Thermodynamic efficiency limits

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{I_{\text{max}} V_{\text{max}}}{P_{\text{in}}} \]

- Thermodynamical (Carnot) limit \( \eta = 93\% \)
  
  Ts=5760 K
  T=300 K
  \( \eta = 93\% \)

- Photoelectric current energy = energy absorbed – energy emitted \( \eta = 86\% \)

- Queisser – Schockley limit \( \eta = 30-33\% \)
Single junction efficiency limit

Power spectrum from black body sun at 5760K

Irradiance $\Phi$ (W m$^{-2}$ eV$^{-1}$)

0.00 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00

Photon Energy (eV)

Lost by transmission

Lost by thermalisation

Optimum cell converts 31% of power

Single band gap
Queisser-Schockley limit

- one electron-hole pair per photon
- carriers in thermal equilibrium with the lattice
- only one loss mechanism: radiative recombination

\[ \eta = 33\% \]

\[ X_g = \frac{E_g}{kT} \]

Shockley and Queisser 1961
I generation cells: Si
II generation: thin film cells
III generation cells: beyond the limits

more bands absorbing the light
tandem cells, intermediate band cells
low dimensional structures

more energy from one photon
hot carriers, impact ionisation

transformation of sunlight
UP and DOWN converters
More bands: multijunction “tandem” cells

for 3 junctions $\eta_{\text{max}} = 63\%$ (under max concentration)
Record tandem cells

GaInP/GaAs/InGaAs

$\eta = 37.3\%$ (under concentrated light)

GaInP/GaAs/Ge; $\eta = 33.78\%$ (1 Sun)

NREL 2007

World present record 44% (942x)

A-SLAM technology (Solar Junction)

(Adjustable Spectrum Lattice Matched)
Multijunction structure (tandem cell)
Efficient solar cells use multiple semiconductors with fixed energy gaps (e.g., a GaInP/GaAs/Ge triple junction cell) to capture as much of the solar spectrum as possible (left). LBNL researchers have shown, using materials grown at Cornell University and Japan, that the direct energy gap of In_{1-x}Ga_xN spans nearly the energy range 0.7 – 3.4 eV of the solar spectrum (left), not 2.0–3.4 eV as reported in the literature (dotted line, right). Multijunction solar cell based on this single ternary system could have efficiencies as high as 50%.
Intermediate band cell


maximum $\eta = 63\%$

$E_{g1} = 1.93\, eV$
$E_{g2} = 0.7\, eV$

$(ZnMn)Te:O$
maximum $\eta \cong 63\%$
More bands: quantum wells

additional absorption on energy levels in quantum wells

GaAs MQW in AlGaAs p-i-n

More energy: hot carriers cells

high energy carriers collected before thermalisation by energy-selective contacts (tunneling junctions?)

cooling slower in quantum dots?
More energy from one photon: impact ionization

1 photon  more than 1 electron-hole pair
observed in Si, Ge

in PbSe


Impact ionisation in QD

\[ (E_{2,e} - E_{0,h}) \geq 2 (E_{0,e} - E_{0,h}) \]
up and down converters
Quantum dot solar cells
Quantum dots

PbS QD NREL 4%, Univ Toronto 7%
CdSe QD + TiO$_2$
Quantum dots: enhancement of photoexcitation spectrum

InAs/GaAs doped QD
Supersensitisation of mesoscopic cells: TiO2 with CdS and squaraine dye

Tandem QD cells
Challenges and strategies in photovoltaics