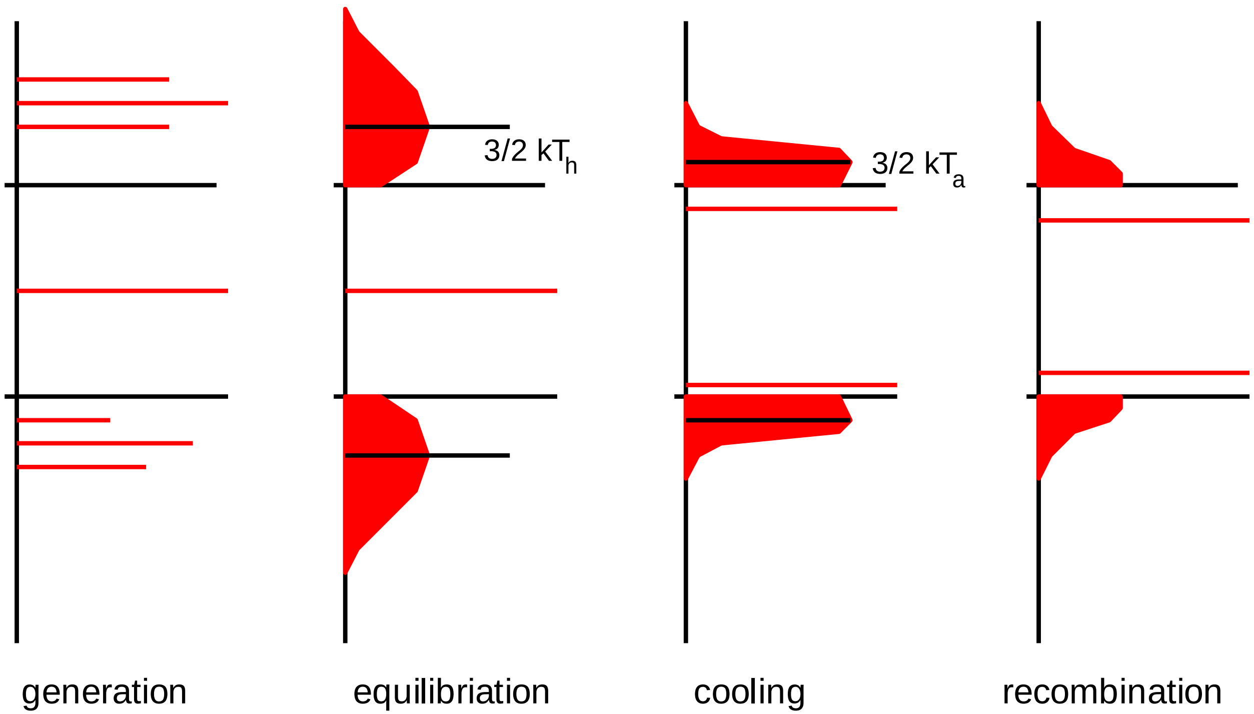




QuantaSol

June 2009 world record:
28.3% at 535 suns

Route 2: Slowed cooling

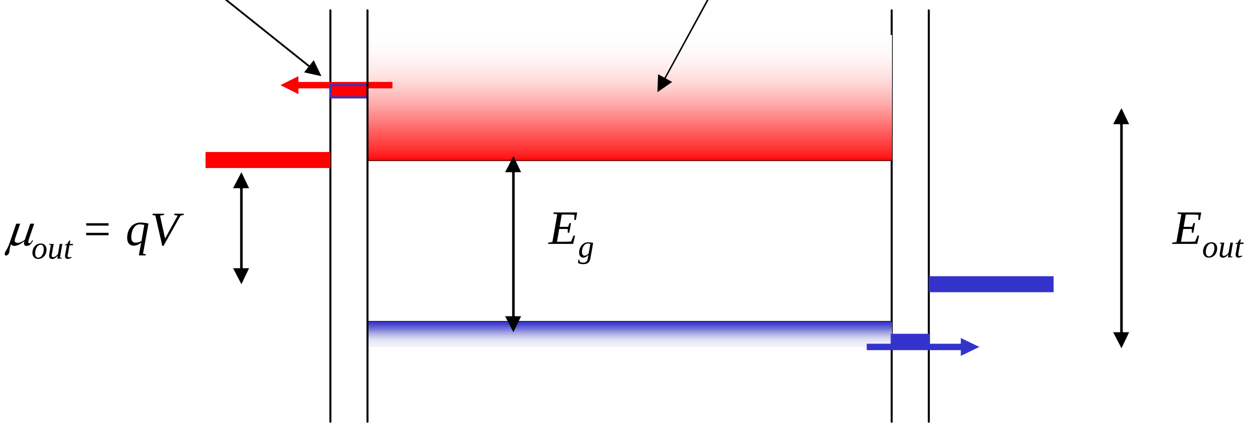


- Use quantum nanostructures or molecular systems to harvest photogenerated charges before cooling?

