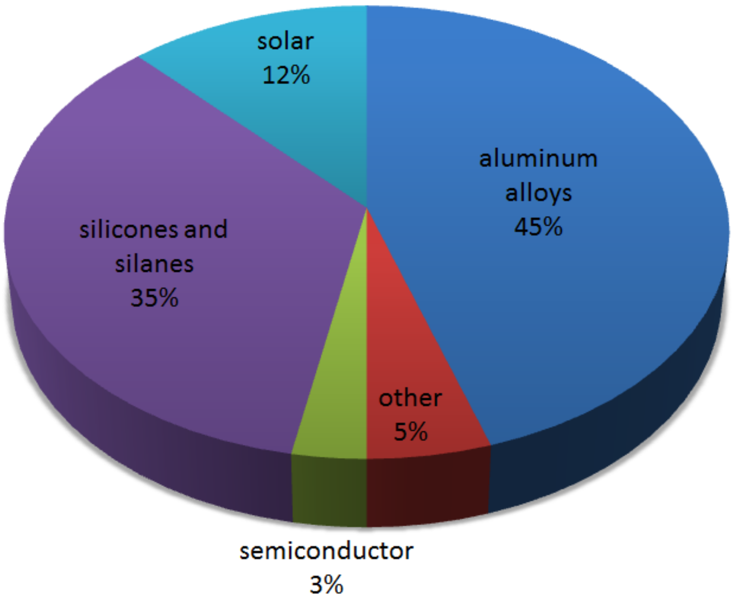
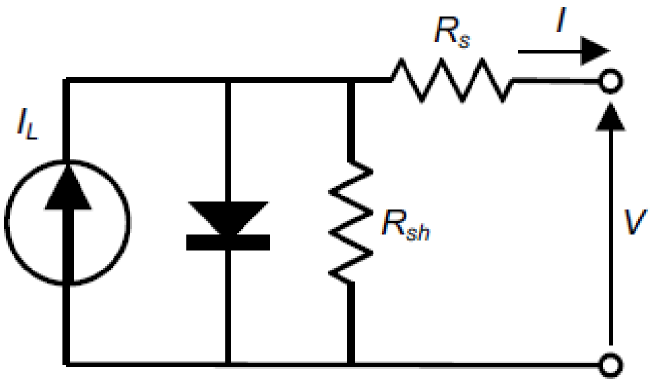
Solar Cells



solar
12%
aluminum
alloys
45%
silicones and
silanes
35%
other
5%
semiconductor
3%



R_s
I
I_L
R_{sh}
V

Energy

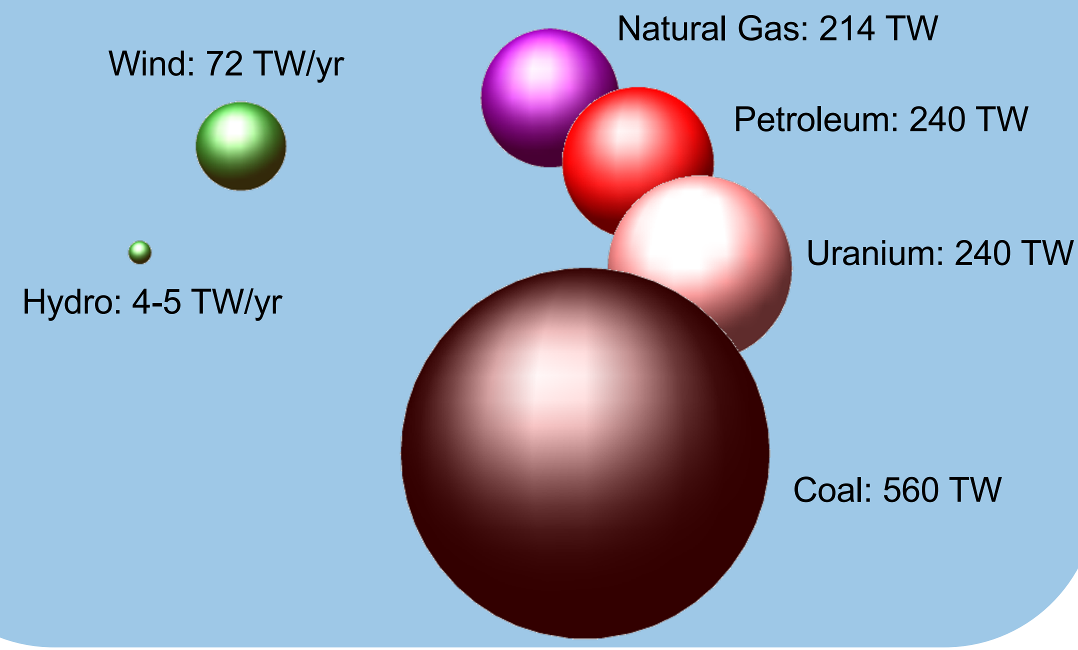
Our Energy Consumption …

- We consume around 20 TW ($10^{12}\ W$) of power each year.

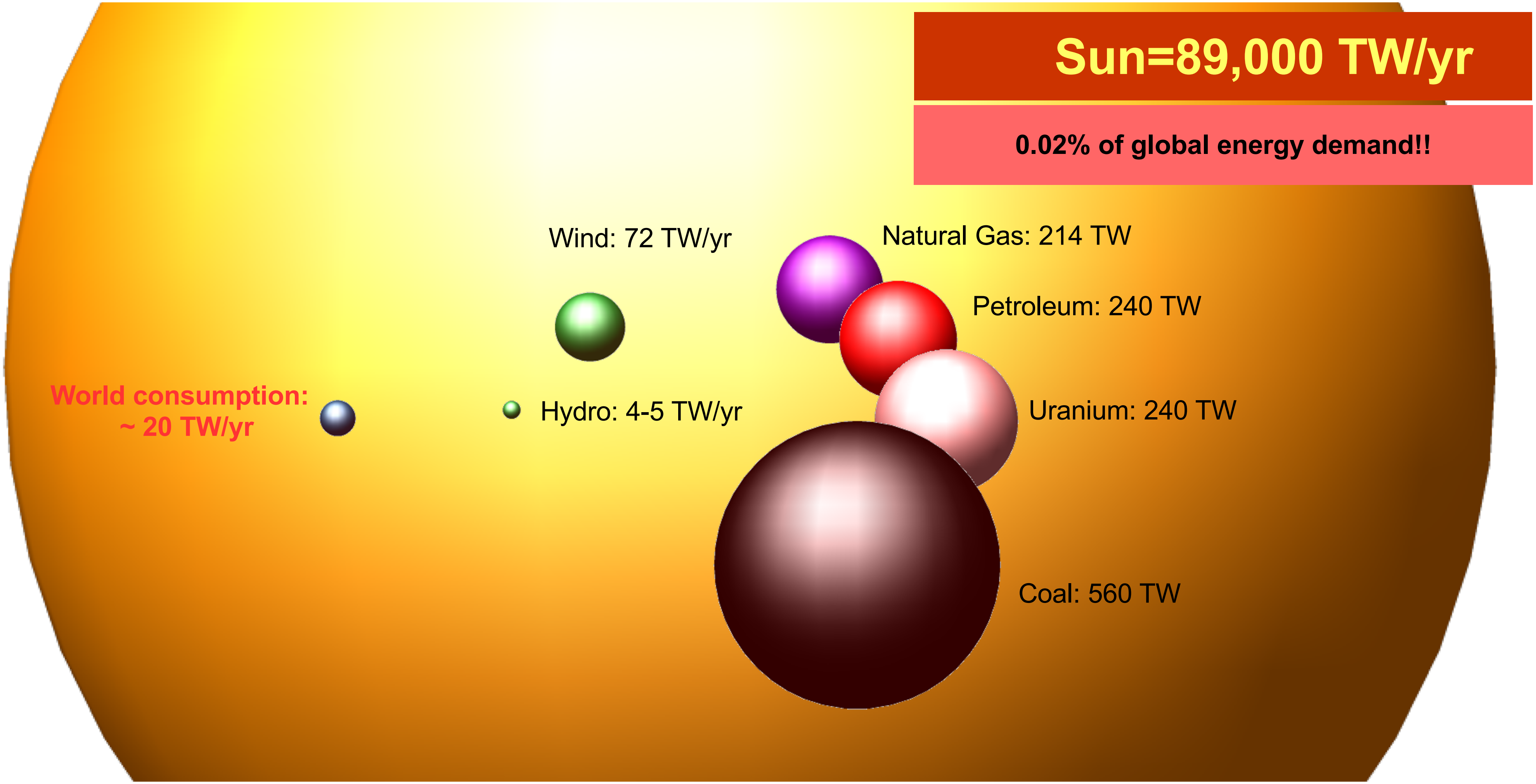
- Around 20 % of that power is consumed by the US.

How much resource is available?

- We have a number of resources to satisfy these needs.



Why Solar Energy?



Why Renewables?

Issues with Burning Fossil Fuels:

- Release of CO_2 and pollutants such as sulfur, arsenic, lead, and mercury.
- Acidification of lakes and streams from sulfur dioxide.
- Issues with obtaining fuels including spills and ash releases

Fossil Fuels

Major fossil fuels are:

- Coal
- Petroleum
- Natural Gas

All fossil fuels are considered non-renewable resources, since they are being consumed at a much faster rate than they are replenished.

https://commons.wikimedia.org/wiki/File:Gas-natural.jpg

https://www.pxfuel.com/en/search?q=brown+coal

Types of Fossil Fuels

Coal:

- Combustable rock made from carbon and hydrocarbon.
- Dervied from ancient plant life that later condensed (via heat and pressure) to peat, then (millions of years later) to coal.

Petroleum:

- Formed from compacted organic sediments. Heat turns this into a waxy material called kerogen and a black hydrocabon bitumen.
- If kerogen is buried deep underground, heat and pressure squeeze any water leaving only hydrocarbon chains. At low temperatures we have oil.

Natural Gas:

- At high temperatures Kerogen turns to natural gas. Contains hydrocarbons such as methane (CH_4) and sulfur.
- Burning methane releases carbon dioxide, water and energy

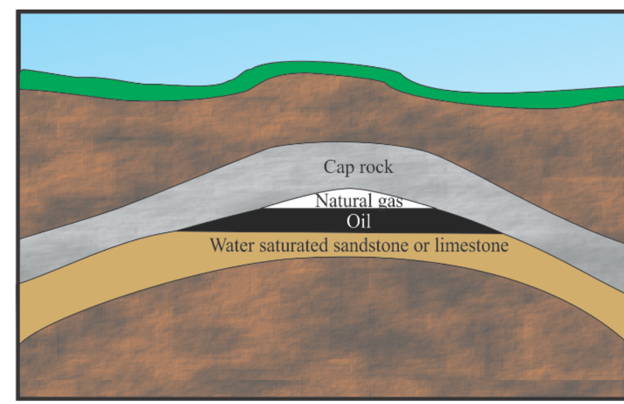


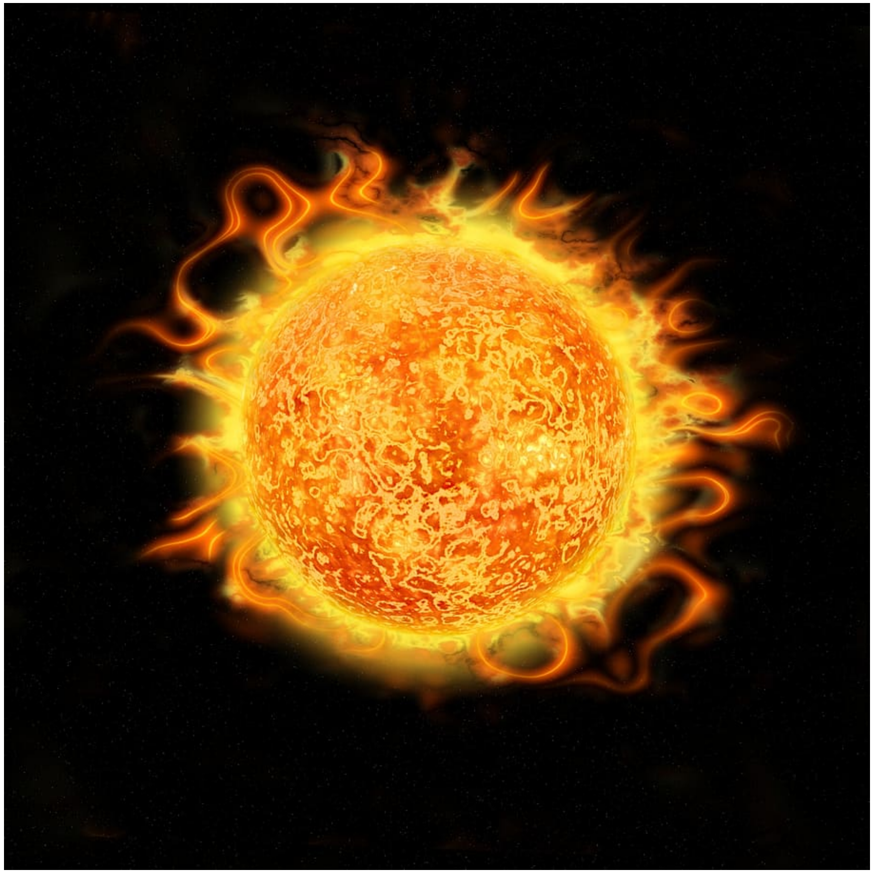
Image From *Renewable Energy Systems*, D. Buchla *et al.* Copyright © 2015 by Pearson Education, Inc.

Why Solar Energy?

The Sun provides a huge resource of energy:

"More solar energy hits the earth in one hour than all the energy the world consumes in a year" [Tsao, 2006].

"Just 0.3% of solar energy from the Sahara Desert is enough to power the whole of Europe" [Jha, 2008].



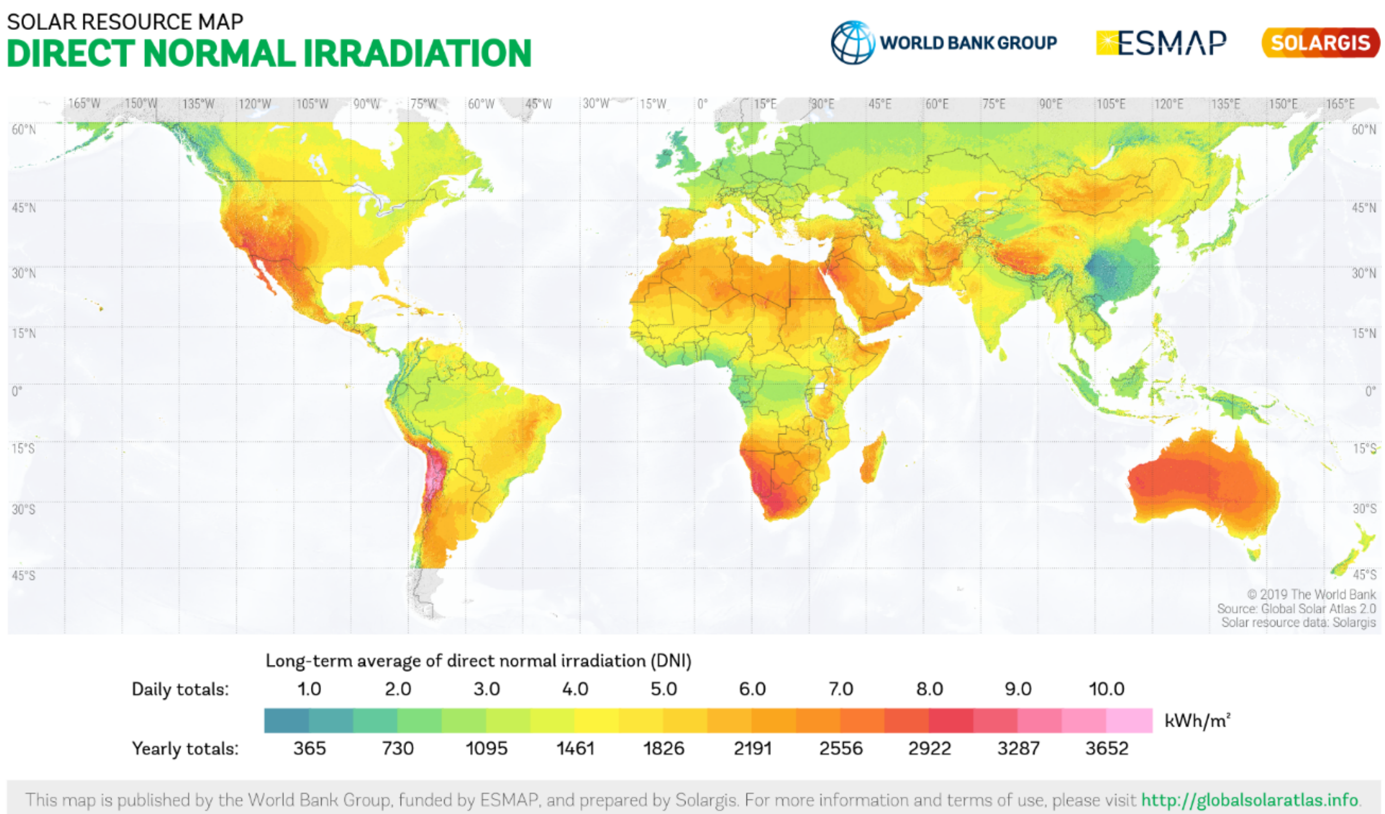
https://www.pxfuel.com/en/free-photo-qviru

[Tsao, 2006] Tsao, J., Lewis, N. and Crabtree, G., 2006. Solar FAQs. US department of Energy, 13.
[Jha, 2008] Jha, A., 2008. Solar power from Saharan sun could provide Europe's electricity, says EU. London: The Guardian.

The Solar Resource Map

- Sunbelt countries receive DNI exceeding 2200 kwh/year.

- Only a small number of power stations around the world, located on each continent, would be sufficient to meet our energy needs.



