The Abdus Salam International Centre for Theoretical Physics

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2 - 11 December 2010

Energy - the biggest problem of our time !

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Energy – the biggest problem of our time!

-

Thomas Edison (American inventor & businessman):

"I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil [2080] and coal [2155] run out before we tackle that."

In conversation with Henry Ford and Harvey Firestone (1931).

Photo: Ford, Edison, and Firestone in Florida, 1929

From the book "Uncommon Friends: Life with Thomas Edison, Henry Ford, Harvey Firestone, Alexis Carrel, and Charles Lindbergh" by James Newton (Mariner Books, 1989) p. 31; LAGI

Photovoltaics: Principles, Materials, and a Novel Approach Using Surface Acoustic Waves

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http://physics.umd.edu/~yakovenk/

Principles of photovoltaics (PV):
- semiconducting p-n junctions
- photocurrent and quantum efficiency
- dark current and open-circuit voltage,
- fill factor and power efficiency
- Shockley–Queisser limit on maximal efficiency

Materials for photovoltaics:
- crystalline Si and amorphous Si,
- GaAs, CdTe, and $Cu(In,Ga)Se_2$ (CIGS)
- organic and dye-sensitized solar cells

Novel proposal for high-efficiency PV using surface acoustic waves (SAW) in piezoelectric semiconductors (arXiv:0912.5390, patent application pending)

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Recommended books

Published by Imperial College Press/World Scientific Publishing Co.

"The Physics of Solar Cells" by Jenny Nelson
(2003, ISBN 978-1860943492)

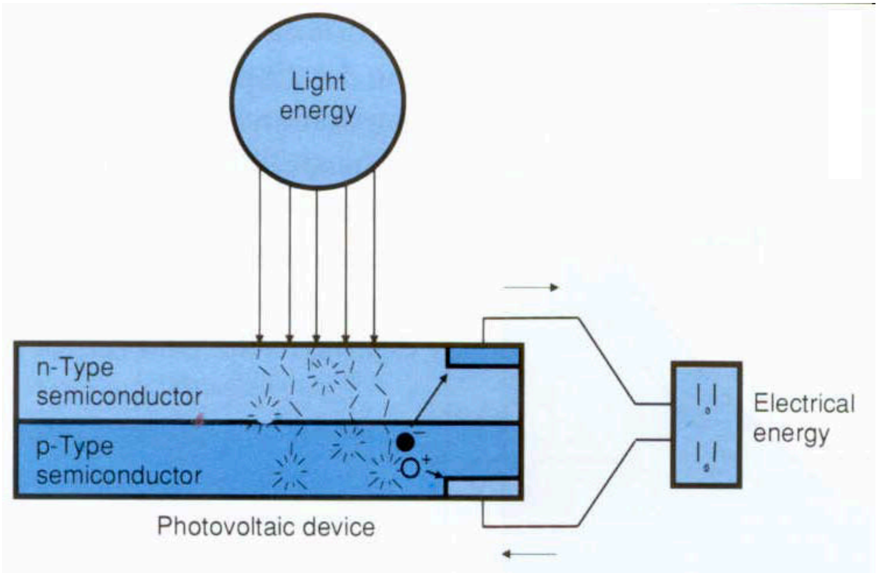
Series on *Photoconversion of Solar Energy*:

Vol. 1, "Clean Electricity from Photovoltaics",
edited by Mary Archer & Robert Hill (2001, ISBN 978-1860941610)

Vol. 3, "Nano-structured and Photo-electro-chemical Systems for Solar Photon Conversion",
edited by Mary Archer & Arthur Nozik (2003, ISBN 978-1860942556)

The photovoltaic effect

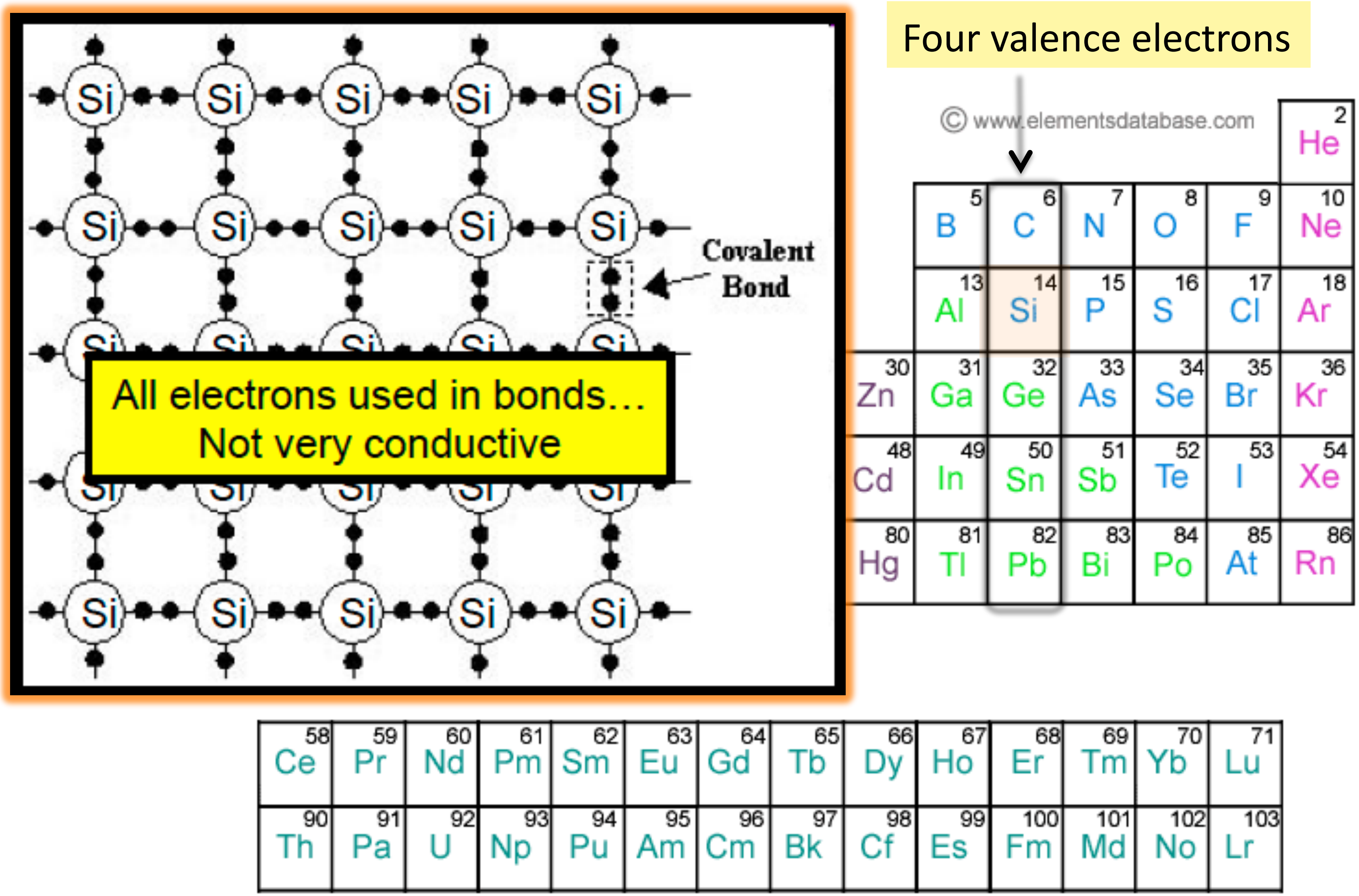
The photovoltaic effect is the generation of a voltage (or an electric current) in a material exposed to light.



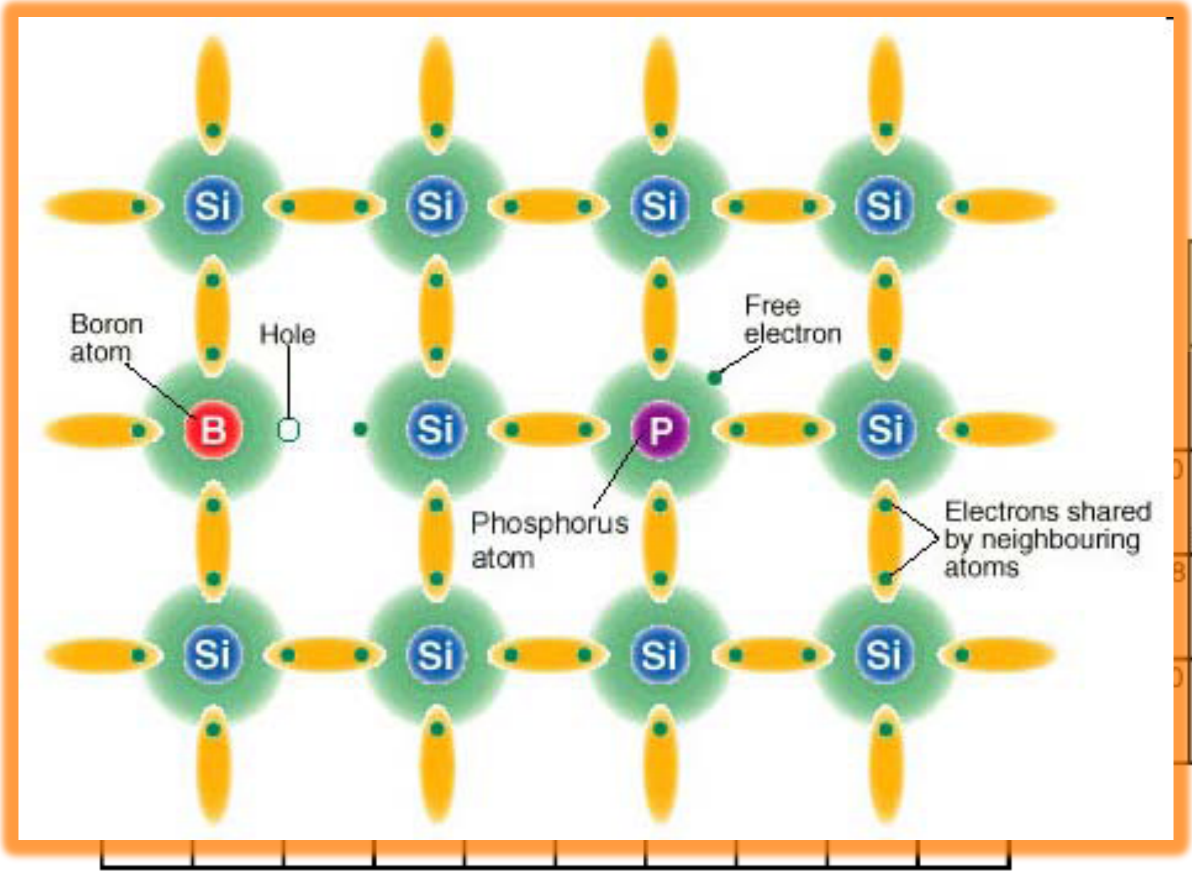
Discovered by the French physicist Alexandre-Edmond Becquerel in 1839 on an electrode (Pt covered by AgCl) immersed in a conductive electrolyte.

