# Solar cells and solar energy

Isofoton.es

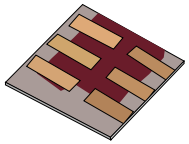


**Dr. Roderick MacKenzie**

roderick.mackenzie@oghma-nano.com

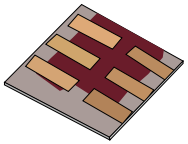
Spring 2016

# Overview



- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Multi-junction solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Concentrator solar cells
- Summary

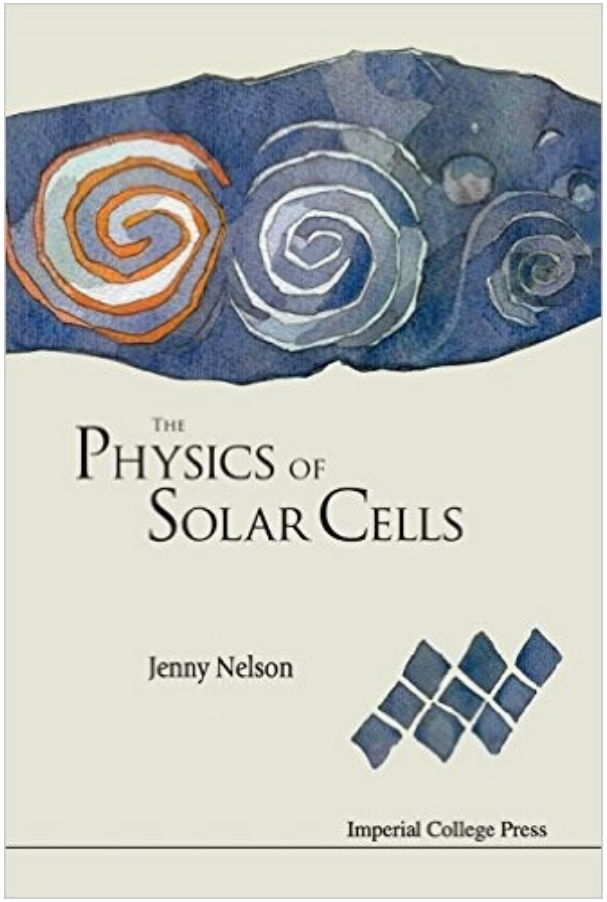
# Aims of lecture



- **What this lecture is:**
  - This lecture aims to give you enough information to understand the operation of solar cells.
  - It is aimed at helping you understand the devices enough to make component choices when designing systems.
- **What this lecture is not:**
  - A solid state physics lecture.

- This lecture was originally given to an MSc class at the University of Nottingham in 2016.

# Recommended book




Jenny Nelson

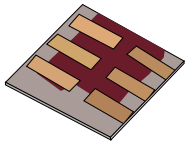
ISBN:1860943497

- This lecture is only 1.5 hours long, so I can't cover everything about solar cells and solar energy.

- The Physics of Solar Cells (Properties of Semiconductor Materials)

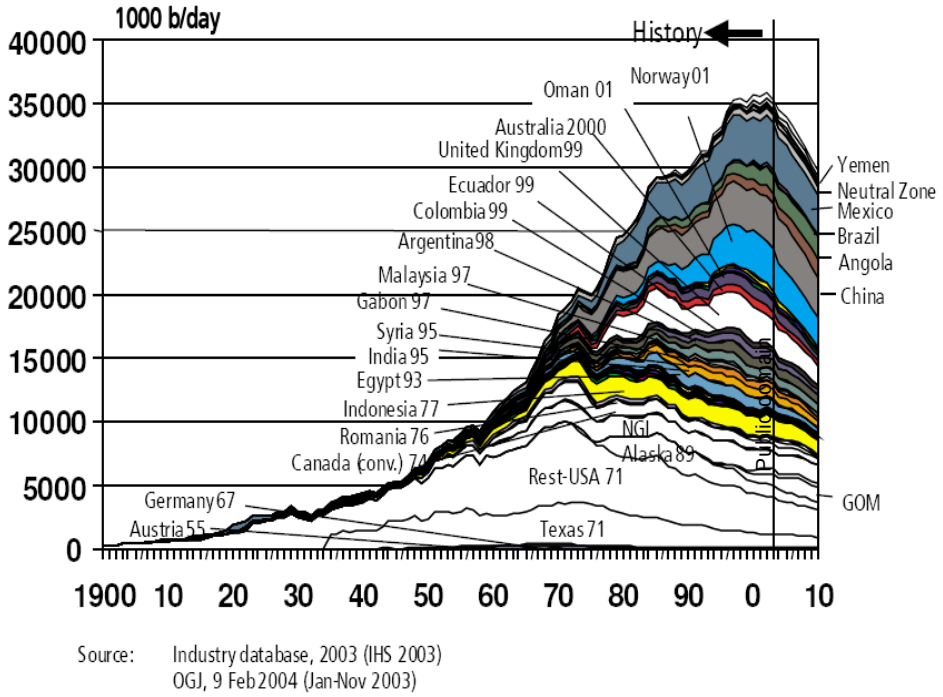
- If you want a deeper understanding get this book.

# Overview

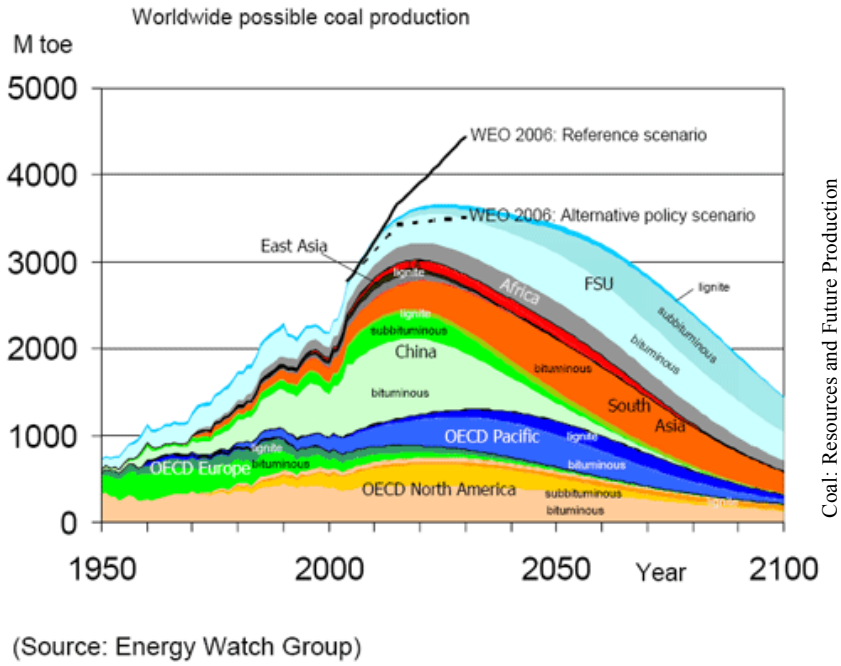


- About me
- **Why Solar energy?**
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# Reason 1: We are running out of oil and coal




Oil production



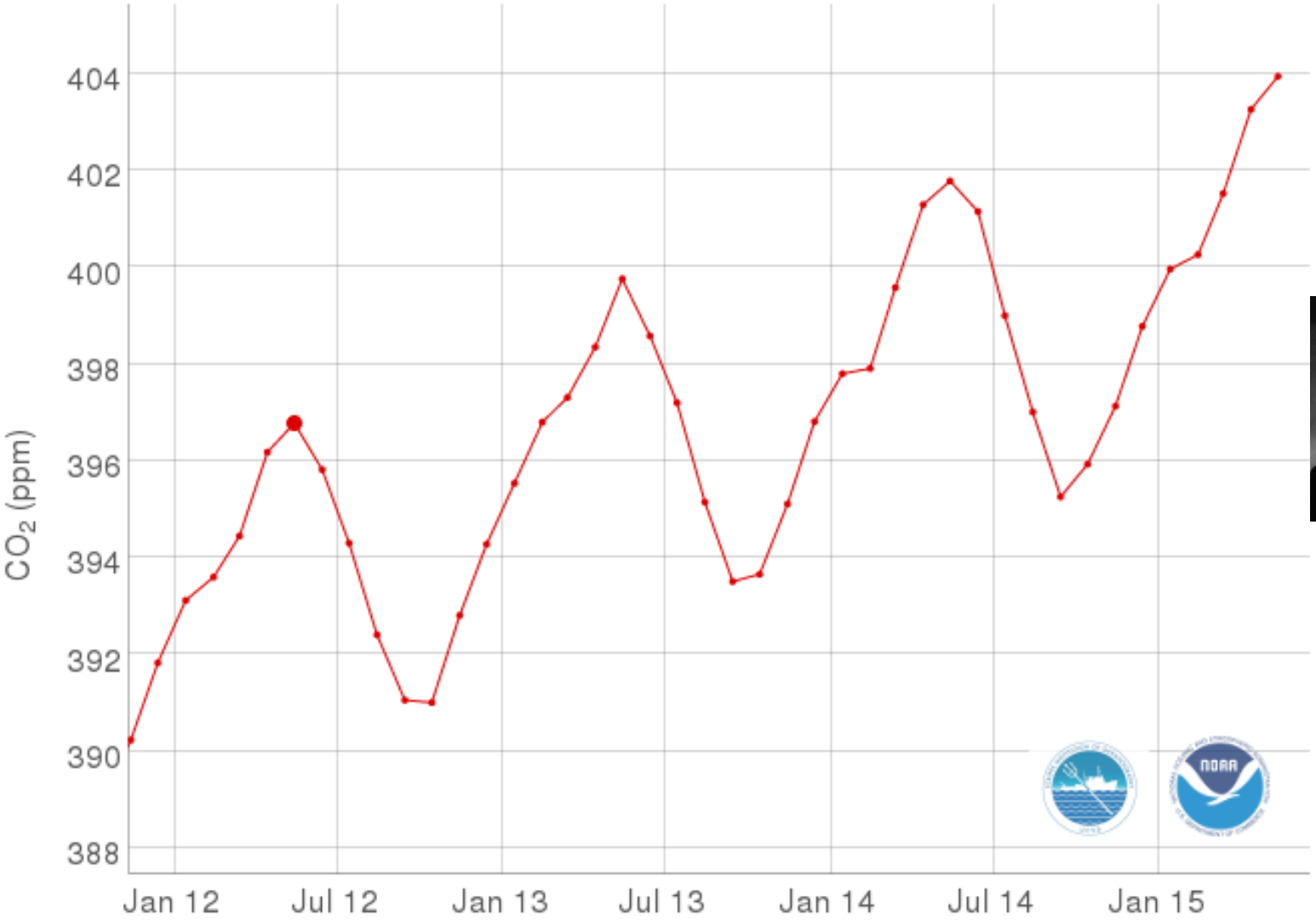

Coal: Resources and Future Production (Energy Watch Group, 2007);

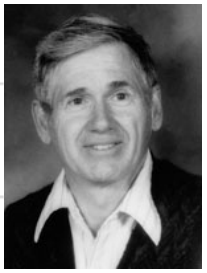
Coal production

- This will damage the economy and our standard of living, our health and well being.

*Nature, January 2012,Vol 481, pp. 433-435*

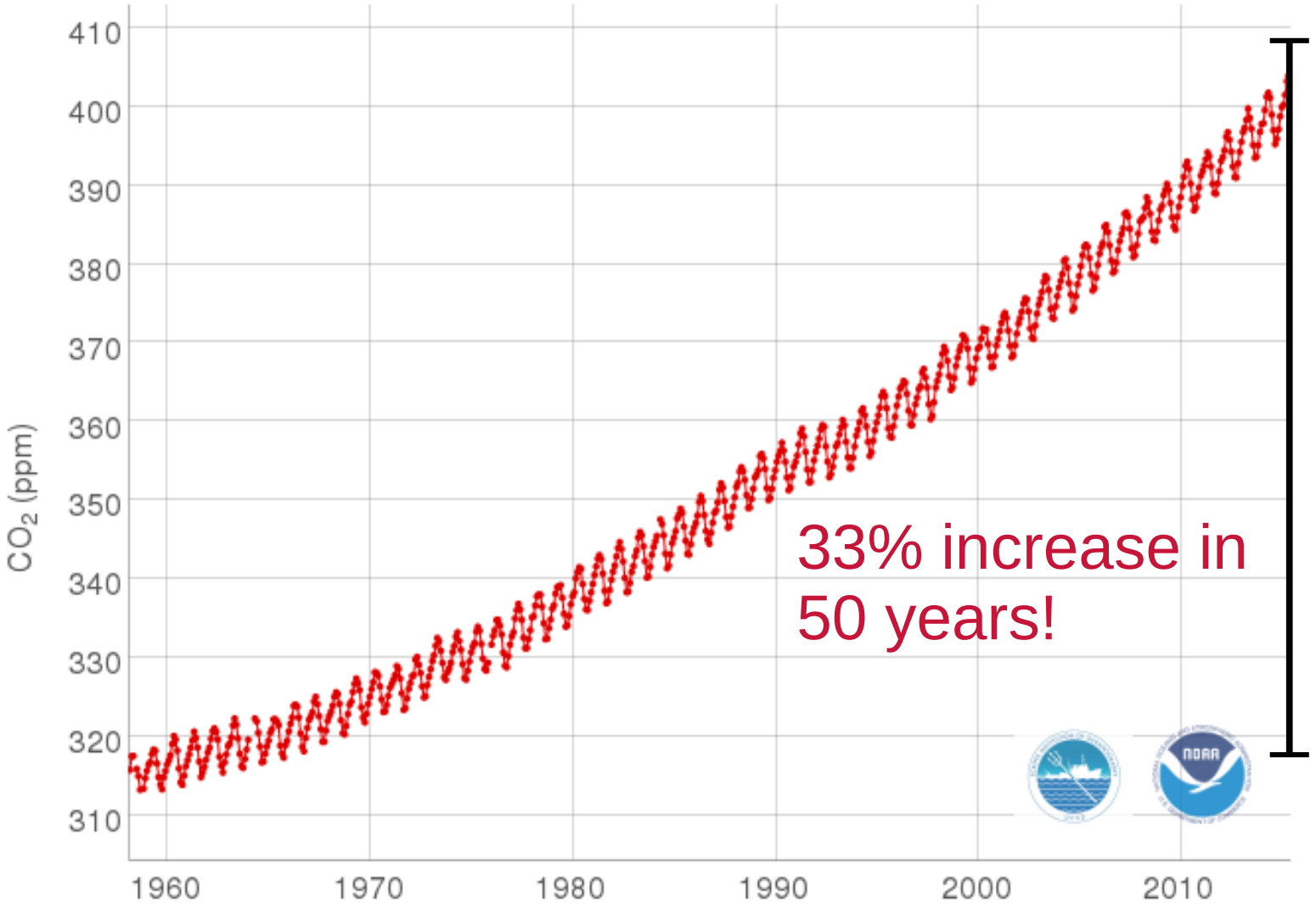
# Reason 2: Global warming



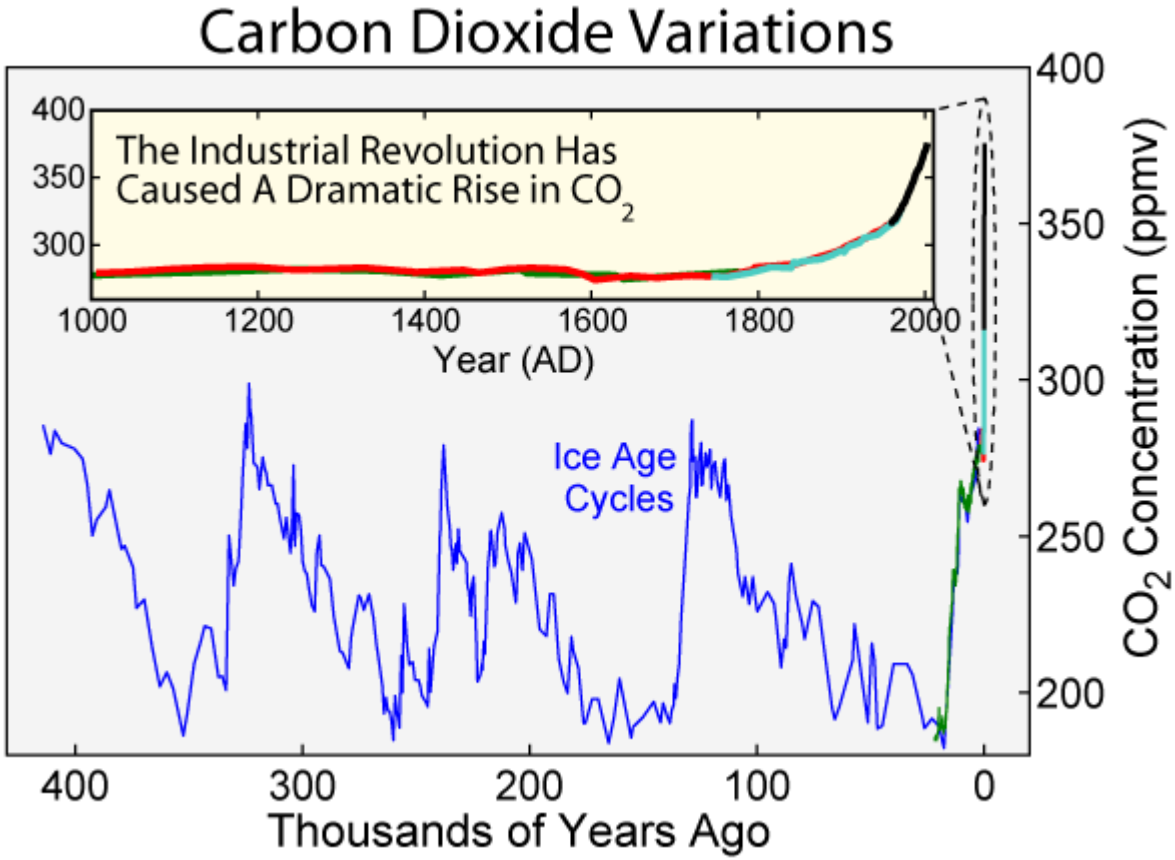



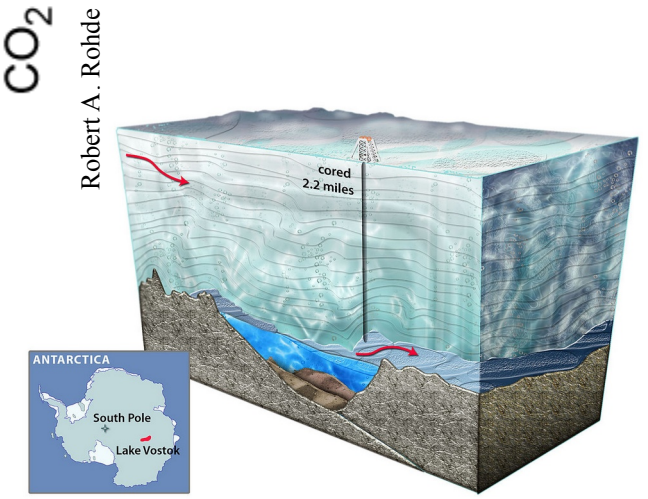
Charles Keeling

# Jan 1980-June 2015

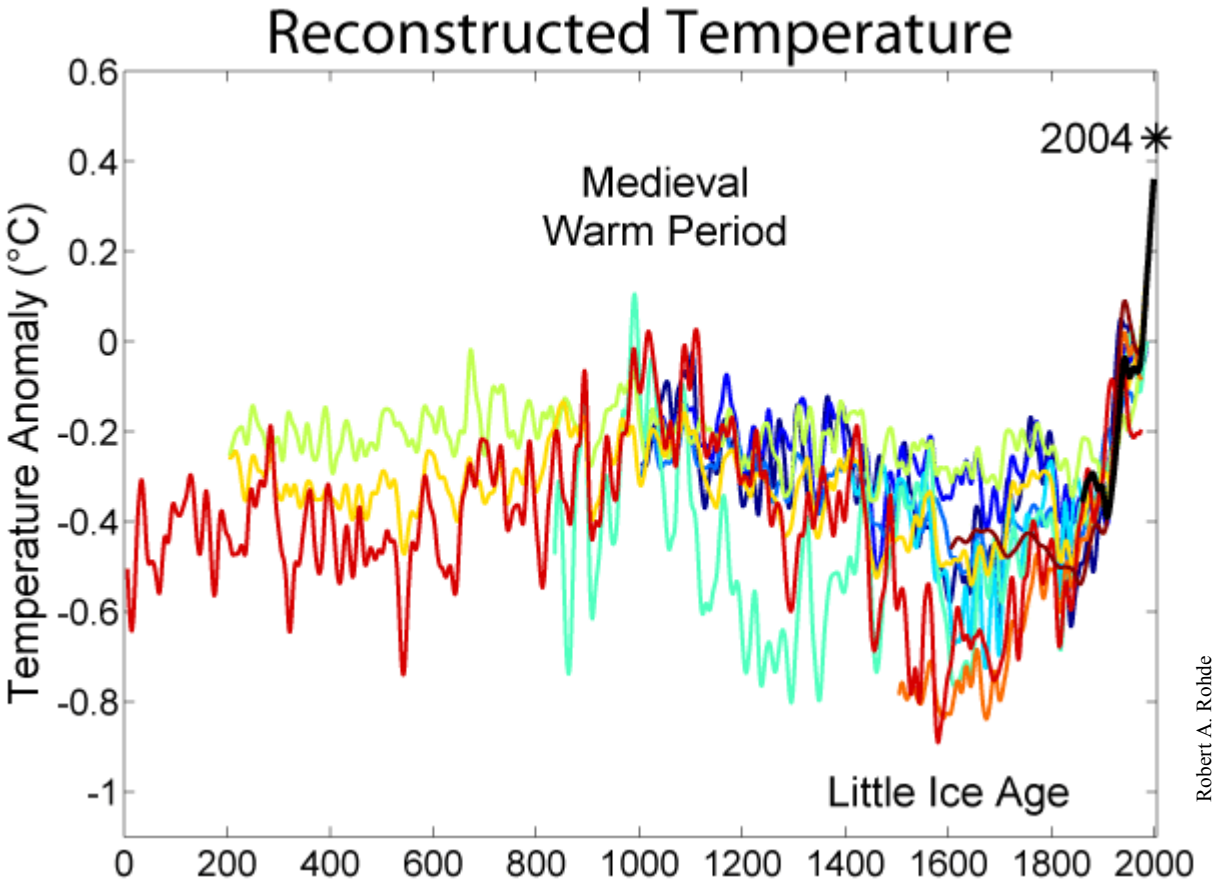


# Carbon dioxide 400 AD – 2009 AD



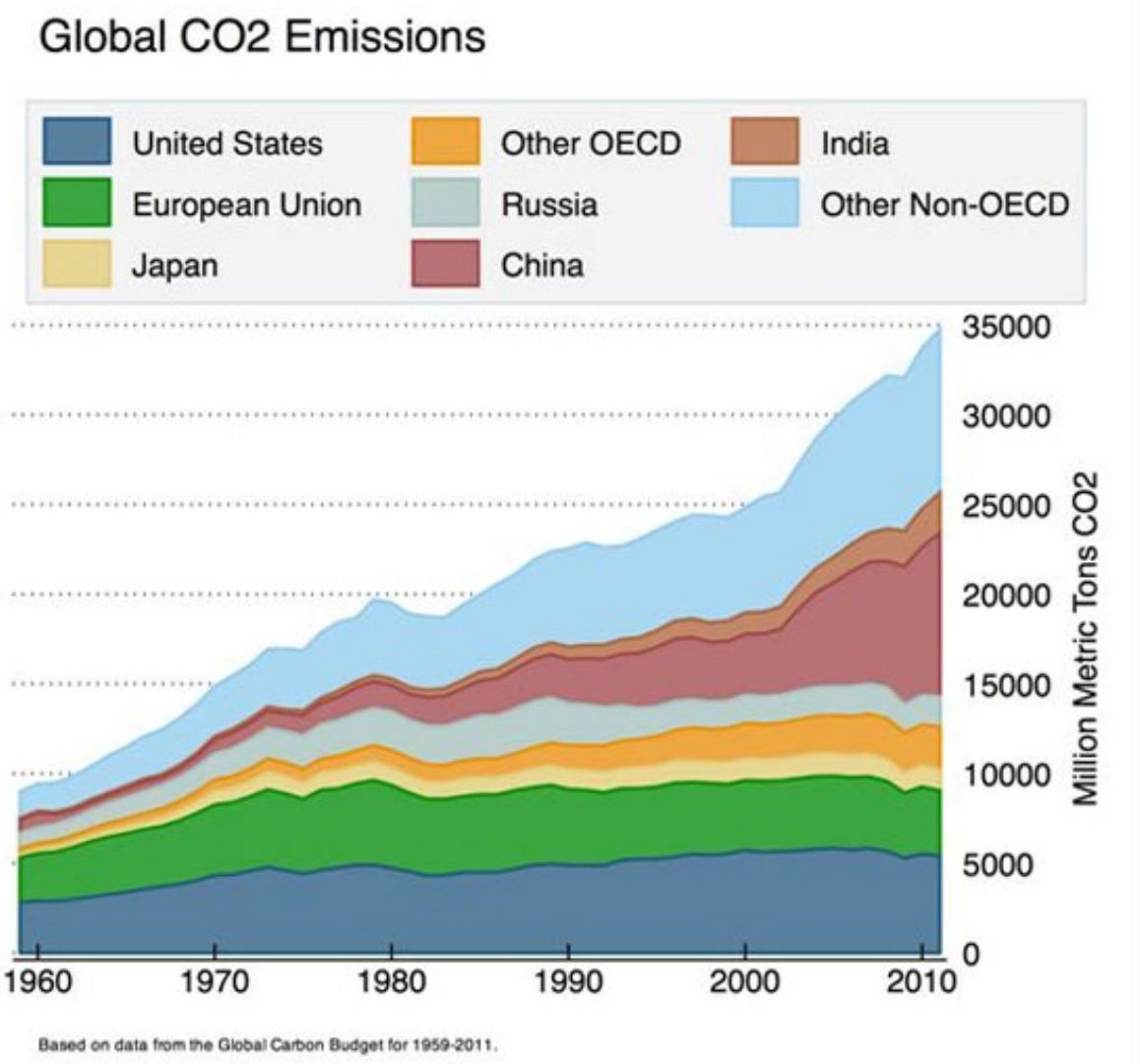



# Global temperature
# 1000 AD – 2000 AD



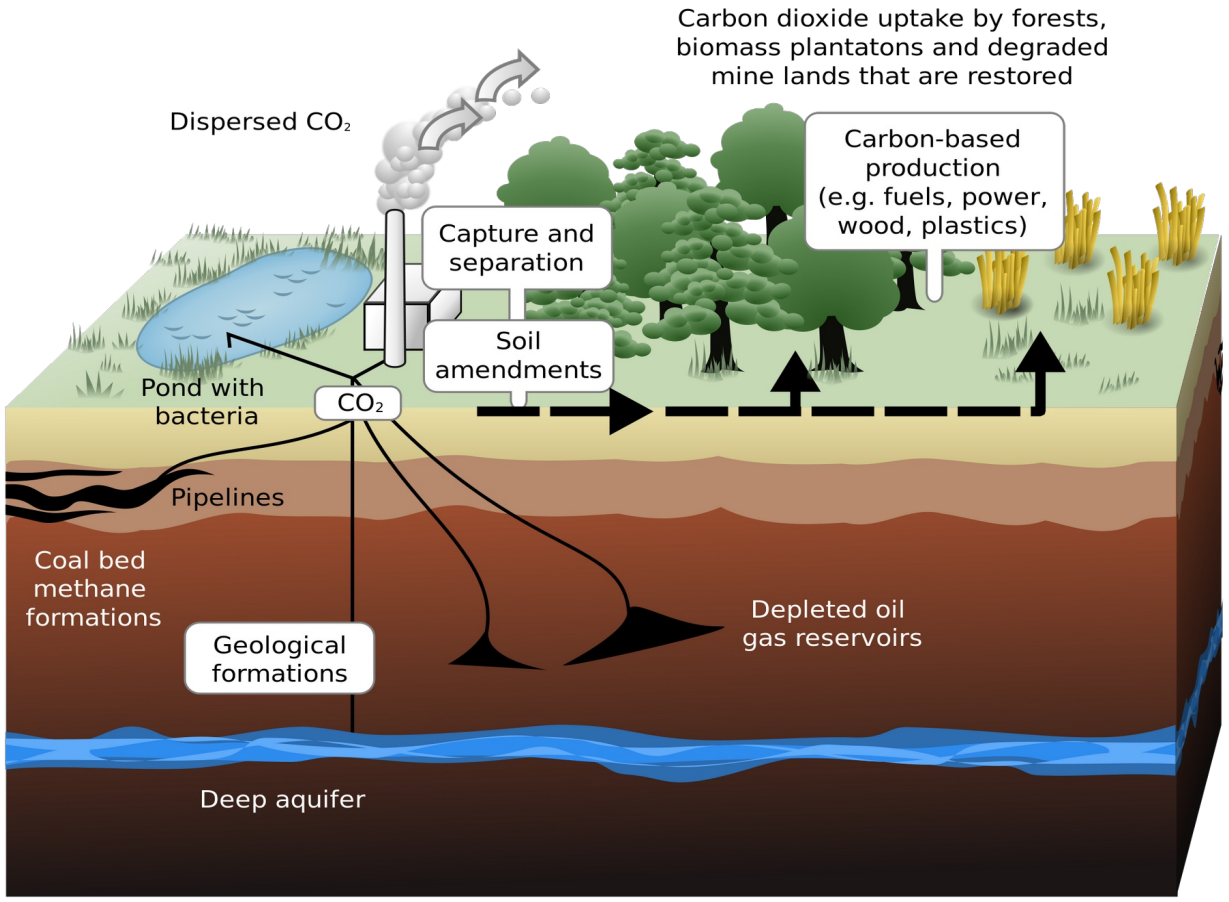

Jensk369

# $CO_2$ Emissions by country



# Carbon capture a silly idea.

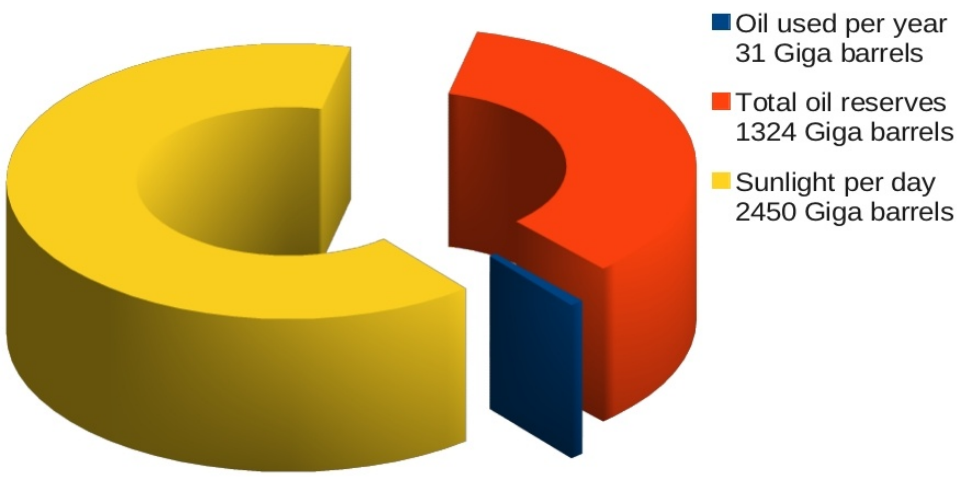
- Transport CO2
- Compress CO2



# Hydrogen cars?


Anyone see a problem?

# Why choose solar energy?




- Solar max power flux:
  ~1500 W / $m^2$
- Average density over the year:
  - Sahara: ~ 400 W / $m^2$
  - UK: ~ 100 W / $m^2$

- Typical solar cell efficiency 15%
- In UK need 40 $m^2$ per person to supply average electricity demand (700 W)

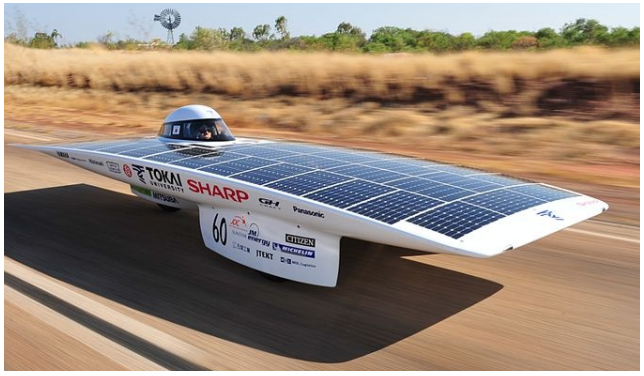
# Where do we find PV systems?

Andrewglaser

Building integrated

Sawu12

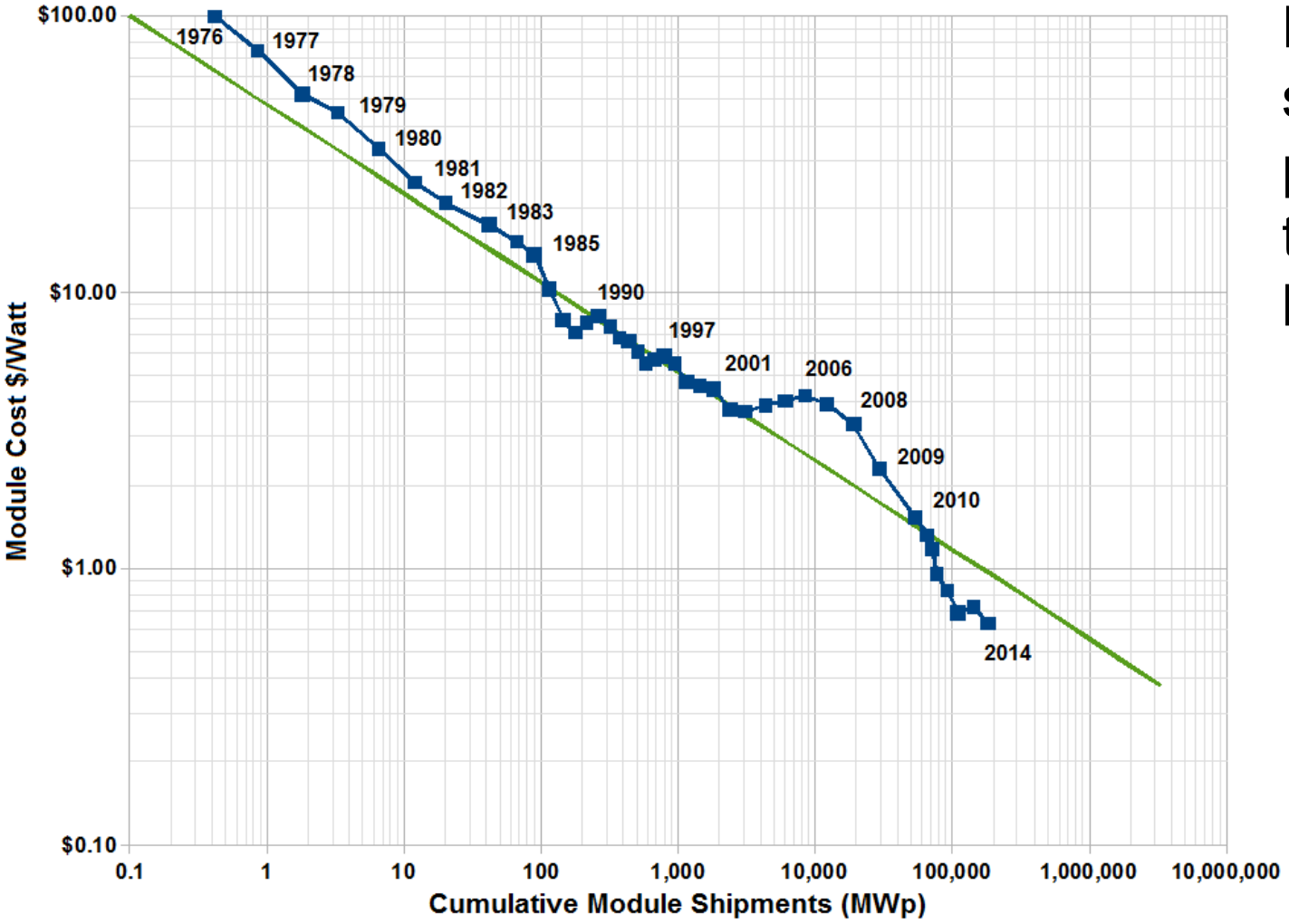
Solar power stations



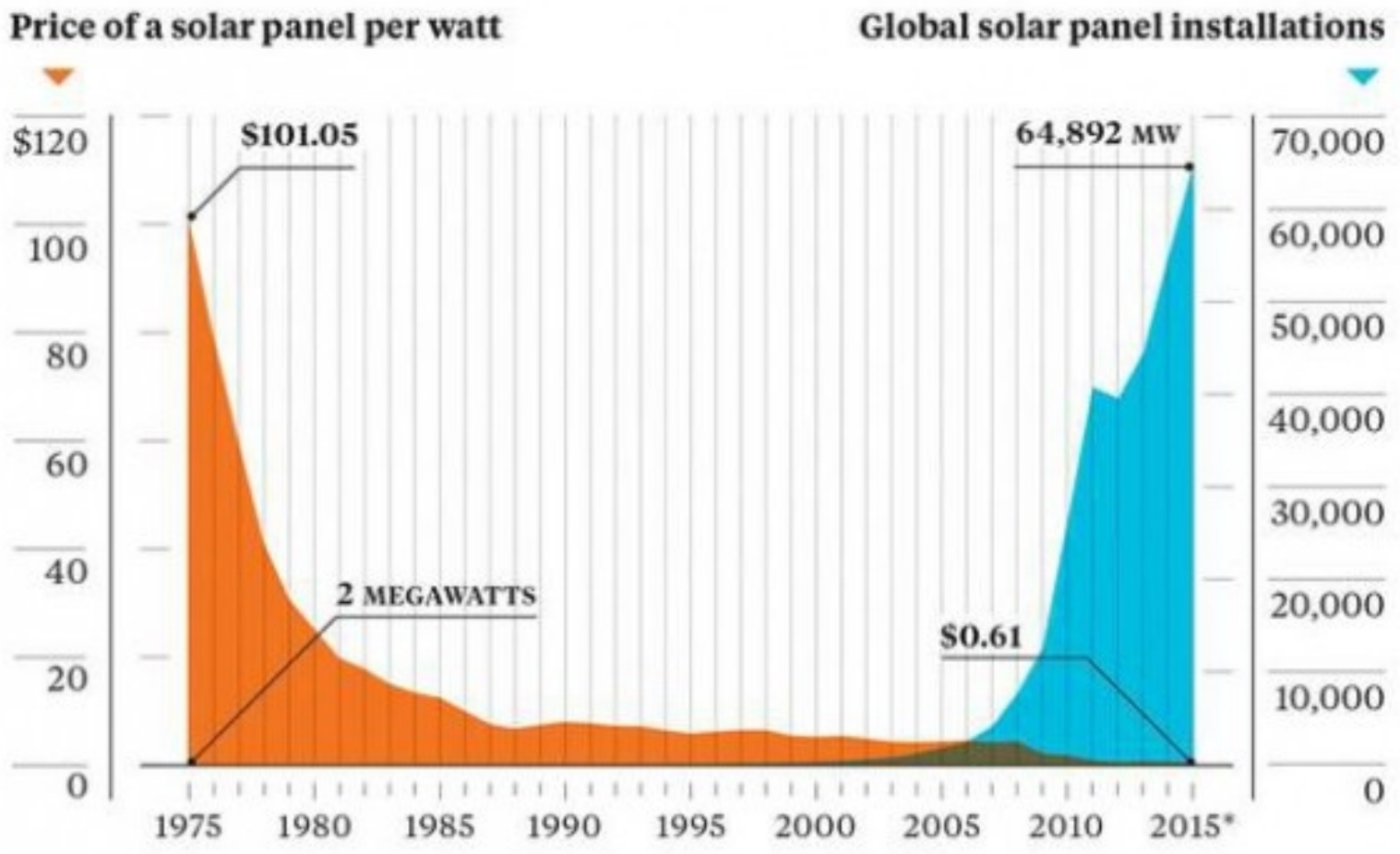

Hideki Kimura, Kouhei Sagawa

Transport integrated??

