Third generation solar cells

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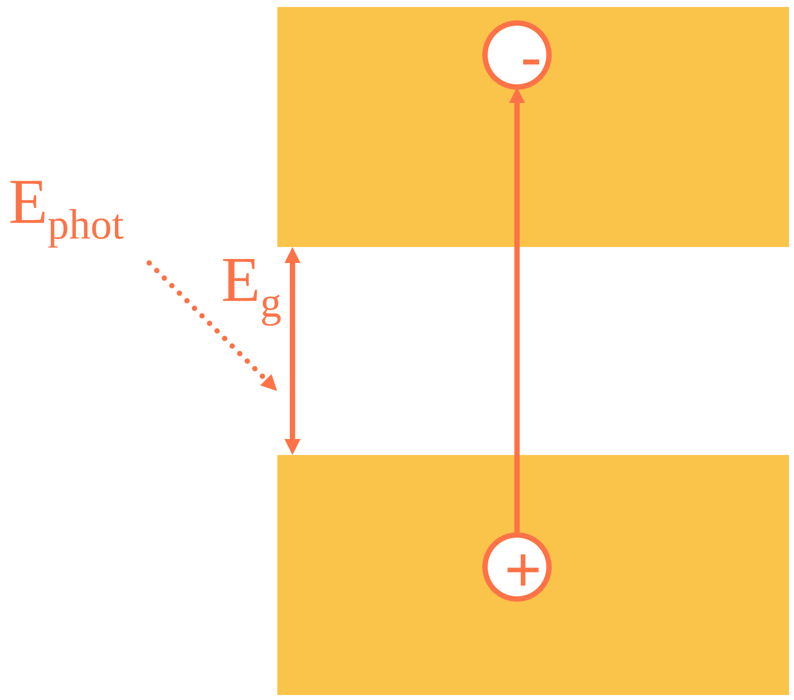
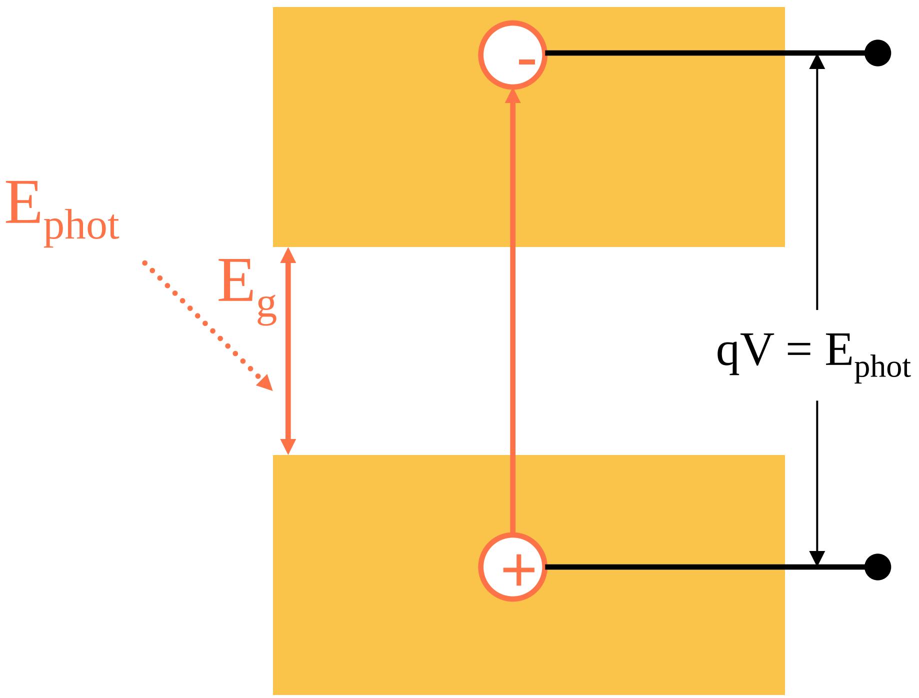
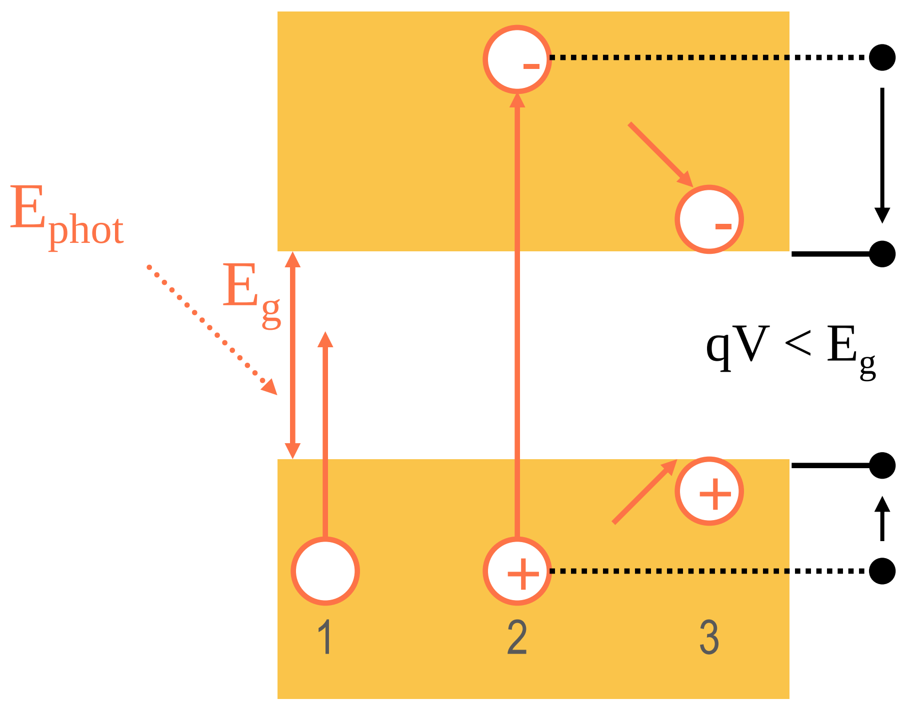
A «normal» solar cell