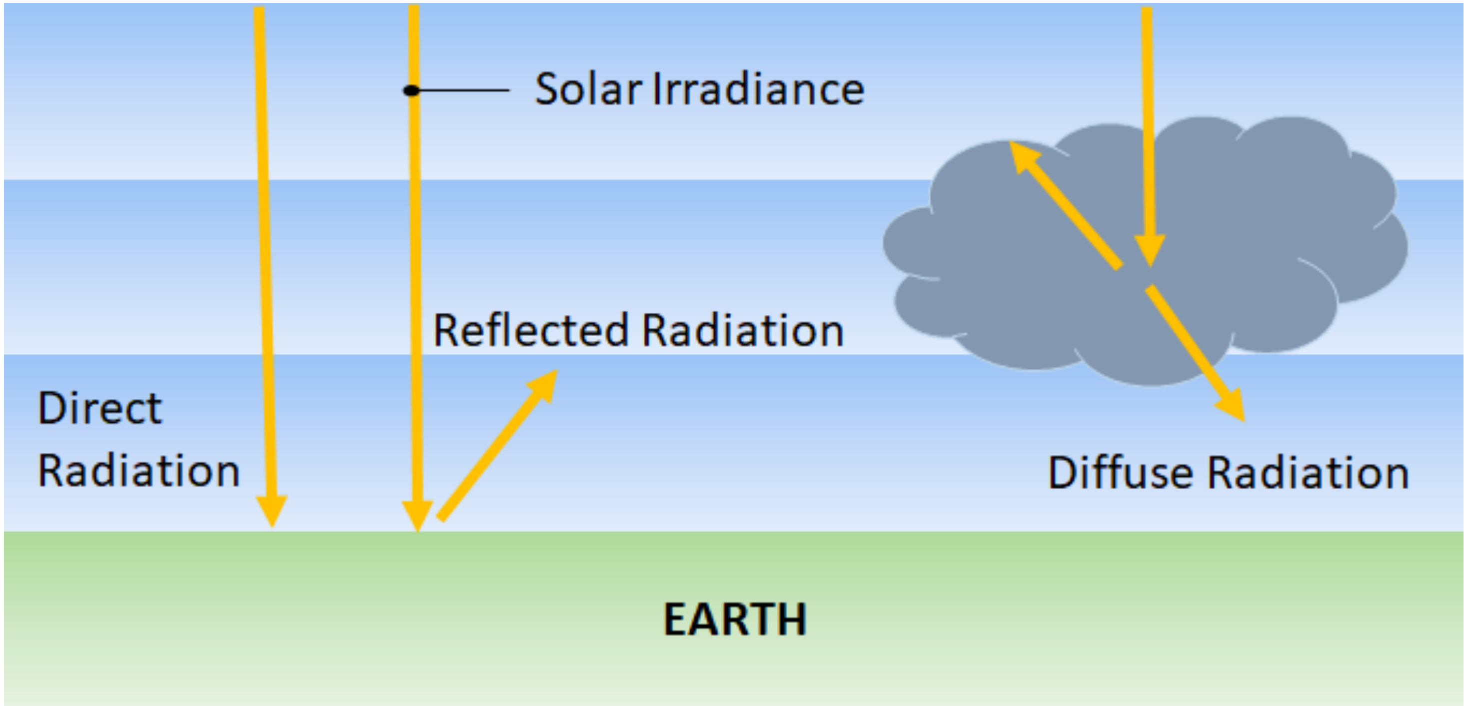
https://upload.wikimedia.org/wikipedia/commons/c/c7/Global_Map_of_Direct_Normal_Radiation_01.png

Types of Solar Radiation

Global: Total amount of radiation received on a horizontal surface.

Direct: Radiation that comes in a straight line from the sun. This is particularly important for concentrating solar systems.

Diffuse: Solar radiation that arrives at the surface from indirect paths. This is useful for solar thermal systems.



Important Concepts

The solar spectrum includes a visible region and energy above and below the visible region.

Solar technology aims to convert as much of the Sun's spectrum as possible.

Current technologies are best at converting the Sun's spectrum in the "visible" wavelength region into electricity.

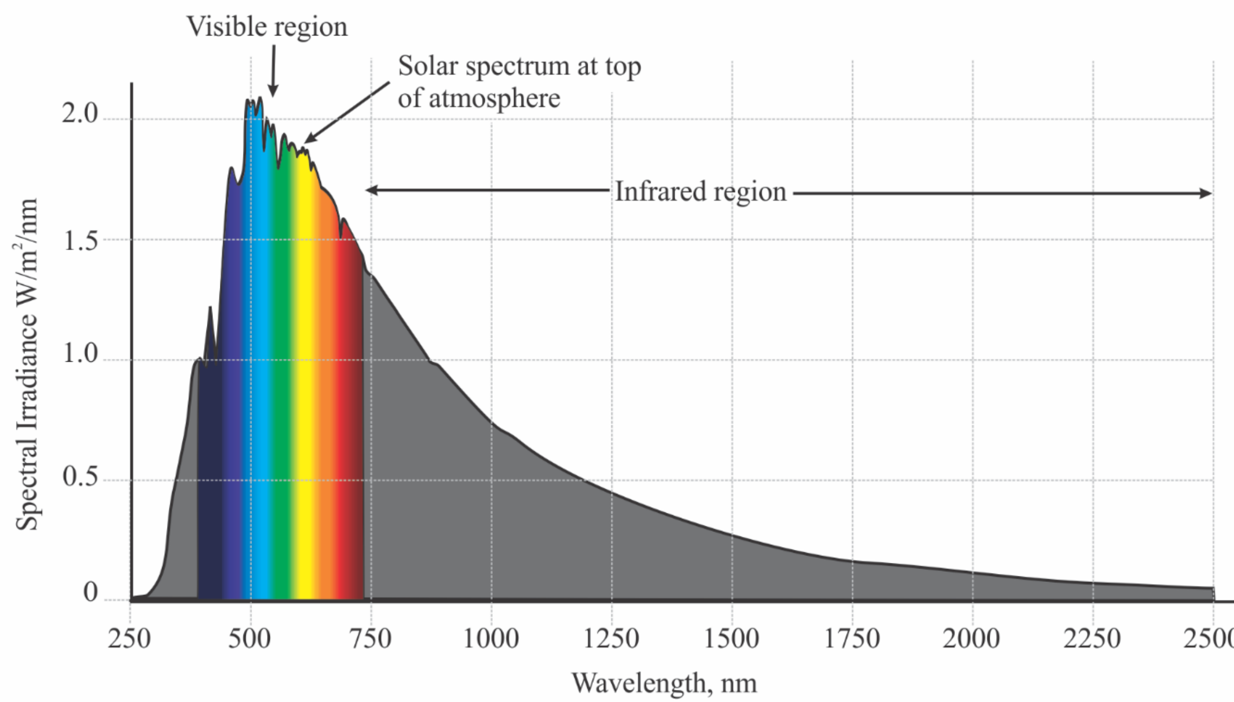
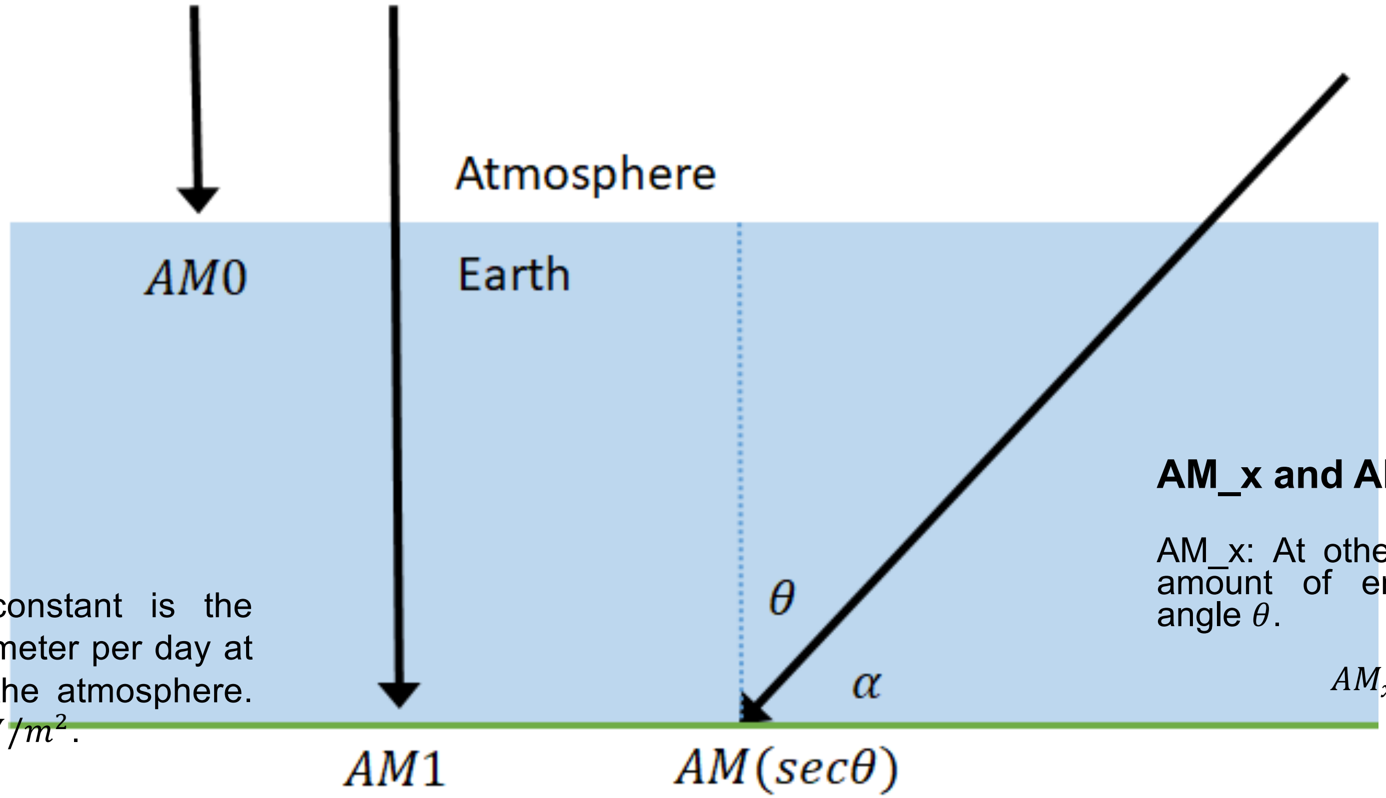


Figure from *Renewable Energy Systems*, D Buchla (© Pearson, 2020)

Important Definitions



AM0 & AM1

AM0: The solar constant is the energy per square meter per day at the outer edge of the atmosphere. This is often $1368\ W/m^2$.

AM1: The amount of energy reaching the earth's surface is less than AM0, due to absorption and some reflection.

AM_x and AM1.5

AM_x: At other zenith angles the amount of energy depends on angle θ.

$$AM_x = \frac{1}{\cos\theta}$$

AM1.5: This is the standard zenith angle used for testing or rating solar cells ($\theta \approx 48^0$). Solar irradiance at AM1.5 is often considered $1000\ W/m^2$.

Solar Cells History

1839 - Alexandre Edmond Becquerel (right) observed the photovoltaic effect via an electrode in a conductive solution exposed to light.

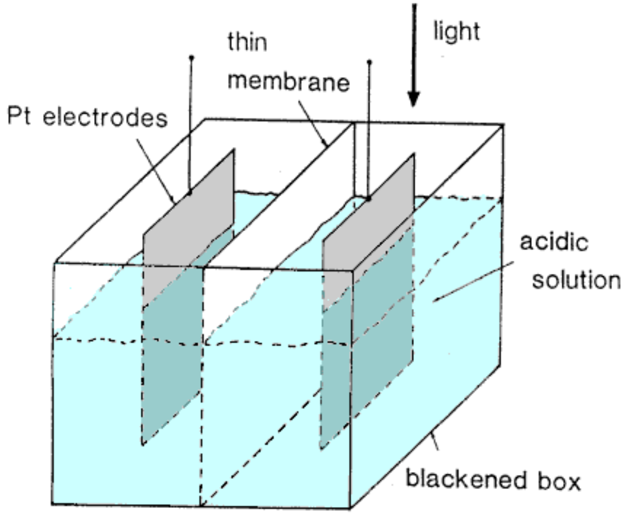
1941 - Russell Shoemaker Ohl was an American engineer who is generally recognized for patenting the modern solar cell (US Patent 2402662, "Light sensitive device") based on pn-junction device.

1954 - Bell Labs announces the invention of the first practical silicon solar cell. At the National Academy of Science Meeting, solar cells with an efficiency of 6% are shown. The New York Times forecasts that solar cells will eventually lead to a source of "limitless energy of the sun."

Early Solar Cells

Beginnings:

Edmond Becquerel appears to have been the first to demonstrate the photovoltaic effect.



Modern Solar Cells:

Emergence of semiconductors and the pn-junction diode resulted in the first modern silicon cell in 1954 by Chapin, Fuller and Pearson. These cells had an efficiency of 6%, about 15 times higher than earlier devices, opening the first real prospects for power generation using photovoltaics.

www.nrel.gov

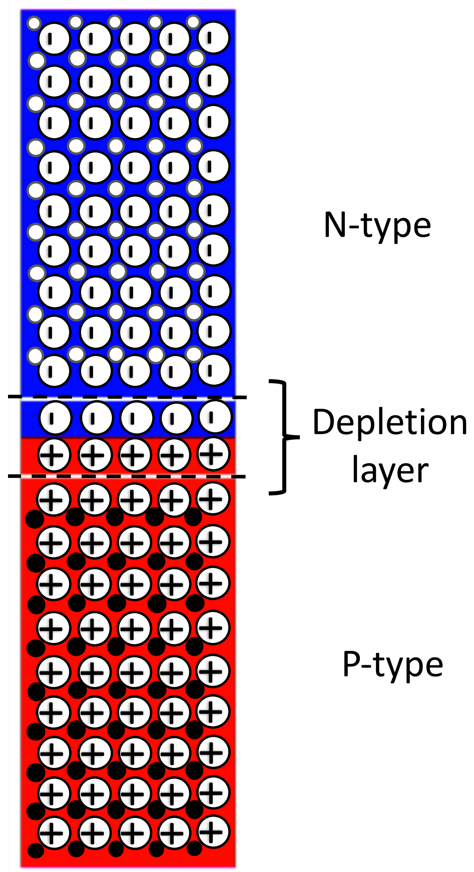
The PN Junction

Solar Cells are made from semiconducting materials such as Silicon.

Two types of semiconducting materials are required: an n-type and a p-type semiconductor.

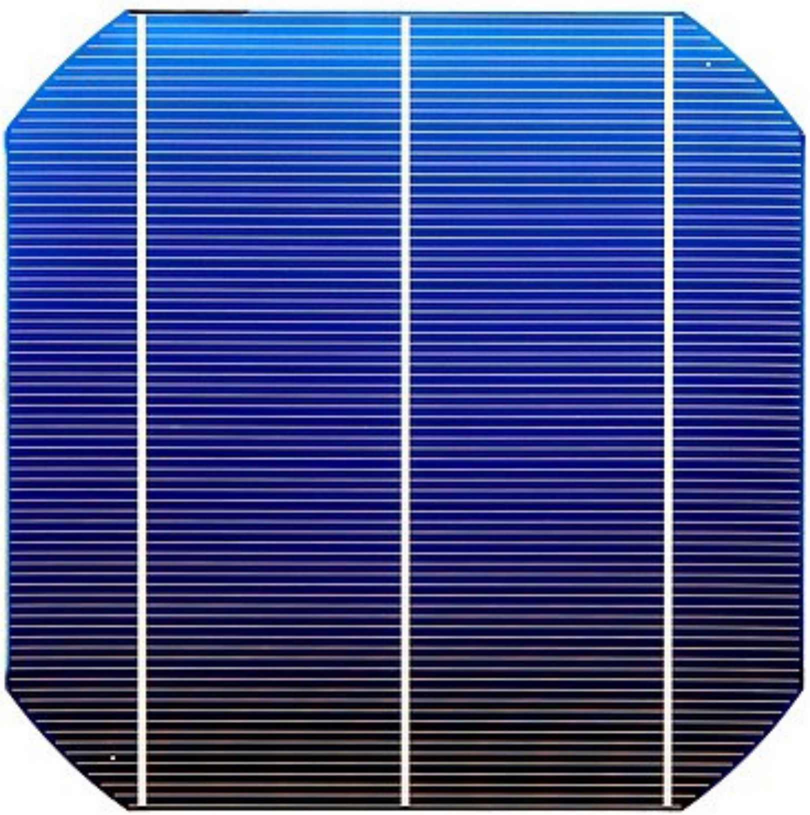
The process of “doping” is used to create *n* and *p* materials, which have excess electrons or holes.

The boundary between the two types of semiconductors is known as the PN junction.



