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Instituto de Energía Solar

Fundamentals of photovoltaic energy conversion and conventional solar cells

A.Martí

17-20 September 2018,
MATENER 2018

ICMAB, Campus UAB, Barcelona

Outline

- Fundamentals of photovoltaic energy conversion
- Conventional (inorganic) solar cells

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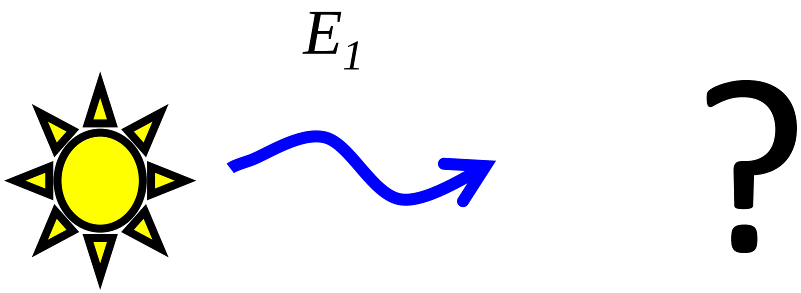
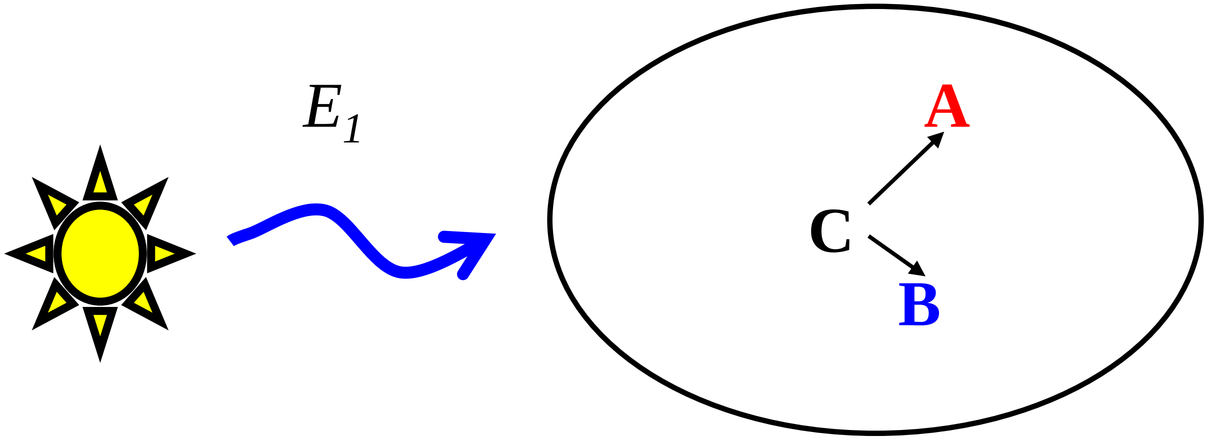
- Fundamentals of photovoltaic energy conversion
- Conventional (inorganic) solar cells

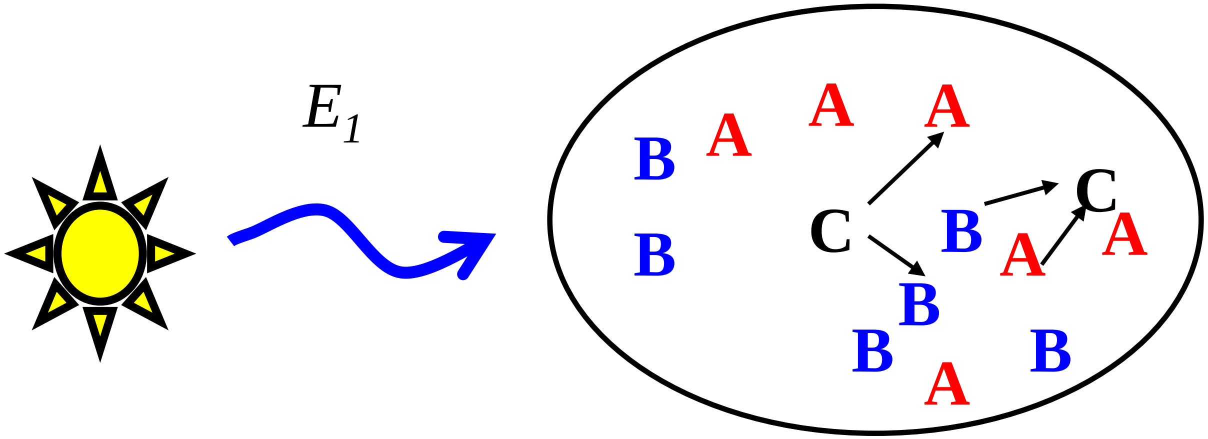
What is needed for a PV converter?



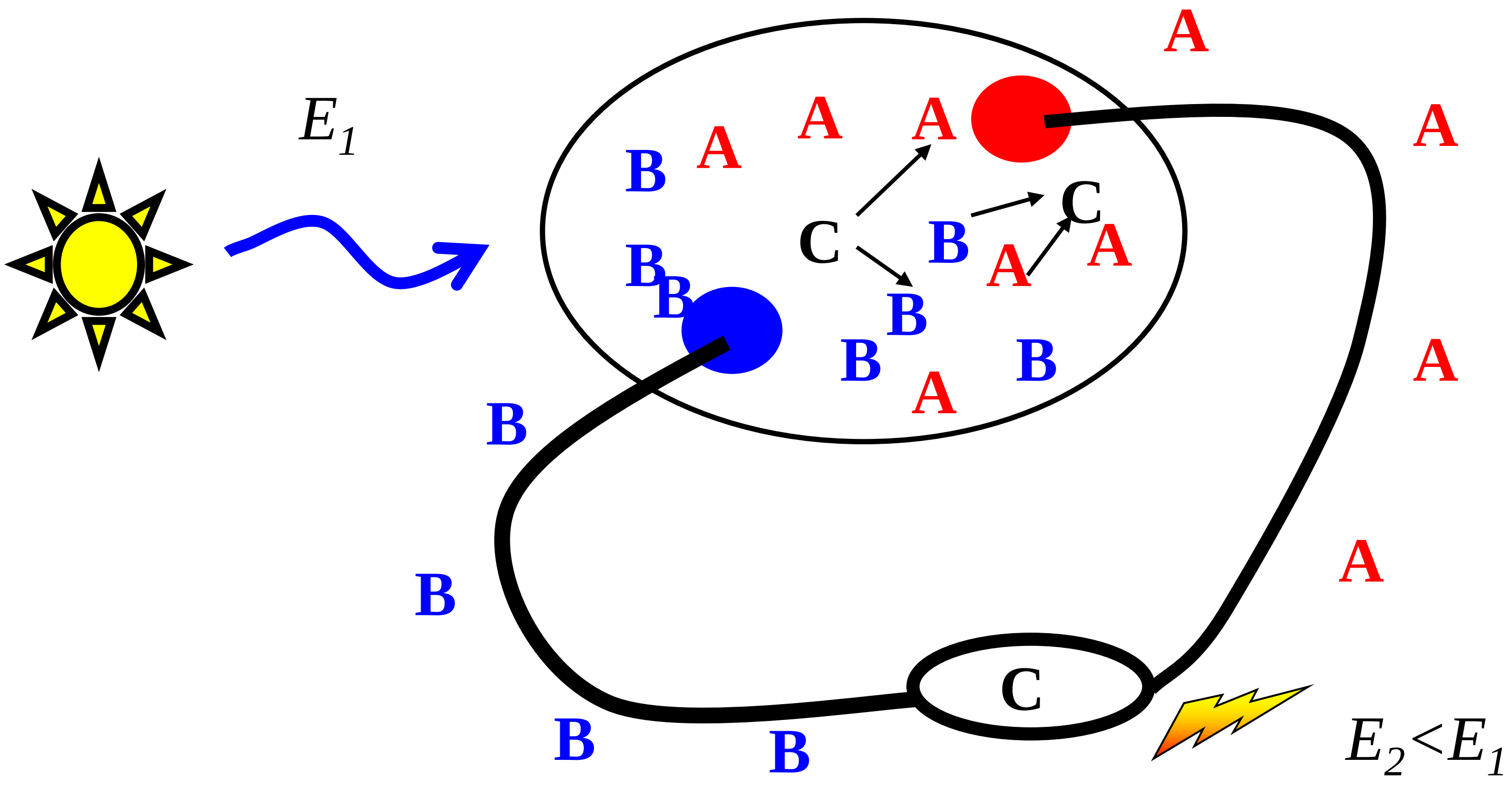
What is needed for a PV converter? A material sensitive to light



What is needed for a PV converter?: Transport x lifetime

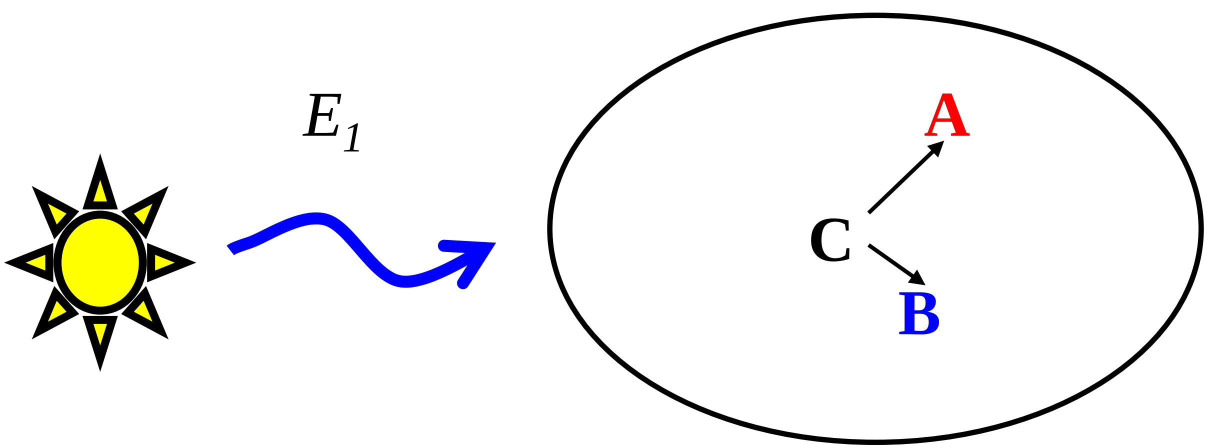


What is needed for a PV converter? Selective contacts

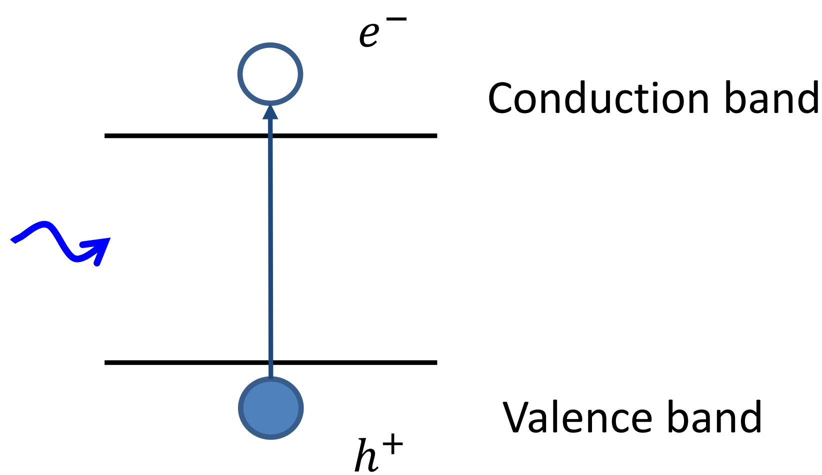


$$\text{Efficiency} \equiv \eta = \frac{E_2}{E_1}$$

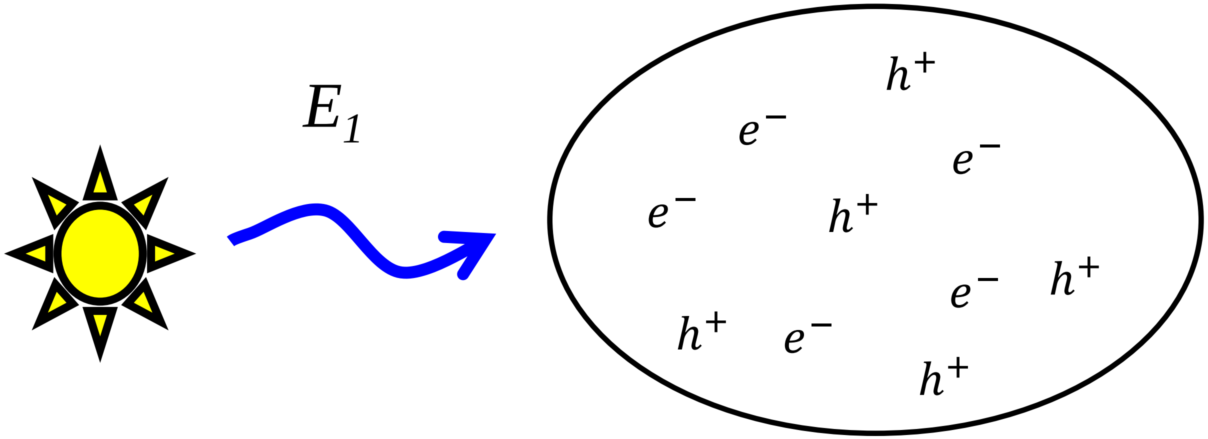
A material sensitive to light: A semiconductor



By Enricoros at English Wikipedia

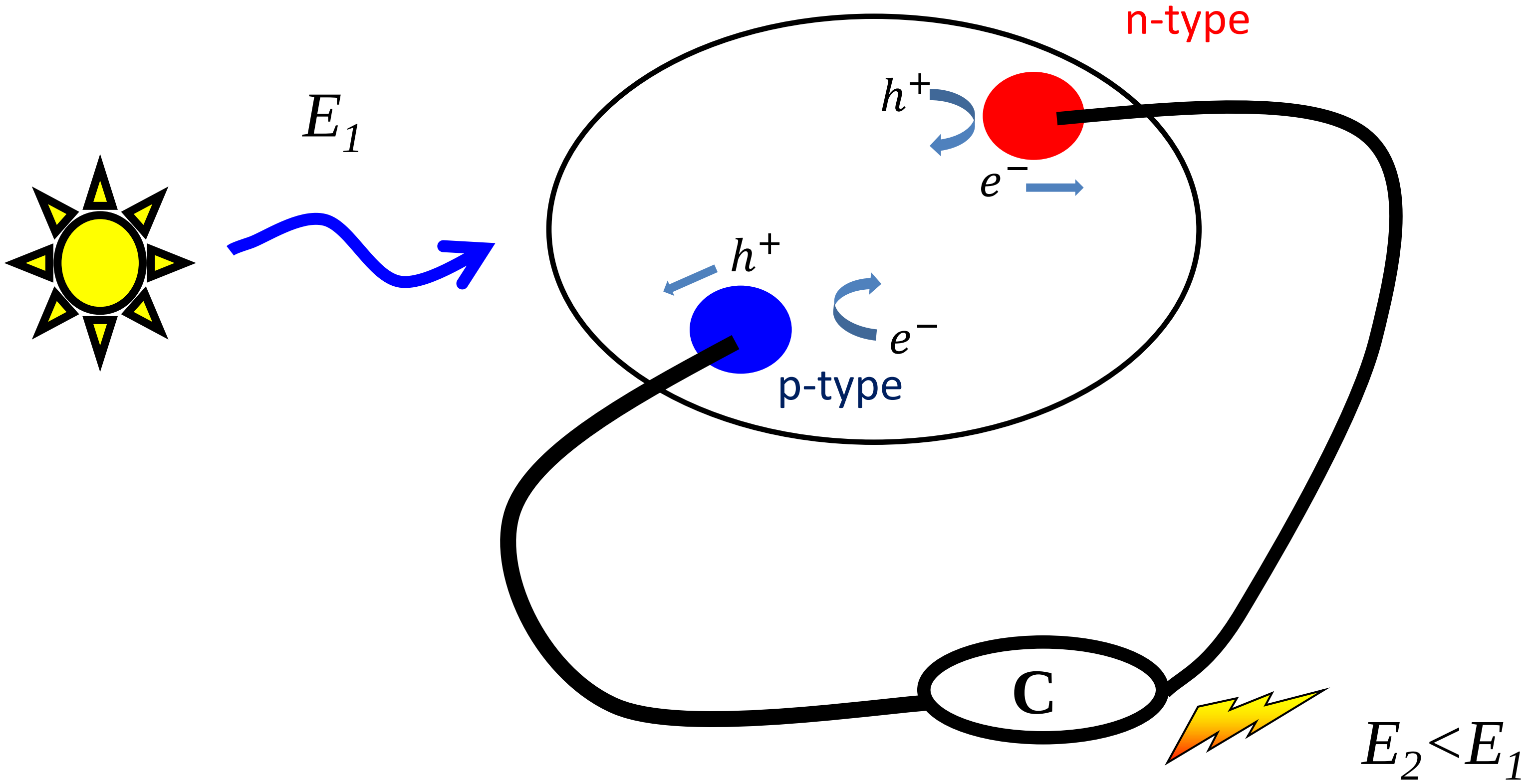


Transport x lifetime

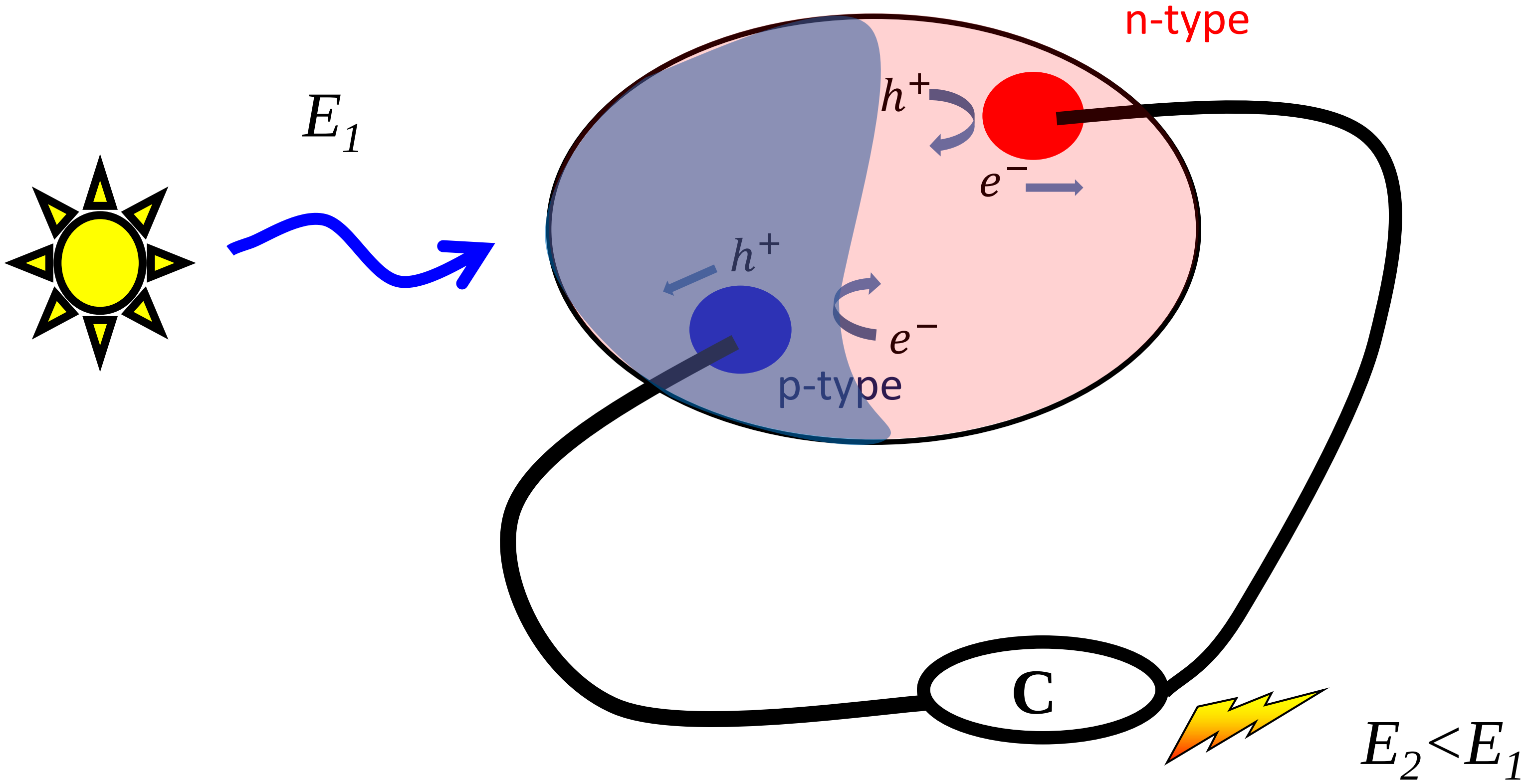


$$\text{Diffusion length} \propto \sqrt{\text{mobility} \times \text{lifetime}}$$

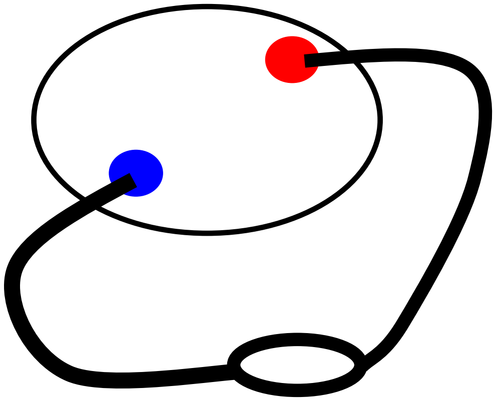
Selective contacts: p-type and n-type semiconductors



Selective contacts: p-type and n-type semiconductors



The solar cell as pn junction



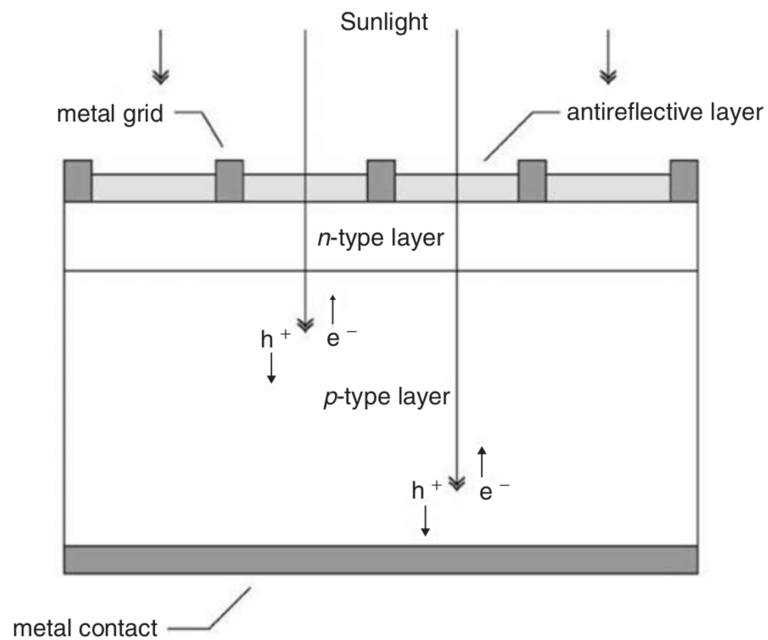
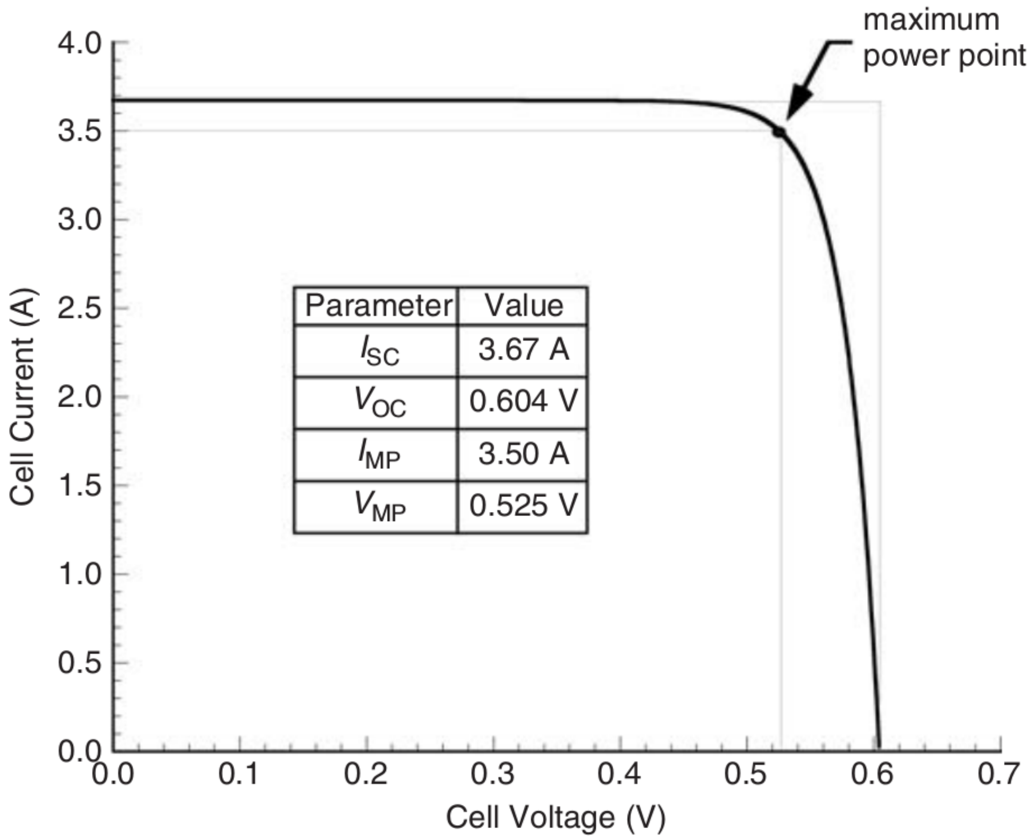


Figure 3.1 A schematic of a simple conventional solar cell. Creation of electron–hole pairs, e^- and h^+, respectively, is depicted

J.L.Gray, Handbook of photovoltaic Science and Engineering 2 ed. (John Wiley & Sons, Chichester, 2004).