(He is the son of the electrochemist Antoine César Becquerel and the father of Henri Becquerel, the discover of radioactivity.)

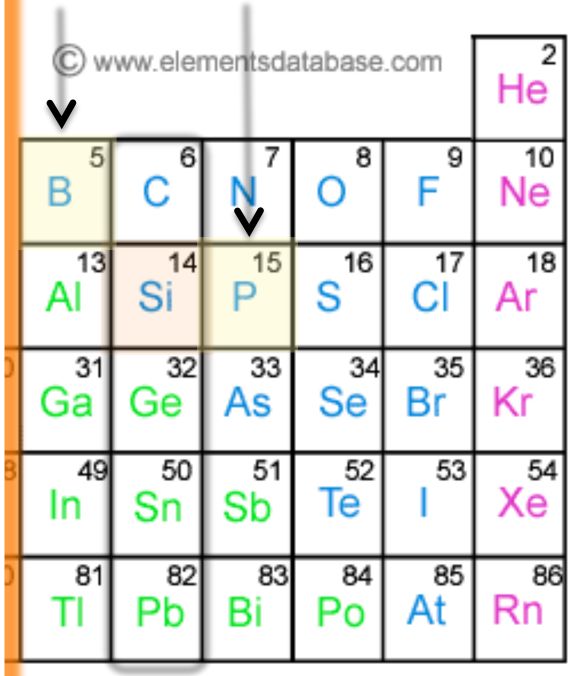
Semiconductors: pure silicon



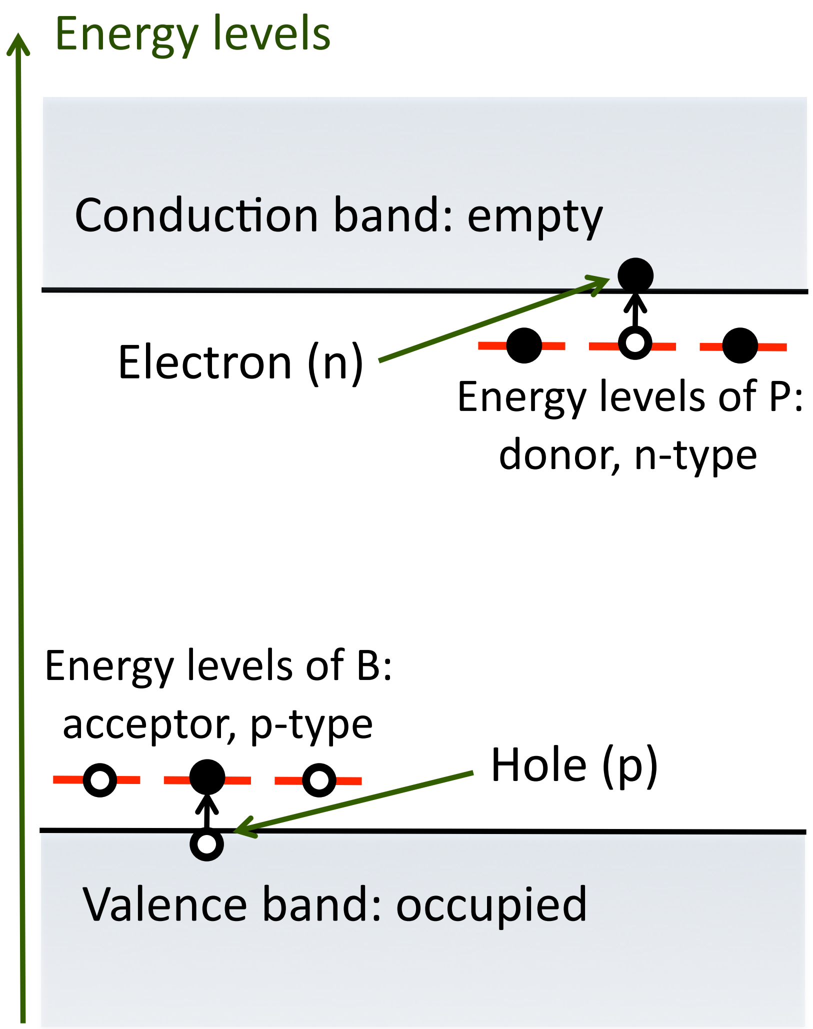
Doping Si with B and P



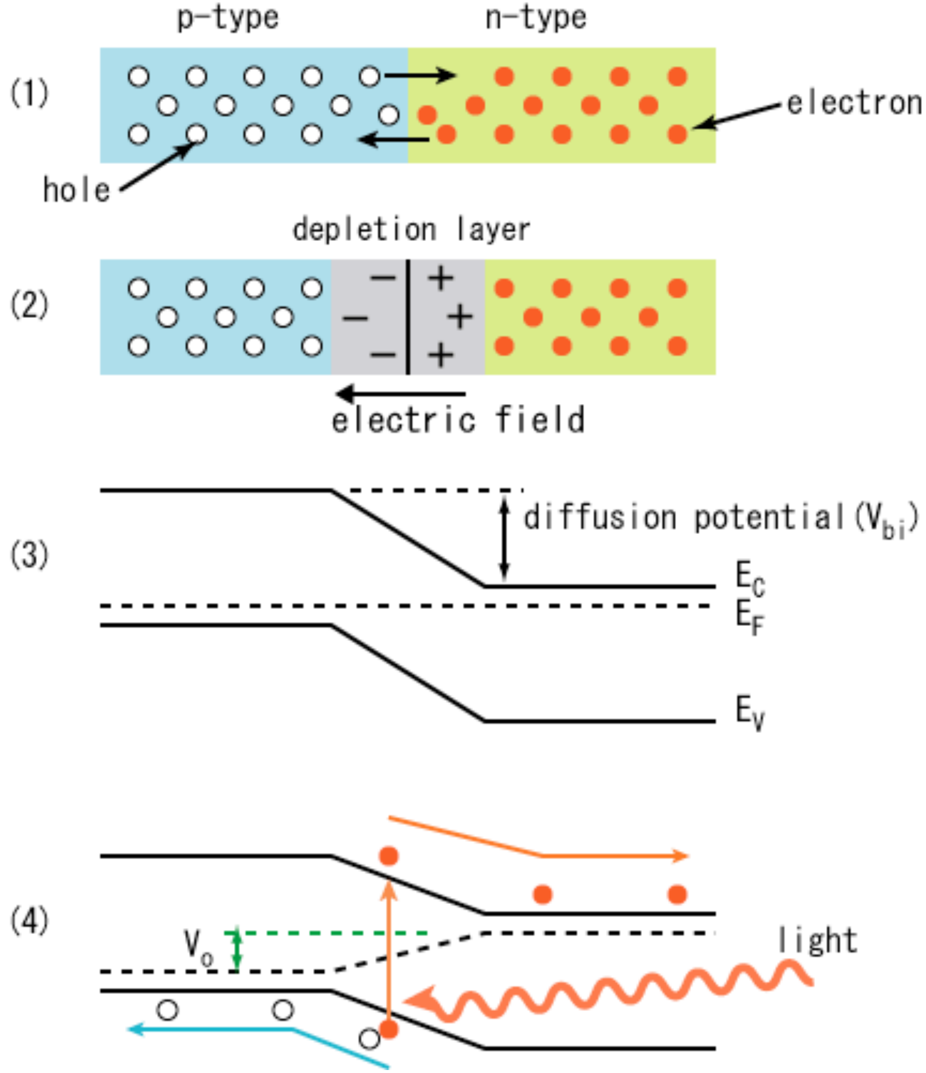
Valences 3 and 5



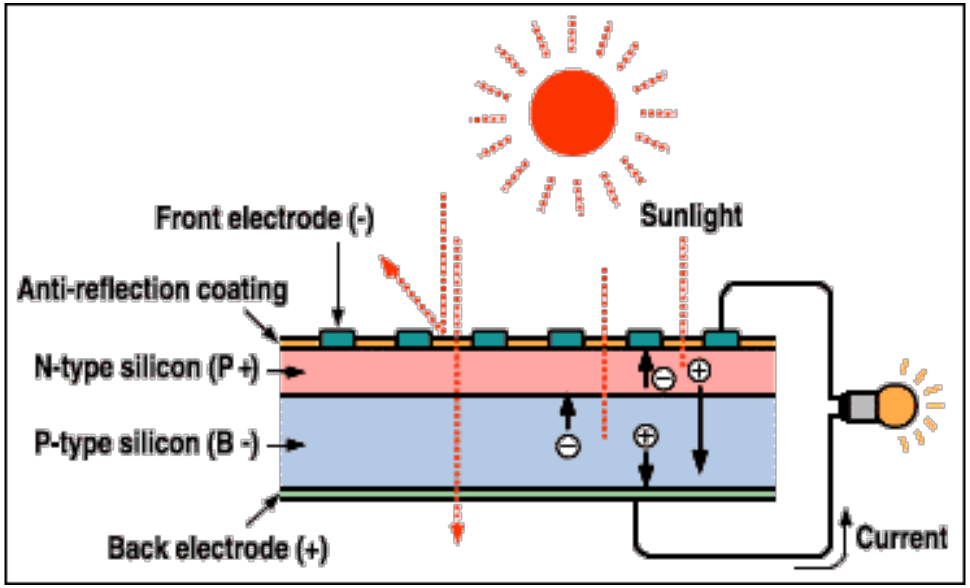
Band structure



p-n junction

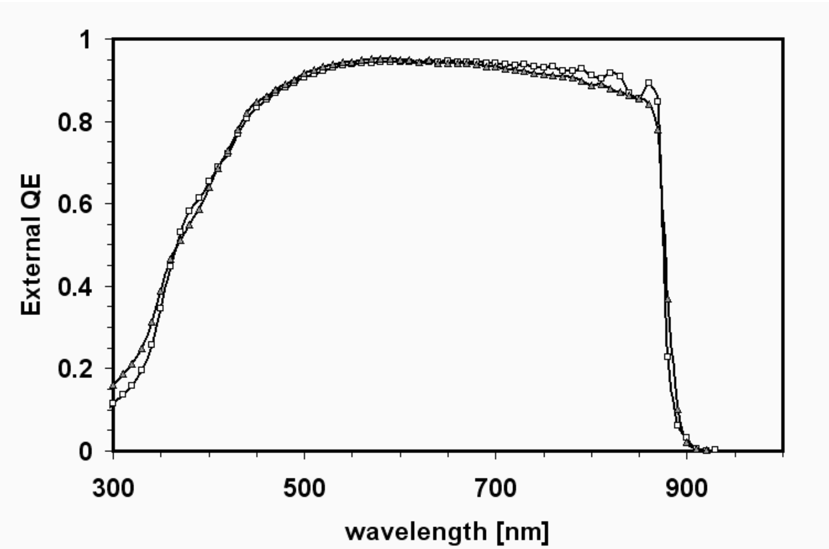


http://upload.wikimedia.org/wikipedia/commons/4/48/PnJunction-PV-E.PNG



Short-circuit current, quantum efficiency

For an electric load with R=0 (zero resistance), we obtain the short-circuit photo-current $I_{sc}=I_{photo}$