Hot carrier solar cells

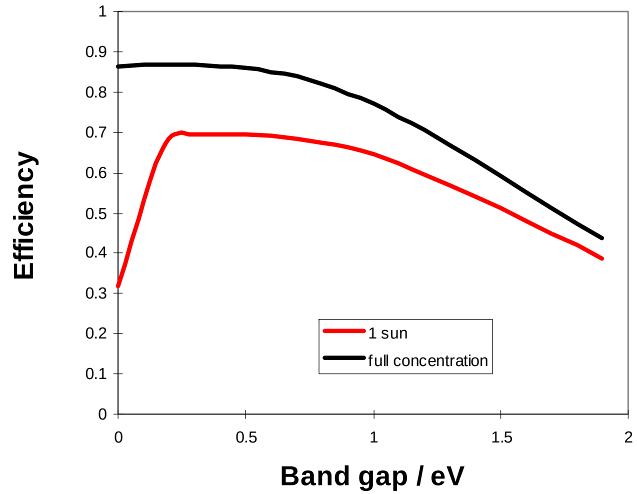
Electrons extracted isoentropically through narrow bandwidth contact

Photogenerated electrons scatter with each other but not with lattice
⇒ Fermi Dirac distribution at temperature T_H *(*$>T_a$*) and* μ_H

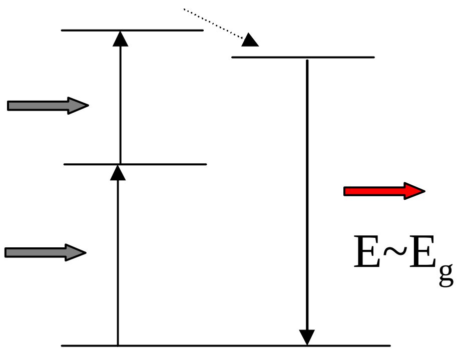


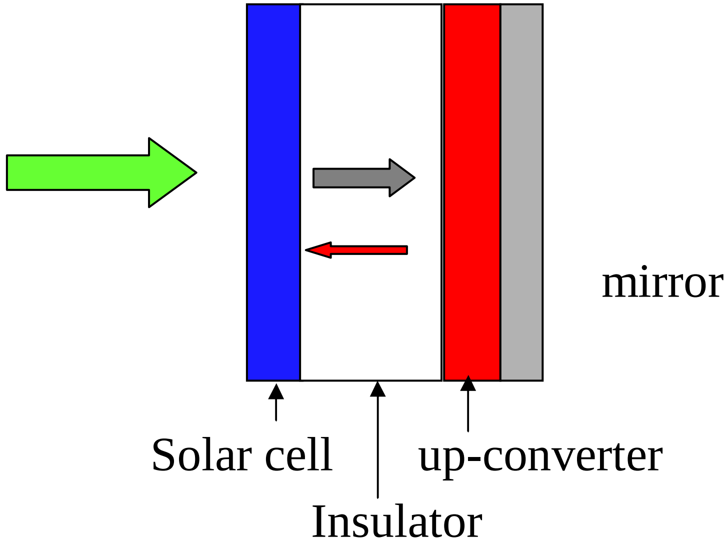
Efficiency of hot carrier solar cell:

Maximum efficiency same as thermodynamic limit



Route 3: Utilising high and low energy photons by up- and down-conversion

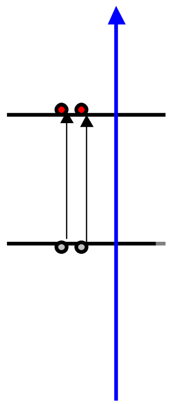


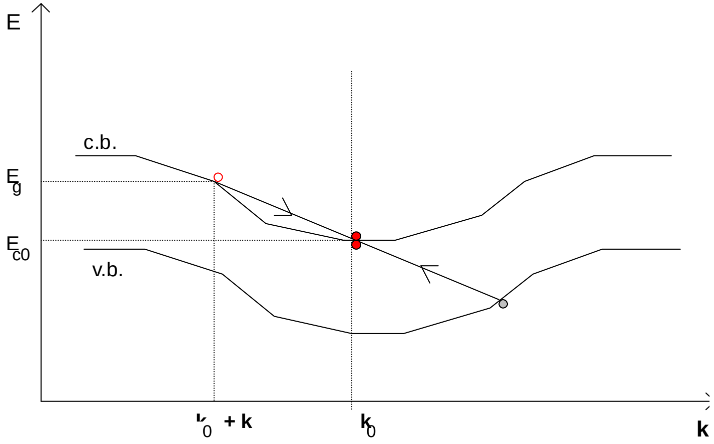


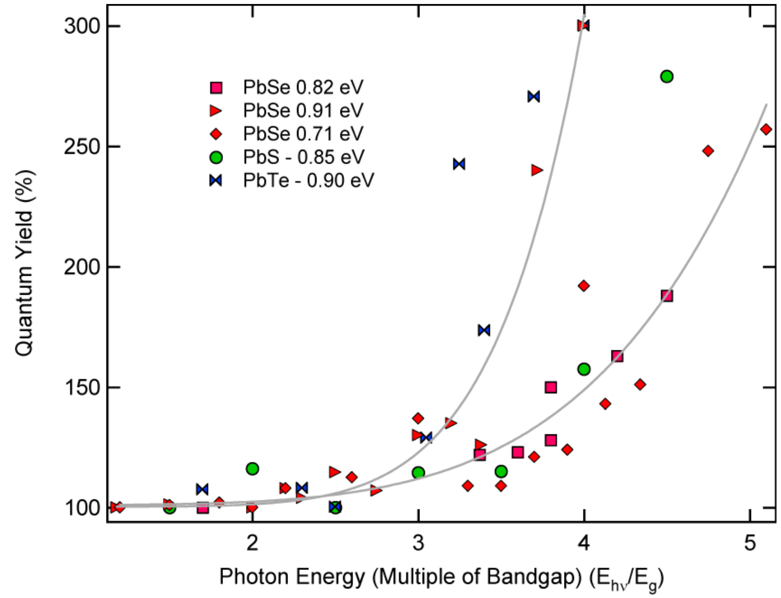
- Up-conversion: low energy photons converted into high energy photon (~ E_g) and absorbed by device. E.g. rare earth doped ceramics

- Down-conversion: high energy photons generate multiple lower energy photons (~ E_g)