Present Day Solar Cells

https://commons.wikimedia.org/wiki/File:Silicon_solar_cell_(PERC)_front_and_back.jpg



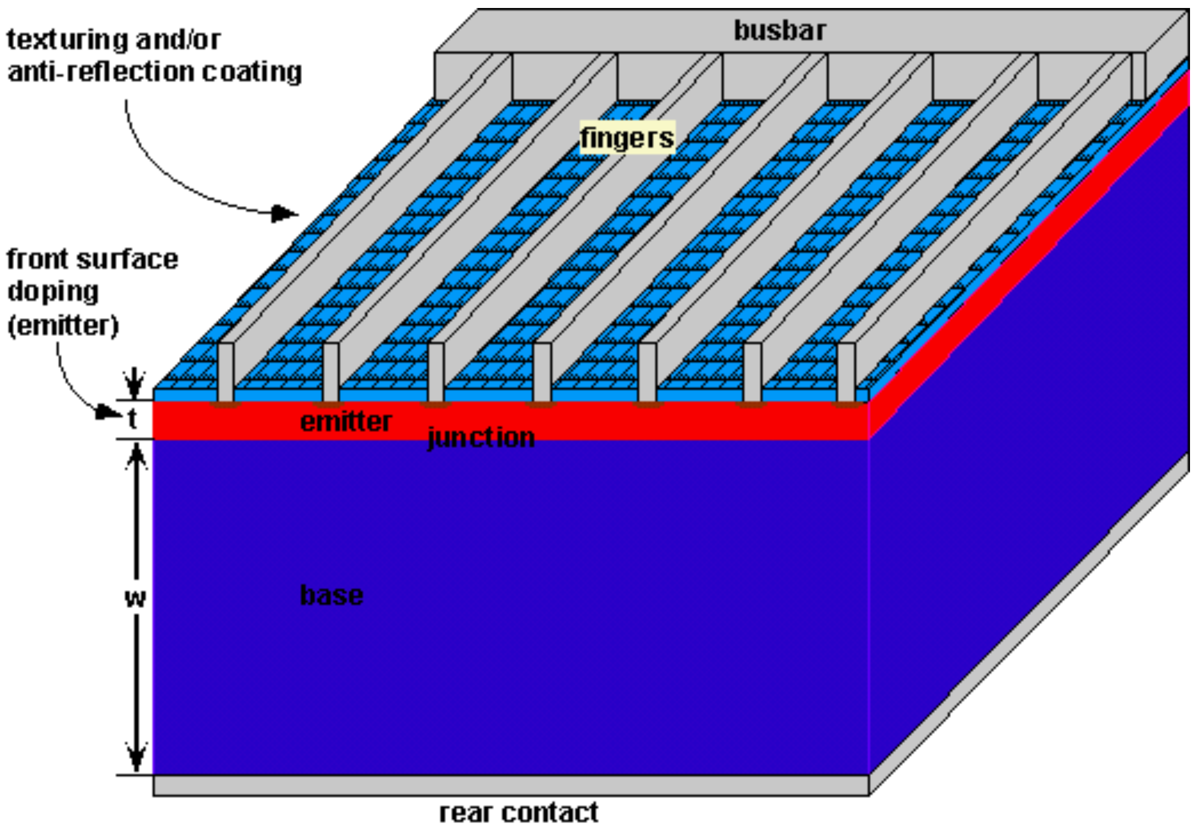
Most solar cells use crystalline silicon.

The main material used for transistors.

silicon-based semiconductor fabrication is now a mature technology that enables cost-effective devices to be manufactured.

Typical Si-based solar cell efficiencies range from about **18-24%**.

Present Day Solar Cells



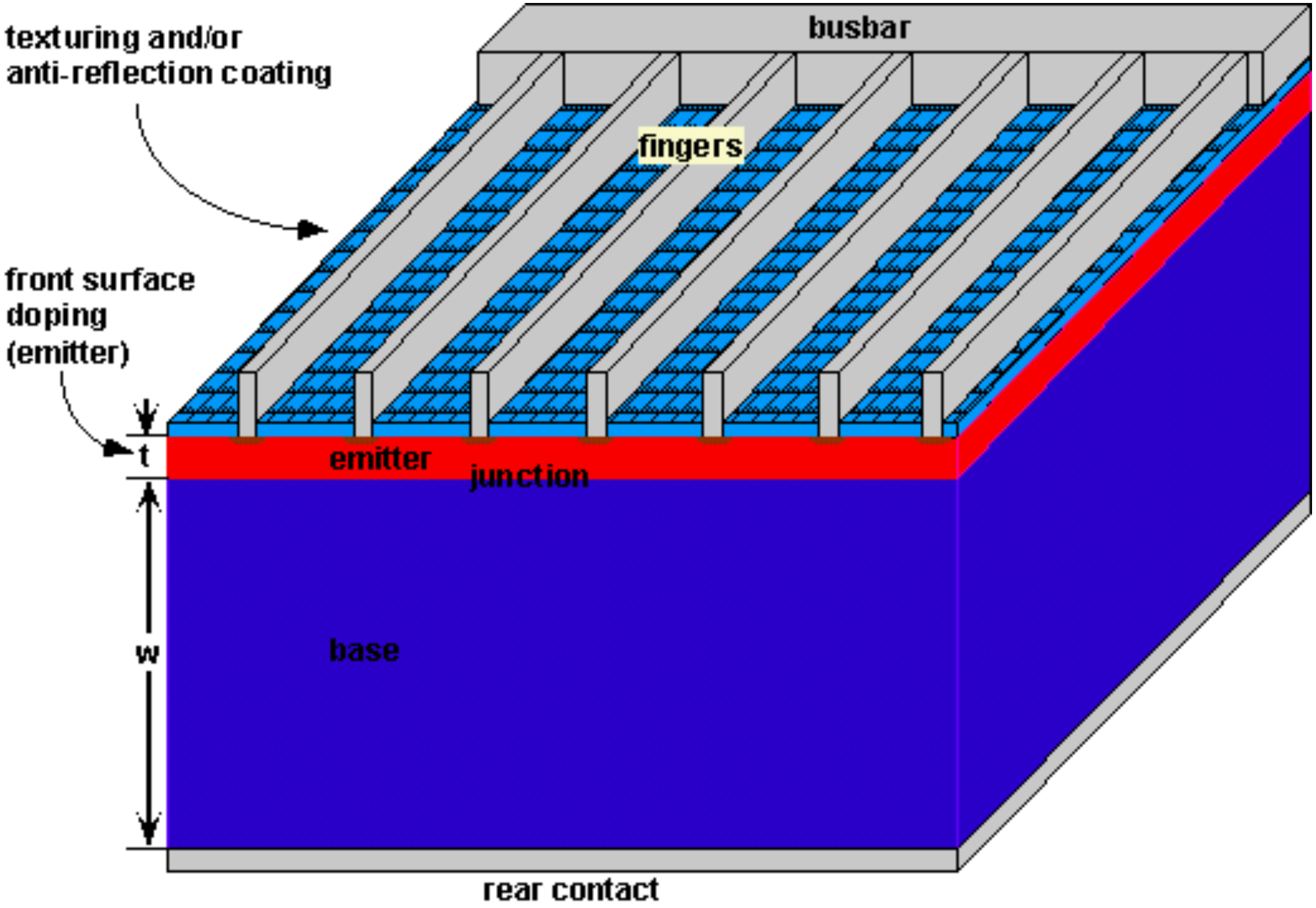
An optimum silicon solar cell with light trapping is about 100 μm thick. Thickness between 200 and 500 μm typically used for practical issues.

Front surface is textured to increase the amount of light coupled into the cell.

The Emitter is made from N-type silicon, which has higher surface quality than p-type silicon, so it is placed at the front of the cell where most of the light is absorbed.

By making the front layer very thin, a large fraction of the carriers generated by the incoming light are created within a diffusion length of the p-n junction.

Present Day Solar Cells



From *Principles of Electronic Materials and Devices, Fourth Edition*, S.O. Kasap (© McGraw-Hill Education, 2018)

Metallic contacts at the top and bottom of the cell are used to conduct current away from the cell.

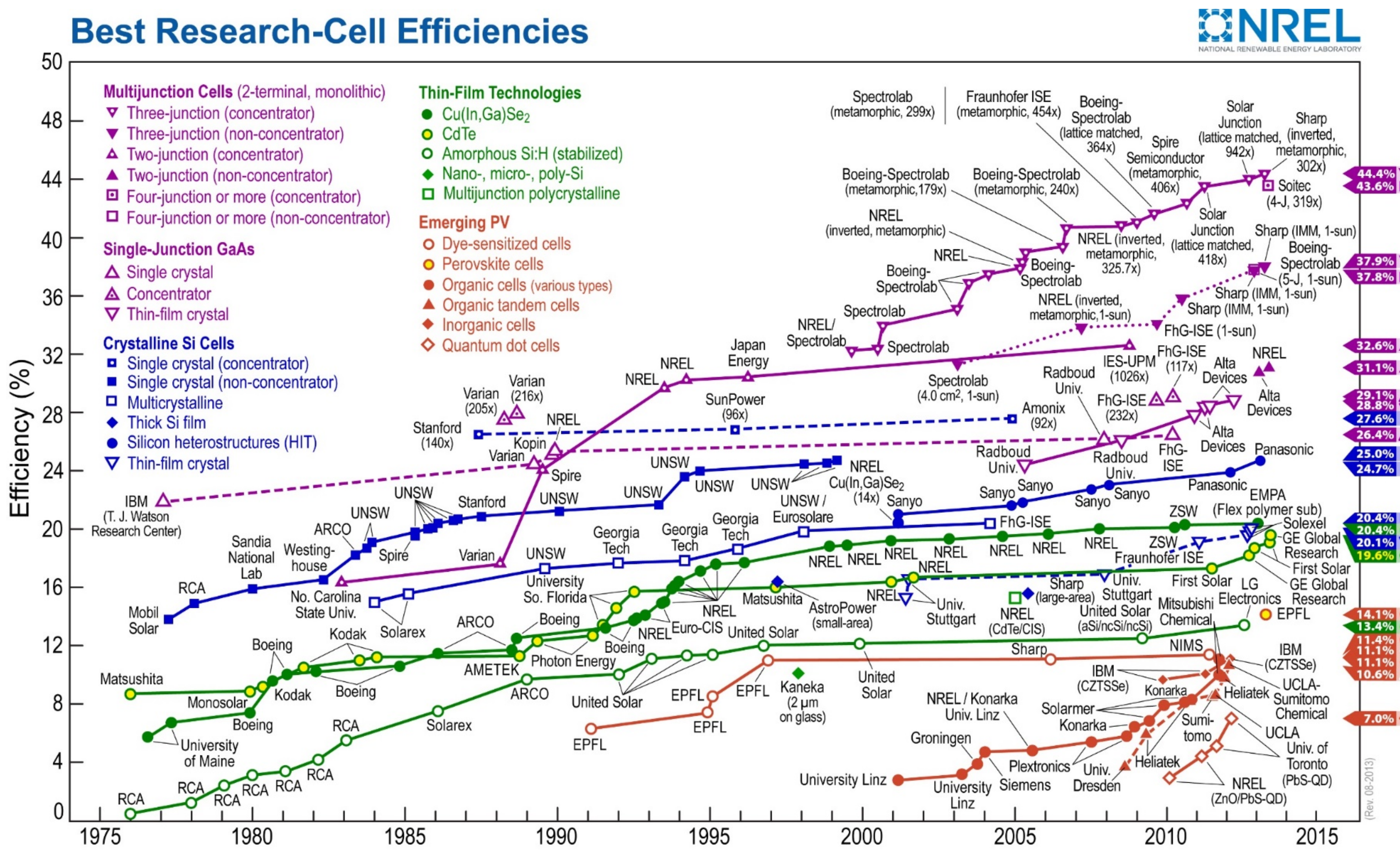
A grid pattern at the top is used to allow light to penetrate through the cell and reduce shading.

Rear contacts are much less important than the front contact since they are further from the junction.

Solar Cell Efficiencies

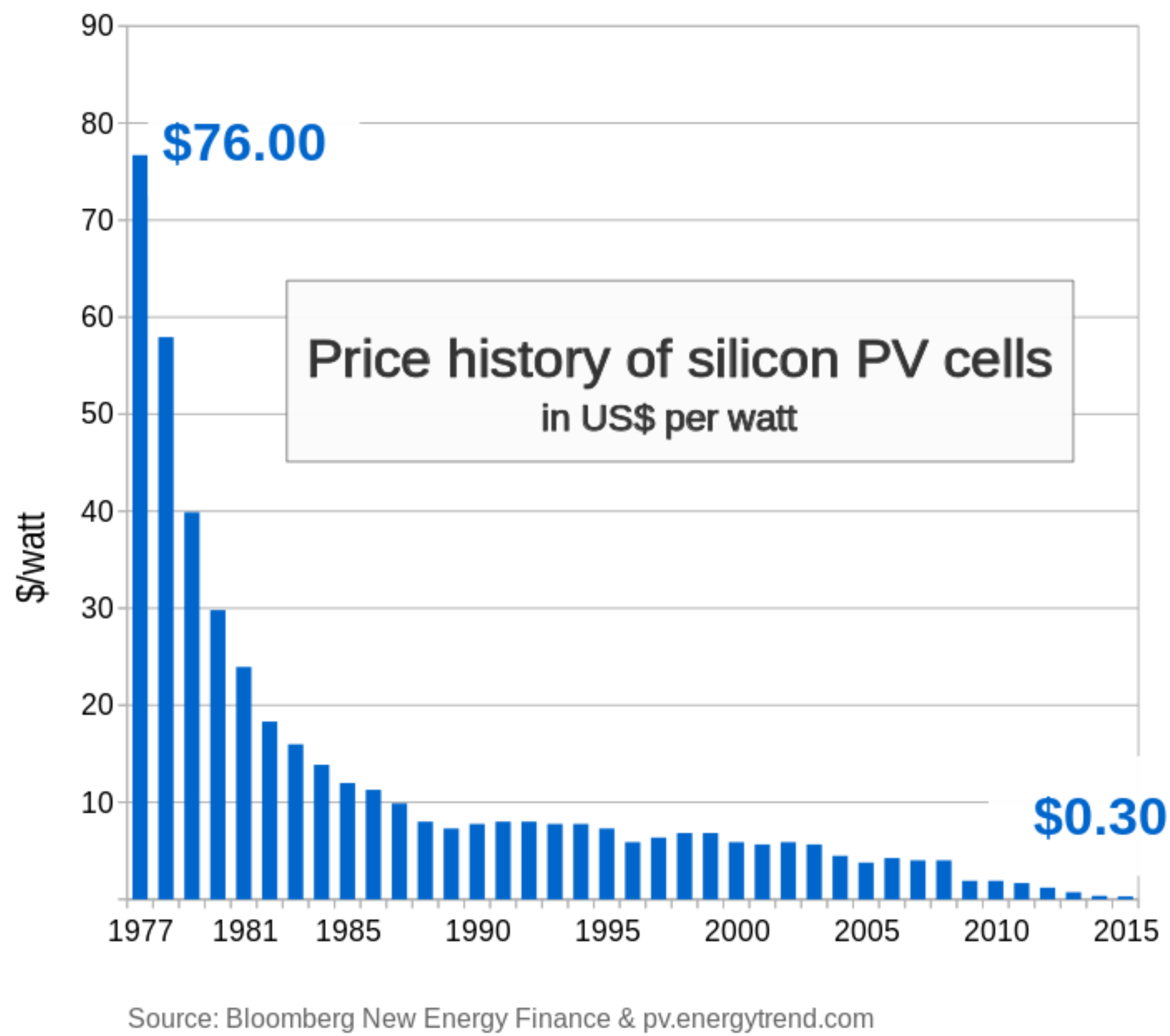
- Advances in solar cell materials and device processing results in continuous improvement is the ability of solar cells to convert the Sun's energy into electrcity, as shown from the image on the right.

- Highest efficiencies are obtained with multi-junction solar cells, which we will discuss in section

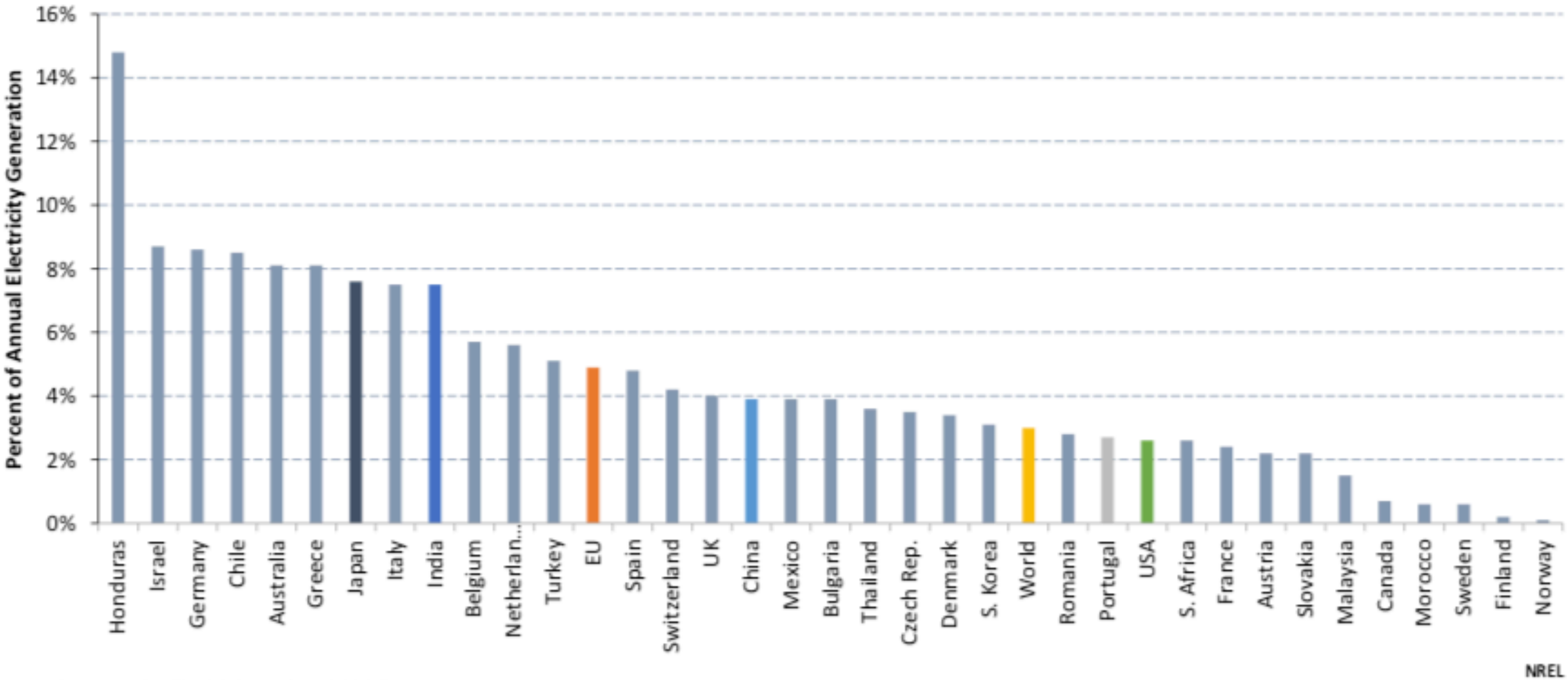


Solar Cell Prices

- Due to an increase in the supply, solar cells have witnessed a continuous decrease in prices.
- The image on the right shows the decline in the cost of a solar module (combination of solar cells).
- We are now approaching $0.19/W for crystalline silicon modules (i.e. a packaged combination of PV cells).



