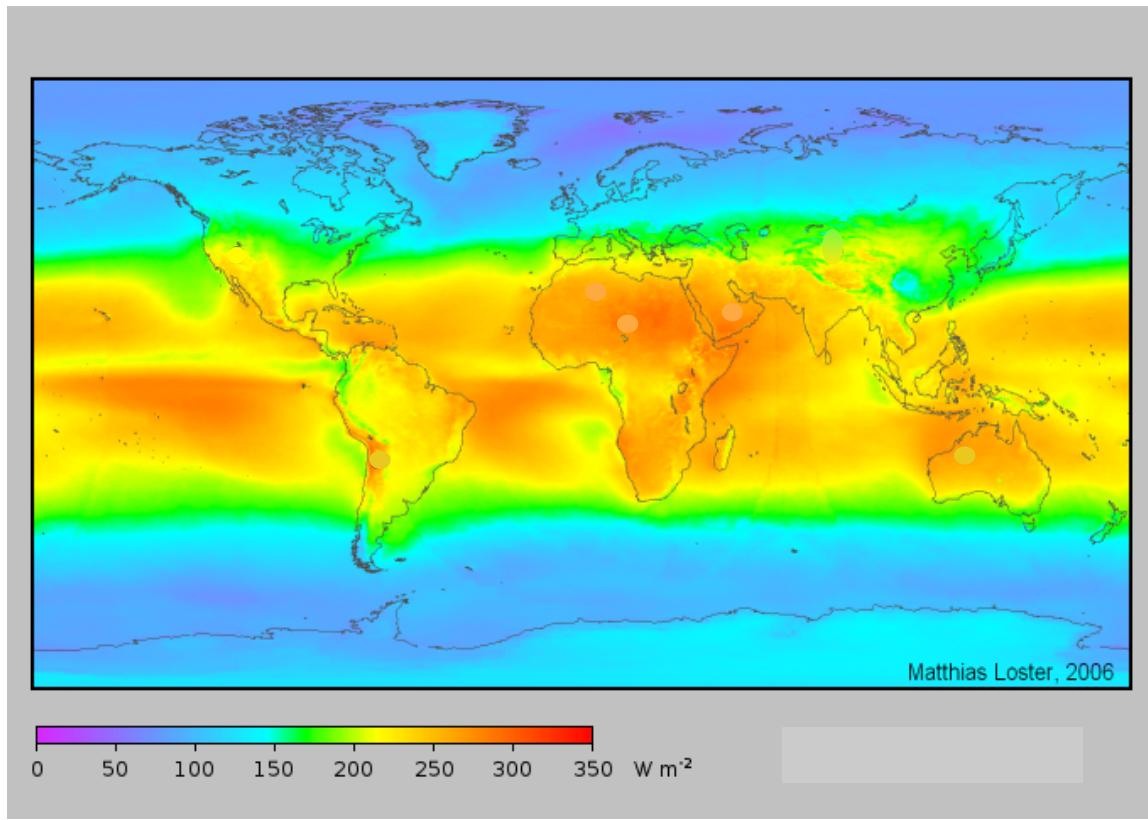


Albert Polman

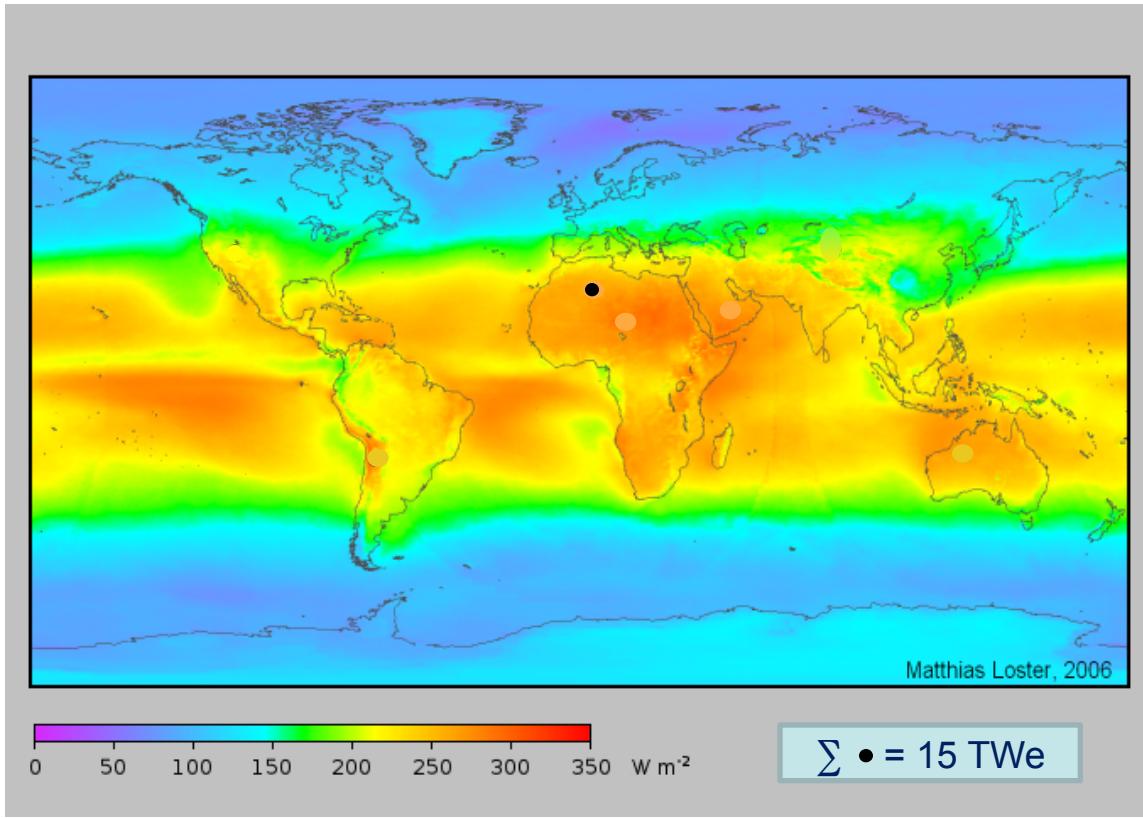
FOM Institute AMOLF

Photovoltaic solar energy conversion

Solar irradiance on earth

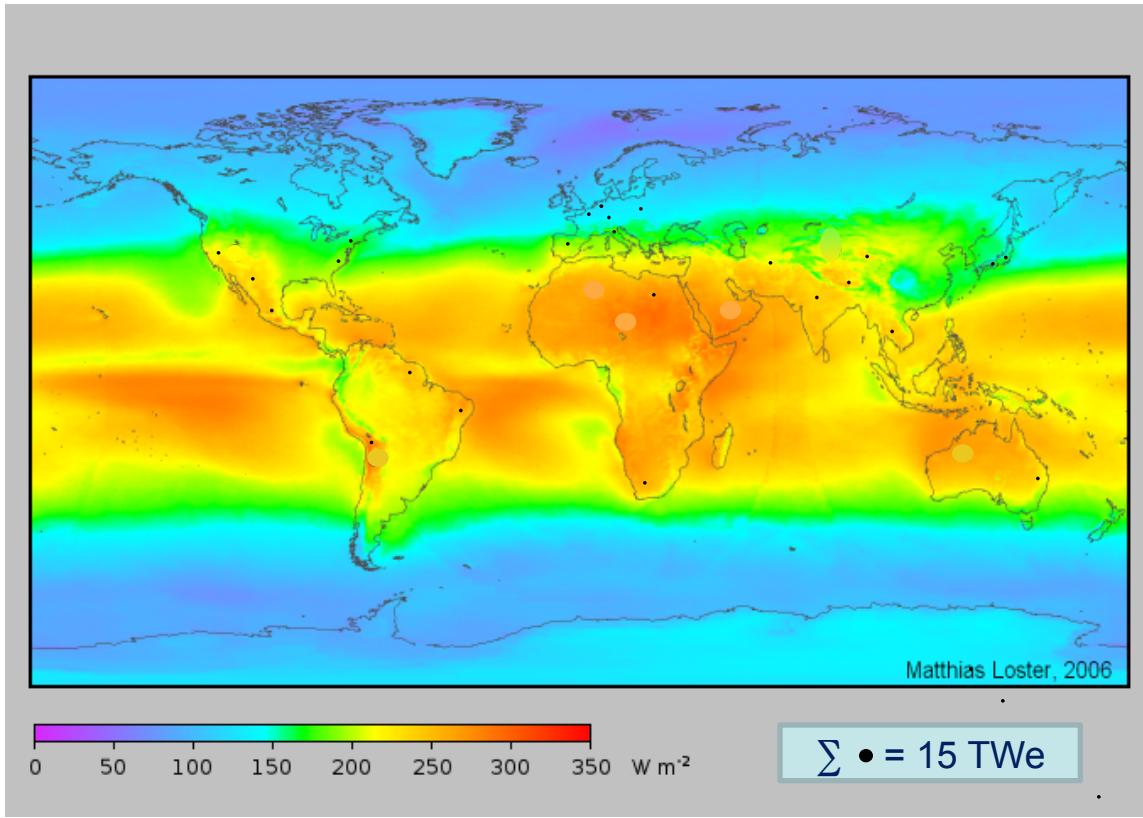


Solar irradiance on earth



Black dot:
area of solar
panels needed
to generate all
of the worlds
primary energy
(all energy consumed:
electricity, heat, fossil
fuels)

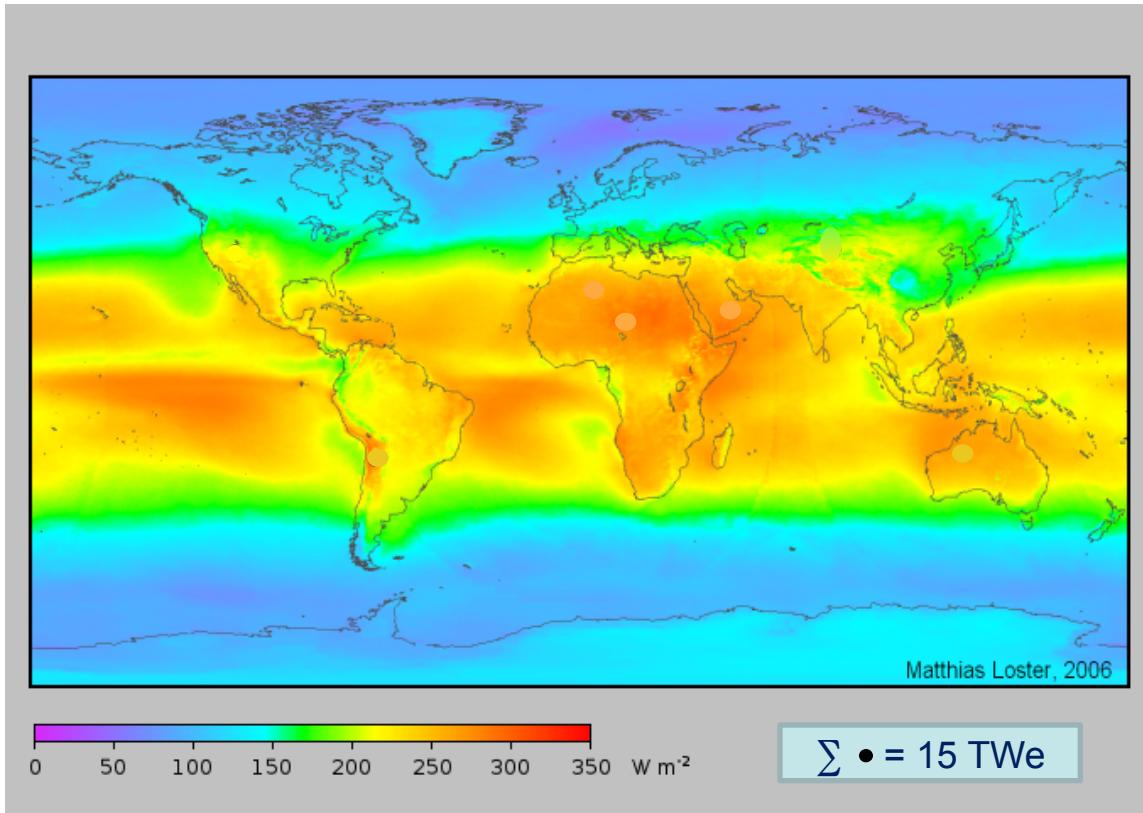
Solar irradiance on earth



assuming 30 %
efficient solar panels

20 black dots:
area of solar
panels needed
to generate all
of the worlds
primary energy
(all energy consumed:
electricity, heat, fossil
fuels)