External quantum efficiency =

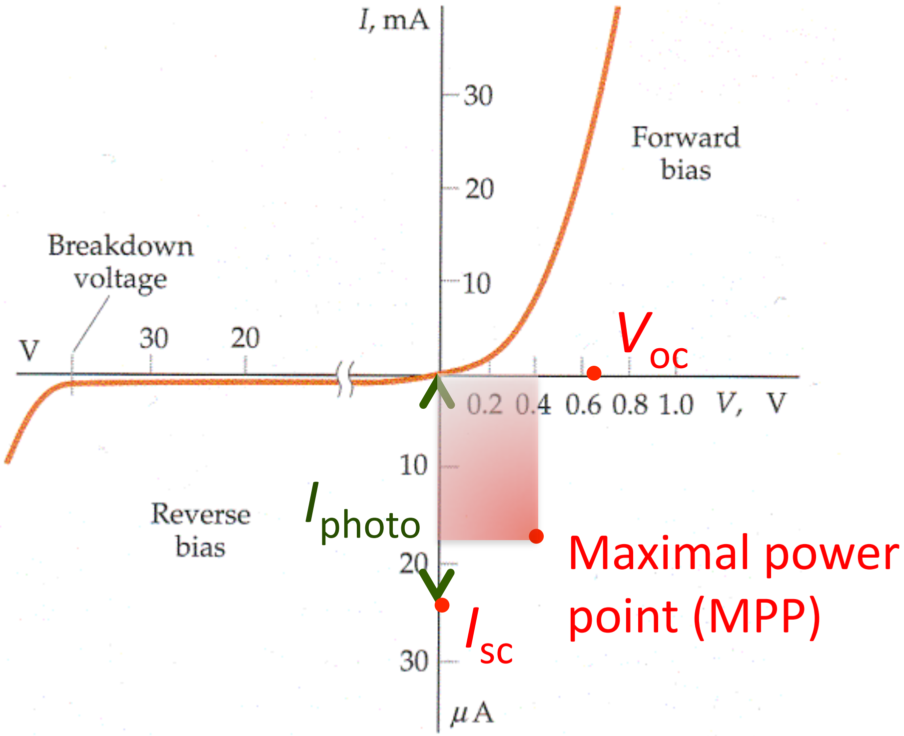
$$\frac{\text{Number of collected electrons}}{\text{Number of incoming photons}} = \frac{I_{sc}}{e}\frac{h\nu}{P_{in}}$$

In the best modern solar cells, the quantum efficiency is above 90%.

External quantum efficiency of a GaAs solar cell,
from Bauhuis *et al.* (Nijmegen), 20th Euro PV Conference (Barcelona, 2005), p. 468.

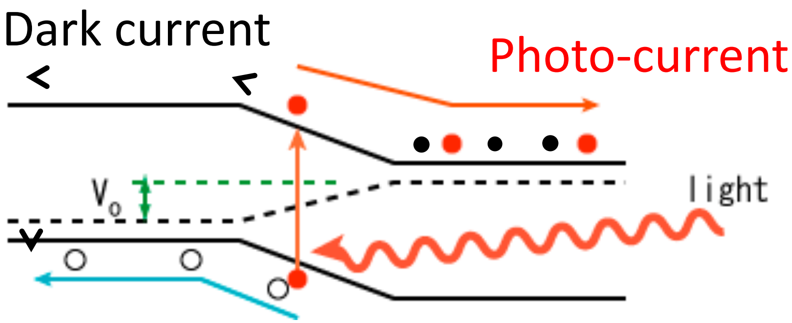
Dark current, open-circuit voltage, fill factor

Current-voltage *I-V* relation for a p-n junction (a diode) in the dark (no light)



$$I_{dark} = I_0\left(e^{eV/kT} - 1\right)$$

Energy efficiency = P_{max}/P_{in}



The total current is

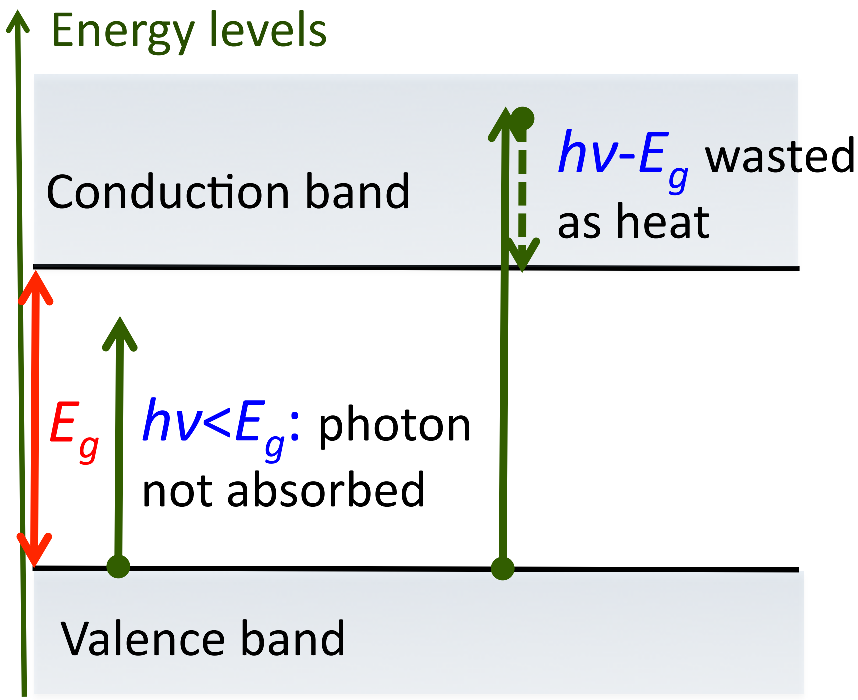
$$I(V) = I_{dark} - I_{photo} = I_0\left(e^{eV/kT} - 1\right) - I_{photo}$$

The open circuit voltage V_{oc} is such that $I(V_{oc}) = 0$: $\quad eV_{oc} = kT\ln\left(\frac{I_{photo}}{I_0} + 1\right)$

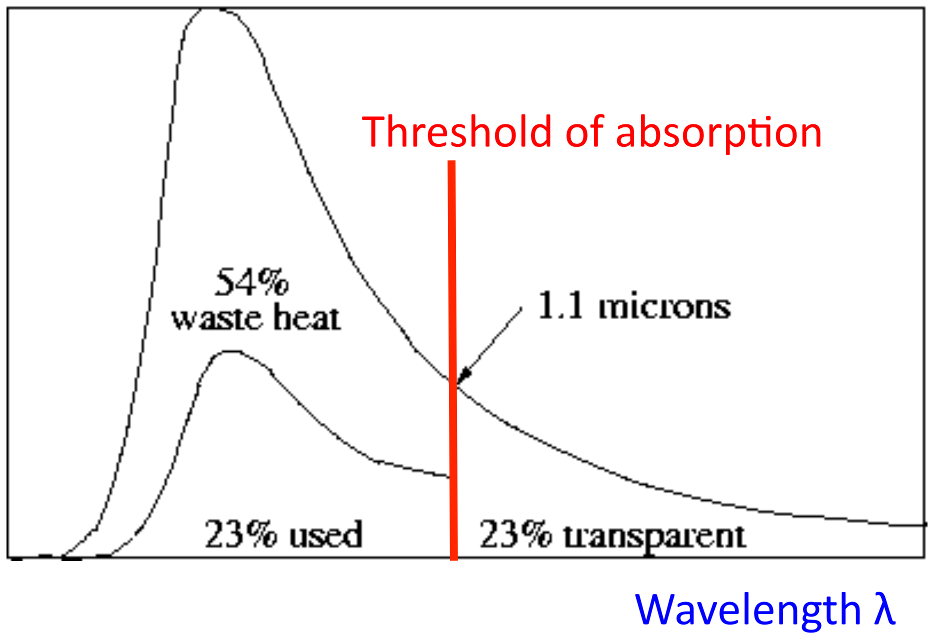
To maximize V_{oc}, we need $I_{photo} >> I_0$, photo-concentration helps.