A «normal» solar cell

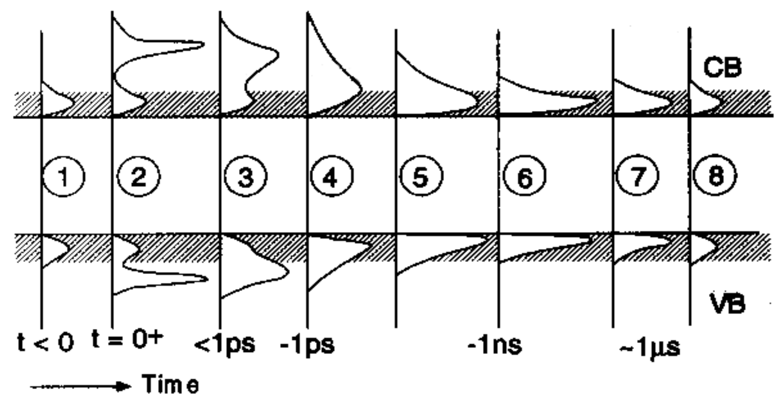


The trouble with «normal» solar cells



Thermalization

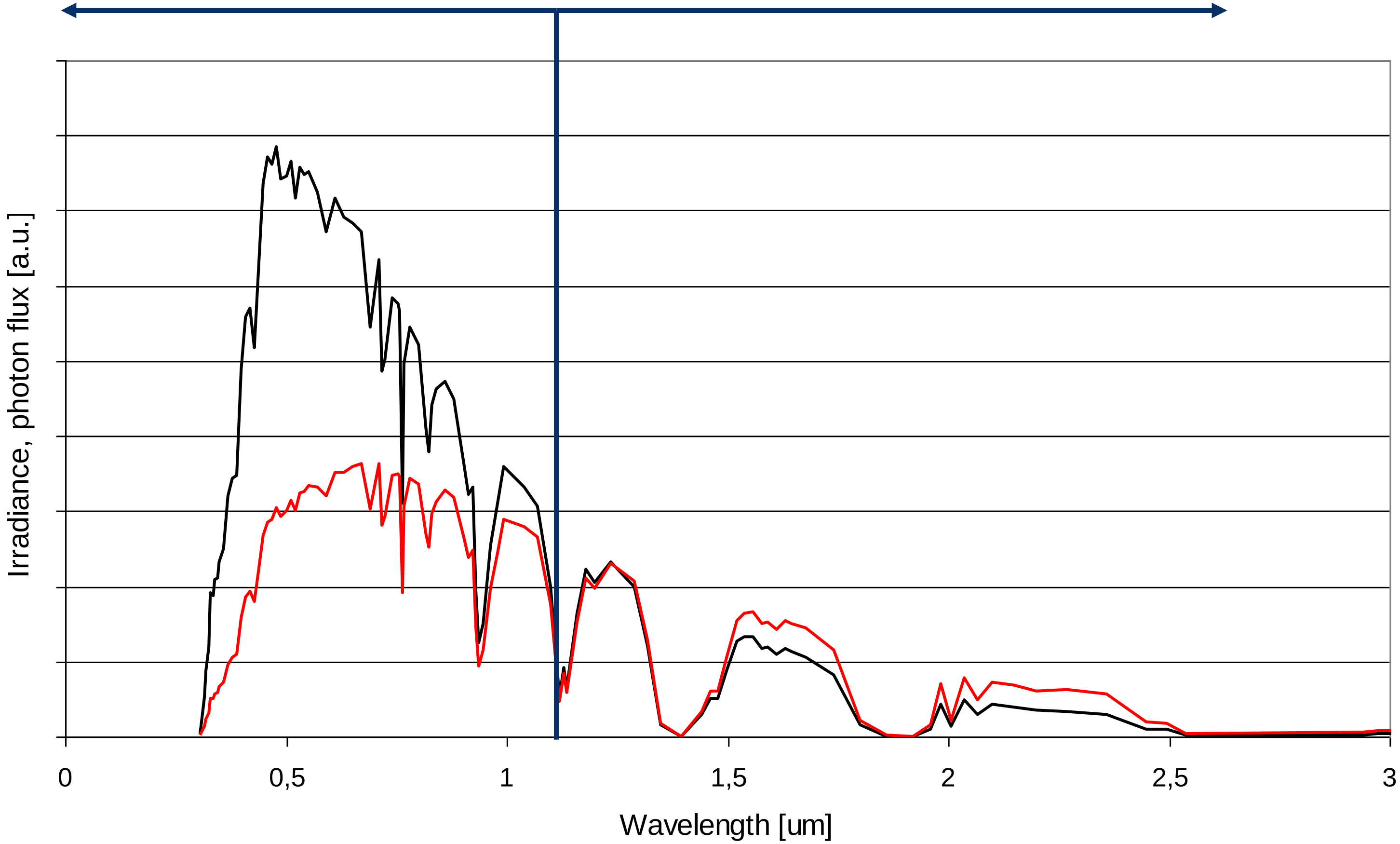
- Thermalization within solar cell materials normally occurs on an extremely rapid time scale
- Thermalization in Si:
  1: Initial concentration of charge carriers
  2: Initial exitation of charge carriers after exposure to laser pulse
  3-4: Carrier-carrier collisions lead to an energetic redistribution around carrier temperature
  5-6: Carrier-phonon interactions cool down carriers
  7-8: Recombination across band gap



M.A. Green, UNSW

Consequences

NON-OPTIMAL USE OF PHOTONS TRANSMITTED PHOTONS



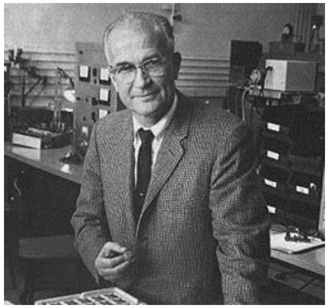
Consequences

- Large current densities can be obtained by selecting a material with a low band gap energy
- However, due to thermalization, the band gap puts an efficient upper limit to the extractable voltage.
  - If we should be even so lucky!
    - Si bandgap: 1.12 eV
    - **Good** open circuit voltage: 700 mV

Theoretical efficiency limits

The Shockley-Queisser limit

- Si p-n homojunction solar cell: ~29 % efficiency
- Assumptions
  - All photons incident on cell captured
  - Complete absorption of all photons with $\mathrm{E} > \mathrm{E_g}$
  - Complete thermalization occurs
  - Lossless transport and collection of charge carriers
  - Ideal materials: auger and/or radiative recombination dominating recombination mechanism



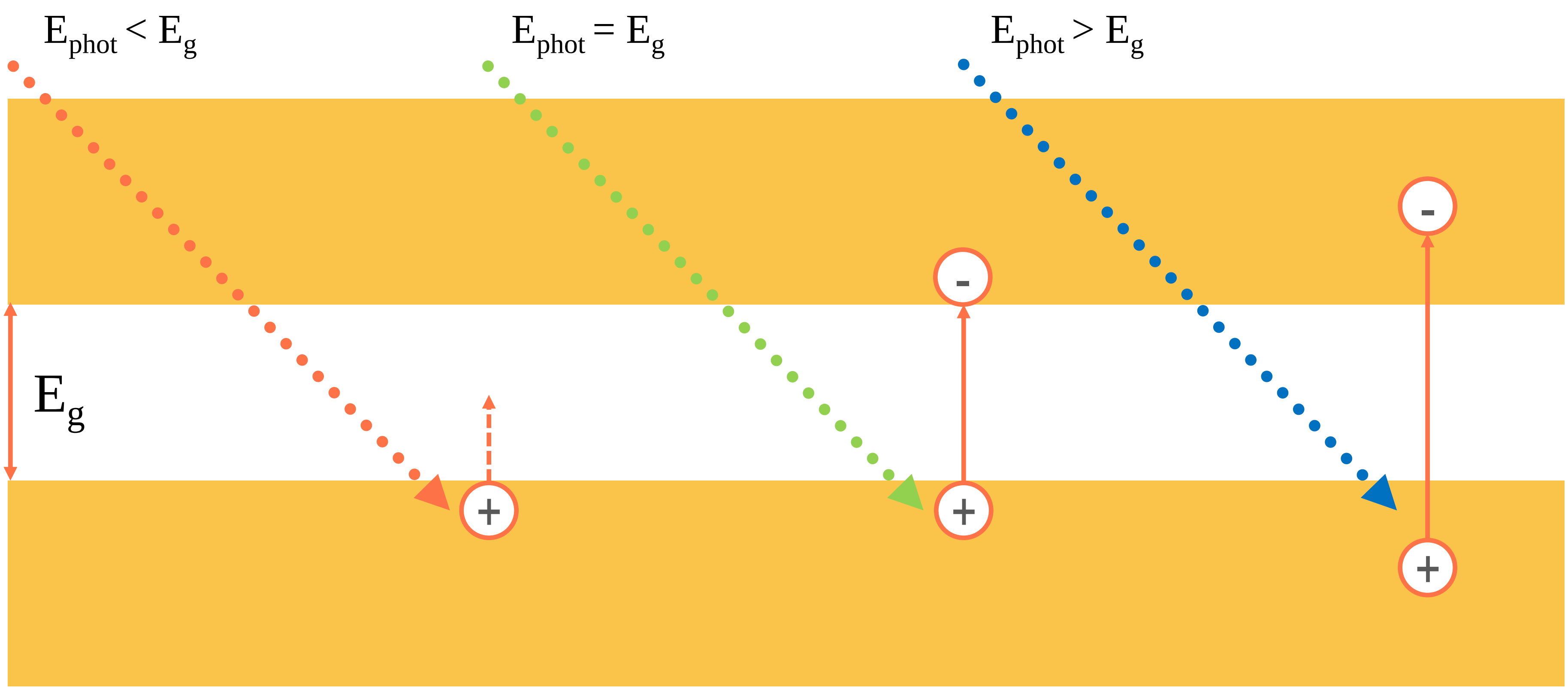
The Shockley-Queisser limit

- Upper limit for homo-junction efficiency: **33%**
- Where do the remaining **67%** go?

Thermalization ($E > E_g$)	47%
Transmission ($E < E_g$)	18.5%
Recombination	1.5%
Remaining efficiency	33%
Total	100%

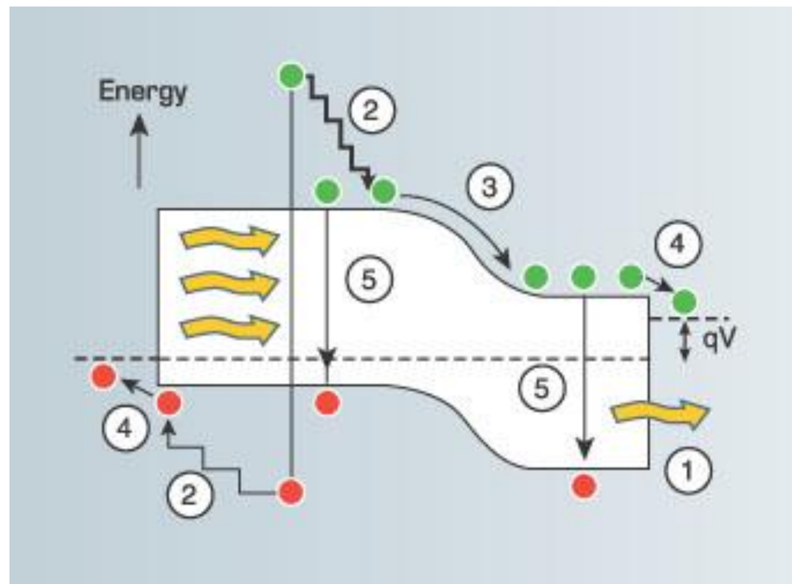
M.C. Beard et al., Nano Letters 7 (2007) p 2506