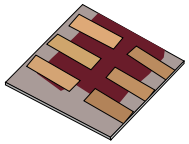
# Swanson's law



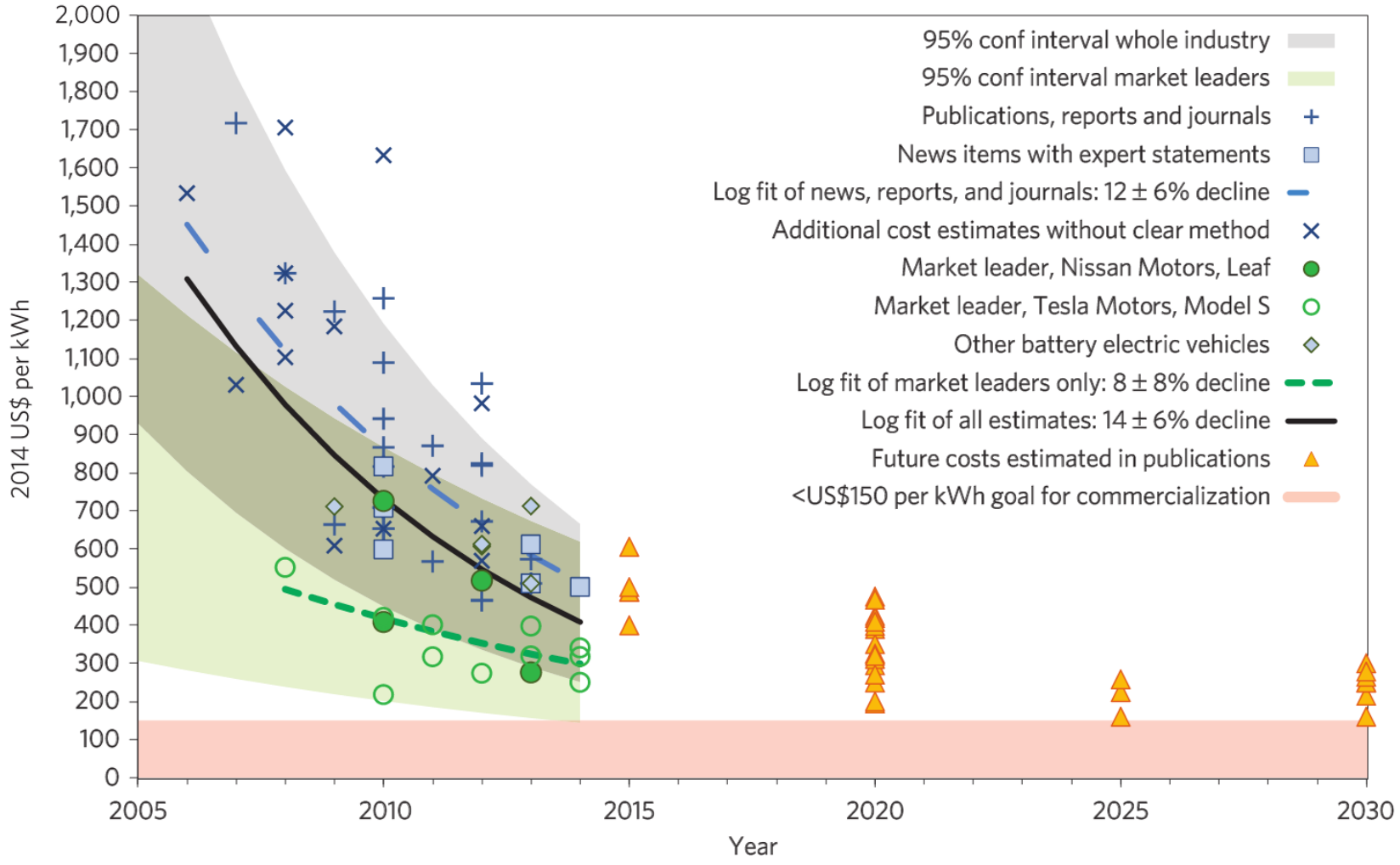

Every time solar cell production the price falls by 20%.


Price of a solar panel per watt
Global solar panel installations
$120
100
80
60
40
20
0
$101.05
2 MEGAWATTS
64,892 MW
$0.61
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
1975
1980
1985
1990
1995
2000
2005
2010
2015*

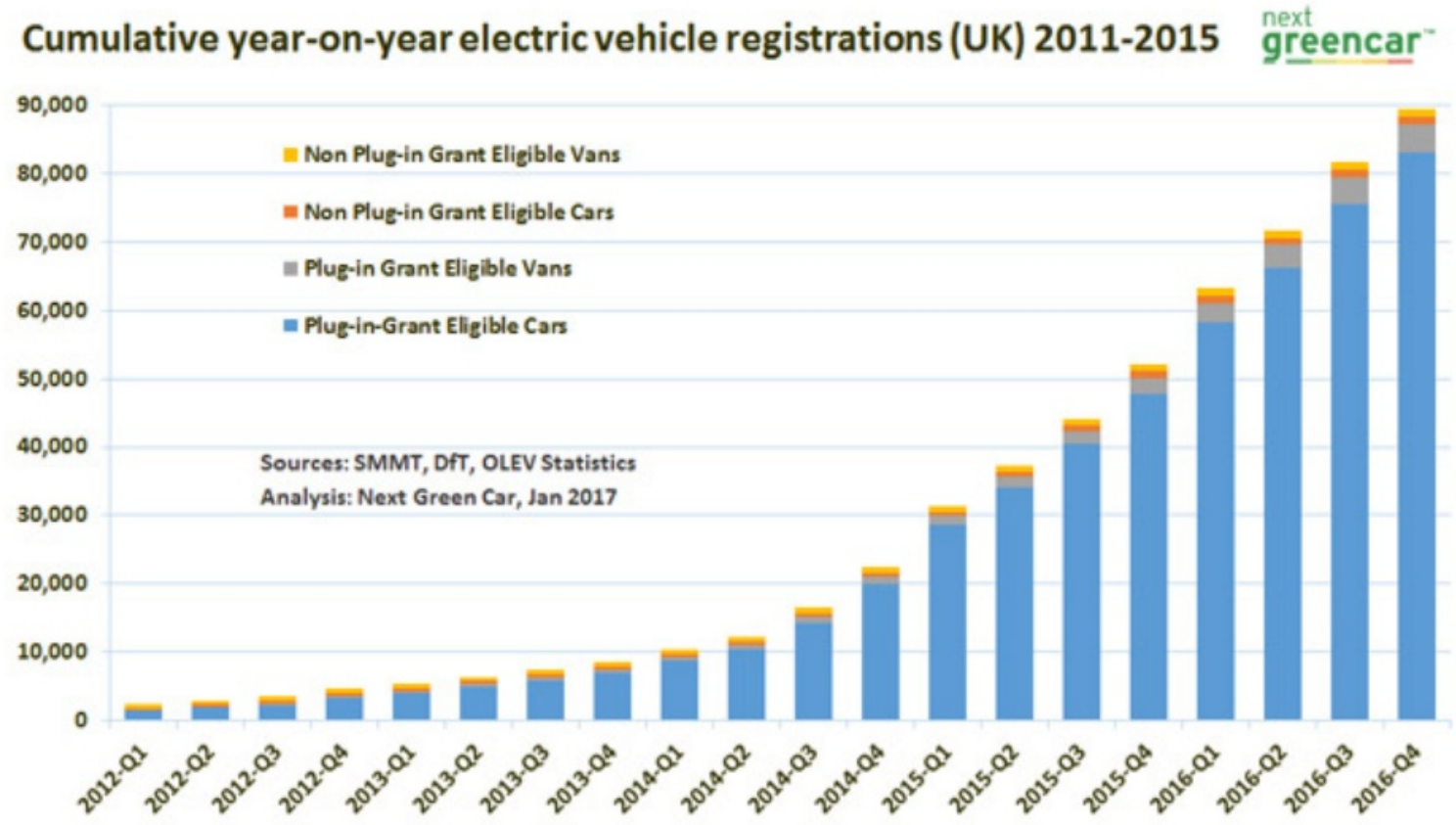
# Video



# Cost of Li batteries

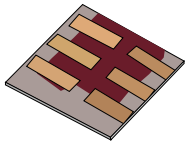


# EV car registrations



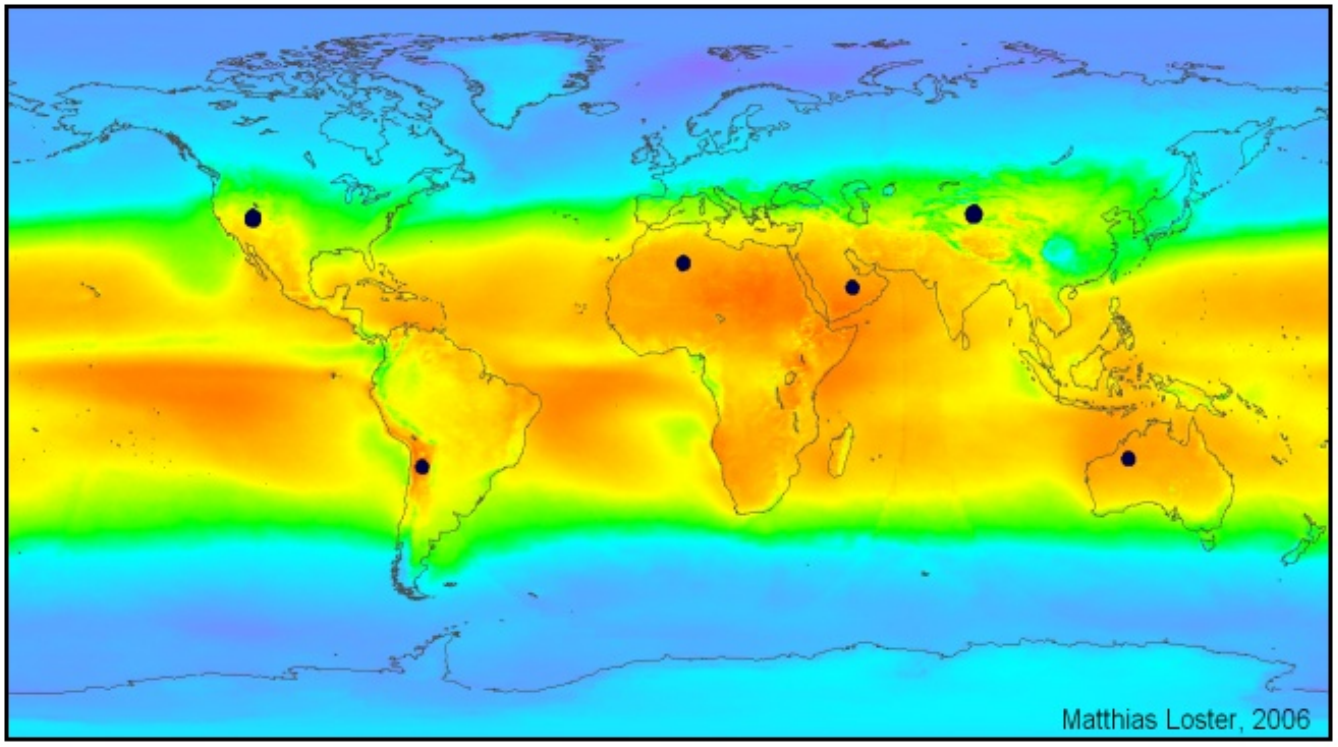
# Cell production

# Overview



- Who am I?
- Why Solar energy?
- **Sunlight**
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# Solar radiation map

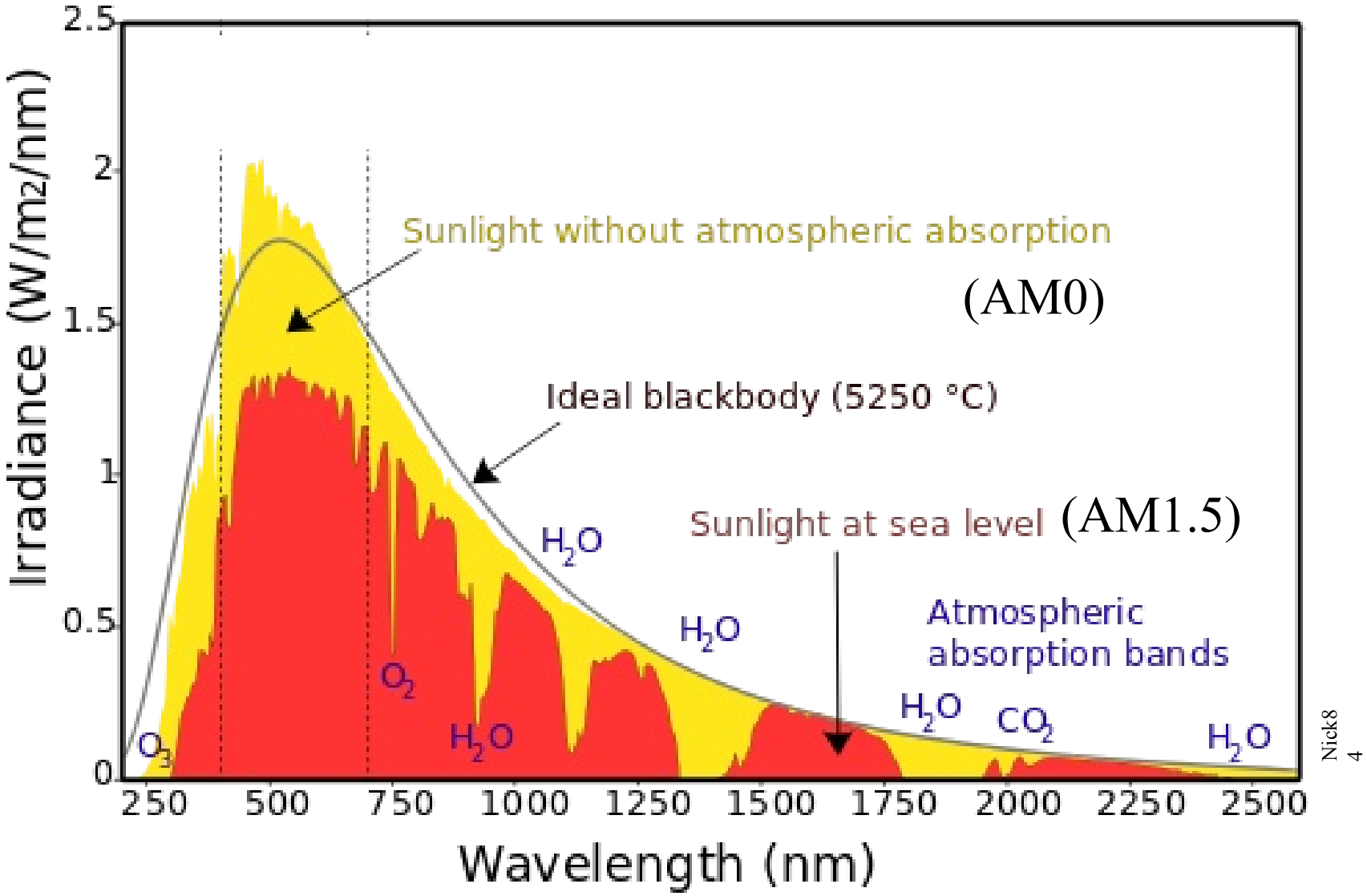



Mlino7

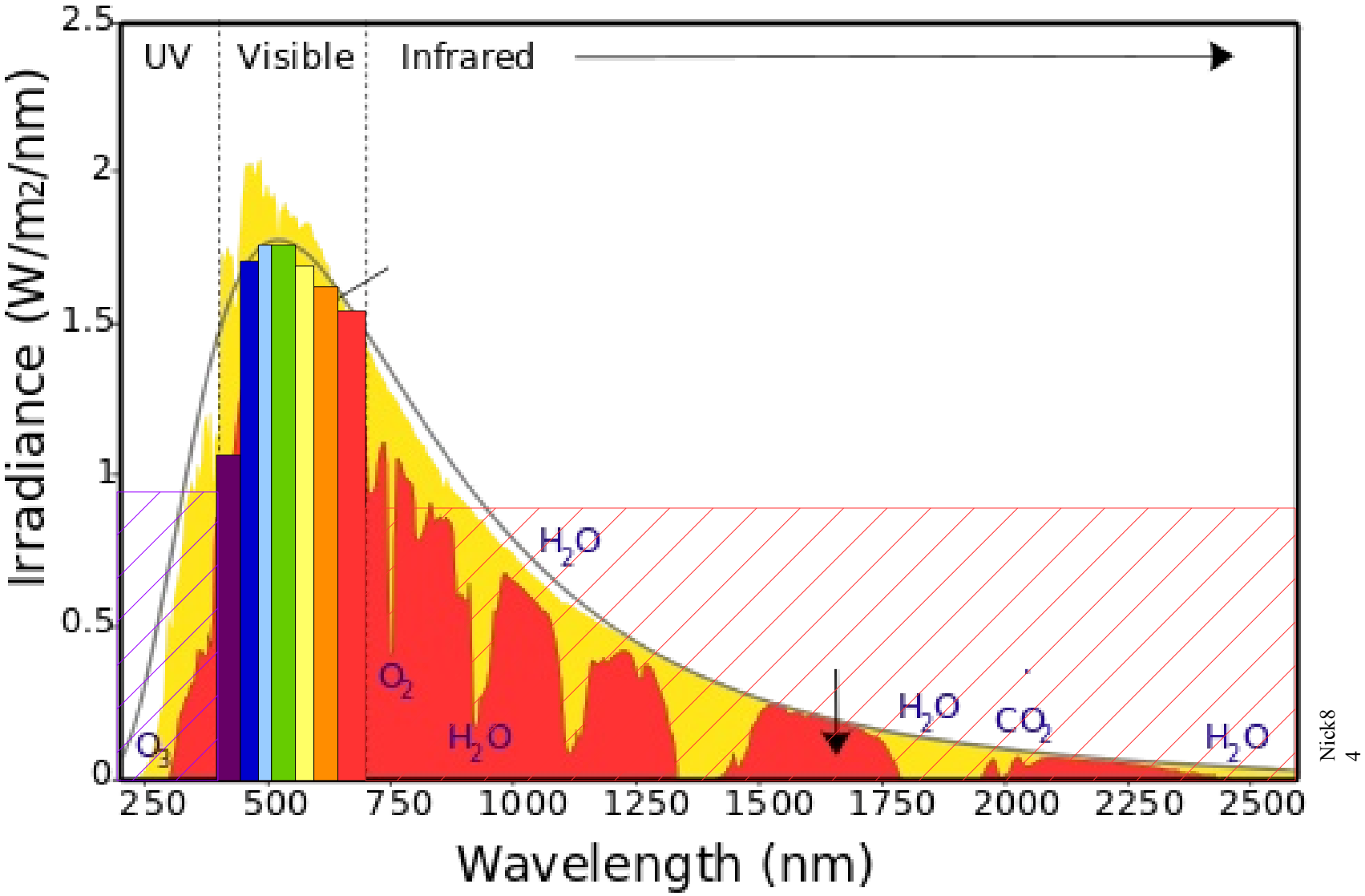
6

Wiki: “Solar areas defined by the dark disks could provide more than the world's total primary energy demand (assuming a conversion efficiency of 8%). That is, all energy currently consumed, including heat, electricity, fossil fuels, etc., would be produced in the form of electricity by solar cells. The colors in the map show the local solar irradiance averaged over three years from 1991 to 1993 (24 hours a day) taking into account the cloud coverage available from weather satellites.”

# What is sunlight exactly: The solar spectrum?

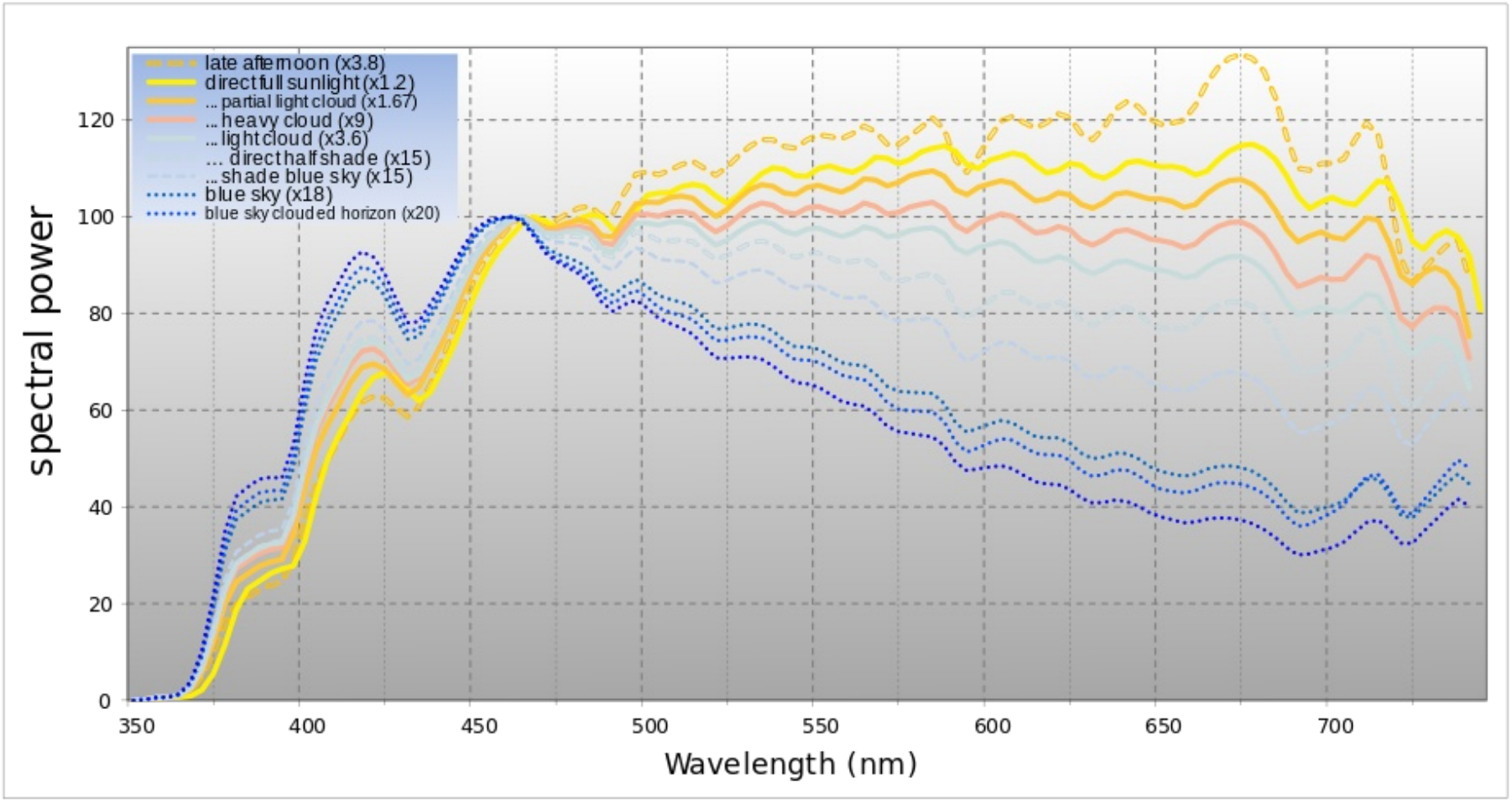


# The solar spectrum




Nick8
4

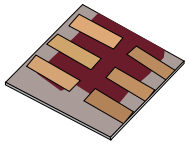
# Clouds and sunlight

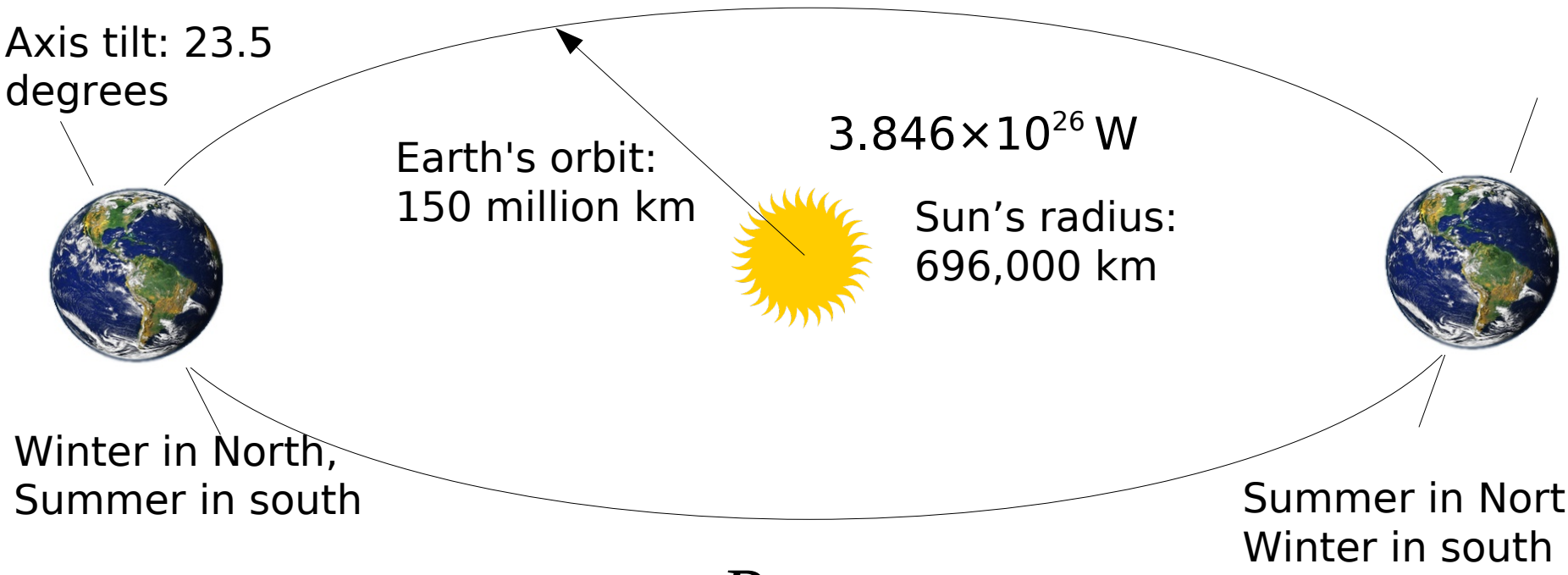



Txbangert

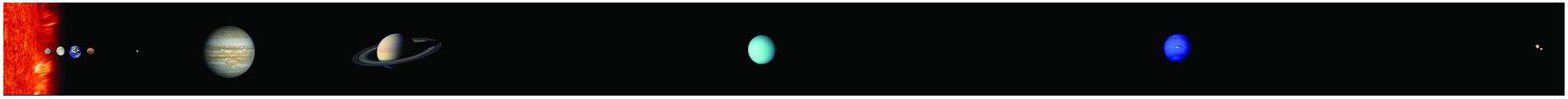
# What do you think this is an image of?

# Seasonal variation in solar intensity






$$Intensity_d = \frac{Power}{4\pi d^2}$$



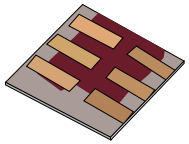
# Class exercise

$$Intensity_d = \frac{Power}{4\pi d^2}$$

$$Intensity_d = \frac{3.846 \times 10^{26}}{4\pi \left(150000\, x\, 10^6\right)^2}$$

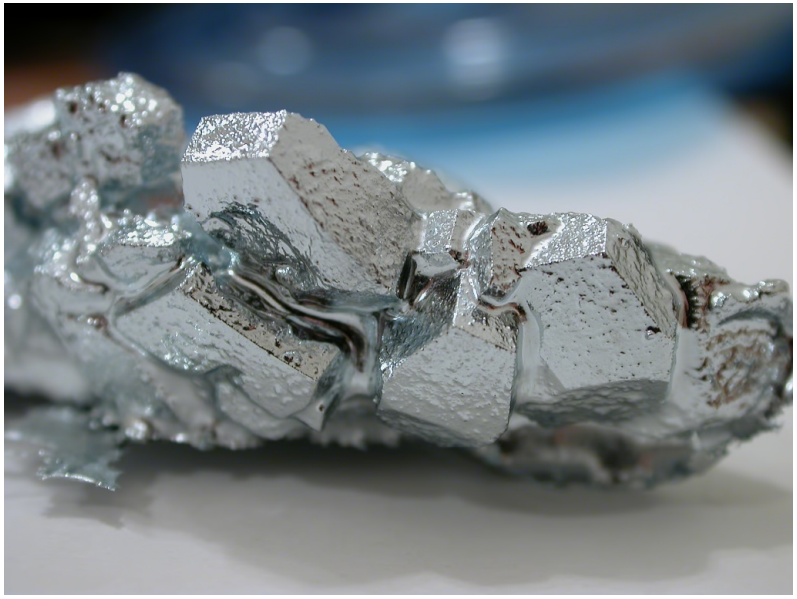
$$Intensity_d = 1360.2\, Wm^{-2}$$

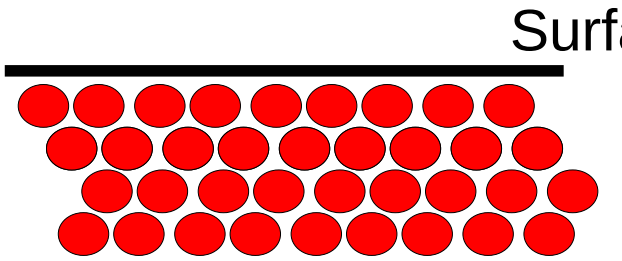
# Overview



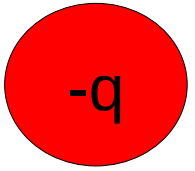
- About me
- Why Solar energy?
- Sunlight
- **Absorbing sunlight in materials**
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# Fundamental principle of semiconductors: Let's first think about **metals**





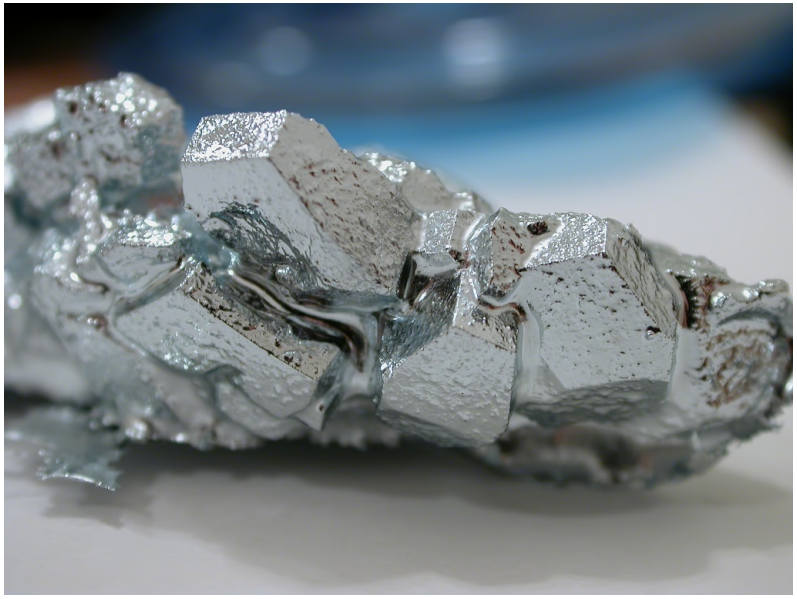

•You can think of a metal as a see of electrons.

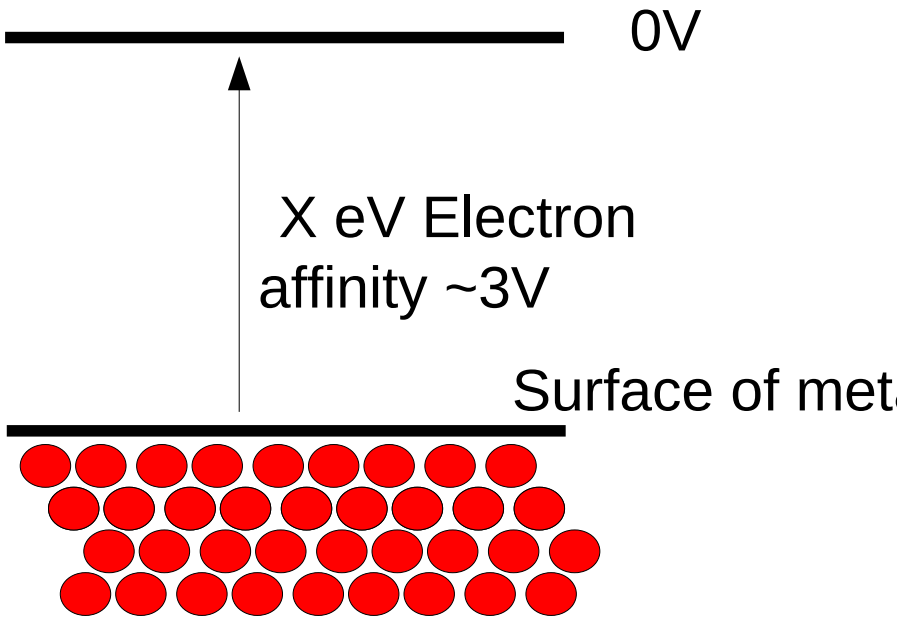



electron

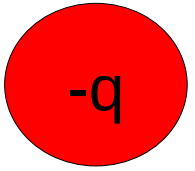
$q=1.60217657 \times 10^{-19}$ coulombs

# Fundamental principle of semiconductors: Let's first think about **metals**






- You can think of a metal as a see of electrons.
- You need energy X (Electron affinity) to remove an electron from the surface of the metal.




electron

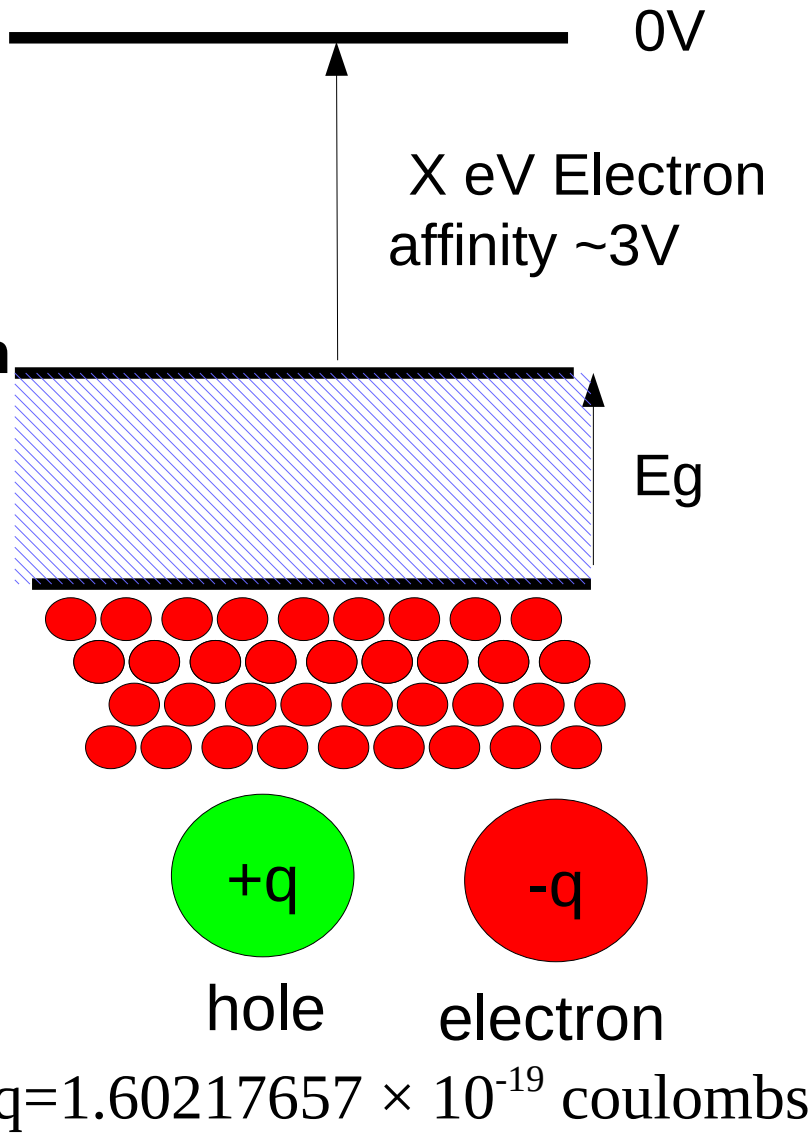
$q=1.60217657 \times 10^{-19}$ coulombs

# Fundamental principle of semiconductors: **Semiconductors and the band gap**

- Solar cells are made from a special type of material called a semiconductor.