PV Penetration



Source: IEA "PVPS Snapshot 2020."

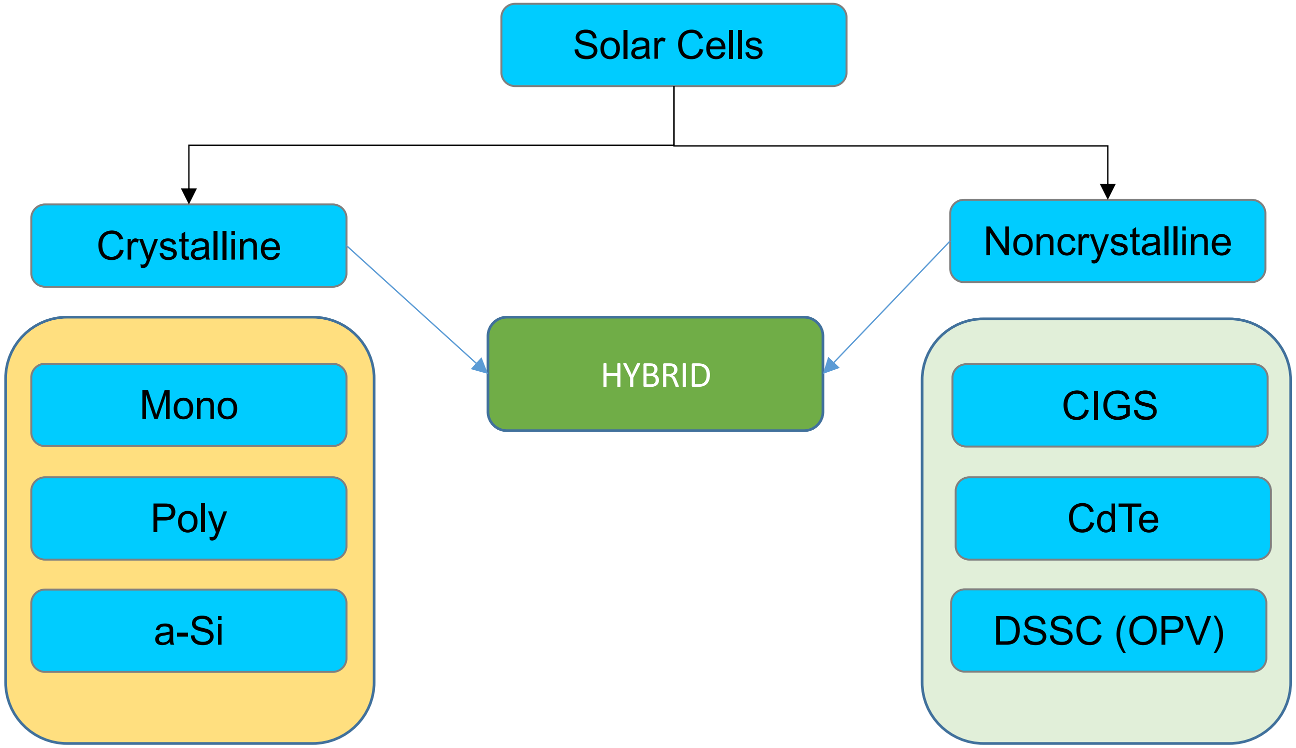
- Almost 4% of the UK's electricity is generated from PV.
- Germany leads the EU countries in PV penetration.
- Few Sunbelt countries are adopting PV technologies

Types of Solar Cells

Solar Cells can be divided into two broad types: crystalline and non-crystalline. Examples of crystalline solar cells include: monocrystalline, polycrystalline, amorphous silicon.

Examples of non-crystalline cells include Dye Sensitized Solar Cells (DSSCs), Cadmium Telluride (CdTe) and (CIGS).

Presently, there is research in combining both types of materials to form "hybrid" solar cells.

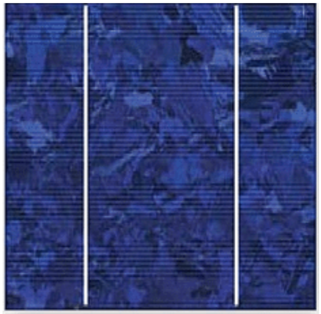


Crystalline Solar Cells

Mono-crystalline

- Colour = Dark blue/black
- Efficiency = 16-19%
- Thickness = 0.2-0.3mm
- Size = 4-8” (10x10cm – 15x15cm)

Poly-crystalline

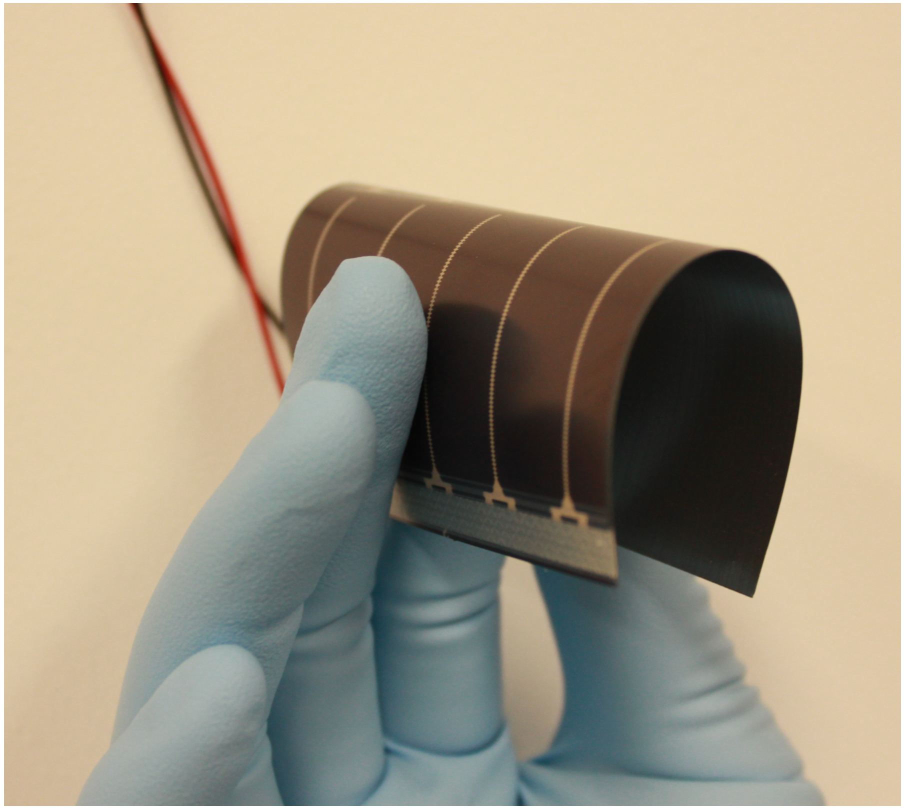


- Colour = blue
- Efficiency = 14-17%
- Thickness = 0.2-0.3mm
- Size = 4-8” (10x10cm – 21x21cm)

Thin Film Solar Cells

Examples include:

- Cadmium Telluride (CdTe).
- Amorphous silicon (a-Si).
- Copper Indium Gallium Selenide (CIGS).



- These materials are highly absorptive. Therefore, a small layer is sufficient (1-5 microns).
- Thin Film cells are not restricted to any size or shape.
- They can be deposited on any substrate.
- They can be connected monolithically during coating process.

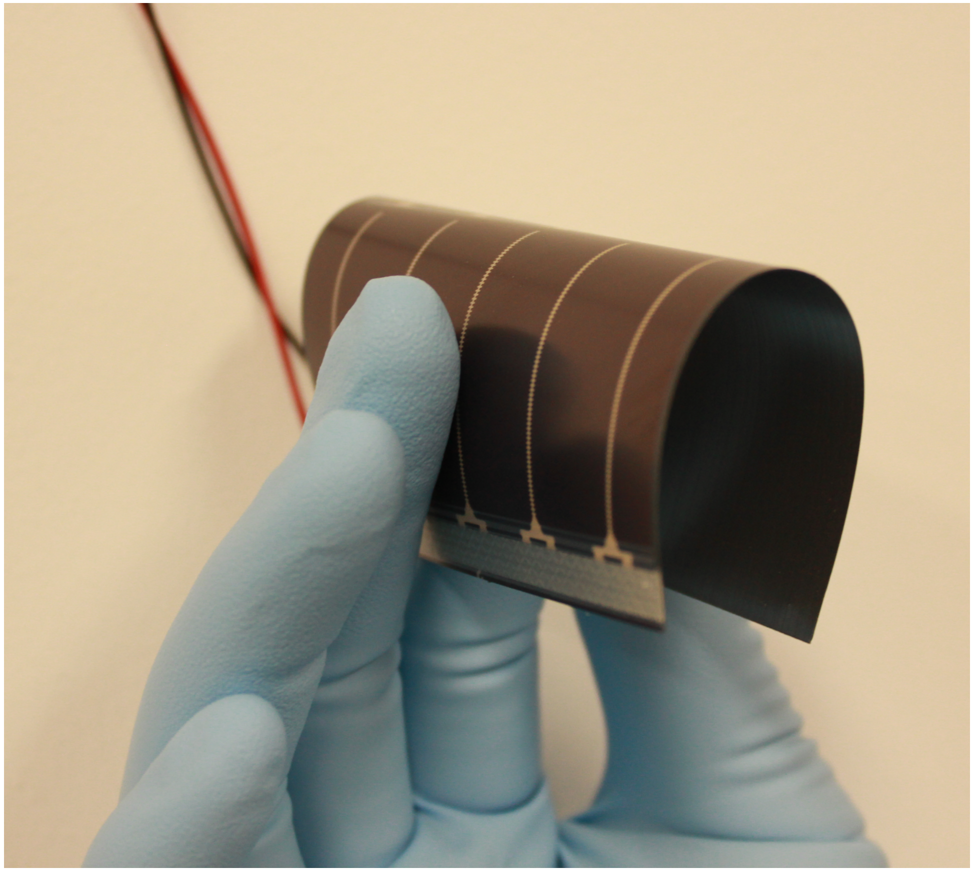
Thin Film Solar Cells

Advantages of Thin Film Cells are:

- Low cost.
- Low degradation of efficiency with temperature (in comparison with silicon).
- Less susceptible to shading effects.

Disadvantages are:

- Low efficiency (9-13%)
  - New light trapping techniques aiming to combat this.



Solar Cells

Solar cell inventors at Bell Labs (left to right): Gerald Pearson, Daryl Chapin, and Calvin Fuller. They are checking a Si solar cell sample for the amount of voltage produced (1954).
© Nokia Corporation.

This is Solar Impulse, a plane powered by solar cells.
Courtesy of Solar Impulse SA, Switzerland

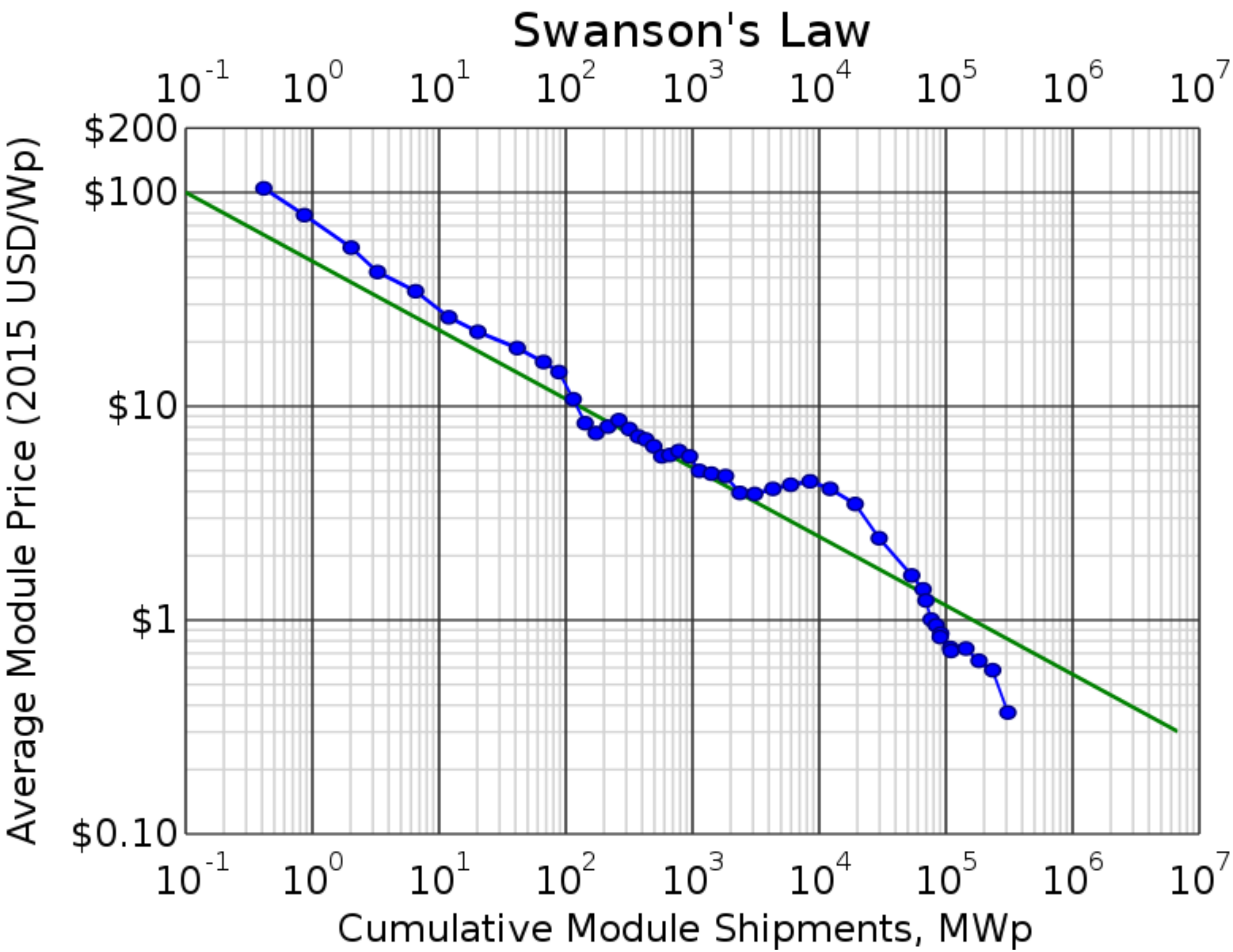
Solar Cells

Most solar cells use crystalline silicon since silicon-based semiconductor fabrication is now a mature technology that enables cost-effective devices to be manufactured.

Typical Si-based solar cell efficiencies range from about **18% for polycrystalline** to **22-24% in high-efficiency single-crystal devices** that have special structures to absorb as many of the incident photons as possible.

Solar cells fabricated by making a pn junction in the same crystal are called **homojunctions**.