Shockley-Queisser



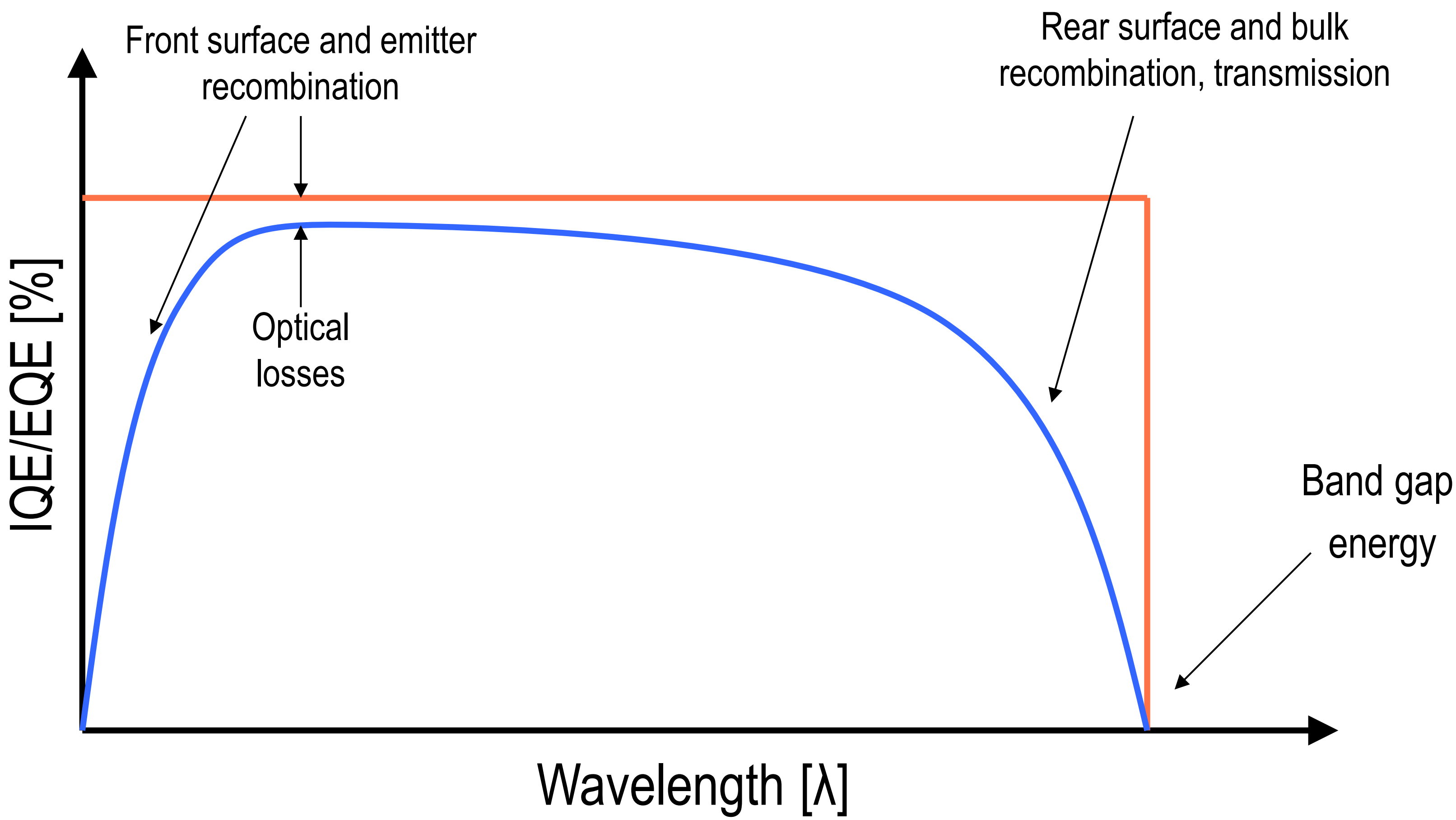
Fundamental loss mechanisms

1. Insufficient photon energies
   - $E < E_g$
2. Thermalization of energetic carriers
   - If $E > E_g$, $E \longrightarrow E_g$
3. Energy loss across p-n junction
4. Energy loss at contacts
5. Recombination



M.A. Green, UNSW

Quantum efficiency

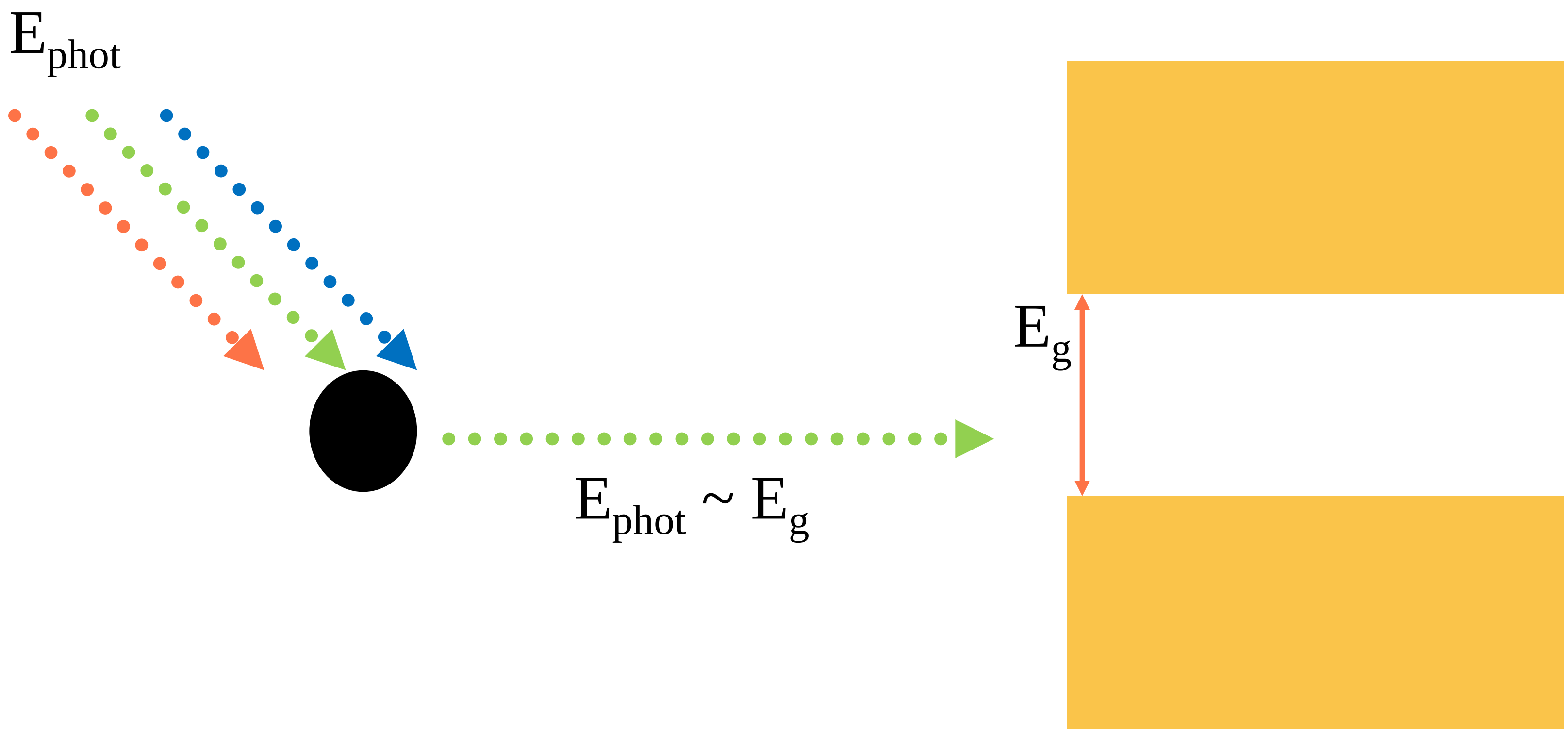


«3rd generation photovoltaics»