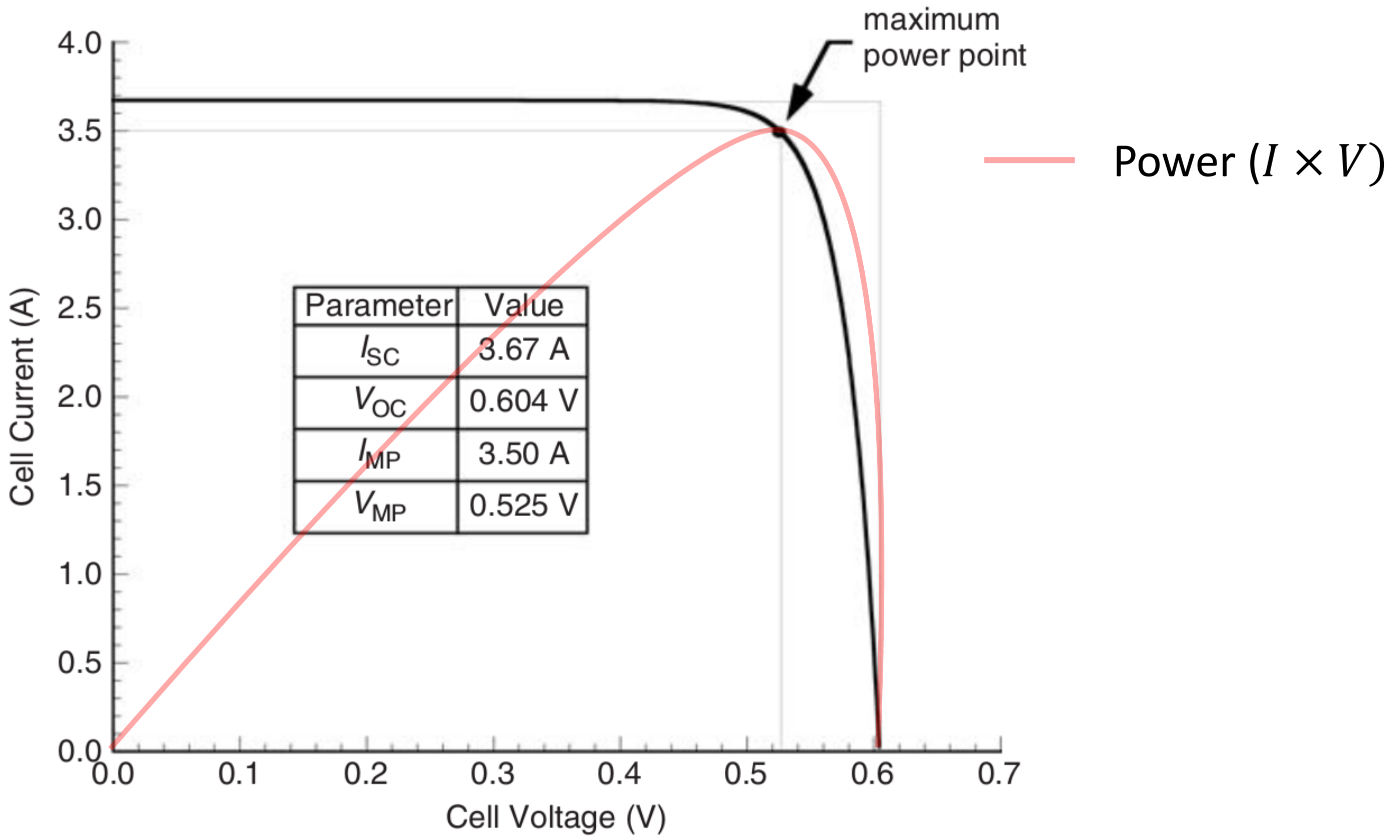
Current-voltage characteristic of a solar cell



Parameter	Value
I_{SC}	3.67 A
V_{OC}	0.604 V
I_{MP}	3.50 A
V_{MP}	0.525 V

J.L.Gray, Handbook of photovoltaic Science and Engineering 2 ed. (John Wiley & Sons, Chichester, 2004).

Current-voltage characteristic of a solar cell

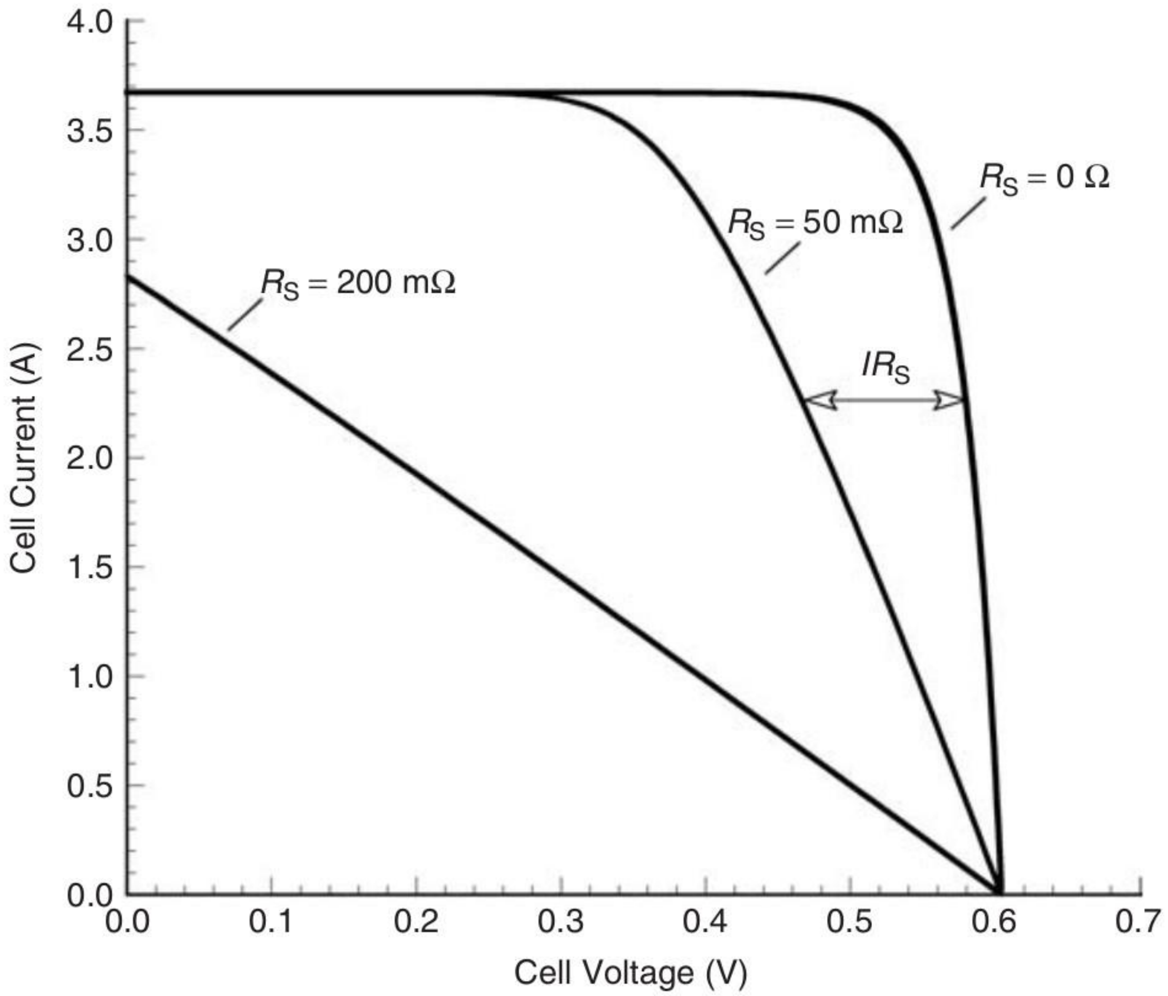


Parameter	Value
I_{SC}	3.67 A
V_{OC}	0.604 V
I_{MP}	3.50 A
V_{MP}	0.525 V

$$\eta = \frac{I_{MP} \times V_{MP}}{\text{Incicent Pw}} = \frac{I_{MP} \times V_{MP} \times FF}{\text{Incicent Pw}}$$

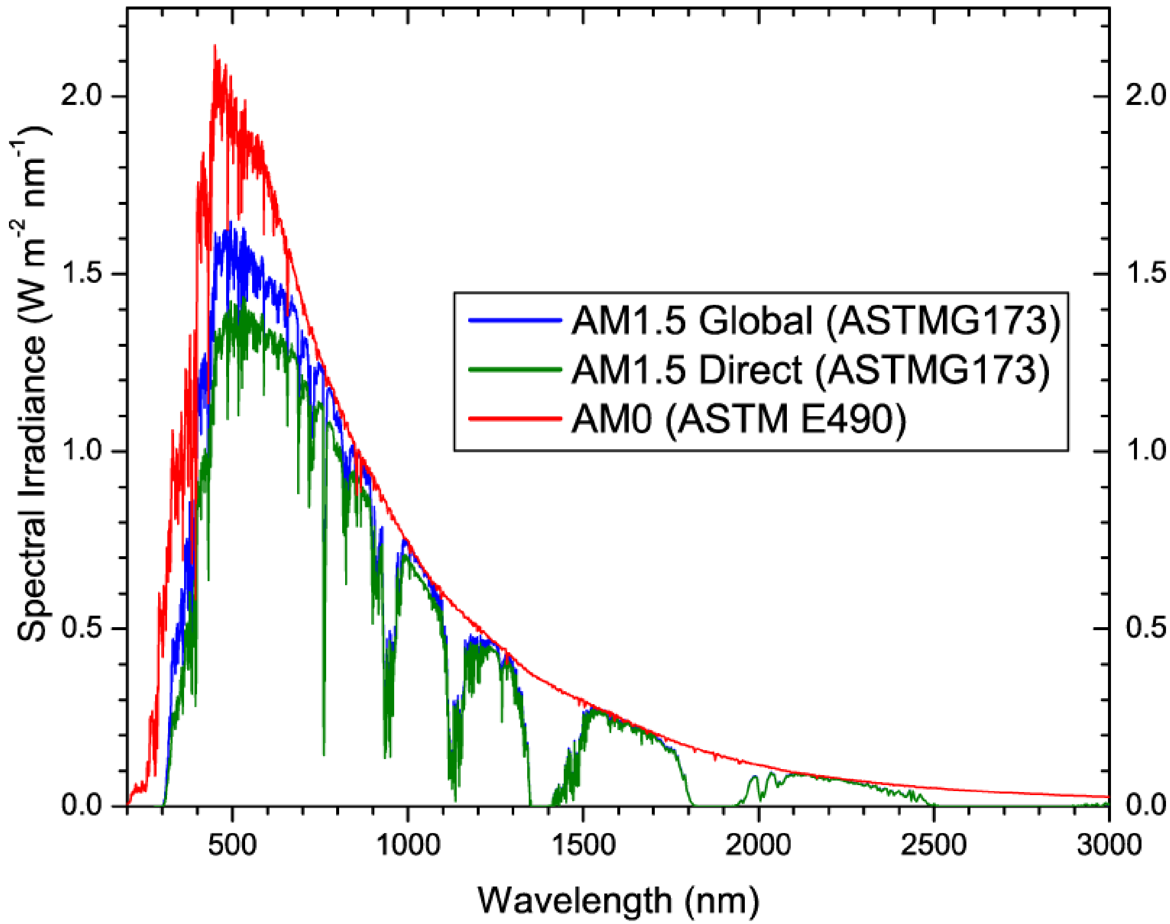
J.L.Gray, Handbook of photovoltaic Science and Engineering 2 ed. (John Wiley & Sons, Chichester, 2004).

Impact of series resistance on FF



J.L.Gray, Handbook of photovoltaic Science and Engineering 2 ed. (John Wiley & Sons, Chichester, 2004).

Input power (solar spectra)

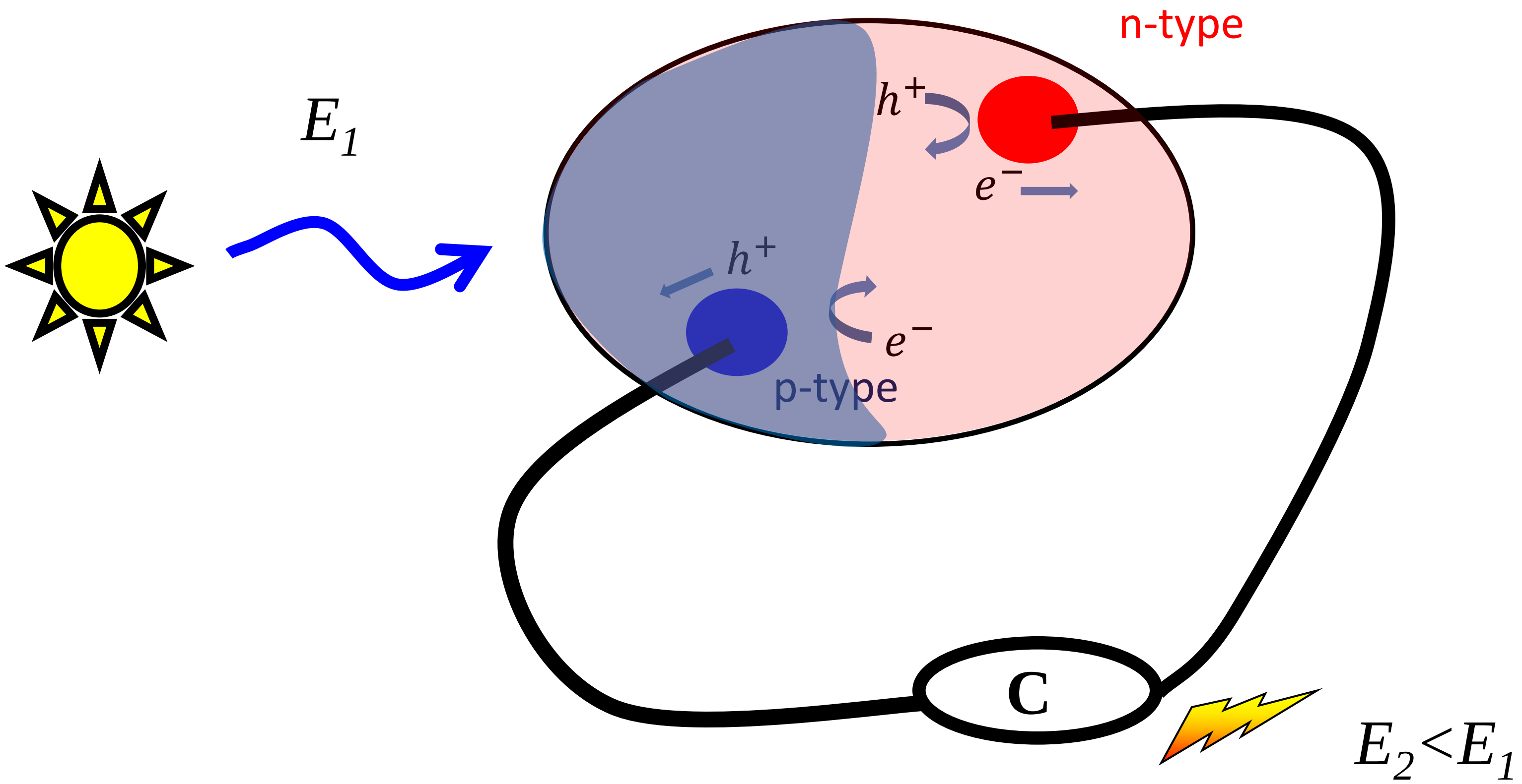


$1000\ \mathrm{Wm^{-2}}$

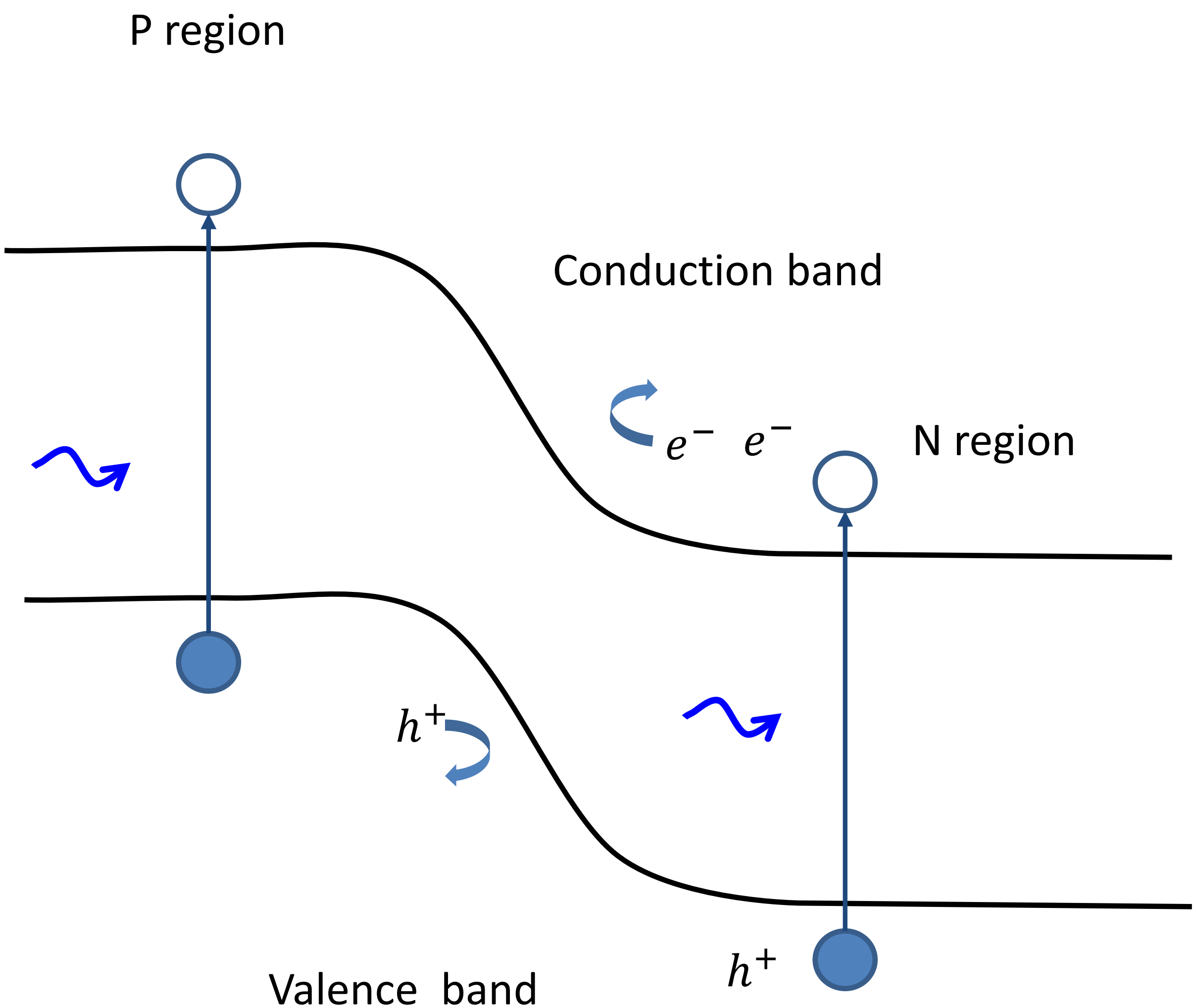
$900\ \mathrm{Wm^{-2}}$

$1350\ \mathrm{Wm^{-2}}$

Selective contacts: p-type and n-type semiconductors



Pn junction bandgap diagram



The role of the electric field

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CURSO DE ENERGIA SOLAR FOTOVOLTAICA

Capítulo 1

Fundamentos de la Conversión Fotovoltaica:
La Célula Solar

Antonio Martí
Instituto de Energía Solar - UPM

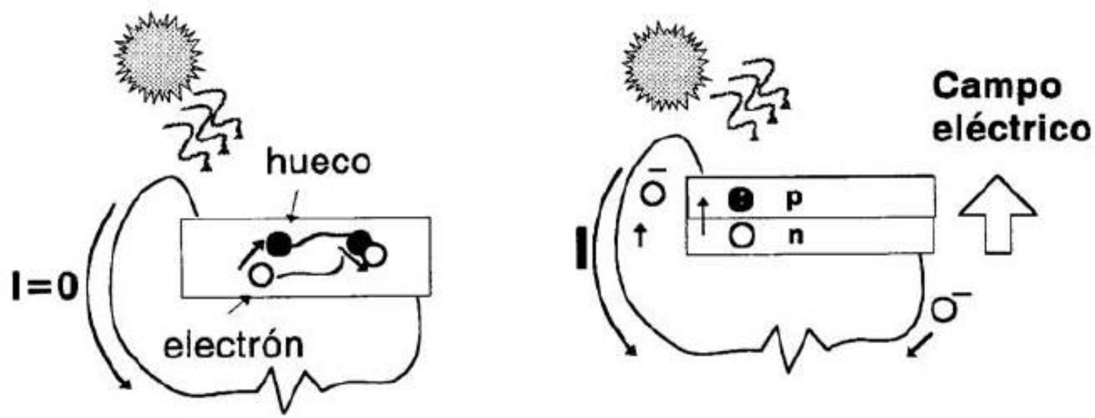
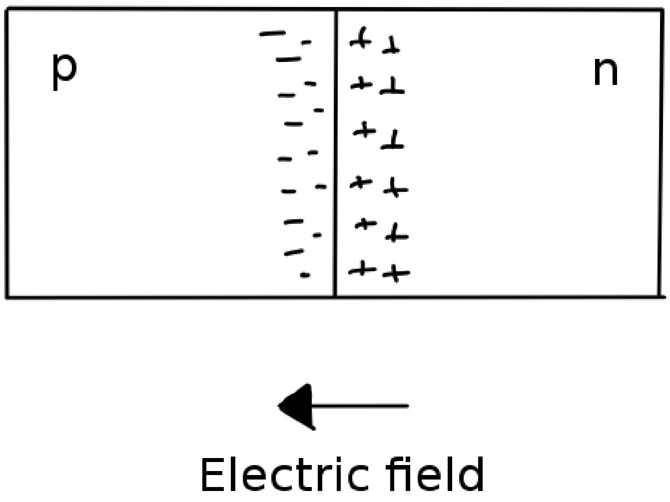
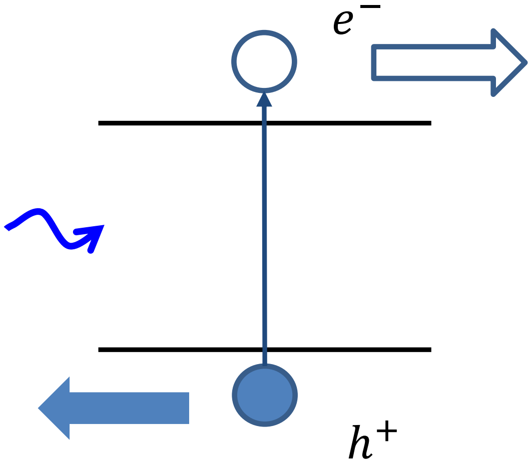


Figura 7. Un semiconductor, sin estructura *pn*, (izquierda) aunque se ilumine no provoca la circulación de corriente eléctrica. La unión *pn* hace posible la circulación de la corriente eléctrica gracias a la presencia de un campo eléctrico.