Multiple electrons per photon

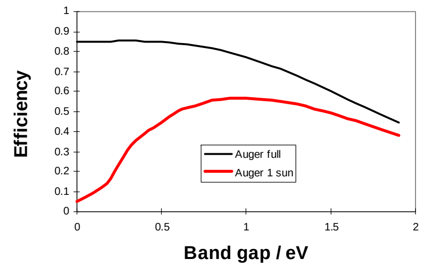






Ellingson et al, SPIE, 2006

- Generate multiple electrons per photon by impact ionisation (or Auger generation)
- Observed experimentally in Si and Ge, and now in PbSe quantum dots
- Analysis equivalent to hot electron solar cell with $\mu_H = 0$

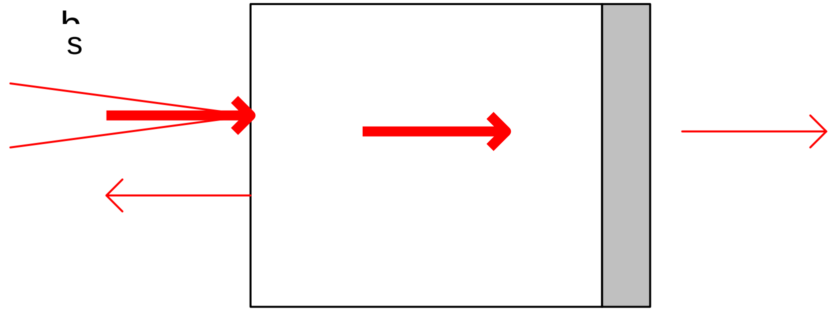


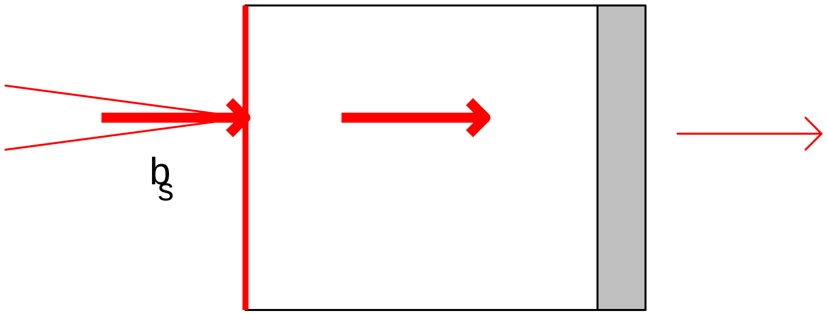
Imperial College London

Outline

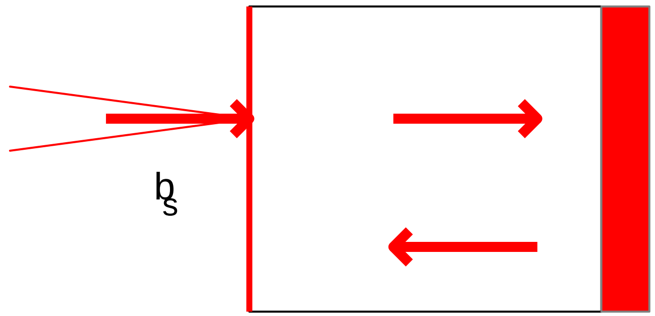
1. **Future directions for PV**
2. **Using cheaper photovoltaic materials**
3. **Limiting efficiency of solar cells**
4. **Routes to more work per photon**
5. **More efficient light harvesting**