Solar irradiance on earth



assuming 30 %
efficient solar panels

1000 black dots:
area of solar
panels needed
to generate all
of the worlds
primary energy
(all energy consumed:
electricity, heat, fossil
fuels)

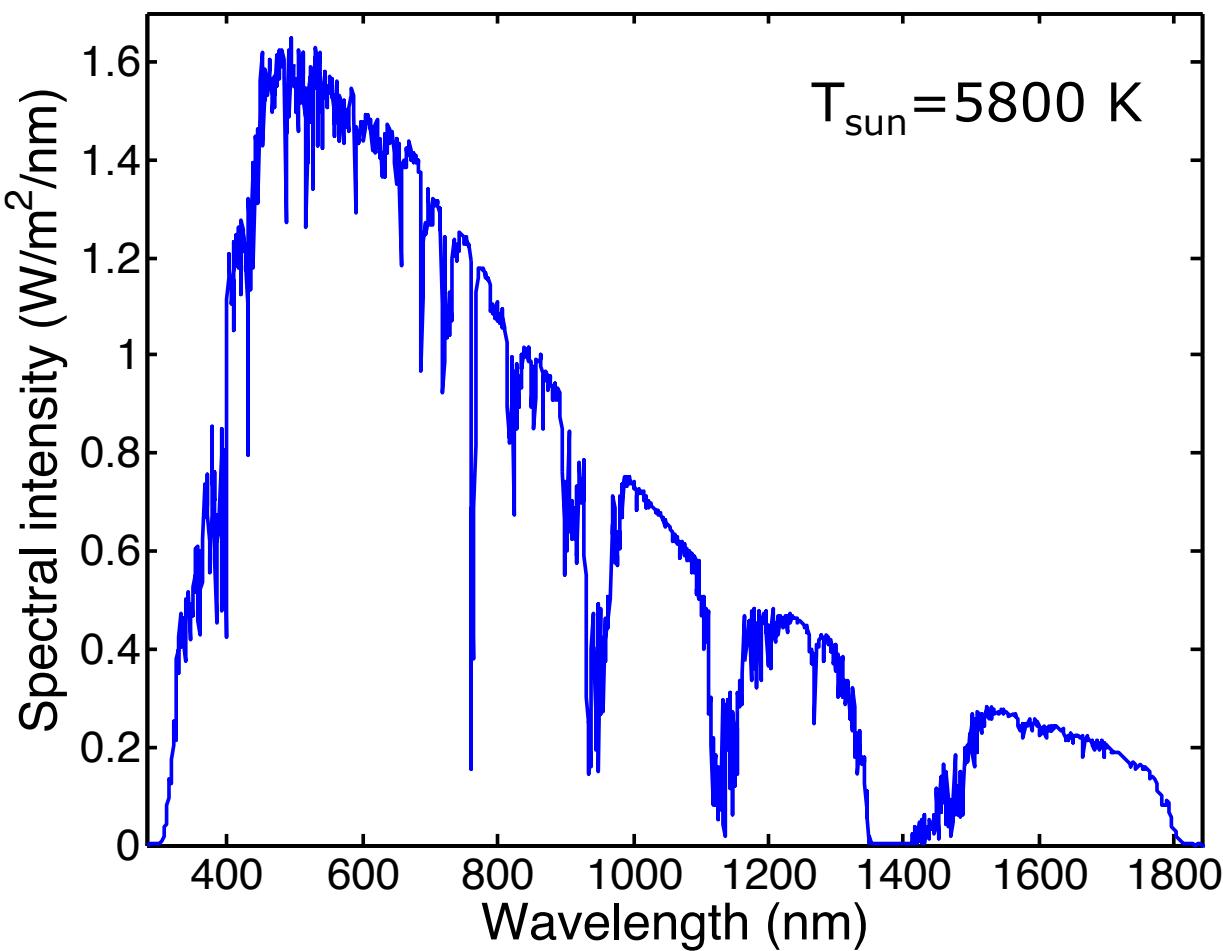
Needed:
1) Lower costs
2) Higher efficiency



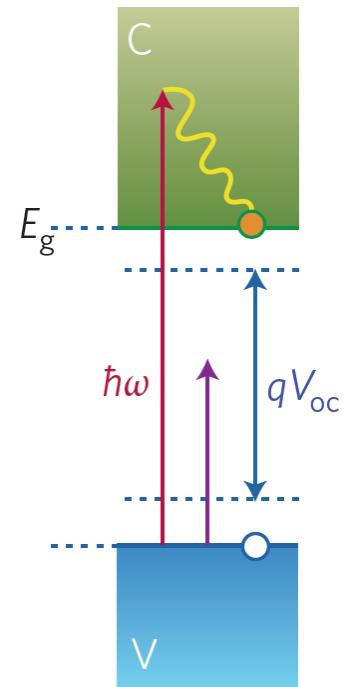
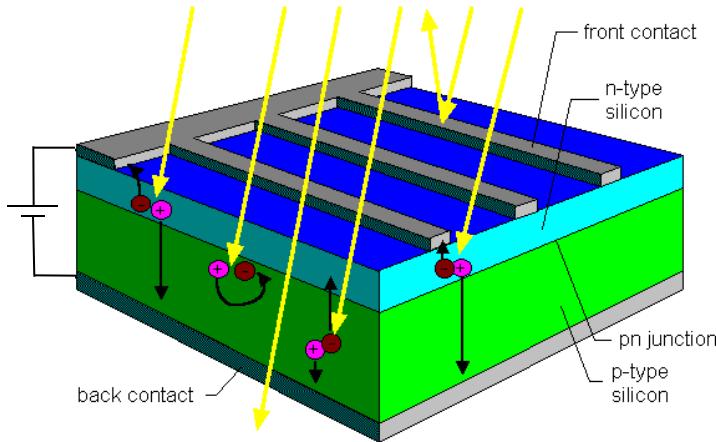
Earth