Fill factor $f = \frac{P_{max}}{I_{sc}V_{oc}}; \quad P_{max} = f\, I_{sc}V_{oc}$

Shockley–Queisser limit on max efficiency



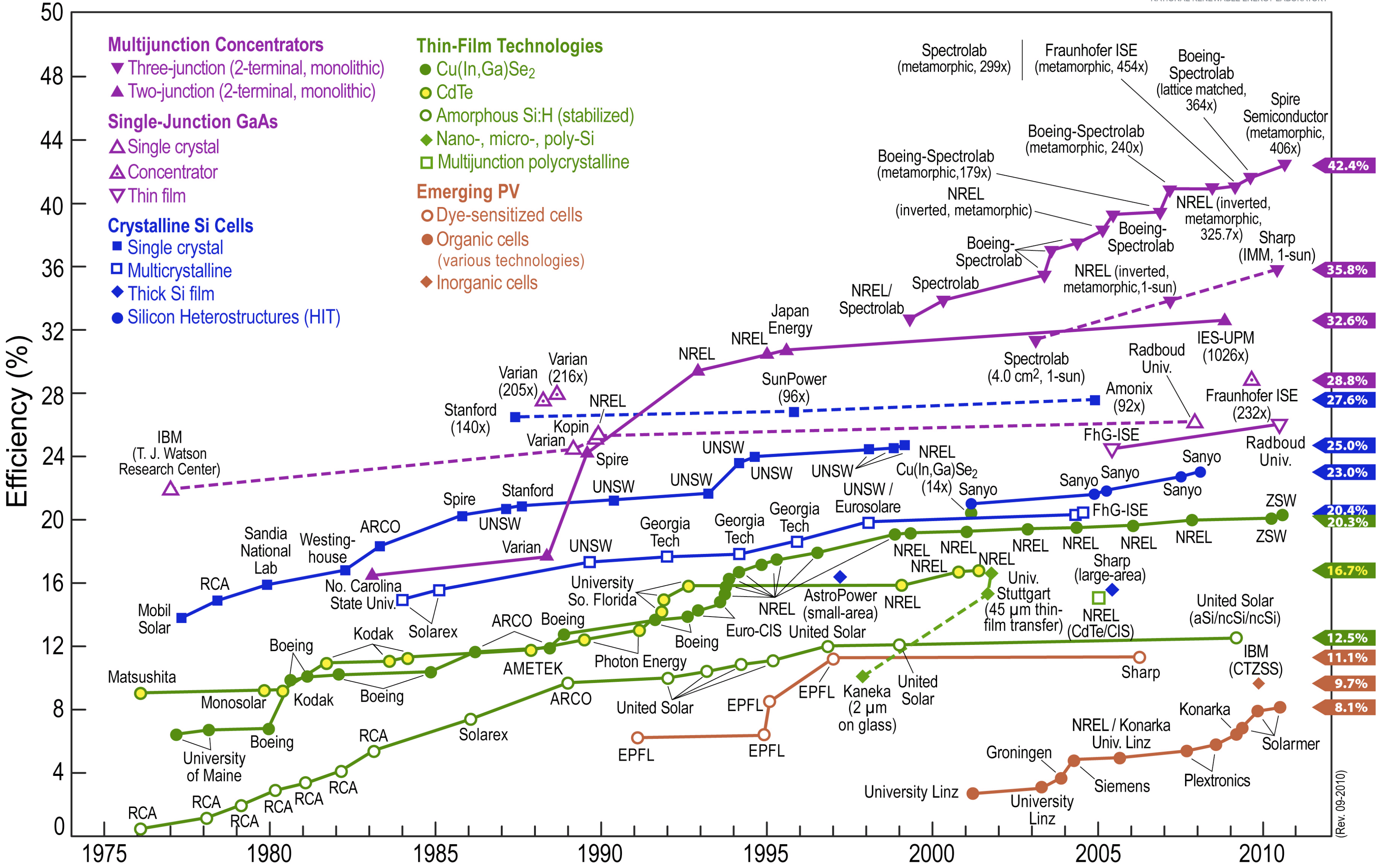
Solar spectrum



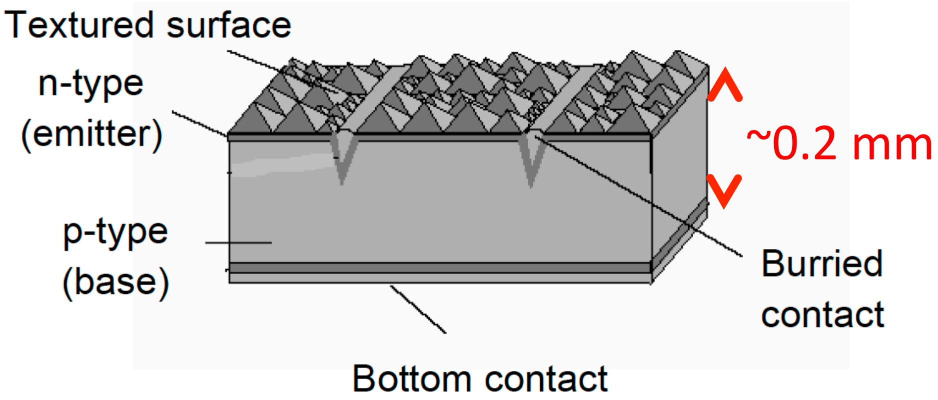
For Si, E_g=1.1 eV and λ_g=1.1 μm.

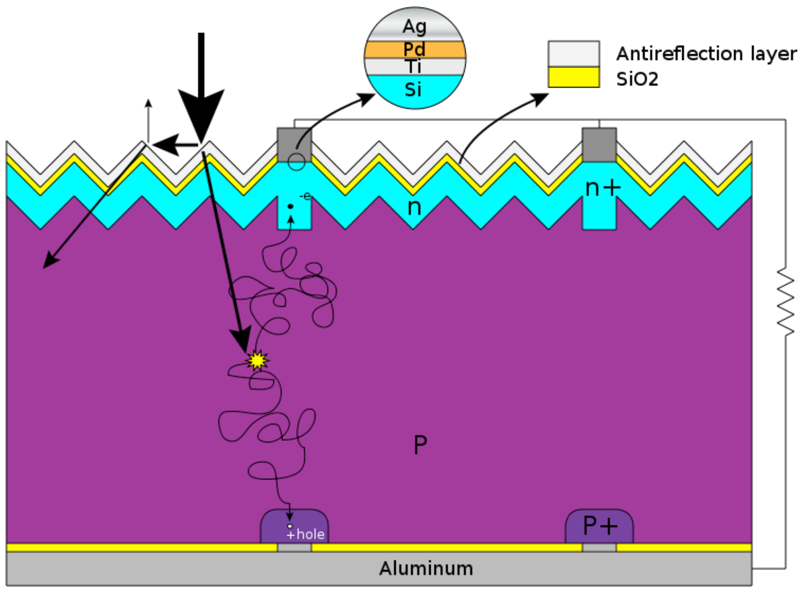
Shockley and Queisser calculated in 1961 for the solar spectrum and the Si energy gap that the maximal theoretical solar-power conversion efficiency is about 33.7%. This limit can be exceeded by using multi-junction solar cells with different energy gaps.

Best Research-Cell Efficiencies



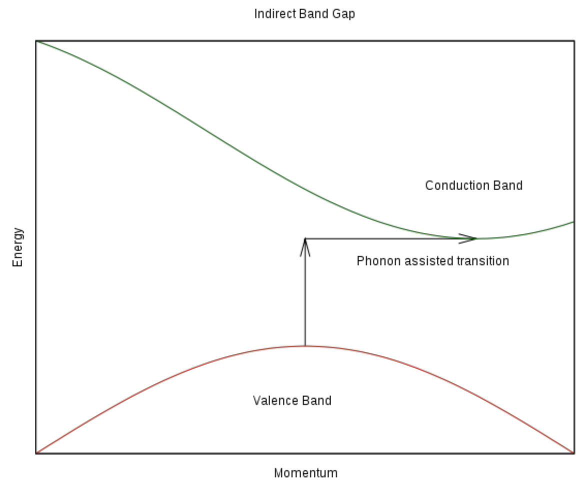
Typical crystalline Si solar cell





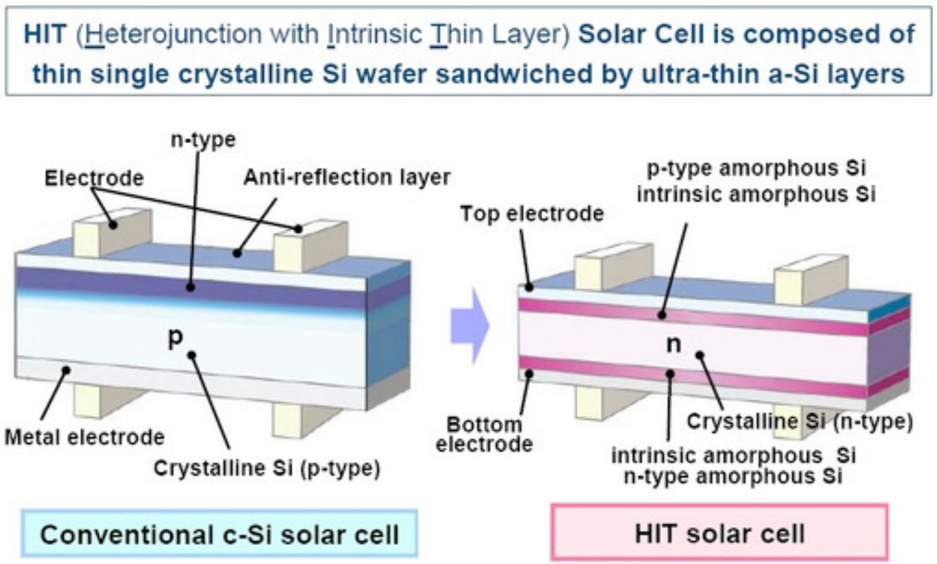
http://en.wikipedia.org/wiki/Solar_cells

Si has an indirect band gap.

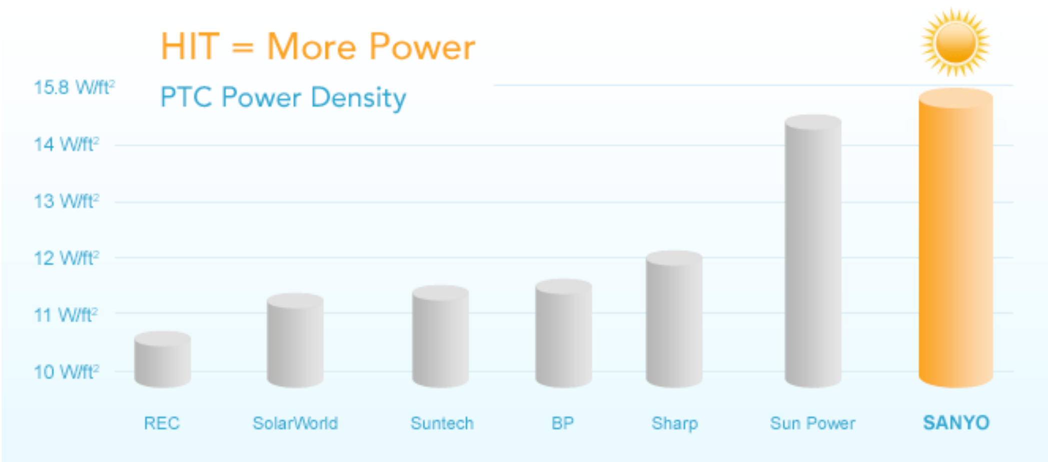


Absorption of a photon requires absorption of a phonon to satisfy conservation of momentum, so the probability of absorption is greatly reduced. Because Si poorly absorbs light, it has to be **thick** >0.2 mm and clean with a long mean-free path for carriers.

Novel HIT design by Sanyo



HIT Double collects light from two sides.