# Fundamental principle of semiconductors: **Semiconductors and the band gap**

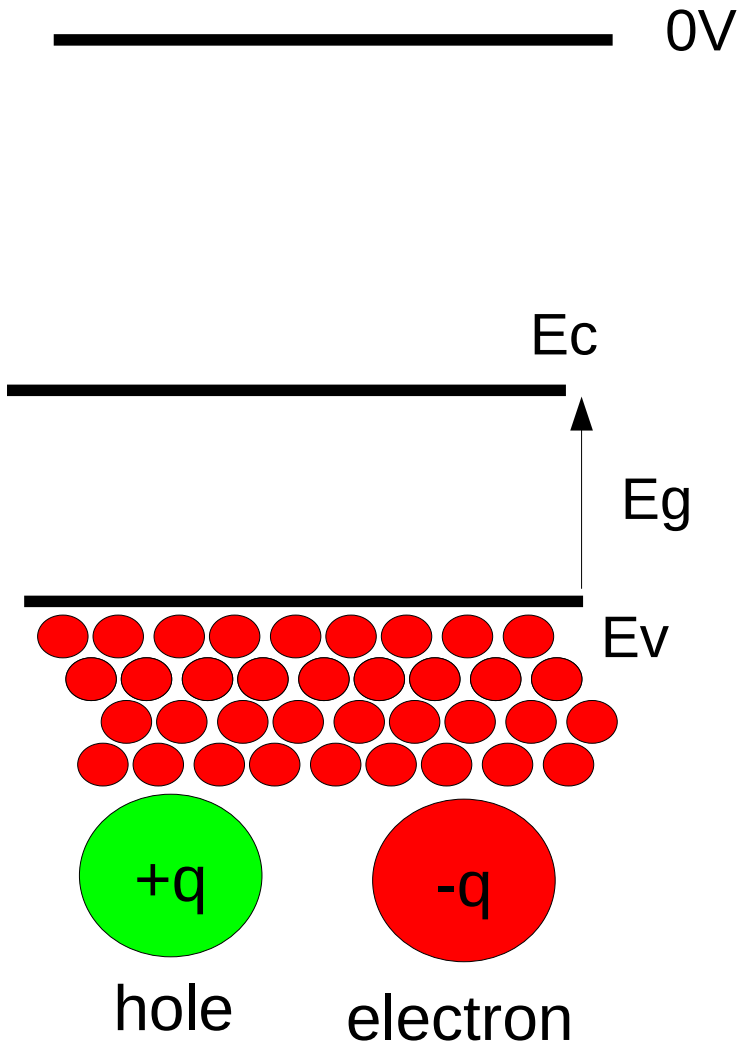
- Solar cells are made from a special type of material called a semiconductor.
- A semiconductors are a special because they have a **forbidden region** called the **band gap (Eg)** where no charge can exist.




$q=1.60217657 \times 10^{-19}$ coulombs

# Fundamental principle of semiconductors: **Semiconductors and the band gap**

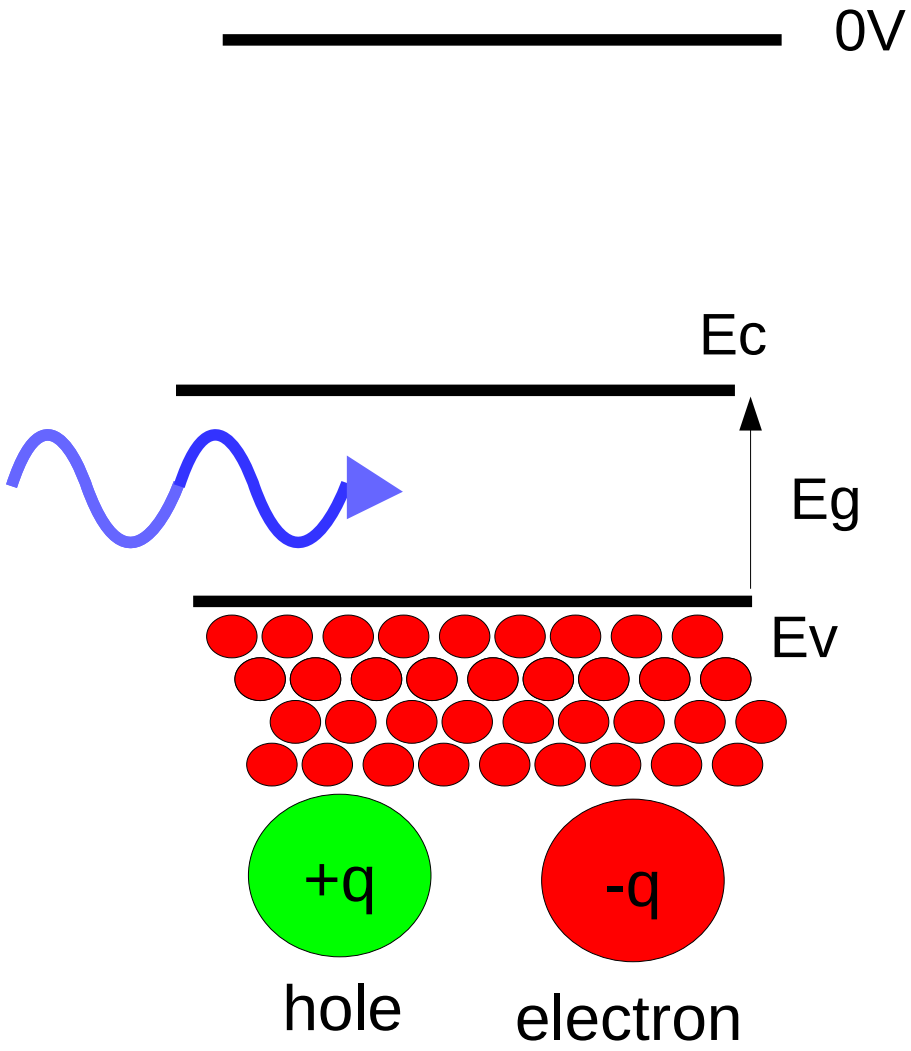
- Light can be absorbed by semiconductors.




$q = 1.60217657 \times 10^{-19}$ coulombs

# Fundamental principle of semiconductors: **Semiconductors and the band gap**

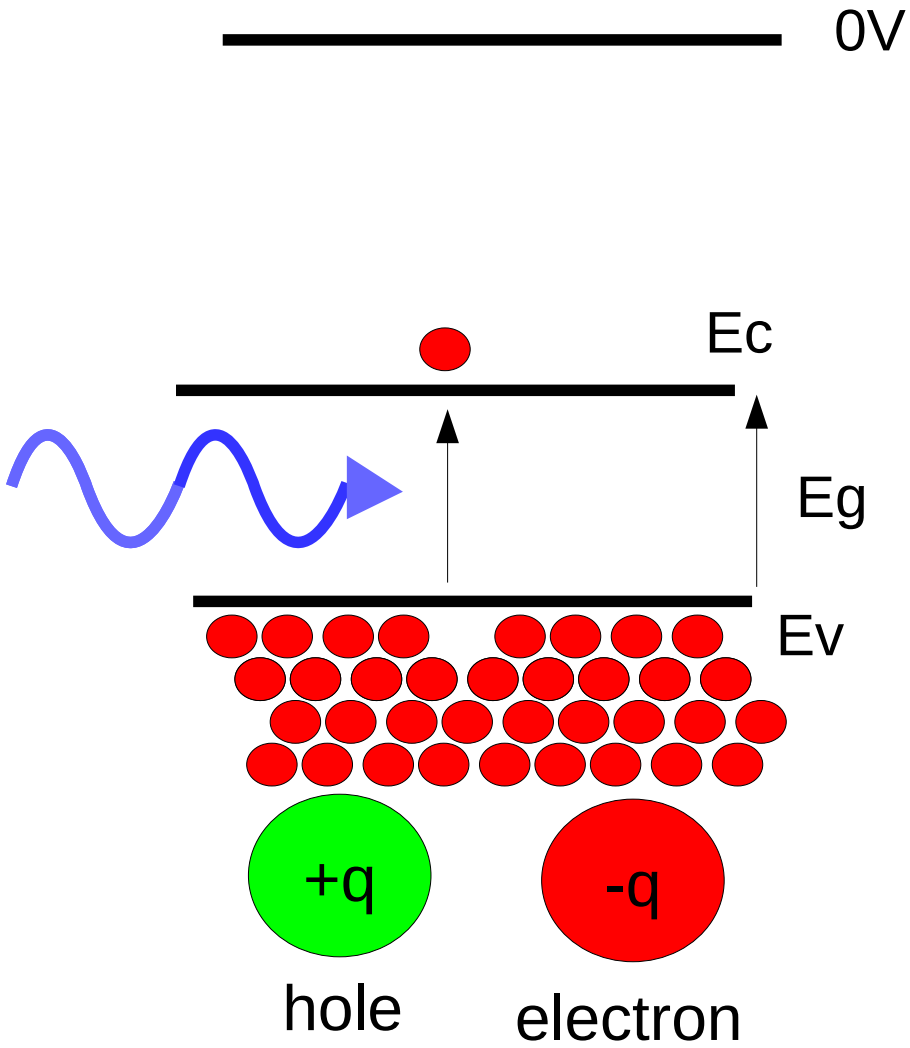
- Light can be absorbed by semiconductors.
- A photon enters the material.




$q = 1.60217657 \times 10^{-19}$ coulombs

# Fundamental principle of semiconductors: **Semiconductors and the band gap**

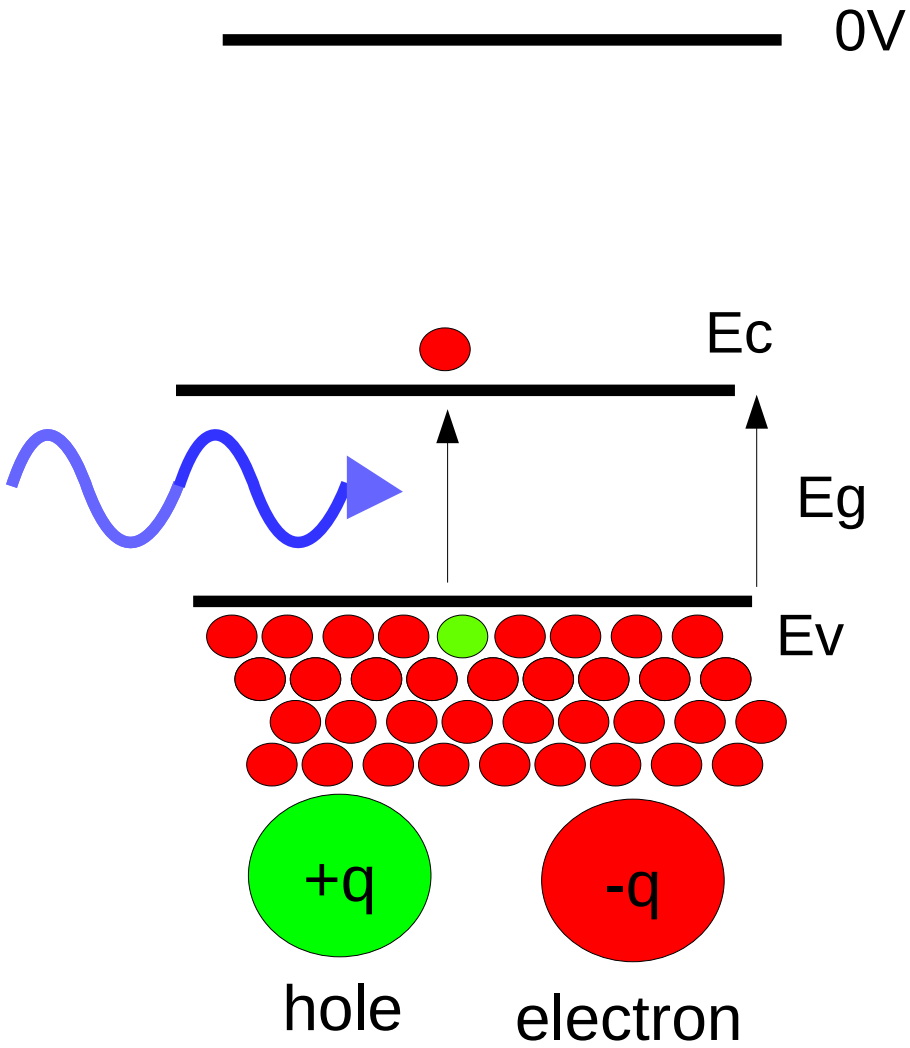
- Light can be absorbed by semiconductors.
- A photon enters the material.
- And promotes an electron from **Ec** to **Ev**.




$q = 1.60217657 \times 10^{-19}$ coulombs

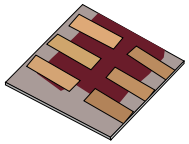
# Fundamental principle of semiconductors: **Semiconductors and the band gap**

- Light can be absorbed by semiconductors.
- A photon enters the material.
- And promotes an electron from **Ec** to **Ev**.
- The gap that the electron leaves is called a hole.



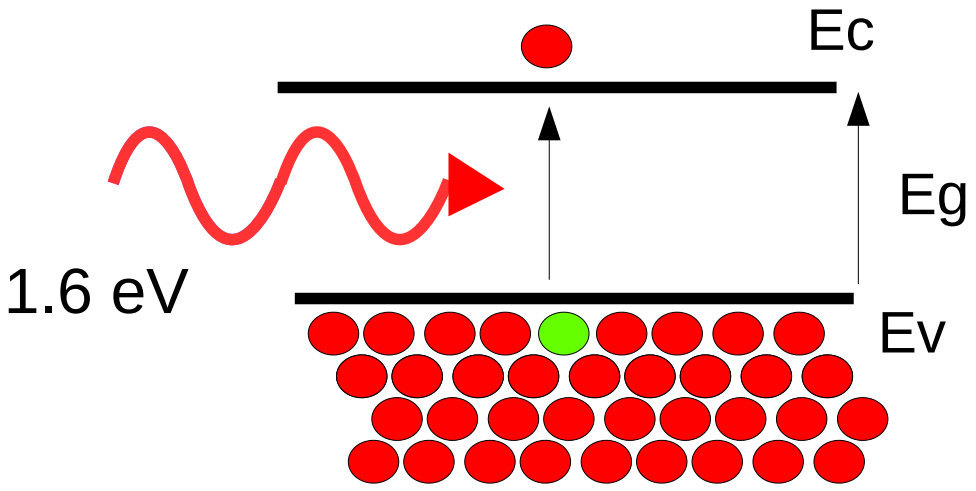

$q = 1.60217657 \times 10^{-19}$ coulombs

# Fundamental principle of semiconductors: **Absorption**

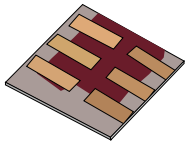


- Silicon has a band gap of Eg 1.6 eV

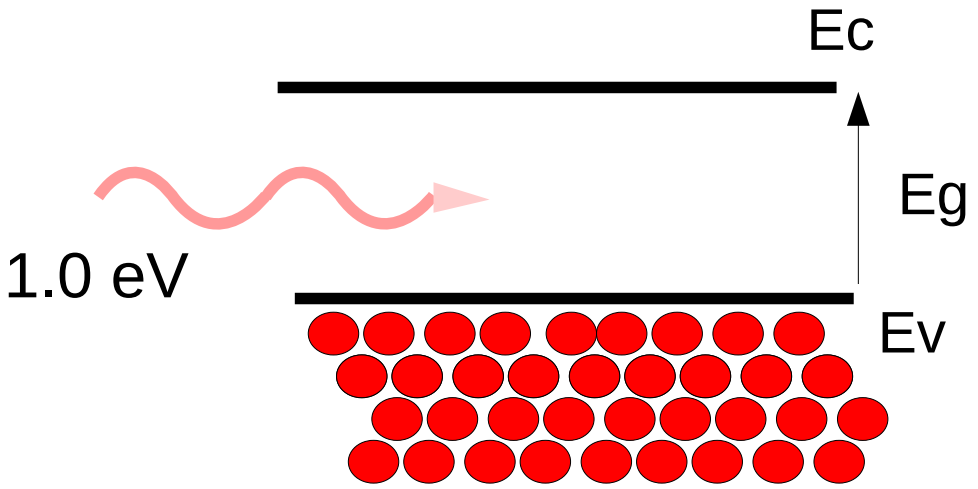
- So if a photon has exactly 1.6 eV (deep red) it will be absorbed.



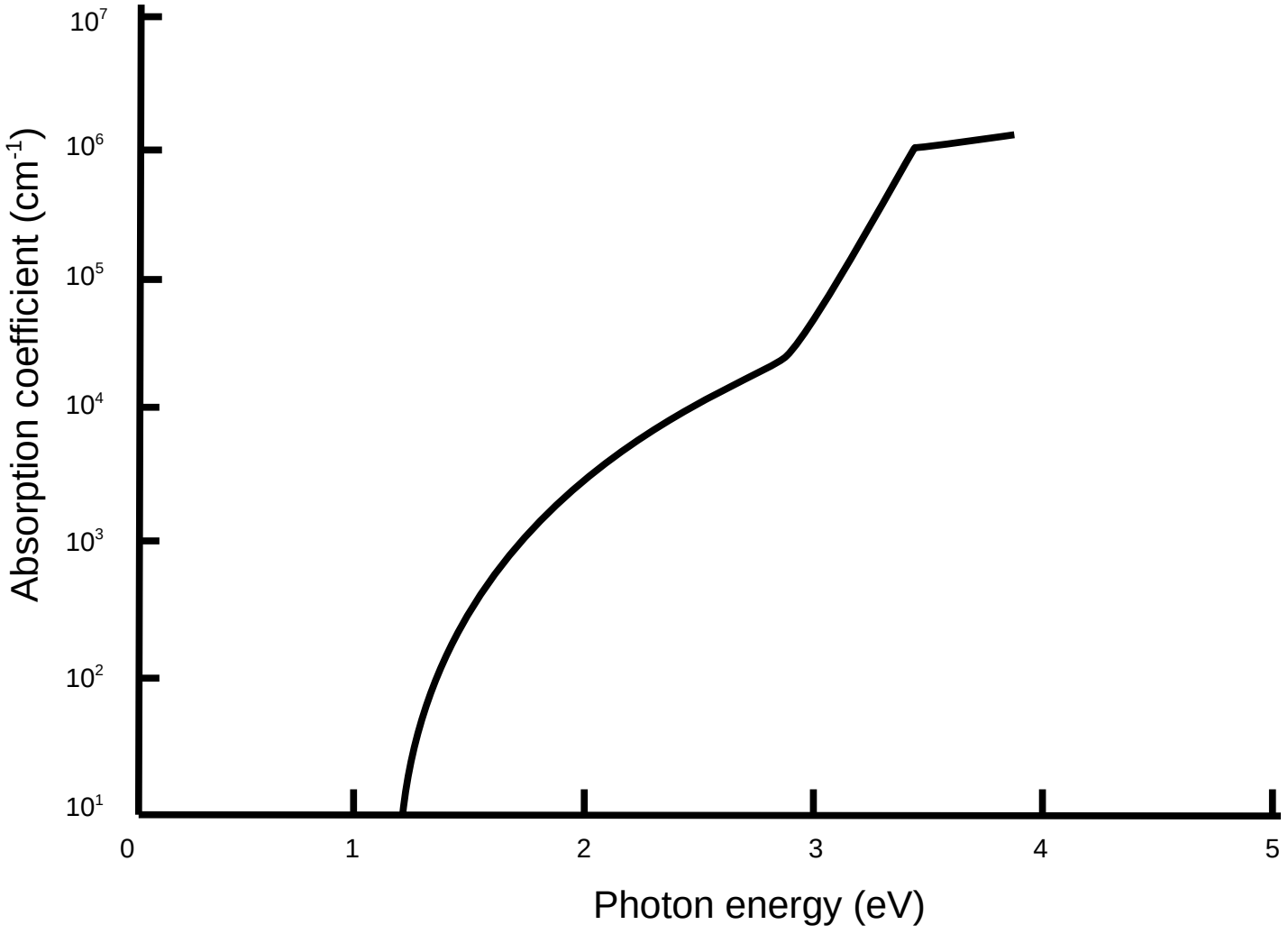

# Fundamental principle of semiconductors: **Absorption**



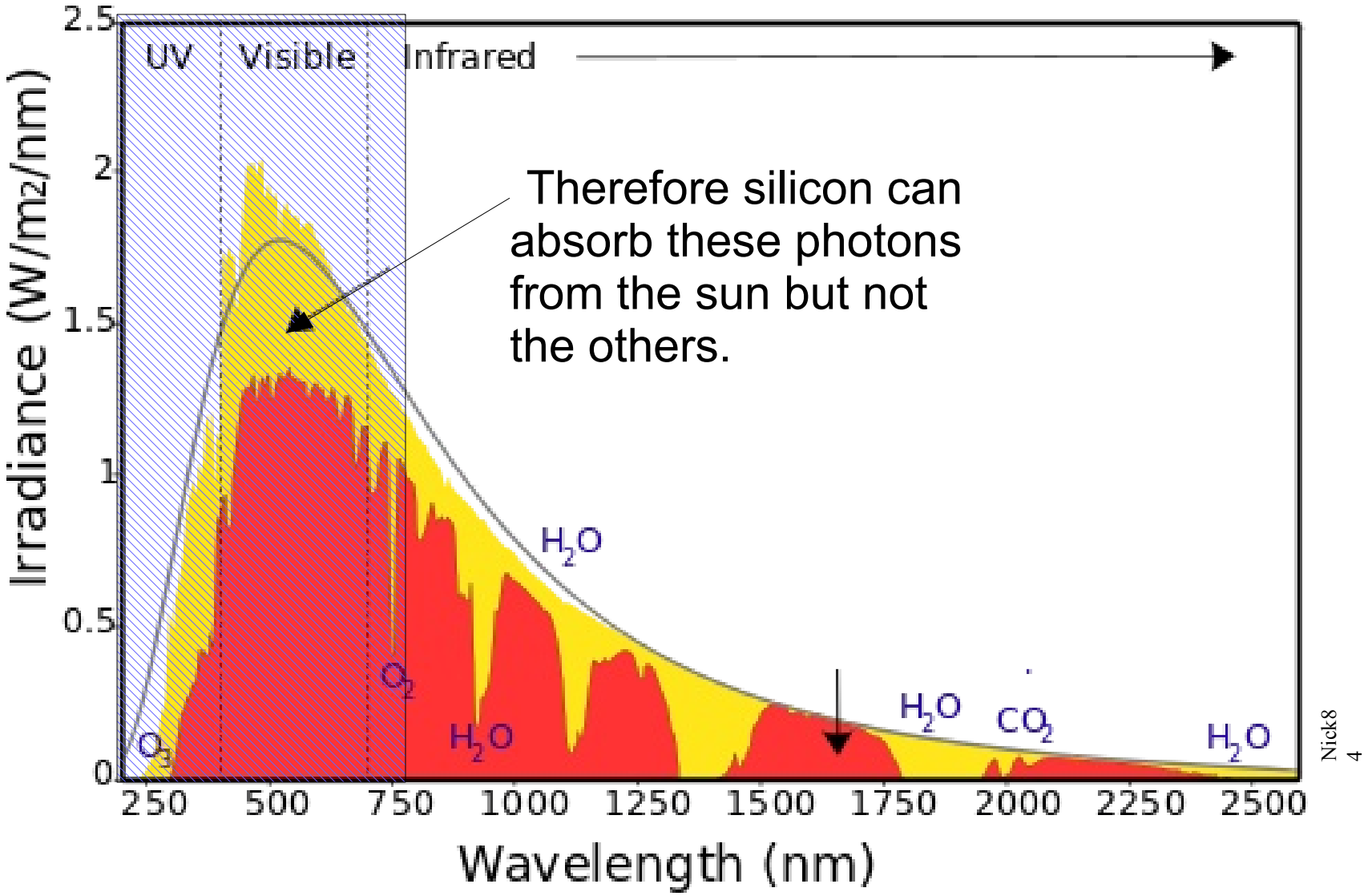
- If a photon has less than 1.6 eV of energy say (infrared red) it will not be absorbed because it does not have enough energy to promote an electron from Ev to Ec.



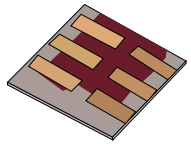

# Absorption spectrum of silicon.



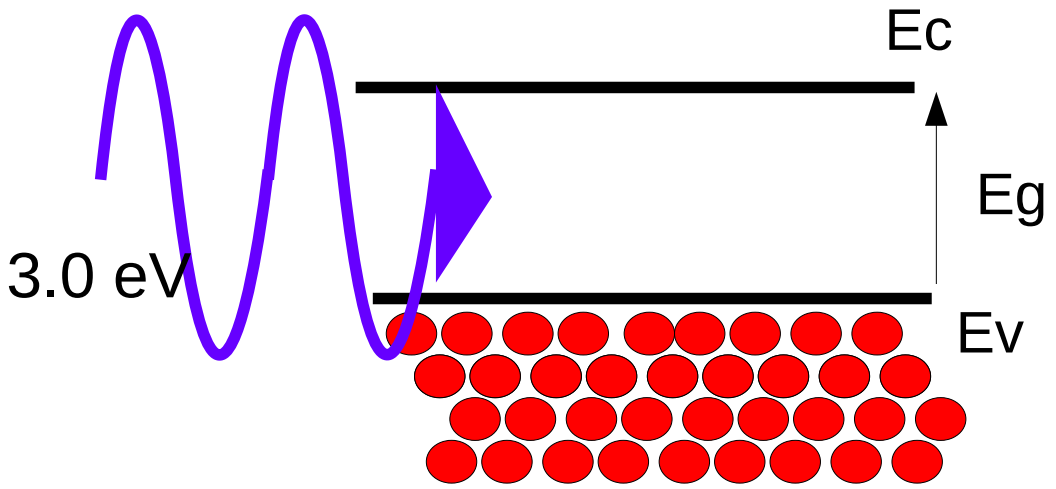
# The solar spectrum



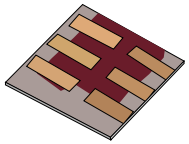
# Fundamental principle of semiconductors: **Absorption**



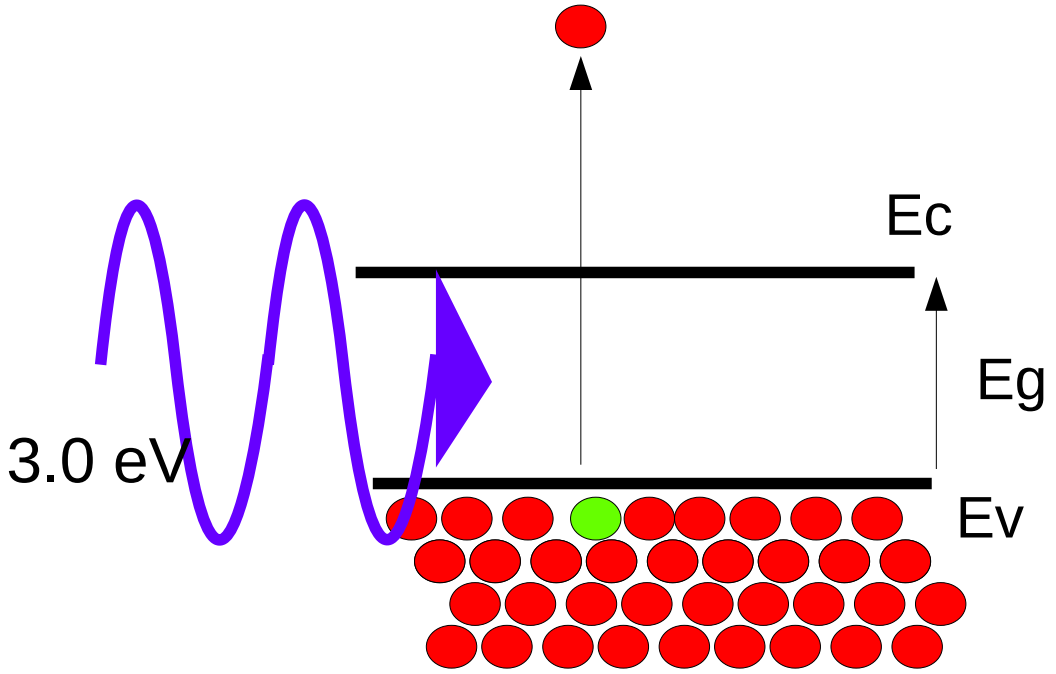
•If a photon has more than 1.6 eV it will lift a electron higher that Ec. However the electron will quickly relax to Ec loosing the excess energy to heat.



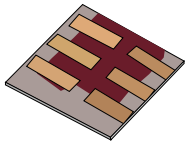
# Fundamental principle of semiconductors: **Absorption**



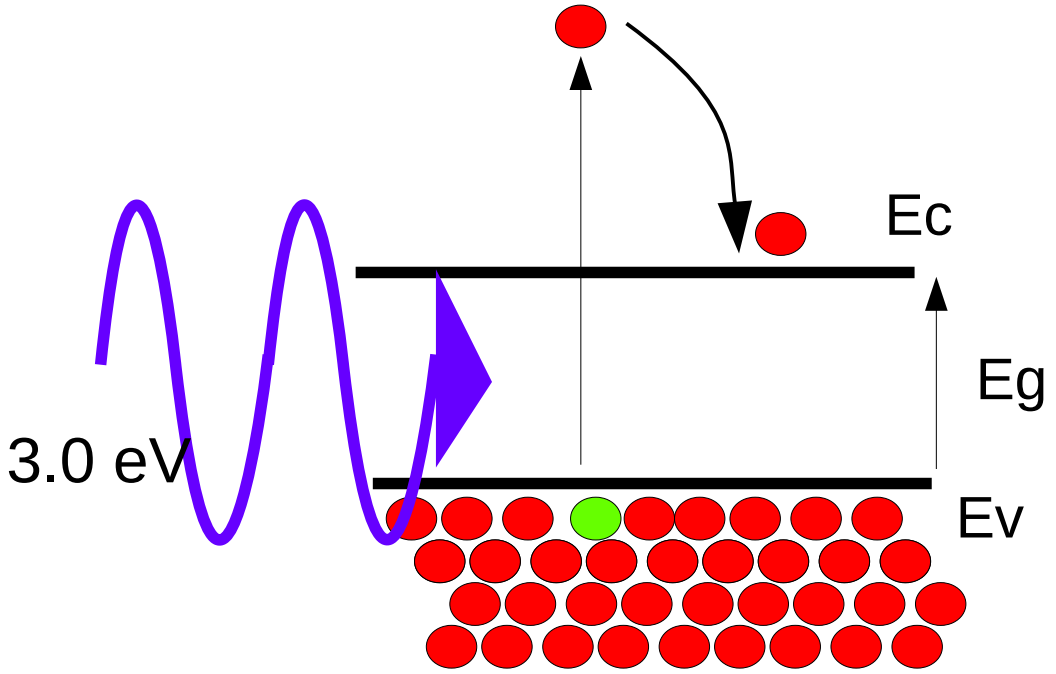
- If a photon has more than 1.6 eV it will lift a electron higher that Ec. However the electron will quickly relax to Ec loosing the excess energy to heat.



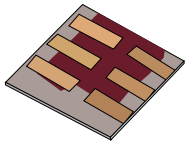
# Fundamental principle of semiconductors: **Absorption**



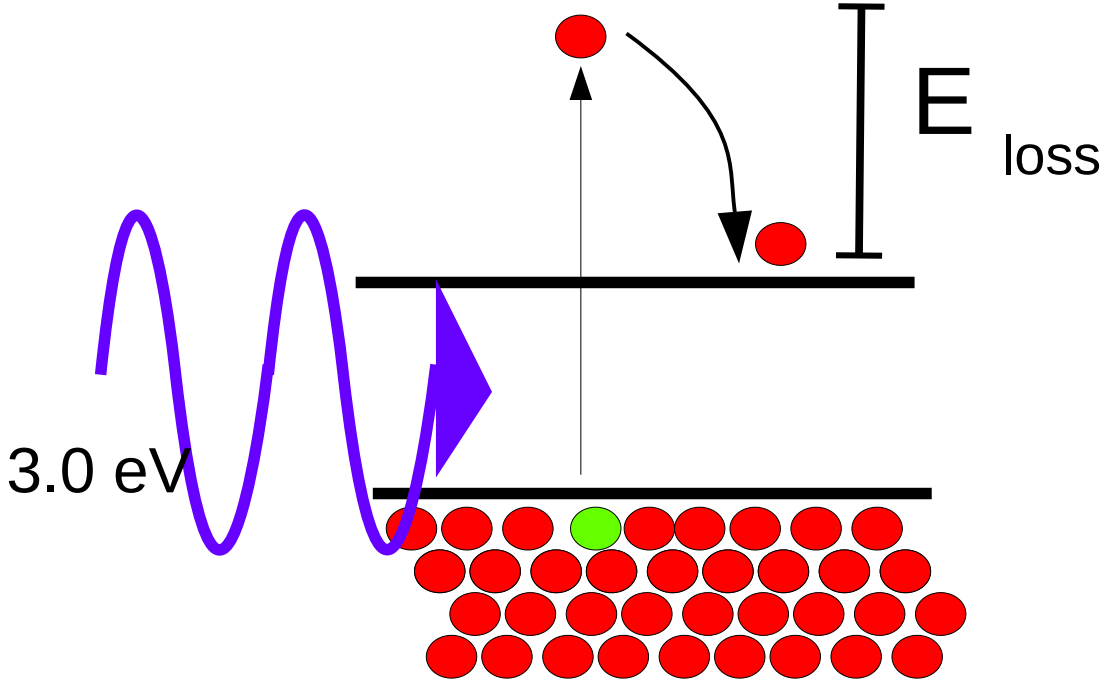
•If a photon has more than 1.6 eV it will lift a electron higher that Ec. However the electron will quickly relax to Ec loosing the excess energy to heat.



# Fundamental principle of semiconductors: **Absorption**



•If a photon has more than 1.6 eV it will lift a electron higher that Ec. However the electron will quickly relax to Ec loosing the excess energy to heat.




$$E_{loss} = E_{photon} - E_g$$

# From Energy to wavelength

Plank's constant

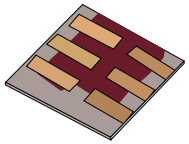
$$E = hf \qquad c = f\lambda$$

$$E = h\frac{c}{\lambda}$$

h=6.62607004 × $10^{-34}$ $m^2$ kg $s^{-1}$

c=3x$10^{8}$ $m^{-2}$

# From Energy to wavelength



Plank's constant

$$E = hf \qquad c = f\lambda$$

$$E = h\frac{c}{\lambda}$$

$h=6.62607004 \times 10^{-34}\ m^2\ kg\ s^{-1}$

$c=3x10^{8}\ m^{-2}$

If the band gap of silicon is 1.6eV what is wavelengths of light can it absorb?

# From Energy to wavelength

$$\lambda = h\frac{c}{E}$$

h=6.62607004 × $10^{-34}$ $m^2$ kg $s^{-1}$

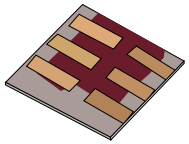
c=3x$10^8$ $m^{-2}$

$$\lambda = \frac{3\,x\,10^{8} * 6.6\,x\,10^{-34}}{\left(1.6 * 1.6\,x\,10^{-19}\right)}$$

$$\lambda = 7.7344\,x\,10^{-07}\,m$$

$$\lambda = 773\,nm$$

# Overview

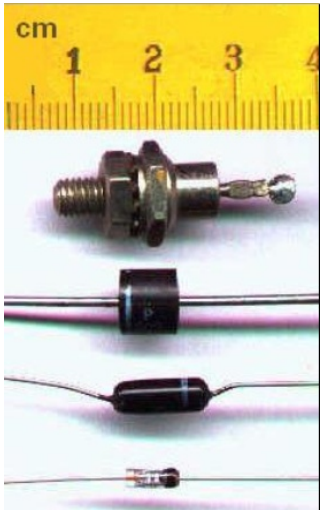


- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- **Fundamentals of diodes**
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# Diodes

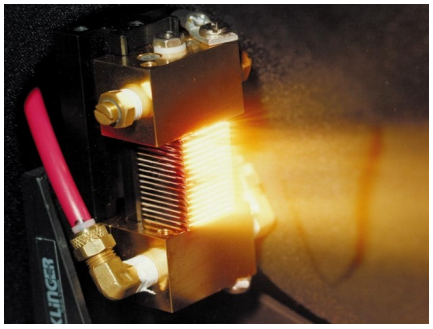
•Before we talk about solar cells and light harvesting we need to know about diodes.

•Diodes are a fundamental electrical component that form the basis for lots of classes of devices.




Power diodes

LEDs

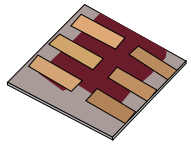


Lasers

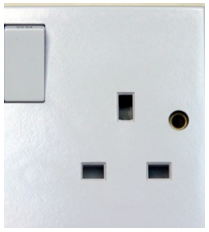
Solar cells

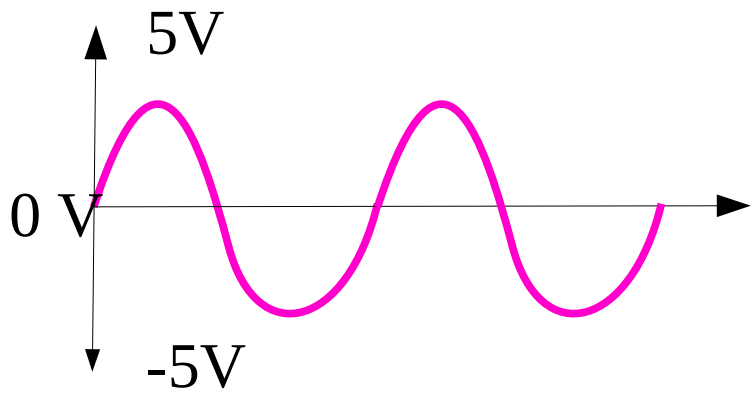
•Before we can understand solar cells we first need to understand diodes.

# Before we think about solar cells, let's think about AC voltage for a moment



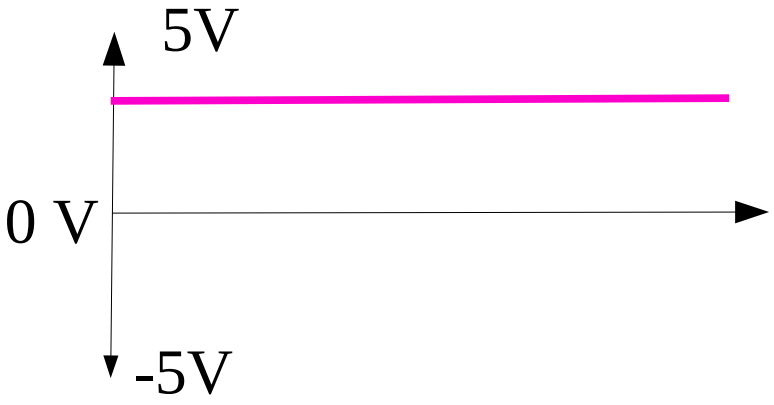
- AC switches **ON** and **OFF** again 100 times a second (50 Hz).