The solar spectrum

1000 W/m²

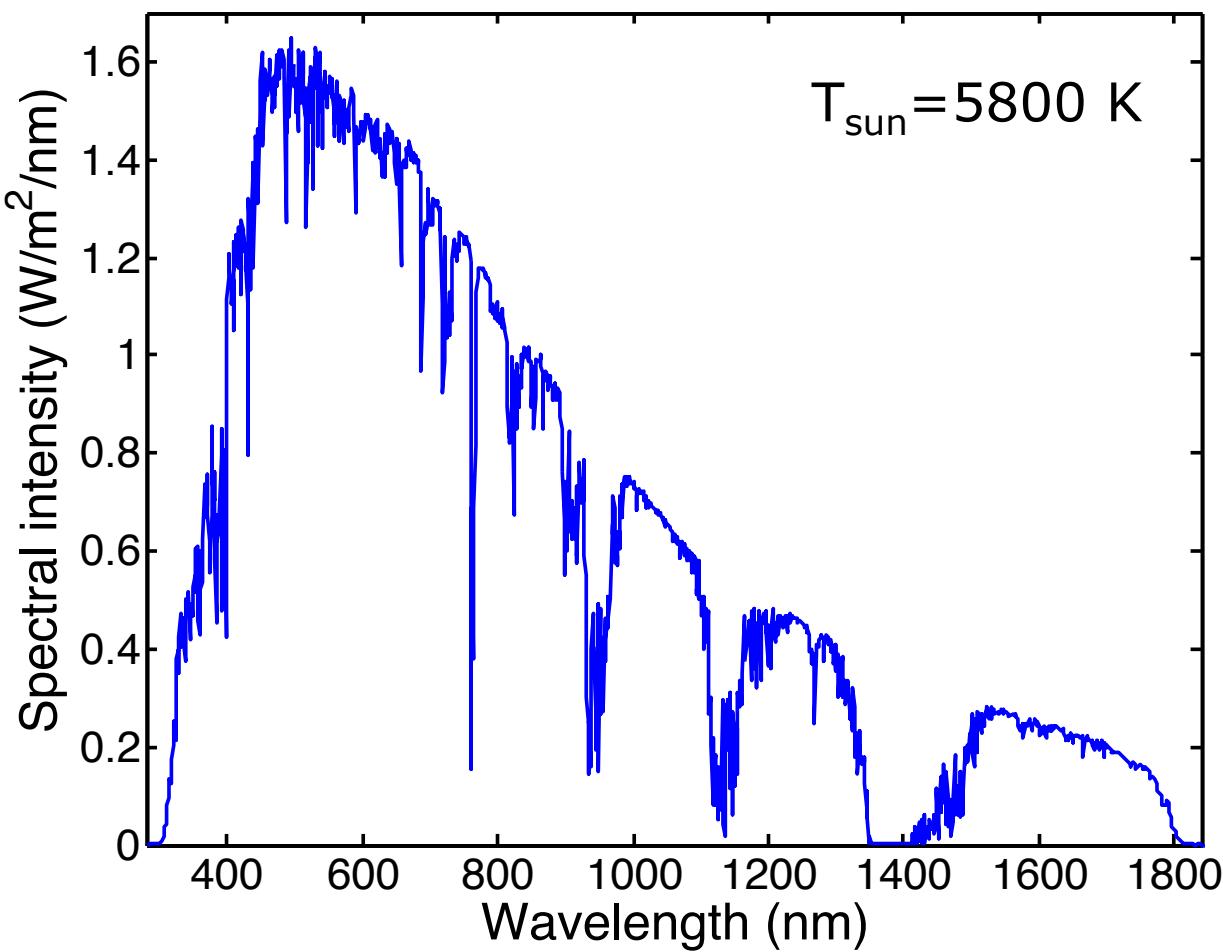


Solar cell basic design

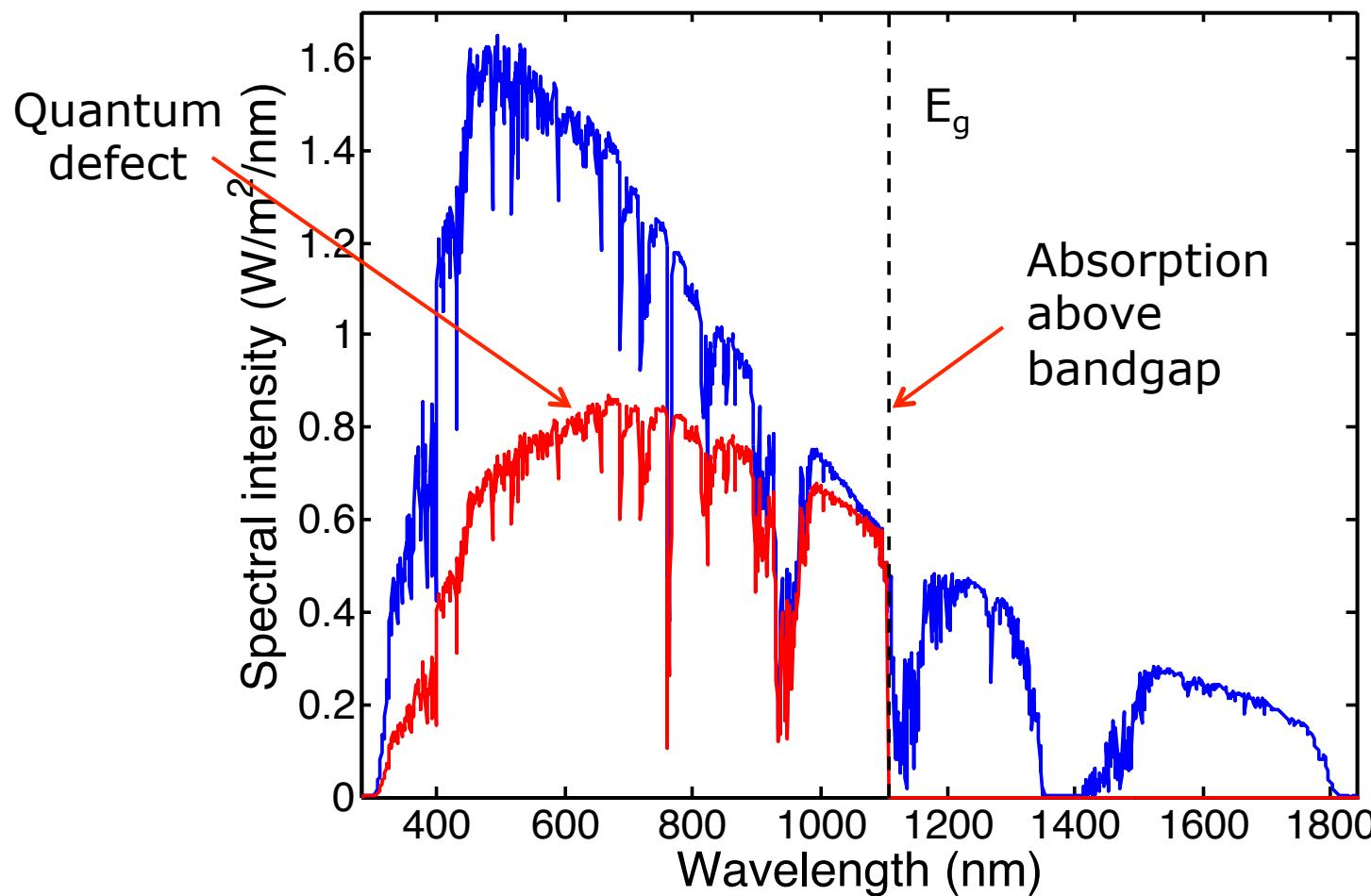


The solar spectrum

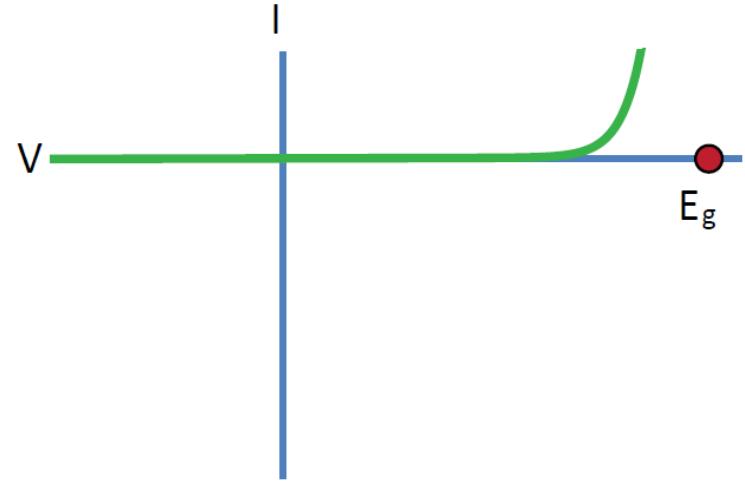
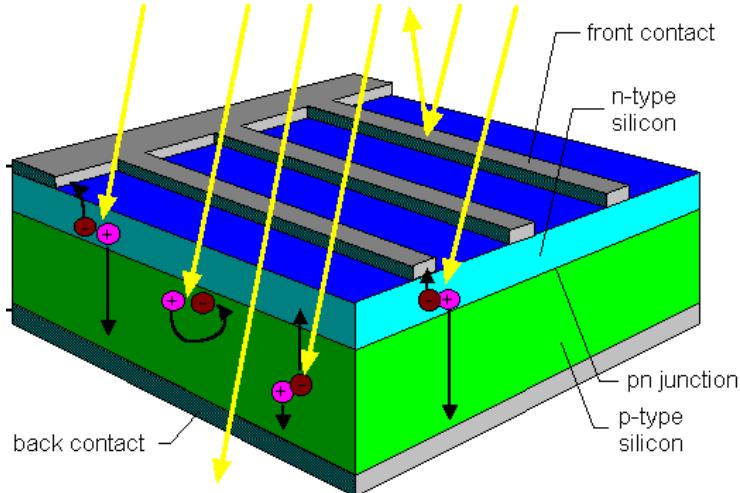
1000 W/m²



Absorption edge and quantum defect

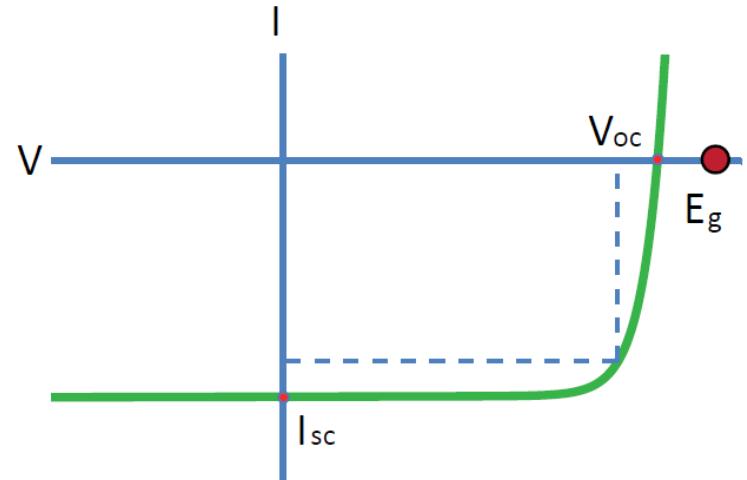
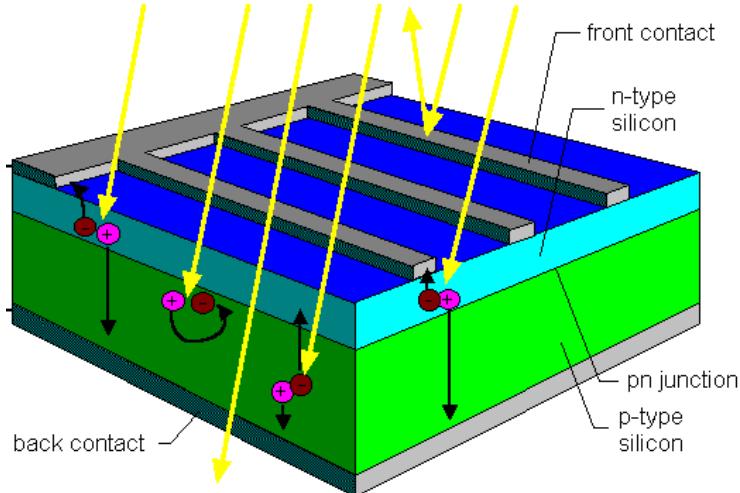


Voltage is lower than bandgap energy



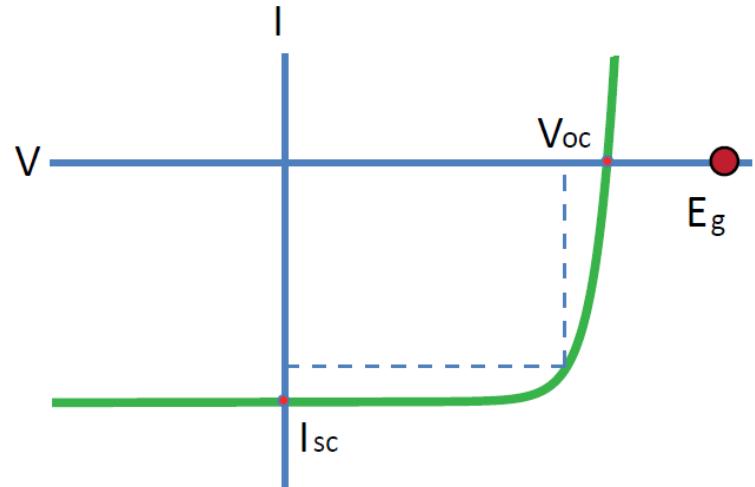
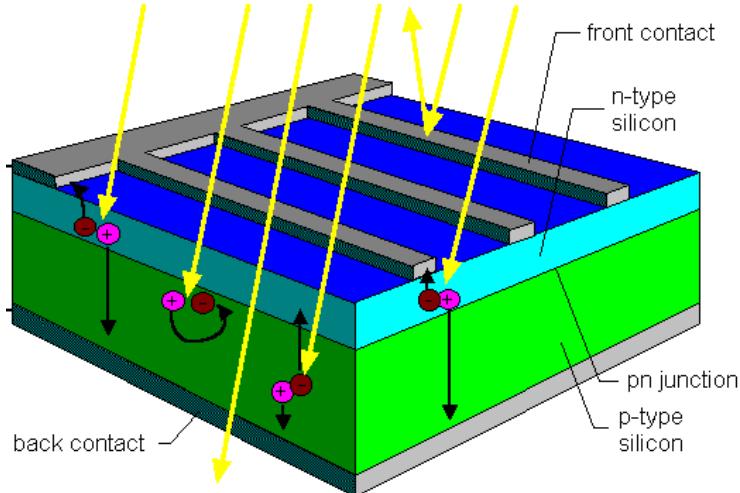
$$I_{\text{ext}} = I_0 \exp(V/kT)$$