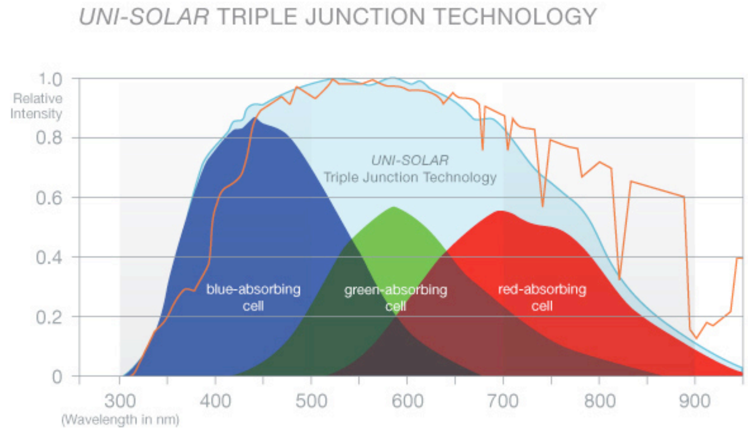


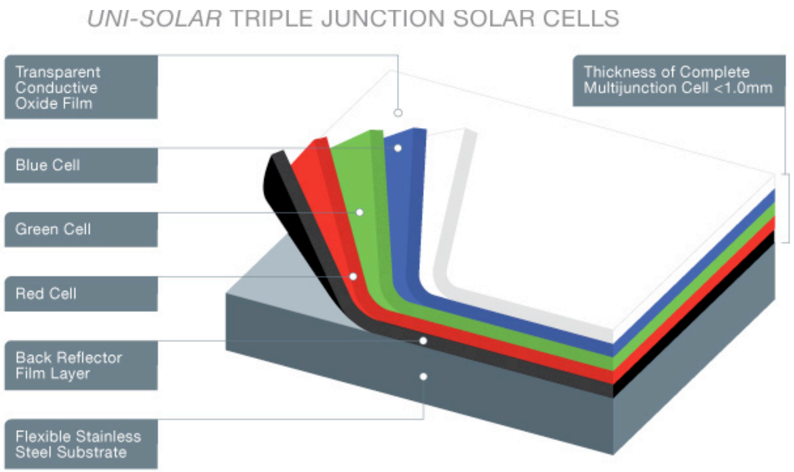
http://us.sanyo.com/Solar/

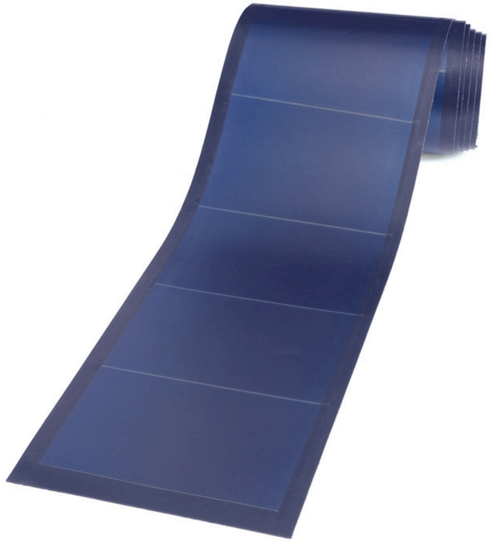
Sanyo solar panels HIT 215A will be installed on the roof of my house next month:
2.15 kW peak power,
cell efficiency 19.3%,
module efficiency 17.1%.

Amorphous thin-film Si solar cells

Because of disorder, momentum is not conserved in amorphous Si, so phonons are not needed, and a thin film (~1 μm) absorbs light well. But the mean-free path of carriers is greatly reduced, and light exposure degrades performance.







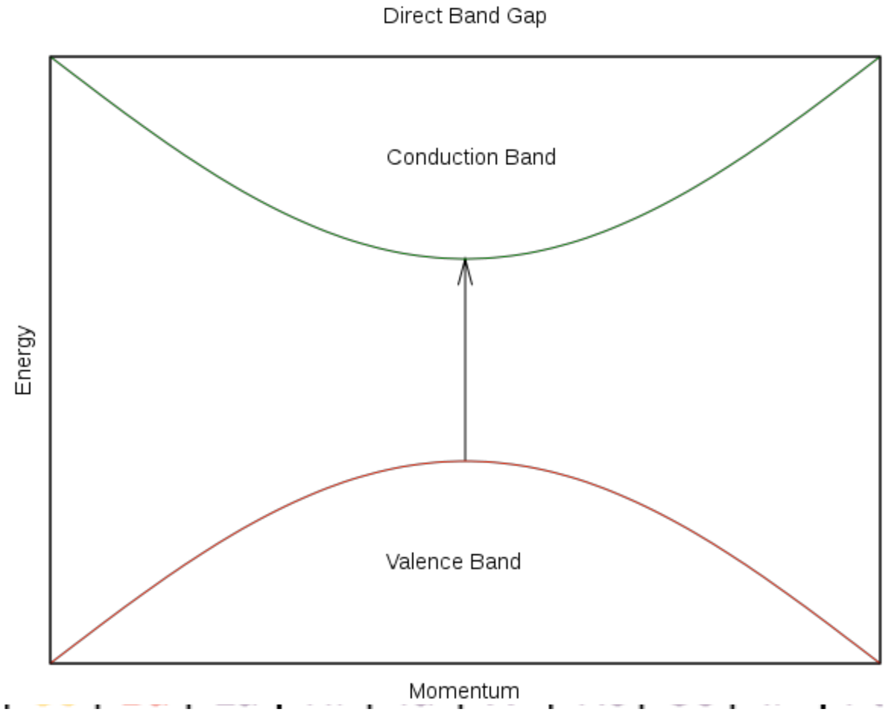
Photovoltaic Laminate by **Uni-Solar**: suitable for large areas, but efficiency is ~0.4 of the Sanyo models (c-Si).

http://www.uni-solar.com/

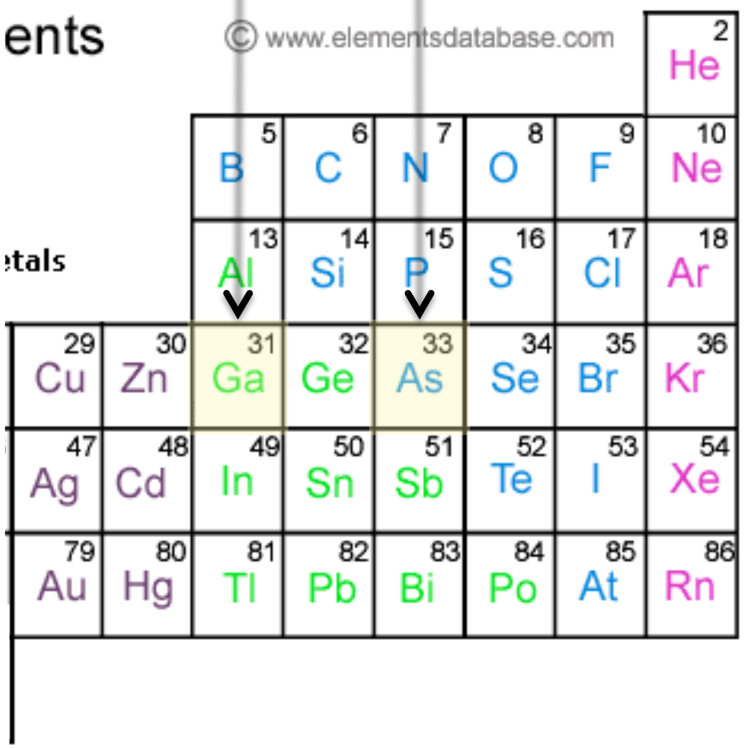
A large-scale installation from Uni-Solar

Rome Trade Fair, Italy, 1.4 MW, 2008, http://www.uni-solar.com/

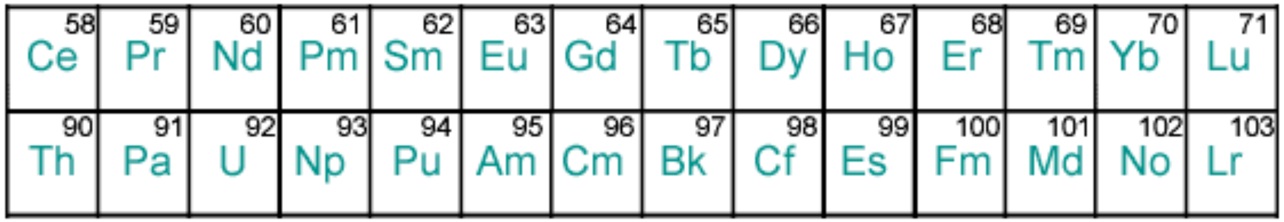
GaAs – direct band gap semiconductor



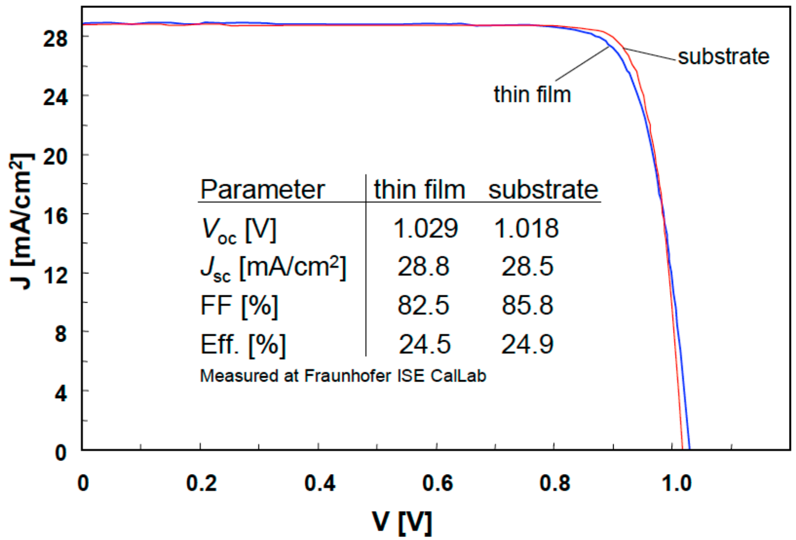
Valences 3 and 5

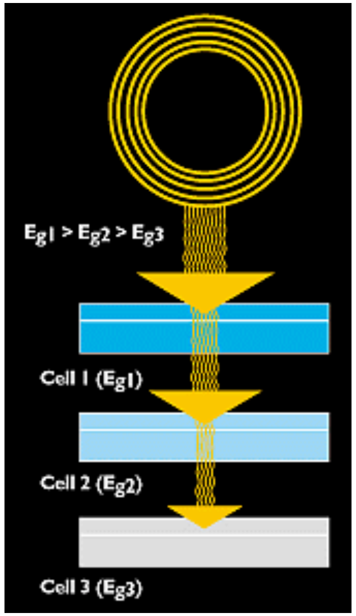


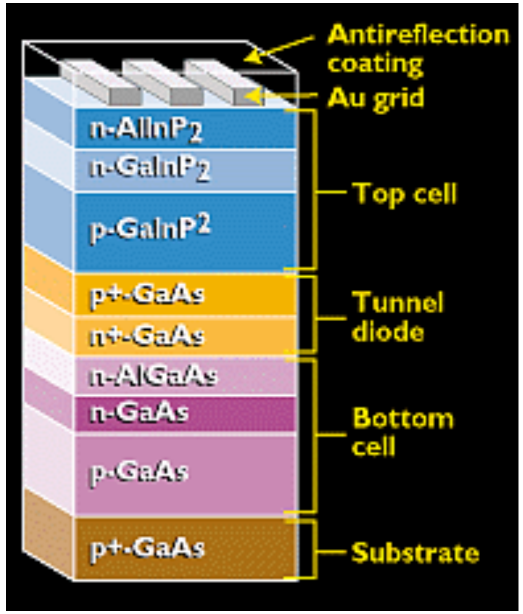
Because of the direct band gap, light is absorbed in a thin layer of a few µm.