More photogeneration per unit volume

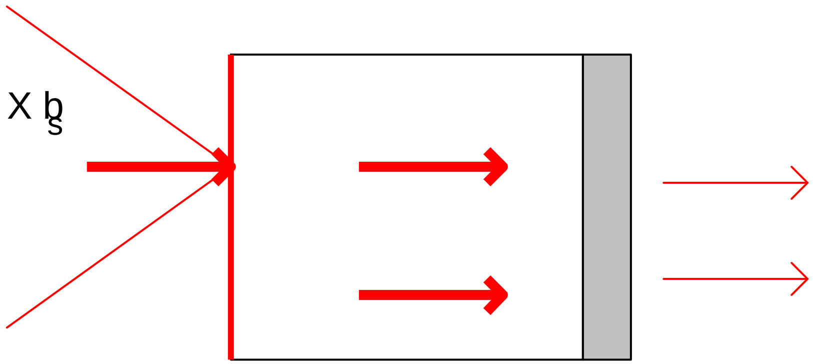




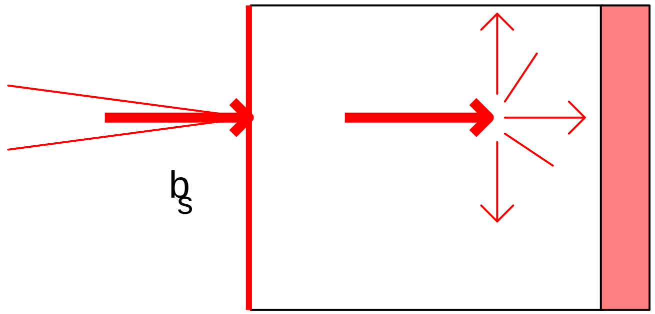
Anti-reflection coatings



Light trapping

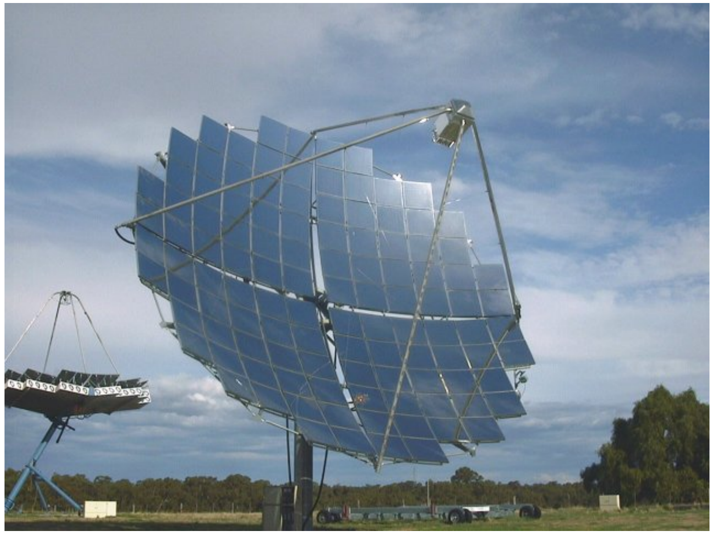


Concentration

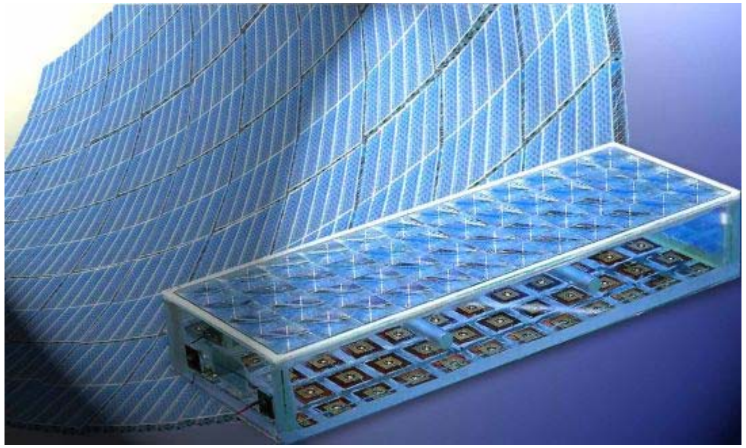


Reabsorbing luminescence

Concentration

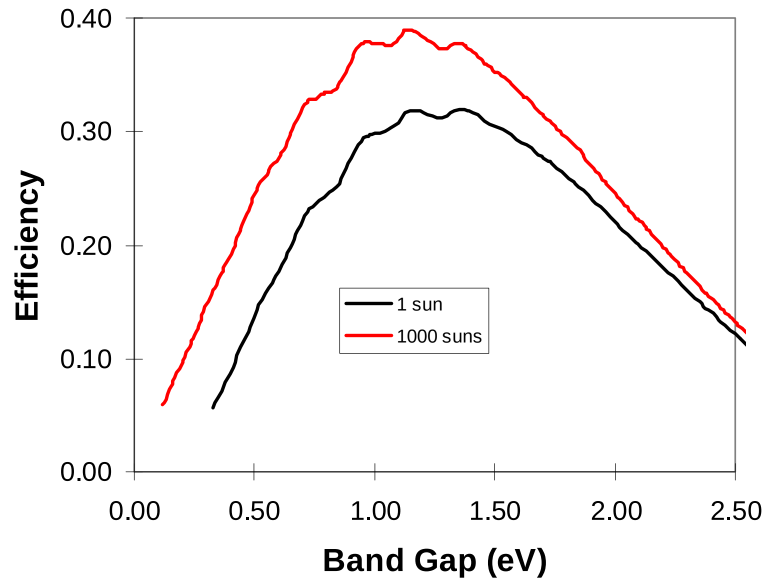


Parabolic concentrator *SolarSystems*

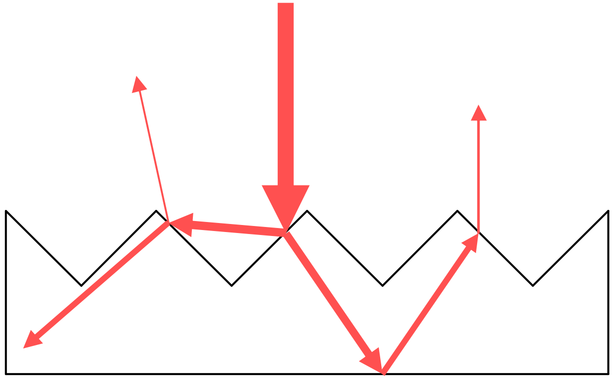


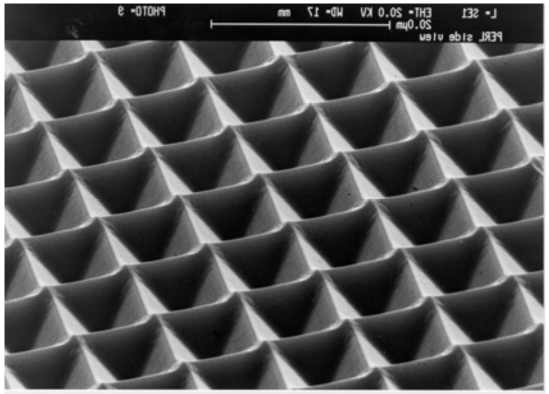
Fresnel lens *FISE, Ioffe Inst.*

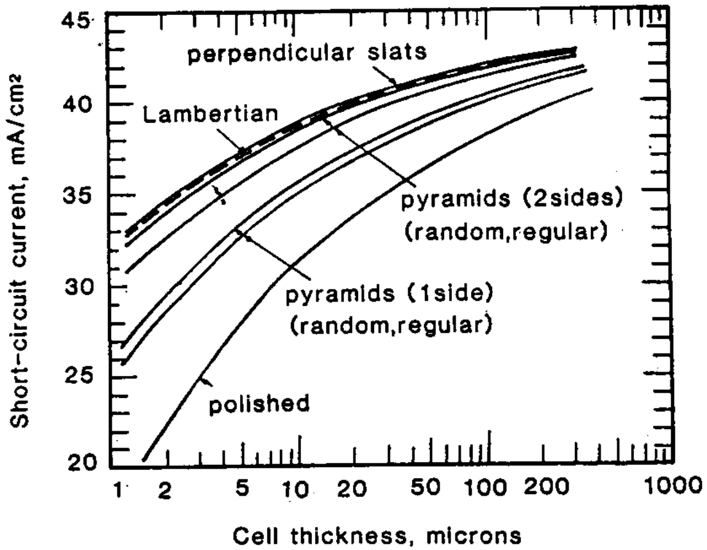
- Parabolic concentrators, Fresnel lenses
- Need for direct sunlight
- Use with high efficiency (III-V) photovoltaic materials
- Use with optical fibre technology?



Light trapping







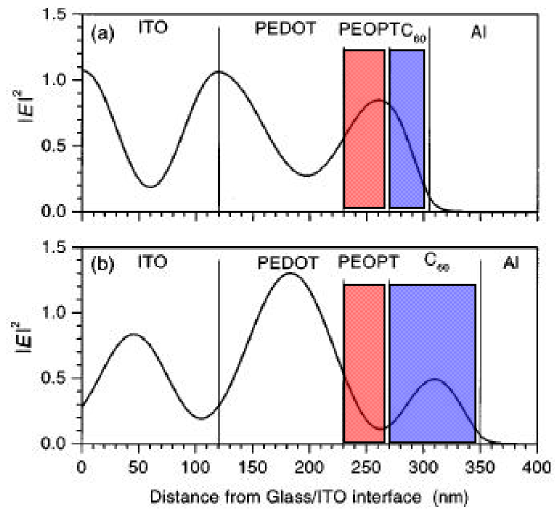
- Light trapping structures: increase optical path length, reduce reflection