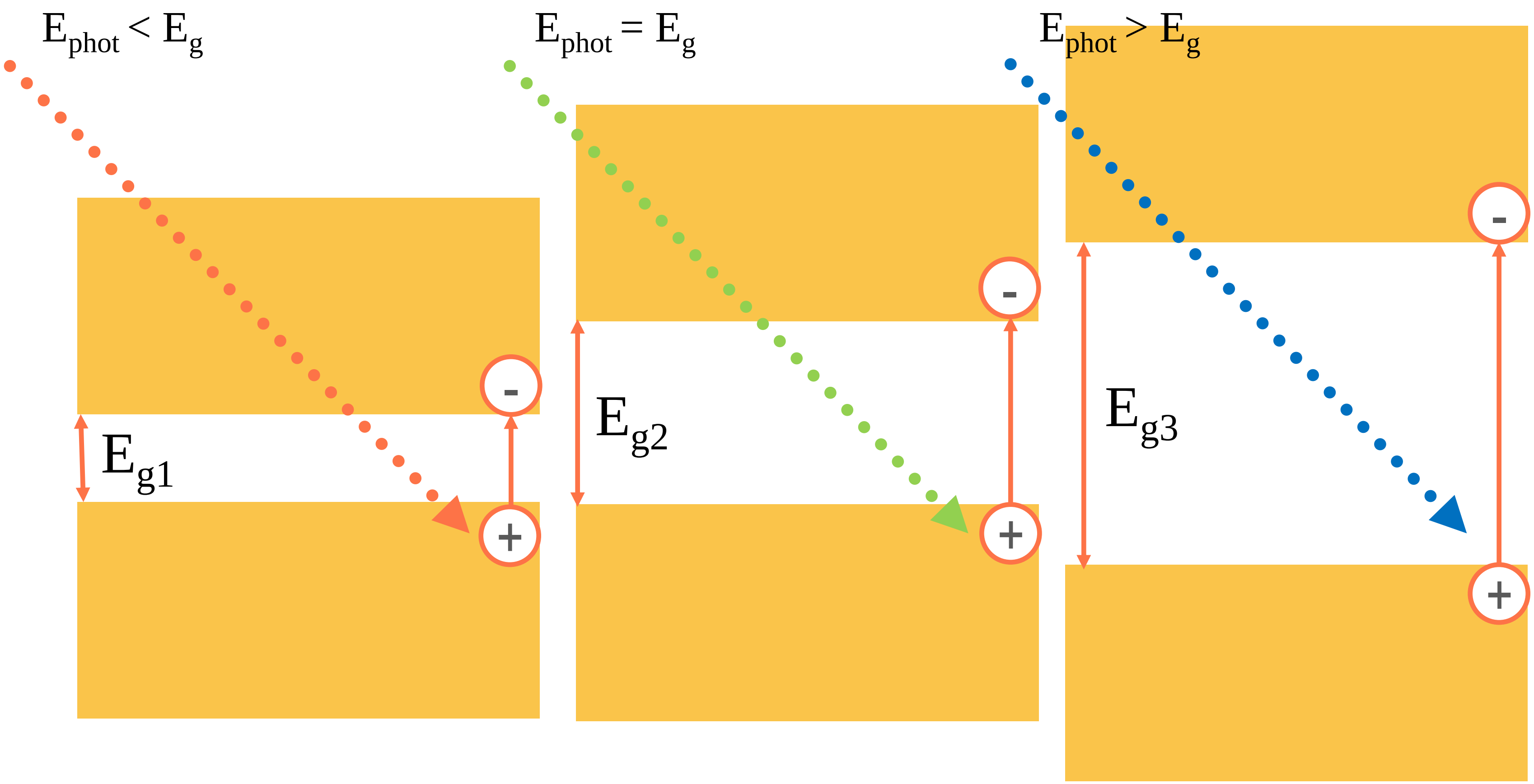
- Useful definition: ”Solar cell concepts that allow for a better utilization of the solar energy than homojunction solar cells”
  - Overcoming the Shockley-Queisser limit

- Three main approaches:
  1. “The solar cell is fine, change the Sunlight instead!”
  2. “One cell for every wavelength!”
  3. “Thermalization is your friend!”

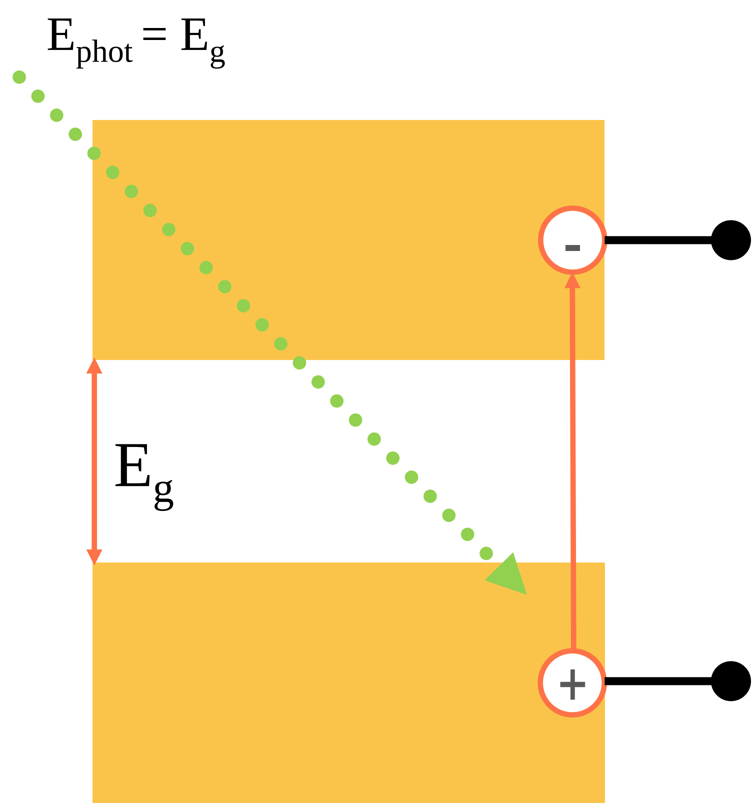
1: Photon energy conversion



2: Multiple band gap solar cells



3: Avoiding thermalization



Theoretical efficiency limits

- Many novel cell concepts allowing for a vastly improved utilization of the photonic energies in the solar spectrum have been proposed
- Theoretical upper efficiencies for these cell concepts have been calculated

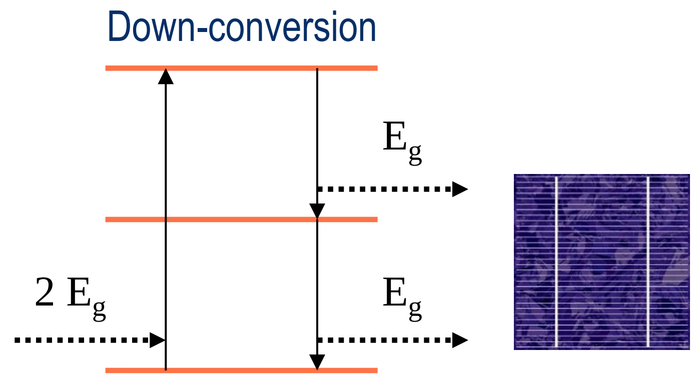
Cell concept	Efficiency (under direct/global irradiation)	Possible realization
Landsberg	93.3%/73.3%	Circulators
Multicolour	86.8%/68.2%	Hot carrier, infinite cell tandem, photon energy conversion, thermo-PV…
Black-body	85.4%/53.6%	
3-level	63.8%/49.3%	3 cell tandem, impurity band …
2-level	55.7%/42.9%	2 cell tandem
Homojunction	40.8%/31.0%	Homojunction
Real cell records	~46%	4 cell tandem

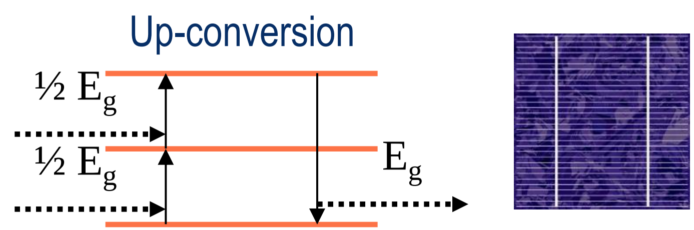
M.A. Green: "Third generation photovoltaics", Springer 2003