GaAs – highest energy conversion efficiency





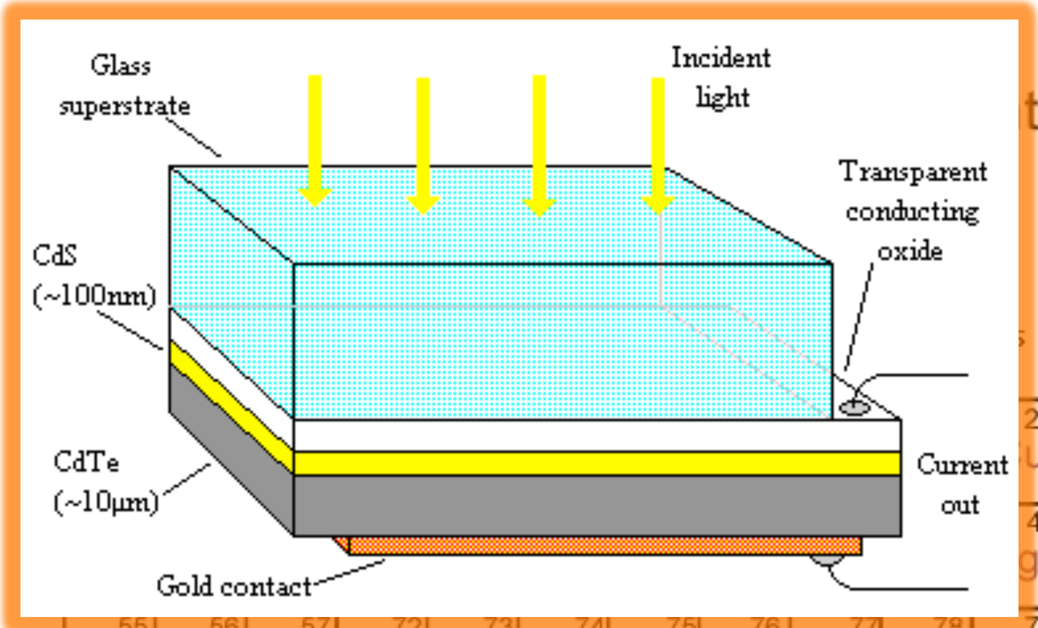


Single-junction GaAs cells: 2 µm thin film and 3.5 µm on substrate, from Bauhuis *et al.* (Nijmegen), 20th Euro PV Conference (Barcelona, 2005), p. 468.

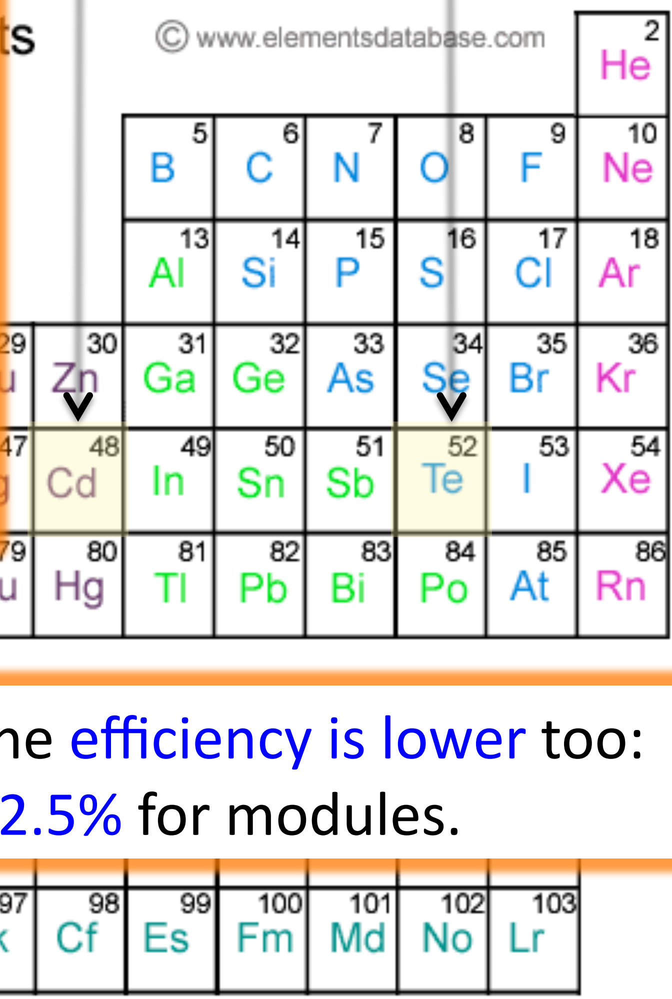
Multi-junction GaAs cells (double and triple) achieve the highest efficiency up to 42.4% in concentrated light.

GaAs solar cells are extremely expensive and are used almost exclusively in space, where weight is the primary consideration.

CdTe – direct band gap, thin film

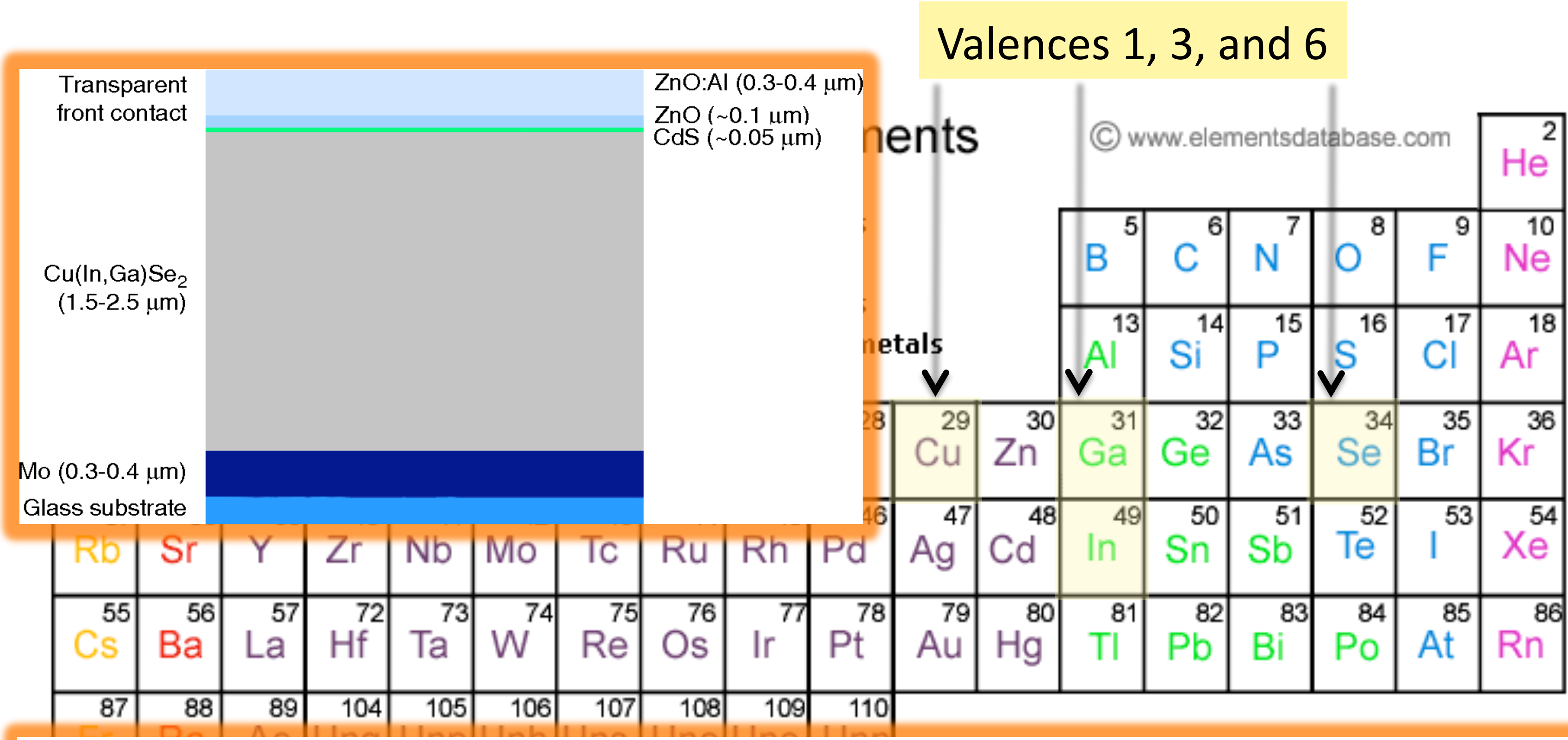


Valences 2 and 6



The cost is lower than for c-Si, but the efficiency is lower too: 16.5% for the top cells and 12.5% for modules.

$CuIn_xGa_{1-x}Se_2$ (CISG) – direct gap, thin film



The highest efficiency ~20% among thin-film cells. **Nanosolar** developed a low-cost, high-throughput deposition of 20 nm nano-particles by roll-to-roll ink printing, then thermally treated to produce thin film. End-product efficiency is ~0.6 of c-Si.

Dye-Sensitized Solar Cells

- Electron-holes separation is very efficient at the interface between TiO_2 and dye with a large effective surface.
- However, charge is transported via diffusion of iodine ions in electrolyte, which is very slow, so efficiency is ~11%.

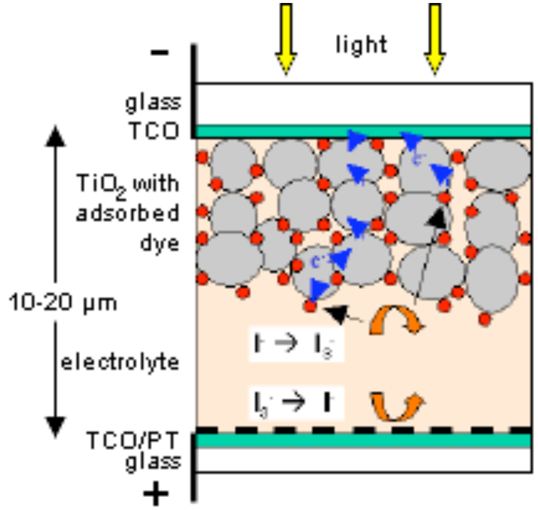
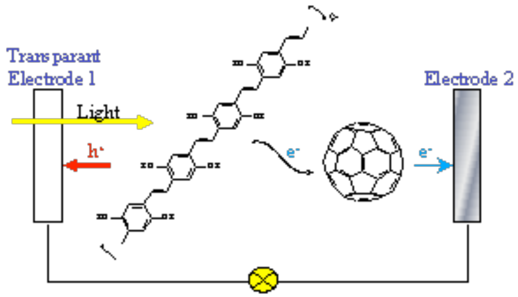
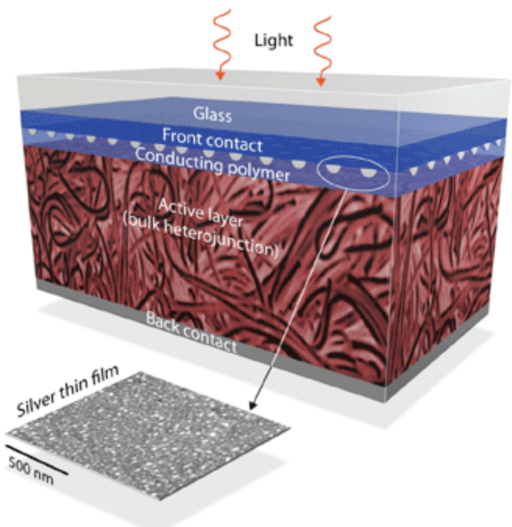


Fig. 1: Schema of dye-sensitezed solar cell

Organic Solar Cells

- Electron-holes separation is very efficient at the interface between buckyballs and polymers with large effective surface.
- However, the random "meatballs and spaghetti" mix poorly transports charges and does not allow separate + and – contacting.
- Cheap, but very low efficiency ~8%.