- Aim to reduce silicon cell thickness from ~300 μm to ~10 μm

More in Prof Bagnall's lecture …

Imperial College London

Better light harvesting with optical design: planar structures

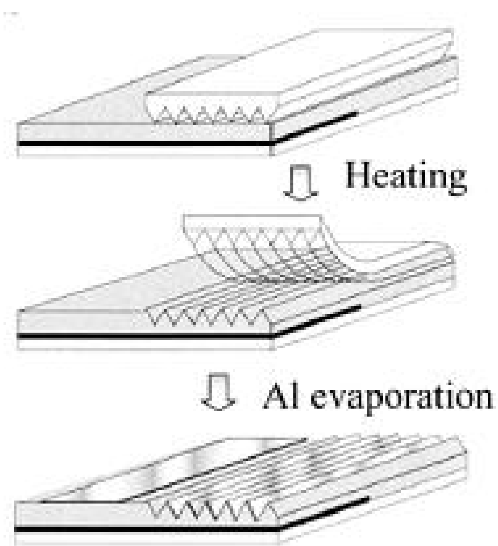
- Device structures ~ wavelength of light
- Interference critically important
- Design device structures to maximise absorption in active layer and at donor-acceptor interface
- Can afford to lose absorption at short λ to gain at long λ

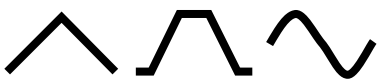


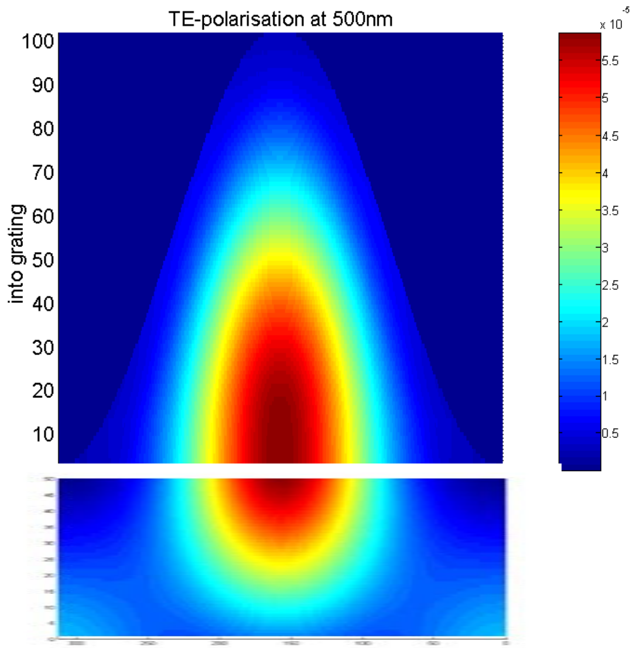
e.g., Pettersson et al, J.Appl.Phys. 86, 487 (1999)

Light trapping in grating structures

- Larger absorption enhancements available with 1D or 2D grating structures.
- Rigorous Coupled Wave Analysis to predict absorptance of patterned device
- Soft embossing to imprint grating on polymer