Photon energy conversion

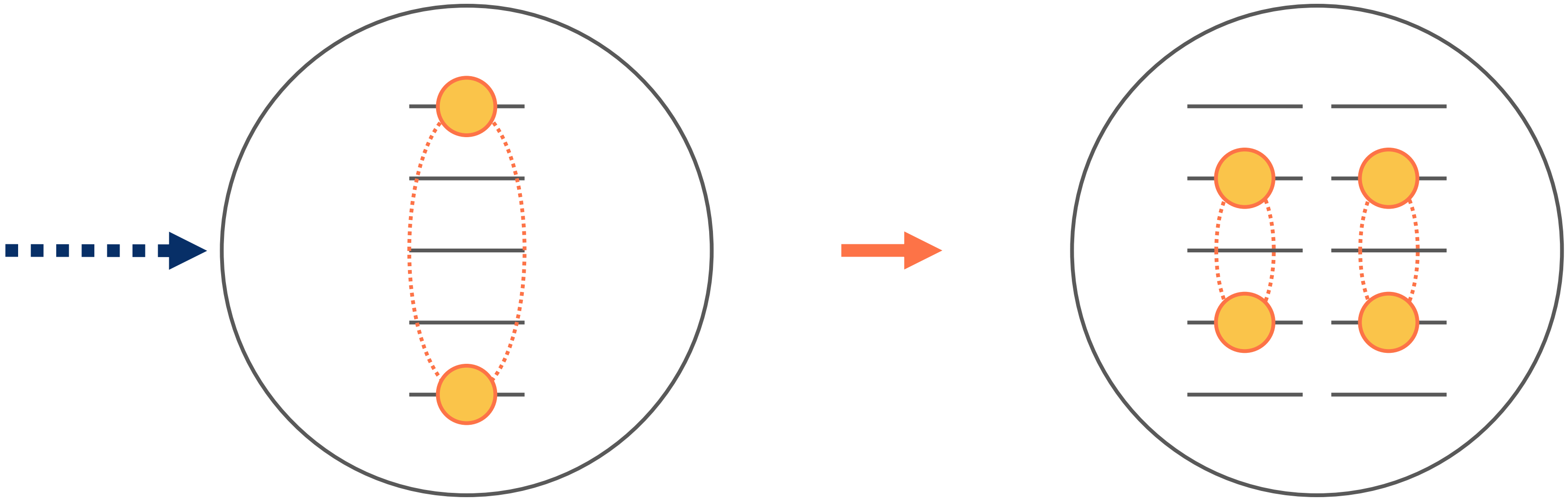
- **Photon energy down-conversion:** one energetic photon creates more than one sufficiently energetic photon.

- **Photon energy up-conversion:** two or more low energetic photons create one sufficiently energetic photon.





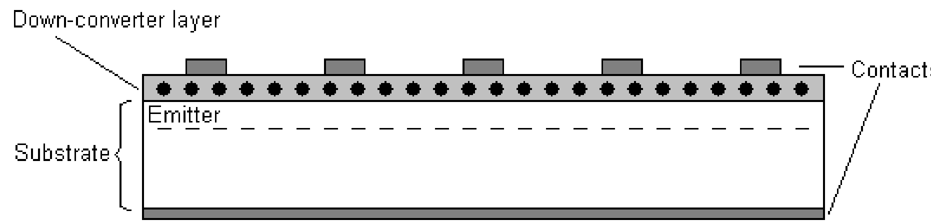
Cool property of nanocrystals: *Multiple exciton generation (MEG)*



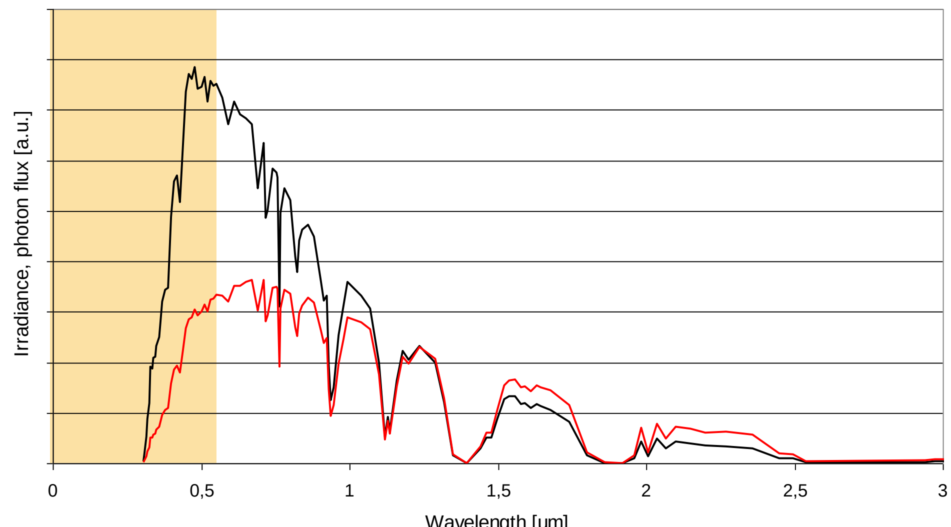
Photon energy down-conversion on Si

- The "**pixie dust**" approach: simply add photon energy down-conversion materials in front of the solar cell
  - Anti-reflection coating
  - Transparent conductive layer
  - Laminates
  - Cover glass
  - Separate layer (plan B)

- Theoretical efficiency on Si: **38.6%**



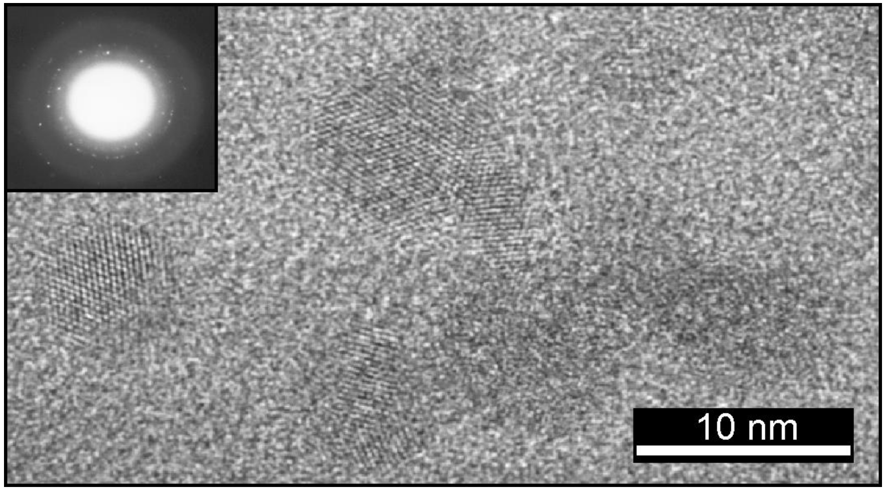
Down-conversion solution for Si solar cell



B.S. Richards et al., Sol. En. Mat. and Sol. Cells 90 (2006) p. 1189

Photon energy conversion materials

- Commonly suggested materials
  - Nanocrystals
  - Rare earth-based phosphors
- Several reports of modest efficiency increases in the scientific literature using both material types
  - ~ 1% absolute
- Positive features
  - Simple implementation possible (?)
  - Can be a linear process ($I_{em} \sim I_{abs}$)
- Drawbacks
  - Possibly disturbing
  - Emission in all directions



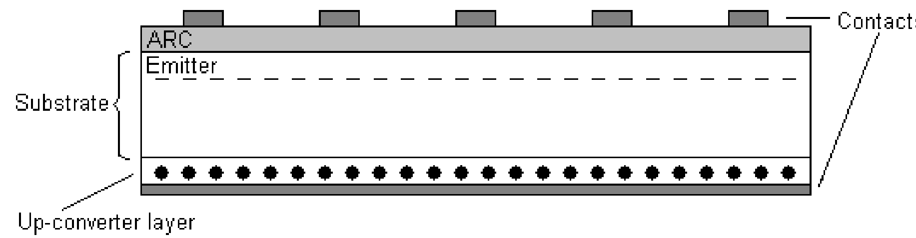
TEM image and SAD pattern of nanocrystalline Ge in SiO_2

Marstein IFE/UiO

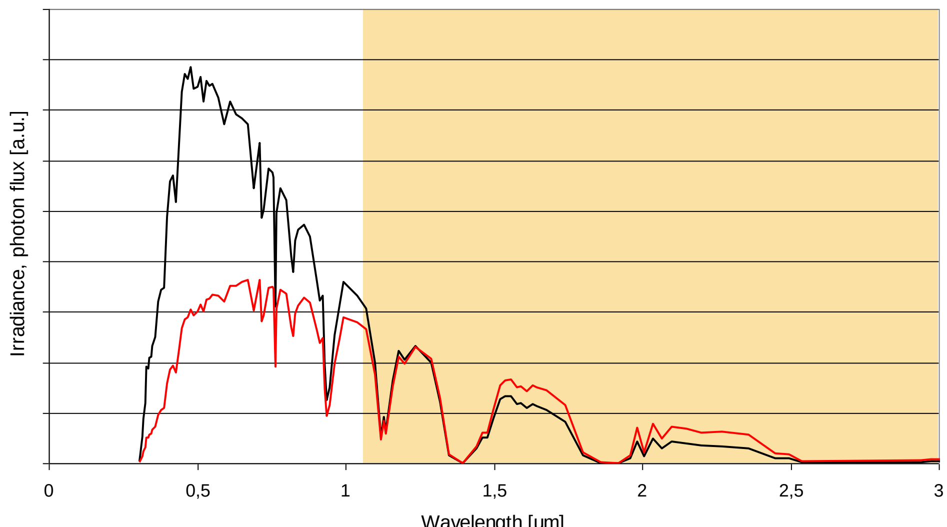
Photon energy up conversion on Si

- Photon energy up-conversion on the rear of the solar cell
  - Surface passivating dielectric
  - Rear side dielectric mirror
  - Separate layer (plan B)