Voltage is lower than bandgap energy



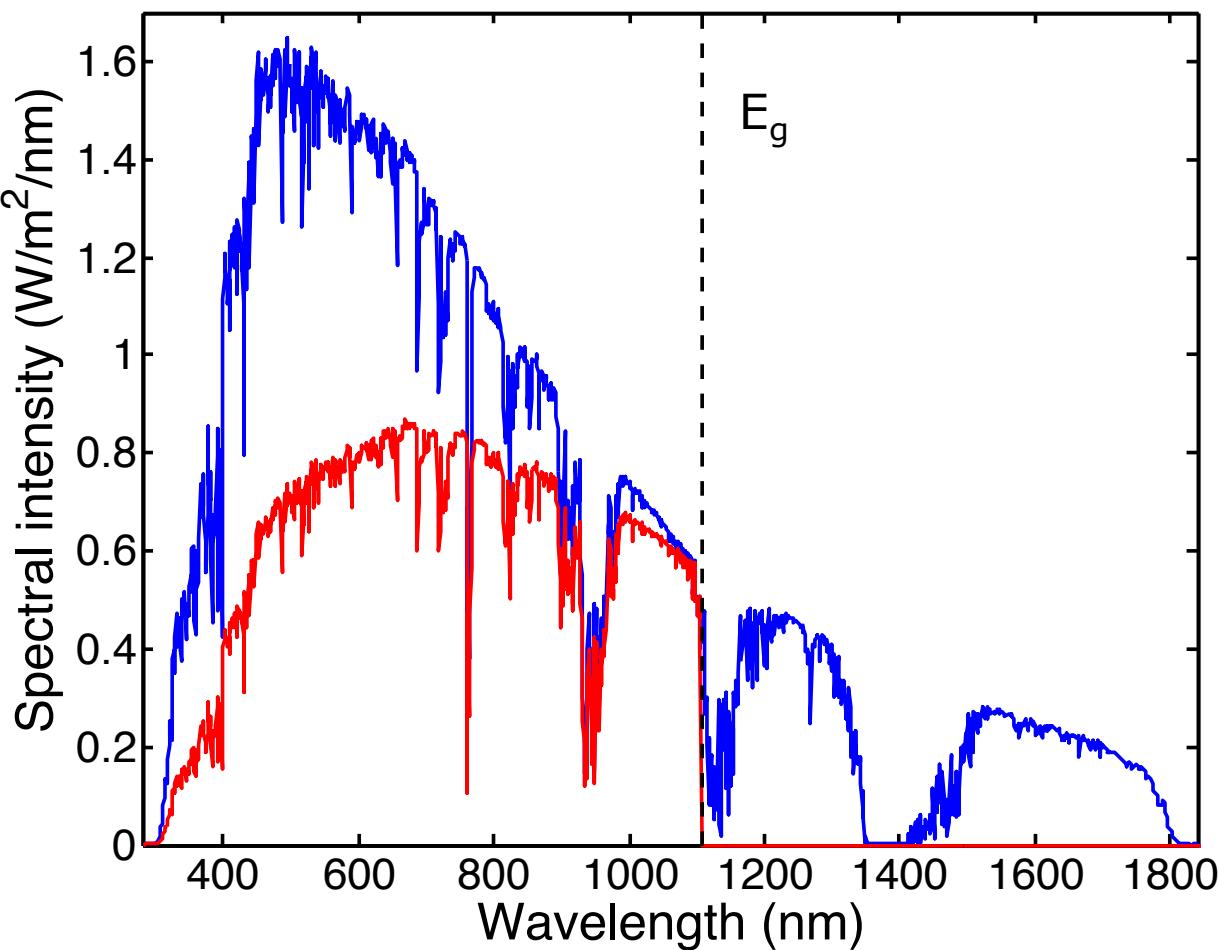
$$I_{ext} = I_0 \exp(V/kT) - I_{SC}$$

Voltage is lower than bandgap energy

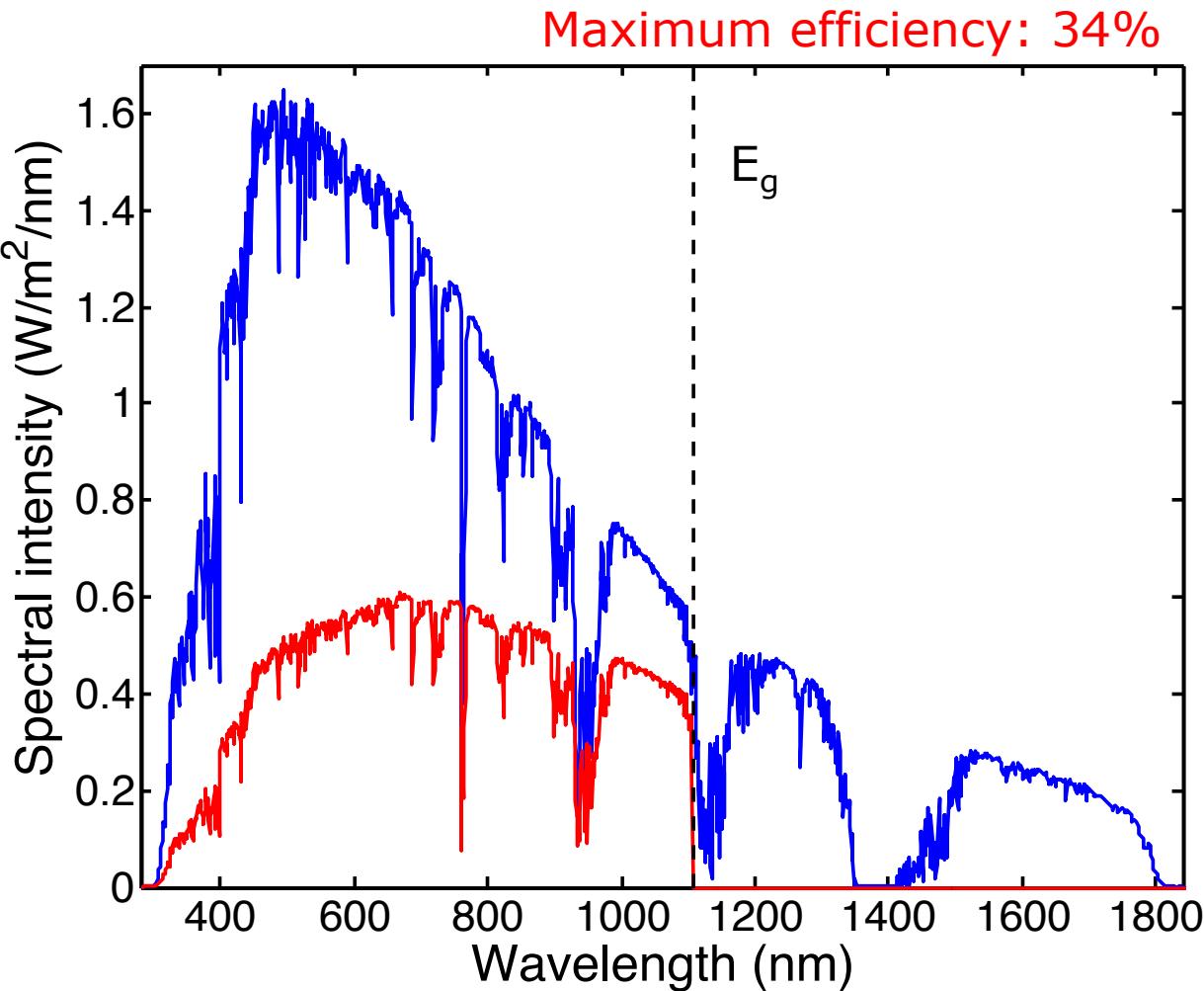


$$I_{ext} = I_0 \exp(V/kT) - I_{SC}$$

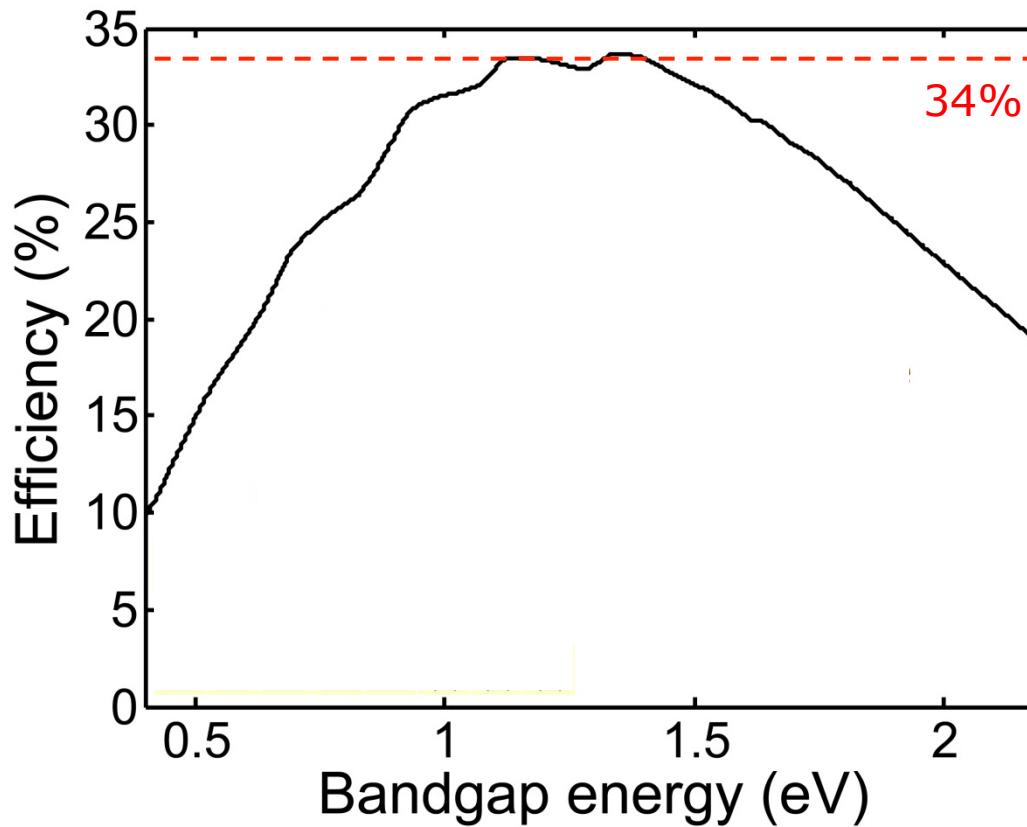
Voltage is lower than bandgap energy



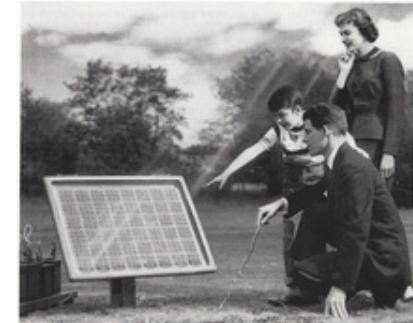
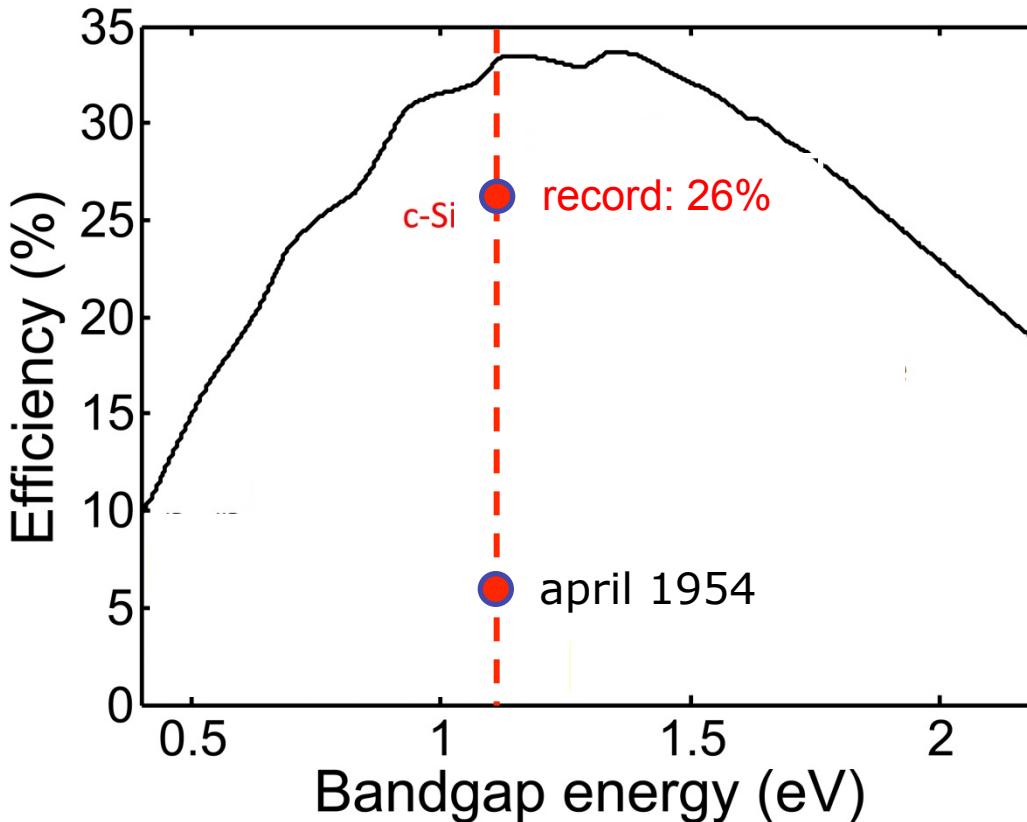
Voltage is lower than bandgap energy