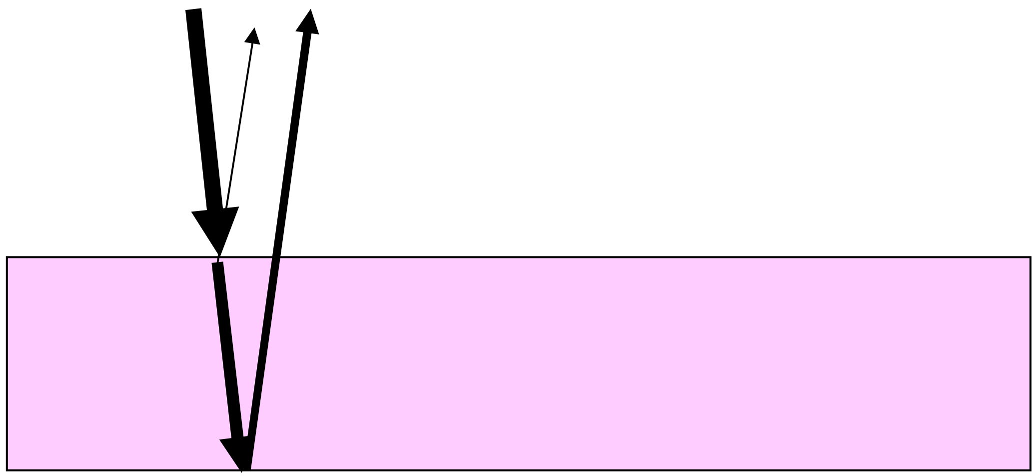




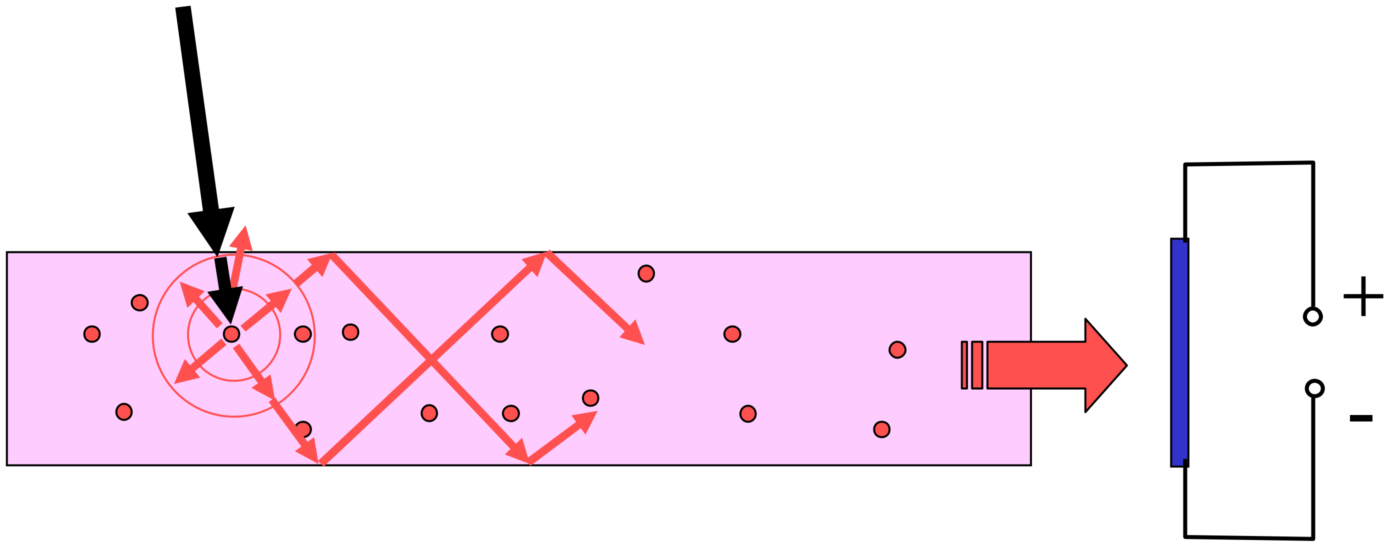


Felix Braun

Luminescent concentrator

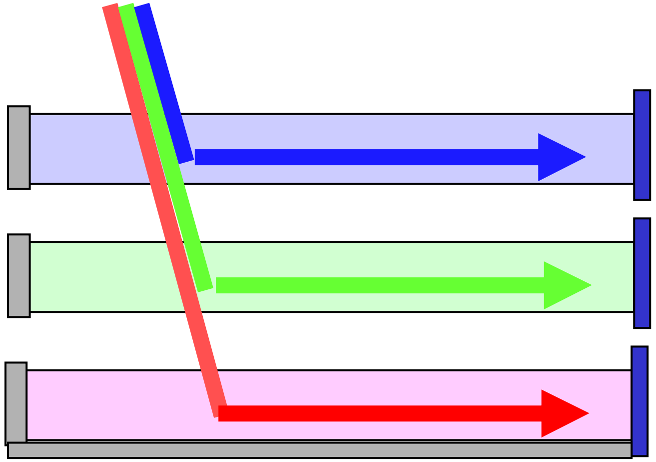


Luminescent concentrator



- Luminescent dyes or quantum dots dispersed in refractive material
- Cheaper than imaging concentrators
- Harvests diffuse light
- Able to concentrate photon energies near band gap of cell

Stacked luminescent concentrators



- Stacked luminescent concentrators to split the solar spectrum
- Selective band gap cells for higher efficiency (more work per photon)
- Research at Imperial on use of II-VI quantum dots as luminescent species, (A. J. Chatten et al.)