- Theoretical efficiency on Si: **40.2%**

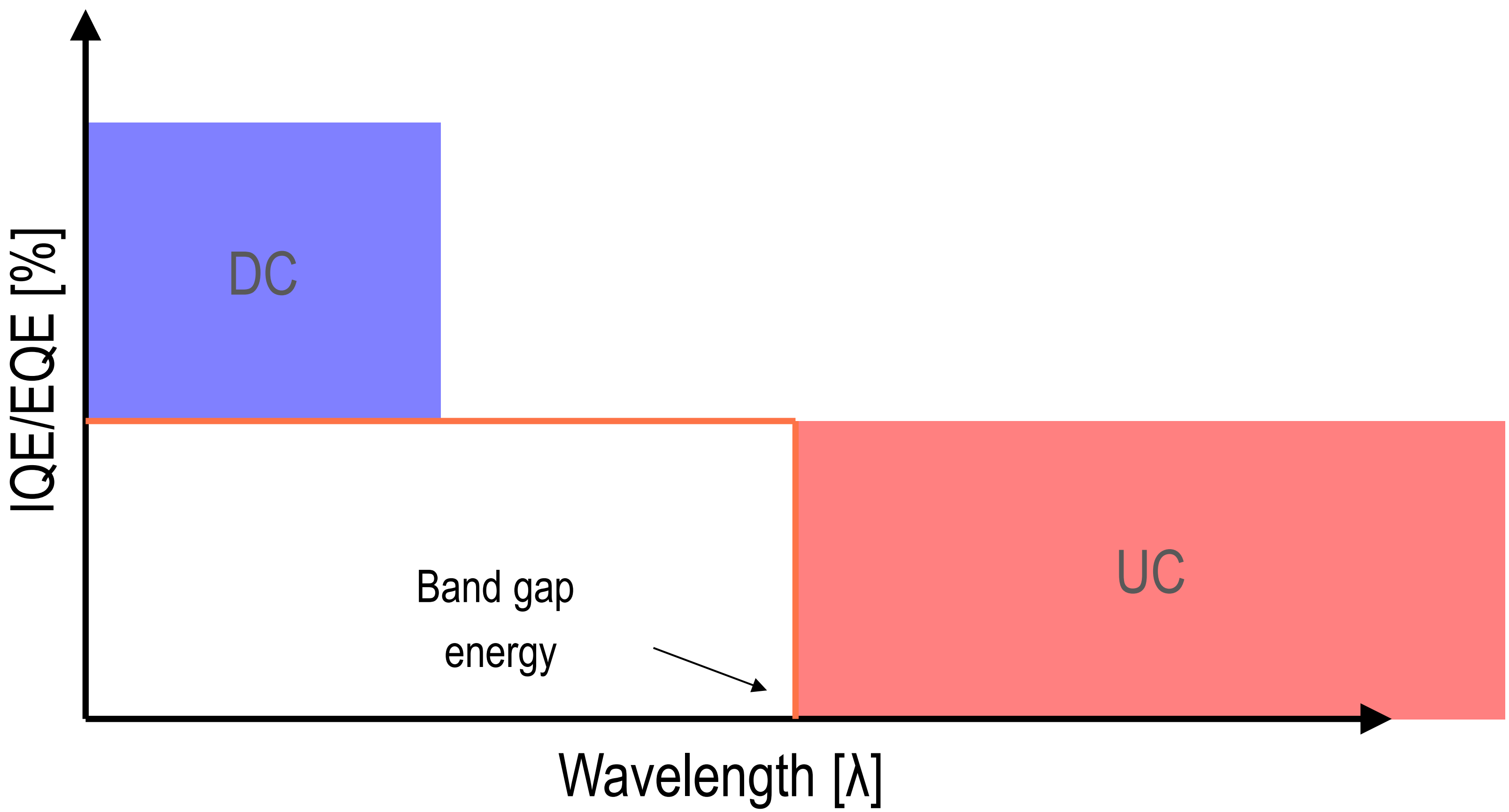


Up-conversion solution for Si solar cell



A Shalav et al, APL 86 (2005) p.013505

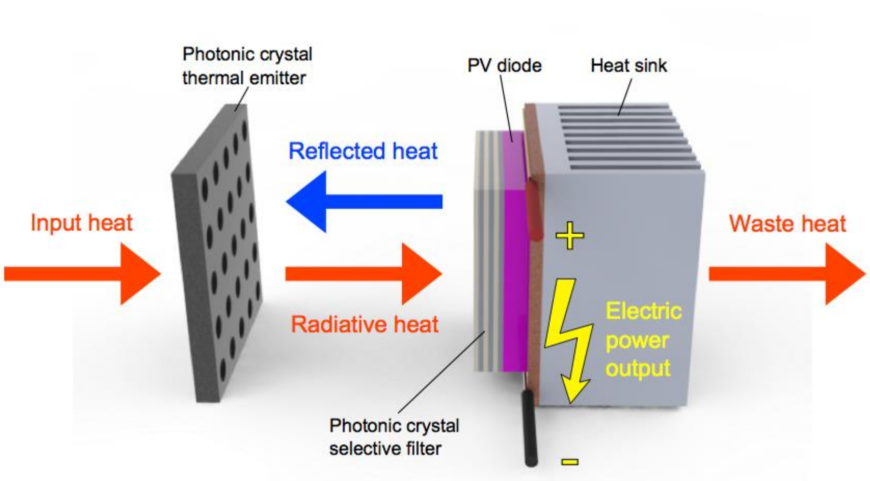
Up- and down conversion (UC/DC)



Alternative: Thermophotovoltaics

Principle of operation:

1. Sunlight heats a layer above cell
2. This layer radiates at a temperature more suited to the band gap of the solar cell beyond



Features

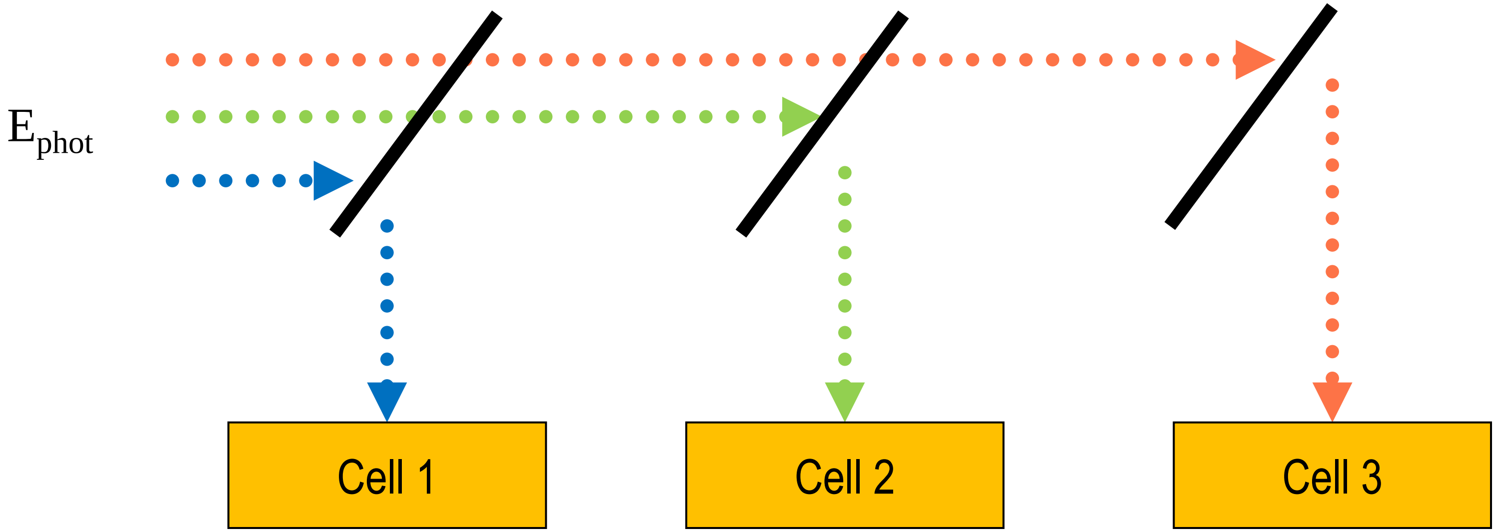
- Fewer high energy photons are generated
- Low energy photons are reflected from the solar cell and “recycled”

MIT (2011)