Shockley-Queisser efficiency limit: 34%



Silicon is ideal: SQ limit = 33 %



Something New Under the Sun. It's the Bell Solar Battery, made of thin discs of specially treated silicon, an ingredient of common sand. It converts the sun's rays directly into usable amounts of electricity. Simple and trouble-free. (The storage battery behind the solar battery stores up its electricity for night use.)

Bell System Solar Battery Converts Sun's Rays into Electricity!

Bell Telephone Laboratories invention has great possibilities for telephone service and for all mankind.

Ever since Archimedes, men have been searching for the secret of the sun.

For it is known that these same kindly rays that help the flowers and the grains and the fruits to grow also send us almost limitless power. In the past, however, it was believed that all known reserves of coal, oil and uranium,

If this energy could be put to use — there would be enough to turn every wheel and light every lamp that mankind could ever need.

The time of ages has been brought closer by the Bell System Solar Battery. It was born from the desire of man to put the energy of the sun to practical use.

BELL TELEPHONE SYSTEM

The silicon solar cell turned 60 !



April 25, 1954

New York Times: *the beginning of a new era, leading eventually to the realization of one of mankind's most cherished dreams – the harnessing of the almost limitless energy of the sun for the uses of civilization*

Bell Telephone Laboratories invention has great possibilities for telephone service and for all mankind

Ever since Archimedes, men have been searching for the secret of the sun. For it is known that the same kindly rays that help the flowers and the grains and the fruits to grow also send us almost limitless power. It is nearly as much every three days as in all known reserves of coal, oil and uranium. If this energy could be put to use — there would be enough to turn every wheel and light every lamp that mankind would ever need. The dream of ages has been brought closer by the Bell System Solar Battery. It was invented at the Bell Telephone Laboratories after long research and first announced in 1954. Since then its efficiency has been doubled and its usefulness extended.

There's still much to be done before the battery's possibilities in telephony and for other uses are fully developed. But a good and pioneering start has been made.

The progress so far is like the opening of a door through which we can glimpse exciting new things for the future. Great benefits for telephone users and for all mankind may come from this forward step in putting the energy of the sun to practical use.

BELL TELEPHONE SYSTEM 

The first practical solar cell
Si: 6 % efficiency

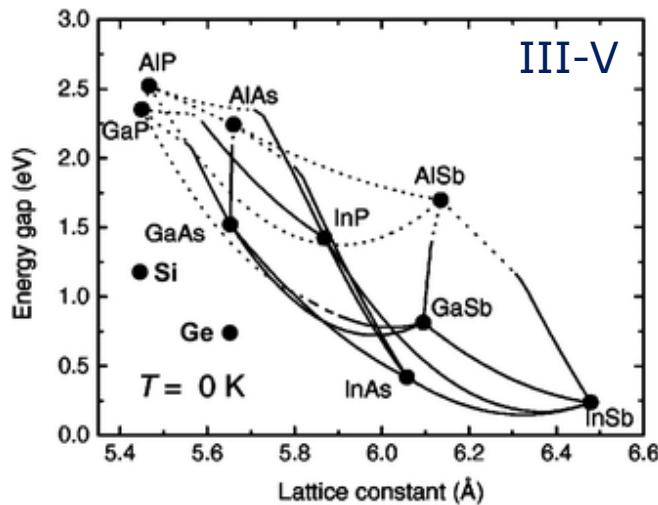
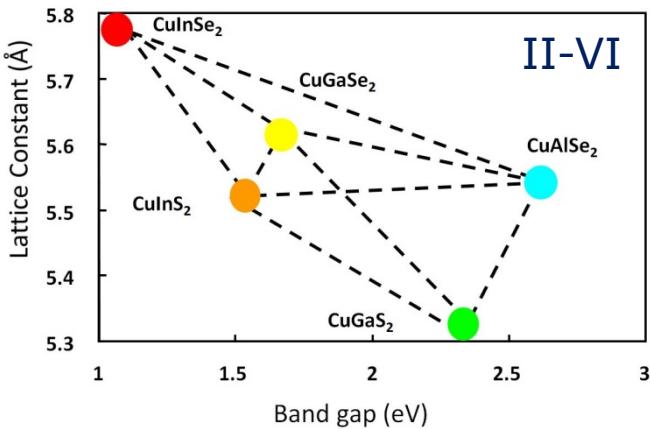
Vanguard satellite 1958



2014



Periodic Table of solar elements



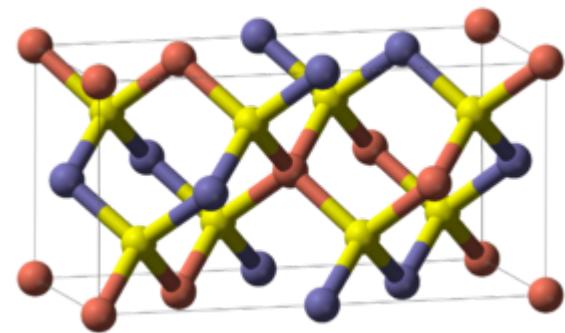
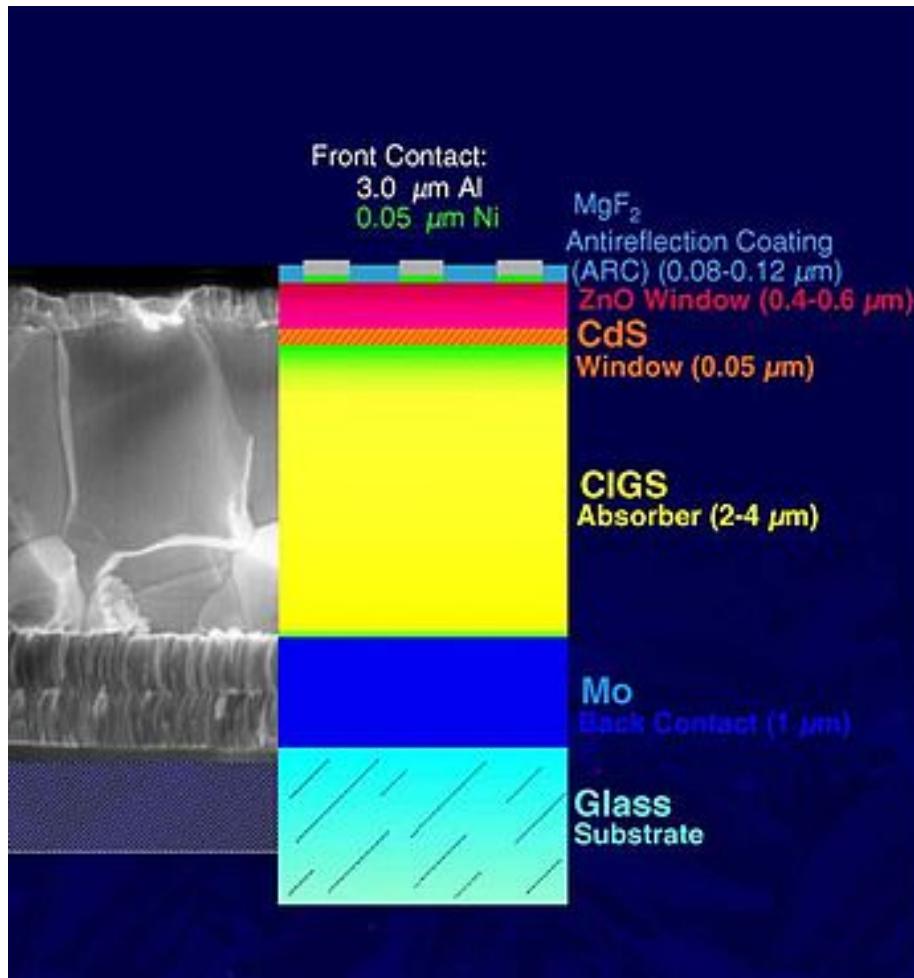
Periodic Table of elements:

						VIIIA	
						² He 4.003	
						Ne 20.183	
						Ar 39.948	
						Cl 35.453	
						Br 79.909	Kr 83.80
						Se 78.96	Xe 131.30
						Te 127.60	Rn (222)
						I 126.904	
						Po (210)	
						At (210)	
						Au 196.967	
						Hg 200.59	
						Tl 204.37	
						Pb 207.19	
						Bi 208.980	