The solar cell as pn junction (wrong argument)

- p, n regions absorb light and the electric field is negligible
- Instead, the concept of electrochemical potential as driving force must be used





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- Fundamentals of photovoltaic Energy conversion
- Conventional (inorganic) solar cells

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- Conventional (inorganic) solar cells
  - silicon
  - III-Vs (multi-junction solar cells, GaAs, InGaP, InGaAs…)
  - thin films

Solar Cell Efficiency records (as in 2018)

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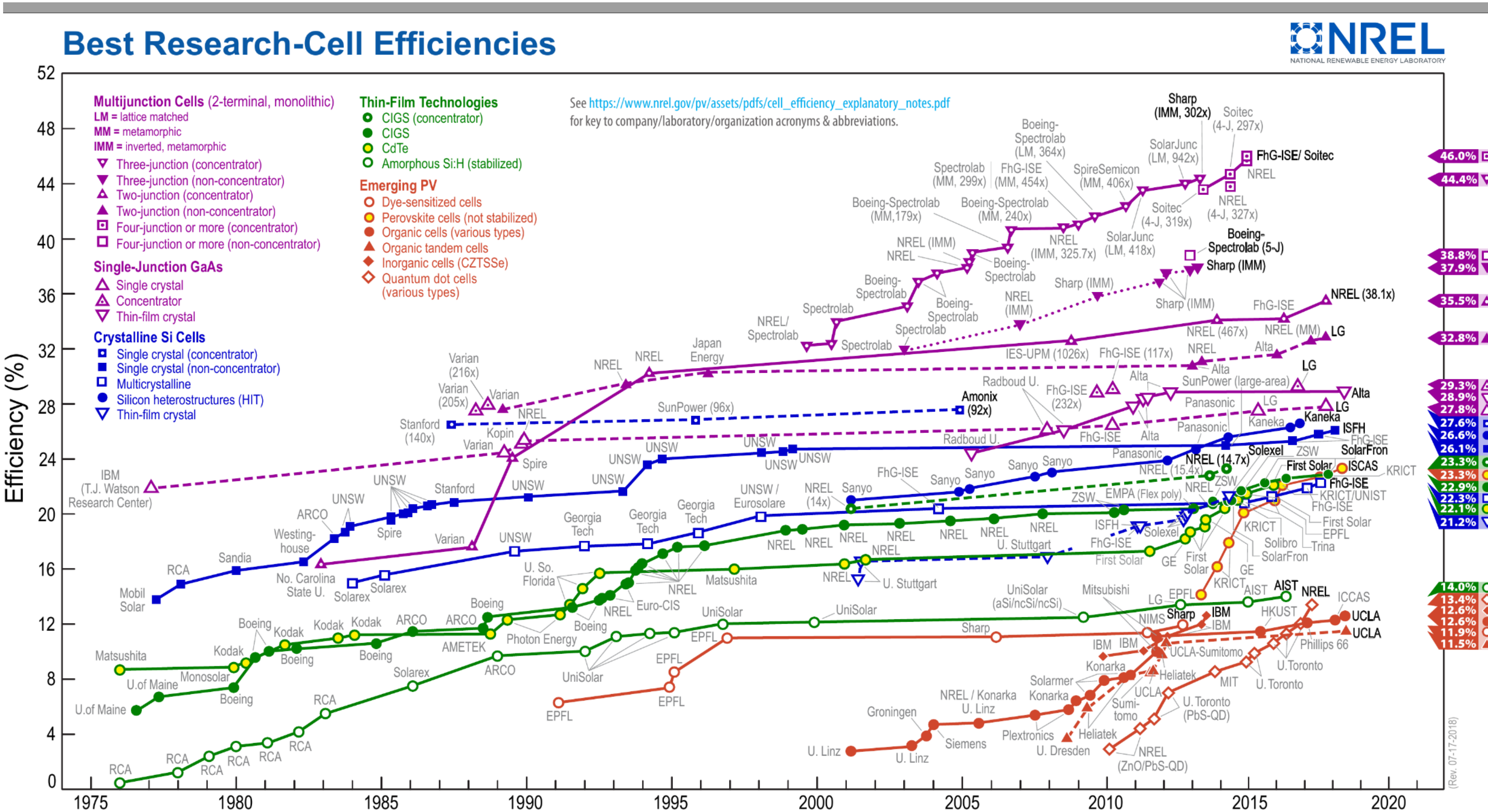
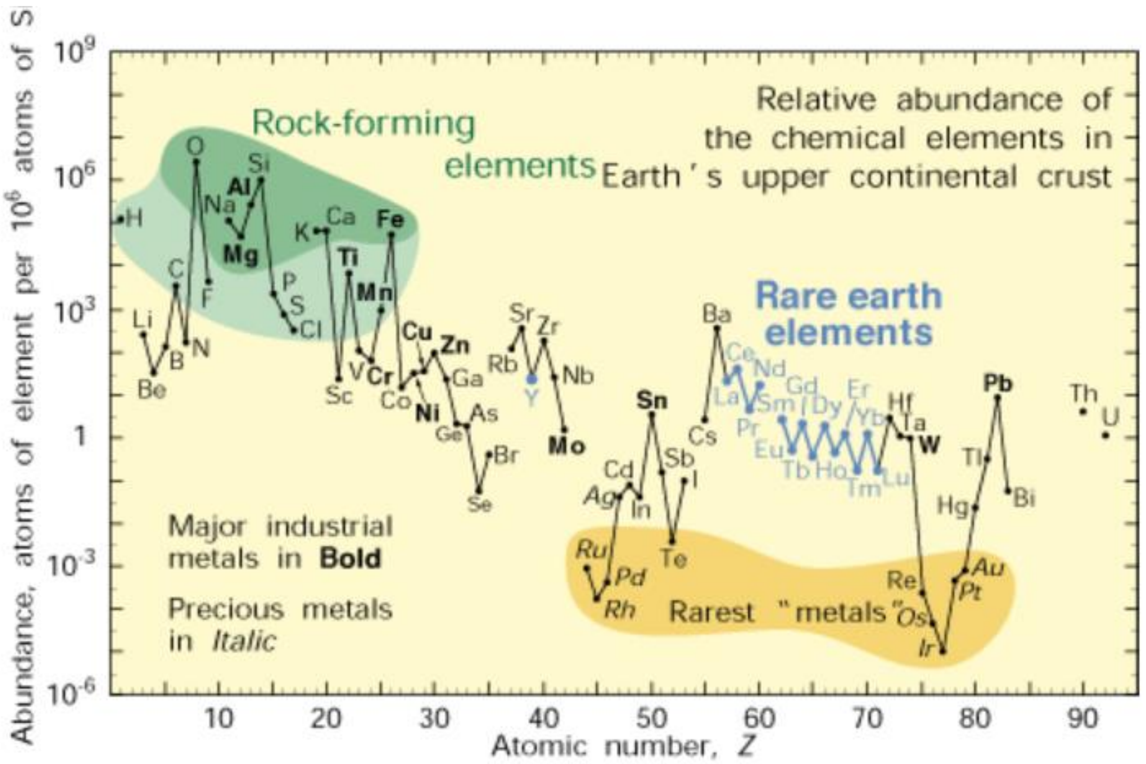


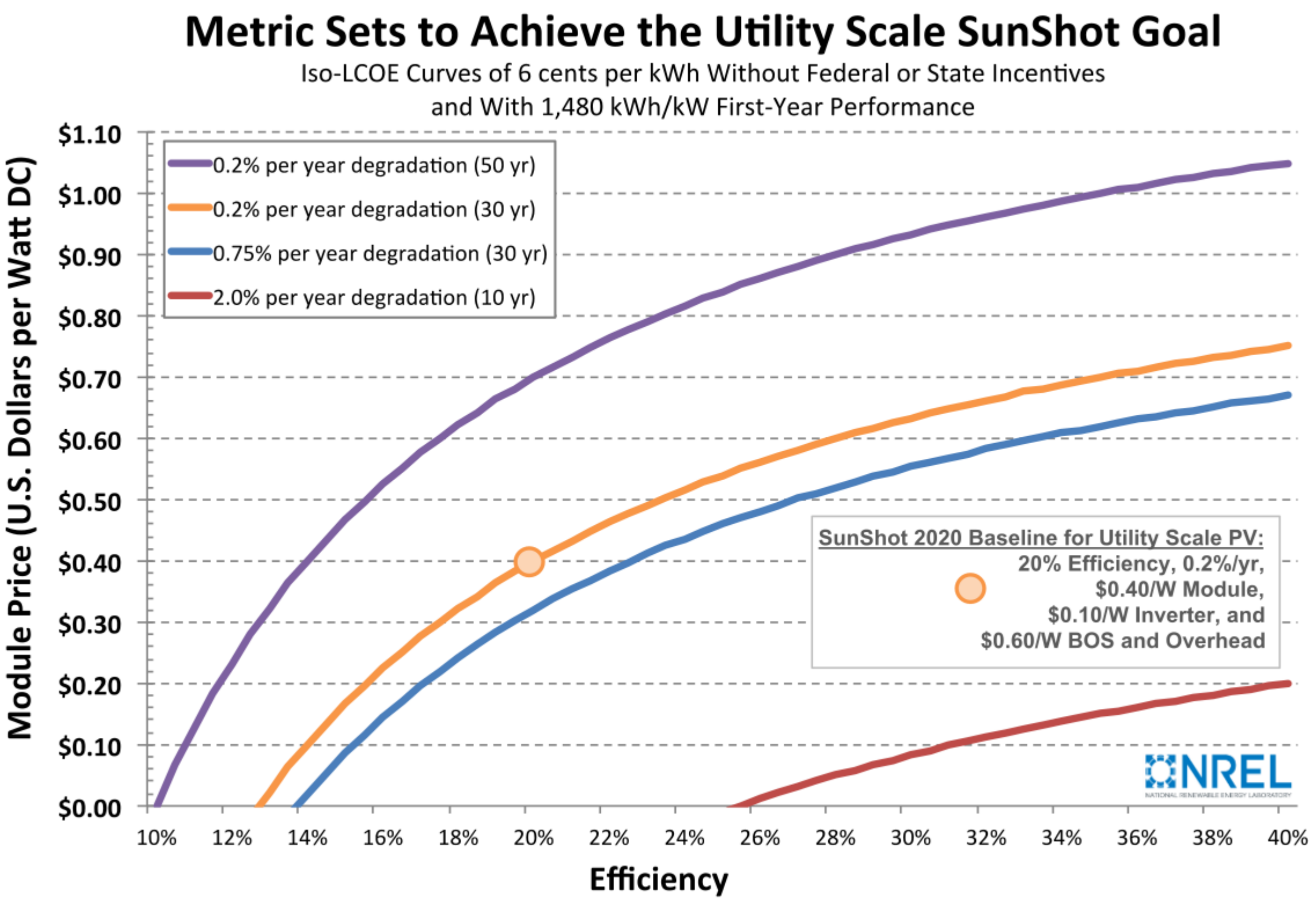
The abundance of materials problem

- Si – not a problem
- Cu(InGa)Se_2 -> In
- CdTe -> Te
- Multijunction -> Ge



P.H. Stauffer et al, Rare Earth Elements - Critical Resources for High Technology, USGS (2002)

Impact of stability on cost



R. Jones-Albertus, D. Feldman, R. Fu, K. Horowitz, and M. Woodhouse, "Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity," *US DOE and NREL (http://energy.gov/sites/prod/files/2015/09/f26/NREL%20Paper%2009-16-15.pdf), 2015.*

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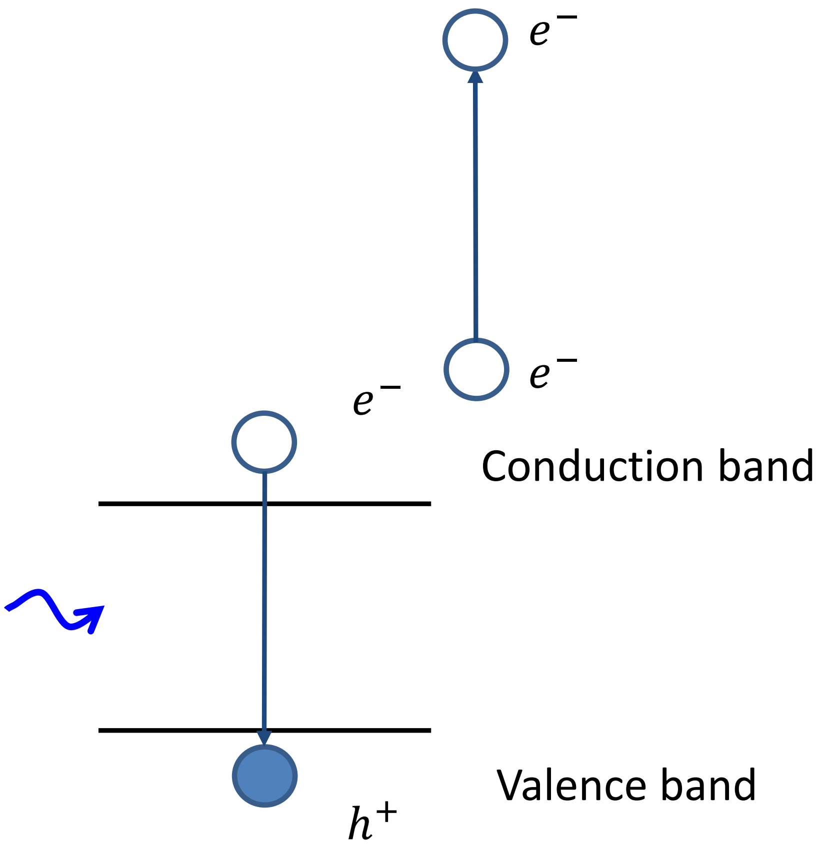
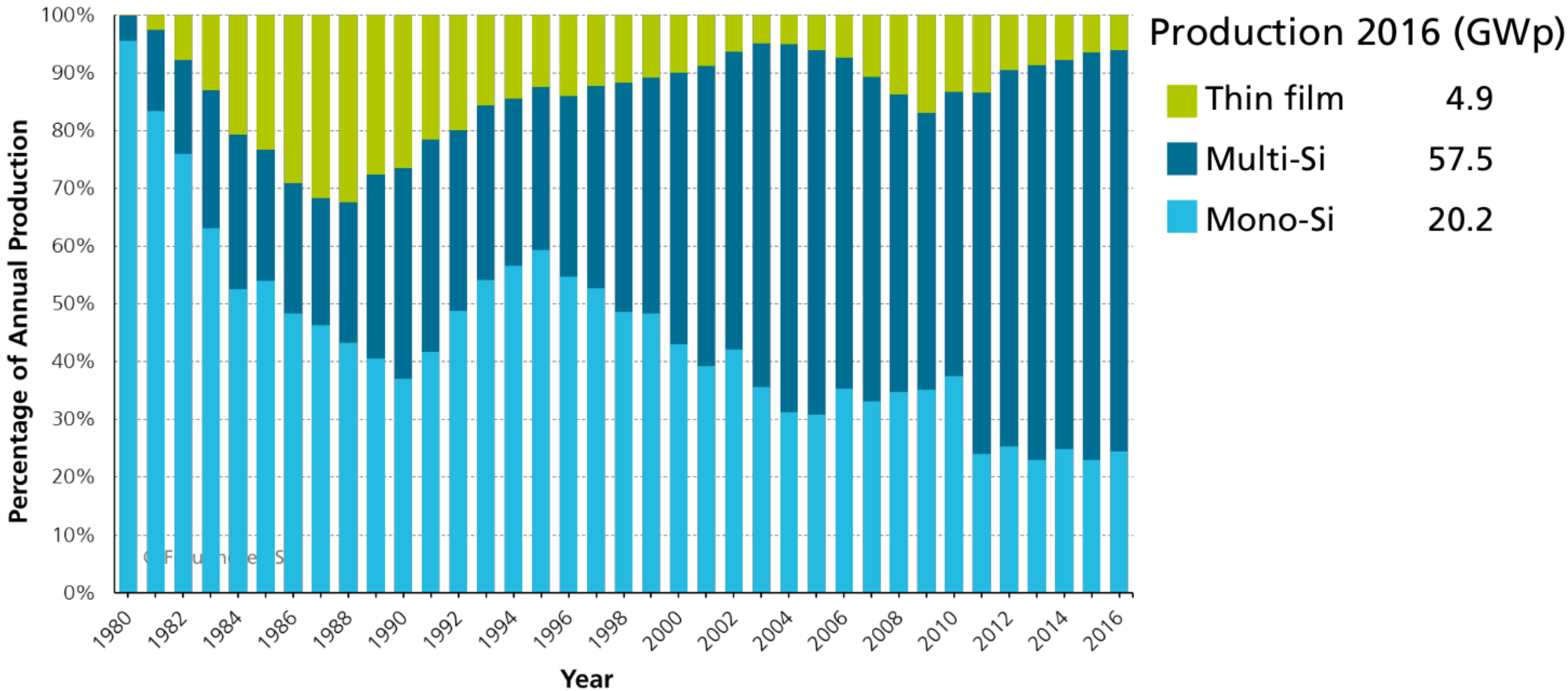
  - silicon
  - III-Vs (multi-junction solar cells, GaAs, InGaP, InGaAs…)
  - thin films

Silicon: some properties

- Weak absorption
- Recombination limited by Auger

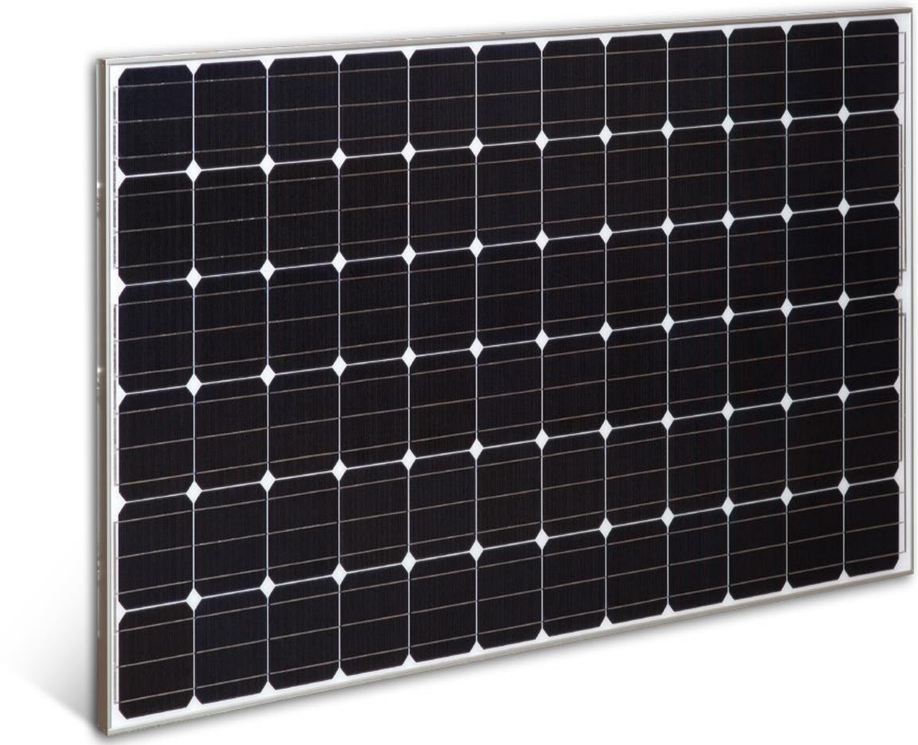


Silicon dominates de market



PHOTOVOLTAICS REPORT (2017). Fraunhofer ISE.

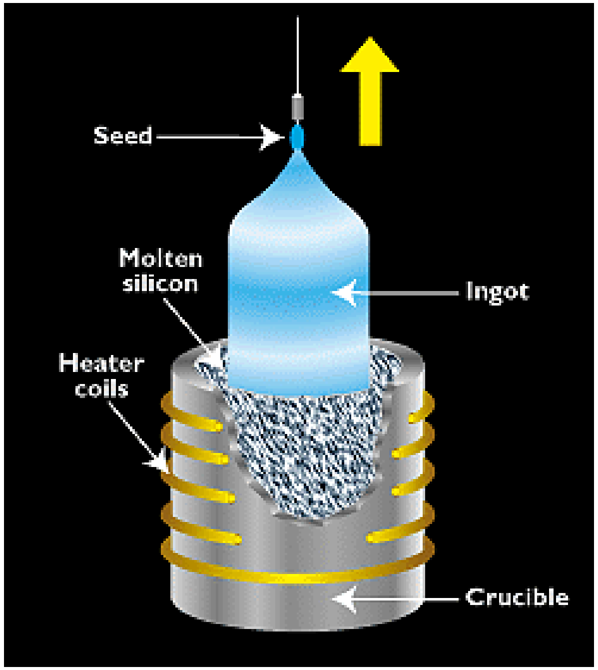
Monocrystalline and Multicrystalline modules

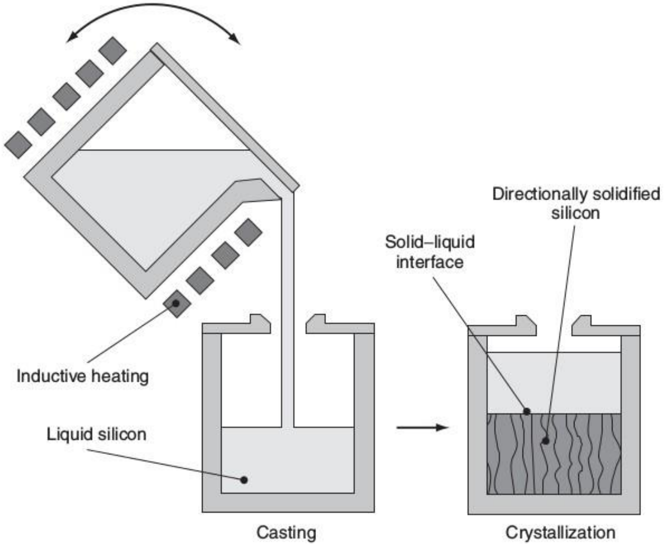


Mono

Multi

Monocrystalline and Multicrystalline modules



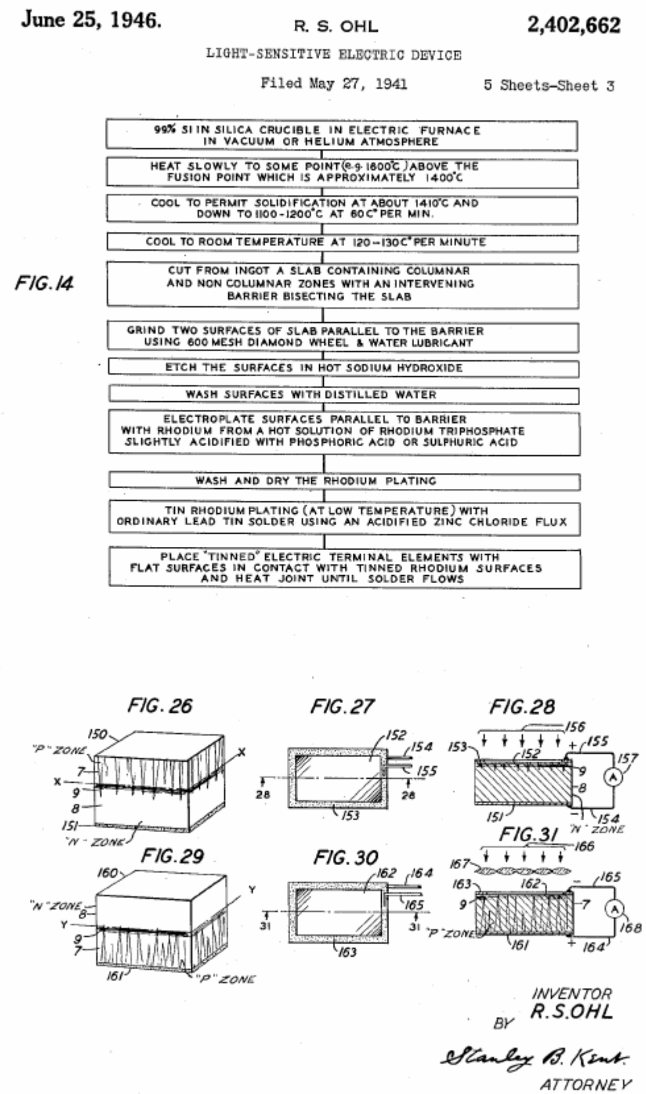


Mono

Multi

1946 - 1%

Russel Ohl
(Technology Review)



June 25, 1946. R. S. OHL 2,402,662

LIGHT-SENSITIVE ELECTRIC DEVICE

Filed May 27, 1941 5 Sheets-Sheet 3

FIG. 14

99% SI IN SILICA CRUCIBLE IN ELECTRIC FURNACE IN VACUUM OR HELIUM ATMOSPHERE

HEAT SLOWLY TO SOME POINT (e.g. 1600°C) ABOVE THE FUSION POINT WHICH IS APPROXIMATELY 1400°C

COOL TO PERMIT SOLIDIFICATION AT ABOUT 1410°C AND DOWN TO 1100-1200°C AT 60C° PER MIN.