SURFACE AREA REQUIRED TO POWER THE WORLD

WITH ZERO CARBON EMISSIONS AND WITH SOLAR ALONE → www.landartgenerator.org

BOXES TO SCALE WITH MAP

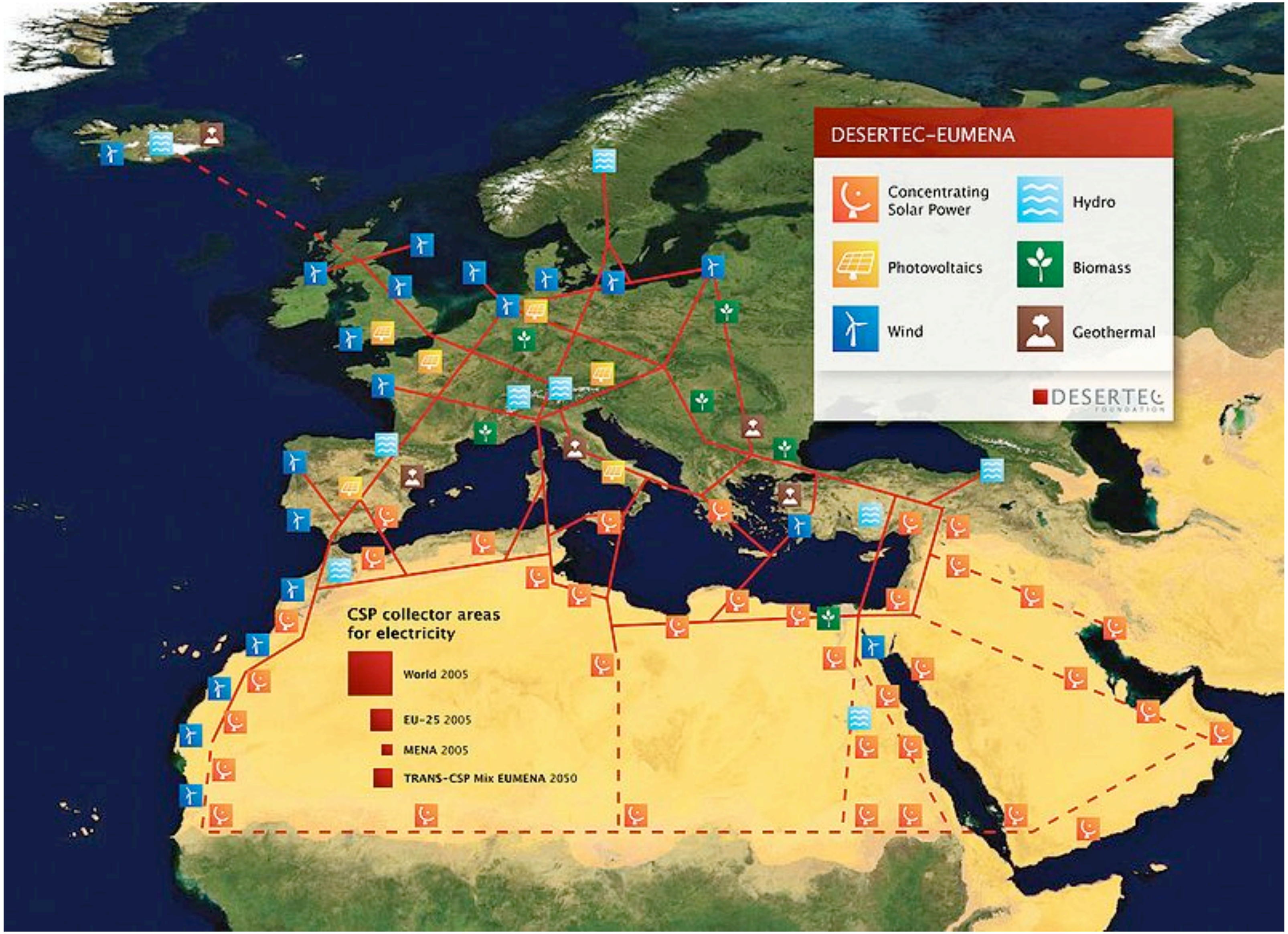
- 1980 (based on actual use)
  207,368 SQUARE KILOMETERS
- 2008 (based on actual use)
  366,375 SQUARE KILOMETERS
- 2030 (projection)
  496,805 SQUARE KILOMETERS

Required area that would be needed in the year 2030 is shown as one large square in the key above and also as distributed around the world relative to use and available sunlight.

- Areas are calculated based on an assumption of 20% operating efficiency of collection devices and a 2000 hour per year natural solar input of 1000 watts per square meter striking the surface.
- These 19 areas distributed on the map show roughly what would be a reasonable responsibility for various parts of the world based on 2009 usage. They would be further divided many times, the more the better to reach a diversified infrastructure that localizes use as much as possible.
- The large square in the Saharan Desert (1/4 of the overall 2030 required area) would power all of Europe and North Africa. Though very large, it is 18 times less than the total area of that desert.
- The definition of "power" covers the fuel required to run all electrical consumption, all machinery, and all forms of transportation. It is based on the US Department of Energy statistics of worldwide Btu consumption and estimates the 2030 usage (678 quadrillion Btu) to be 44% greater than that of 2008.
- Area calculations do not include magenta border lines.

LAND ART GENERATOR INITIATIVE

DESERTEC Industrial Initiative: concentrated solar power



Moroccan Agency for Solar Energy (MASEN): 2 GW of solar capacity by 2020

New approach to PV using surface acoustic waves in piezoelectric semiconductors

in collaboration with

Dennis Drew
Department of Physics, University of Maryland, College Park

Matthew Grayson
Department of Electrical Engineering, Northwestern University

ARPA-E Finalist 2009. Patent application pending. Preprint arXiv:0912.5390

Steps for photovoltaic energy conversion:

1. Photon is absorbed across an energy gap, and electron-hole pair is created
2. Electrons and holes are spatially separated by an electric field to prevent recombination
3. Electrons and holes are transported to the collecting electrodes
4. Electrons and holes are collected by the electrodes and sent to an output circuit

Basics of surface acoustic waves (SAW)

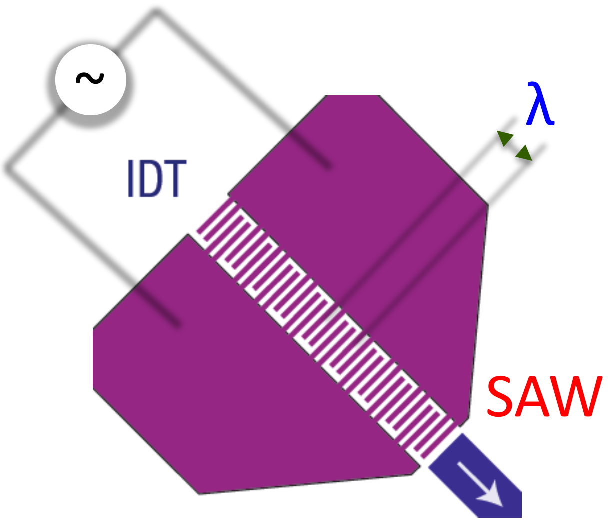
SAWs are generated by applying ac voltage to interdigitated transducers (IDTs).

The spacing λ of IDTs defines the wave number $k=2\pi/\lambda$.

When the applied frequency ω matches the dispersion of SAW, $\omega=\omega_{SAW}(k)$, the surface acoustic waves are excited.

SAWs propagate with the speed of sound v.

SAWs are deformations of the crystal lattice and produce periodic modulation of electric charge and potential in piezoelectric semiconductors (GaAs, CdTe).

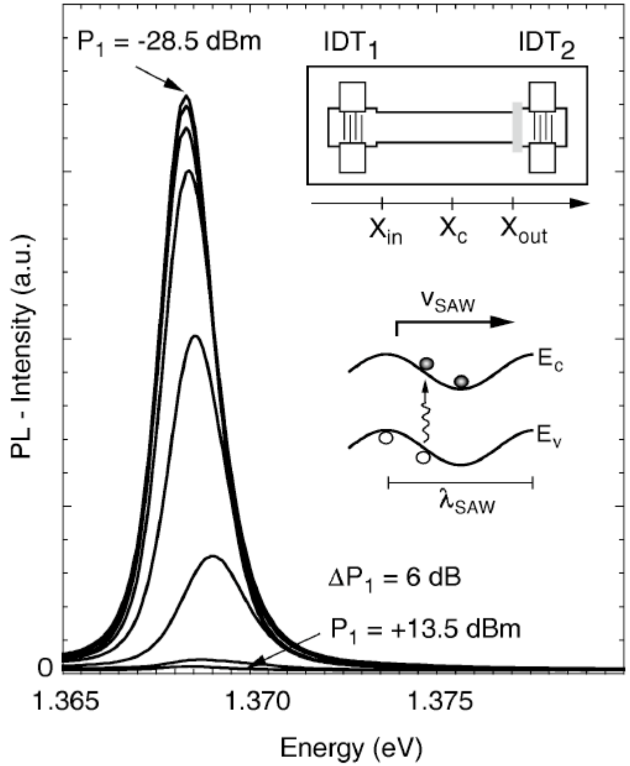


Some typical parameters of SAW:

- Frequency $f = 840$ MHz
- Period $\lambda = 3.4$ μm
- Speed $v \approx 3$ km/s

SAWs are commonly used as frequency filters and delay lines, e.g., in cell phones.

Optoelectronics of surface acoustic waves (SAW)



Rocke, Zimmermann, Wixforth, Kotthaus, Böhm, Weimann (Ludwig-Maximilian University, München) *PRL* **78**, 4099 (1997)

Photons create electron-hole pairs.

Electrons go to the minima of the periodic potential of SAW, and holes go to the maxima.