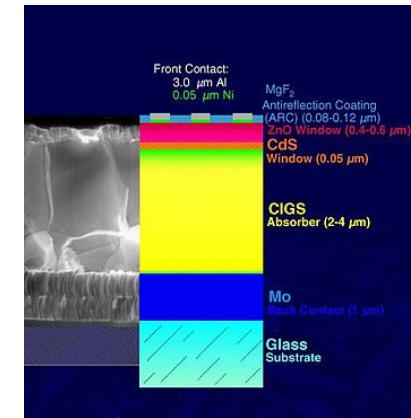
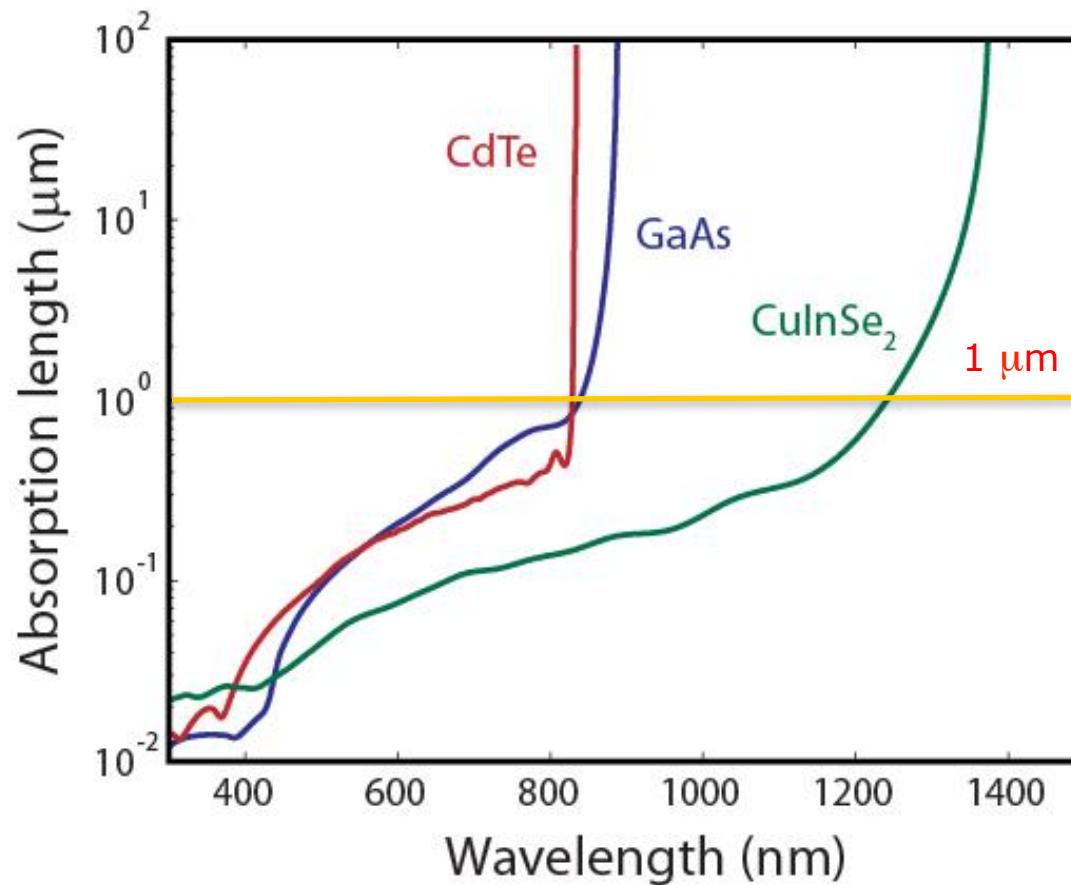
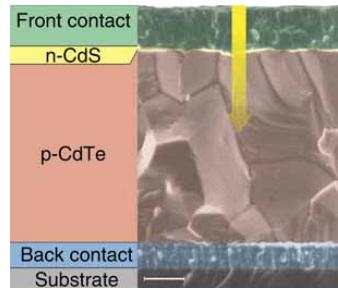
Detailed data for the highlighted element Si:

Element	Symbol	Atomic Number	Atomic Mass (g/mol)
Silicon	Si	14	28.086

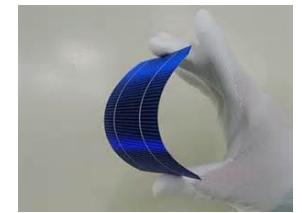
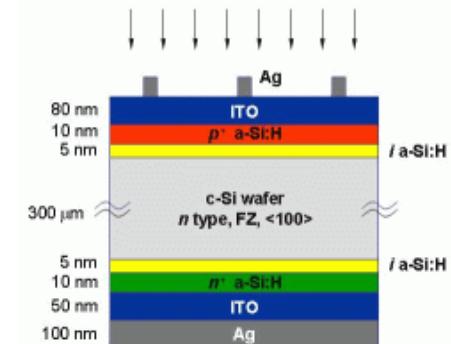
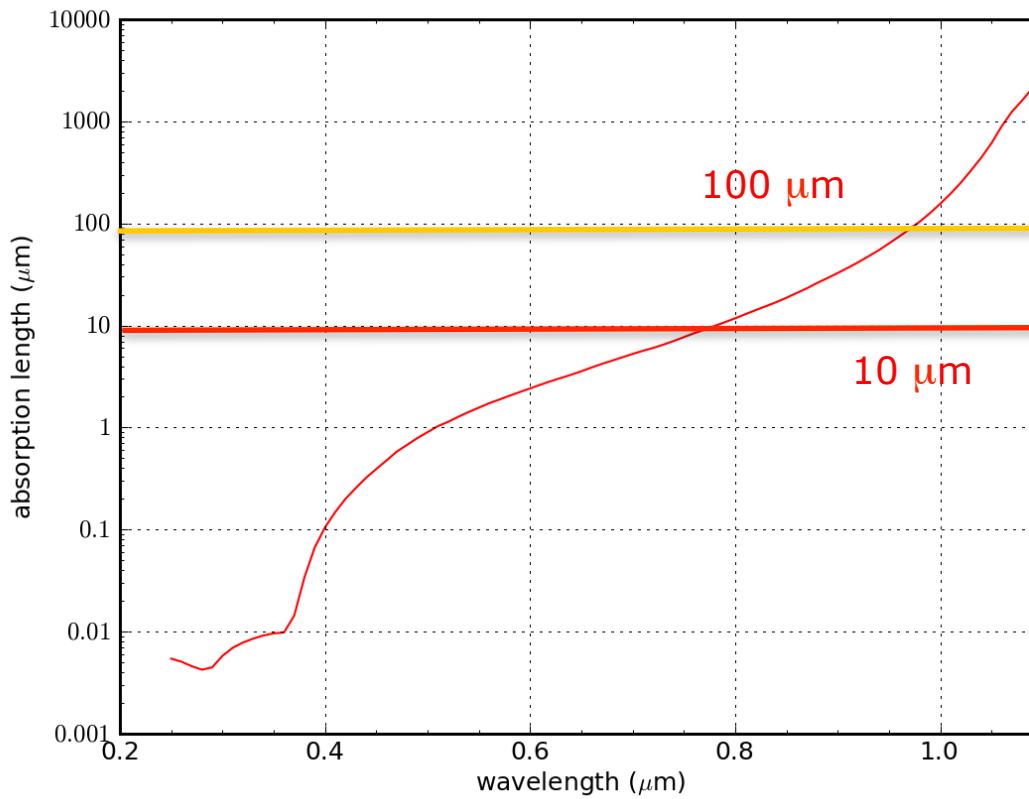
$\text{CuIn}_x\text{Ga}_{(1-x)}\text{Se}_2$ (CIGS) cells: 20.8%



Absorption length in compound semiconductors



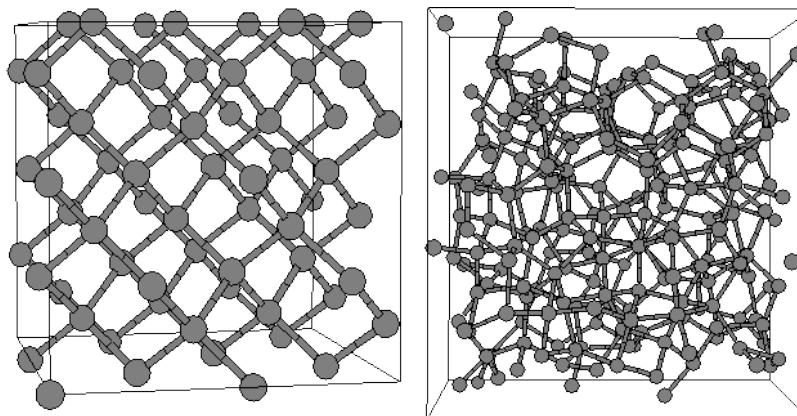
Absorption length in silicon



Si solar cell efficiencies

Material	Thickness	Efficiency	Source
Monocrystalline Si	260 µm	25.6 %	Panasonic (Jap)
Polycrystalline Si	99 µm	20.4 %	FhG-ISI (Ger)
Nanocrystalline Si	2 µm	10.1 %	Kaneka (Jap)
Amorphous Si	300 nm	10.1 %	Oerlikon (Swi)