COOL TO ROOM TEMPERATURE AT 120-130C° PER MINUTE

CUT FROM INGOT A SLAB CONTAINING COLUMNAR AND NON COLUMNAR ZONES WITH AN INTERVENING BARRIER BISECTING THE SLAB

GRIND TWO SURFACES OF SLAB PARALLEL TO THE BARRIER USING 600 MESH DIAMOND WHEEL & WATER LUBRICANT

ETCH THE SURFACES IN HOT SODIUM HYDROXIDE

WASH SURFACES WITH DISTILLED WATER

ELECTROPLATE SURFACES PARALLEL TO BARRIER WITH RHODIUM FROM A HOT SOLUTION OF RHODIUM TRIPHOSPHATE SLIGHTLY ACIDIFIED WITH PHOSPHORIC ACID OR SULPHURIC ACID

WASH AND DRY THE RHODIUM PLATING

TIN RHODIUM PLATING (AT LOW TEMPERATURE) WITH ORDINARY LEAD TIN SOLDER USING AN ACIDIFIED ZINC CHLORIDE FLUX

PLACE "TINNED" ELECTRIC TERMINAL ELEMENTS WITH FLAT SURFACES IN CONTACT WITH TINNED RHODIUM SURFACES AND HEAT JOINT UNTIL SOLDER FLOWS

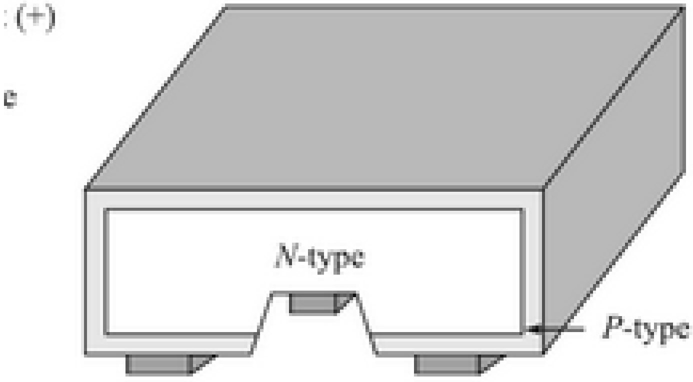
FIG. 26 FIG. 27 FIG. 28

FIG. 29 FIG. 30 FIG. 31

INVENTOR
R. S. OHL
BY
Stanley B. Kent
ATTORNEY

1954 (6%)

Person, Chapin, Fuller (Perlin, The silicon solar cell turns 50)

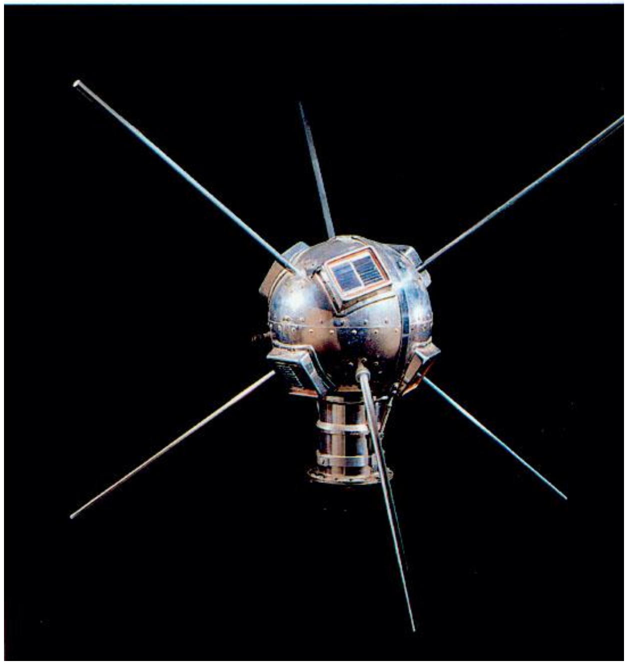


b) Structure of 6% efficient solar cell in CZSi wafer and diffused junction developed in 1954

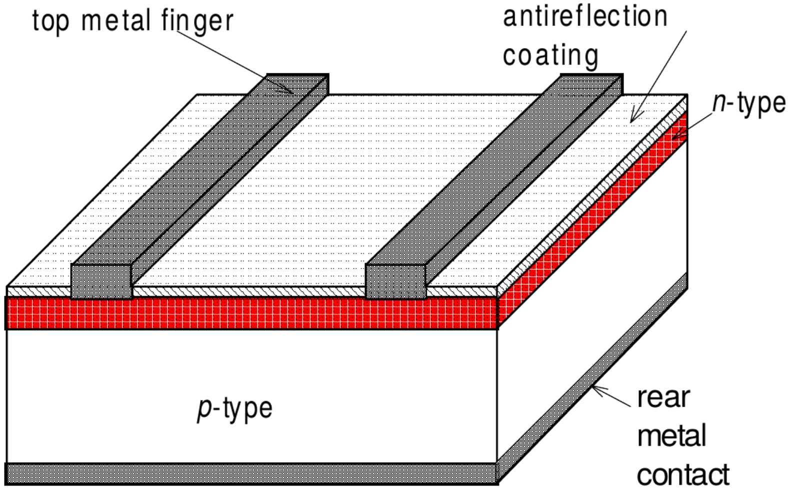
First advertisement

1956 advisement of “Look magazine” (Perlin, The silicon solar cell turns 50)

1958-1972 – 14 %   “Space”

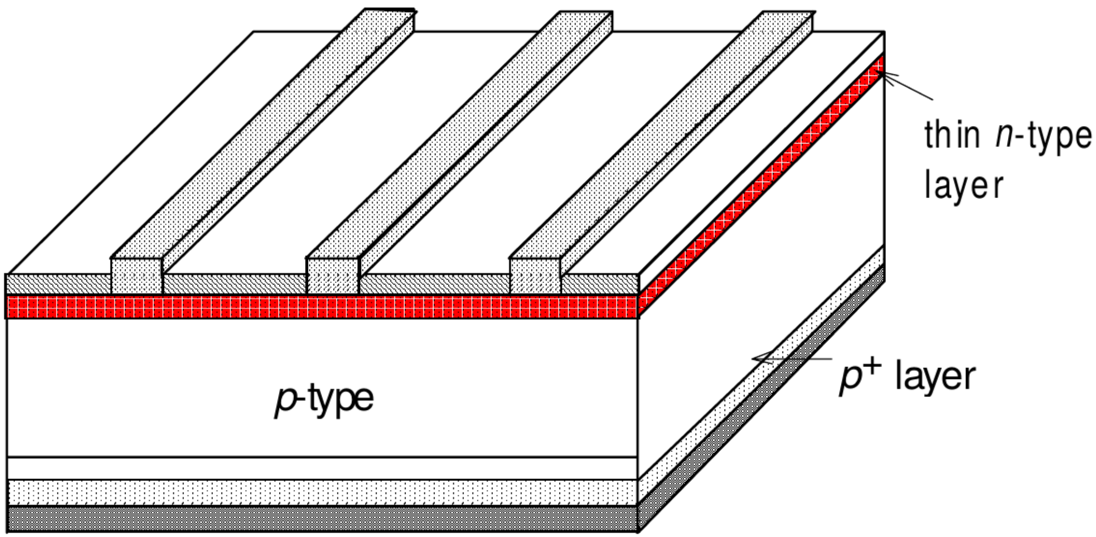


Vanguard I (1958)



(Source: M.A.Green, Chap 4 in Clean Energy from Photovoltaics)

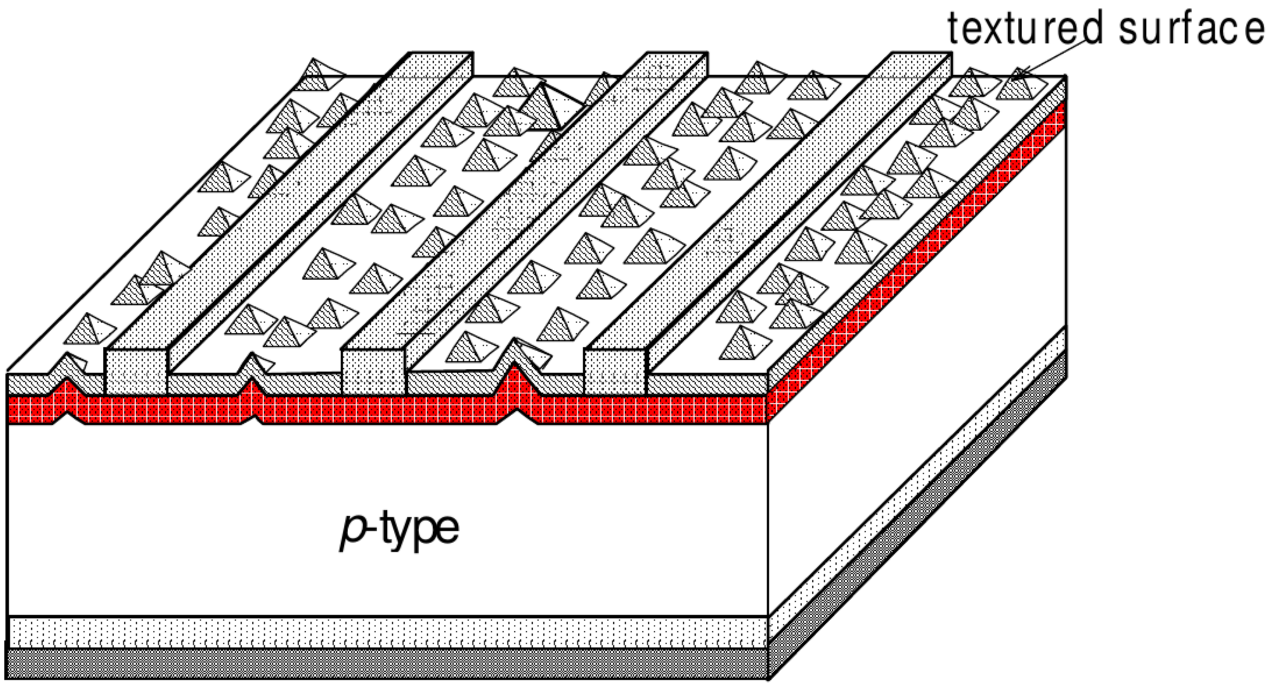
1972 – 15 % (Violet cell)



Selective contact!

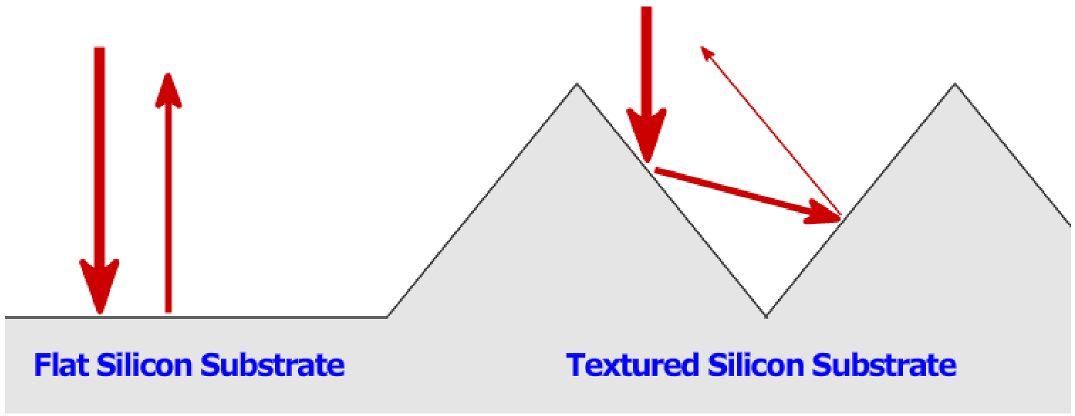
(Source: M.A.Green, Chap 4 in Clean Energy from Photovoltaics)

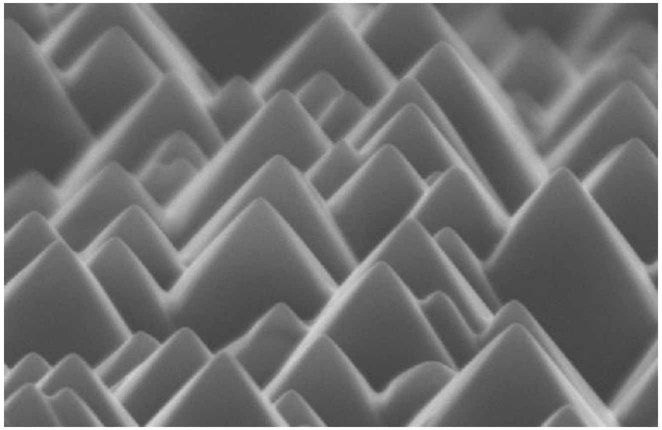
1974 – 18% (Black cell)



(Source: M.A.Green, Chap 4 in Clean Energy from Photovoltaics)

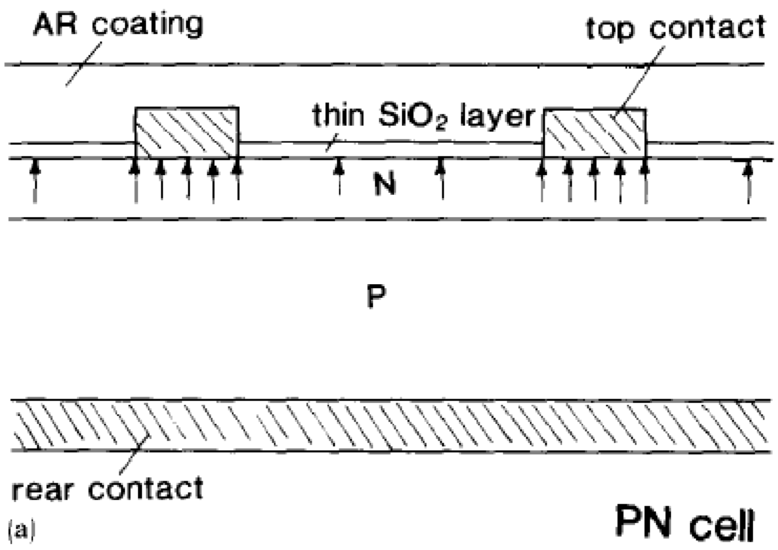
Texturing

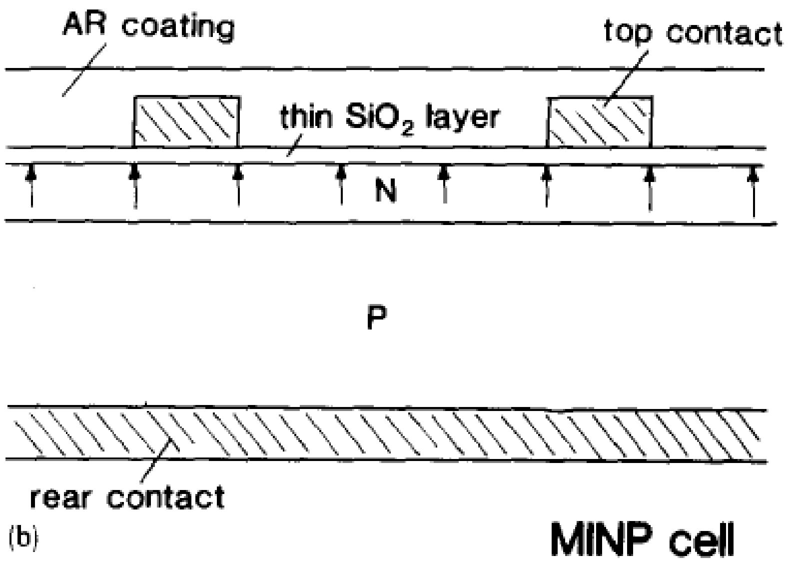




Source: PVEducation

1983 – 18% (Metal to insulator np junction - MINP cell)

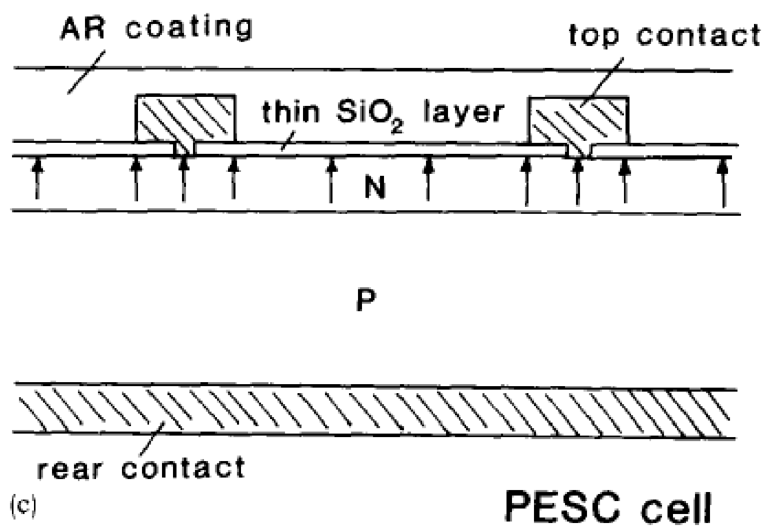




Green, M. A., Blakers, A. W., Shi, J., Keller, E. M., & Wenham, S. R. (1984). 19.1% efficient silicon solar cell. *Applied Physics Letters*, *44*(12), 1163-1164.

UNSW

1984 – 19% (Passivated emitter solar cell – PESC)



Green, M. A., Blakers, A. W., Shi, J., Keller, E. M., & Wenham, S. R. (1984). 19.1% efficient silicon solar cell. Applied Physics Letters, 44(12), 1163-1164.

1986 – 20 % (μg-PESC)

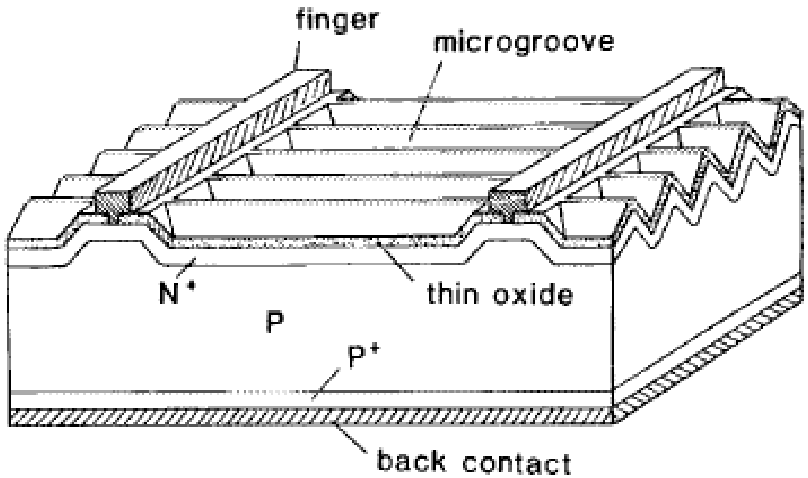
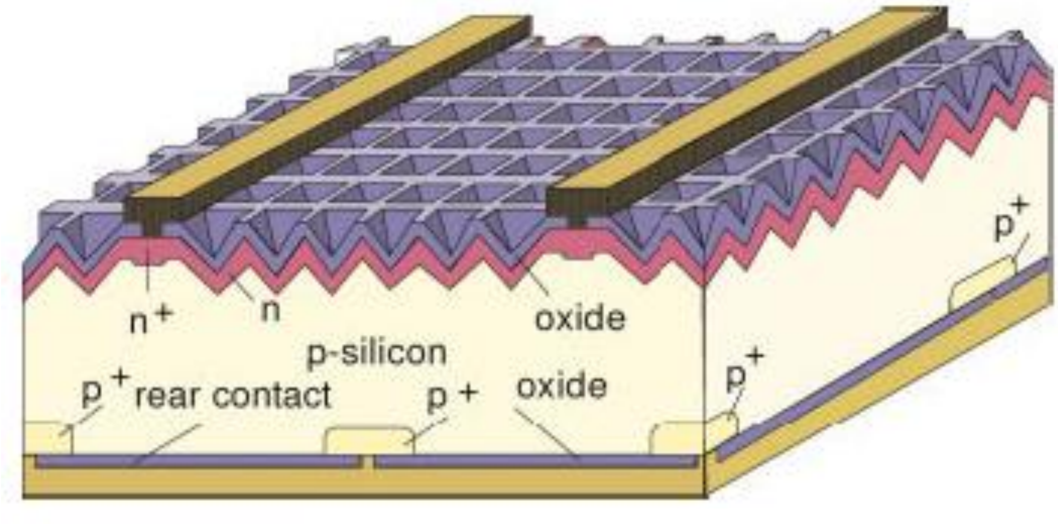


FIG. 1. Schematic diagram of a microgrooved passivated emitter solar cell (PESC). The cell double layer antireflection coating is not shown (not to scale).

Blakers, A. W., & Green, M. A. (1986). 20% efficiency silicon solar cells. *Applied physics letters*, *48*(3), 215-217.

UNSW

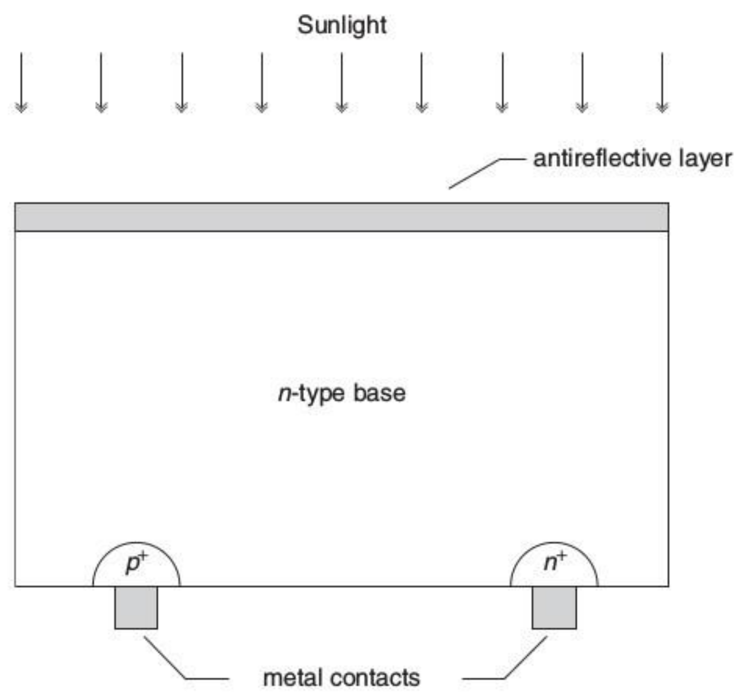
2009 – 25 % (Passivated emitter locally diffused PERL cell)



Green, M. A. (2009). The path to 25% silicon solar cell efficiency: History of silicon cell evolution. Progress in Photovoltaics: Research and Applications, 17(3), 183-189.