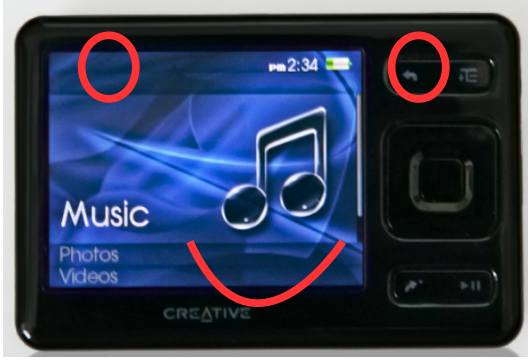






- But most chips need a steady **DC** supply to run.

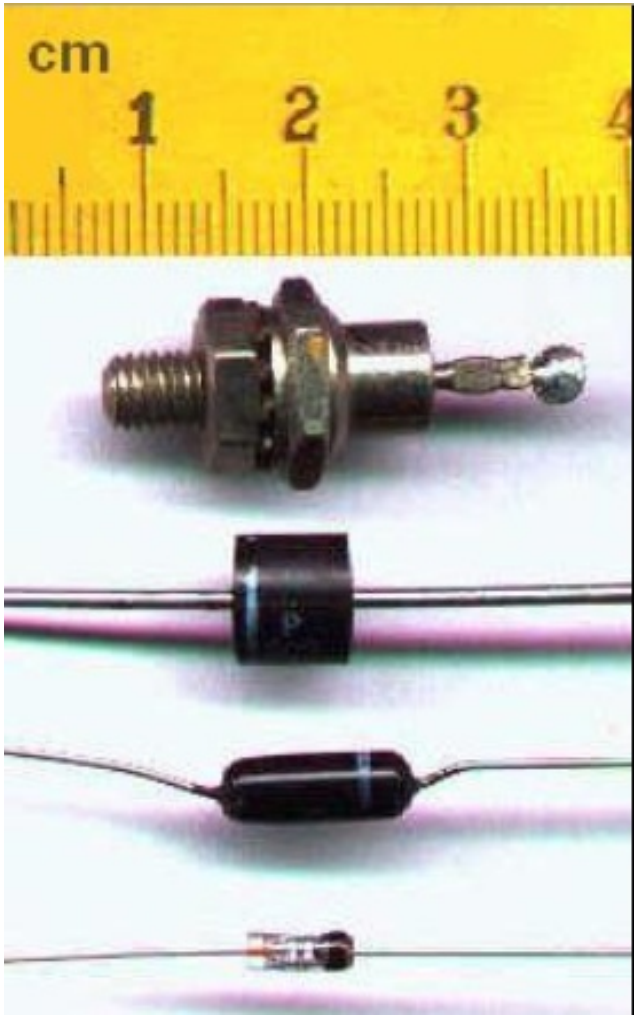


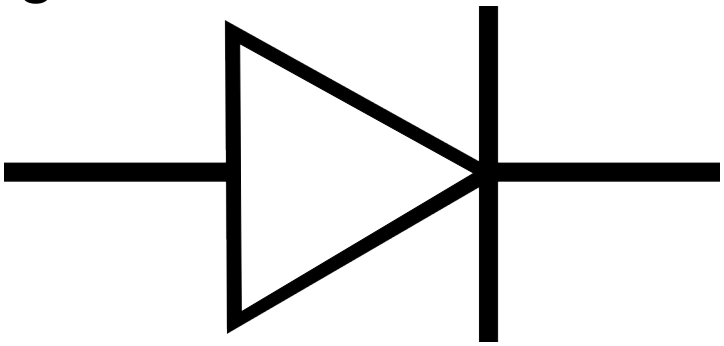

- **Power diodes are used to transform AC to DC.**

# Diode basics: Diodes for power electronics – what do they look like?

- Diodes you find in high power electronics look like this

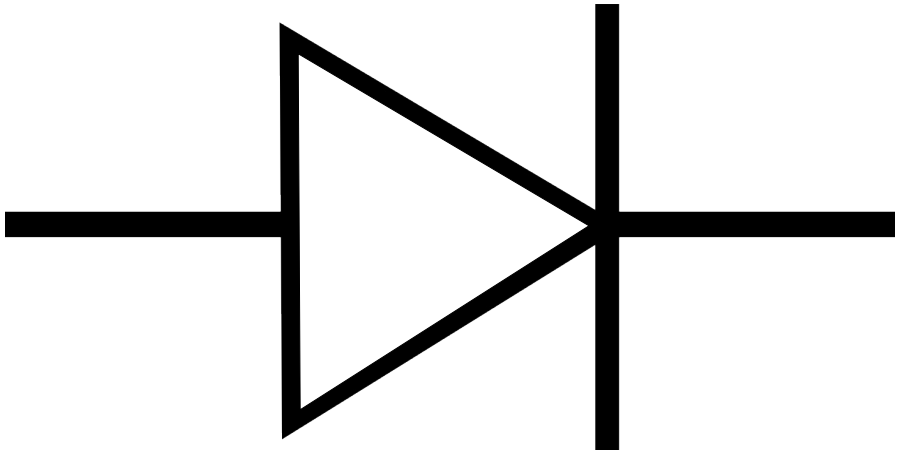


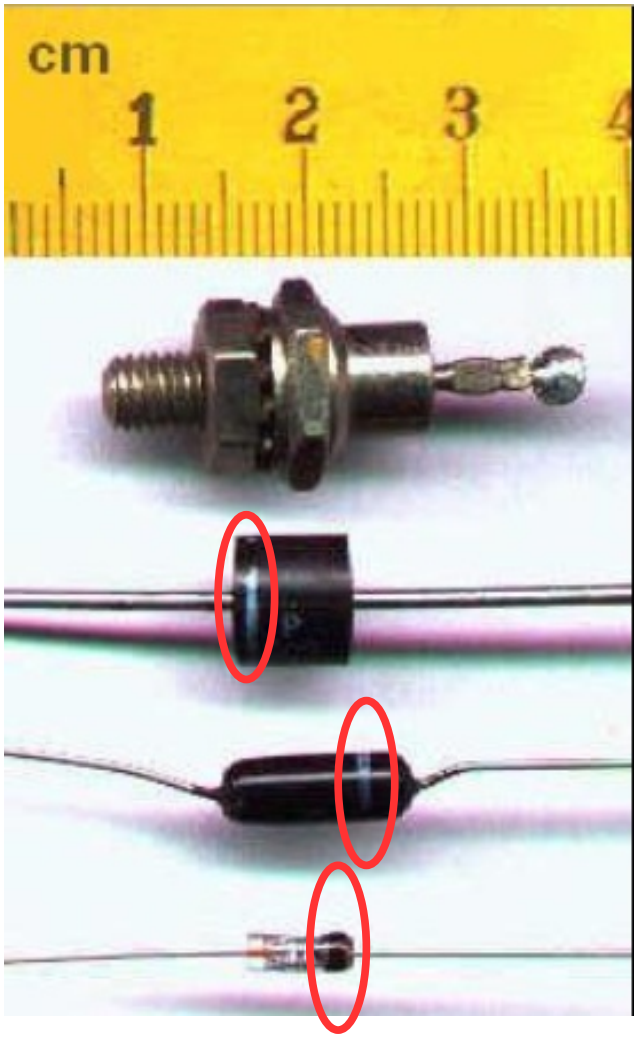

- Little black beads with two wires sticking out.



- We are looking at power didoes because they are the simplest type of diode.

# Diode basics: Notice...

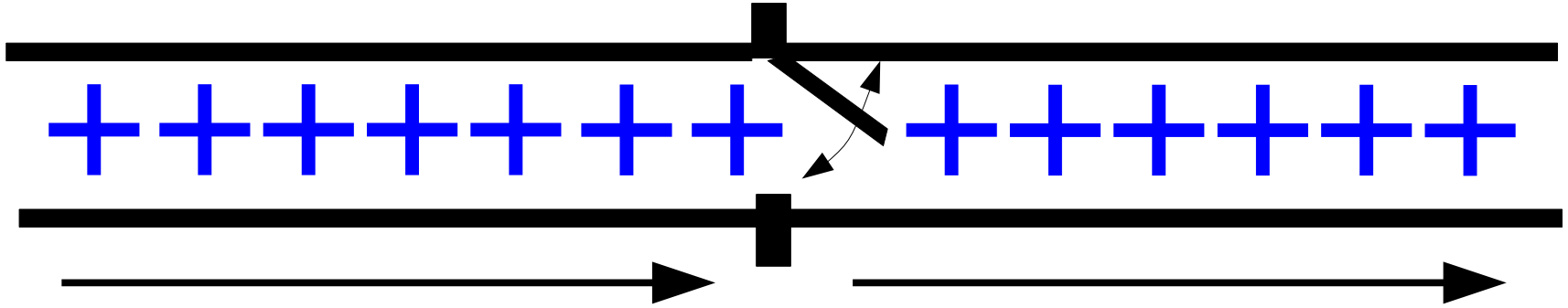


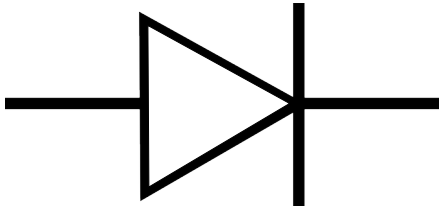



- Notice the silver bar on the end, this is the same as the bar in the diagram.

# Diode basics: What do they do?

You can think of a diode as a one way valve for electrons

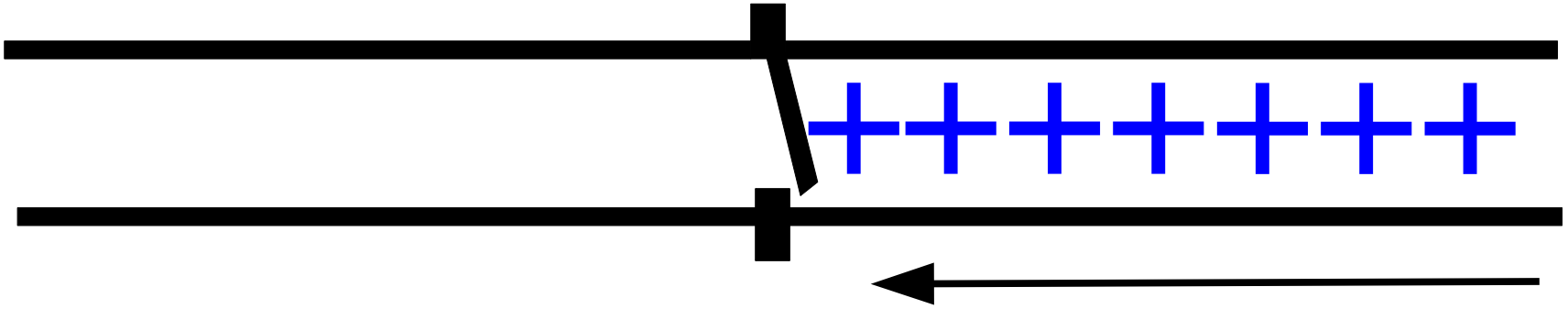


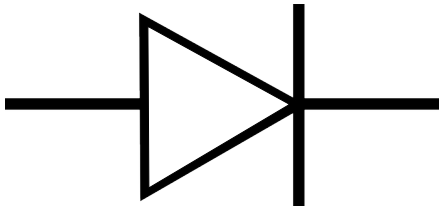


If current flows in one direction the diode will allow it to pass.

# Diode basics: What do they do?

If current tries to flows in the **other direction** it will not be allowed to pass.





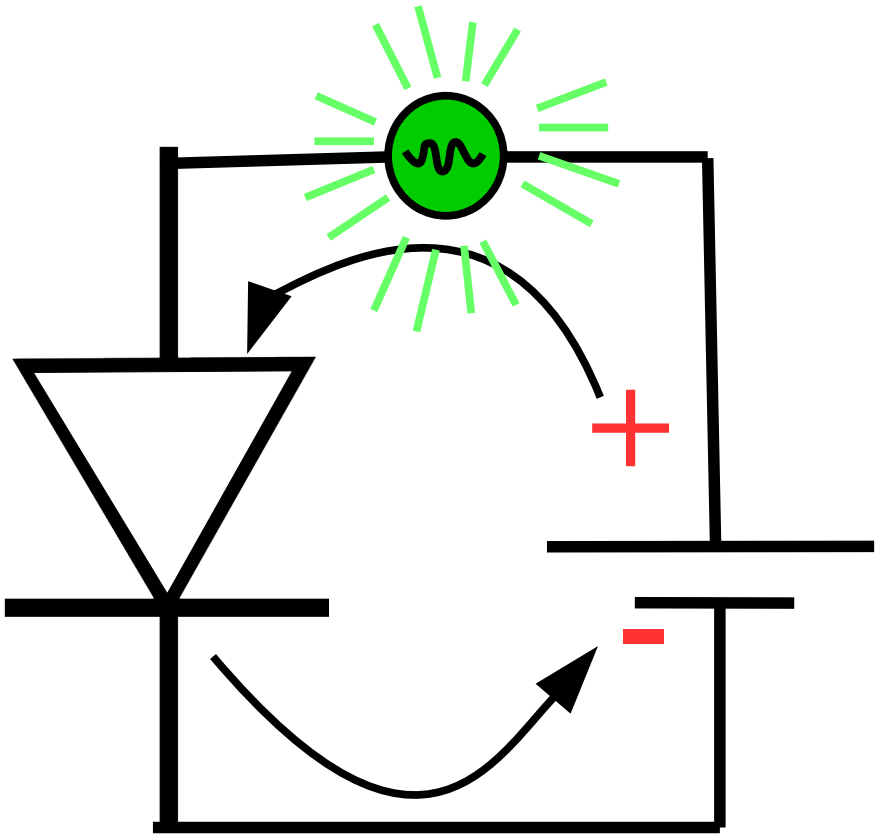
# Diode basics: A one way cat flap....

You can also think of a diode as a one way cat flap for electrons.

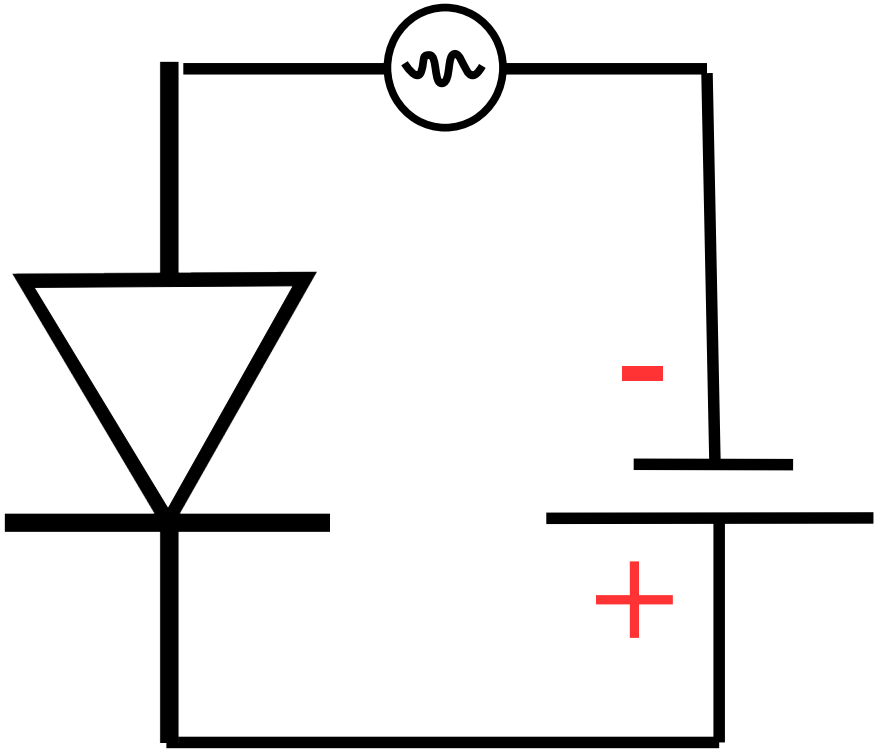
•Electrons (or the cat) are only allowed to go through one way but not the other.

Andrew Dunn

# Diode basics: A diode as a one way trap door for current

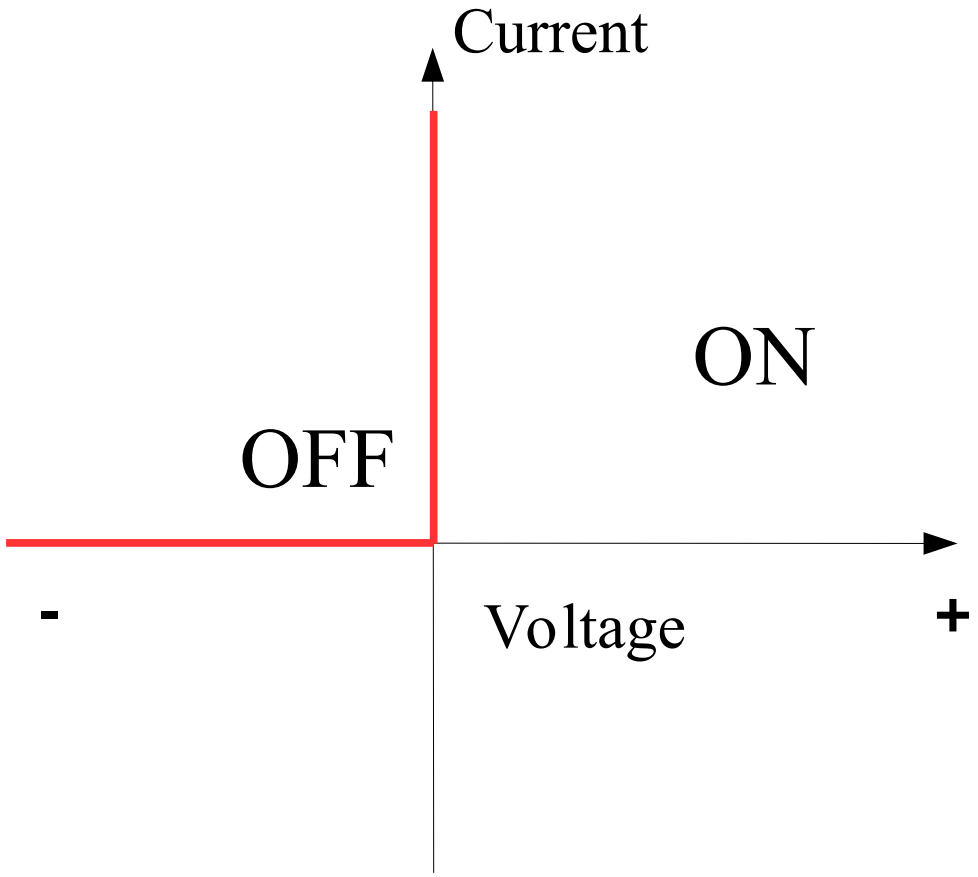



With positive applied voltage current flows




With negative applied voltage no current flows

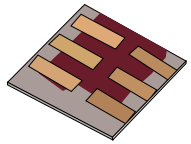
# Diode basics: What does the ideal current voltage curve look like?

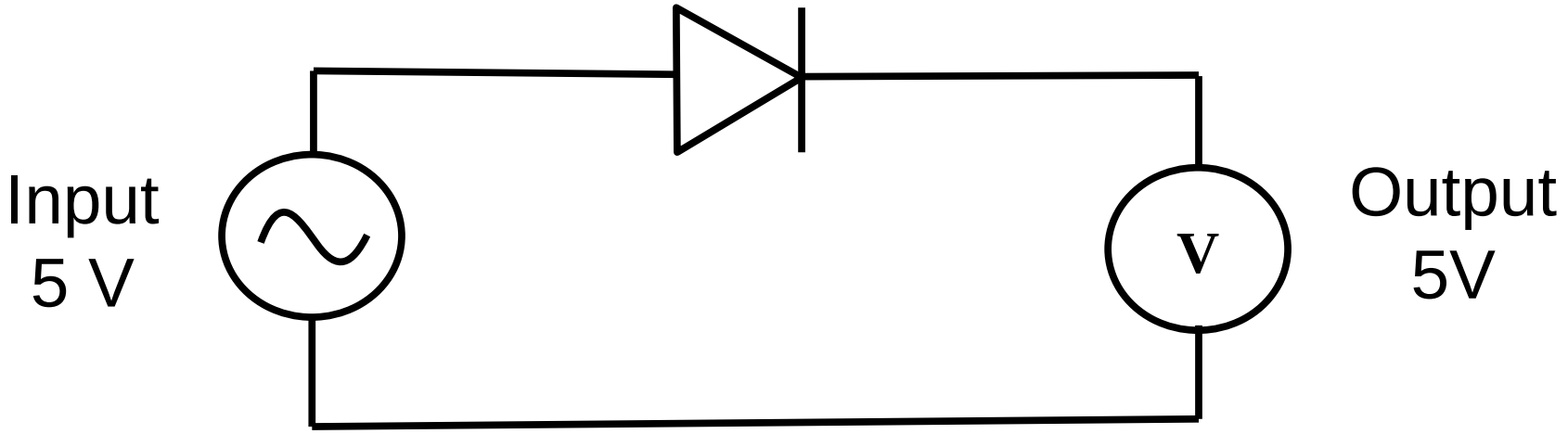


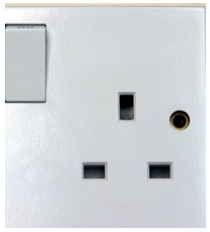

At negative voltages it blocks current

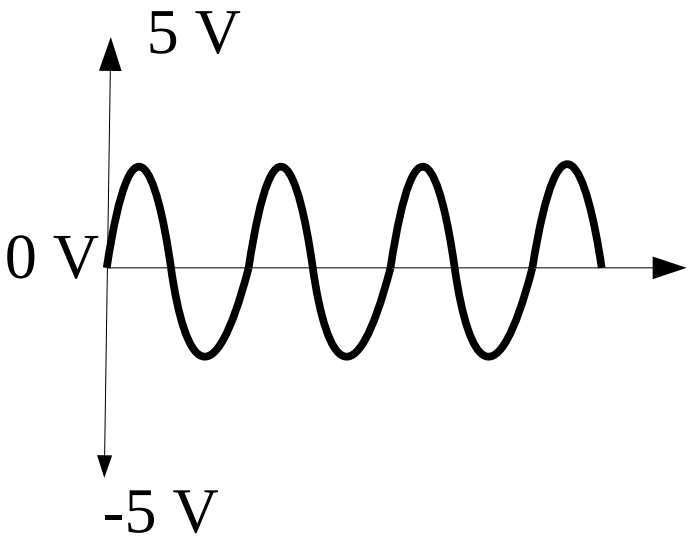
At positive voltages any amount of current can flow

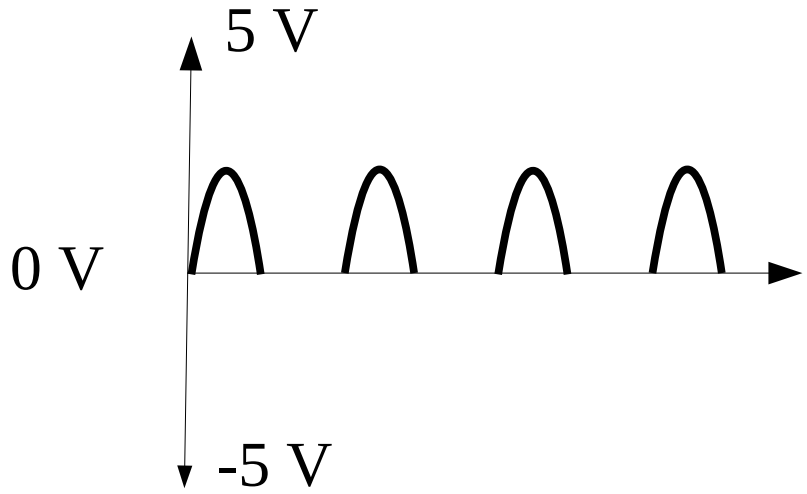
# If we apply an AC signal to a diode, it will only let through the positive voltage



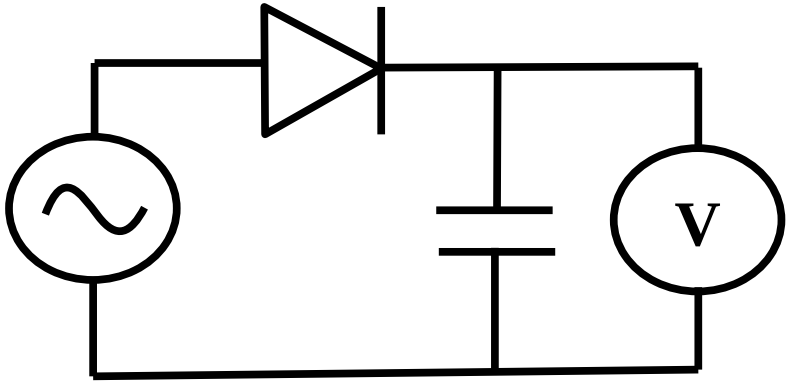




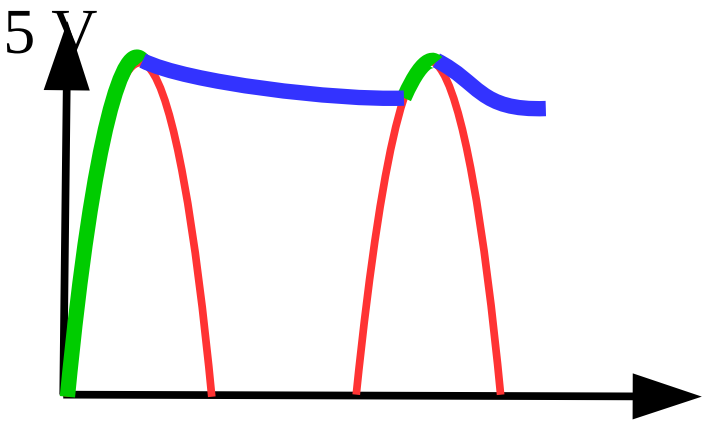



# If we add a capacitor to our circuit we now get DC (sort of).

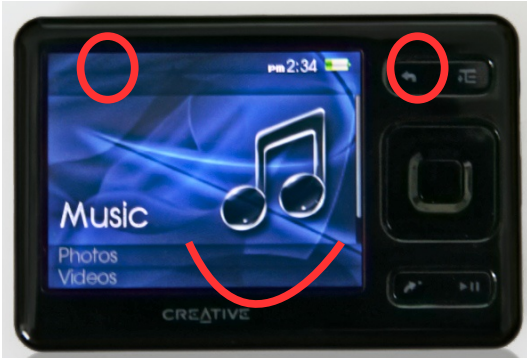



Input
5 V

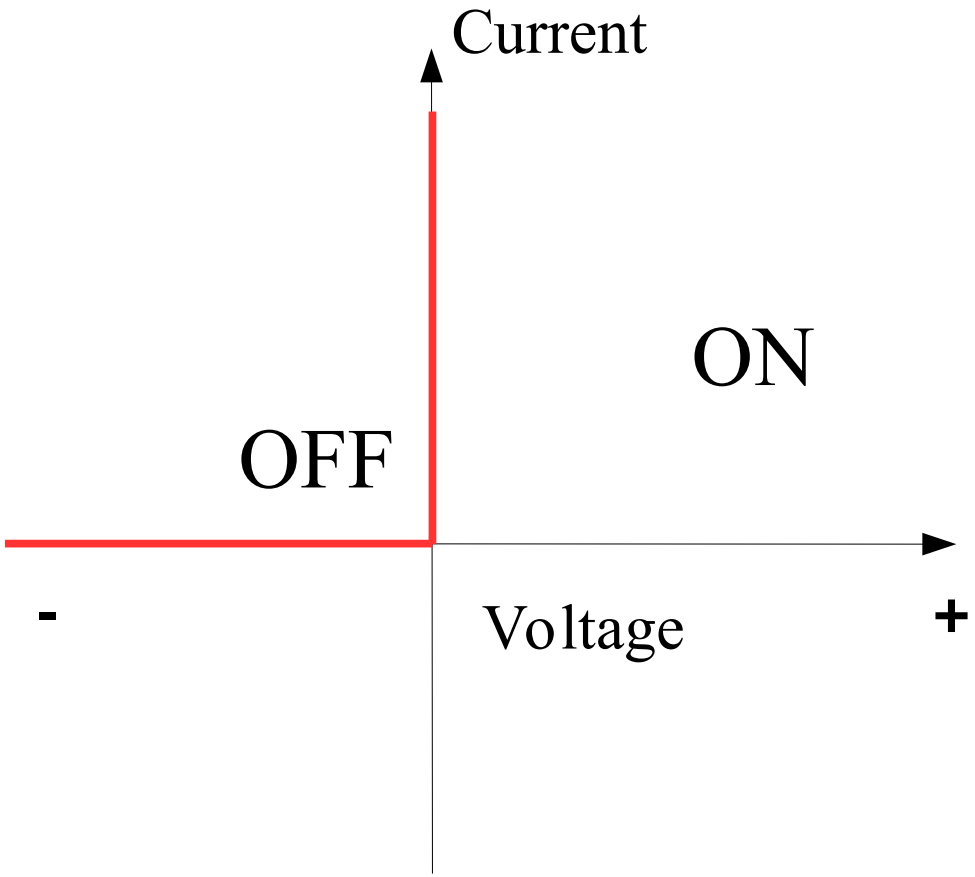
Output
5V




And a happy (working) MP3 player.



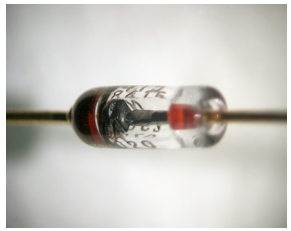
# What we have looked at so far is the ideal diode.



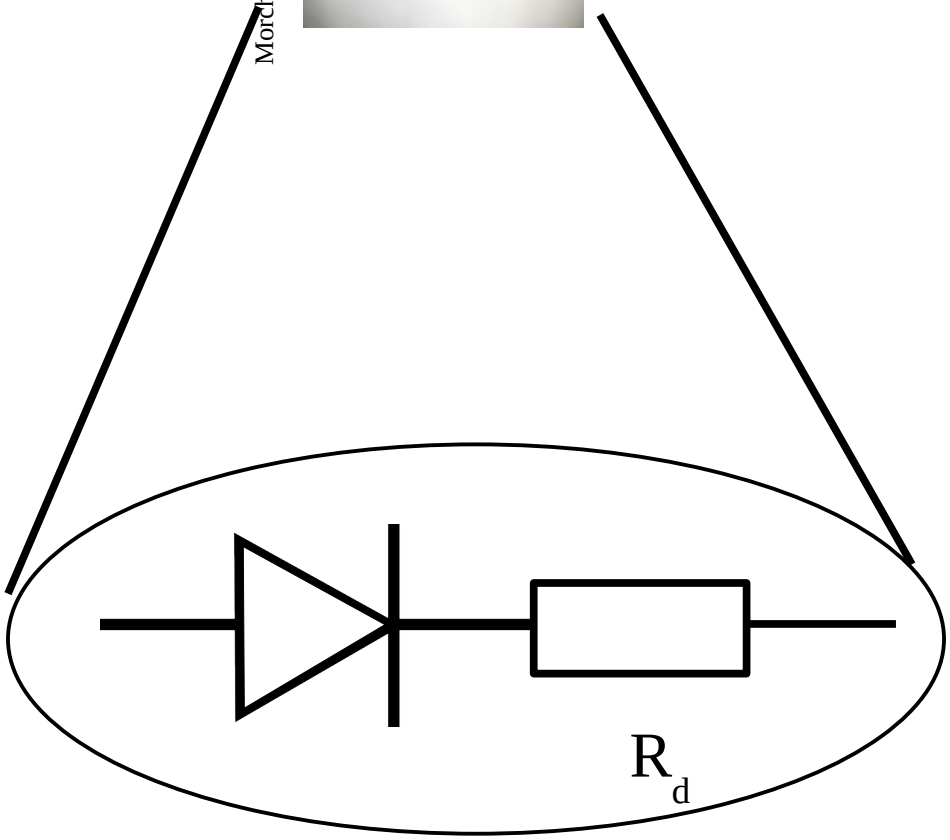

At negative voltages it blocks current

At positive voltages any amount of current can flow

# A less ideal diode



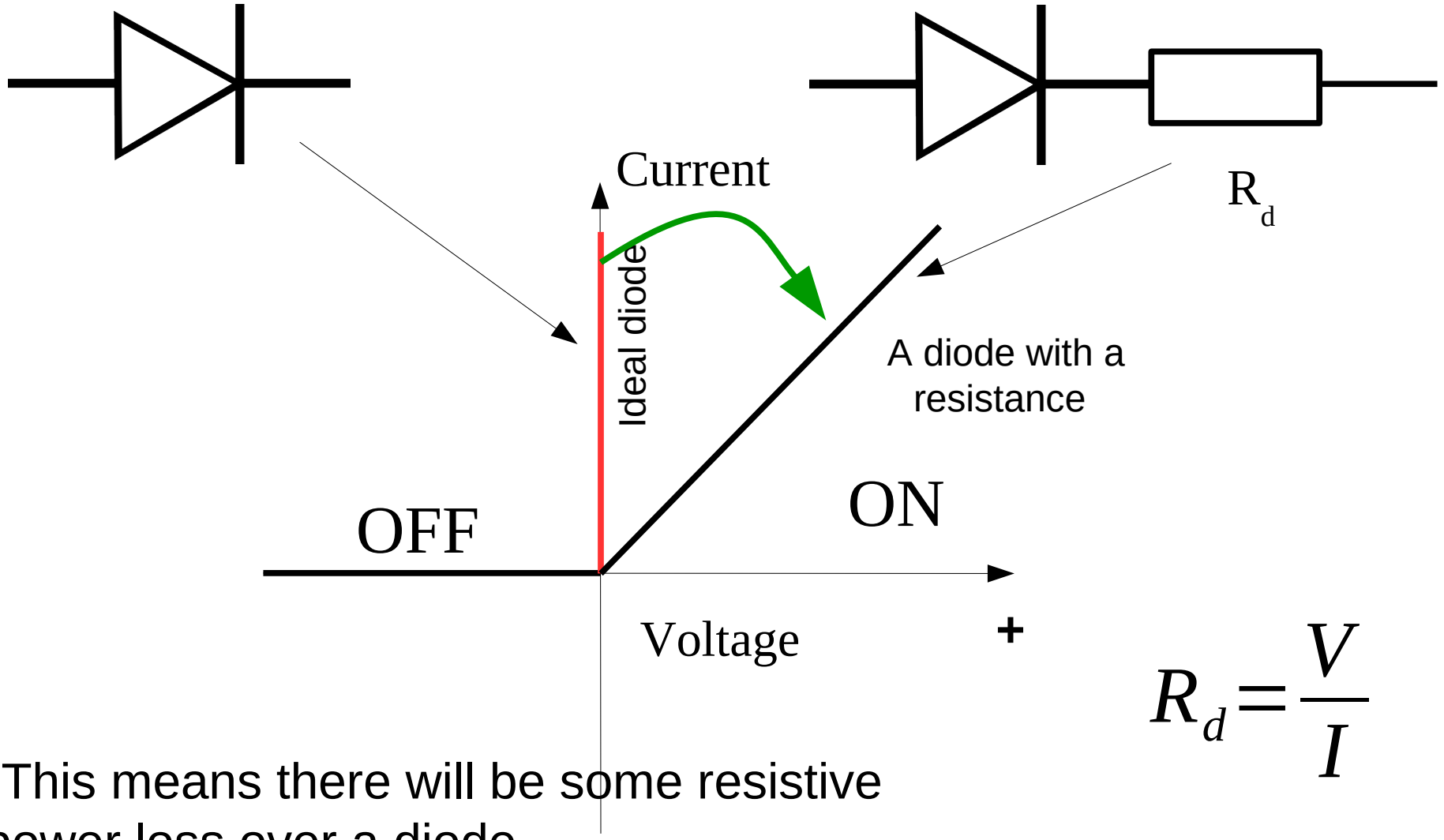
Morcheeba at en.wikipedia




- However real diodes are like any other device they have a resistance $R_d$ associated with them (because all things have resistance).

- So you can think of them as an ideal diode in series with a resistor.

# A less ideal diode

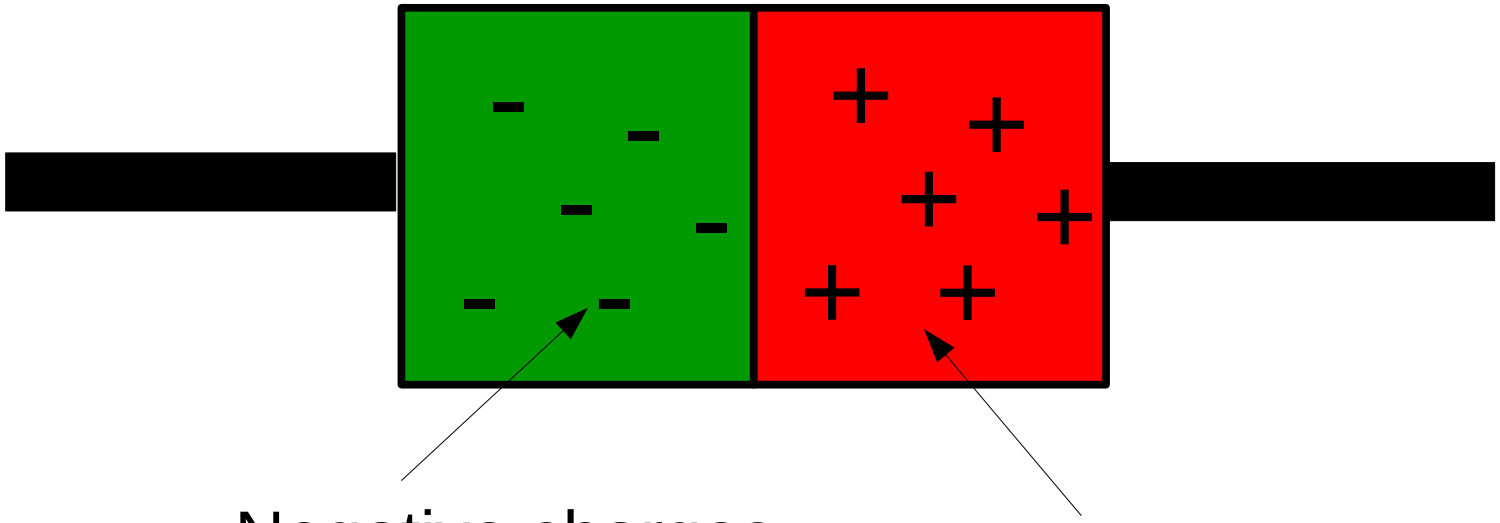



$$R_d = \frac{V}{I}$$

- This means there will be some resistive power loss over a diode.