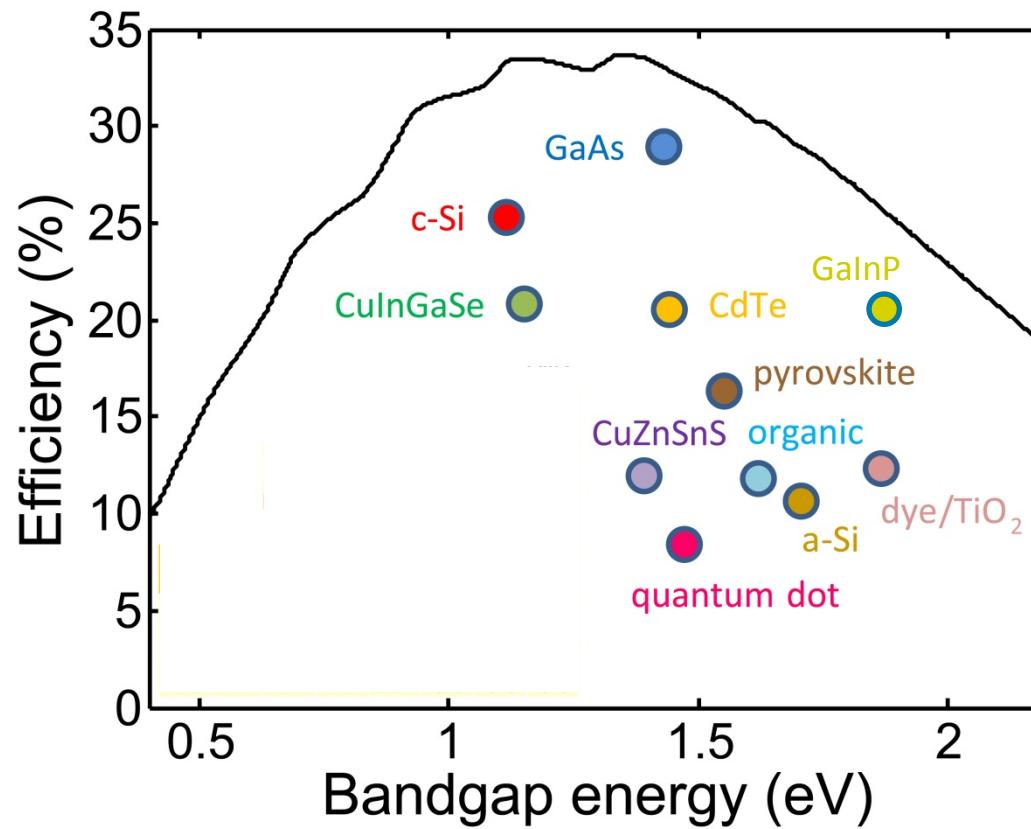
cheap ↑
↓ expensive



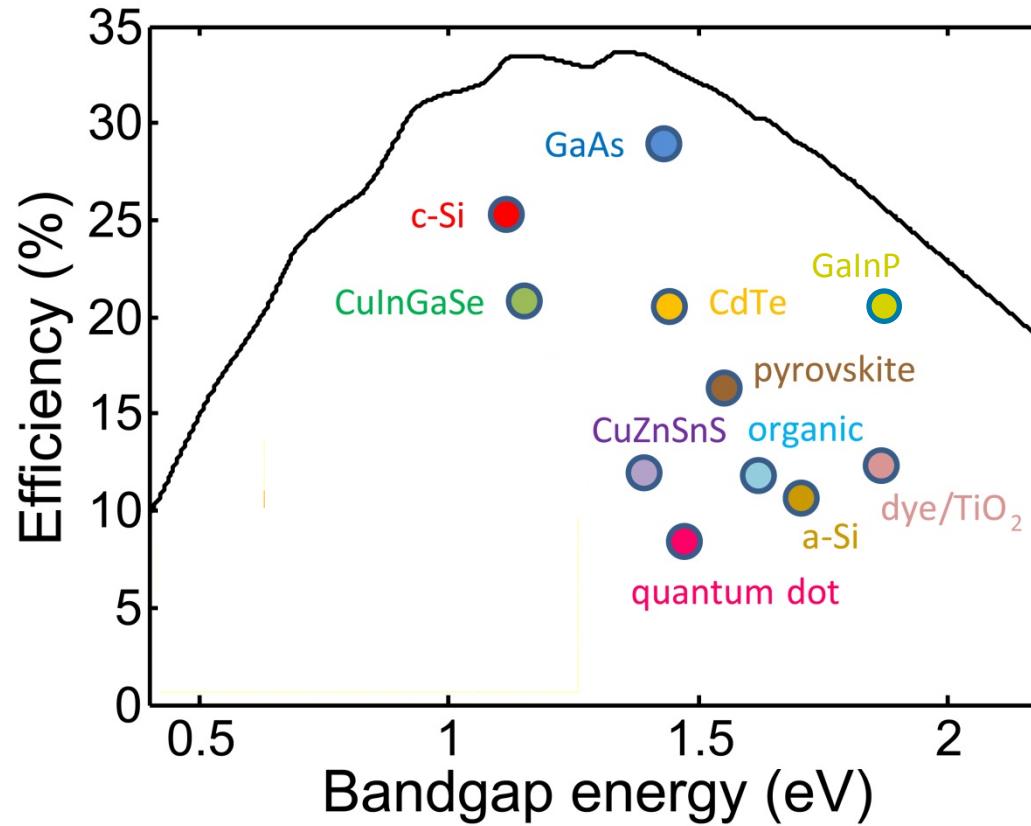
<http://www.physics.rutgers.edu/~nakhmans/Pro/thesis/node6.html>

Figure 1.1: Crystalline Si and CRN amorphous Si models. Left: 64 atom model of crystalline silicon; right: 216 atom CRN model of amorphous silicon.

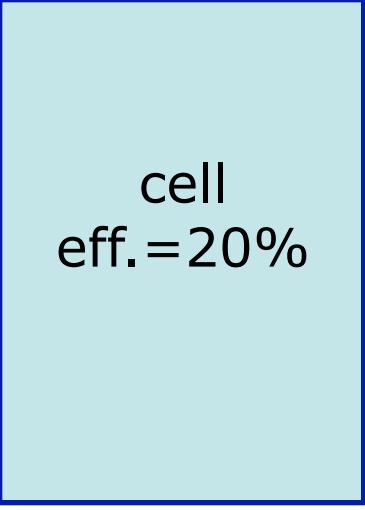
Demonstrated solar cell efficiencies



Despite 60 years of research: No material reaches the thermodynamic limit !



Solar power generation system =
cells + panel + inverter + system + installation + land



cell
eff.=20%

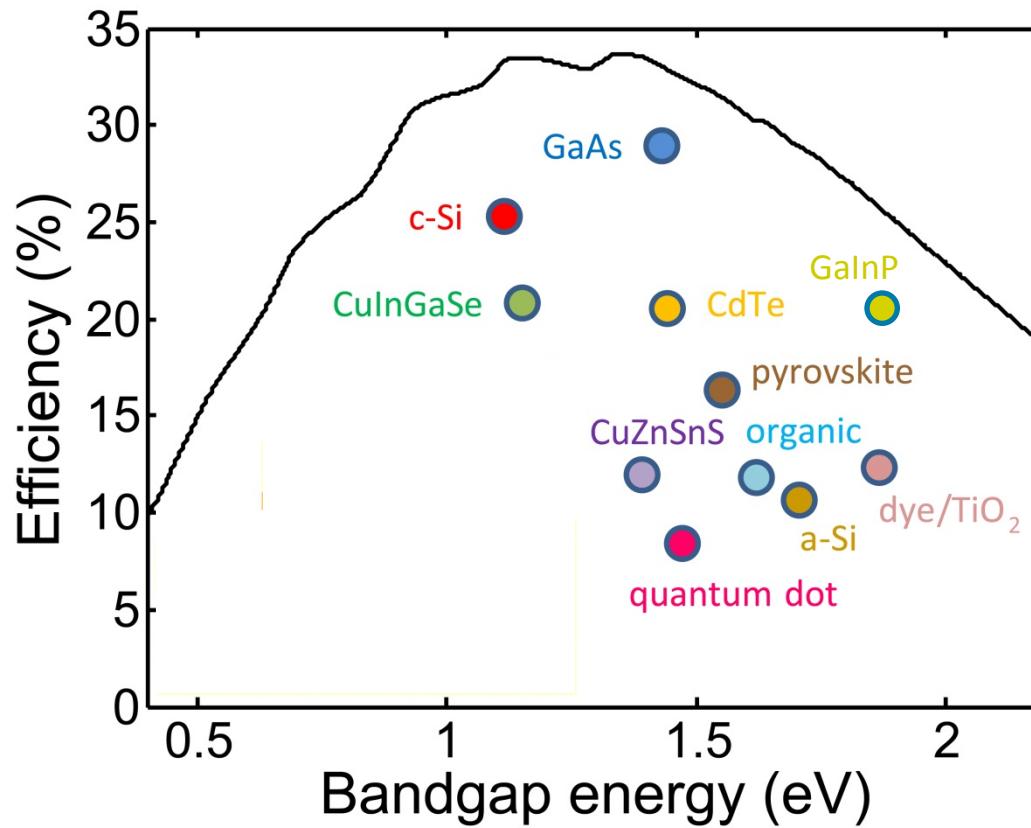
panel	€ 100
cells	€ 100
Total	€ 200

Solar power generation system =
cells + panel + inverter + system + installation + land

cell
eff.=10%

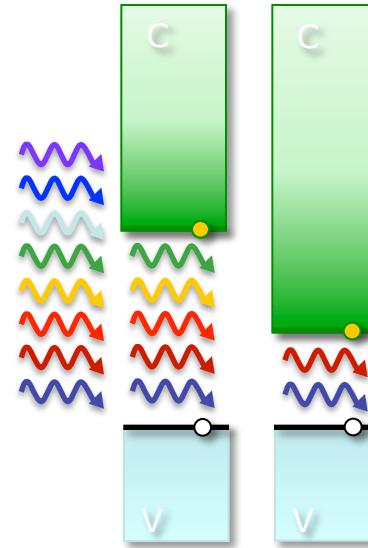
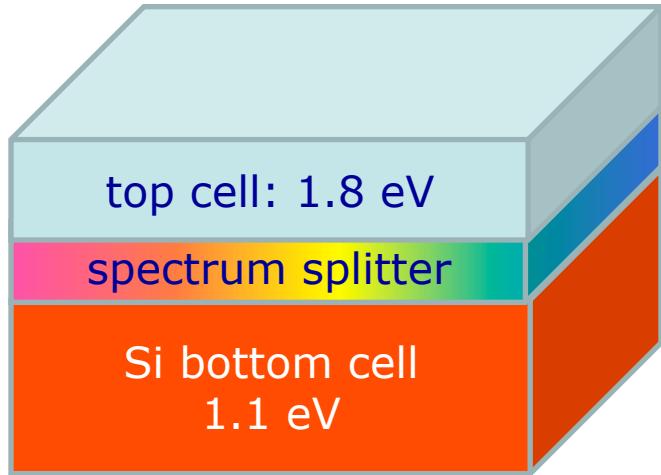
cell
eff.=10%

High efficiency is “more important” than low cost

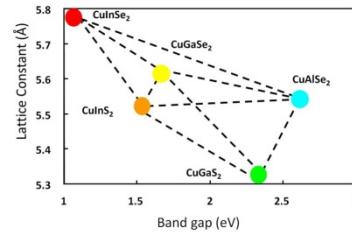
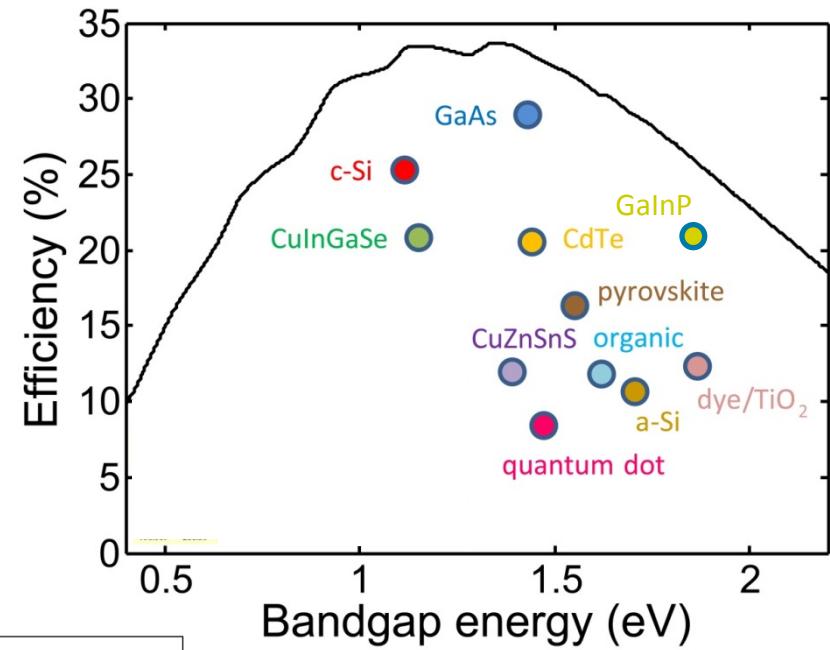
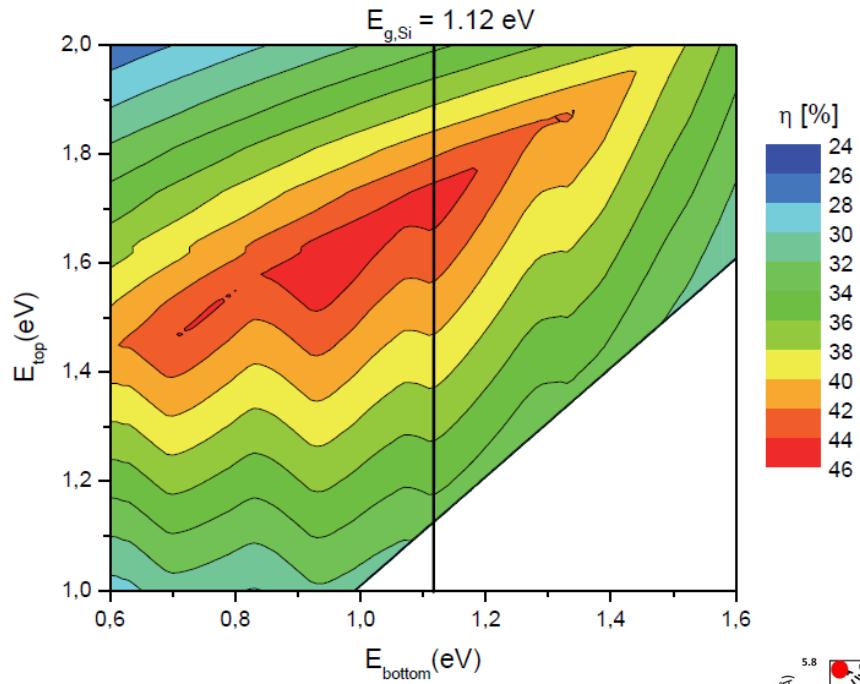