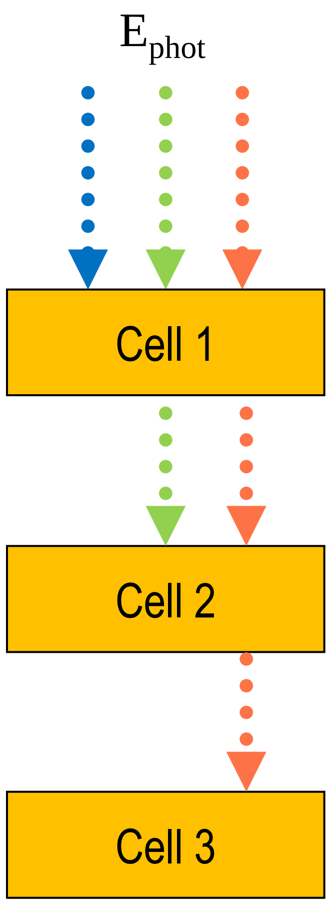
Multiple band gap solar cells

- Multiple band gap solar cells can be realized in a number of ways
  - Tandem solar cells
    - Physical splitting of the solar spectrum onto different solar cells
    - Works in practice!
    - World's most effective solar cell
  - Intermediate band gap solar cells

Multiple band gap solar cells in practice

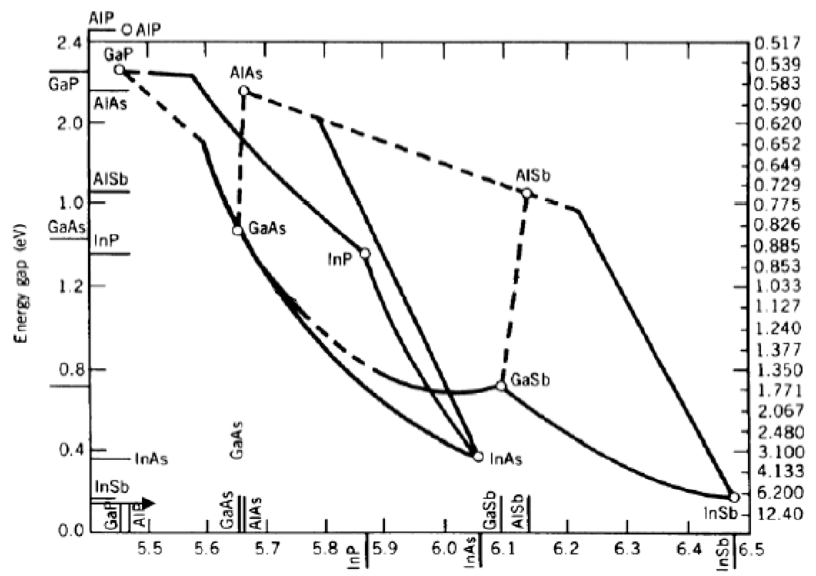


Multiple band gap solar cells in practice

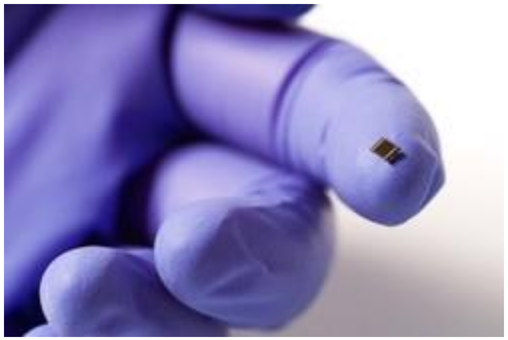


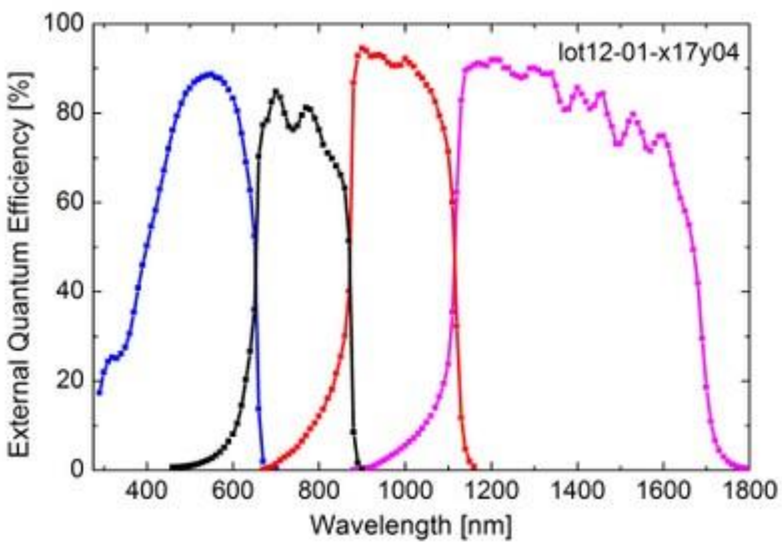
Tandem solar cells

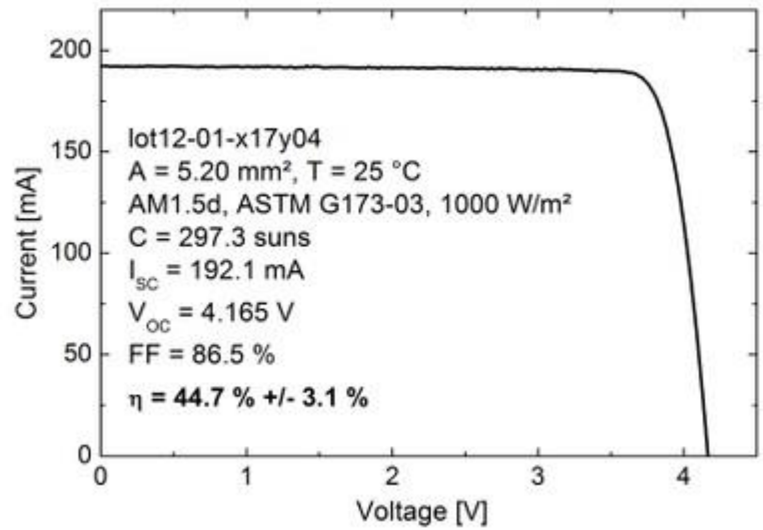
- Considerations
  - Matching of current throughput is essential, since all cells in the tandem stack are series connected
  - Very vulnerable to variations in spectral density, which will distort the current matching
    - Less of a problem in space
  - Often difficult to grow the desired materials on top of each others due to mismatched lattice constants.
- Many realizations:
  - GaAs technology, a-Si:H technology, possible dye sensitized solar cells



Tandem

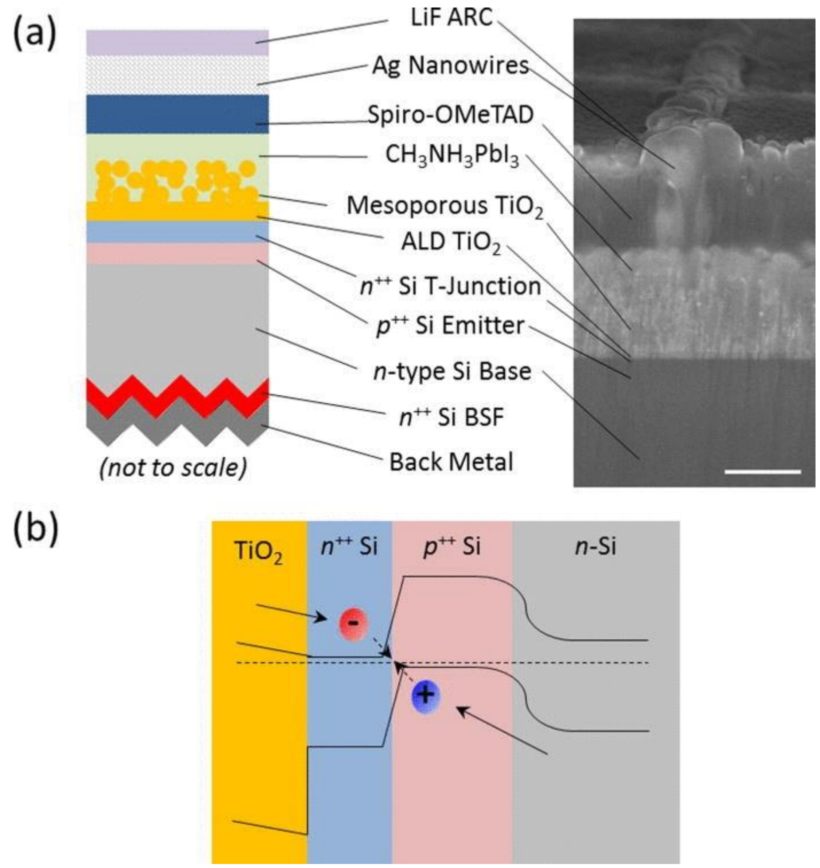






FhG ISE (2014)