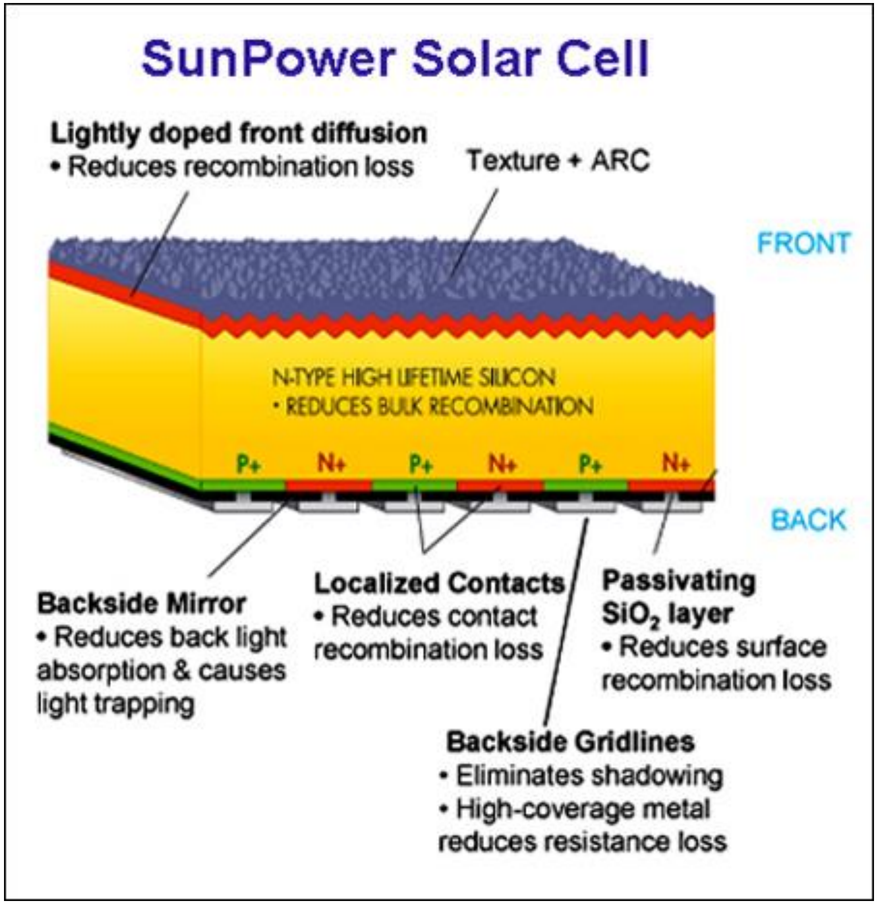
UNSW

1990 – 22 % (back contact, rear junction solar cell)

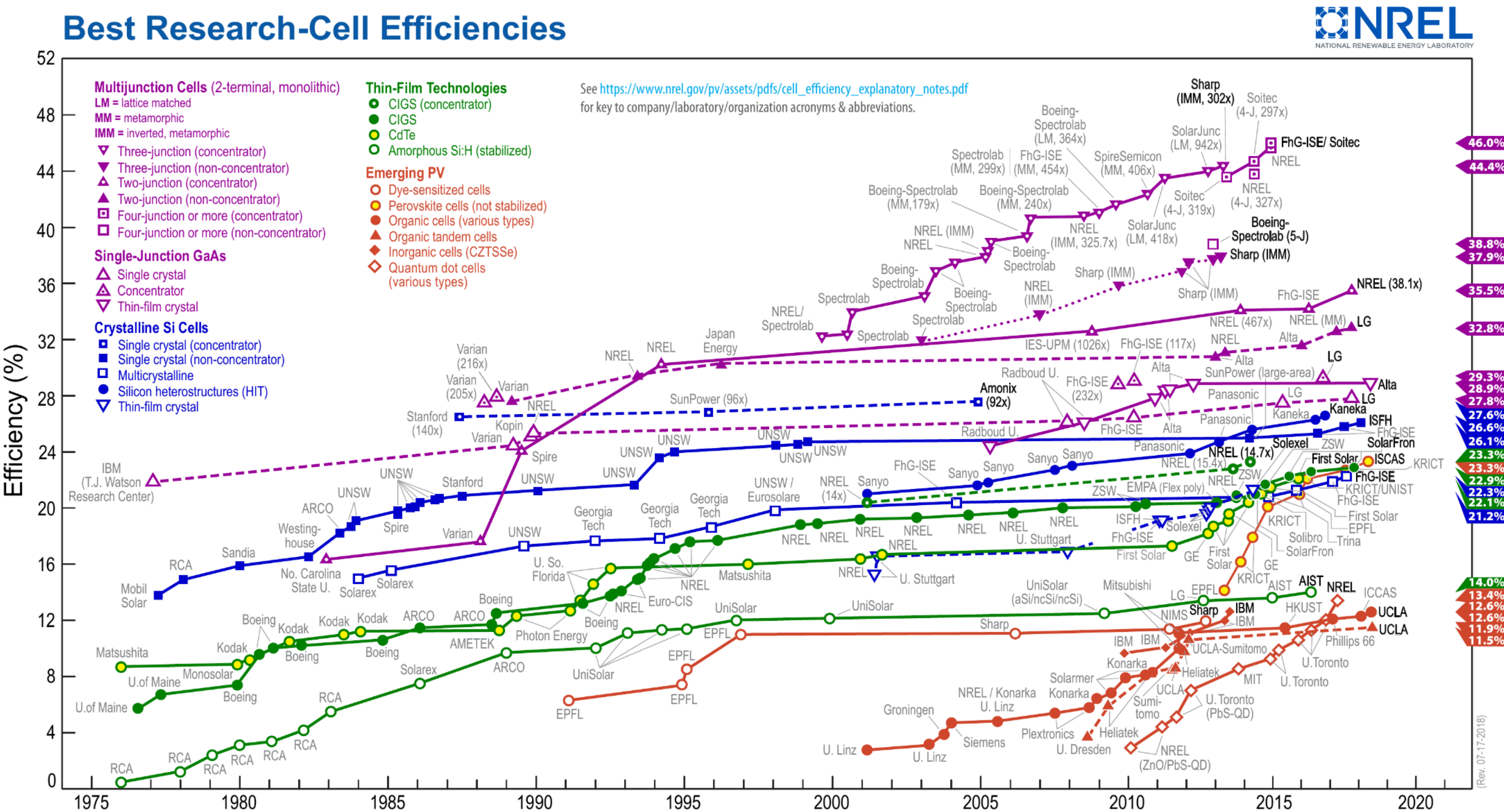


R. Swanson & Sinton

Back contact, rear junction cell (commercial)

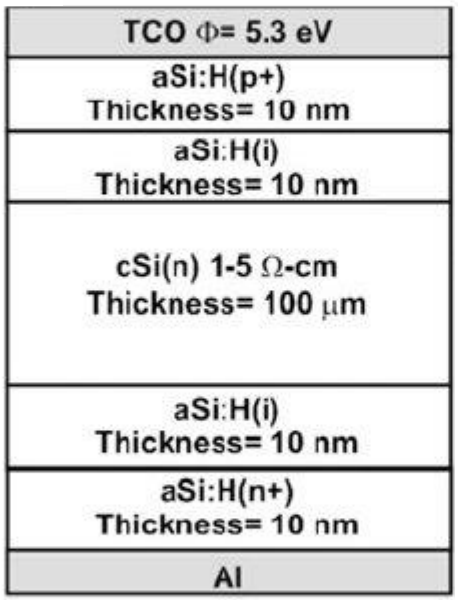


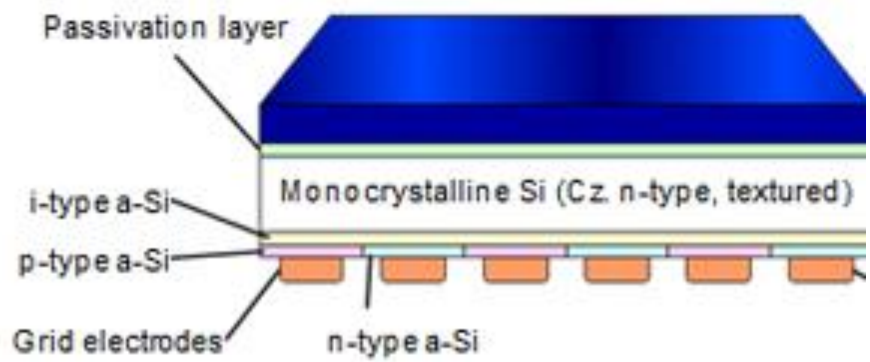
Solar Cell Efficiency records (as in 2018)



L.L. Kazmerski, National Renewable Energy Laboratory (NREL), Golden, CO, September 2018

2014- 26 % HIT cell

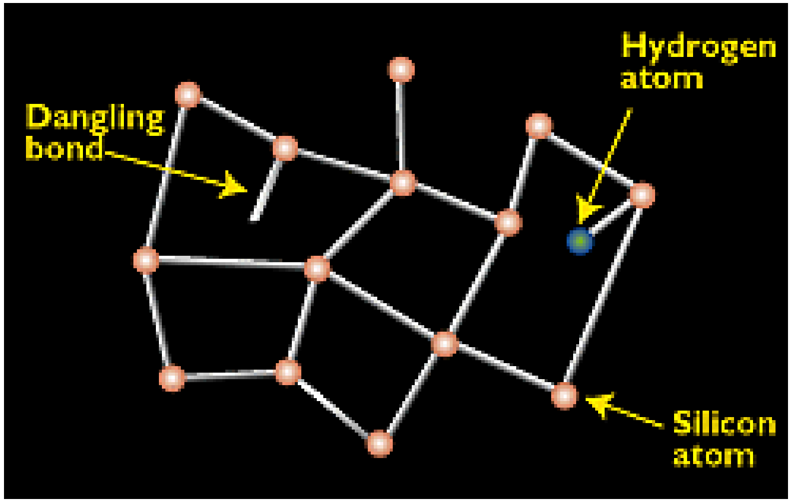


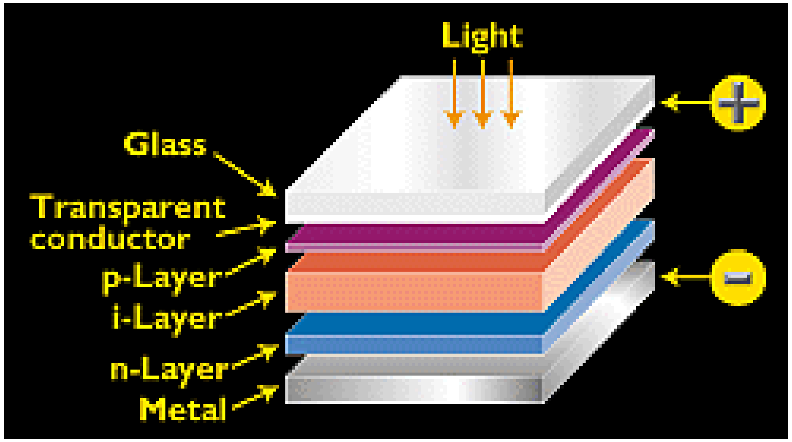


Panasonic

http://news.panasonic.com/global/press/data/2014/04/en140410-4/en140410-4.html

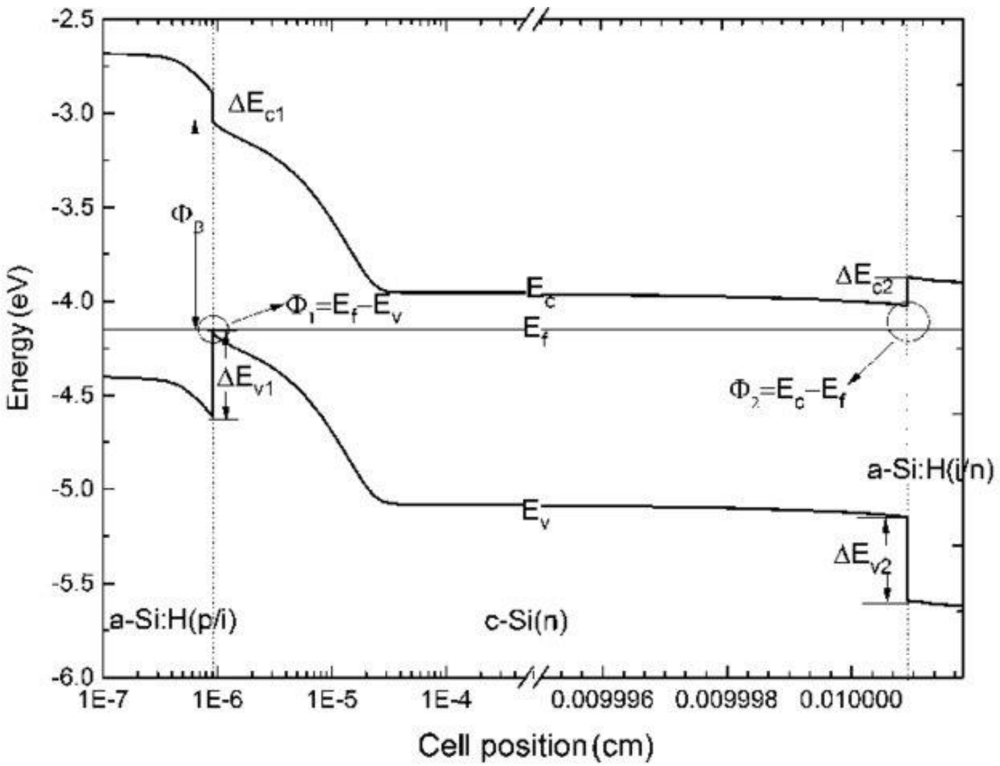
Thin-films: a:Si





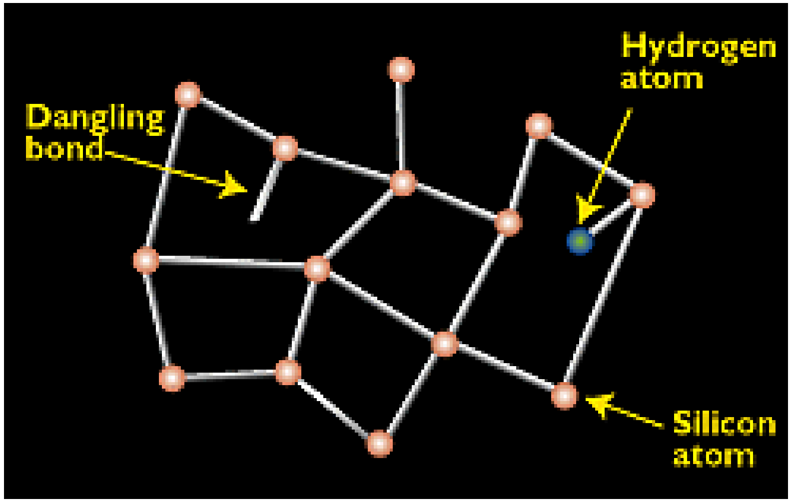
- Hydrogenated amorphous silicon: a-Si:H
- Greater absorption (thinner cells)
- Fabricated by CVD technology (RF PECVD)
- Degradation problems
- Tunable bandgap (1,7 eV):
  - with Ge, decreases (1.45 eV)
  - with C,N increases (2 eV)
- Possibility of tandem solar cells

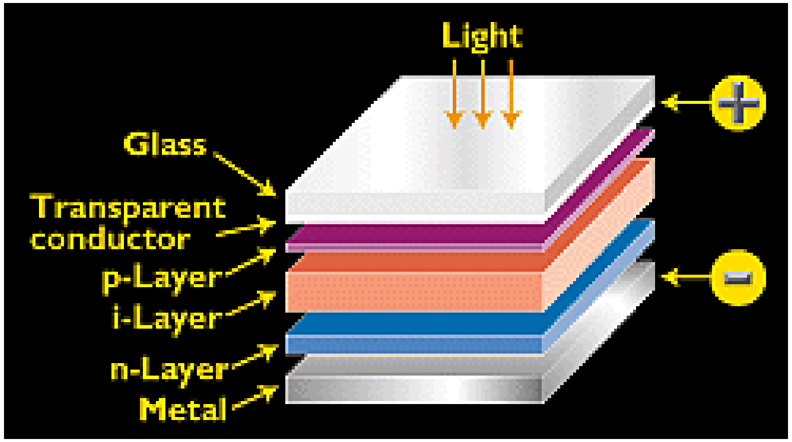
Band diagram of a HIT cell



Shen et al. Solar Energy 97:168-175

Thin-films: a:Si





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  - with C,N increases (2 eV)
- Possibility of tandem solar cells

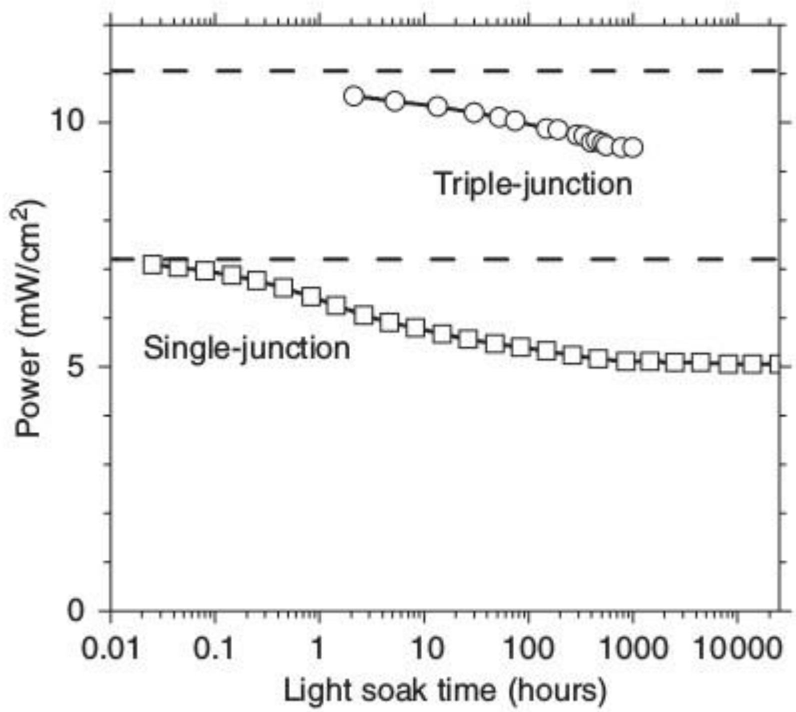
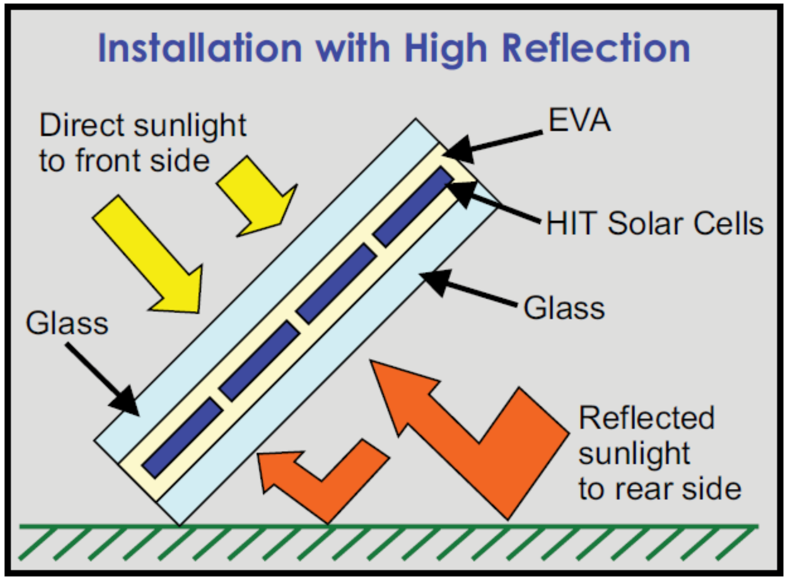


Figure 12.4 The conversion efficiency in a-Si:H-based solar cells declines noticeably upon the first exposure to sunlight. The figure illustrates this decline under a solar simulator (100 mW/cm^2) for a single-junction cell (260 nm *i*-layer thickness) and for a triple junction module made at United Solar Ovonic [16, 17]; the dashed lines indicate the initial power measured for each device

E. A. Schiff, S.Hegedus and X. Deng, Chap. 12 in Handbook of photovoltaic Science and Engineering 2 ed

Bifacial solar cells and modules



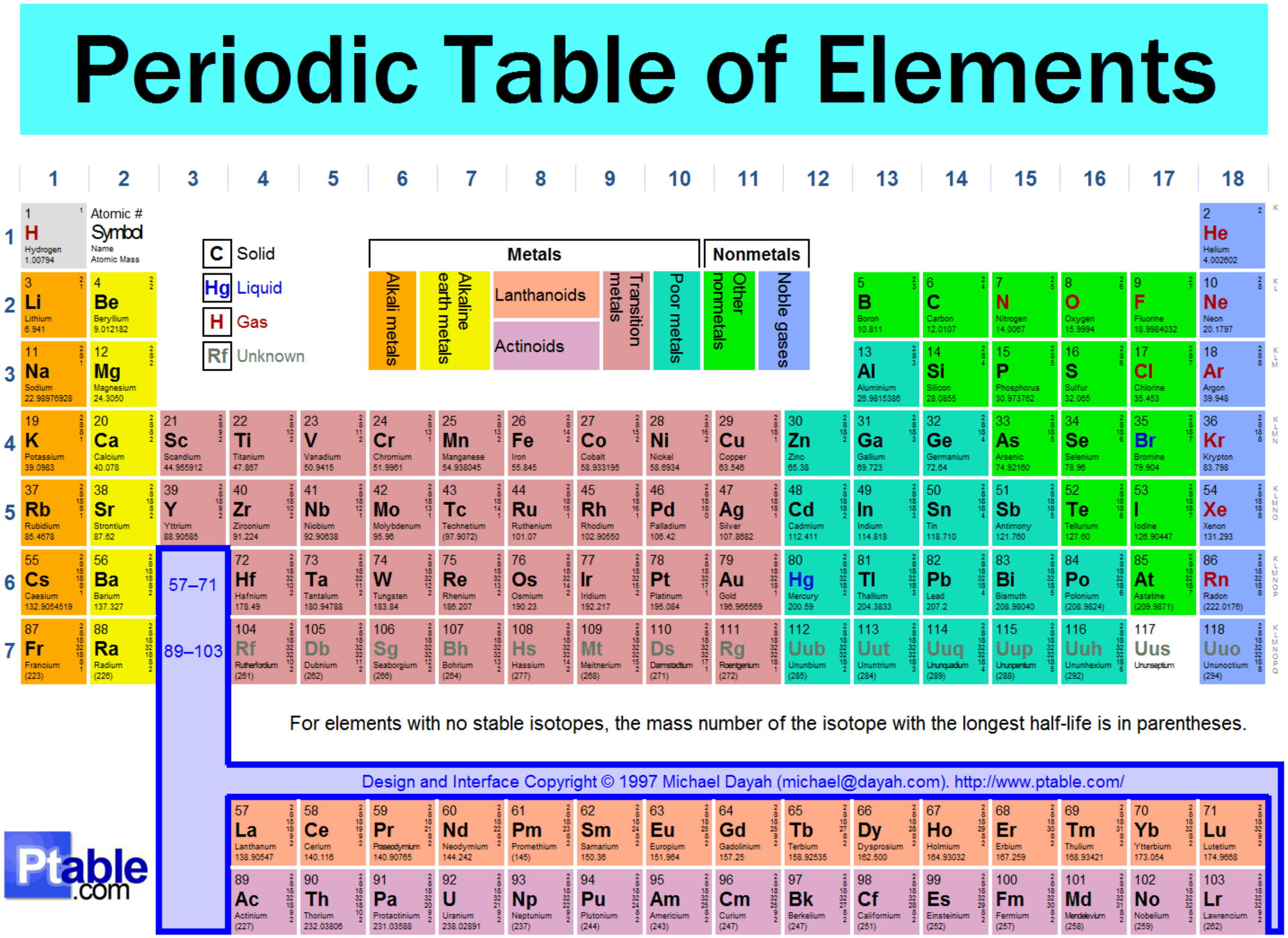
Source: Sanyo Energy Corporation

Source: Silfab (Oregon park)

Outline

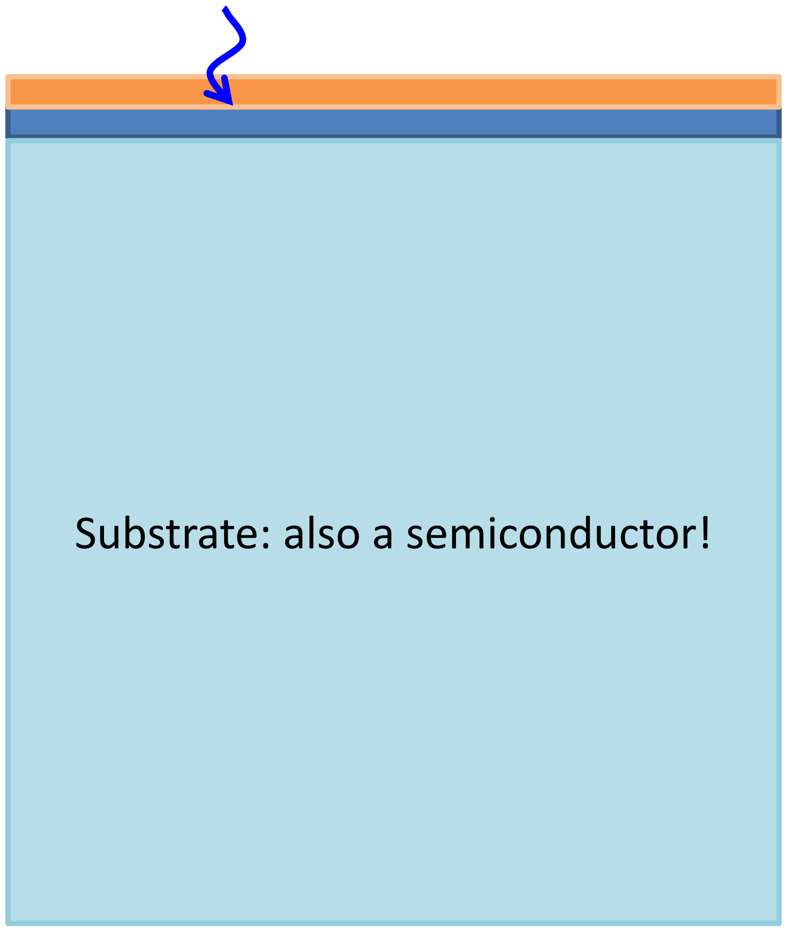
- Fundamentals of photovoltaic Energy conversion
- Conventional (inorganic) solar cells
  - silicon
  - III-Vs (multi-junction solar cells, GaAs, InGaP, InGaAs…)
  - thin films

What means III-Vs?