Dual-junction solar cell: thin-film-on-silicon

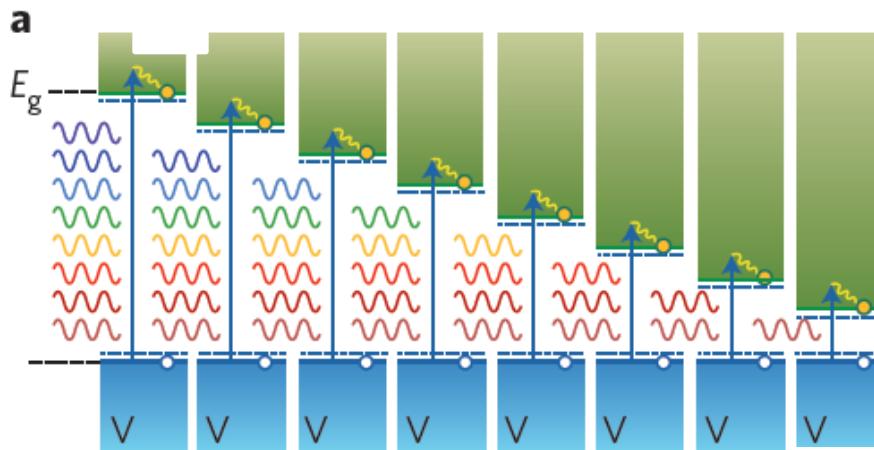
SQ limit: 44%



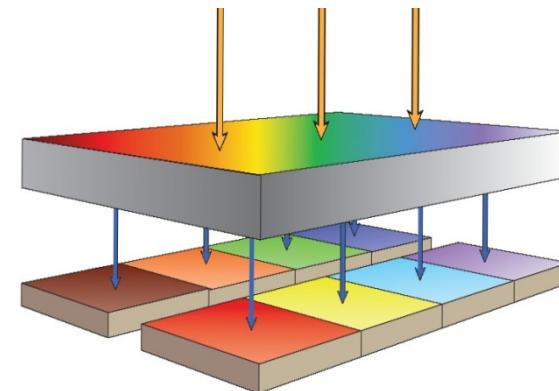
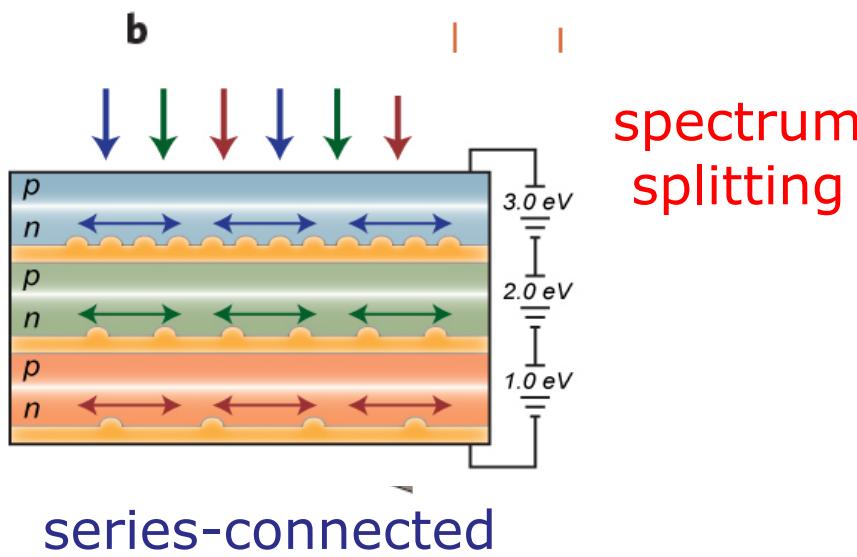
Dual-junction solar cell: thin-film-on-silicon SQ limit: 44%



Multi-bandgap solar cell designs



Efficiency potential
 $> 50\%$



Strategies towards high efficiency at low costs

1) Wafer-based Si solar cells ($\rightarrow 25\text{-}29\%$)

- Reduce costs (=reduce wafer thickness: 10-20 μm)
- Decrease recombination at surface, junctions, contacts
- Increase light trapping, angular emission restriction,..

2) Thin-film solar cells

- Increase efficiency & reduce costs

3) Dual-junction solar cells on silicon ($\rightarrow 30\text{-}35\%$)

- Increase efficiency and bandgap of top cells
- Define spectral splitting architectures

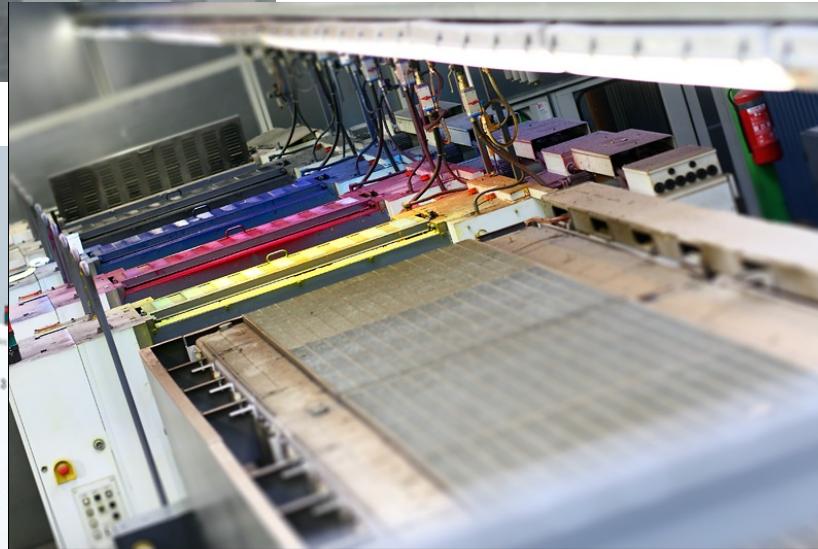
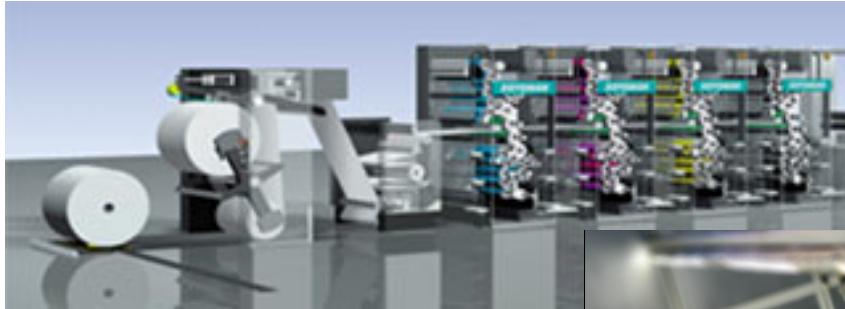
4) New materials and designs ($\rightarrow >40\%$)

- Novel multijunction cell architectures
- Nanowire solar cells
-

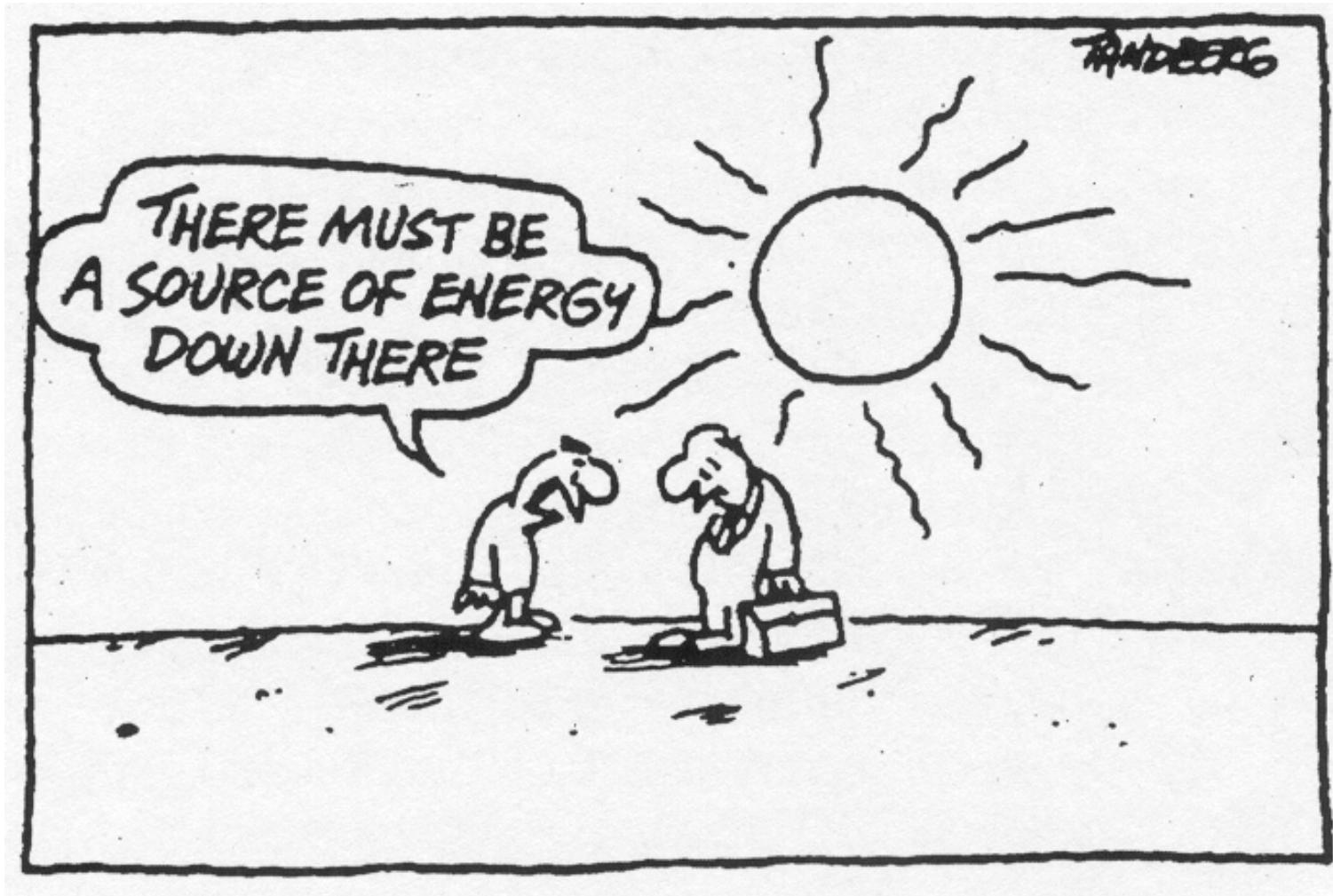
Towards ultra-large-area PV systems worldwide



Large-scale printing of solar cells



Energy from the sun



Energy from the sun

is a
science challenge
&
technology challenge
&
societal/political challenge



A large, bright orange and yellow sun is positioned in the center of the frame, partially submerged in a dark, rippling ocean. The sky above the sun is a deep red, transitioning to a darker shade towards the horizon. In the distance, a few small birds are visible against the horizon line.

Thank you