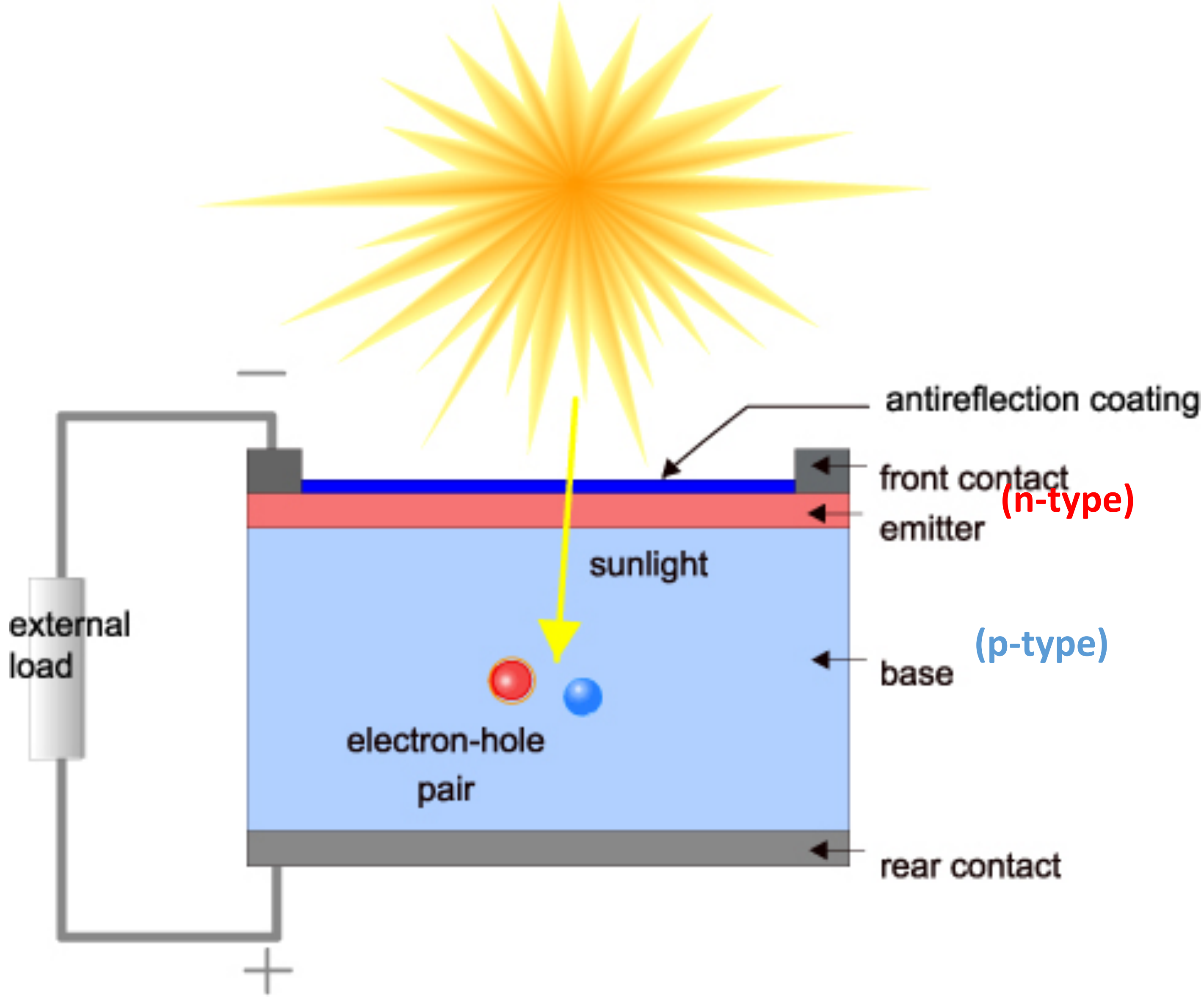
Solar Cells



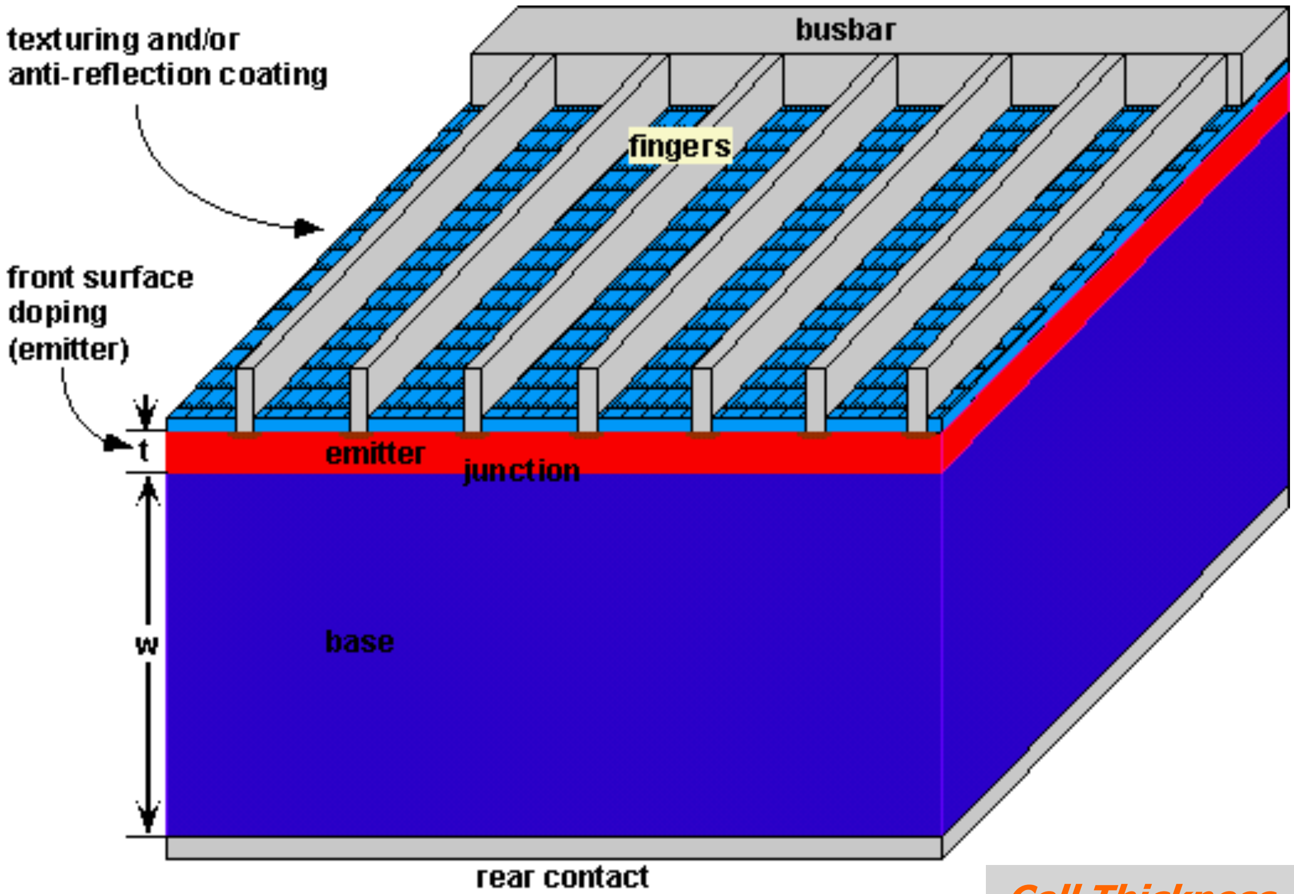
Swanson's Law
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
$200
$100
$10
$1
$0.10
Average Module Price (2015 USD/Wp)
Cumulative Module Shipments, MWp

Solar Cells

https://www.youtube.com/watch?v=qIJx2PRGKqw



Typical Solar Cell Parameters



Substrate Material

Bulk crystalline silicon dominates the current photovoltaic market. As is also the case for transistors, **silicon does not have optimum material parameters**. In particular, silicon's band gap is slightly too low for an optimum solar cell and since silicon is an indirect material, it has a low absorption co-efficient. While the low absorption co-efficient can be overcome by light trapping, silicon is also difficult to grow into thin sheets. However, silicon's abundance, and its domination of the semiconductor manufacturing industry has made it difficult for other materials to compete.

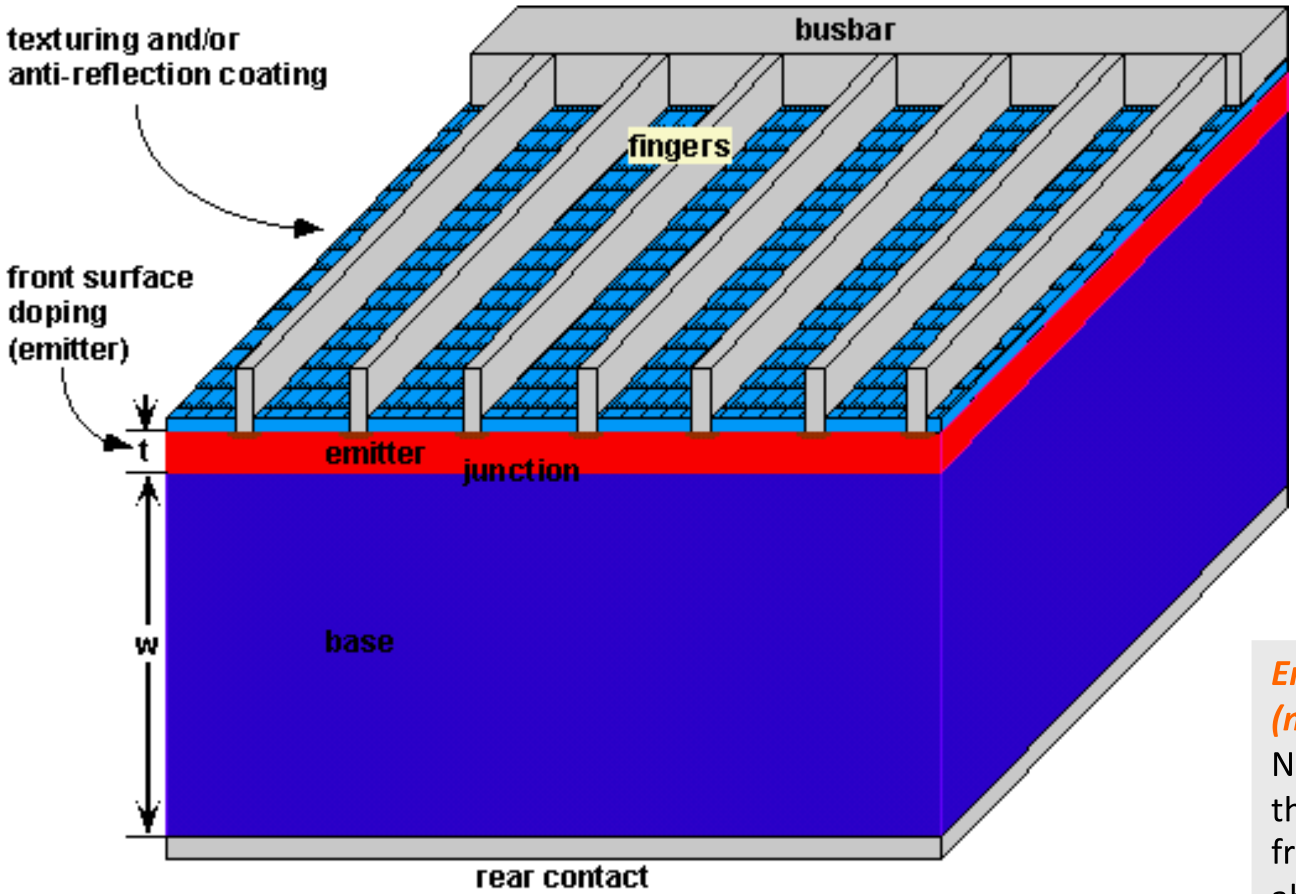
Cell Thickness

An optimum silicon solar cell with light trapping is about 100 µm thick. However, thickness between 200 and 500µm are typically used for practical issues such as making and handling thin wafers.

Doping of Base

A higher base doping leads to a higher V_{oc} and lower resistance, but higher levels of doping result in damage to the crystal.

Typical Solar Cell Parameters

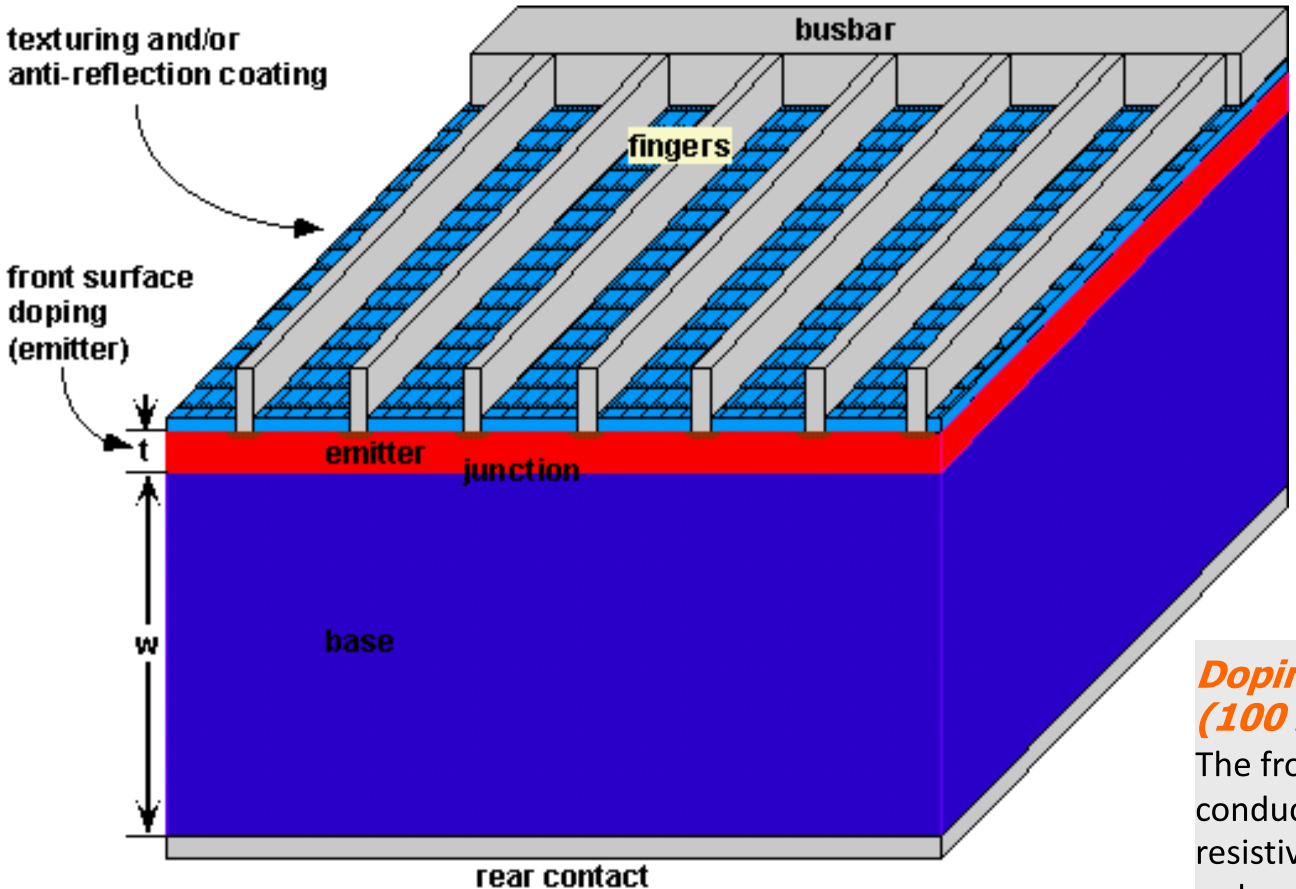


Reflection Control
(front surface typically textured)
The front surface is textured to increase the amount of light coupled into the cell.

Emitter Dopant
(n-type)
N-type silicon has a higher surface quality than *p*-type silicon so it is placed at the front of the cell where most of the light is absorbed. Thus the top of the cell is the negative terminal and the rear of the cell is the positive terminal.

Emitter Thickness
(<1 µm)
A large fraction of light is absorbed close to the front surface. By making the front layer very thin, a large fraction of the carriers generated by the incoming light are created within a diffusion length of the *p-n* junction.

Typical Solar Cell Parameters



Grid Pattern.
(fingers 20 to 200 µm width, placed 1 - 5 mm apart)
The resistivity of silicon is too high to conduct away all the current generated, so a lower resistivity metal grid is placed on the surface to conduct away the current. The metal grid shades the cell from the incoming light so there is a compromise between light collection and resistance of the metal grid.

Doping Level of Emitter
(100 Ω/□)
The front junction is doped to a level sufficient to conduct away the generated electricity without resistive loses. However, excessive levels of doping reduces the material's quality to the extent that carriers recombine before reaching the junction.

Rear Contact.
The rear contact is much less important than the front contact since it is much further away from the junction and does not need to be transparent. The design of the rear contact is becoming increasingly important as overall efficiency increases and the cells become thinner.

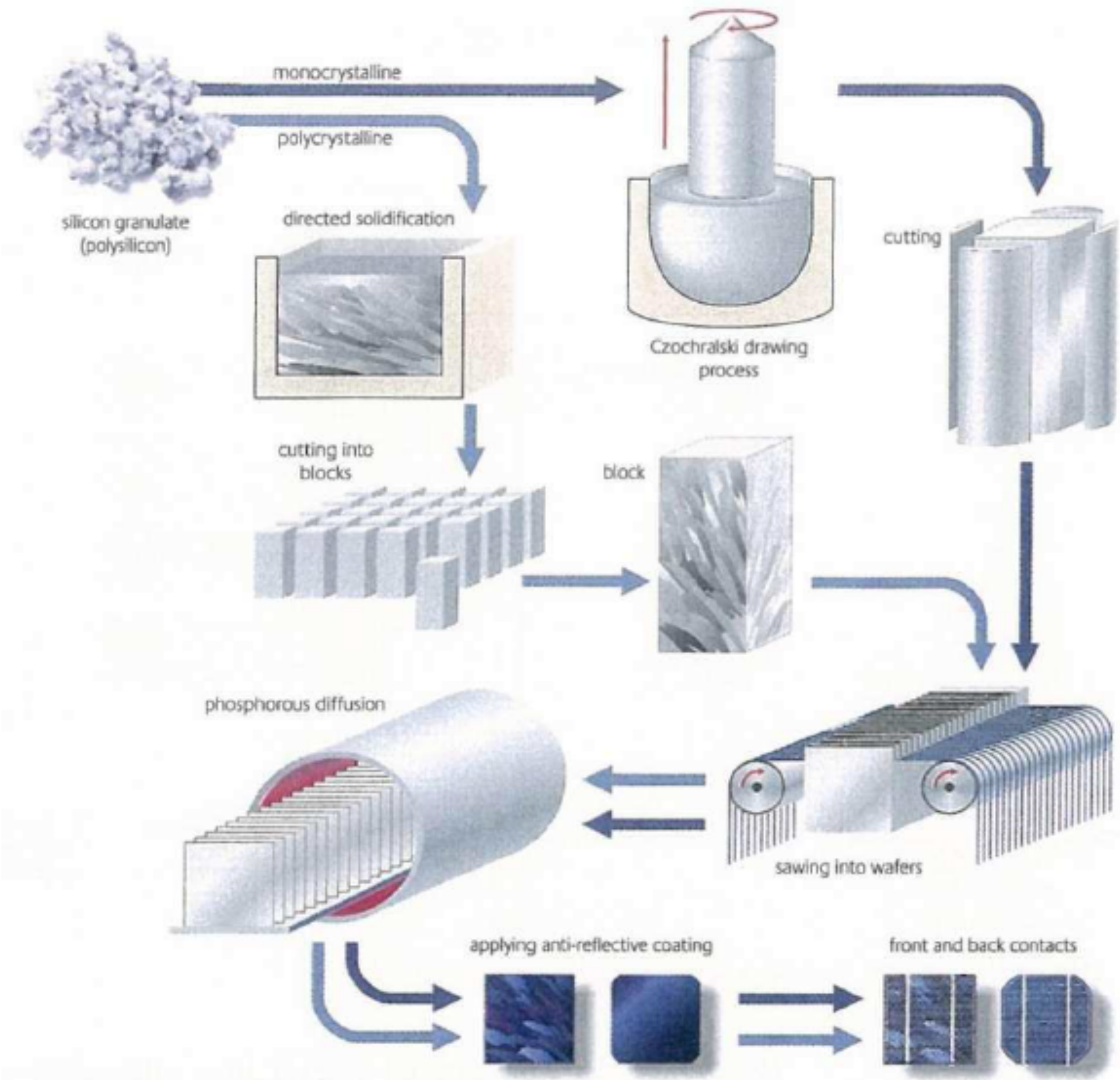
Silicon Solar Cells

Silicon dioxide (SiO_2) is the most abundant mineral in the earth's crust. The manufacture of the hyperpure silicon for photovoltaics occurs in **two** stages:

1) The oxygen is removed to produce metallurgical grade silicon.
2) It is further refined to produce semiconductor grade silicon.