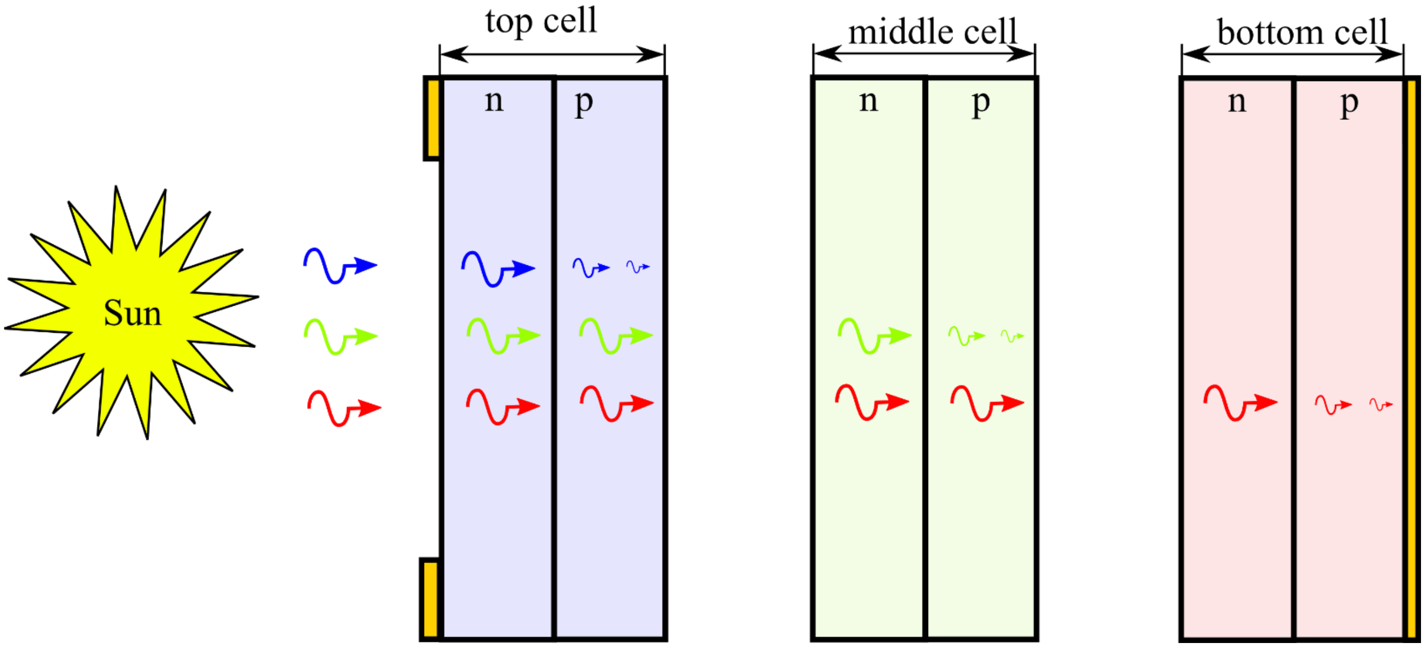
III-Vs: some properties

- Strong absorption
- Difficult to stack
- Work in the radiative limit
- Today driving market are space applications



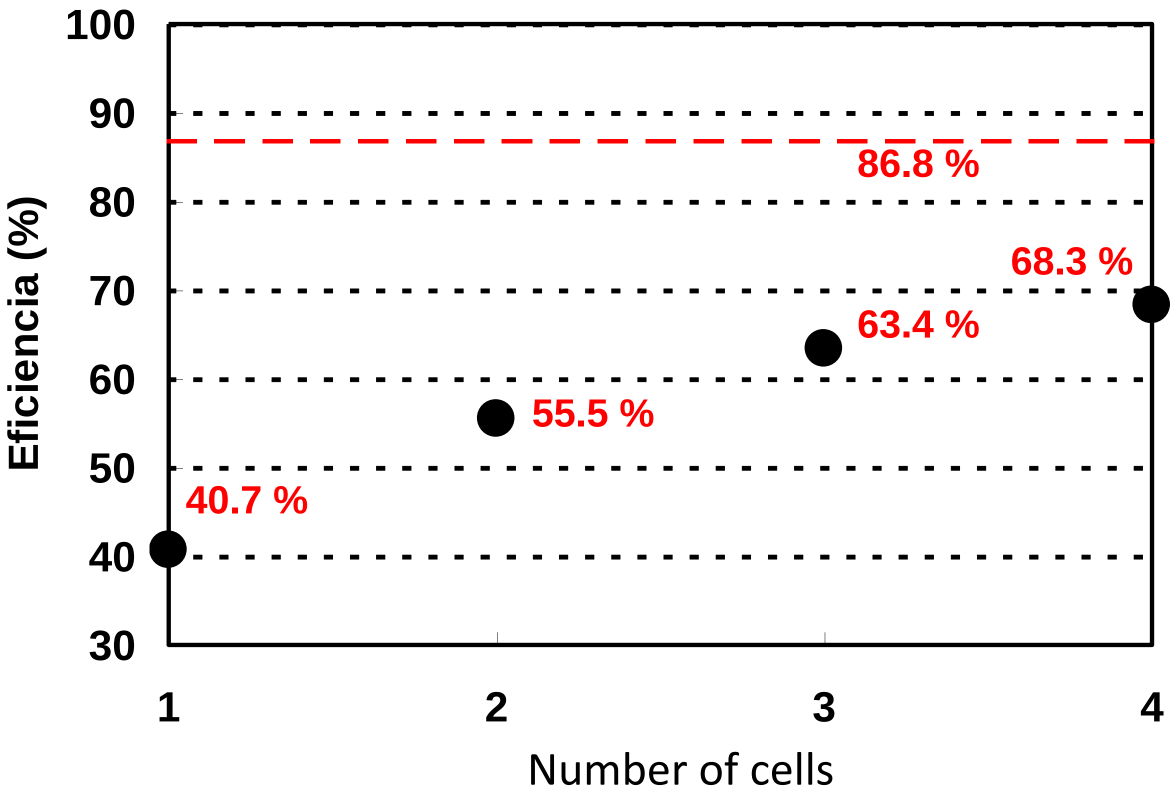
P-n juntion

Tandem cells

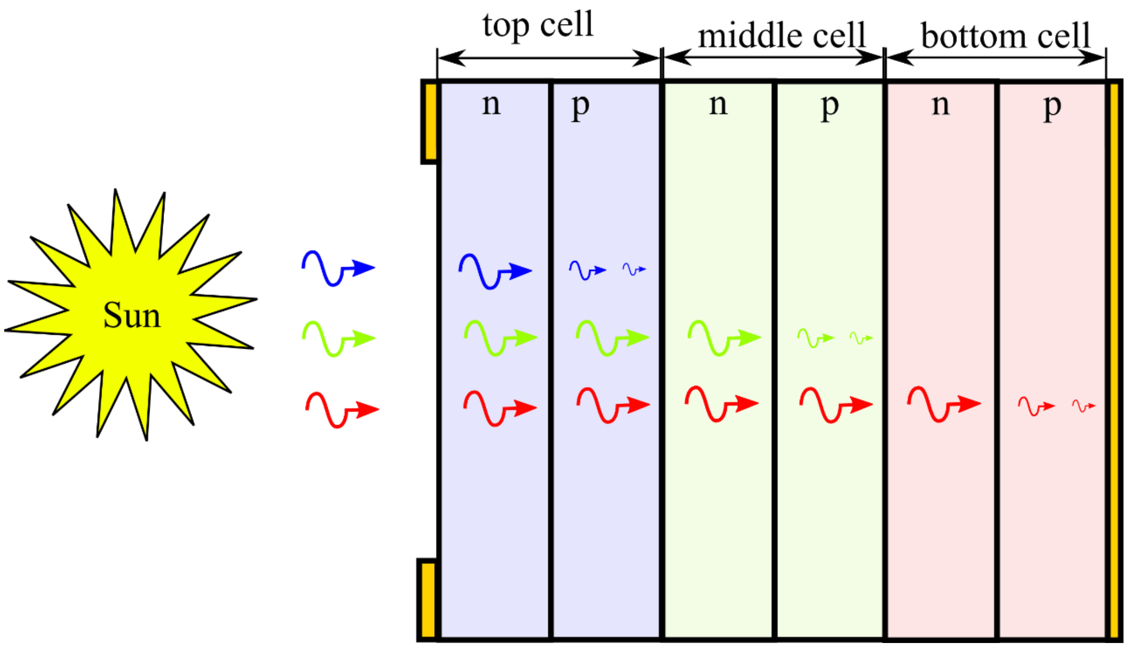


E. D. Jackson, "Areas for improvement of the solar energy converter," Trans. Conf. on the Use of Solar Energy, Tucson, 1955, University of Arizona Press, Tucson, vol. 5, pp. 122-126, 1958.

Tandem cells: Limiting efficiency

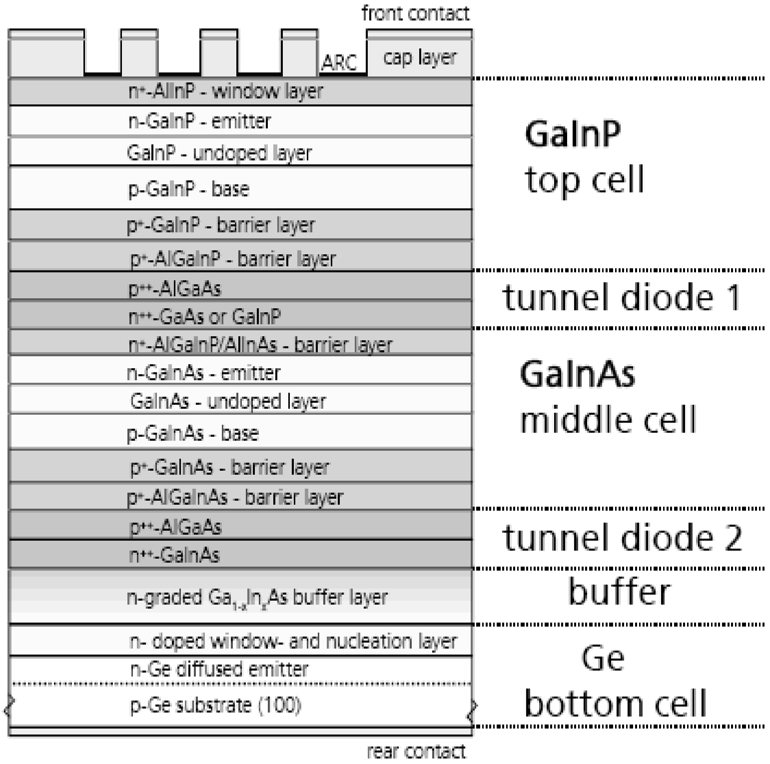


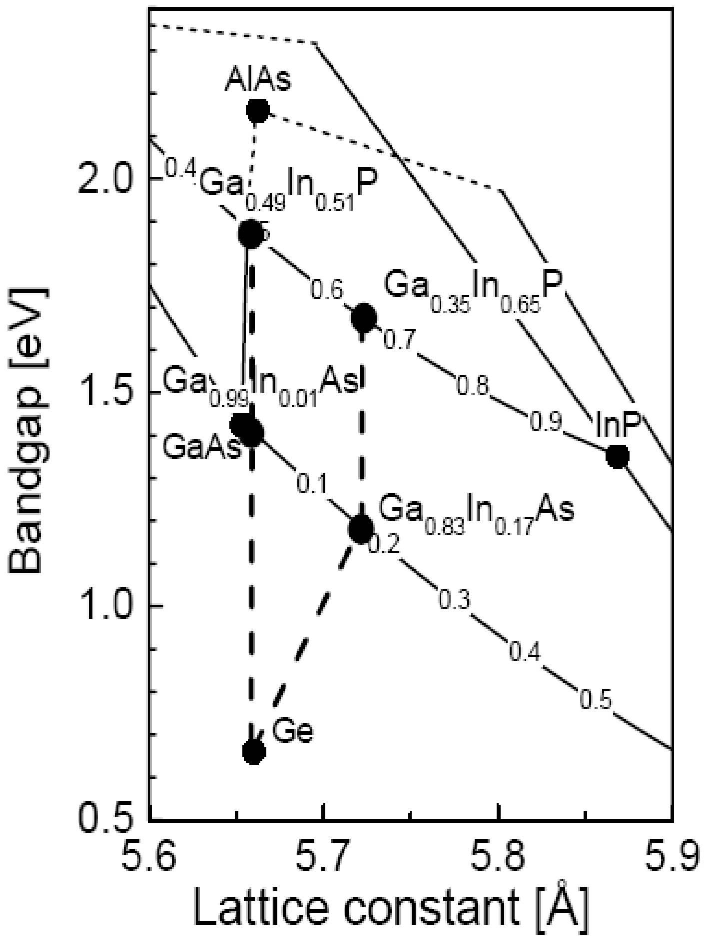
Tandem cells: conexión en serie



The current has to be the same for all the cells

Multi-junction solar cells: lattice matched and methamorphic





C. Baur, A. W. Bett, F. Dimroth, G. Siefer, M. Meusel, W. Bentsch, W. Köstler, and G. Strobl, "Triple junction III-V based concentrator solar cells: perspectives and challenges," ASME Journal of Solar Energy and Engineering, 2006.

Solar Cell Efficiency records (as in 2018)

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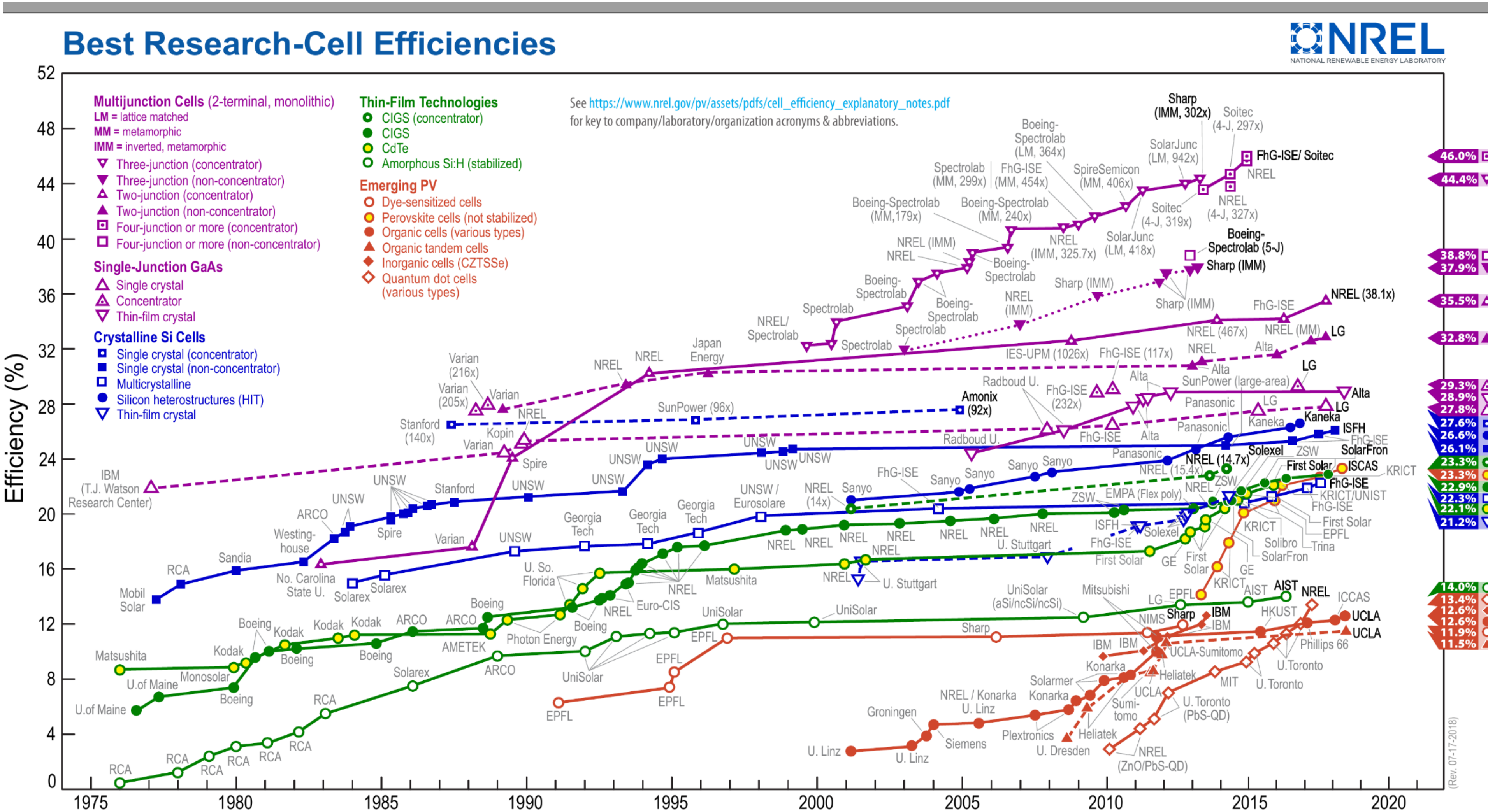


Inverted methamorphic

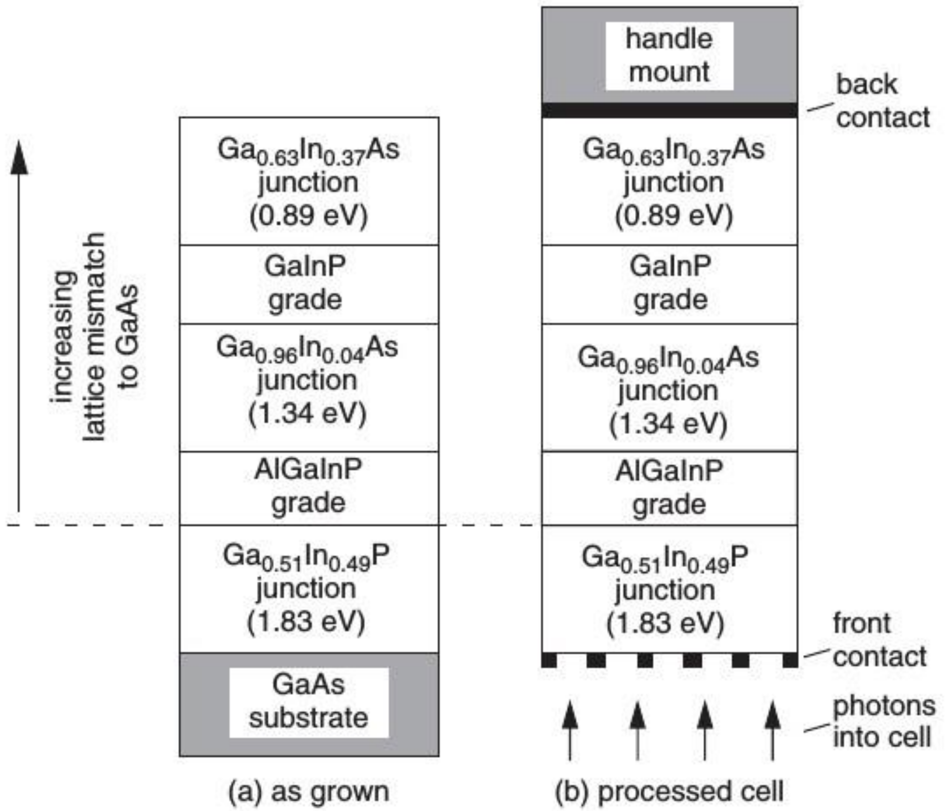
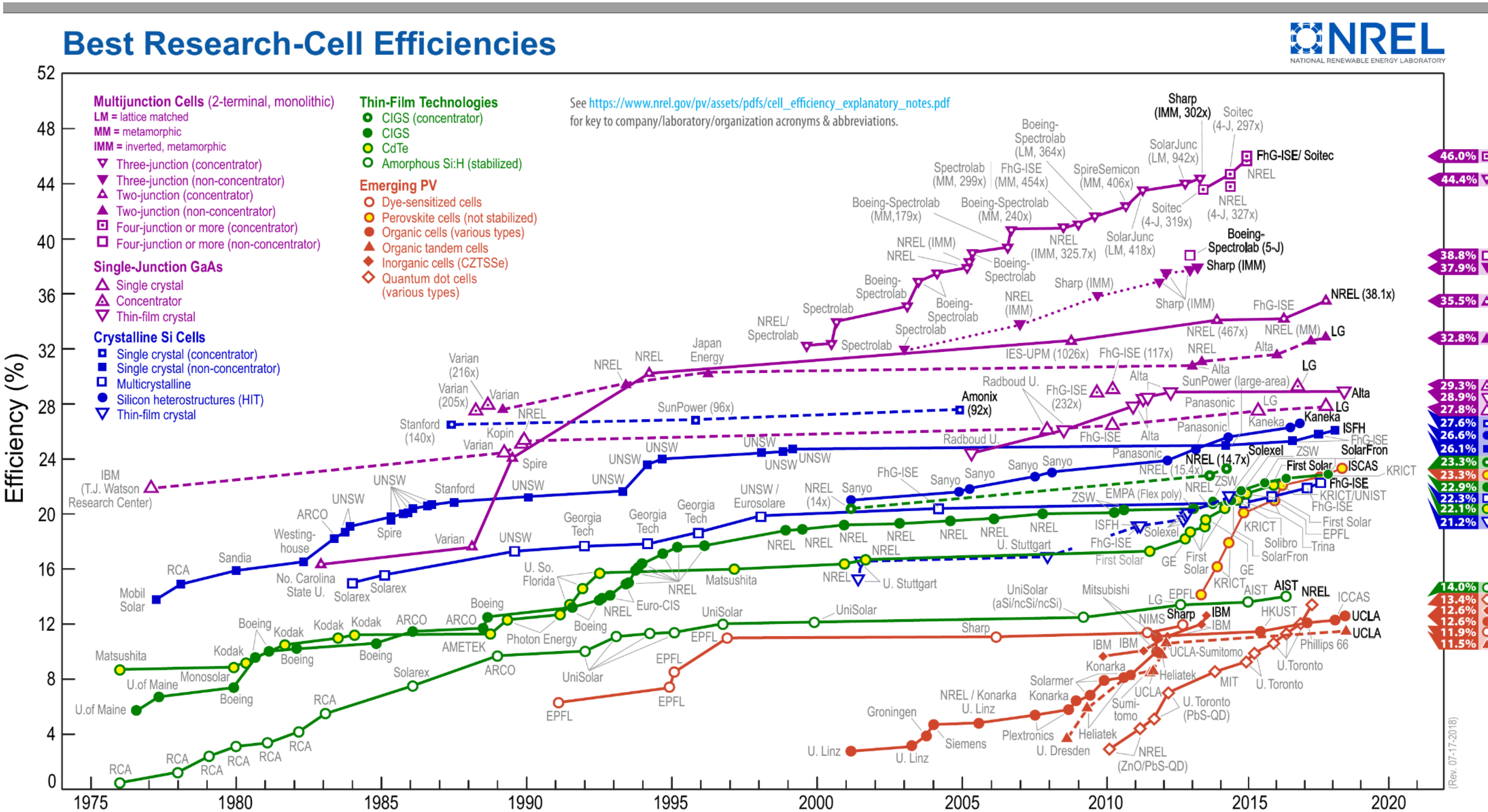