# Furthermore.....

- Diodes are made of two materials, one with lots of negative (n-type) charges and one with lots of positive charges (p-type).

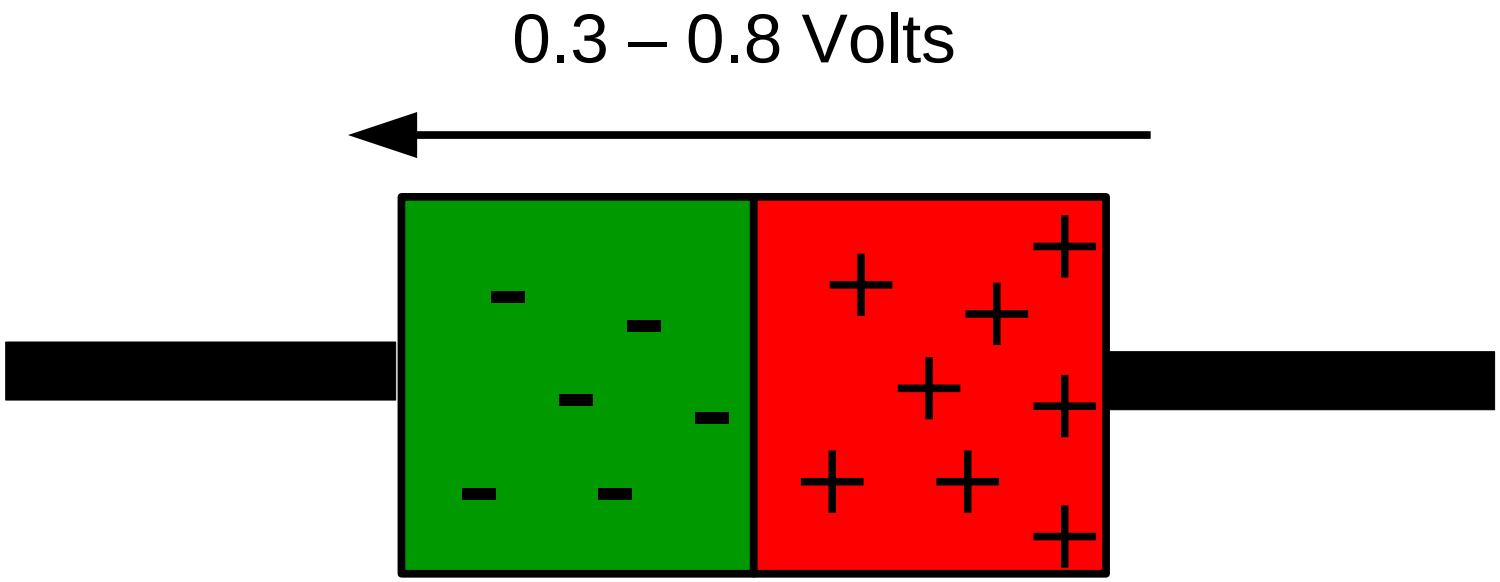


Negative charges called an **n-type** material

Positive charges called a **p-type** material

# Positive and negative charges

- This charge in the device means that every diode produces a voltage of between 0.3 V to 0.8 V.
- This is called the **built in potential**.



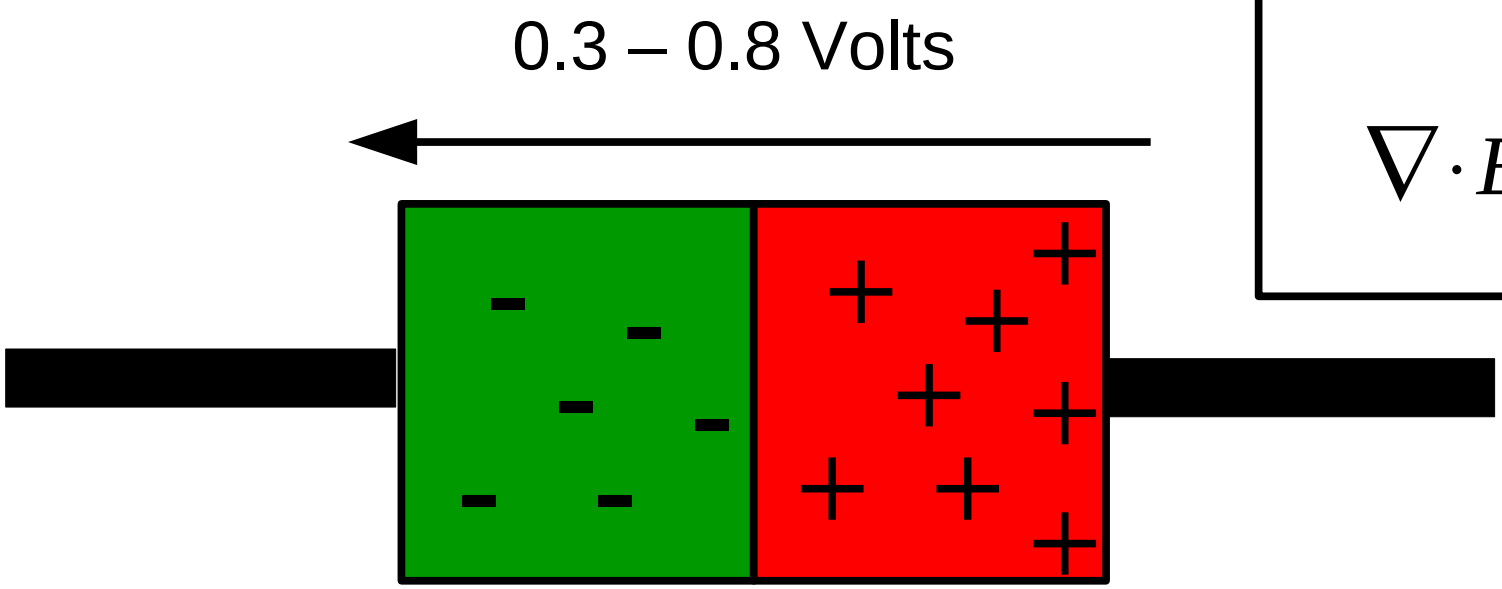

- In some applications this built in potential is a pain, in others it is really useful

# Positive and negative charges

- This charge in the device means that every diode produces a voltage of between 0.3 V to 0.8 V.
- This is called the **built in potential**.

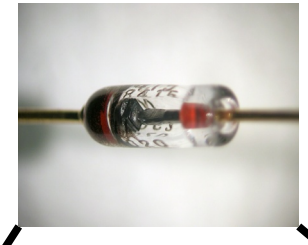
Gausse's law

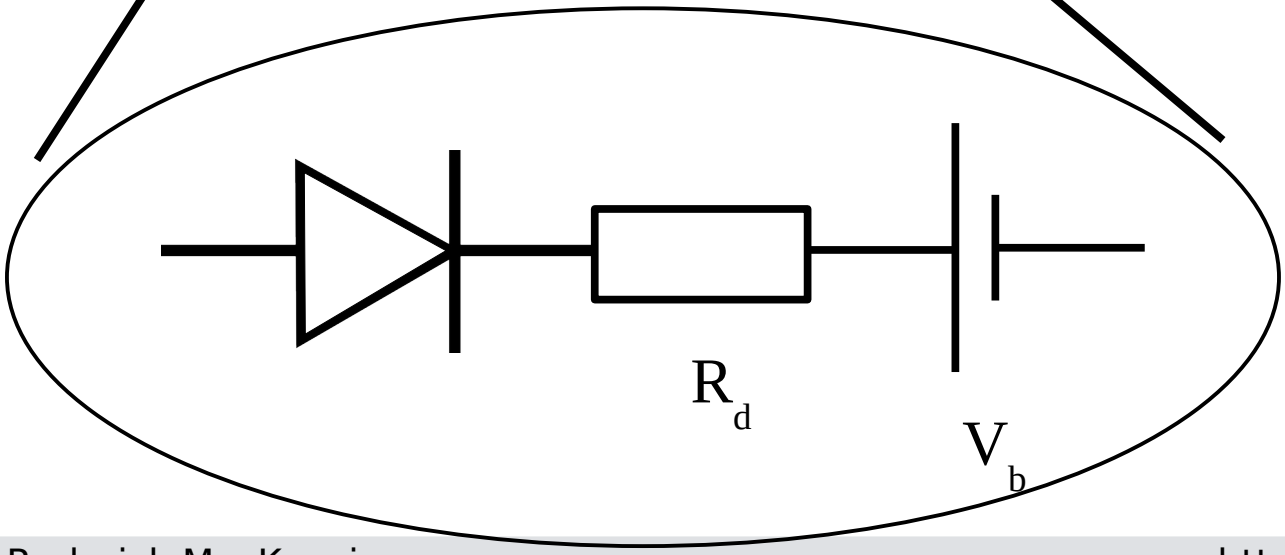
$$\nabla \cdot E = \frac{\rho}{\epsilon_0}$$




- In some applications this built in potential is a pain, in others it is really useful

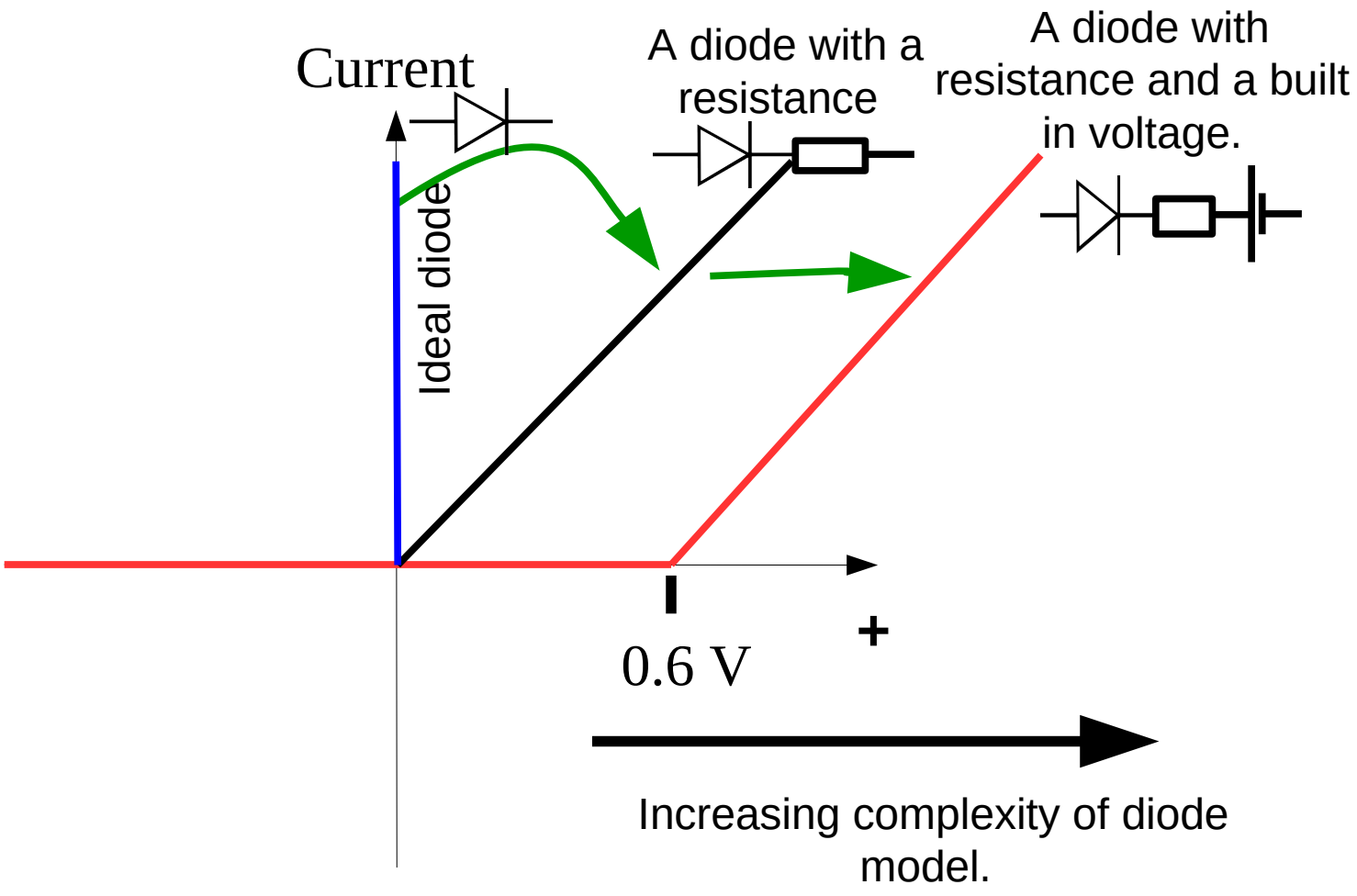
# A diode with a built in potential



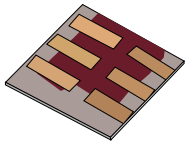



- Because of this built in charge you can actually think of an ideal diode as having a small (0.3 V-0.8 V) battery in series with it.

# The built in potential



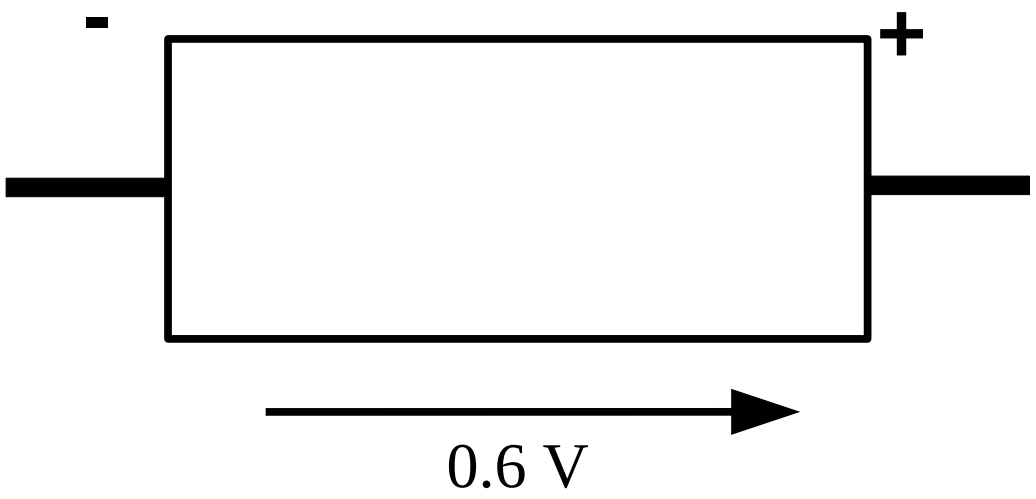
# Overview



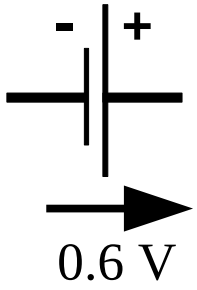
- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- **From diodes to solar cells**
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Multi-junction solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Concentrator solar cells
- Summary

# From a diode to a solar cell..

- Here is our diode again.

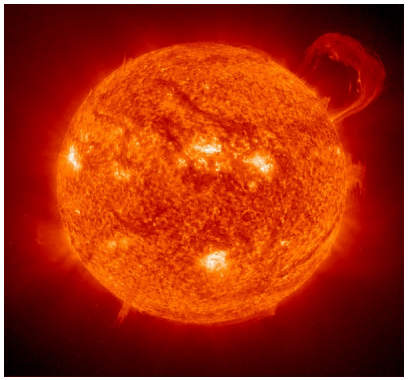


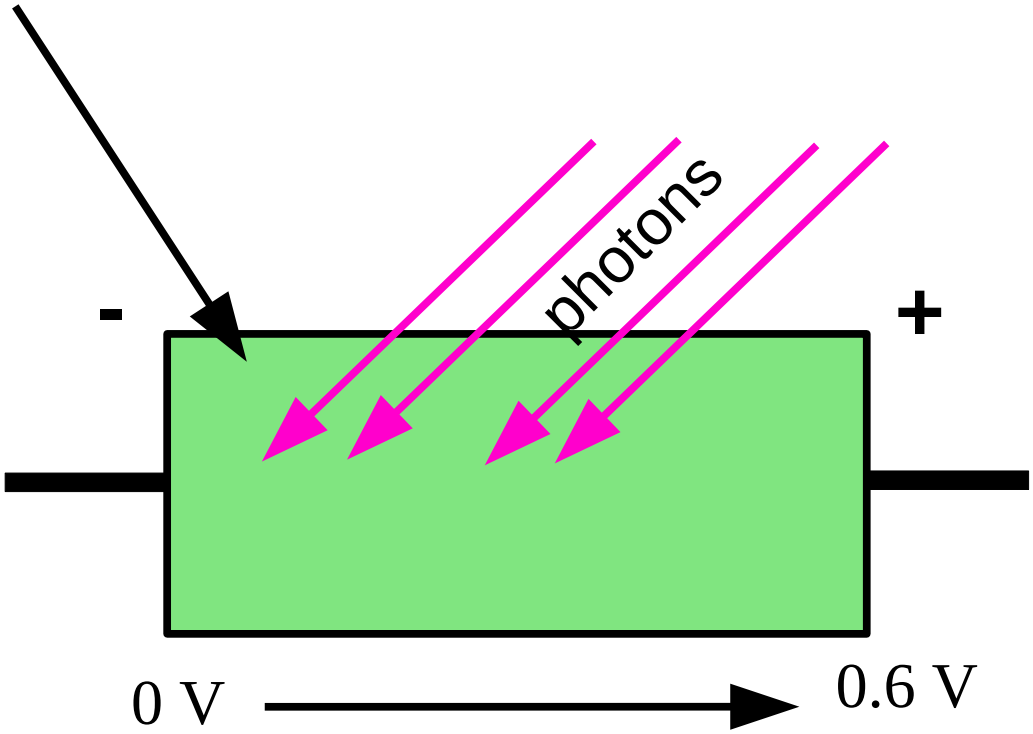

- Now let's change the material so it absorbs light.

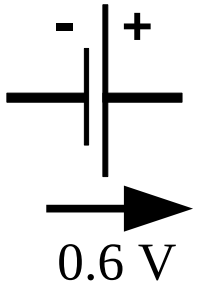


# A light adsorbing diode...

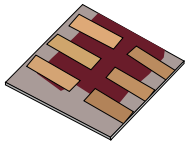
- Light adsorbing material.



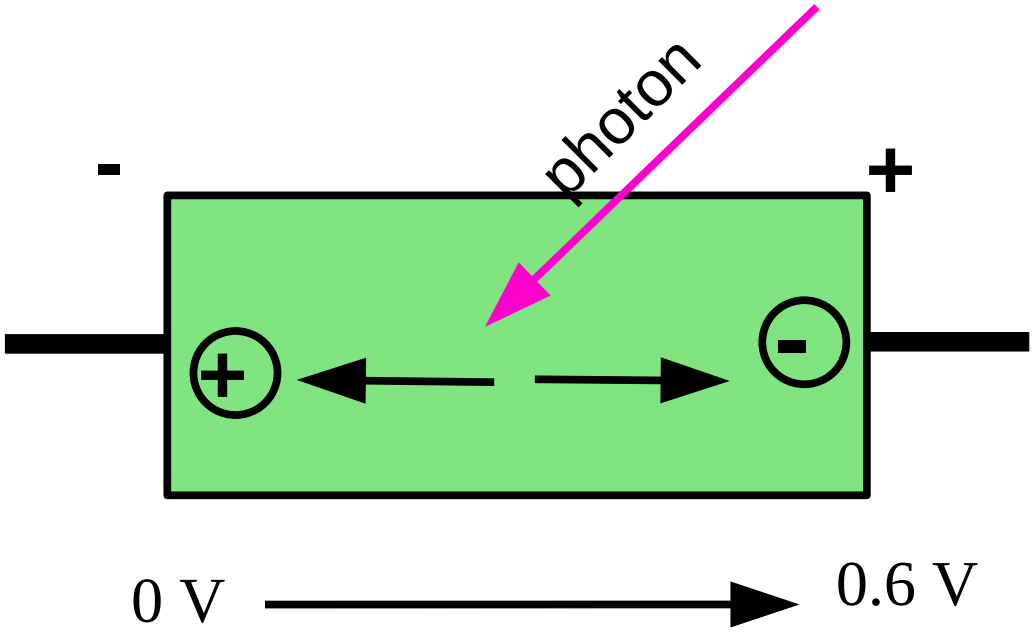


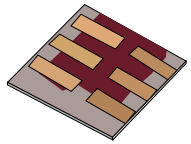
# When a photon is adsorbed in a material.....



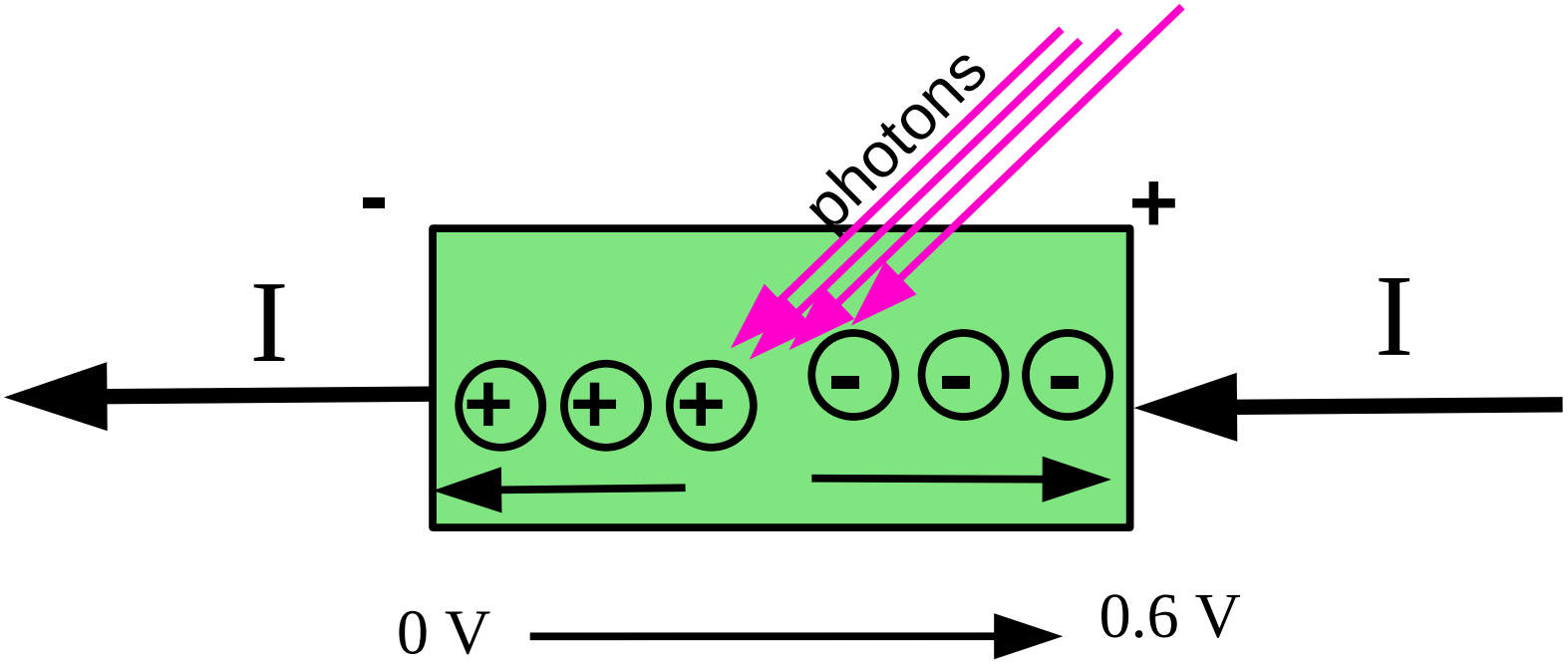
- The positive charge goes to the negative contact and the negative charge goes to the positive contact.



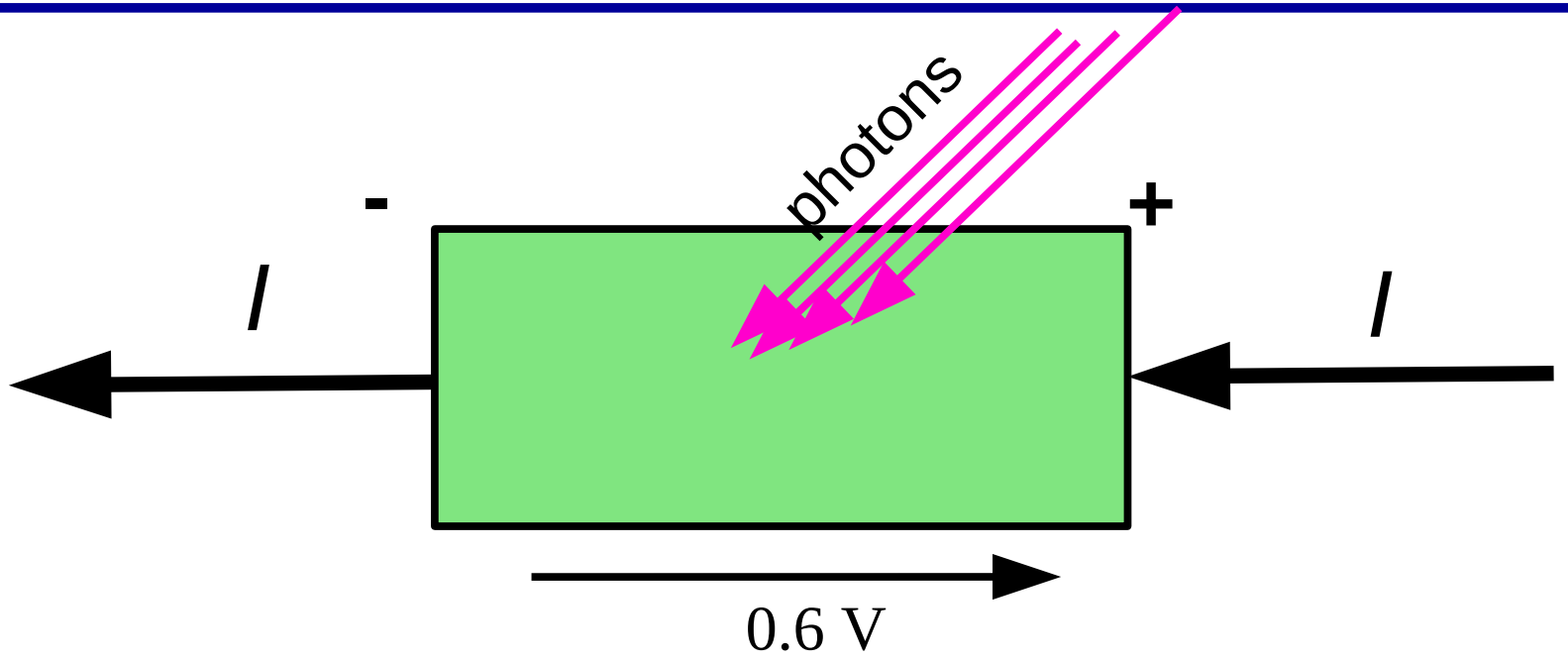
# When a photon is adsorbed in a material.....



•If lots of photons hit the diode lots of positive and negative charges move to the contacts and we get current in the external circuit.



# Power generation.....




Power=I*V

N=Number of photons adsorbed per second per unit area.

A=Area of solar cell.

Power=A*N*q*V

**And we have a solar cell.**

# Exam question

a) A ***0.01 $m^2$*** solar cell produces a voltage of **0.6 V**, it adsorbs **1x$10^{20}$ $m^{-2}$ photons per second** if the charge on an electron is 1**.6x$10^{-19}$ coulombs** how much power will it produce.

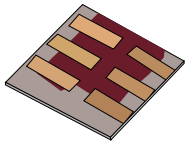
Power=A*N*q*V

Power produced by cell=???

b) How many pink ***500 Watt*** 'Hello Kitty' toasters would that run??

Janine from Mililani

# Exam question



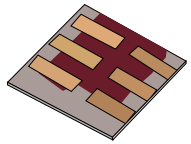
A 0.01 $m^2$ solar cell produces a voltage of 0.6 V, it adsorbs $1x10^{12}$ $m^{-2}$ photons per second if the charge on an electron is $1.6x10^{-19}$ coulombs how much power will it produce.

Power=A*N*q*V

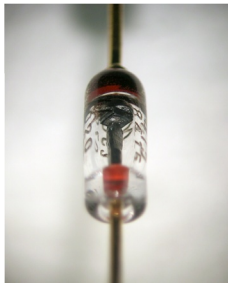
Therefore Power=0.06 W

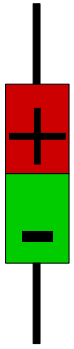
That's not enough to run anything – let along a toaster...

# Power generation.....



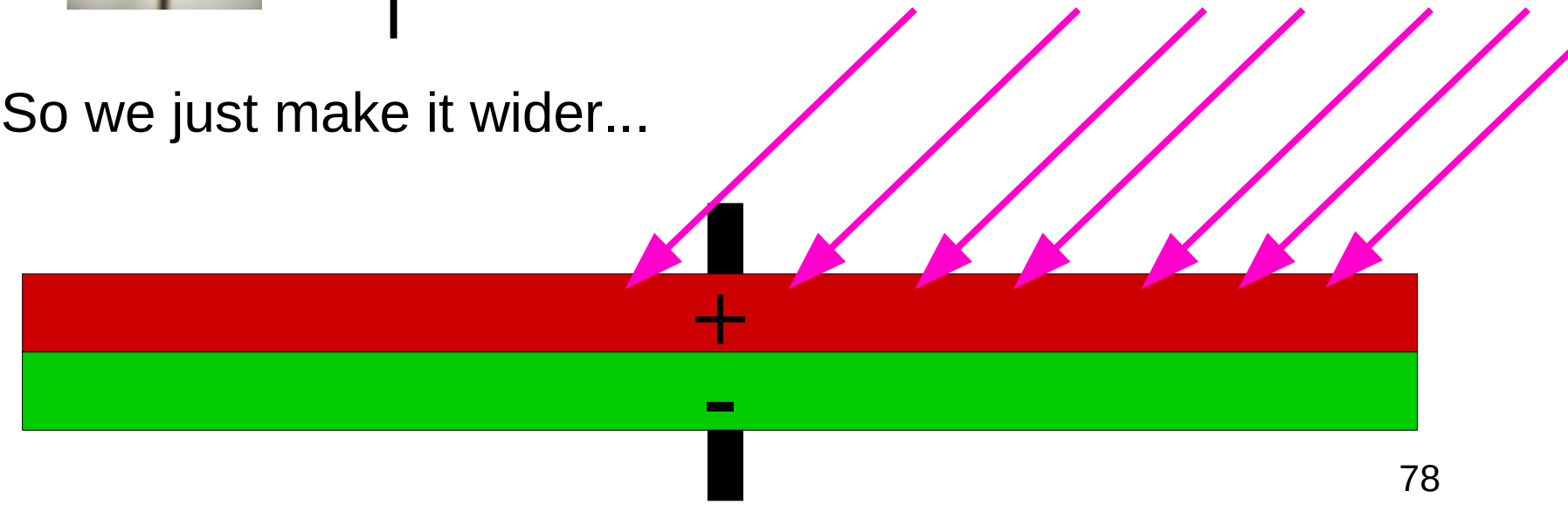
- So what we do is firstly make the diode (solar cell) as big as possible





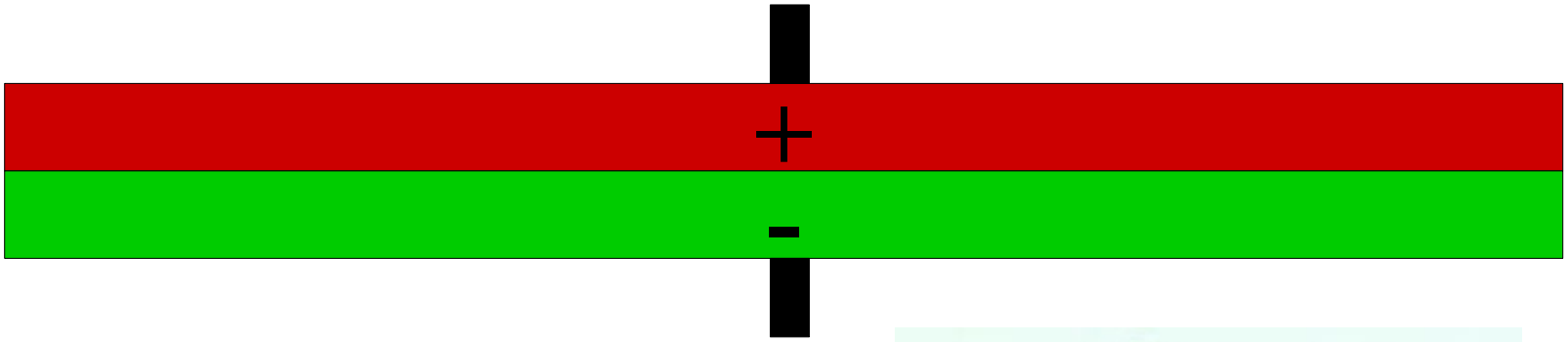

Power=A*N*q*V

- So we just make it wider...



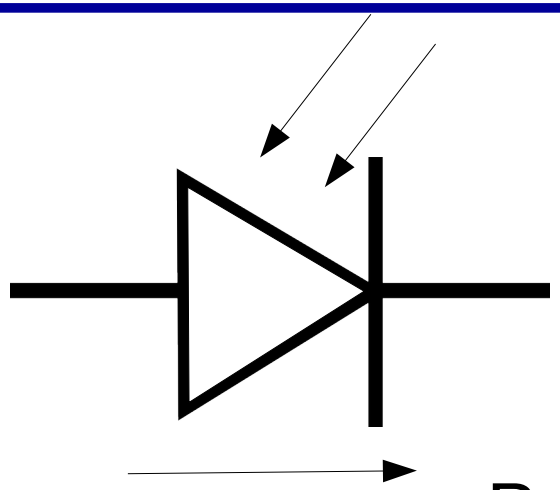
# A solar cell

- And that is all a solar cell is – a wide diode.



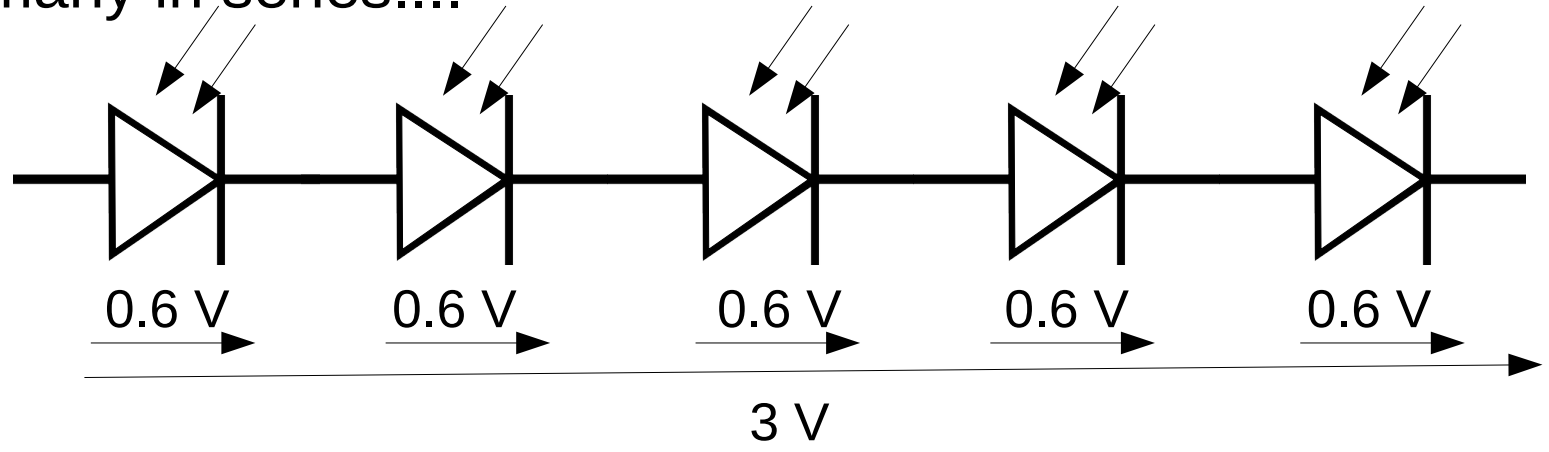

- These metal strips just help the current get out of the diode.

# And then we stack lots together

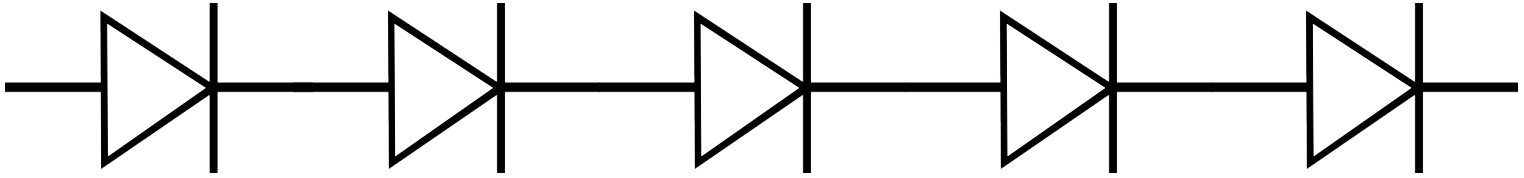



Power=A*N*q*V

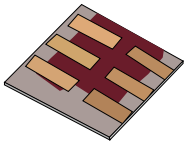
- However 0.6 V is not very much voltage, so we connect many in series....