Summary

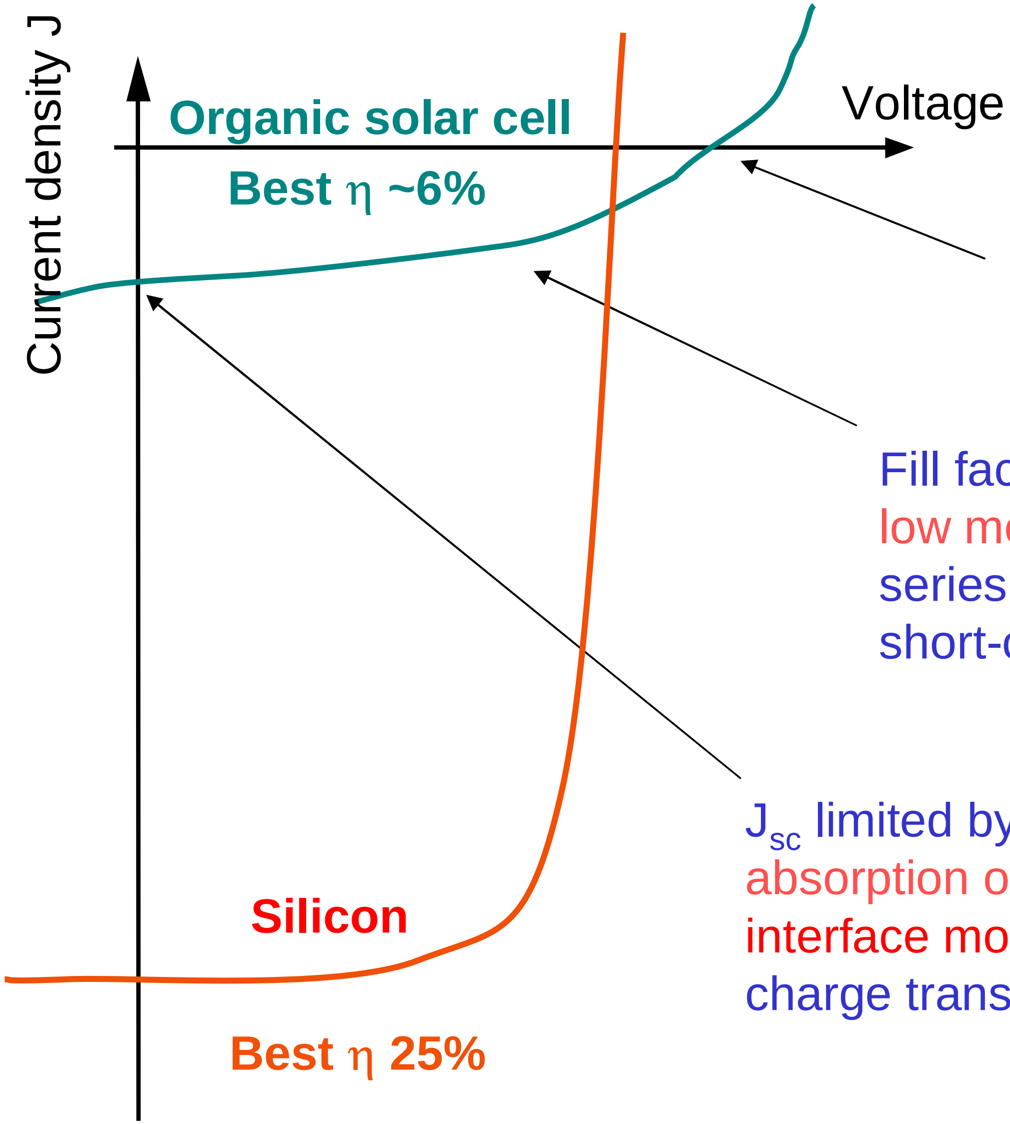
- The cost per Watt of PV electricity can be increased by:

- Reducing the cost of PV material
  - By use of inorganic thin film materials
  - E.g. by use of molecular PV materials

- Increasing the amount of work per photon
  - with multijunction "tandem" structures or other (quantum) heterostructures
  - Exploiting hot carrier effects or multiple electrons per photon

- Reducing the amount of PV material per photon harvested
  - Concentration of light (including luminescent concentrators)
  - Light trapping

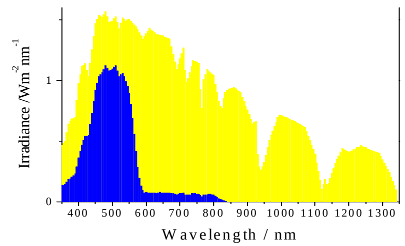
Key challenges



V_{oc} limited by:
interfacial recombination
interfacial energy levels

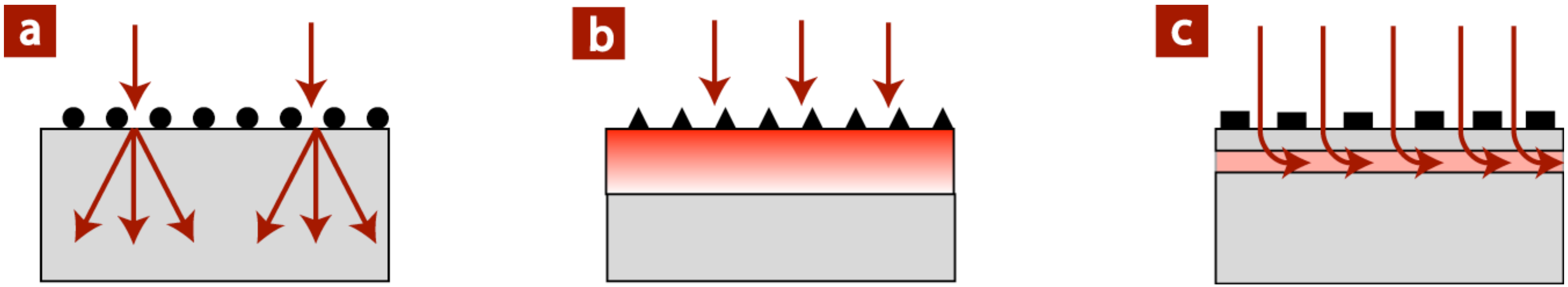
Fill factor limited by:
low mobility
series resistance
short-circuits