An **intermediate** grade with impurity levels between metallurgical silicon and semiconductor grade silicon is often termed **solar grade silicon**.

Monocrystalline



Monocrystalline

The Czochralski process can be summarised as follows:

1) Polysilicon is melted into a crucible at temp 1450C

2) Seed crystal with defined orientation is dipped into crucible and then slowly drawn upwards and rotated simultaneously. Crystal grows into cylindrical shape.

3) cylindrical monocrystals are cut to semi-round or square bars.

Monocrystalline

4) Bars are cut with saw into 0.3mm wafers

5) After wafers are cleaned and chemically wet etched, they are either phosphorous (N-type) or boron (p-type) doped via a diffusion process.

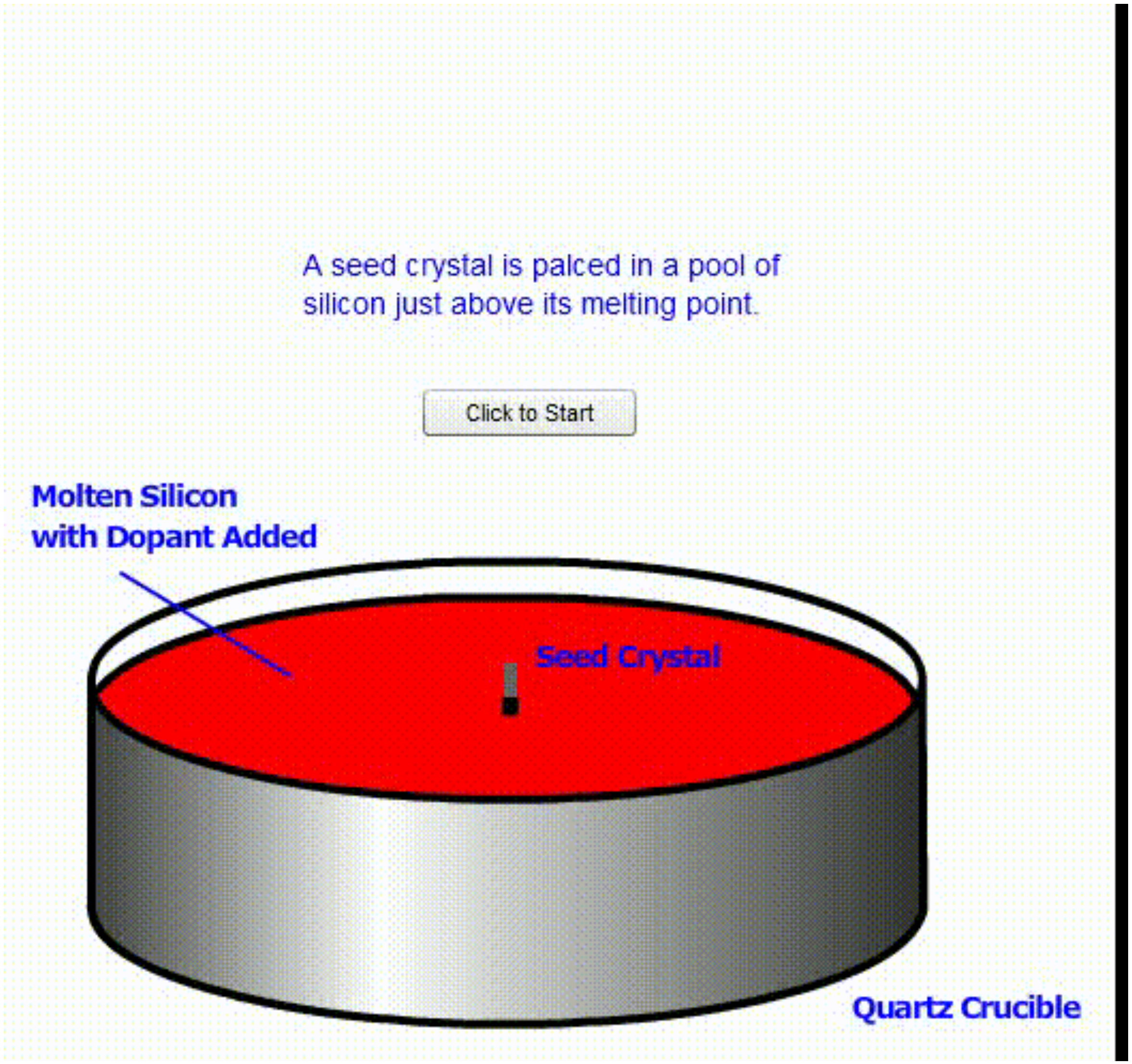
→ P-N junction is formed.

6) Application of AR coating

7) Via screen printing technique, current collector lines on the front of the cell and back contacts are fabricated.

8) Solar cells are etched at the edges to create clean division between p and n layer (prevent short circuit at the edges).

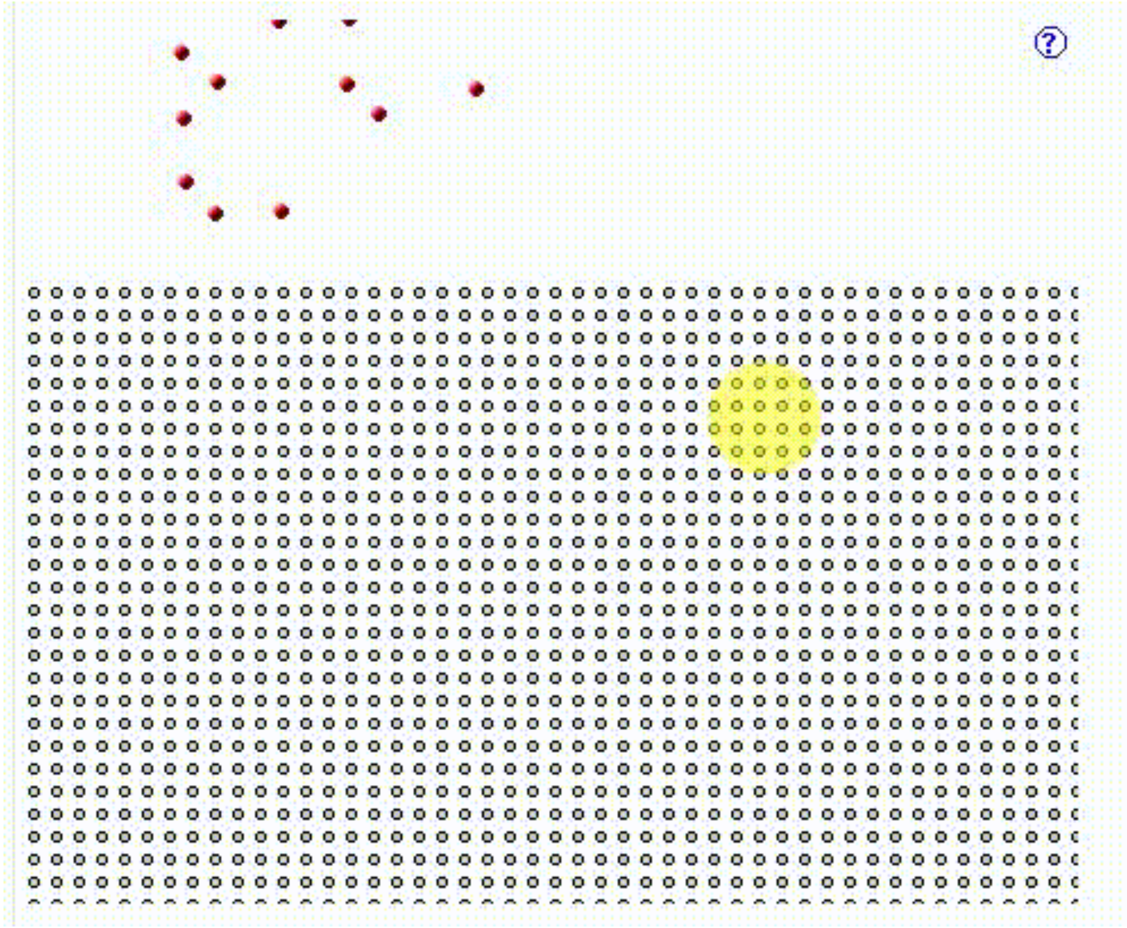
CZ Process



A seed crystal is palced in a pool of silicon just above its melting point.
Click to Start
Molten Silicon with Dopant Added
Seed Crystal
Quartz Crucible

Diffusion Process

Solid state diffusion is a straight forward process and the typical method for introducing dopant atoms into semiconductors. In silicon solar cell processing starting substrates are typically uniformly doped with boron giving a p-type base. The n-type emitter layer is formed through phosphorous doping



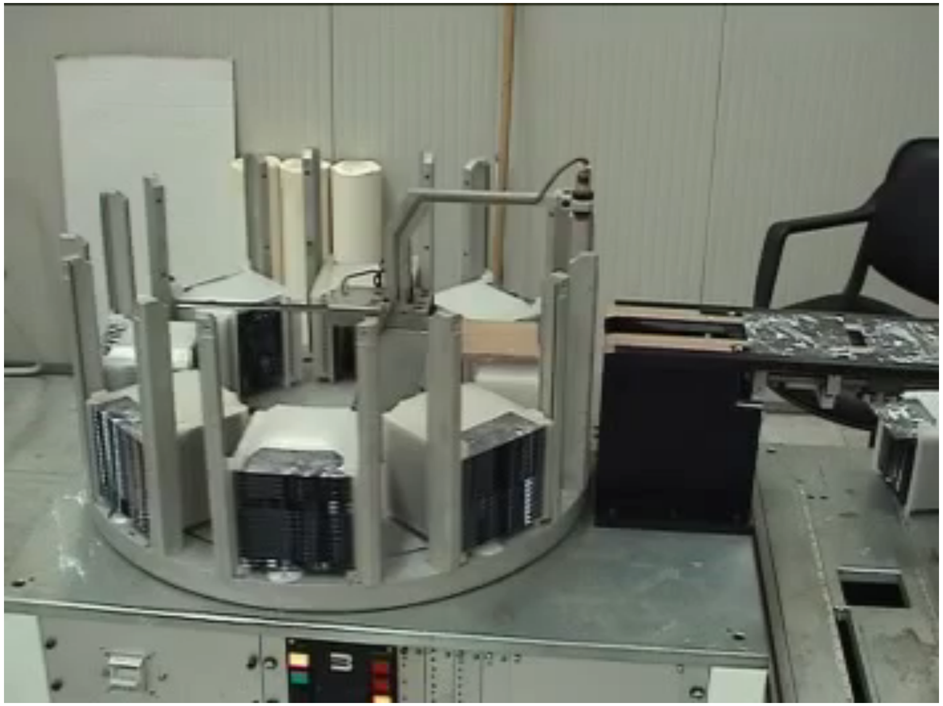
Calculation of Diffusion Profiles

In its simplest form the diffusion process follows Fick's law:

$$j = -D\frac{\partial N}{\partial x}$$

where j is the flux density (atoms cm^{-2}), D is the diffusion coefficient ($cm^2\,s^{-1}$), N is the concentration volume (atoms cm^{-3}) and x is the distance (cm).

Diffusion Process



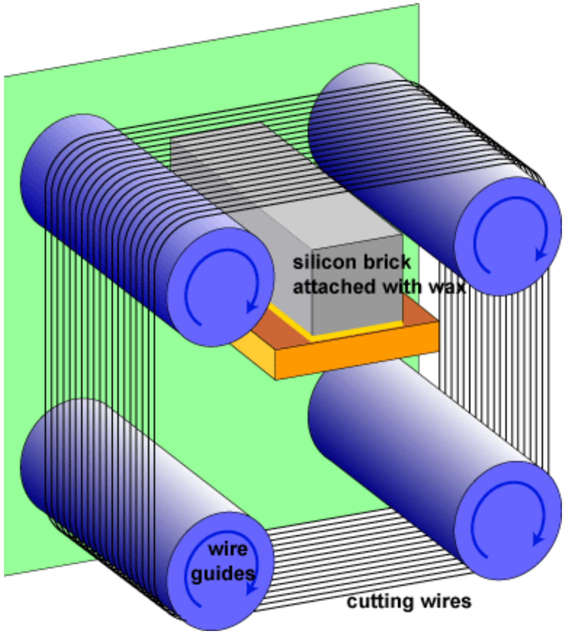
Screen Printing Process

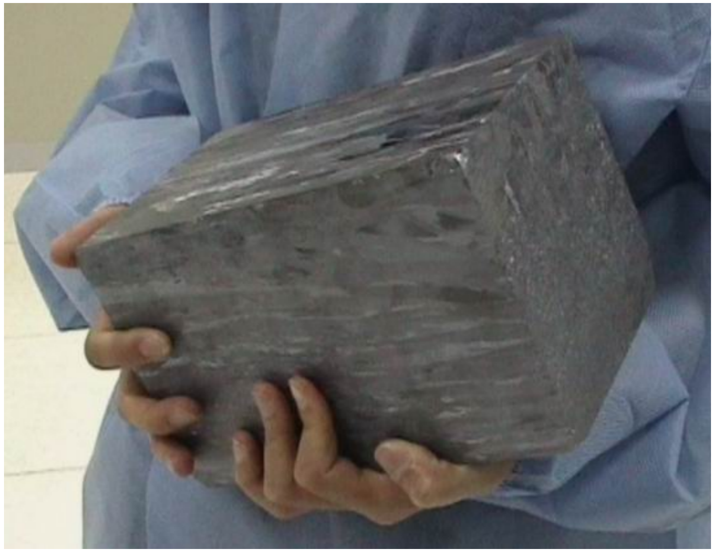
Screen printer in operation (front side)

Here the wafers are loaded into a drier to evaporate off the organic binders in the paste. Driers operate at a low temperature of around 200 °C.

Wafer Cutting

Large multicrystalline silicon block being sliced up into smaller bricks. The smaller bricks are then cut up into wafers with a wire saw.



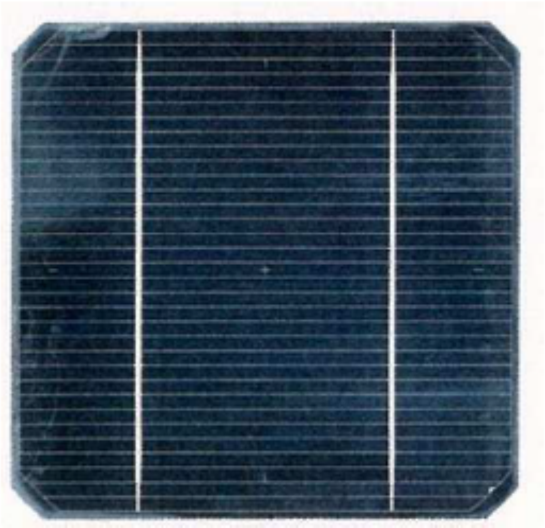


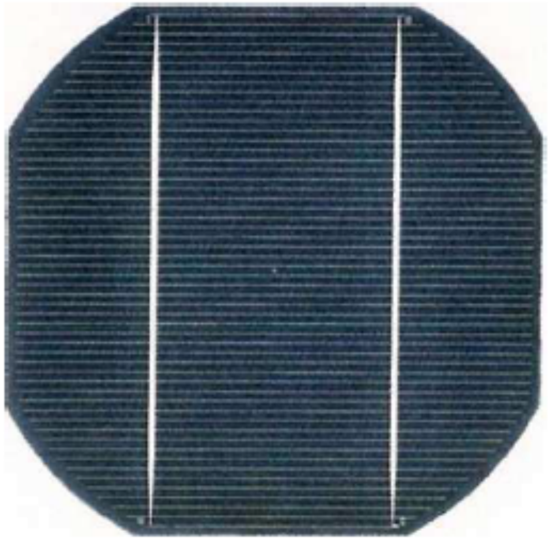
Brick of multicrystalline silicon cut from slab and before being cut up into wafers.

Monocrystalline

List of renowned manufacturers:

- 1) BP Solar
- 2) Kyocera
- 3) Schott
- 4) Mitsubishi
- 5) Photowatt
- 6) Sharp
- 7) Canadian Solar
- 8) SolarWorld





Polycrystalline Solar Cells

1) Silicon material melted and cast into cuboid form.