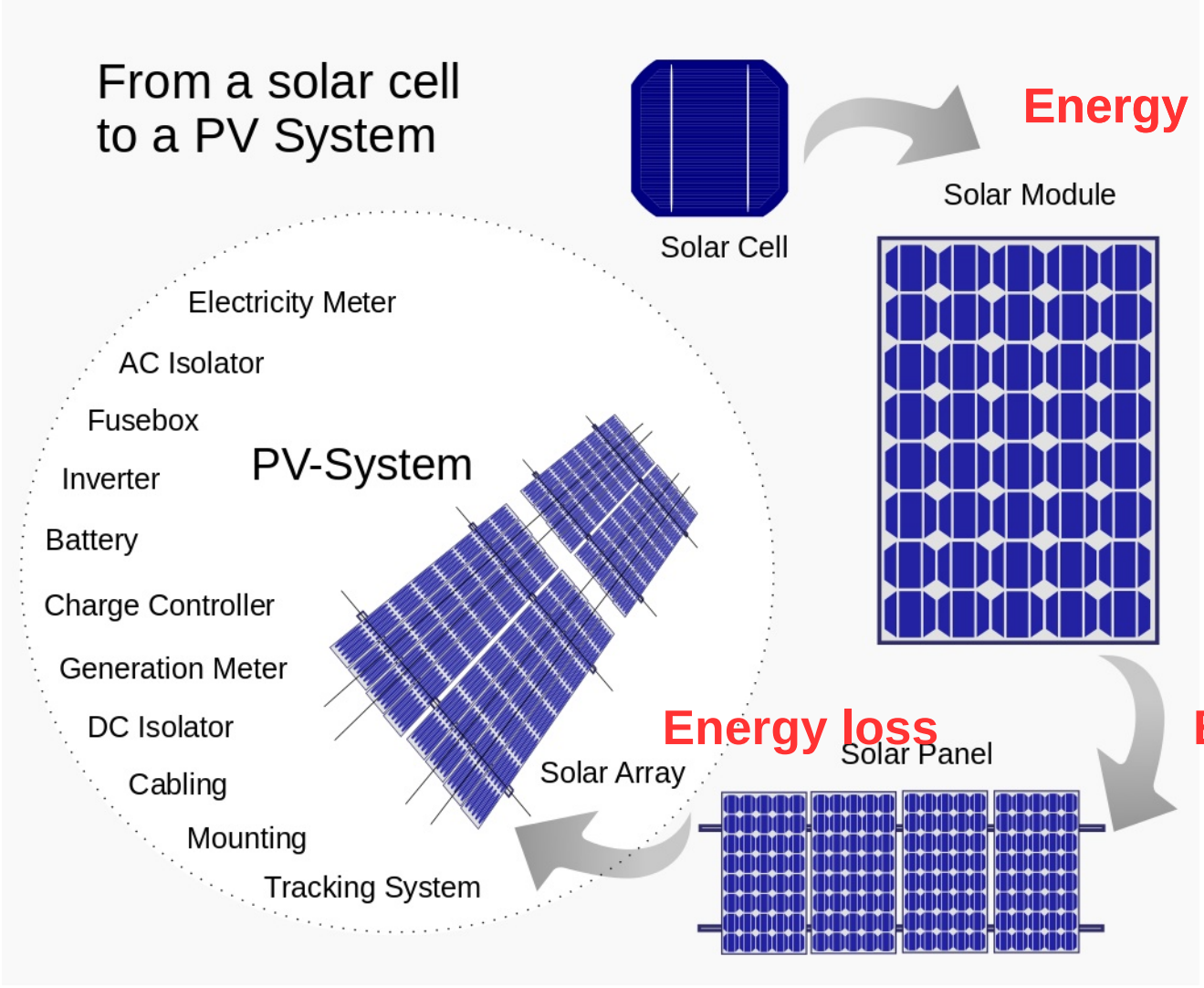


# To make a solar module



# To make a solar module



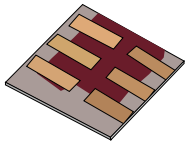



Solar cell 20% efficient

↓

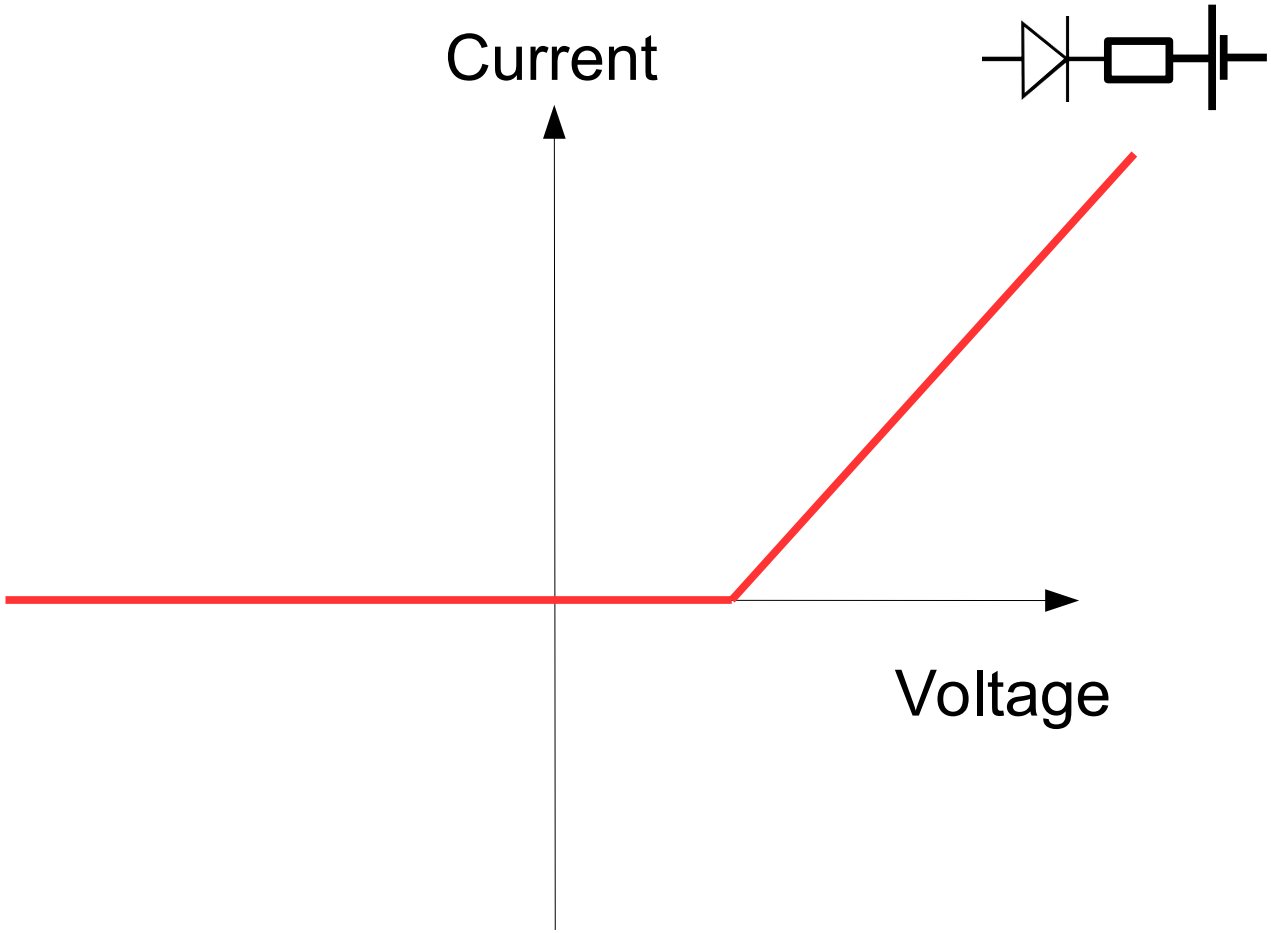
Module 10-15% efficient

# Overview

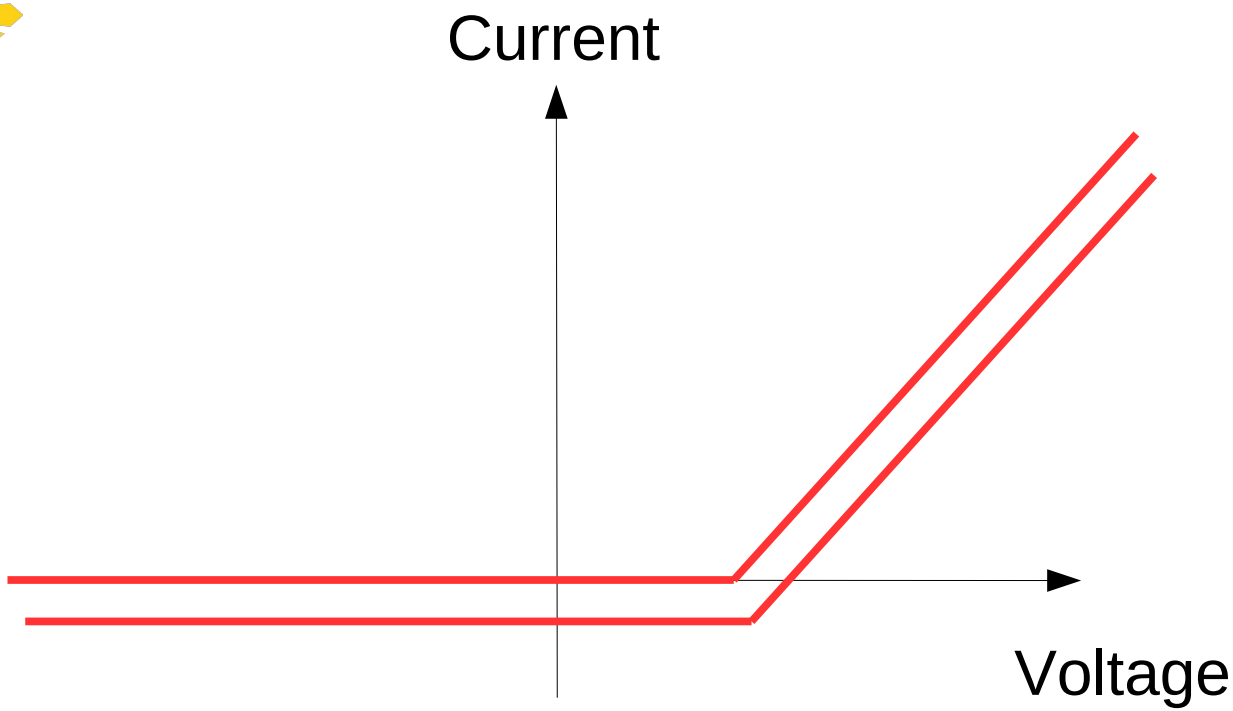


- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- **Diodes current-voltage curves in the light**
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Multi-junction solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Concentrator solar cells
- Summary

# Current Voltage curve of a diode in the light.

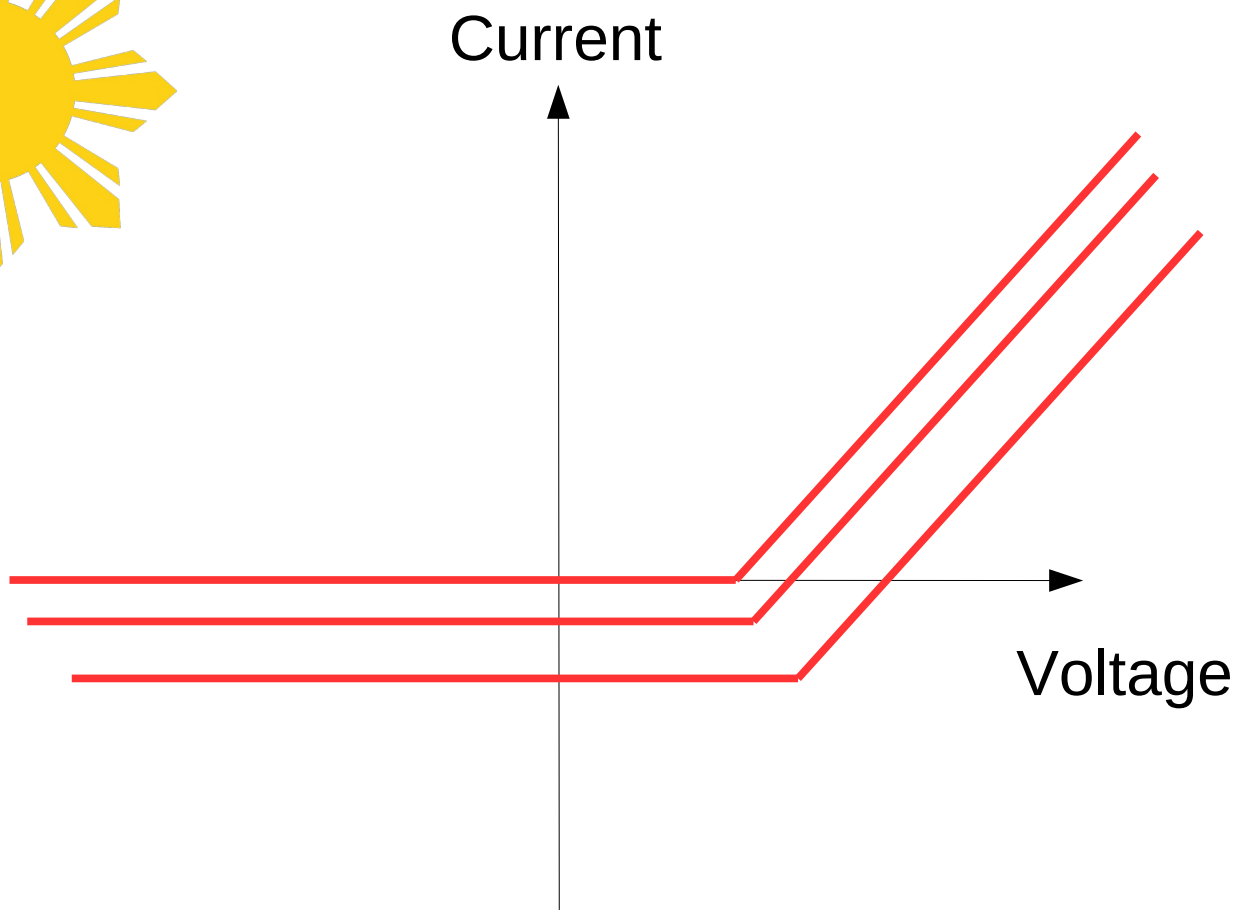


# What do the JV curves look like in the light

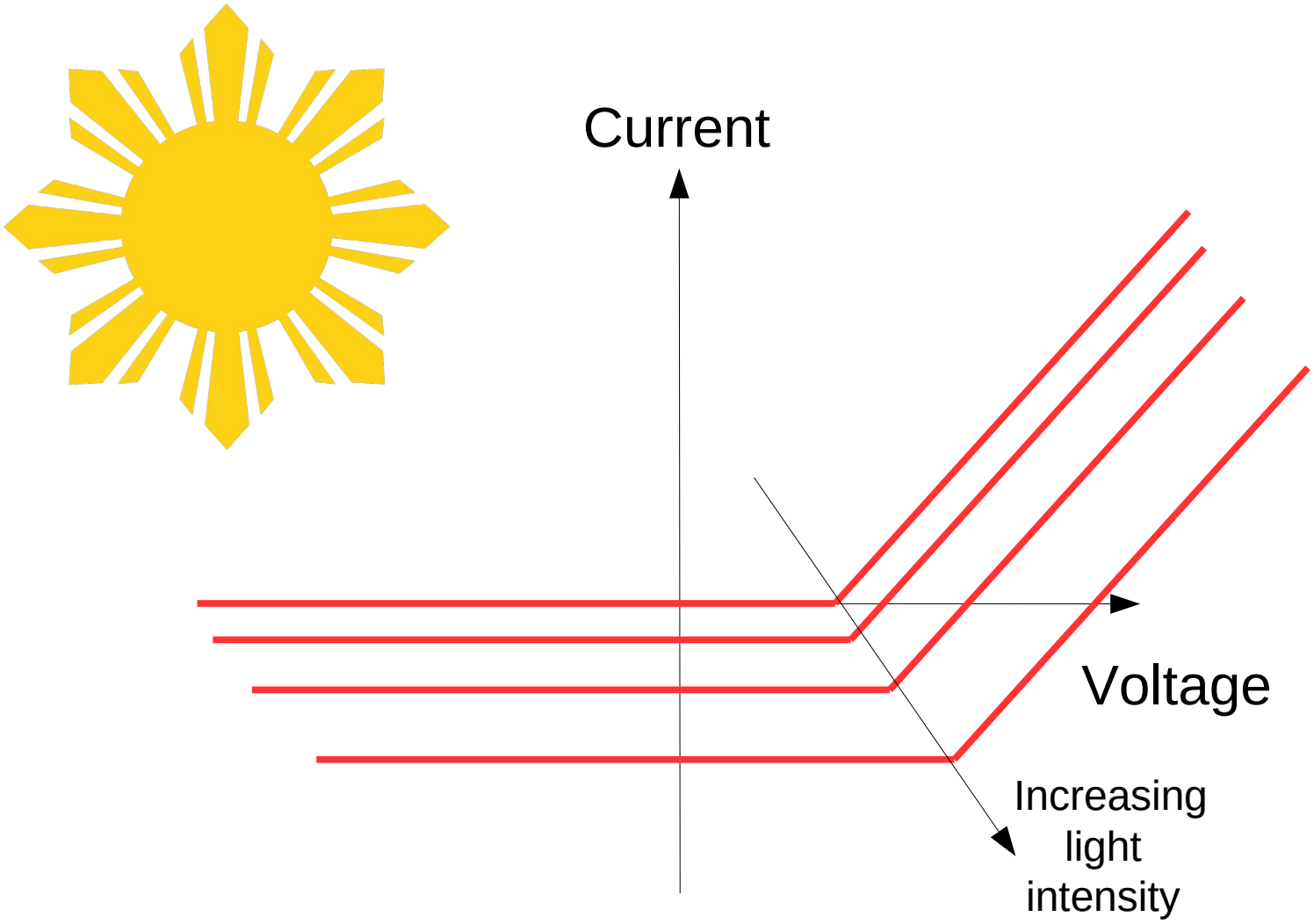



- Negative current means the current is coming out of the device rather that going into it.
- It's generating electricity.

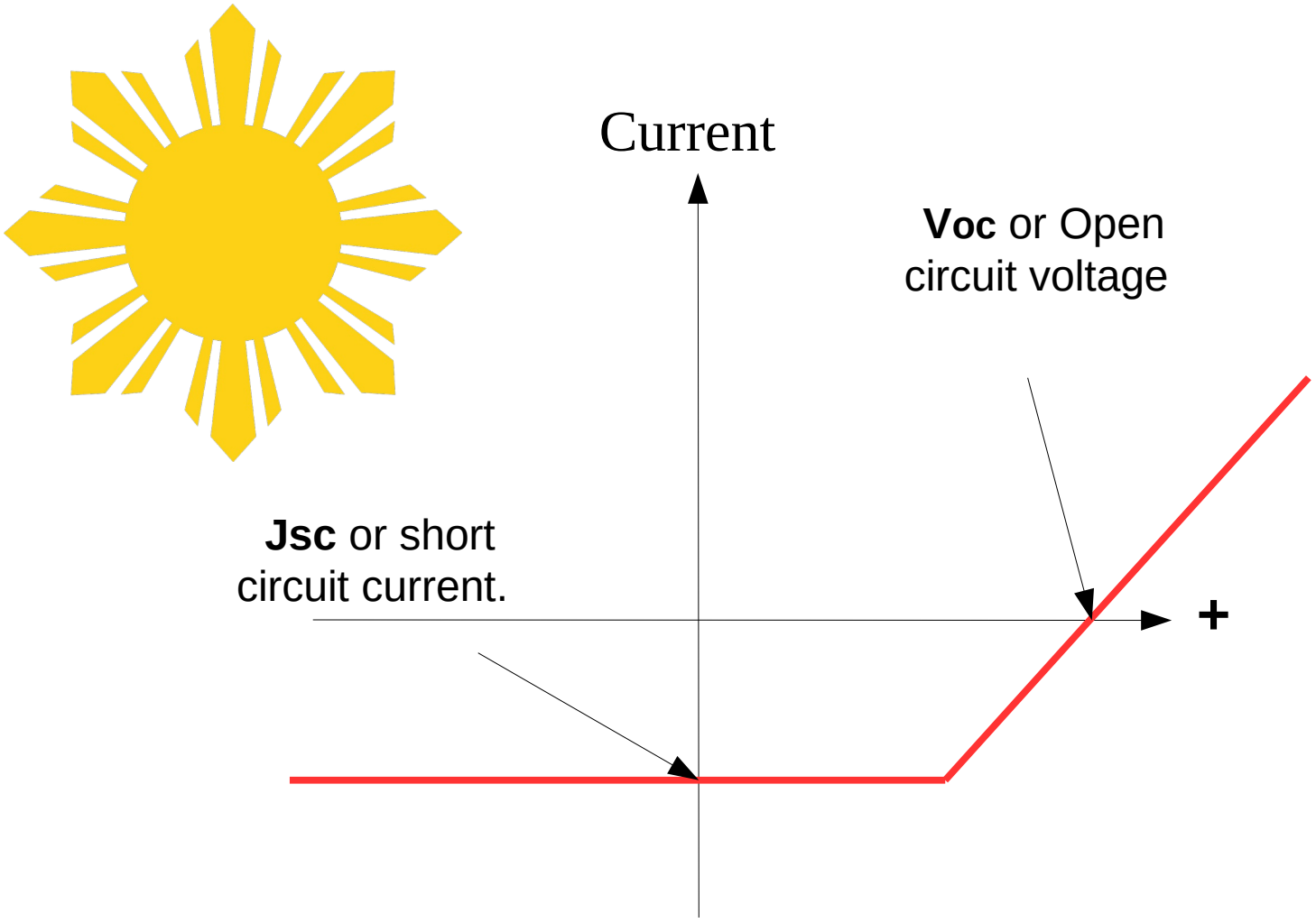
# What do the JV curves look like in the light



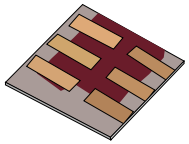
# What do the JV curves look like in the light

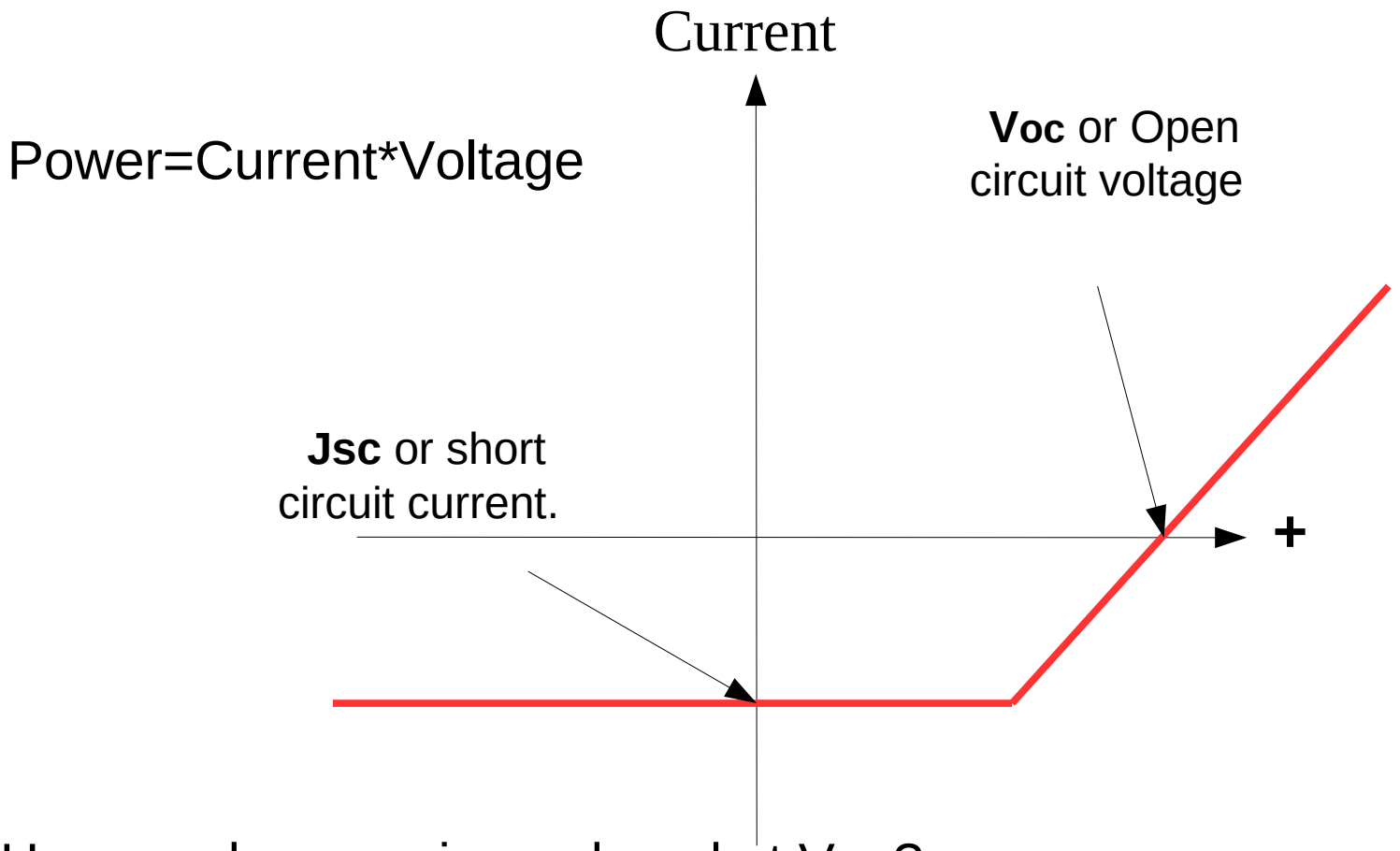


# What do the JV curves look like in the light



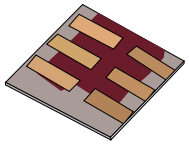
# What do the JV curves look like in the light






- How much power is produced at Voc?
- How much power is produced at Jsc?
- Where will maximum power be produced?

# Overview



- Who am I?
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- **Different types of solar cells**
  - **Silicon solar cells**
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# Silicon solar cells

Gray Watson

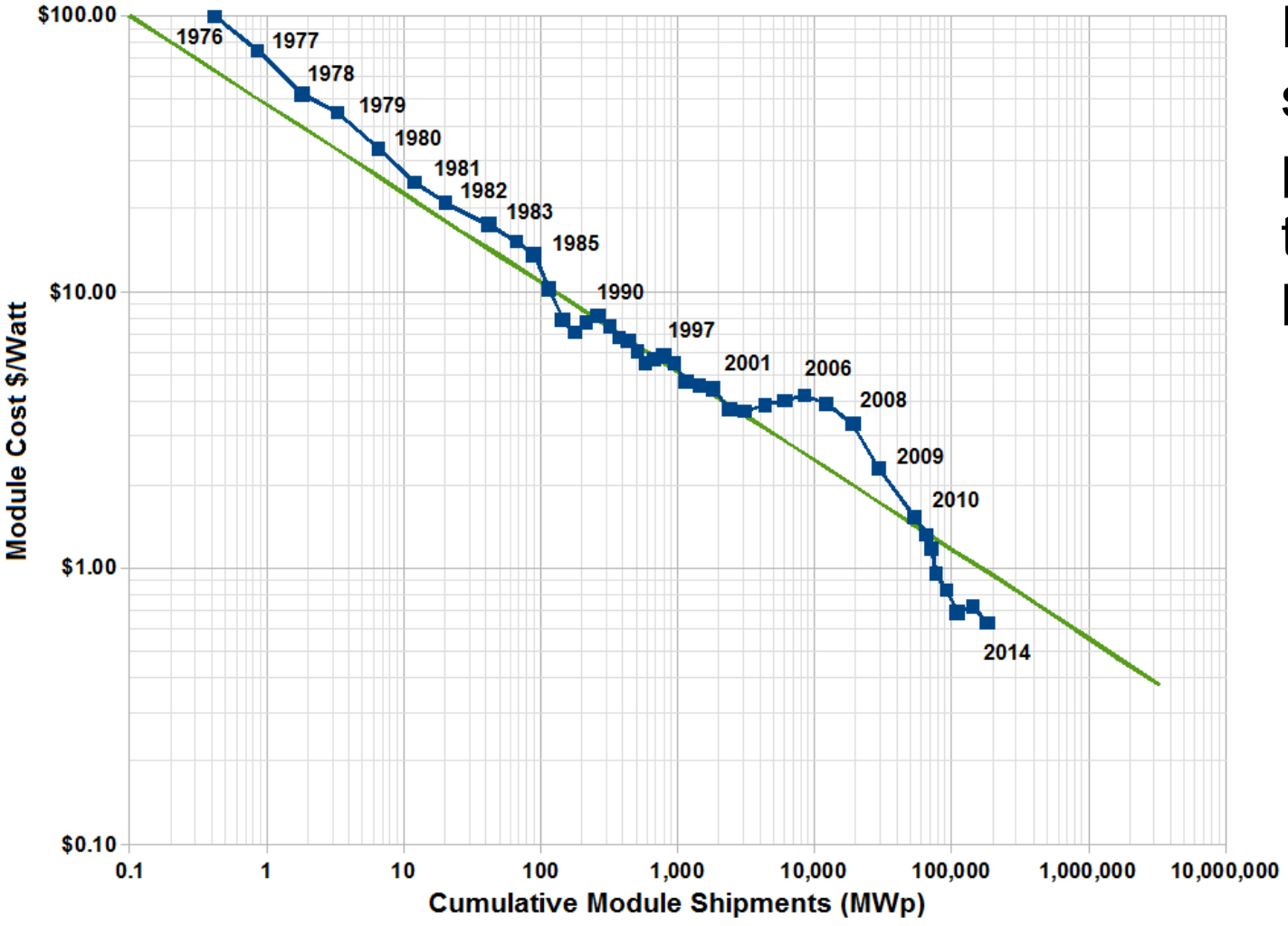
•When you travel through the countryside and look at the roves of houses. You often see deep blue solar cells.

•These are cells made of silicon.

•They are about between 15-20% efficient.

•And have a life time of between 10 and 20 years.

# Swanson's law




Every time solar cell production the price falls by 20%.

# What's wrong with silicon?

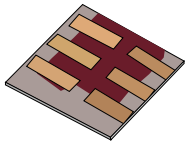
Naturally occurring silicon

Mono-crystalline silicon

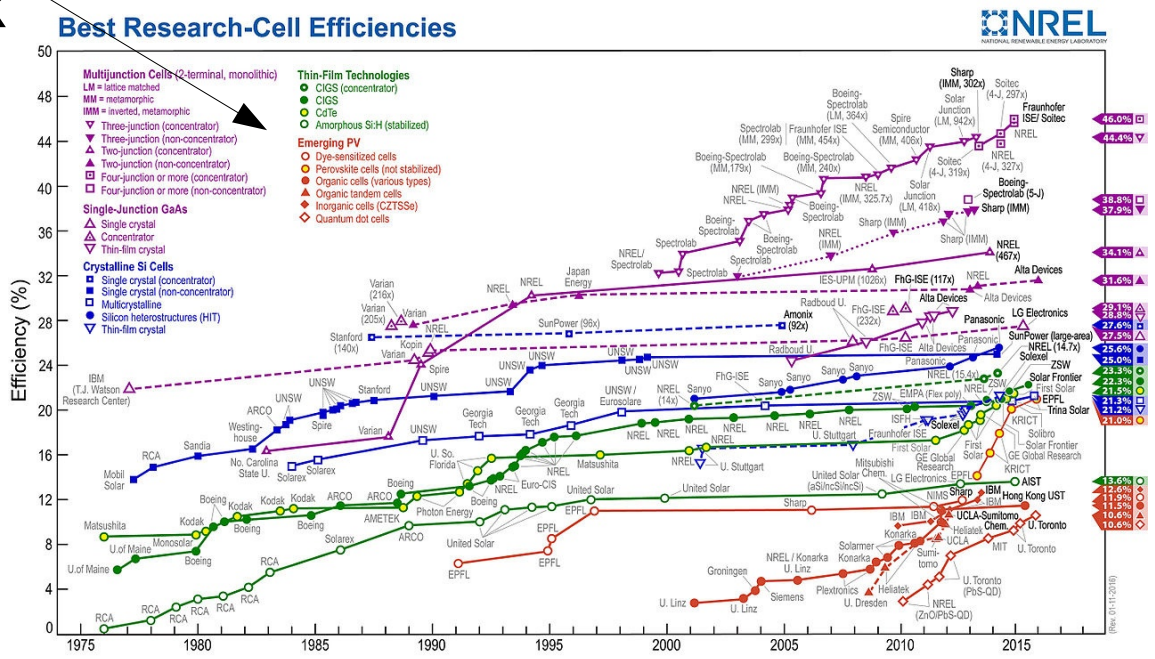
Silicon solar cell

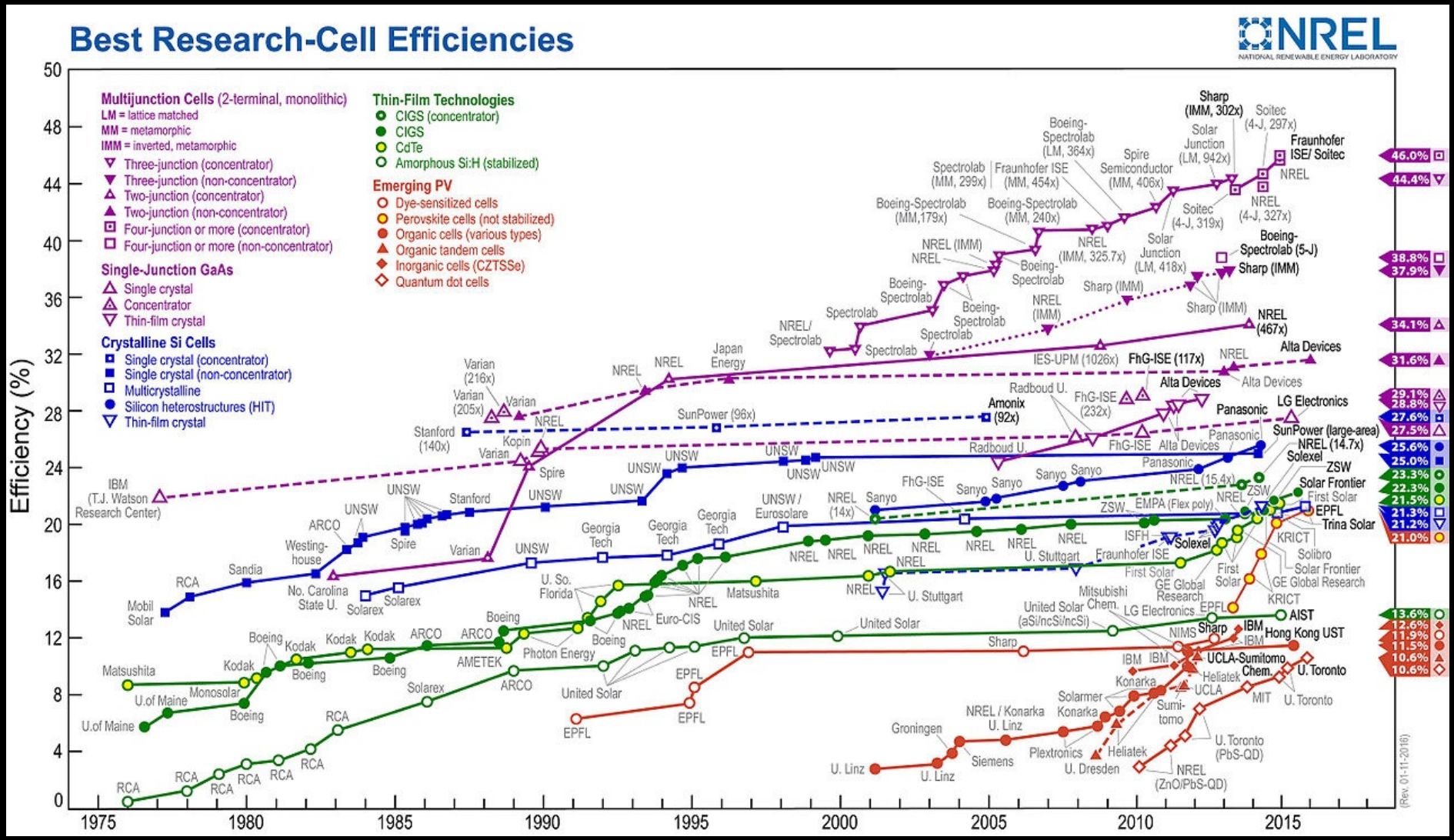
2 GJ per square meter!
(553 kWh)

# Other classes of solar cell

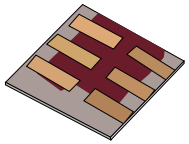


- People have been searching for alternatives to silicon solar cells for a long time
- Below is a graph of efficiency of different types of solar cell as a function of time.
- Let's have a closer look
- Before we look at some of these technologies in more detail.



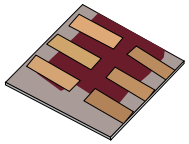

Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
46.0%
44.4%
38.8%
37.9%
34.1%
31.6%
29.1%
28.8%
27.6%
27.5%
25.6%
25.0%
23.3%
22.3%
21.5%
21.3%
21.2%
21.0%
13.6%
12.6%
11.9%
11.5%
10.6%
10.6%
(Rev. 01-11-2016)

# Overview



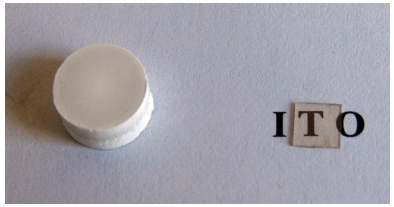
- Who am I?
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# One answer to this problem, the plastic solar cell.