J_{sc} limited by:
absorption of red light,
interface morphology
charge transport



Imperial College London

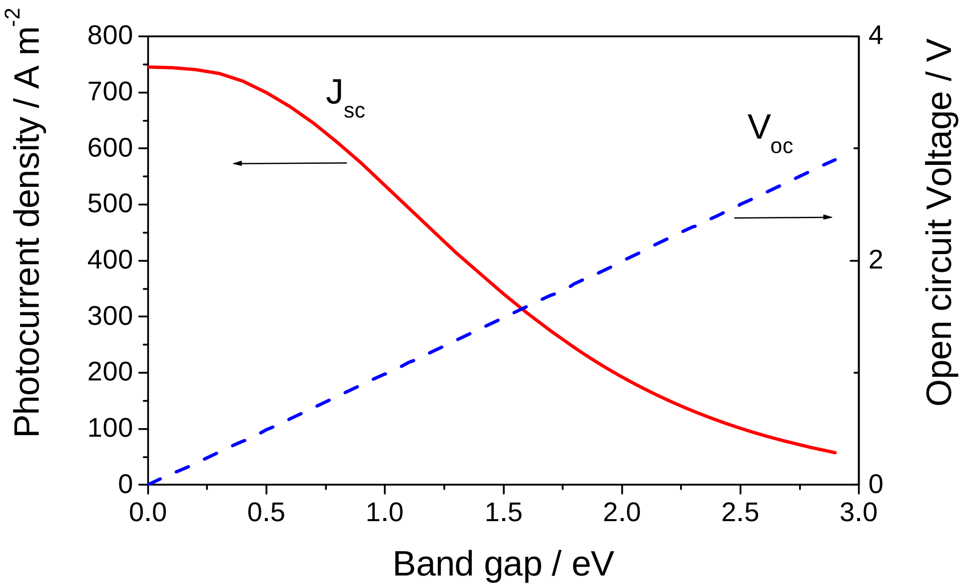
Exploiting Plasmonic Effects in Solar Cells

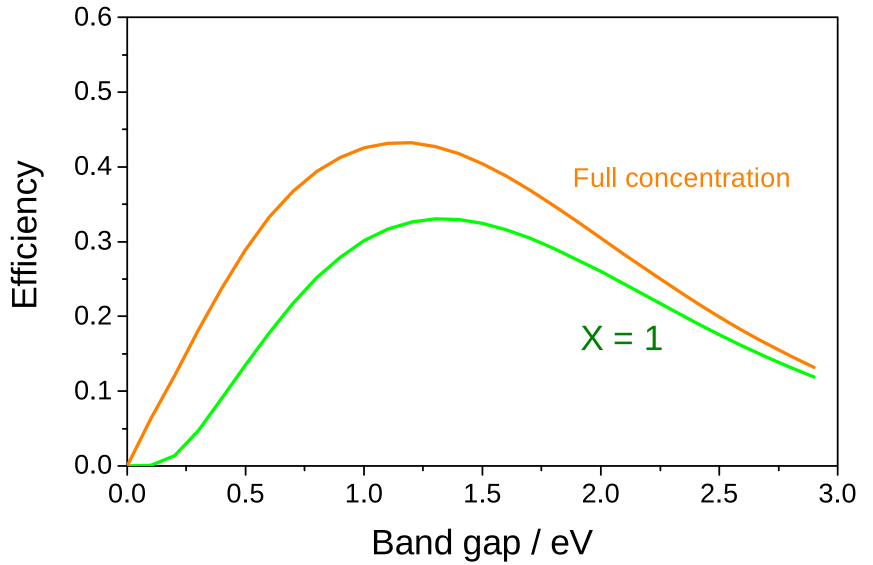


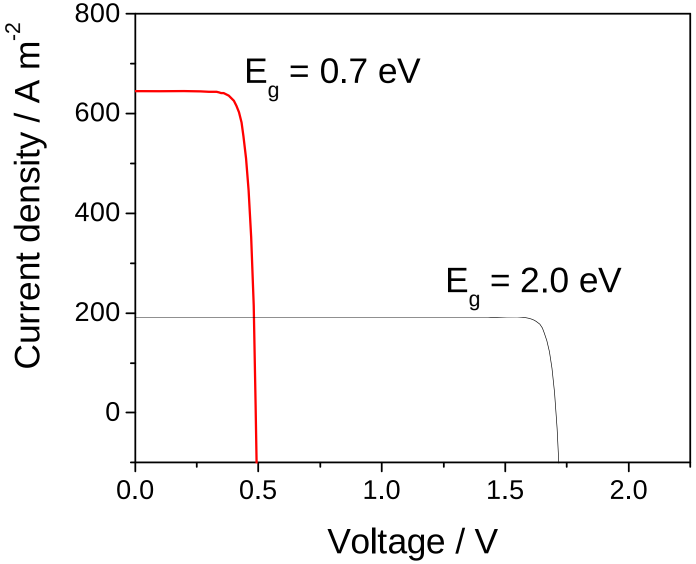
Internal Scattering

Field Enhancement

Surface Plasmon
Polariton Propagation


Photocurrent density / A m-2
Open circuit Voltage / V
Band gap / eV
Jsc
Voc
800
700
600
500
400
300
200
100
0
4
2
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Efficiency
Band gap / eV
Full concentration
X = 1
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Current density / A m-2
Voltage / V
Eg = 0.7 eV
Eg = 2.0 eV
800
600
400
200
0
0.0
0.5
1.0
1.5
2.0