Figure 8.21 (a) Inverted metamorphic three-junction cell as grown. The tunnel-junction interconnects are not shown. The drawing is not to scale. (b) Finished device structure after back-contact deposition, handle mounting, substrate removal, and front-contact deposition

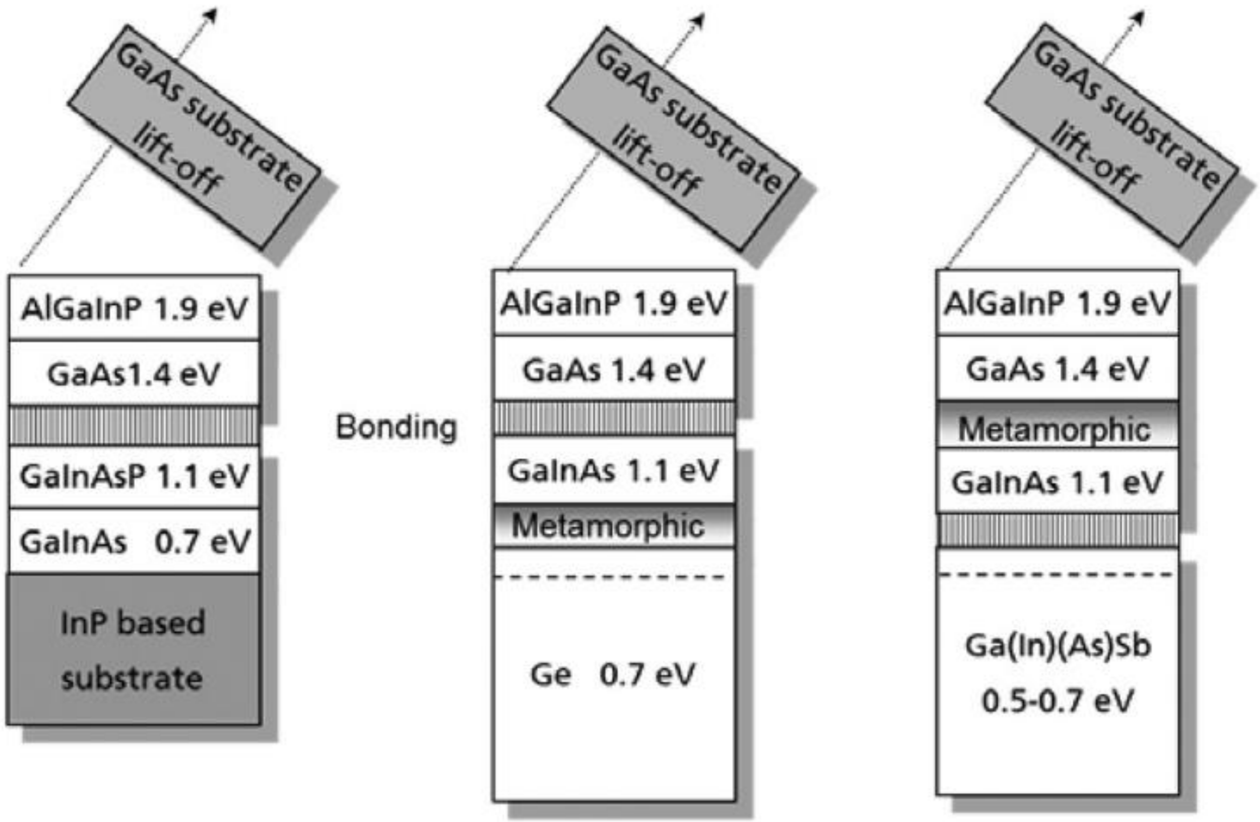
D. J. Friedman, J. M. Olson and Sarah Kurtz, Handbook of photovoltaic Science and Engineering 2 ed. (John Wiley & Sons, Chichester, 2004).

Solar Cell Efficiency records (as in 2018)



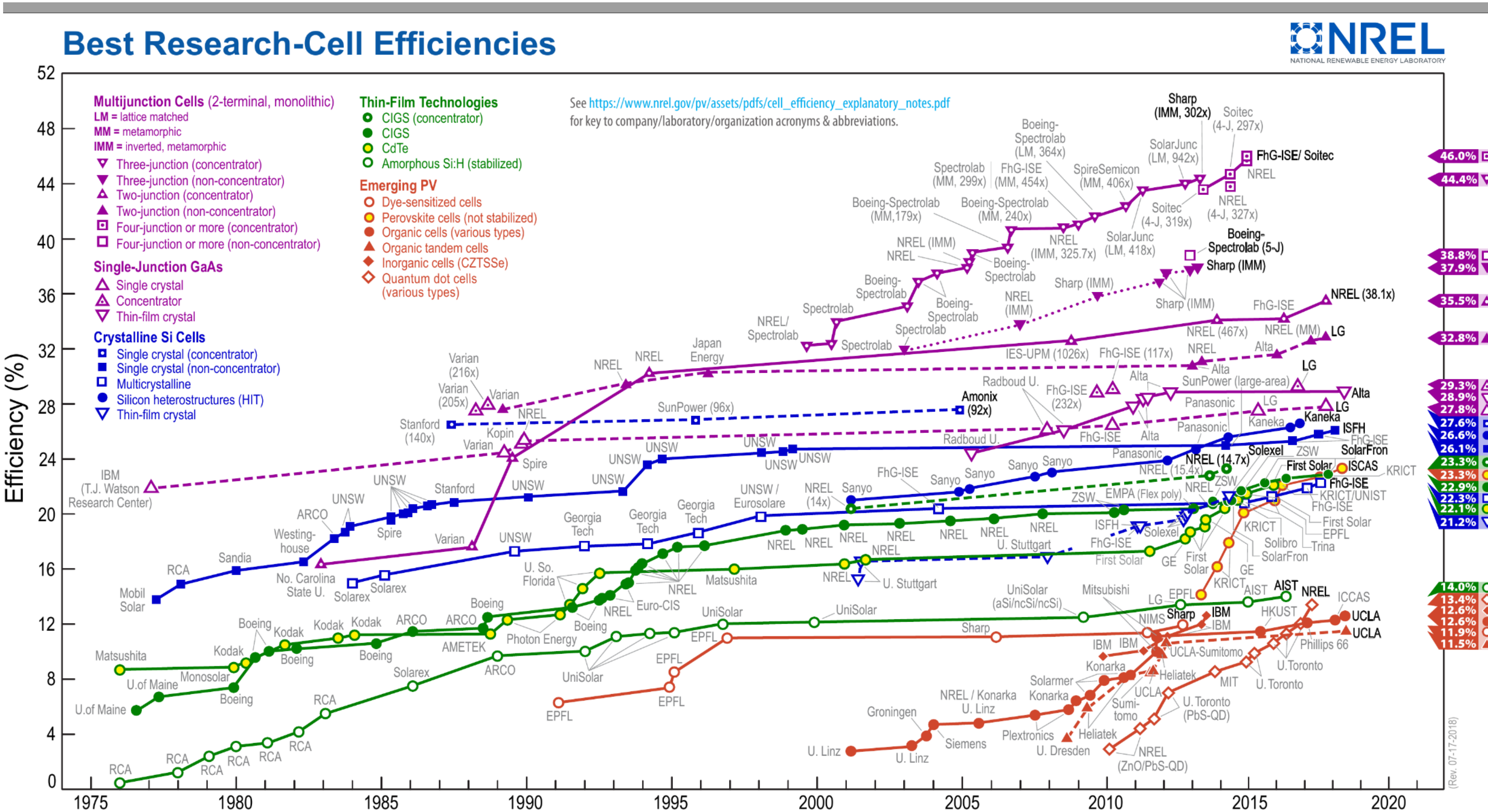
L.L. Kazmerski, National Renewable Energy Laboratory (NREL), Golden, CO, September 2018

Wafer bonding

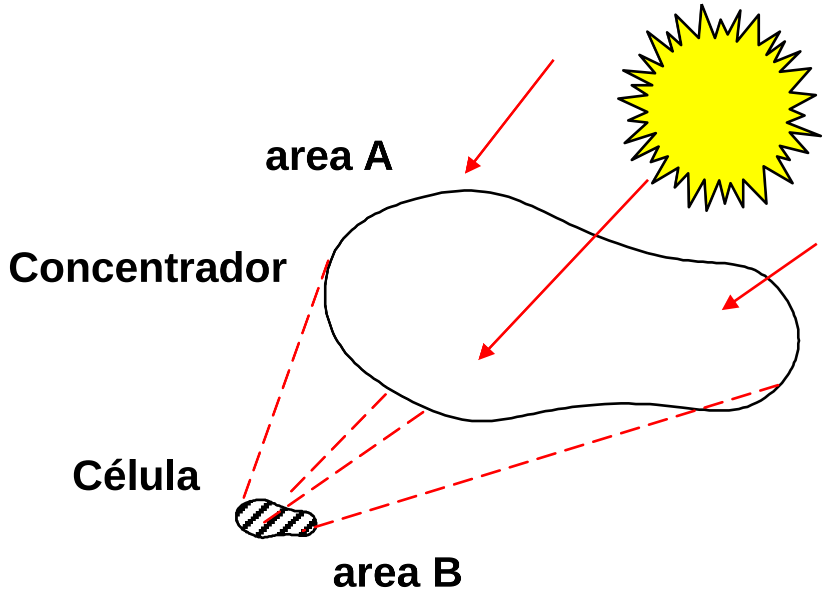


F. Dimroth et al., "Four-Junction Wafer-Bonded Concentrator Solar Cells," IEEE J. Photovolt. **6**, *pp.343, 2016*

Solar Cell Efficiency records (as in 2018)

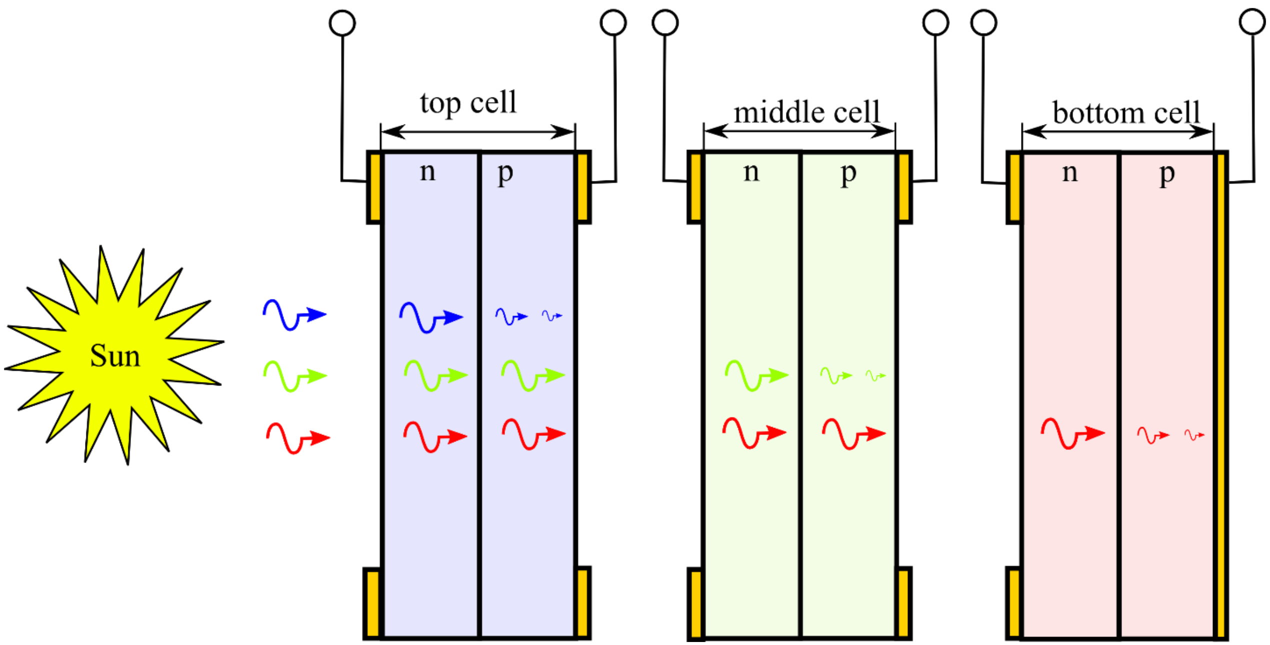


Used in concentration systems

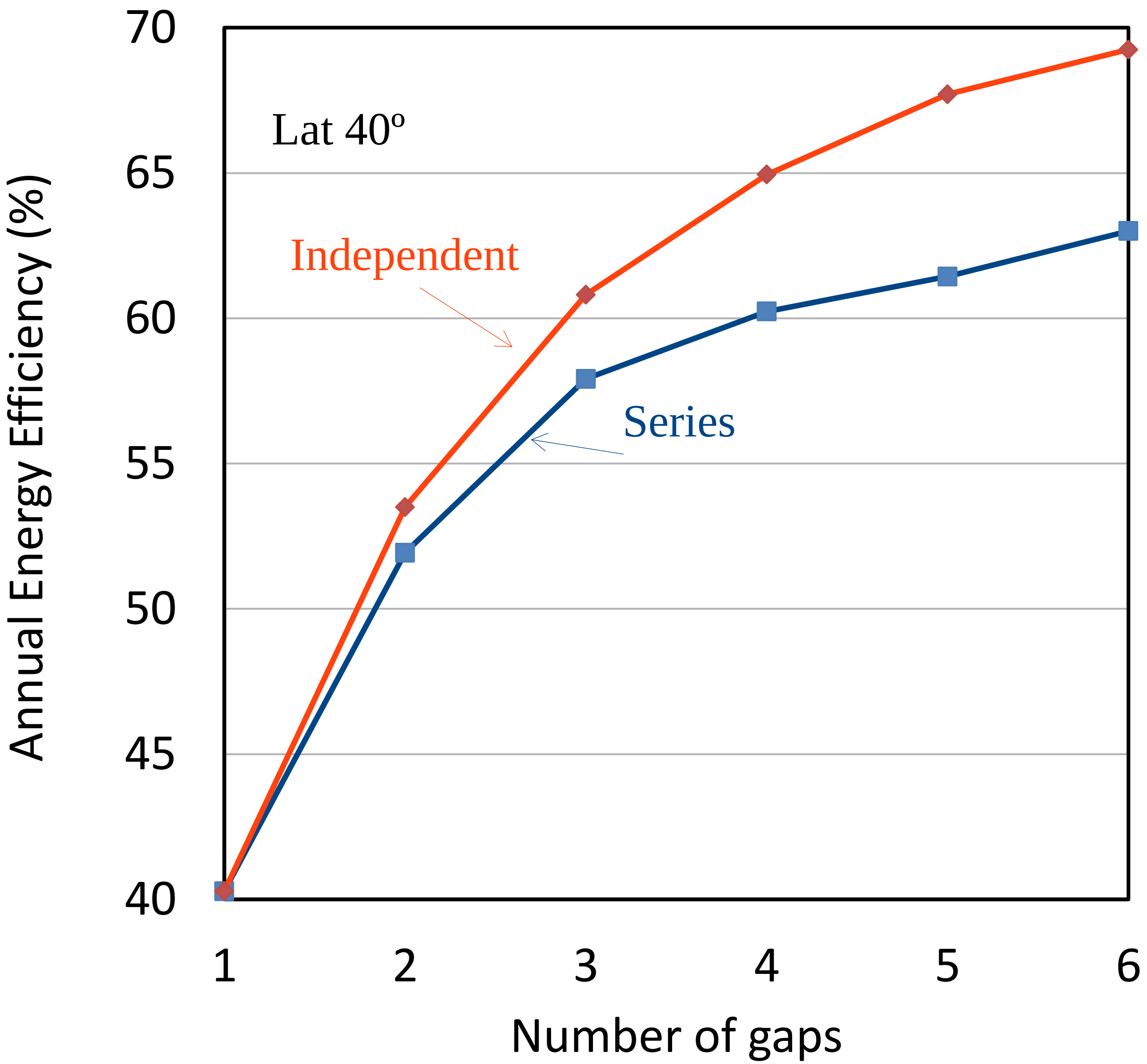


Concentration

Tandem cells: independent conexion

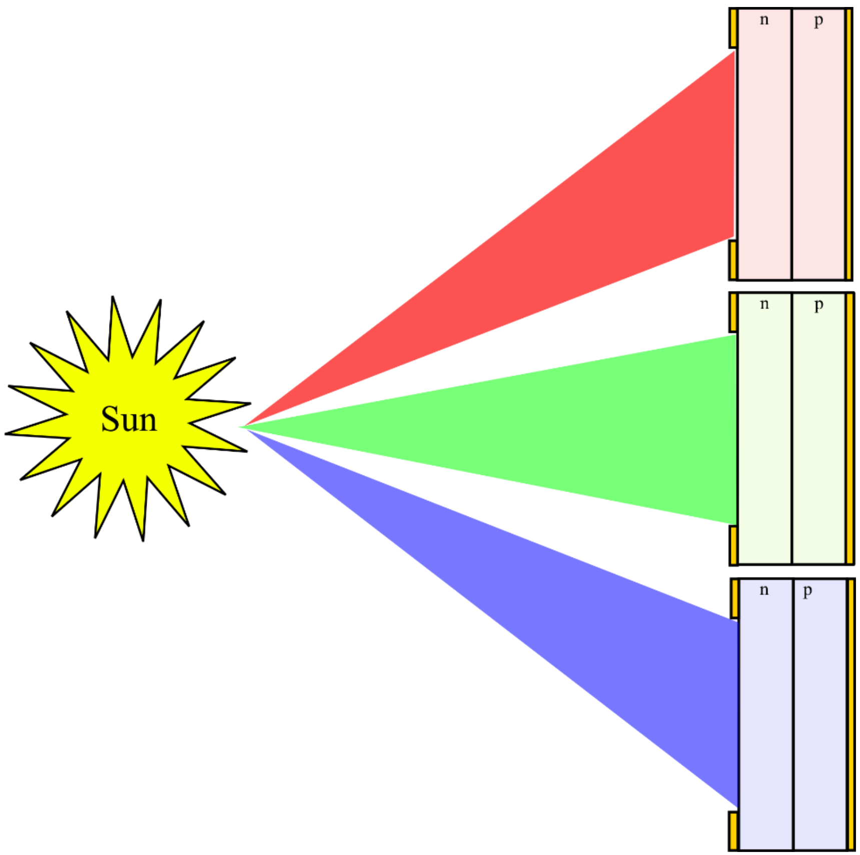


Series vs independent



J. Villa and A.Martí, “Impact on the spectrum, location and interconnection between solar cells in the annual production of photovoltaic energies in photovoltaic concentration systems,” IEEE 43rd PVSC, 2016

Tandem cells: spectrum splitting



Outline

- Fundamentals of photovoltaic Energy conversion
- Conventional (inorganic) solar cells
  - silicon
  - III-Vs (multi-junction solar cells, GaAs, InGaP, InGaAs…)
  - thin films
    - CdTe
    - CIGS
    - (a-Si)

Solar Cell Efficiency records (as in 2018)

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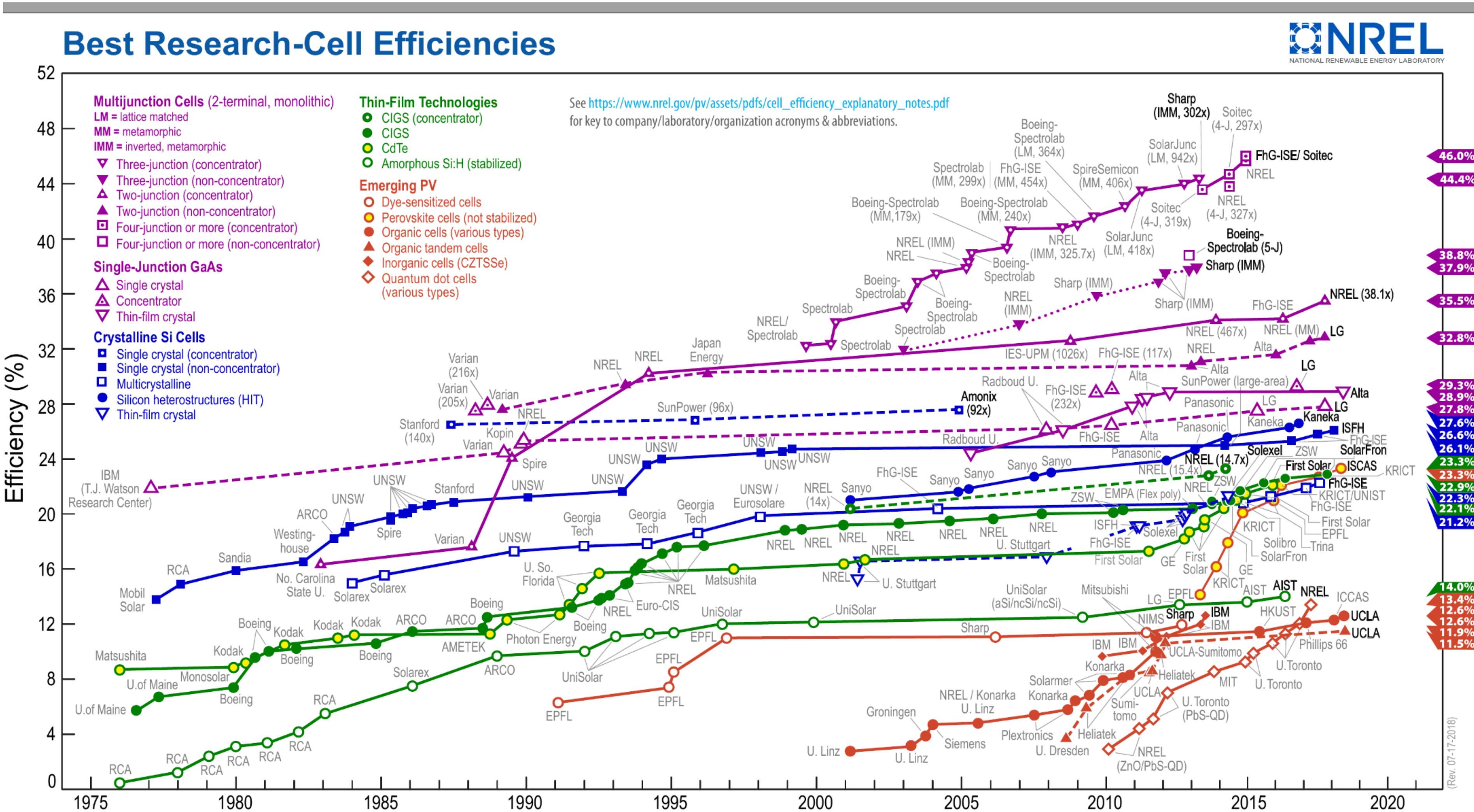

Thin film properties

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- Strong absorption coefficient
- Deposited as polycrystalline materials

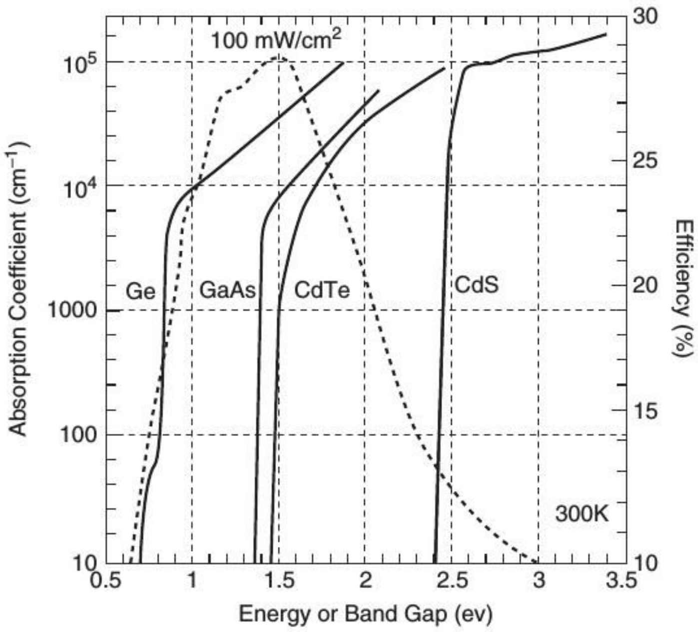


Figure 14.1 Theoretical solar cell efficiency (dotted) for AM1.5 spectral irradiance versus bandgap and absorption coefficient (solid) versus energy. Common absorber materials are highlighted

Brian E. McCandless and James R. Sites, Handbook of photovoltaic Science and Engineering 2 ed. (John Wiley & Sons, Chichester, 2004).