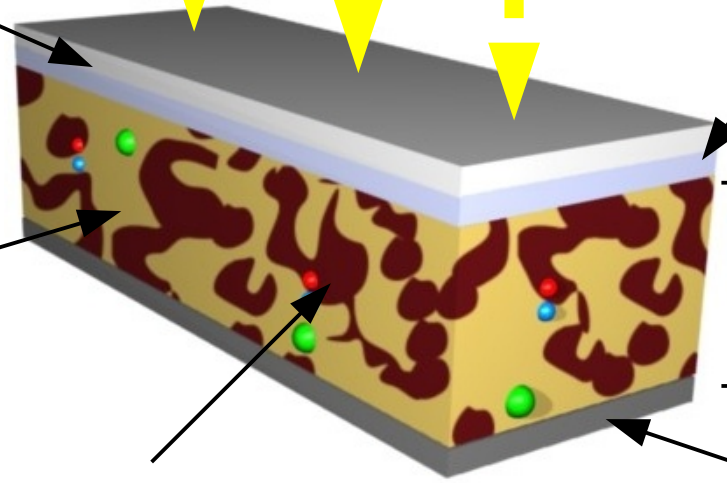


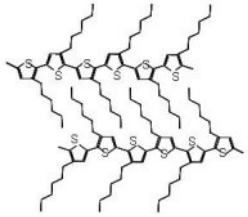
Sun light

Transparent plastic substrate

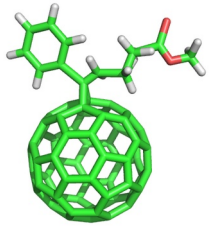



Transparent electrode



Light adsorbing polymer



C60 derivative

Metallic back contact

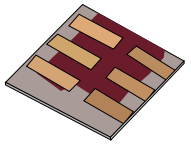
# What are the advantages of organic solar cells?

- Organic molecules are cheep to make.

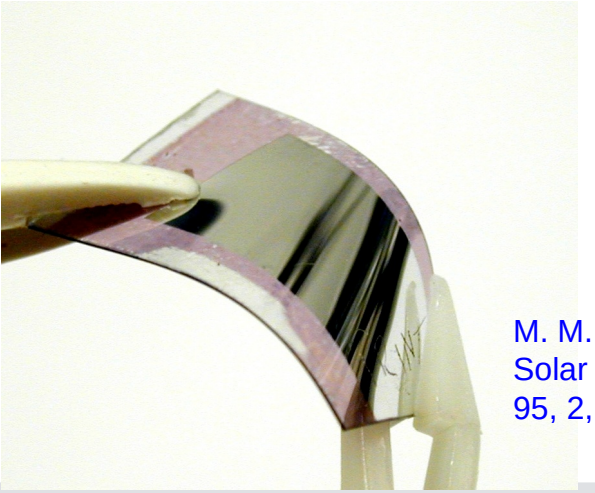
- They are flexible so the cells can be easily integrated into products and buildings.

Images from www.konarka.com

# Advantages of being flexible

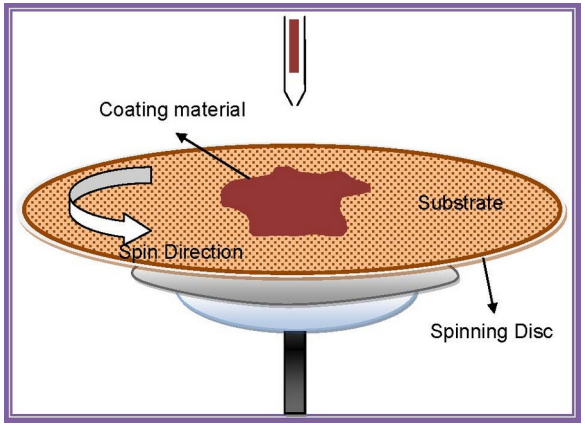


- But most importantly:
  - Organic devices can be printed onto a plastic substrate just like newspapers are printed onto paper at (100>m/min).
  - The principle is that does not matter that they are not very efficient as they are cheep to manufacture.

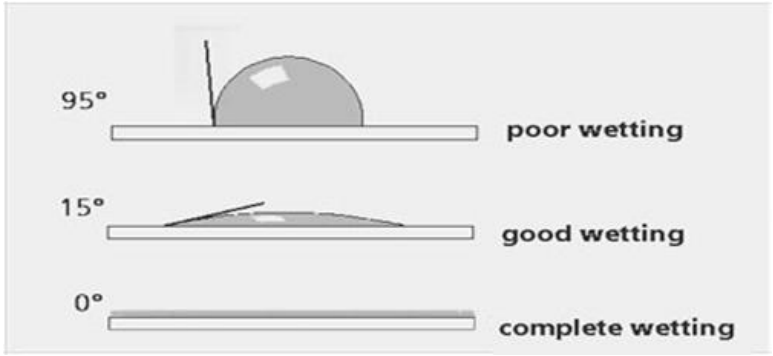


M. M. Voigt, R C.I. Mackenzie, et al. Solar Energy Materials and Solar Cells, 95, 2, 2011, pp. 731-734

# From the lab to the factory: Tuning the ink parameters

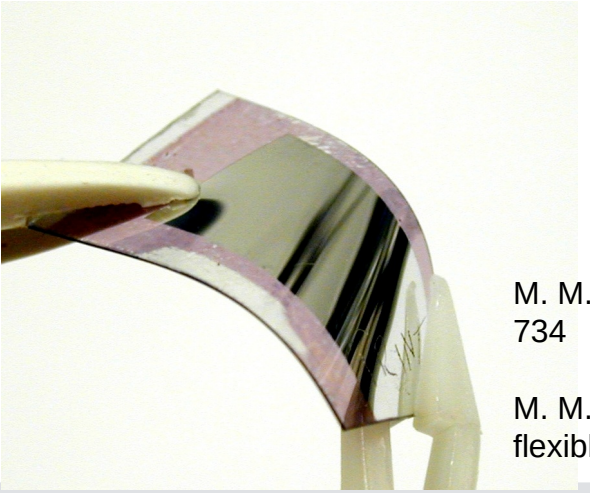



Lab scale production (1 $cm^2$ at most)




Polymer/fullerene have to be optimized for being printed too.

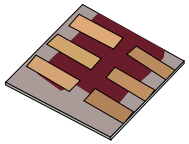
Industrial production (>100 $cm^2$)



M. M. Voigt, R C.I. Mackenzie, et al. Solar Energy Materials and Solar Cells, 95, 2, 2011, pp. 731-734

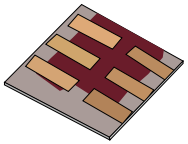
M. M. Voigt, R C.I. Mackenzie, et al."Gravure printing of inverted organic solar cell structures on flexible substrates" Solar Energy Materials and Solar Cells, submitted

# Overview



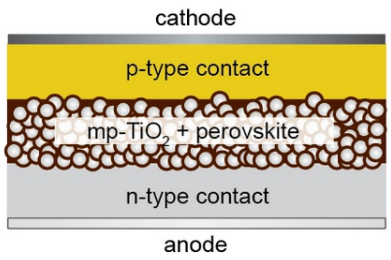
- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - **Perovskite solar cells**
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# Perovskite solar cells



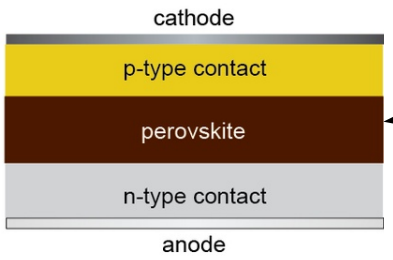
Sensitized perovskite solar cell

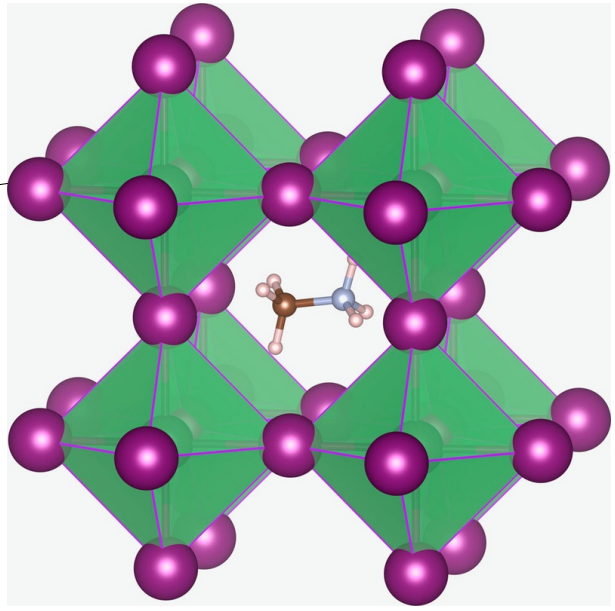
a)




Thin-film perovskite solar cell

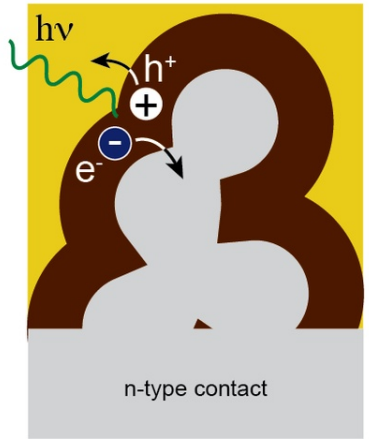
b)



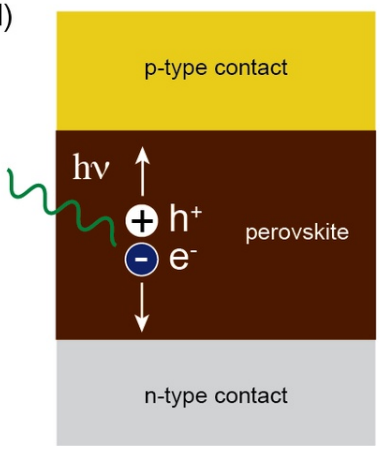



Christopher Eames

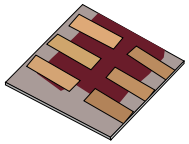
c)



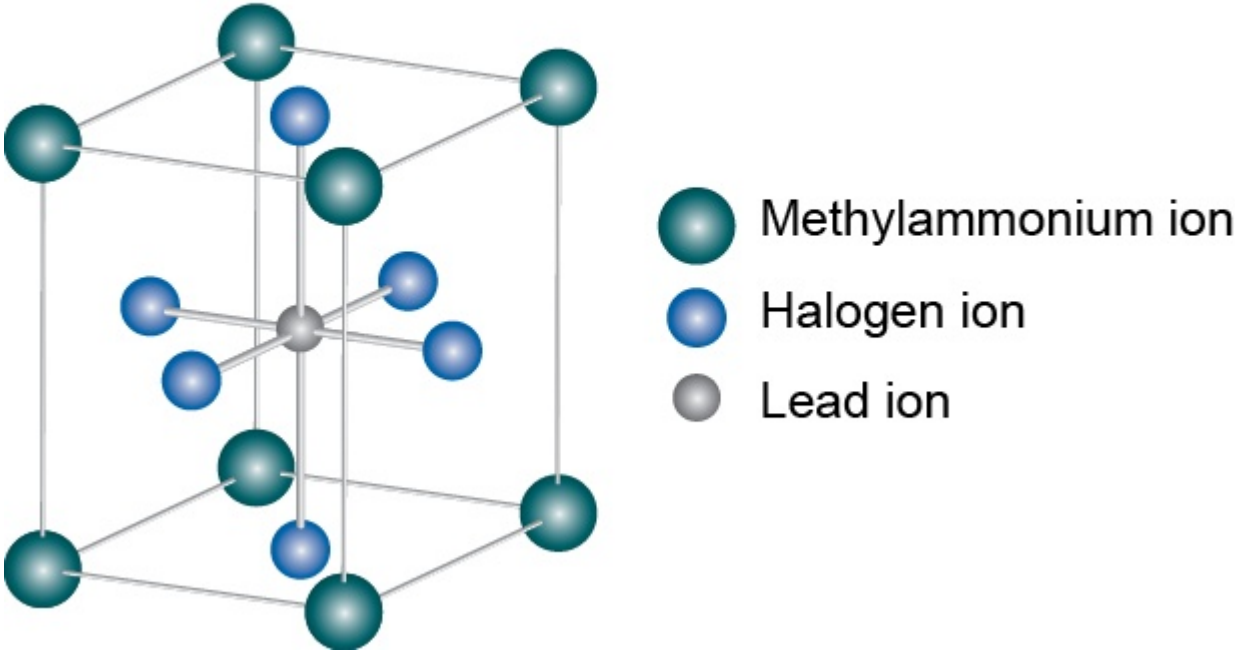

d)



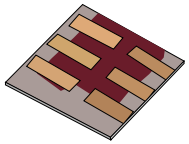
# Anybody see any problems with this solar cell?



$CH_3NH_3PbX_3$

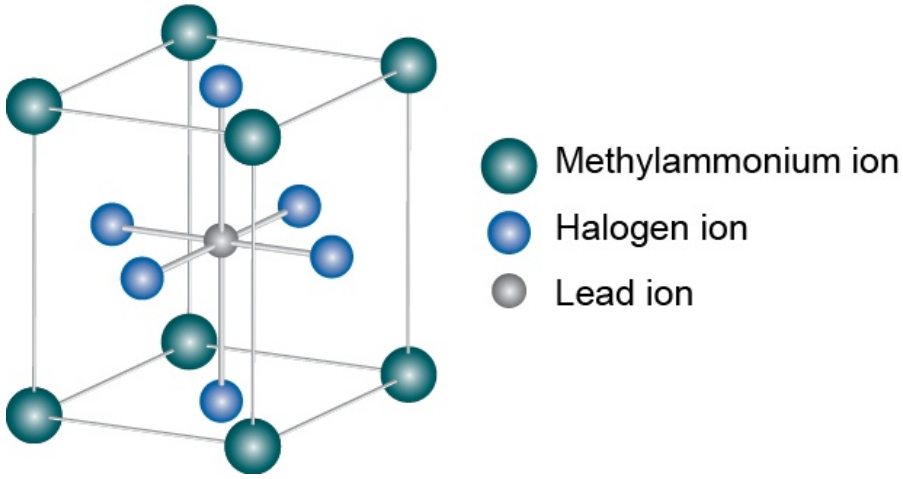


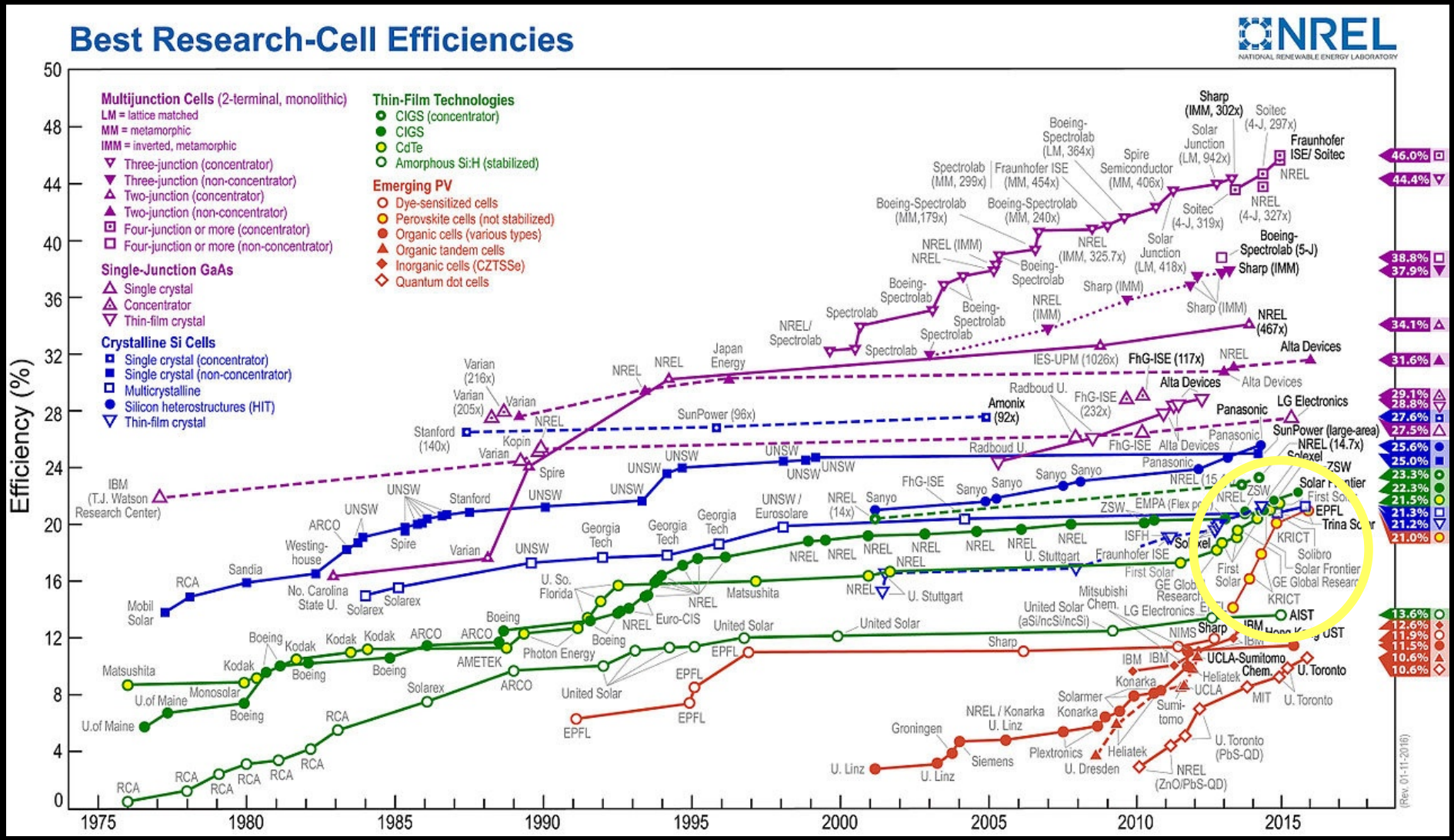
# Anybody see any problems with this solar cell?



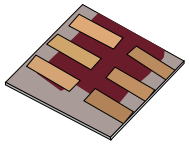
- It contains lead
- It's water soluble
- Also, all the molecules in it can move around meaning it's a pretty unstable material.
- Solar cells typically have a life time of hours.

$CH_3NH_3PbX_3$



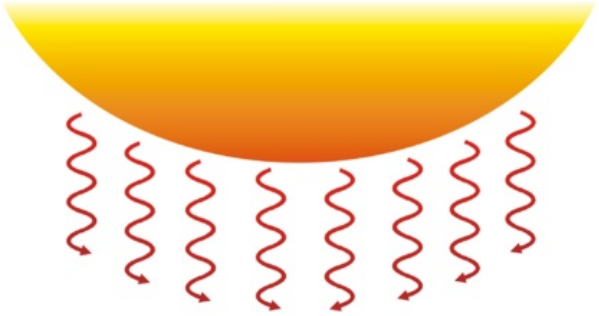

Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
Efficiency (%)
0
4
8
12
16
20
24
28
32
36
40
44
48
50
1975
1980
1985
1990
1995
2000
2005
2010
2015
46.0%
44.4%
38.8%
37.9%
34.1%
31.6%
29.1%
28.8%
27.6%
27.5%
25.6%
25.0%
23.3%
22.3%
21.5%
21.3%
21.2%
21.0%
13.6%
12.6%
11.9%
11.5%
10.6%
10.6%
(Rev. 01-11-2016)

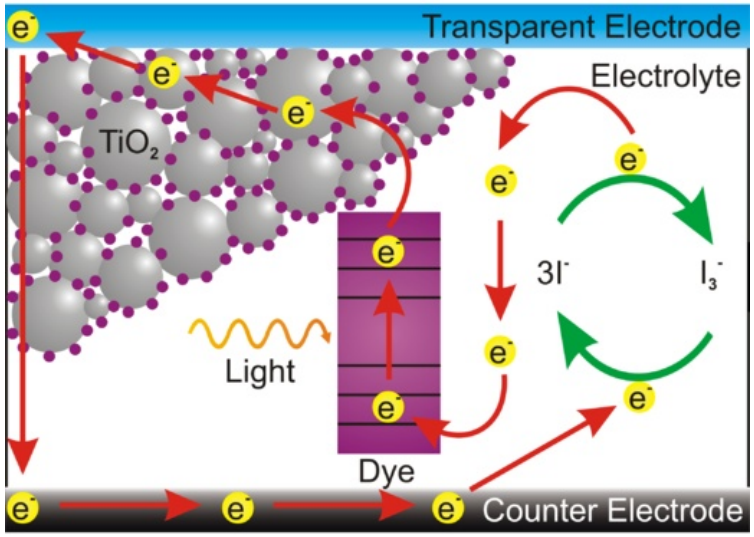
# Overview



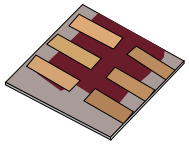
- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - **Dye sensitized solar cells**
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# Dye sensitized solar cell



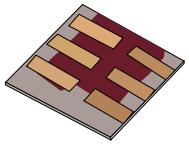



# Dye sensitized solar cell



- Efficiency never really got really high.
- Over taken by perovskite solar cells.
- The liquid in them was a problem.
- Never really very successful.

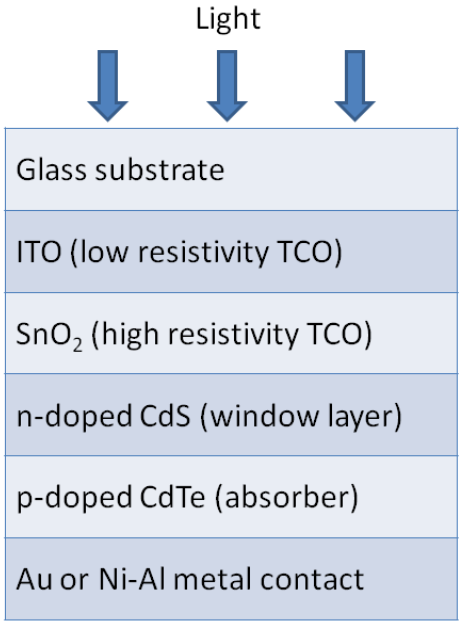
# Overview



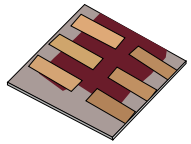
- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - **Cadmium telluride solar cells**
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# Spotting Cadmium Telluride solar cells.

•Generally a deeper blue than silicon and don't have metallic strips on the front of them.



# Problems with Cadmium Telluride solar cells.



GFS CHEMICALS

## SAFETY DATA SHEET

Alchemist-hp

| | | |
|---|---|---|
| **Environmental hazards** | Hazardous to the aquatic environment, acute hazard | Category 1 |
| | Hazardous to the aquatic environment, long-term hazard | Category 1 |
| **OSHA defined hazards** | Not classified. | |
| **Label elements** | | |

| | |
|---|---|
| **Signal word** | Danger |
| **Hazard statement** | Toxic if swallowed. Fatal if inhaled. Suspected of causing genetic defects. May cause cancer. Suspected of damaging fertility. Suspected of damaging the unborn child. Causes damage to organs through prolonged or repeated exposure. Very toxic to aquatic life. Very toxic to aquatic life with long lasting effects. |

# Problems with Cadmium Telluride solar cells.

GFS CHEMICALS

**SAFETY DATA SHEET**

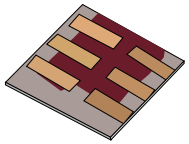
Alchemist-hp

| | | |
|---|---|---|
| **Environmental hazards** | Hazardous to the aquatic environment, acute hazard | Category 1 |
| | Hazardous to the aquatic environment, long-term hazard | Category 1 |
| **OSHA defined hazards** | Not classified. | |
| **Label elements** | | |

| | |
|---|---|
| **Signal word** | Danger |
| **Hazard statement** | Toxic if swallowed. Fatal if inhaled. Suspected of causing genetic defects. May cause cancer. Suspected of damaging fertility. Suspected of damaging the unborn child. Causes damage to organs through prolonged or repeated exposure. Very toxic to aquatic life. Very toxic to aquatic life with long lasting effects. |

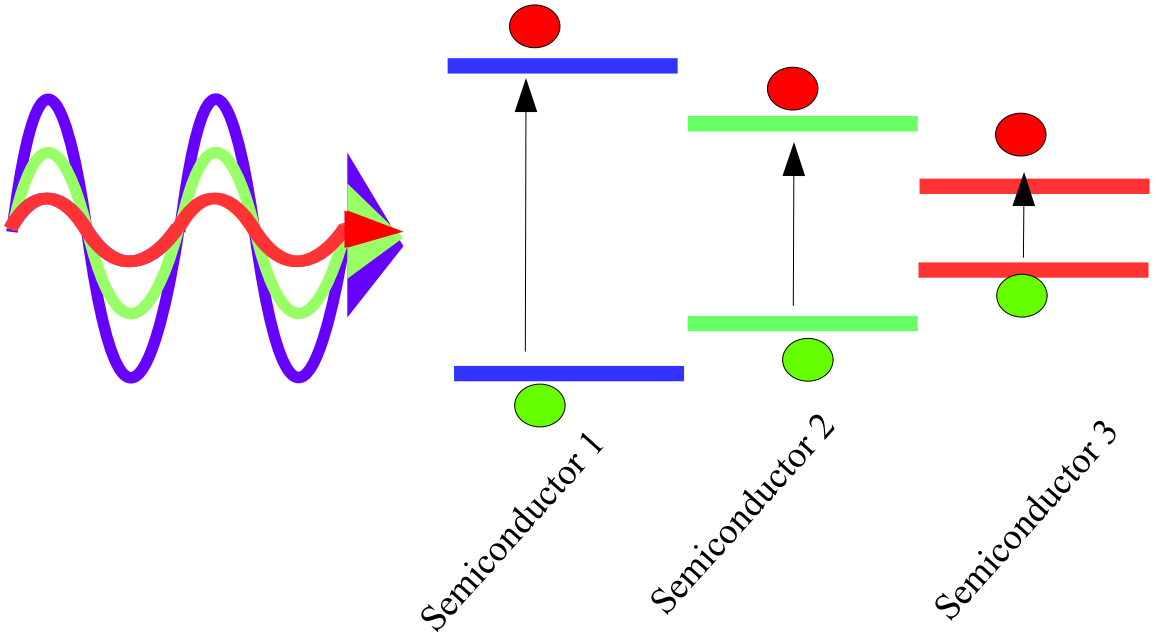
- They fail the 'lick' test. Would you lick a Cadmimum Telluride solar cell?

# Overview



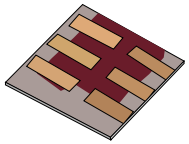
- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - **Multi-junction solar cells/Concentrator solar cells**
- Summary

# Multi-junction solar cell




•Different parts of the solar cell are optimized absorb different parts of the sun's spectrum.

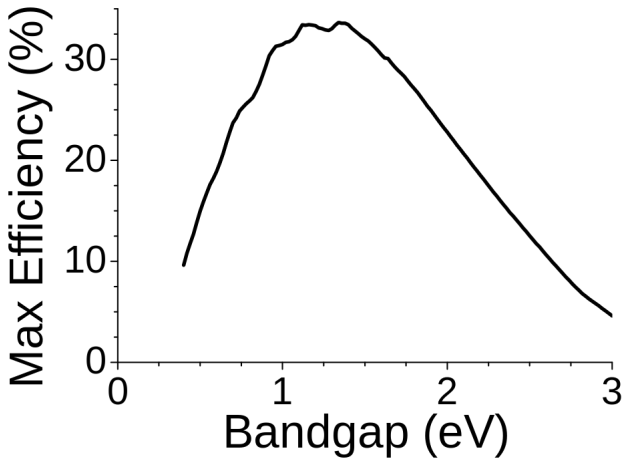
# Advantages of multi-junction cells

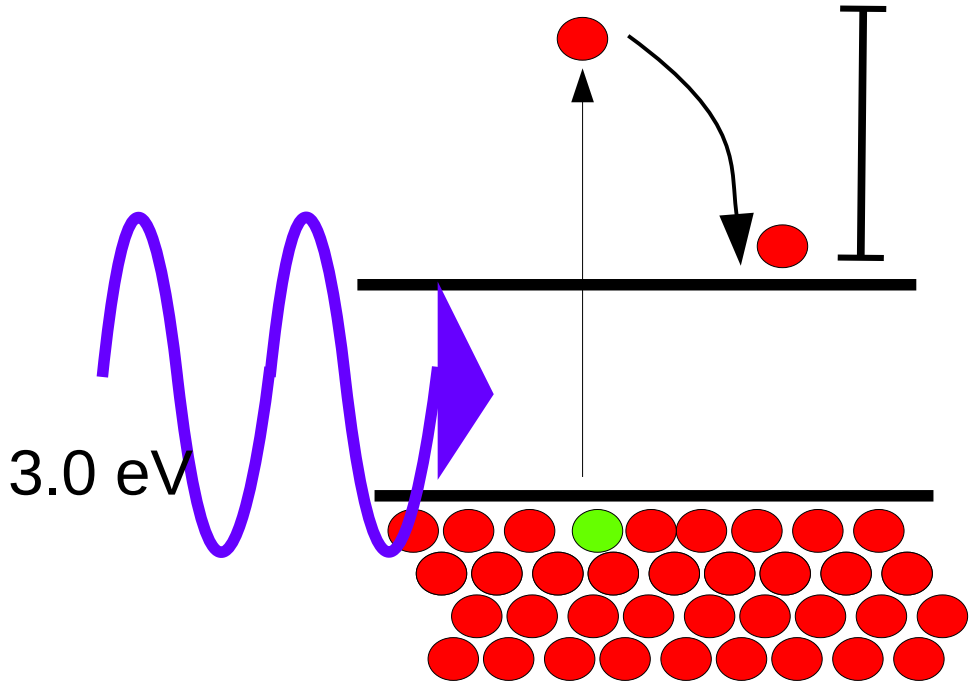


- Multi-junction cells minimize relaxation losses.

- Efficiency limit of a single junction cell is limited to 33.7%.

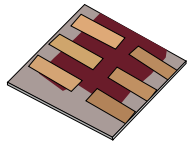
- Shockley–Queisser limit.

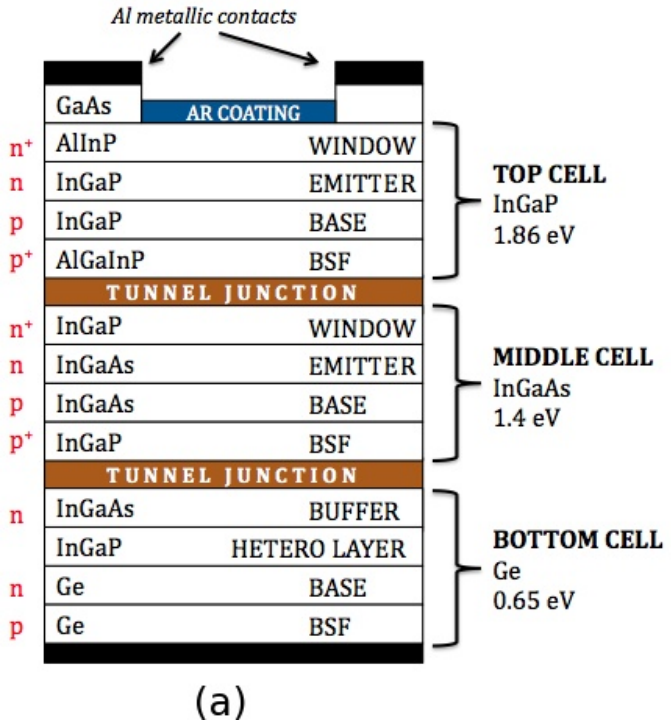


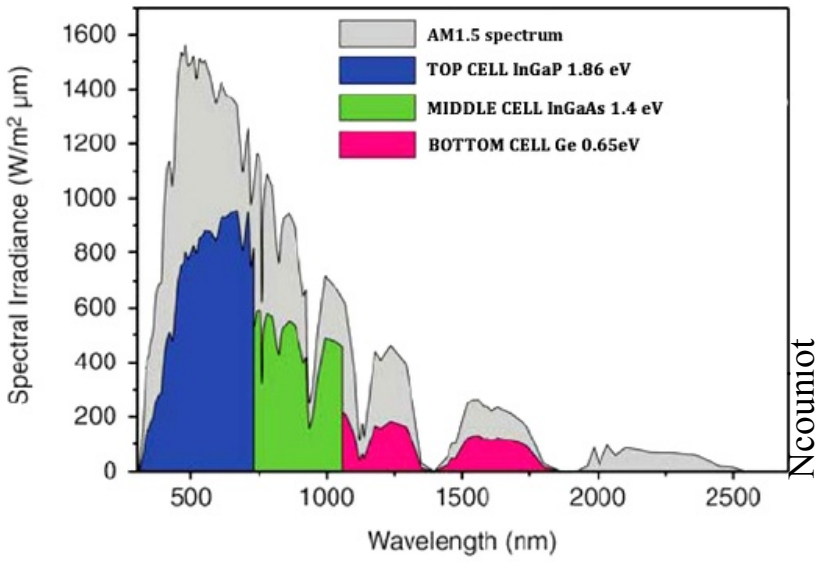

$E_{loss} = E_{photon} - E_g$

# Multi-junction solar cell






(a)




(b)

•Different parts of the solar cell are optimized absorb different parts of the sun's spectrum.

# Concentrator PV

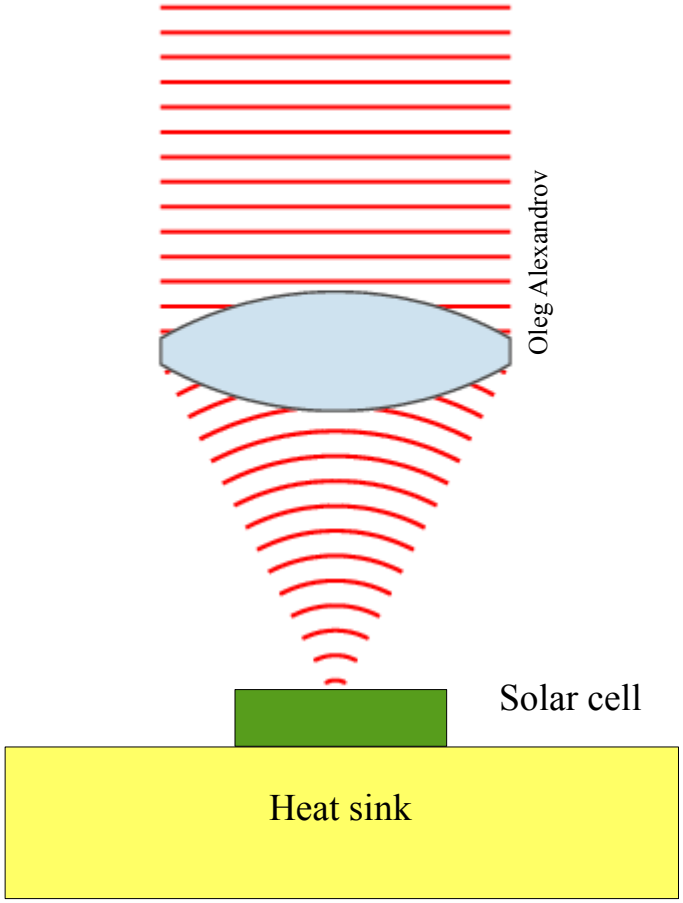
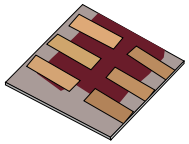



Image copyright http://arzonsolar.com/

The idea is to have a highly efficient (and expensive solar cell), but use it as efficiently as possibly by putting it under 10-1000 suns.
Needs cooling.