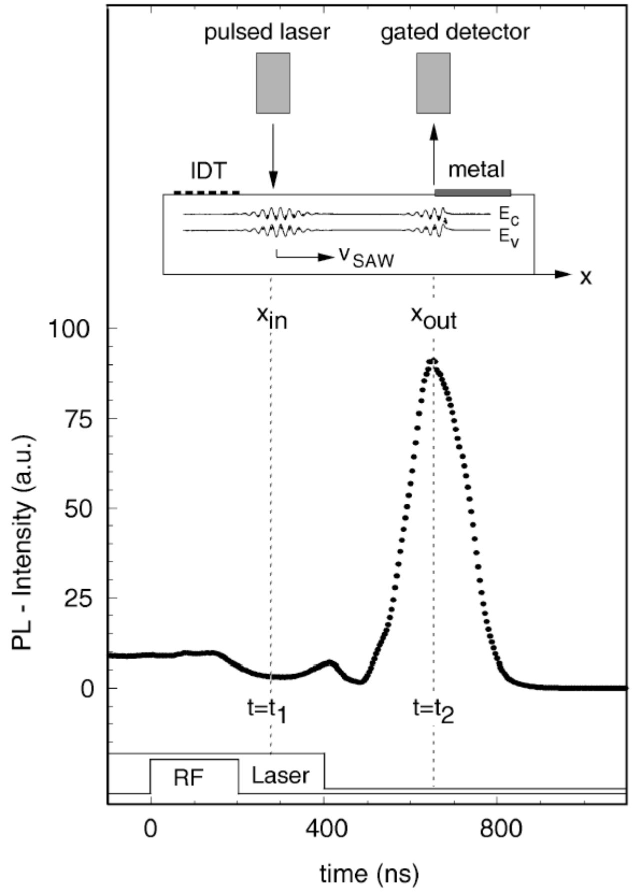
The electric field of SAW, which separates electrons and holes, can be as strong as E = 8 kV/cm.

As a result of spatial separation, recombination of electrons and holes (photoluminescence) is strongly suppressed.

The spatial separation of electrons and holes takes place in the whole volume where SAW is present.

This process works only for moving, not for standing, SAW.

Collective transport of electrons and hole by SAW

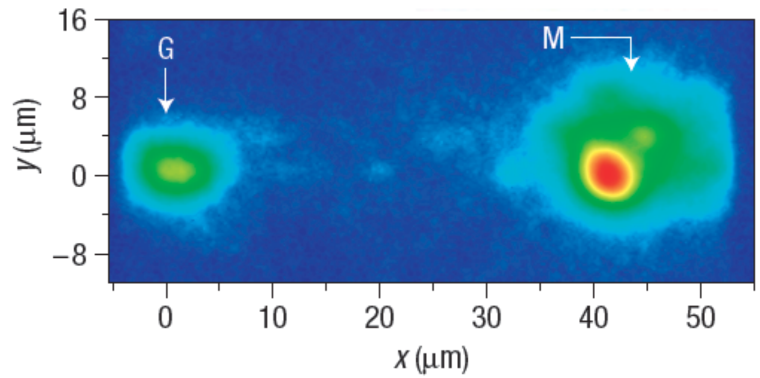


Rocke, Zimmermann, Wixforth, Kotthaus, Böhm, Weimann, *PRL* **78**, 4099 (1997)

Electrons and holes, sitting in the maxima and minima of SAW, are transported collectively with the speed of sound, as passengers on a train.

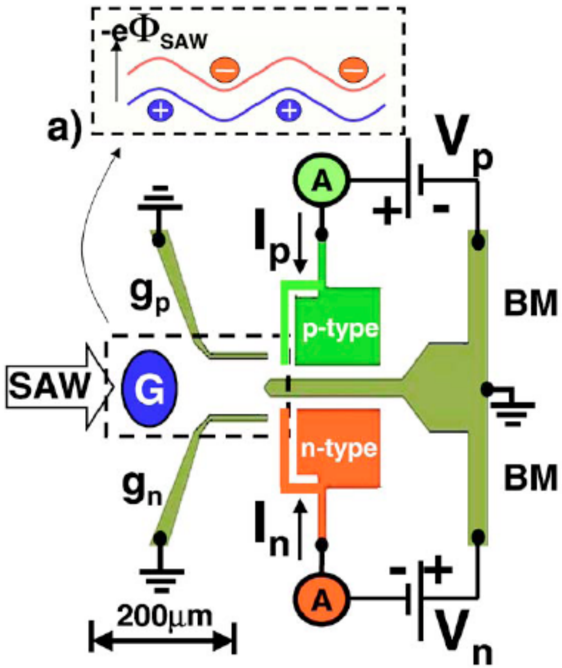
At some distant point, a metal plate screens the periodic potential of SAW, so that electrons and holes recombine and re-emit light.

The transportation distance was as long as 0.3 mm in recent experiments (2009); at room temperature.



Stotz, Hey, Santos, Ploog (Paul-Drude-Institut, Berlin) *Nature Materials* **4**, 585 (2005)

Collection of electrons and hole at electrodes



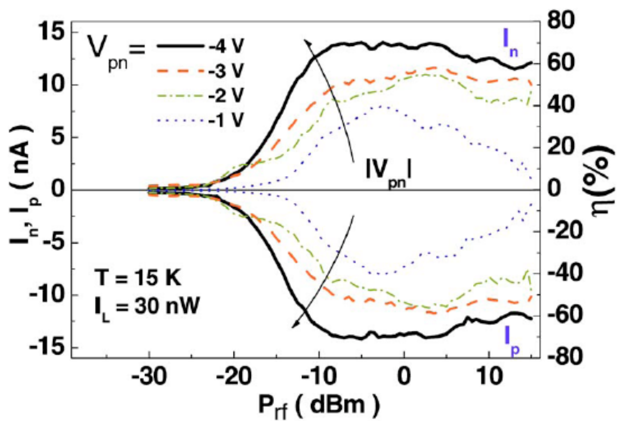
Batista, Hey, Santos,
APL **92**, 262108 (2008)

Jiao, Batista, Biermann, Hey,
Santos, *JAP* **106**, 053708 (2009)

In recent experiments (2008-2009), the ambipolar transport by SAW was utilized to build a sensitive photodetector.

To collect electrons and holes, a lateral *p-n* junction was made by doping GaAs on the sides.

Due to the transverse electric field, electrons and holes move to the opposite contacts across the direction of SAW propagation.

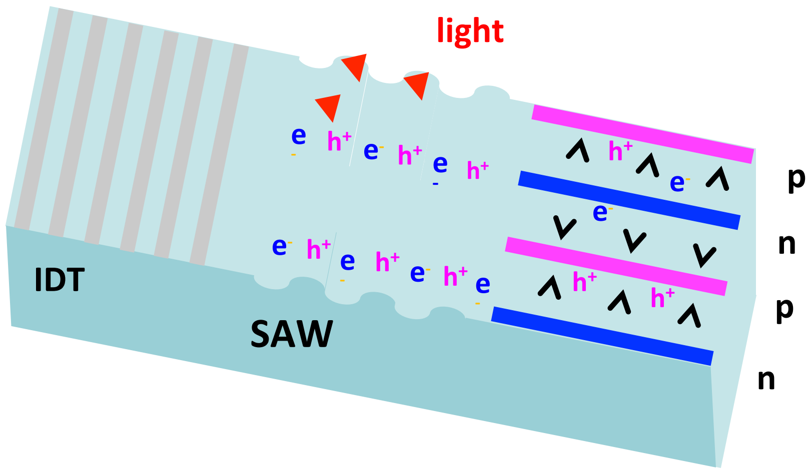


The **quantum efficiency** η (electrons/photons) reached **85%**.

Photovoltaic energy conversion using SAW

Although a photodetector using SAW was built by the group of Paulo Santos in Berlin, there was no attempt to use it for PV energy generation.

The photocurrent was measured, but not the output voltage. Moreover, there were batteries in the output circuit. So, the power efficiency is unknown.



Active design instead of passive: SAW concentrates light energy collected from a large illuminated area into the small contact area.

The design made in Berlin is OK for narrow transverse channels.

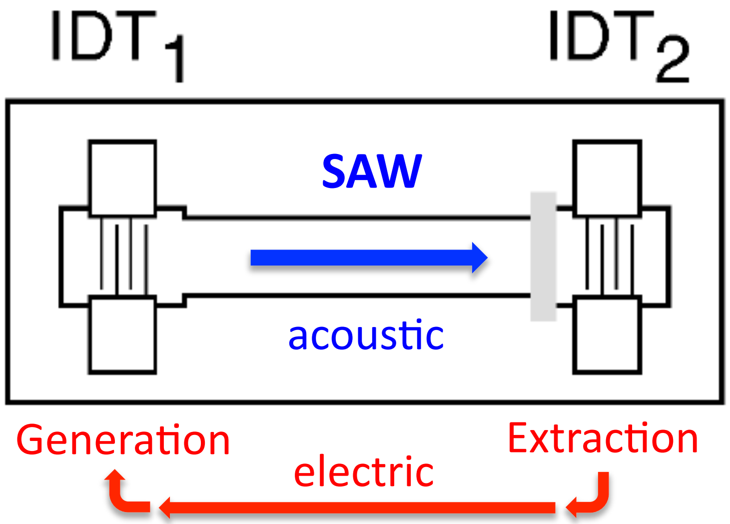
However, for a wide area, we propose to make multiple electrodes on *p* and *n* type parallel to the direction of SAW propagation.

These electrodes create transverse staggered electric field.

They can quickly collect electrons and holes, like unloading passengers off a train to multiple platforms.

Recycling the energy of SAW

Some energy is needed to generate and maintain SAW. However, the energy of SAW can be extracted at the other end of the crystal via IDT and fed back into the loop. Moreover, this is necessary to prevent reflection of SAW.



The energy supplied by an rf generator is only needed to cover losses, which are intrinsically low for SAW.

The total device efficiency depends on scale: how many PV cells are served by an rf generator.

Analogy with consumer appliances: Modern refrigerators use fans in the freezing chamber. Although the fans consume electricity, they increase overall efficiency, because heat convection is more efficient than heat diffusion.

-

Conclusions for PV with SAW

- We present a **radically new design for photovoltaic** energy conversion using surface acoustic waves (SAWs) in piezoelectric semiconductors.
- SAW creates a periodically modulated electric field in a pure (undoped) piezoelectric semiconductor, which spatially separates photogenerated electrons and holes to the maxima and minima of SAW, thus preventing their recombination.
- Electron-hole segregation takes place in a large volume, where SAW is present.
- The segregated electrons and holes are collectively transported by the moving SAW with the speed of sound (about 3 km/s) to the electrodes.
- This **active design** promises high efficiency of photovoltaic energy conversion, as opposed to conventional passive design.
- Recent experiments (2008-2009) using SAWs (albeit designed for photon counting, not for photovoltaics) have demonstrated the photon-to-current **quantum efficiency of 85%**.
- Only the group of Paulo Santos in Berlin has expertise in this subject. We are looking for experimental partners to implement these ideas for photovoltaics.