Thin film properties

- Strong absorption coefficient
- Deposited as polycrystalline materials on cheap substrates
- Second in the market after silicon

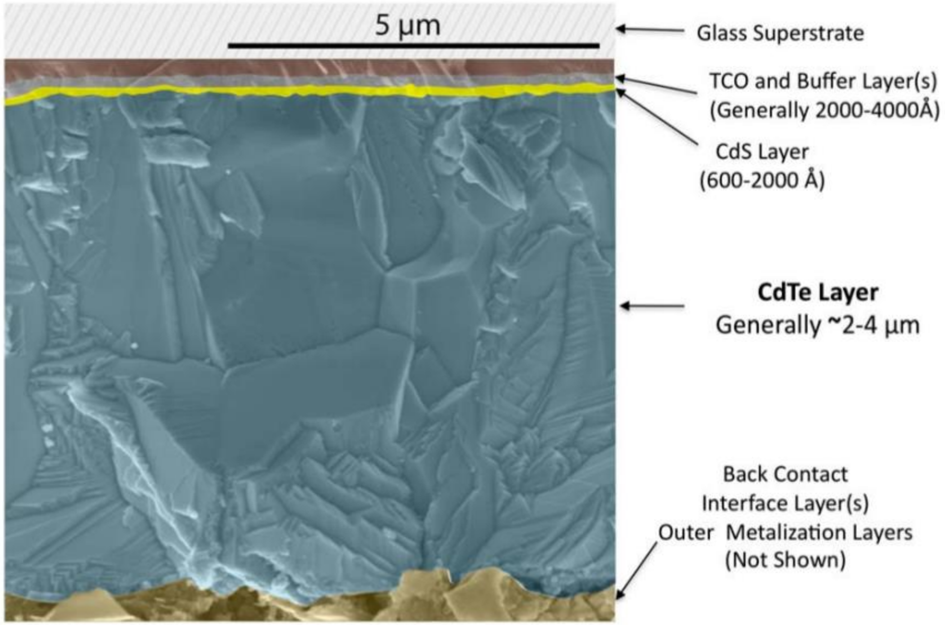


Figure 3.1 SEM micrograph showing cross section of CdS/CdTe superstrate device produced at NREL. Certain layers have been color-enhanced for clarity.

T. Gessert, B. McCandless and
C. Ferekides in A. J. Nozik, G. Conibeer, and M. C. Beard,
Advanced Concepts in Photovoltaics: Royal Society of Chemistry, 2014.

Why it works?

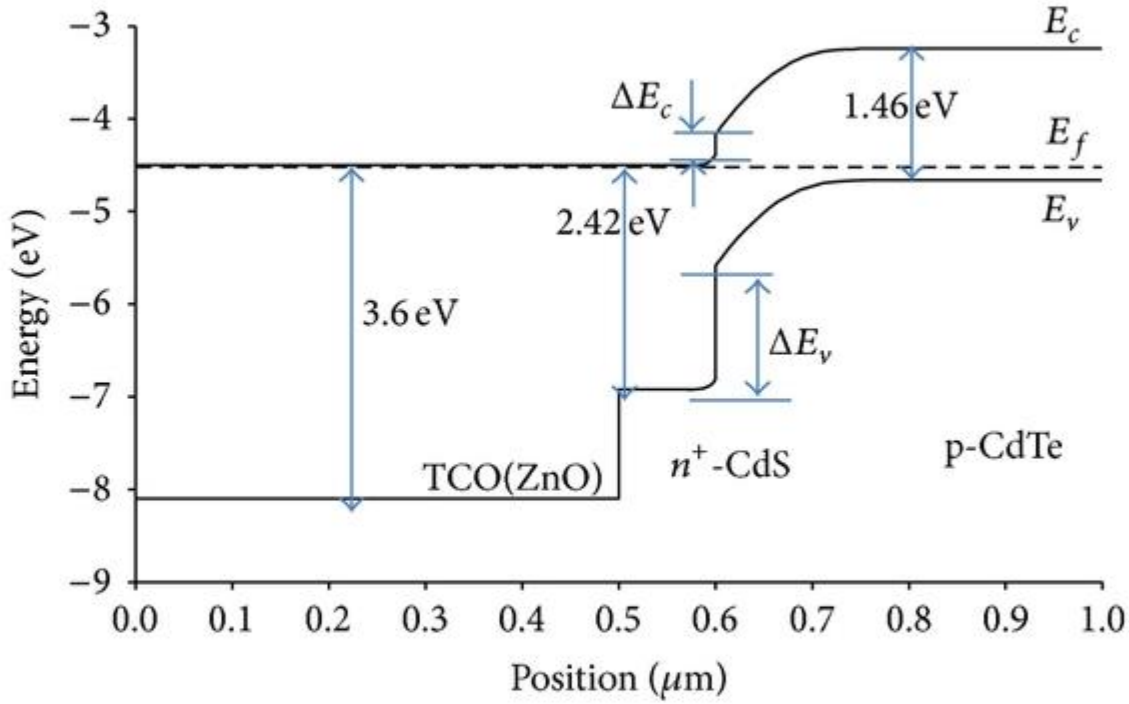
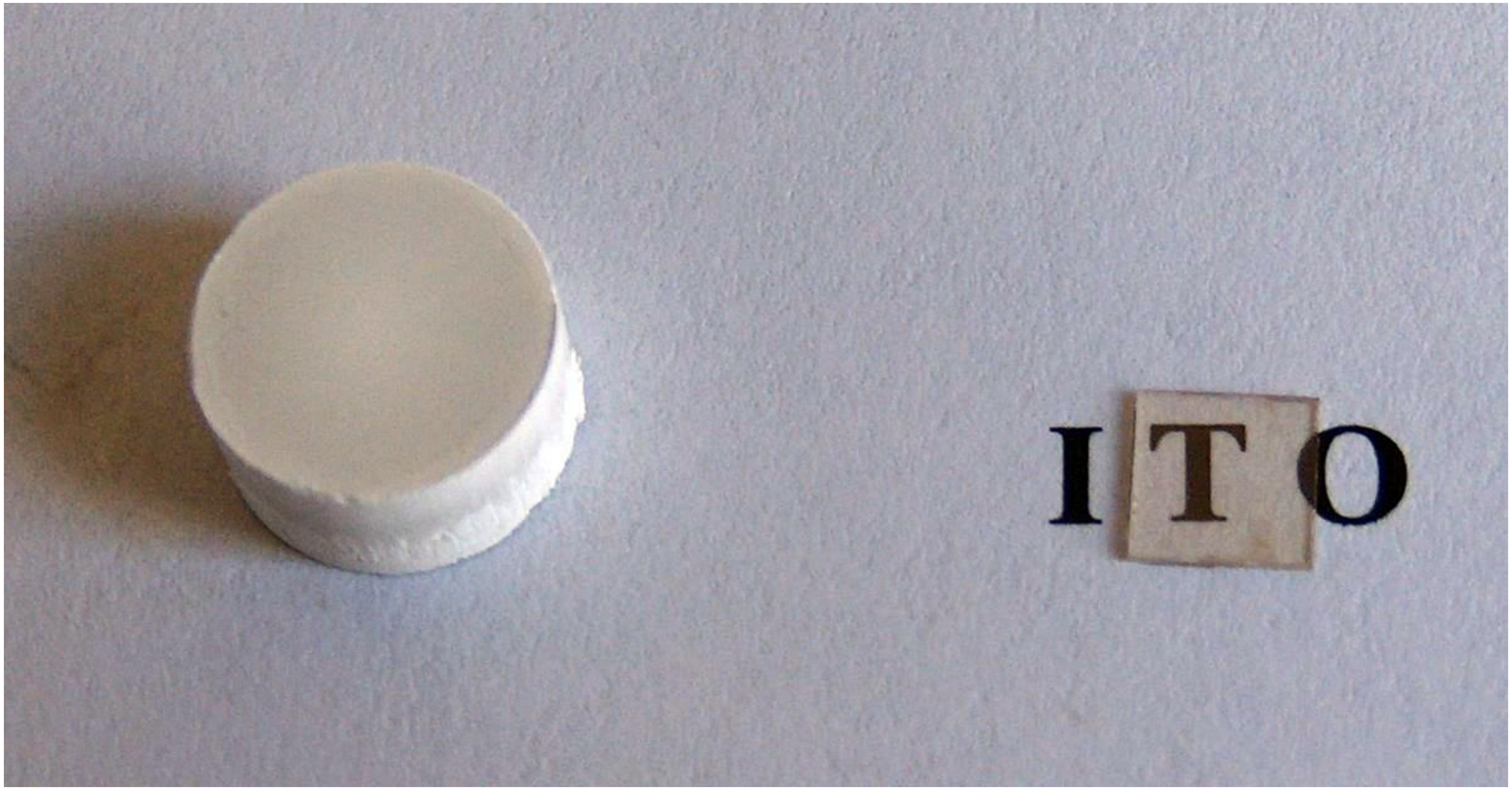


Figure 2: Band diagram of TCO/CdS/CdTe cell without electron reflector layer.

http://www.hindawi.com/journals/ijp/2013/576952/fig2/

TCO: Transparent conductive oxide

ITO: Indium Tin Oxide, 4 eV



From Wikipedia

Cu(InGa)Se2

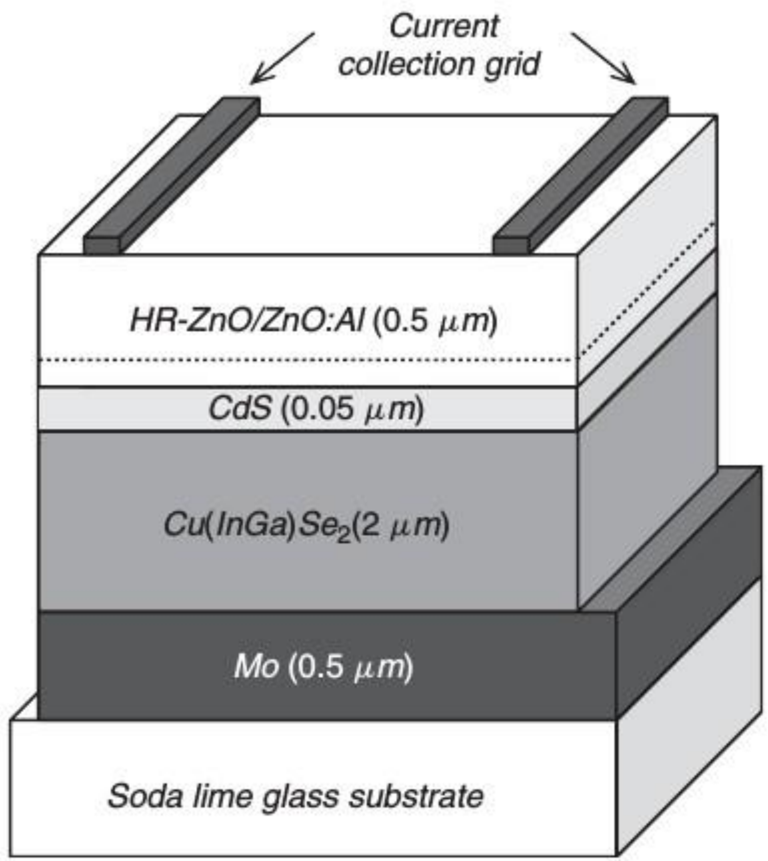


Figure 13.1 Schematic cross-section of a typical Cu(InGa)Se_2 solar cell

W.N. Shafarman, S. Siebentritt, L.Stolt, Handbook of photovoltaic Science and Engineering 2 ed. (John Wiley & Sons, Chichester, 2004).

Cu(InGa)Se2

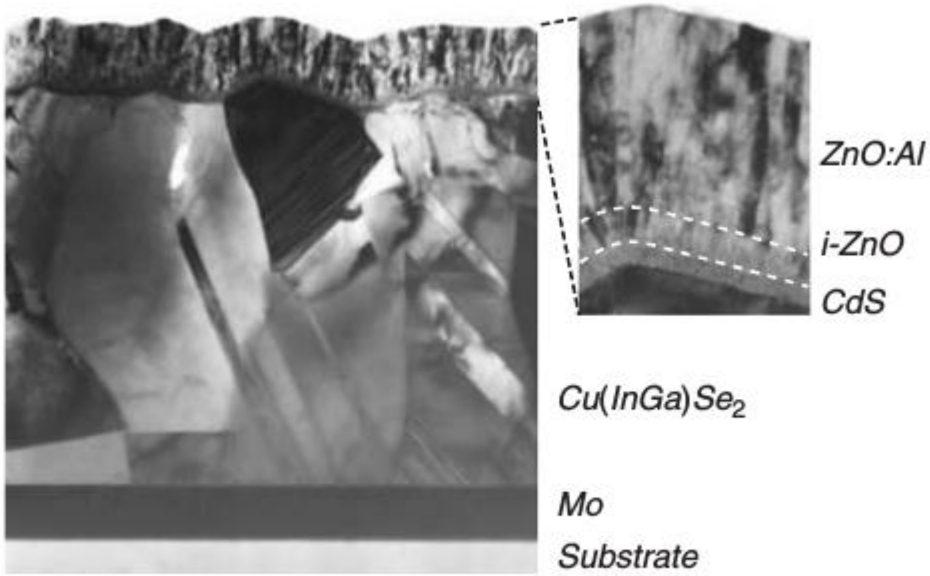


Figure 13.2 TEM cross-section of a Cu(InGa)Se_2 solar cell

W.N. Shafarman, S. Siebentritt, L.Stolt, Handbook of photovoltaic Science and Engineering 2 ed. (John Wiley & Sons, Chichester, 2004).

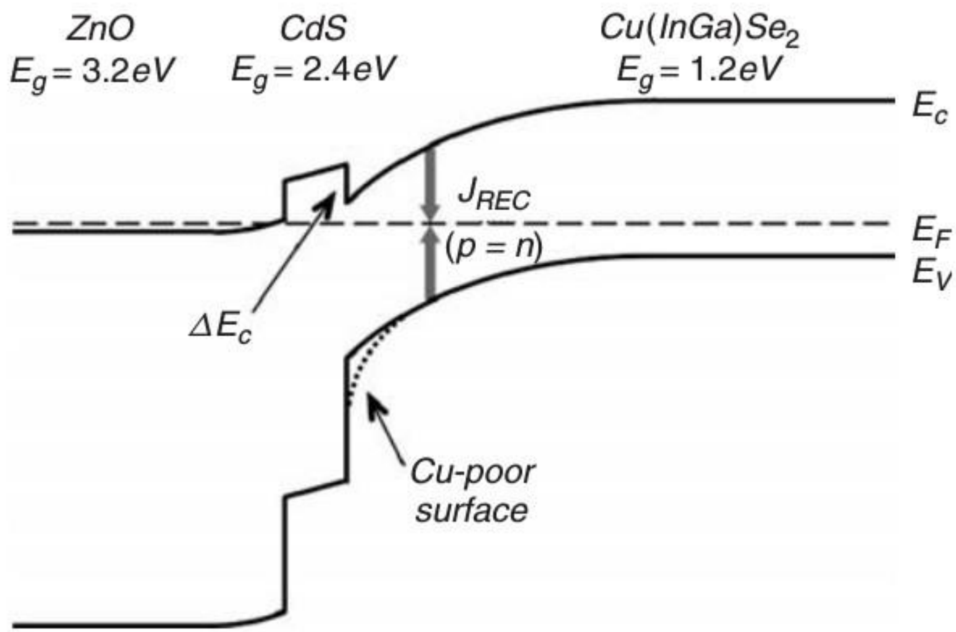


Figure 13.18 Band diagram of a $ZnO/CdS/Cu(InGa)Se_2$ device at 0 V in the dark. The recombination current J_{REC} is greatest where $p = n$ in the space charge region of the $Cu(InGa)Se_2$ and not at the interface. A Cu-poor surface layer is shown by a dashed line

Cu(InGa)Se2

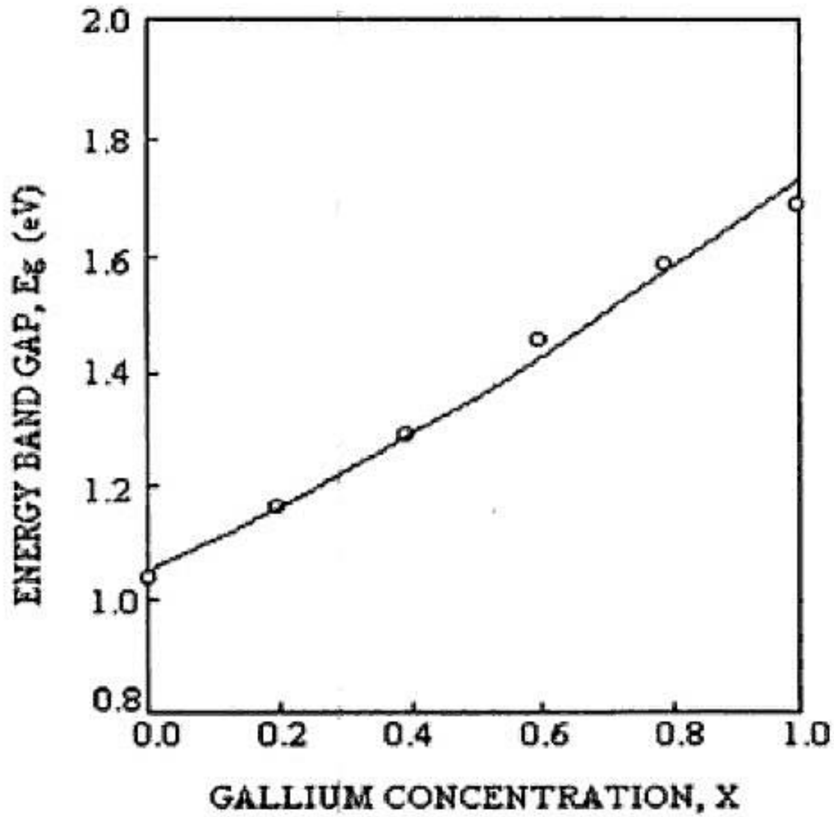
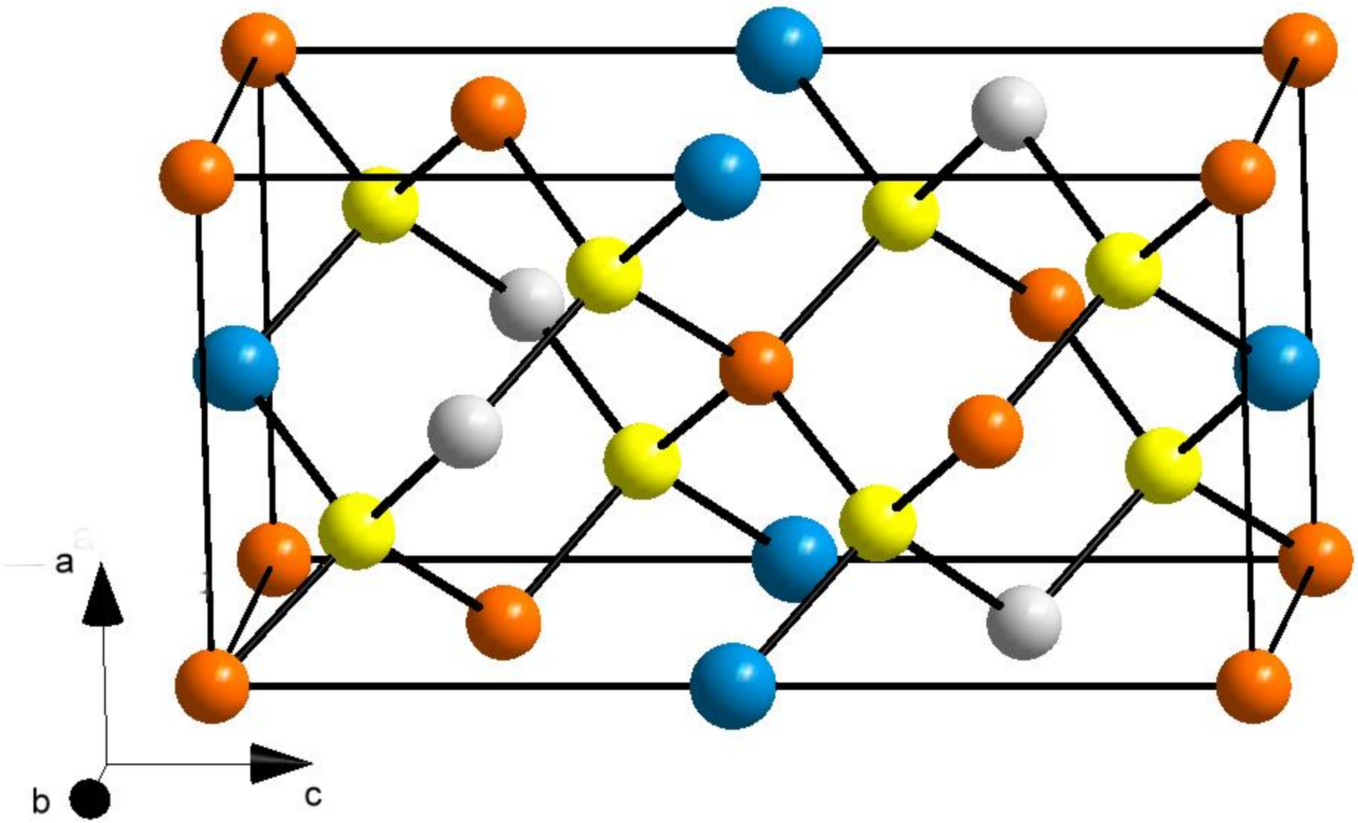


Fig.3. Variation of energy band gap, E_g with gallium concentration in $CuGa_xIn_{1-x}Se_2$ films

CTZS: Cupper Zinc Tin Sulphide (kesterites)



From Wikipedia

Thank you!