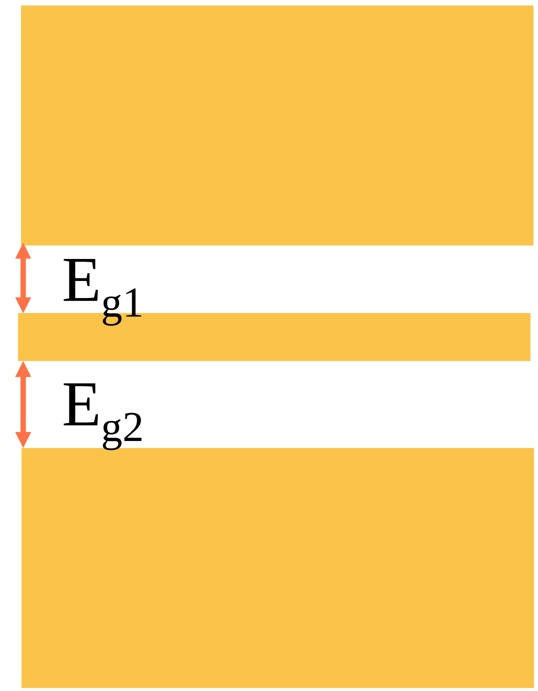
Silicon-perovskite tandem



MIT/Stanford. (2015)

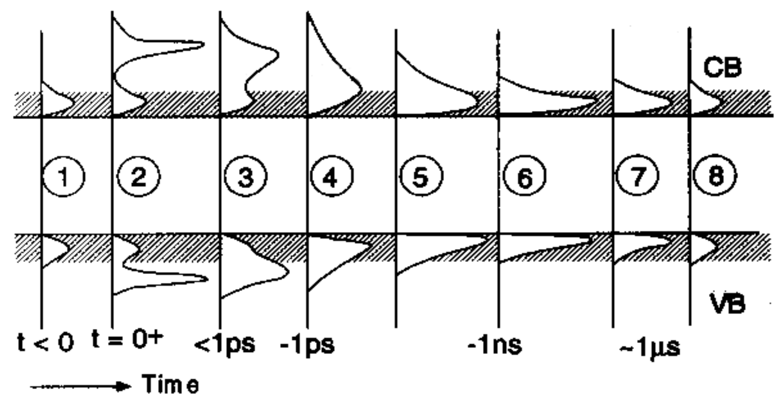
Intermediate band gap solar cells

- Several electronic band gaps can be realized in one material, at least in theory
- Possible realizations
  - Impurity bands
  - Superlattice of quantum structures
- Considerations
  - Can such materials be synthesized on an industrial scale?
  - Can strong recombination through intermediate band(s) be avoided?



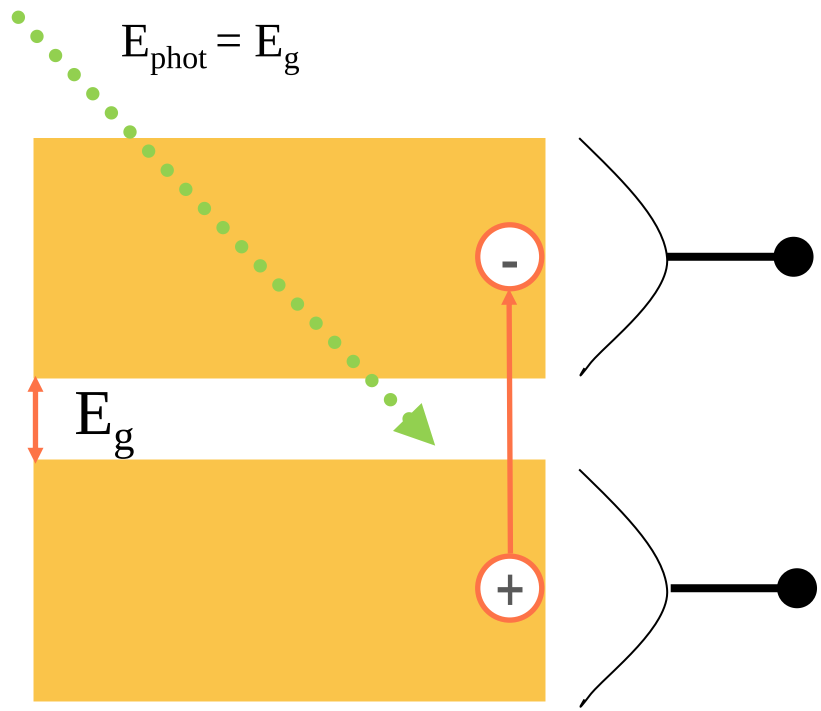
How to avoid (or gain from) thermalization?

- Collect energetic ("hot") charge carriers before significant thermalization occurs
  - Hot carrier solar cells
- Use materials wherein hot carriers collide and subsequently ionize atoms, increasing the number of charge carriers
  - Impact ionization solar cells



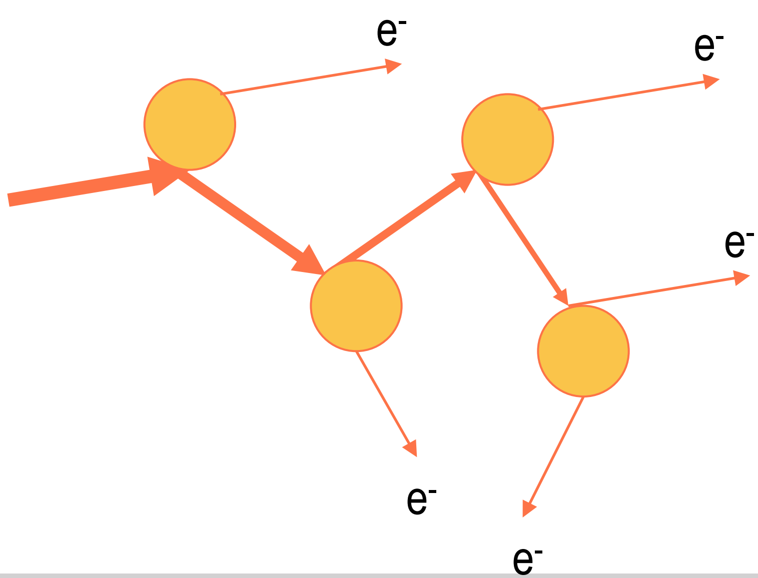
Hot carrier solar cells

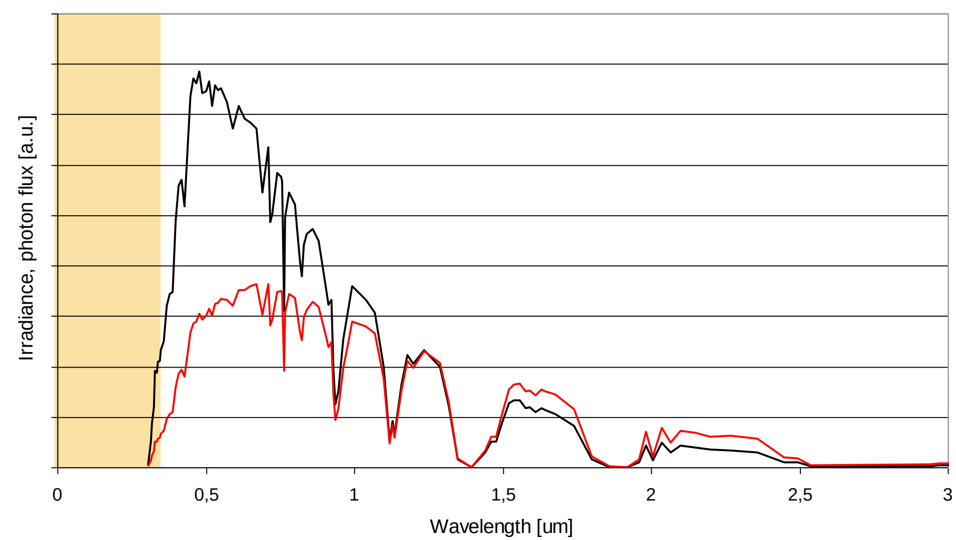
- Use **selective contacts** to collect only carriers well above the energy band edge
  - Higher voltages obtainable
  - Possible realization of contacts: quantum structures with narrow allowable energies
- Additional benefit: this allows for the use of materials with a smaller band gap, resulting in reduced losses from low energy photons
- Considerations
  - Can this be done in industrial cells?



Impact ionization

- Impact ionization of little use in Si solar cells
  - Treshold energy: 3.5 E_g (3.9 eV ~ 315 nm)
  - Quantum yield (QY): 1.4 at 4.5 E_g (5.0 eV ~ 250 nm)





Conclusion

- There is much to gain from substantial increases in solar cell efficiency
- Solar cell efficiencies well in excess of the Shockley-Queisser limit are obtainable, at least in theory, using various 3rd generation solar cell concepts
- Currently, the only really functioning 3rd generation solar cells are tandem solar cells
- However, the physics of these concepts is beautiful…