2) Controlled heating and cooling to allow block to cool in one direction, to allow for homogeneous silicon crystal growth,

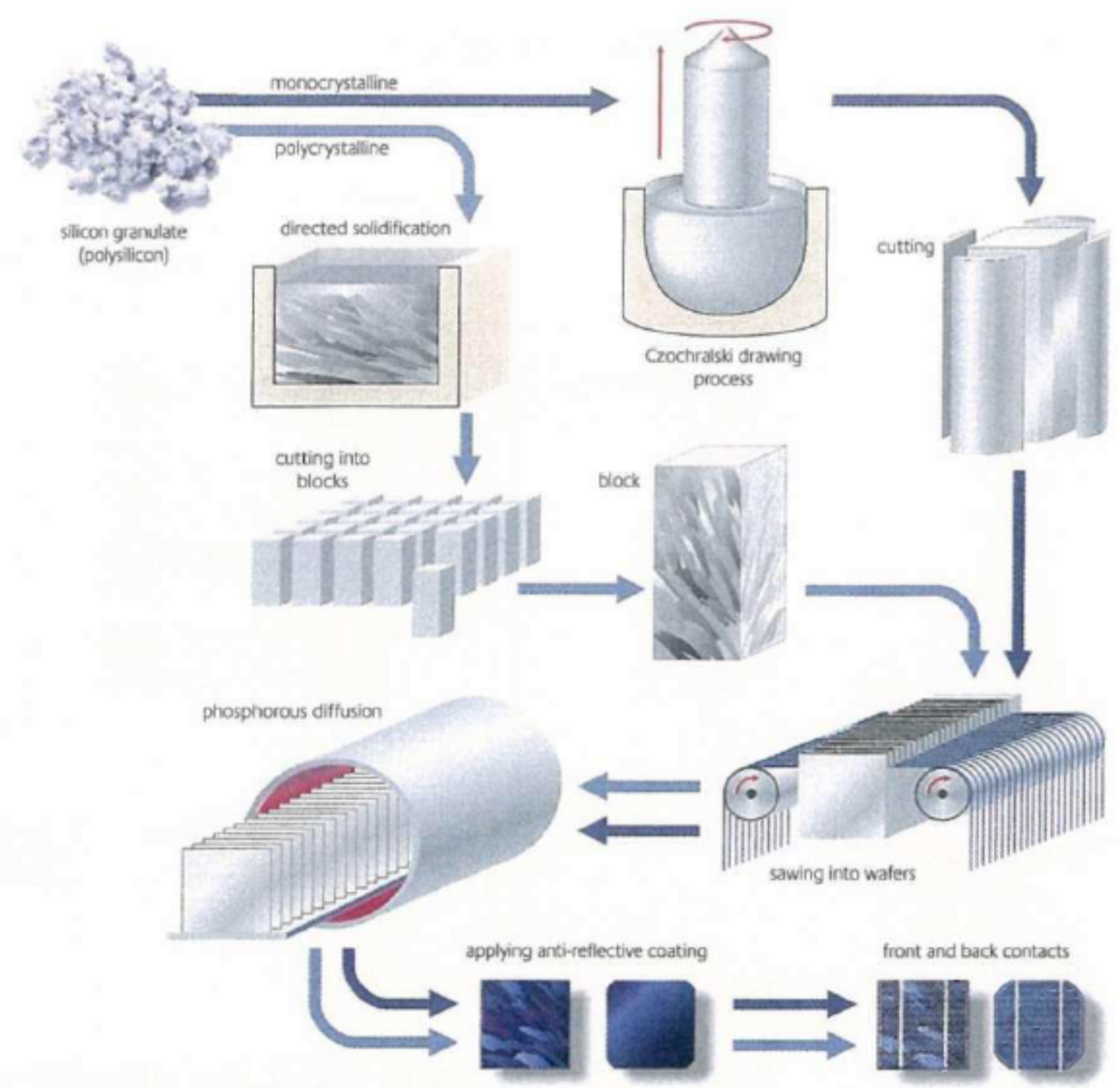
3) The large block is cut into smaller ingots.

4) Ingots sawn into bars then into wafers.

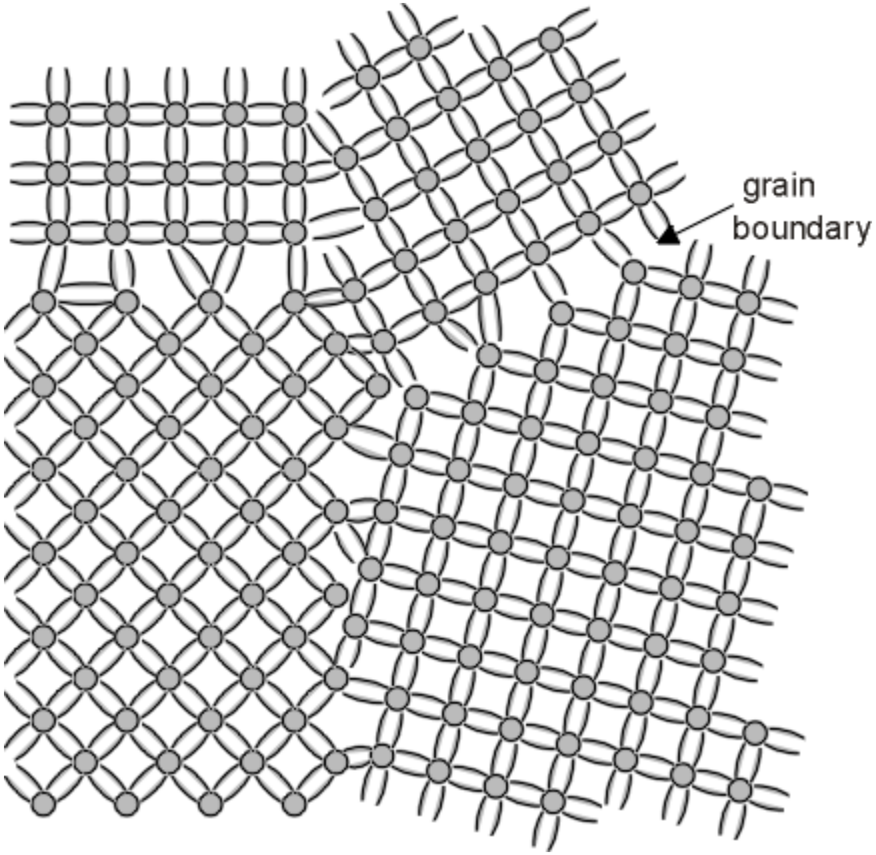
5) After cleaning, wafers are doped and antireflection coating applied.

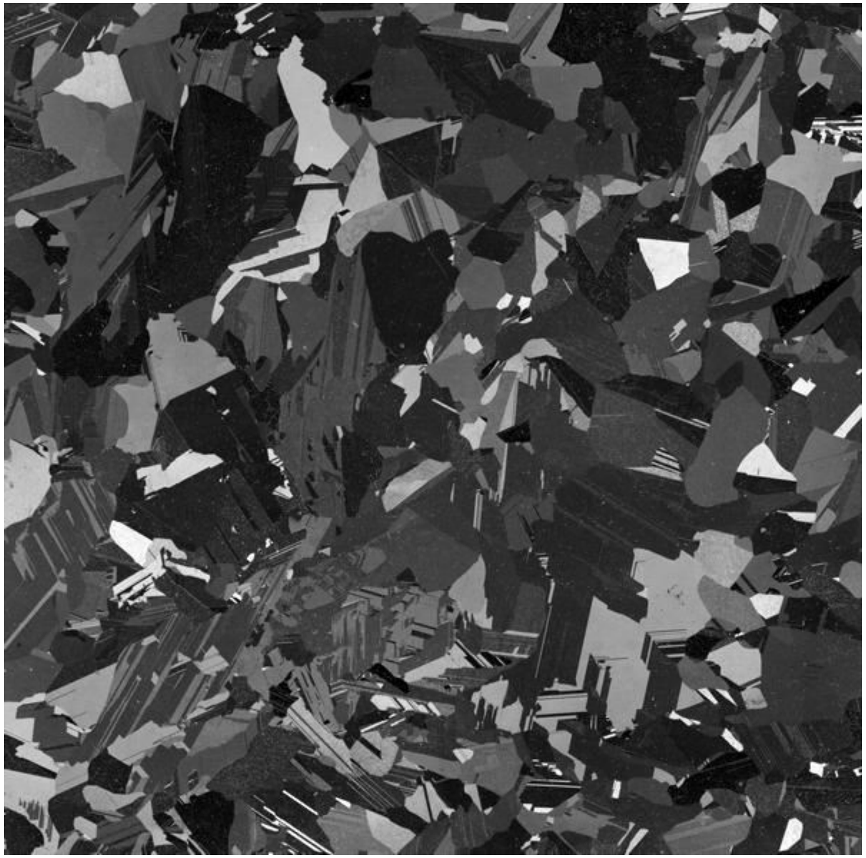
6) Contacts printed and edges etched.

Polycrystalline



Polycrystalline



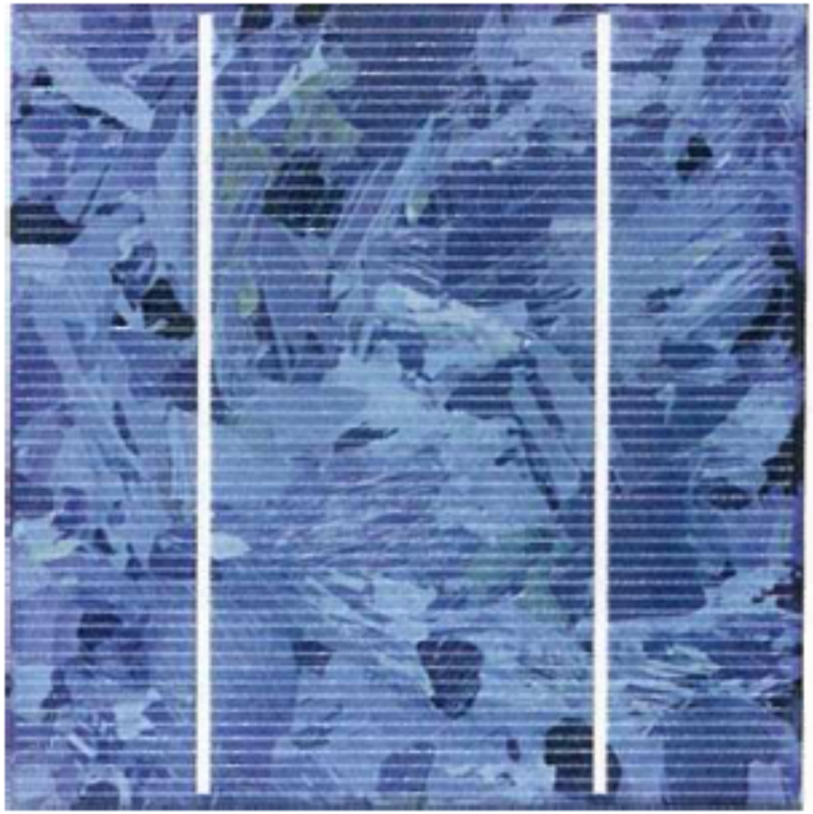


Grain boundaries introduce high localised regions of recombination due to the introduction of extra defect energy levels into the band gap, thus reducing the overall minority carrier lifetime from the material. In addition, grain boundaries reduce solar cell performance by blocking carrier flows and providing shunting paths for current flow across the *p-n* junction

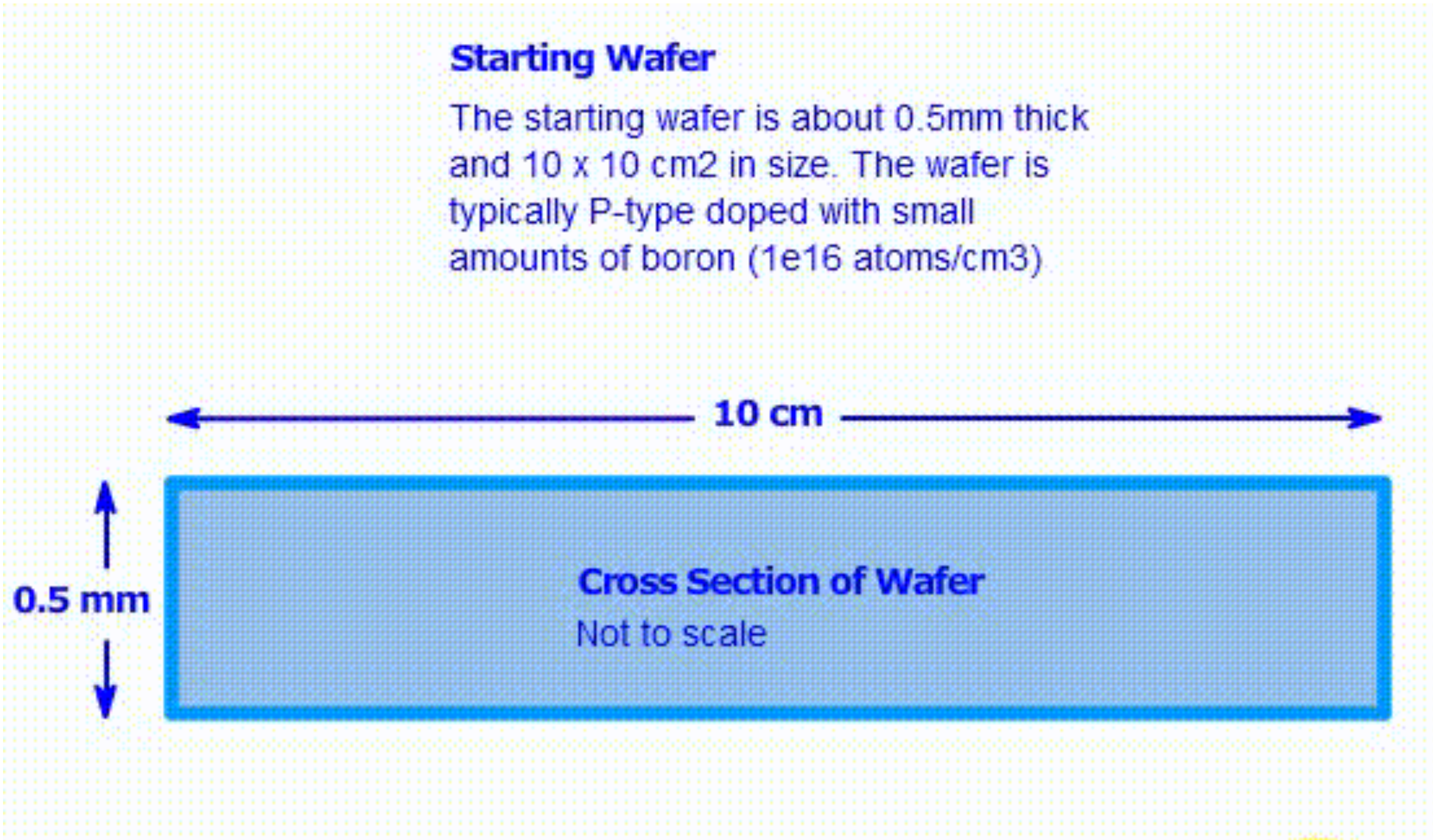
Polycrystalline

List of renowned manufacturers:

- 1) Trina
- 2) Kyocera
- 3) Jinko
- 4) Canadian Solar
- 5) SolarWorld
- ....



Photovoltaic Device Principles



Mono vs Poly Crystalline

- Main characteristics of mono-crystalline cells:
  - Colour = Dark blue/black
  - Efficiency = 16-19%
  - Thickness = 0.2-0.3mm
  - Size = 4-8” (10x10cm – 15x15cm)

- Main characteristics of poly-crystalline cells:
  - Colour = blue
  - Efficiency = 14-17%
  - Thickness = 0.2-0.3mm
  - Size = 4-8” (10x10cm – 21x21cm)

Properties of Light

Particle-wave duality: Photons have discrete quanta of energy. Photons have momentum. Light can be polarized. Light can be diffracted. Light waves can destructively and constructively interfere.

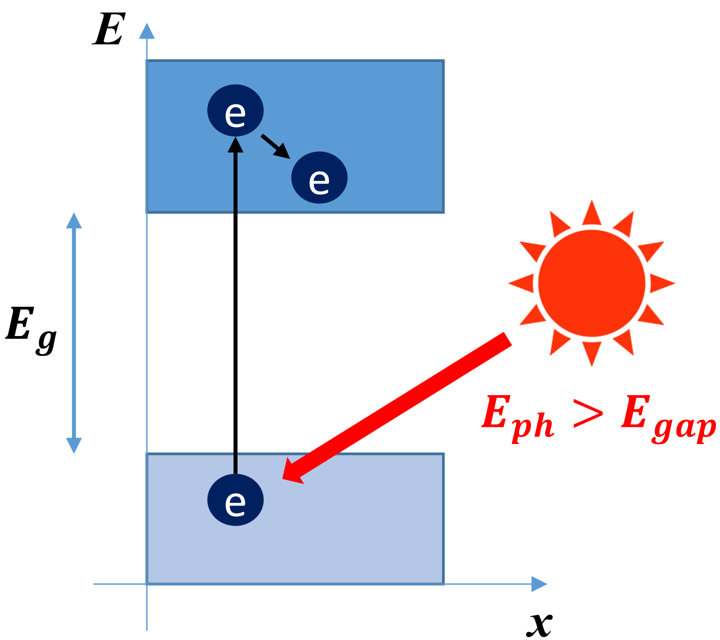
$$E_{Ph} = \frac{hc}{\lambda}$$

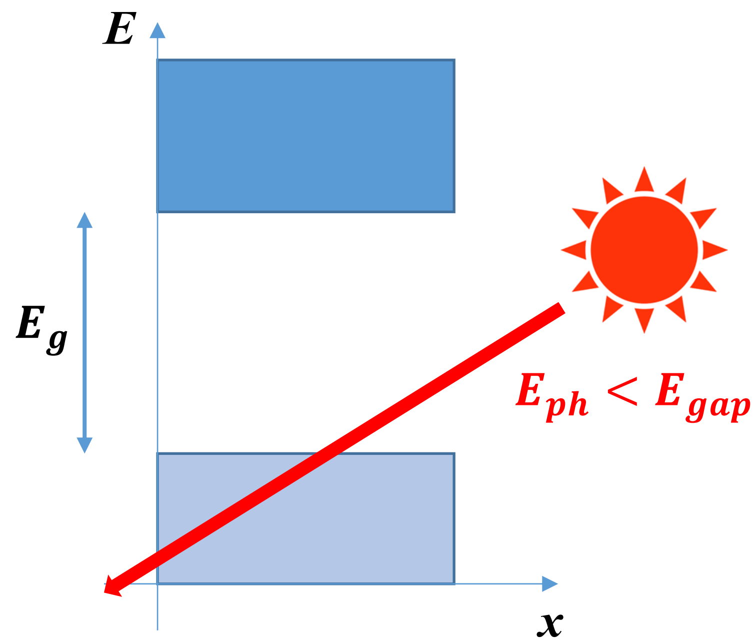
3002 Electronic Devices
R. Ghannam

Charge Excitation

At photon energies above the band gap (i.e., shorter photon wavelengths), light is absorbed by the semiconductor and charge is promoted into the conduction band

At photon energies less than the band gap (i.e., longer photon wavelengths), incident light is not efficiently absorbed and passes through semiconductor.