# Summary

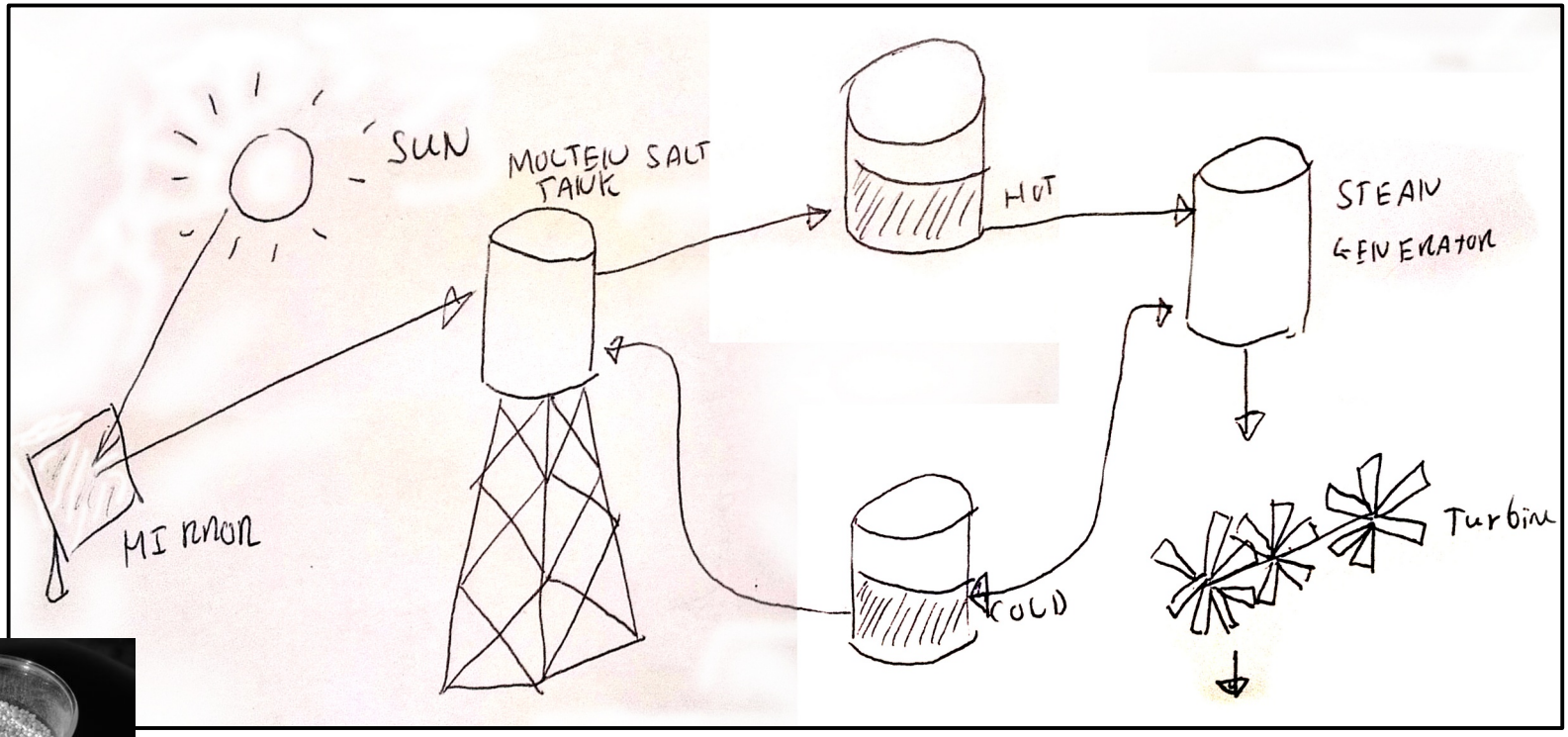


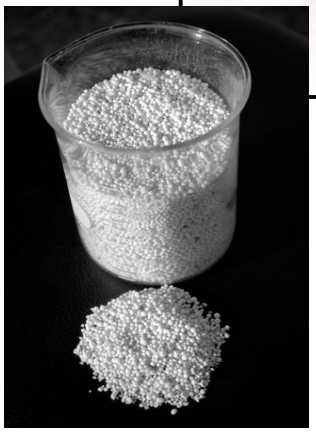
- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Diodes current-voltage curves in the light
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Multi-junction solar cells**/Concentrator solar cells**
- Summary

# Concentrator PV

Harper Lake in California

Z22

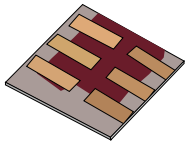

SUN
MOLTEN SALT TANK
HOT
STEAM GENERATOR
MIRROR
COLD
Turbine



# Concentrator PV

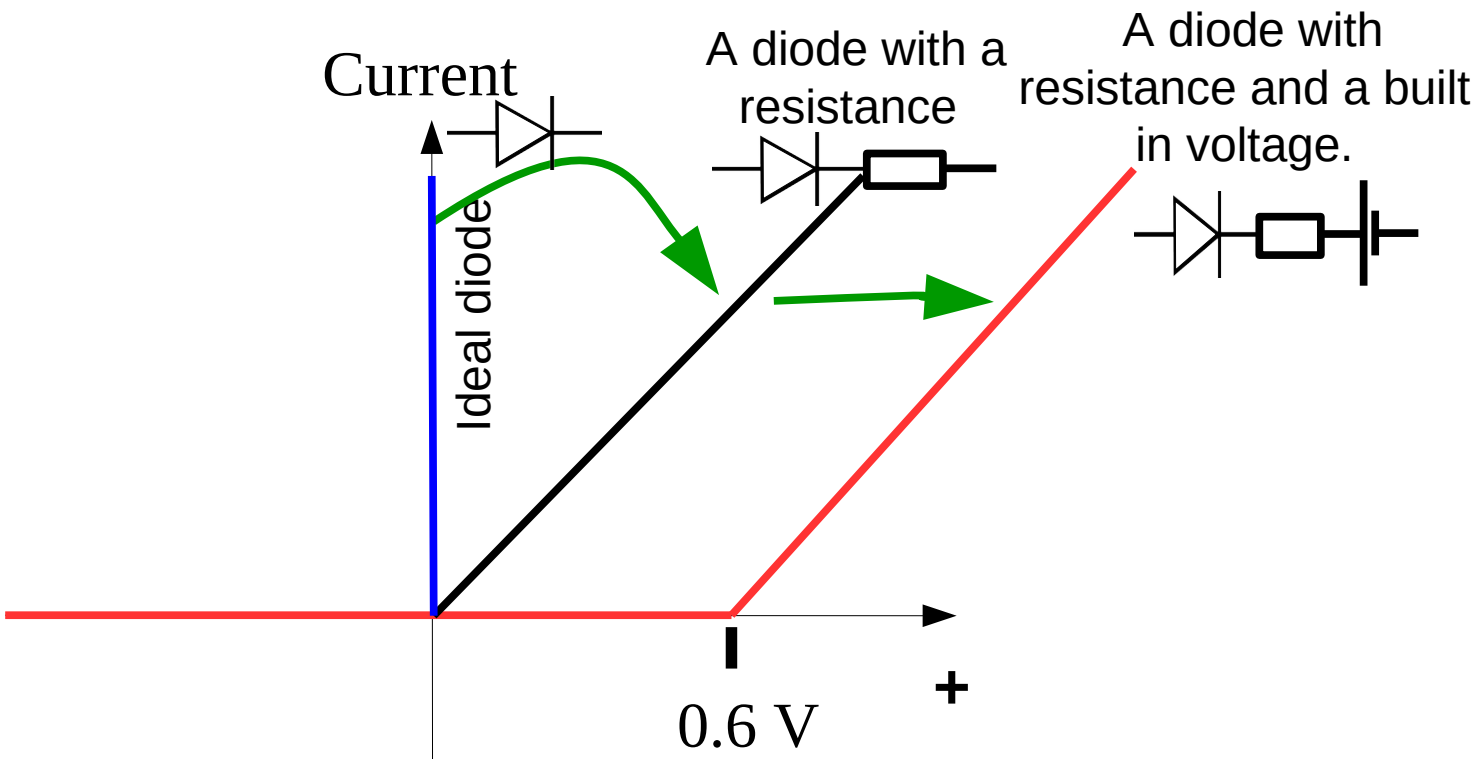
Koza1983

# Summary



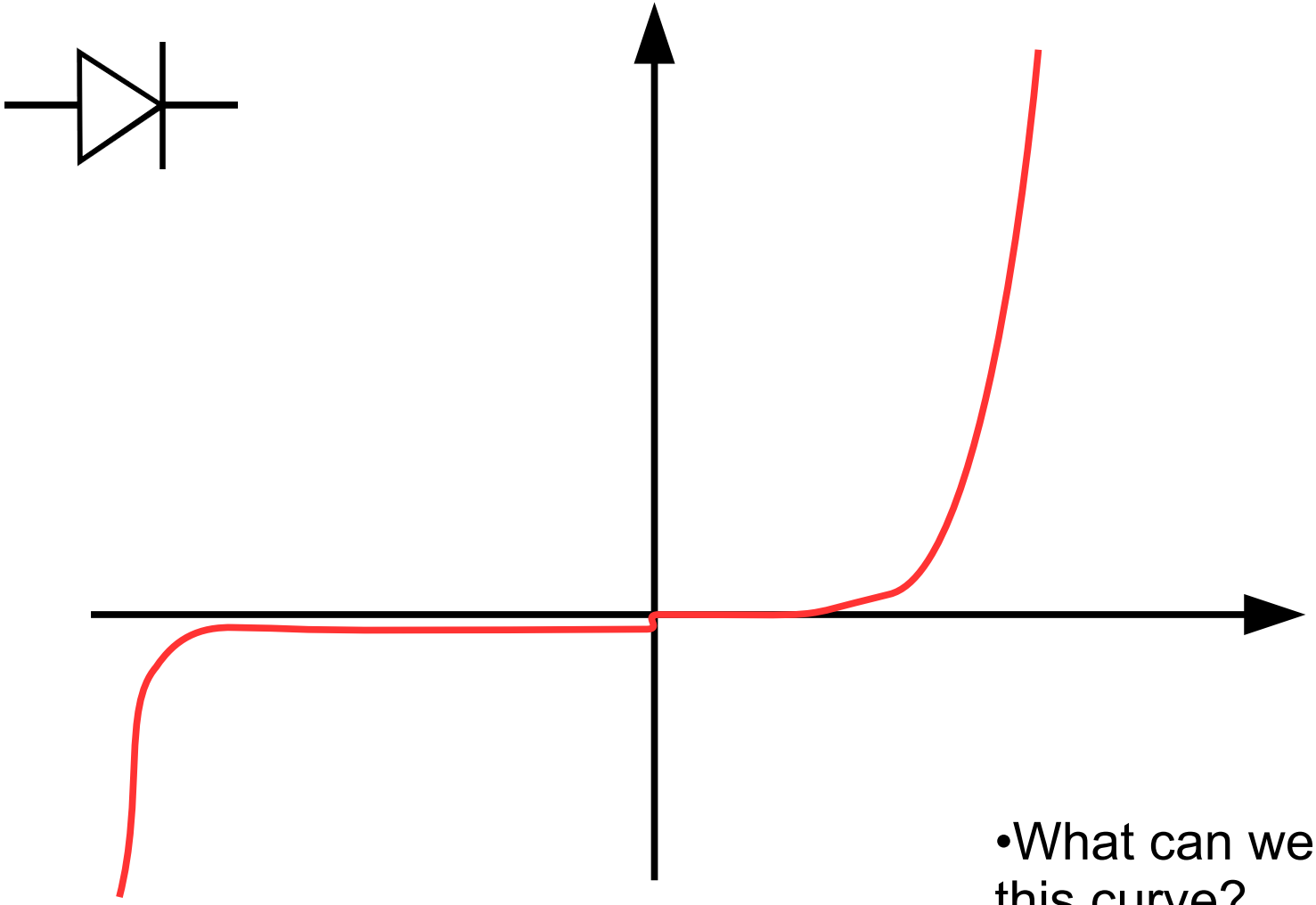
- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary

# Better solar cell models



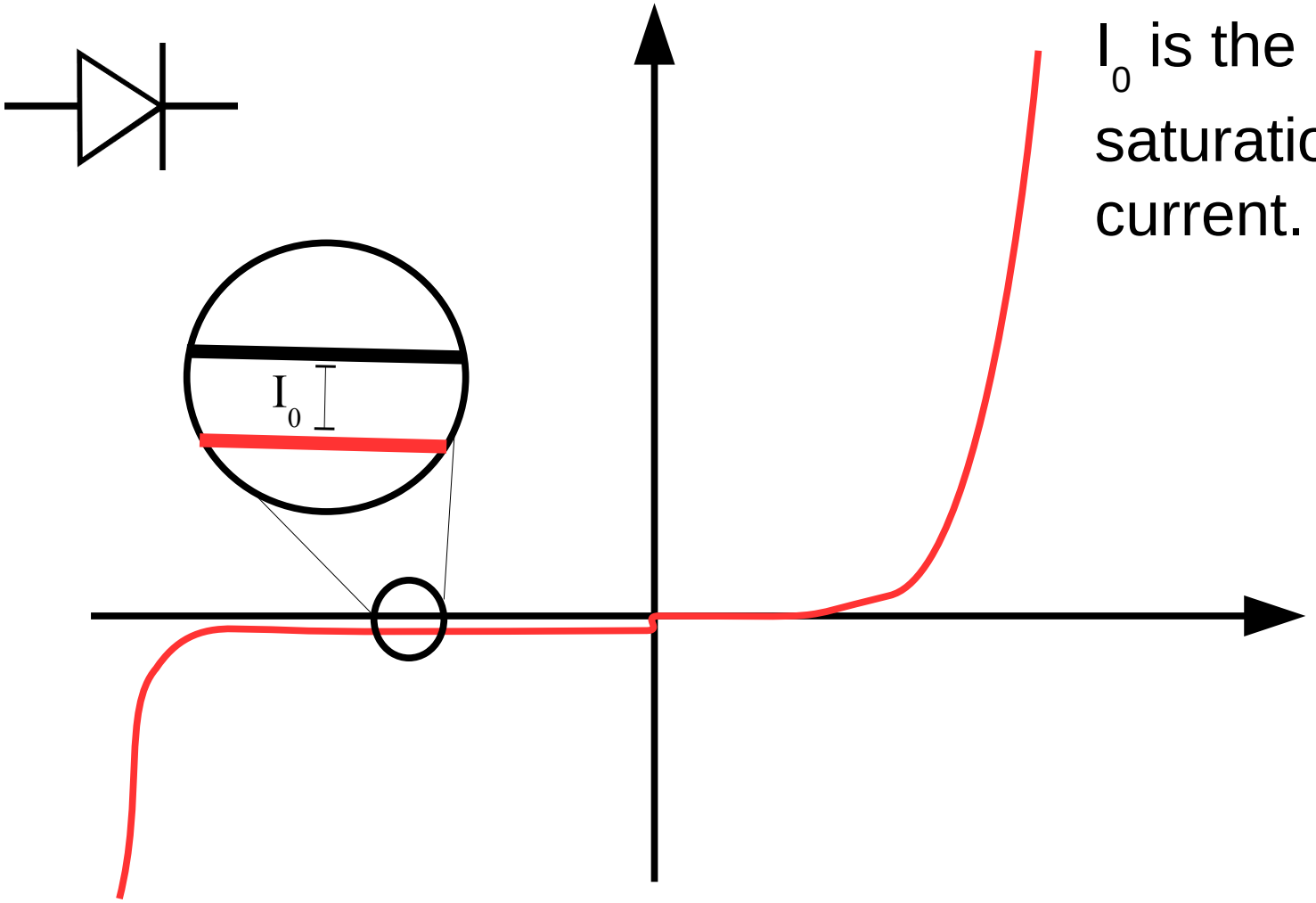

- You might have noticed that this current voltage curve does not look like any component you have ever seen.
- Let's look at a more realistic diode curve.

# A more real diode curve



•What can we see on this curve?

# A real diode curve

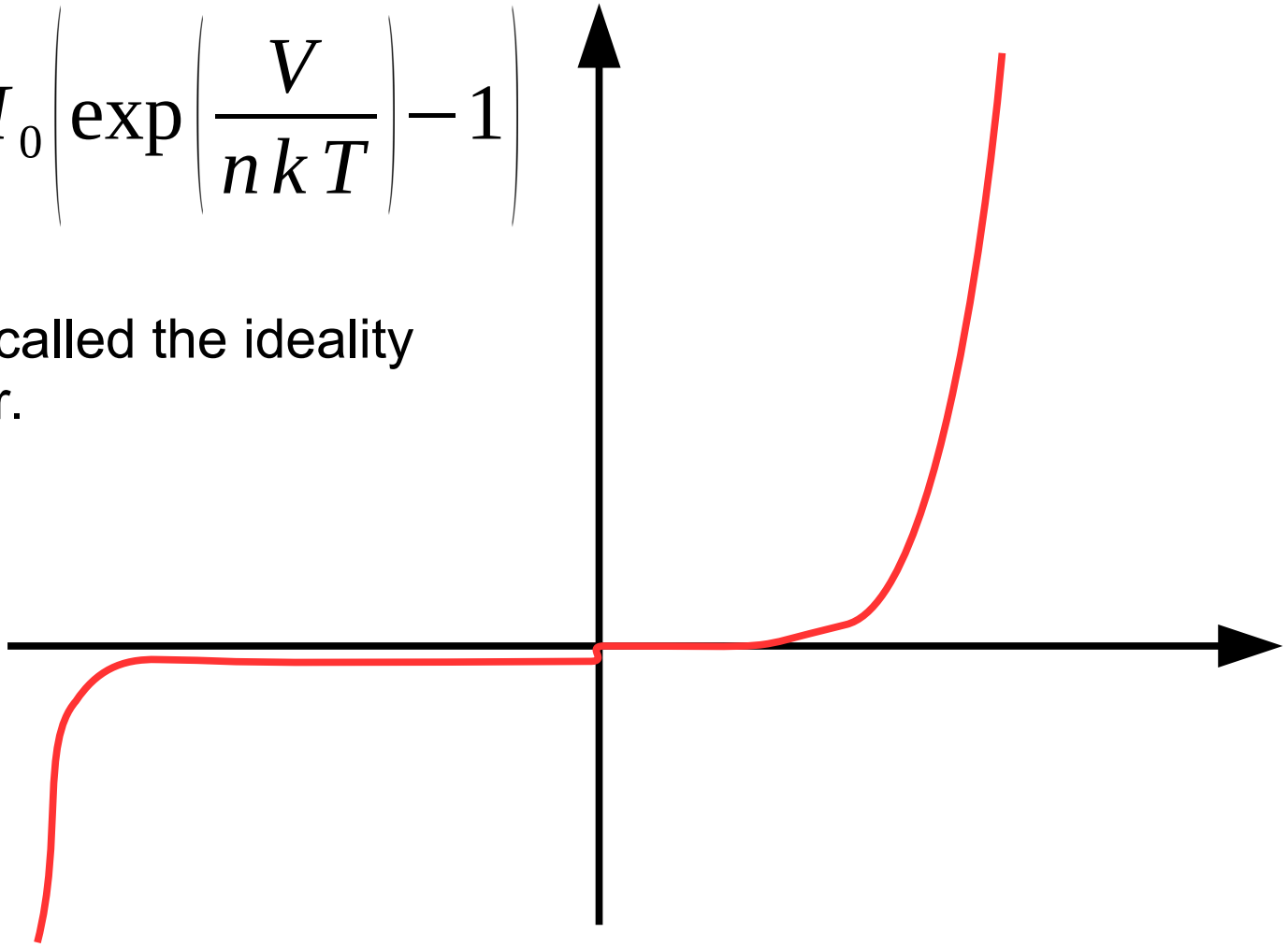



$I_0$ is the saturation current.

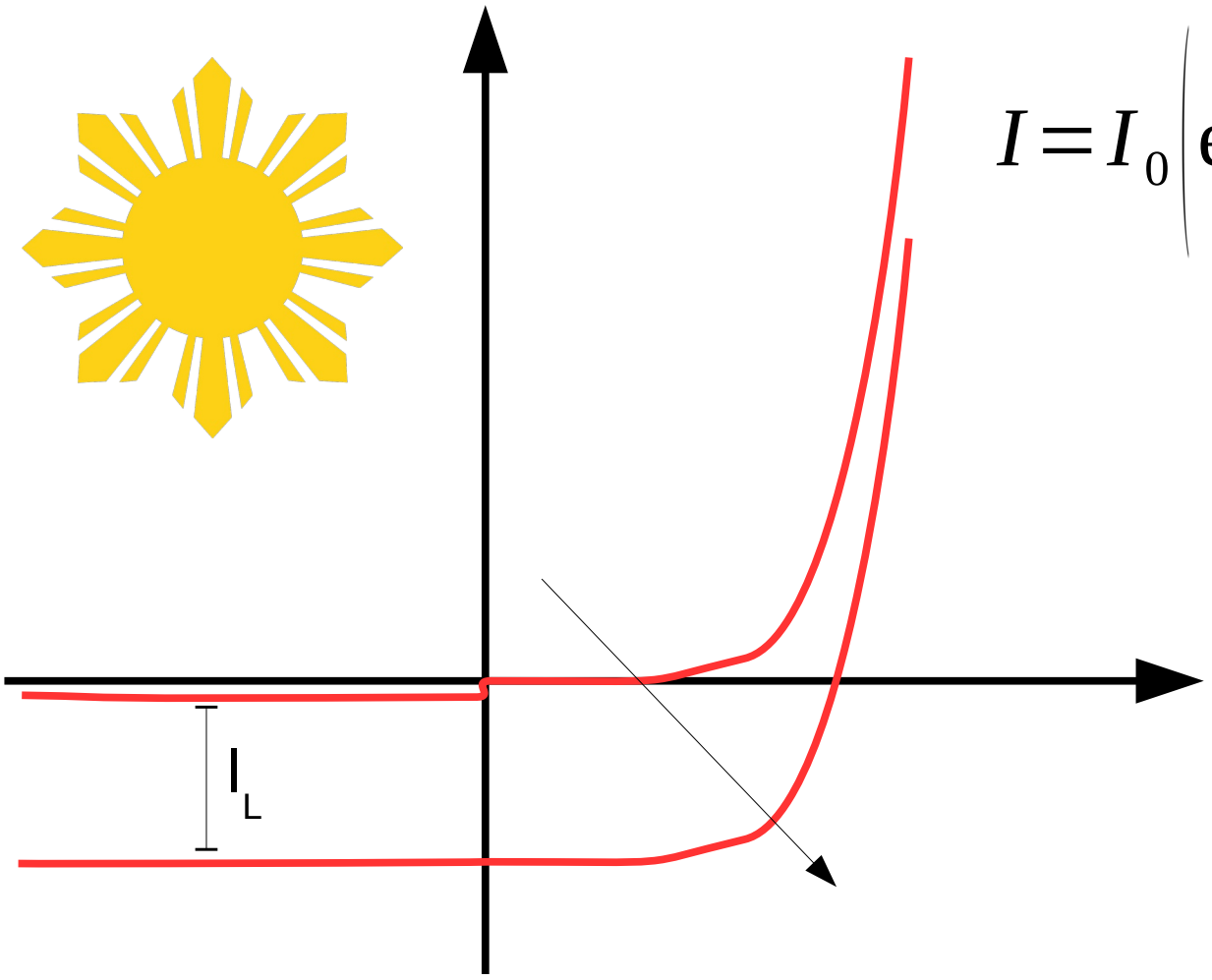
# A better ideal diode model.

$$I = I_0 \left( \exp\left( \frac{V}{n k T} \right) - 1 \right)$$

- n is called the ideality factor.

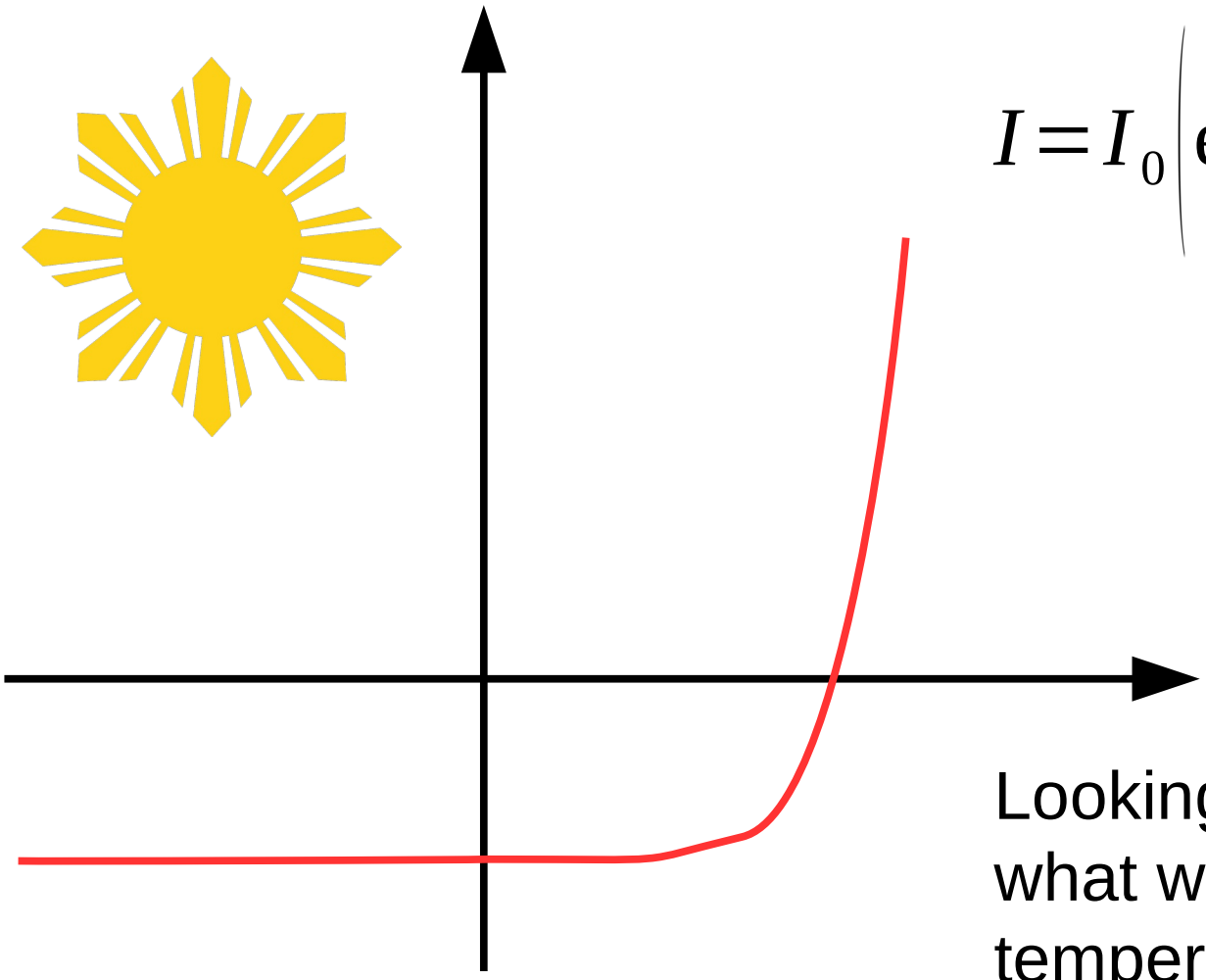


# The diode equation in the light.




$$I = I_0 \left( \exp\left( \frac{V}{n k T} \right) - 1 \right) - I_L$$

# The diode equation in the light.



$$I = I_0 \left( \exp\left( \frac{V}{n k T} \right) - 1 \right) - I_L$$

Looking at the equation what will happen if the temperature is increased?

# The diode equation in the light.

Fir0002

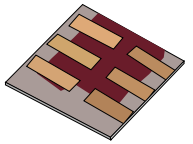
Hot

Cold


$$I = I_0 \left( \exp\left( \frac{V}{n k T} \right) - 1 \right) - I_L$$

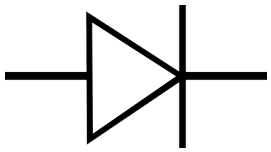
What implications would this have?

# The ideal diode equation



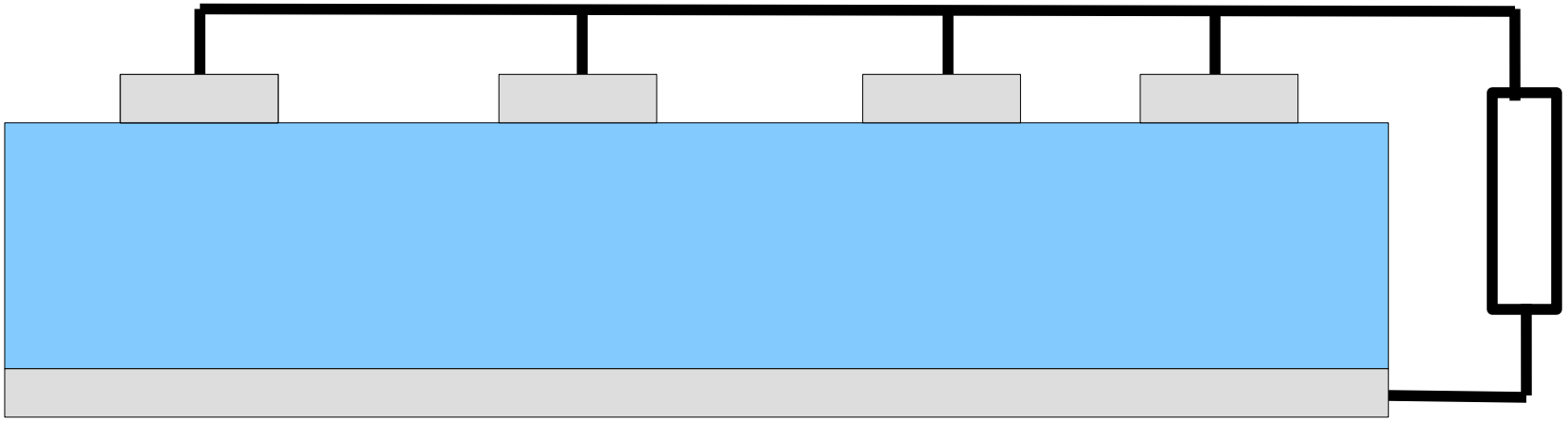
- This equation is for an ideal diode with no resistance. However in a real solar cell there will be:

$$I = I_0 \left( \exp\left( \frac{V}{n k T} \right) - 1 \right) - I_L$$

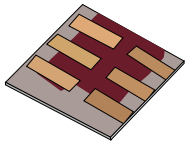


- Series resistance

- And shunt resistance



# The ideal diode equation

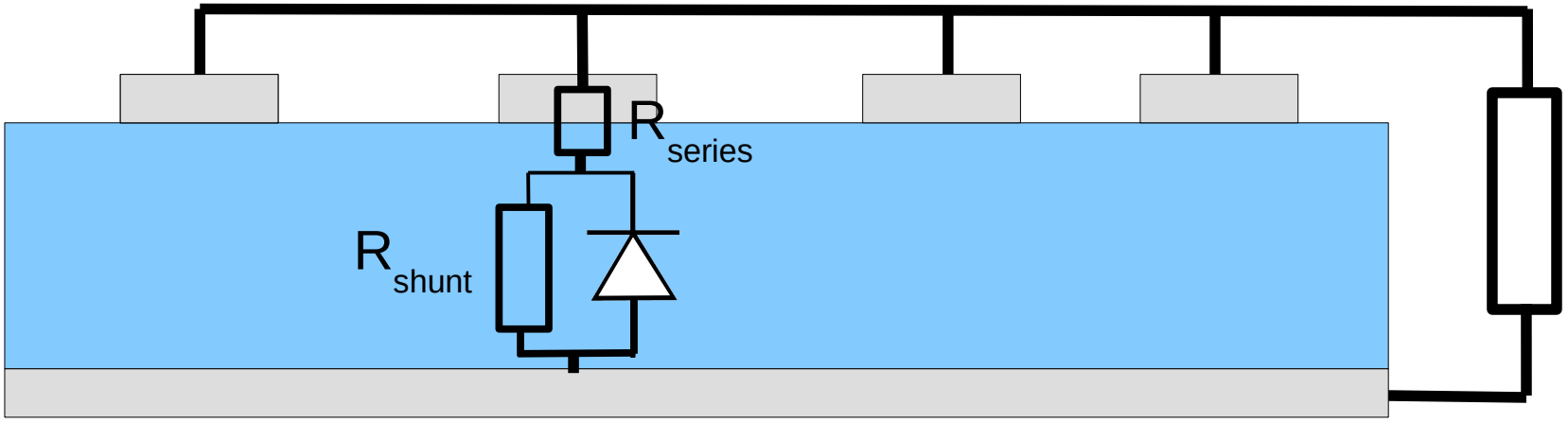


- This equation is for an ideal diode with no resistance. However in a real solar cell there will be:

$$I = I_0 \left( \exp\left( \frac{V}{n k T} \right) - 1 \right) - I_L$$

- Series resistance

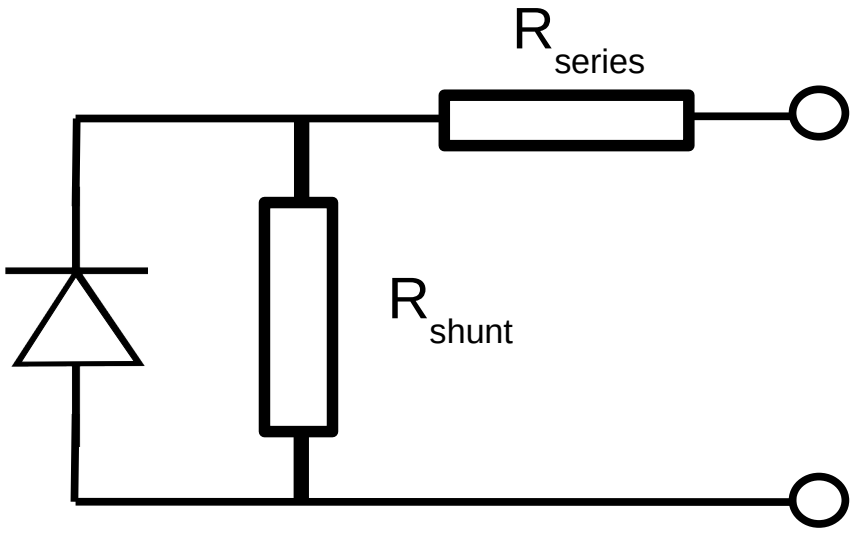
- And shunt resistance



# A better equivalent circuit

- Series resistance (1-10 Ohm)
- And shunt resistance (1 M Ohm)

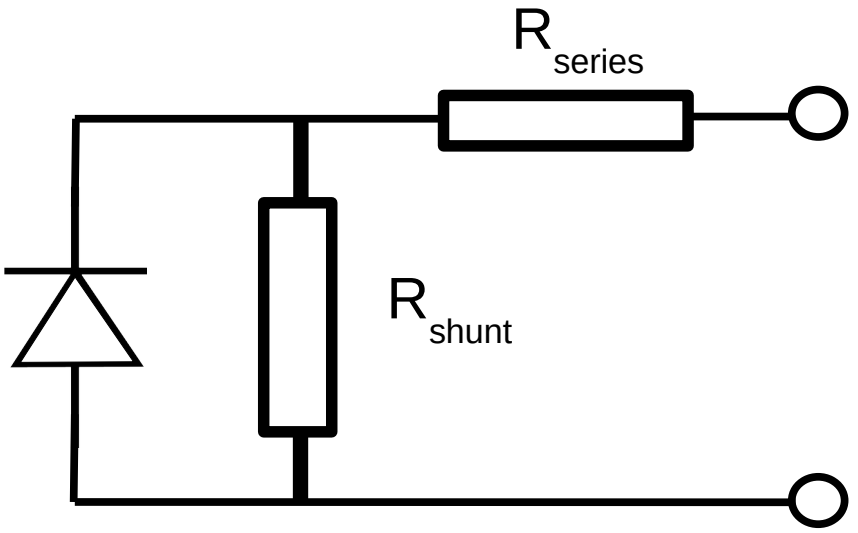
$$I = I_0\left(\exp\left(\frac{V}{n\,k\,T}\right) - 1\right) - I_L$$



# A better equivalent circuit

- Derive non-ideal diode equation

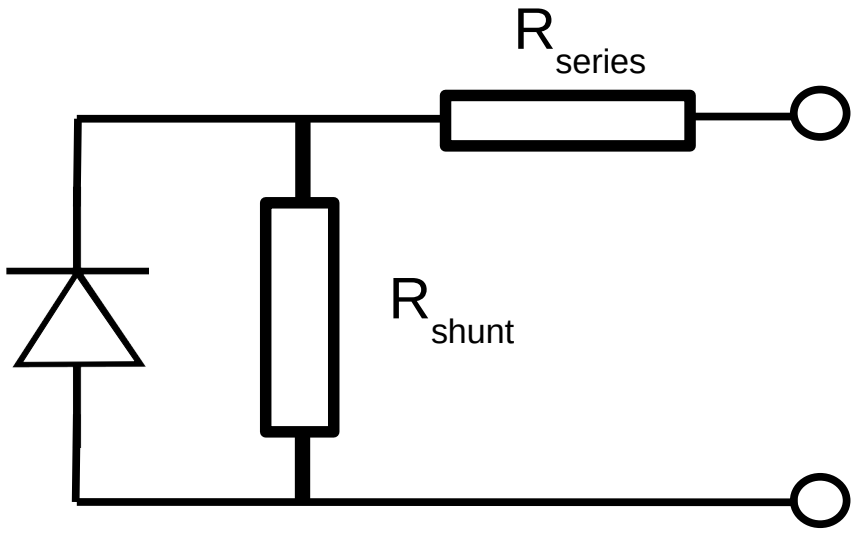
$$I = I_0 \left( \exp\left( \frac{V}{n k T} \right) - 1 \right) - I_L$$



# Dark JV curve

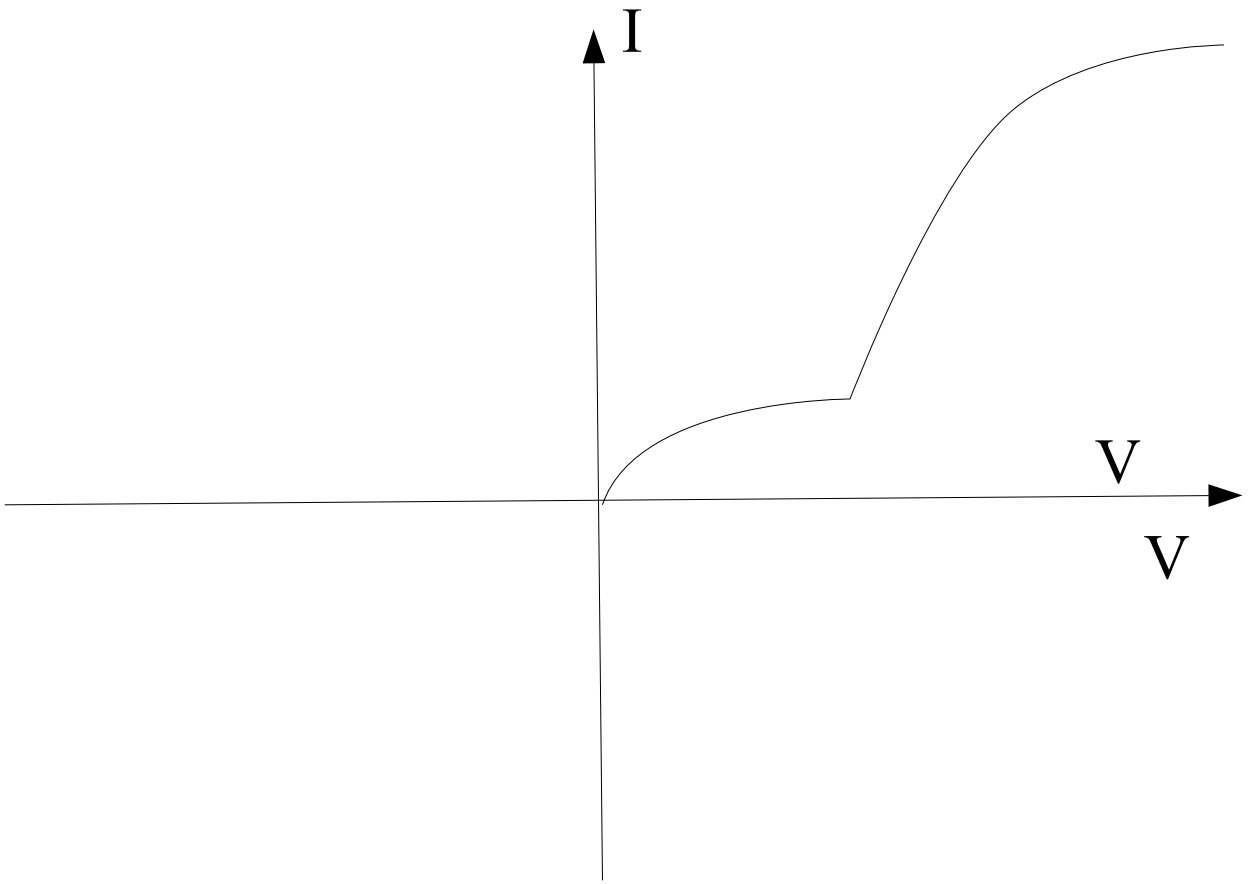
- Derive non-ideal diode equation

$$I = I_0 \left( \exp\left( \frac{V}{n k T} \right) - 1 \right) - I_L$$

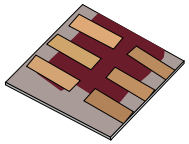


# Dark JV curve

- Derive non-ideal diode equation



# Summary



- About me
- Why Solar energy?
- Sunlight
- Absorbing sunlight in materials.
- Fundamentals of diodes
- From diodes to solar cells
- Different types of solar cells
  - Silicon solar cells
  - Organic solar cells
  - Perovskite solar cells
  - Cadmium telluride solar cells
  - Multi-junction solar cells/Concentrator solar cells
- Summary