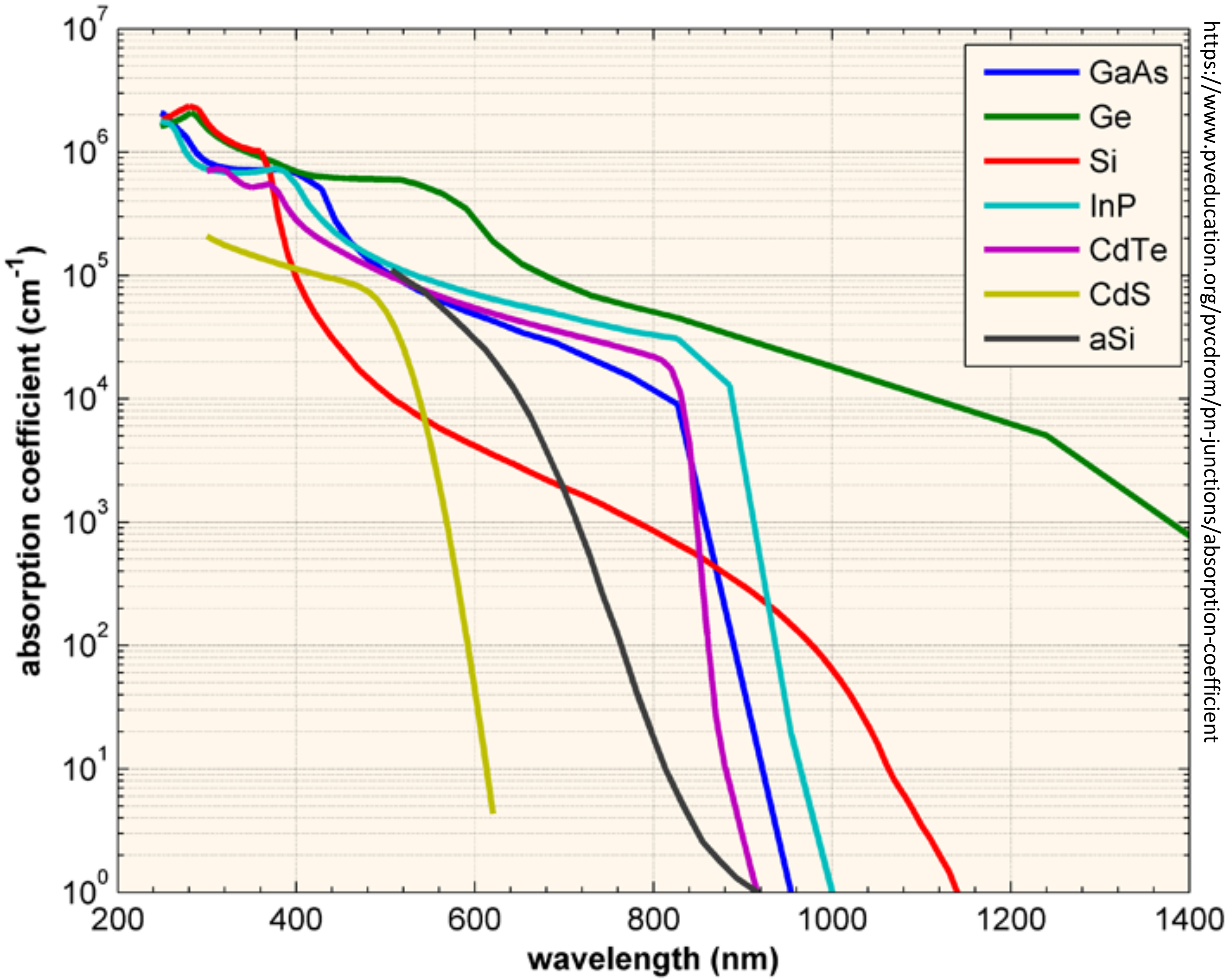




Light Absorption

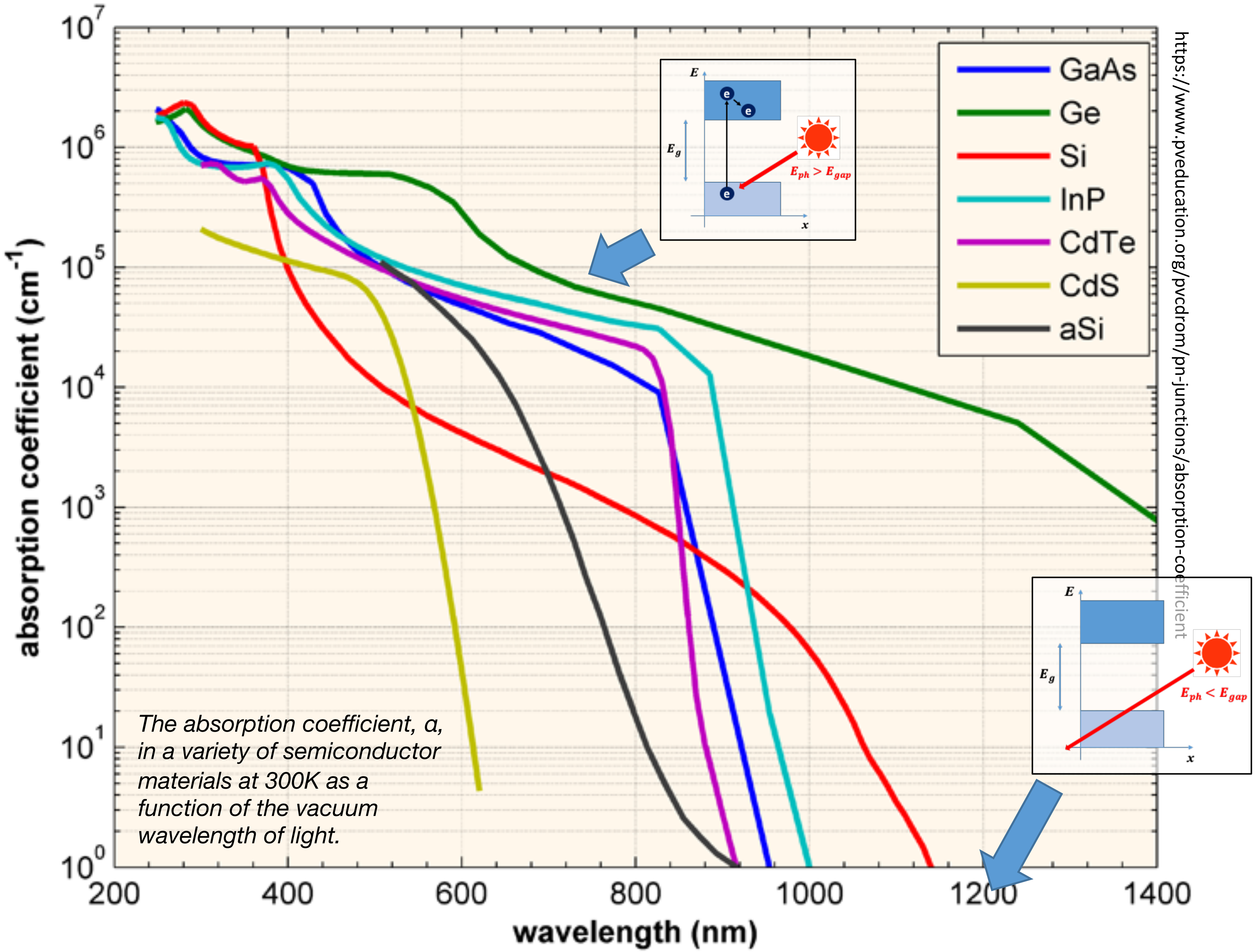
"The absorption coefficient determines how far into a material light of a particular wavelength can penetrate before it is absorbed. In a material with a low absorption coefficient, light is only poorly absorbed, and if the material is thin enough, it will appear transparent to that wavelength."

$$I = I_o e^{-\alpha l}$$



The absorption coefficient, α, in a variety of semiconductor materials at 300K as a function of the vacuum wavelength of light.

Light Absorption

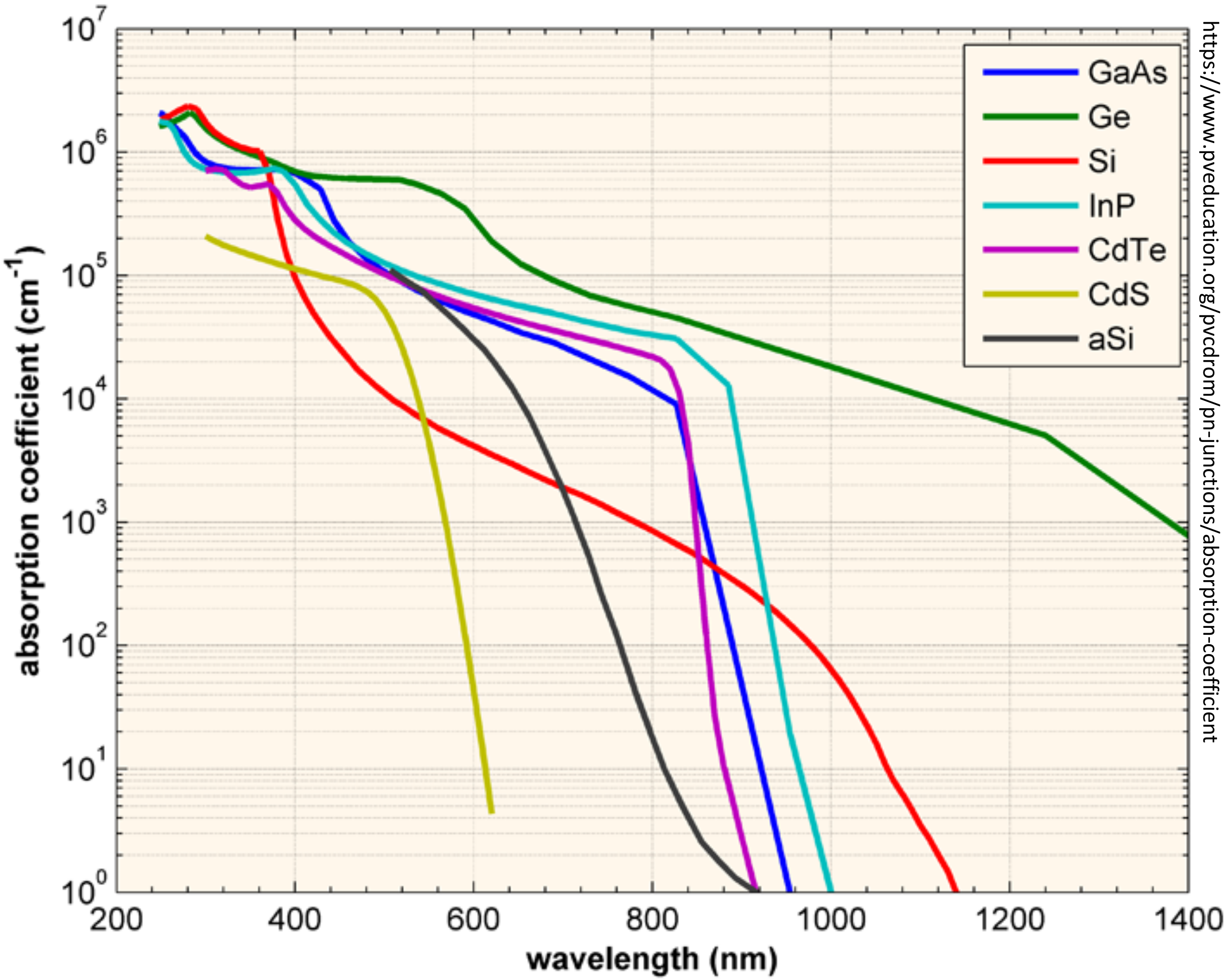


The absorption coefficient, α, in a variety of semiconductor materials at 300K as a function of the vacuum wavelength of light.

Light Absorption

Based on these absorption coefficients, estimate a reasonable thickness for a a Si solar cell, such that 90% of the light at 800 nm is absorbed.

$$I = I_o e^{-\alpha l}$$



The absorption coefficient, α, in a variety of semiconductor materials at 300K as a function of the vacuum wavelength of light.

Photovoltaic Device Principles

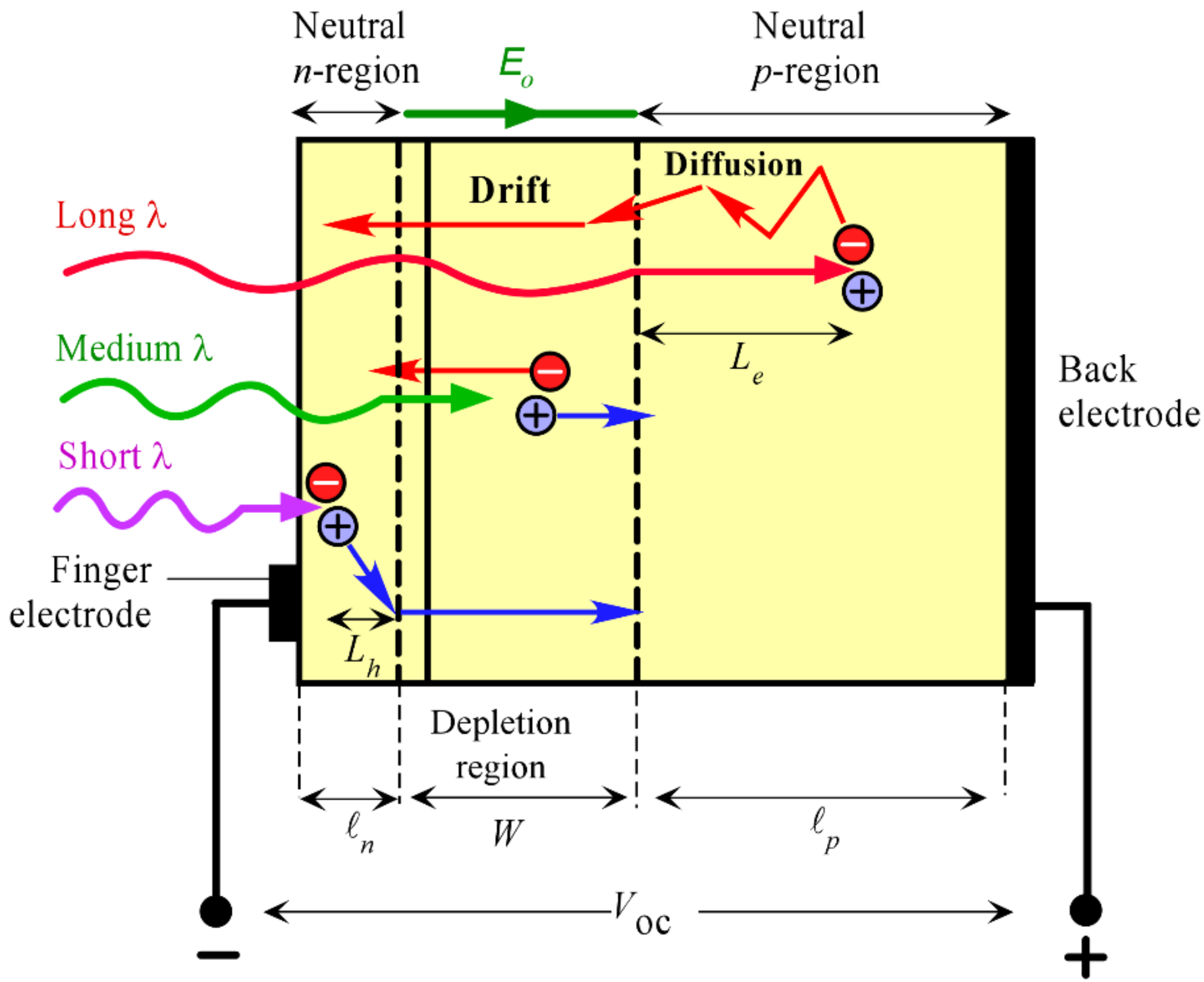
Consider a pn^+ junction. The depletion region (W) extends primarily into the p-side. There is a built-in field E_o in this depletion layer. The finger electrodes on surface of n-side allow illumination to enter the device and at the same time result in a small series resistance.

As the n-side is very narrow, most of the photons are absorbed within the depletion region (W) and within the neutral p-side (l_p) and photogenerate EHPs in these regions. EHPs photogenerated in the depletion region are immediately separated by the built-in field E_o which drifts them apart.

The electron drifts and reaches the neutral n^+ side whereupon it makes this region negative by an amount of charge -q. Similarly the hole drifts and reaches the neutral p-side and thereby makes this side positive.

An open circuit voltage develops between the terminals of the device with the p-side positive with respect to the n-side.

Photovoltaic Device Principles



The basic principle of operation of the solar cell (exaggerated features to highlight principles). The built-in field change upon illumination.

From *Principles of Electronic Materials and Devices, Fourth Edition*, S.O. Kasap (© McGraw-Hill Education, 2018)

Photovoltaic Device Principles

Connecting external load results in excess electron in the n-side to travel around the external circuit, do work and reach the p-side to recombine with the excess hole there. Without the internal field E_o it is not possible to drift apart the photogenerated EHPs and accumulate excess electrons on the n-side and excess holes on the p-side.

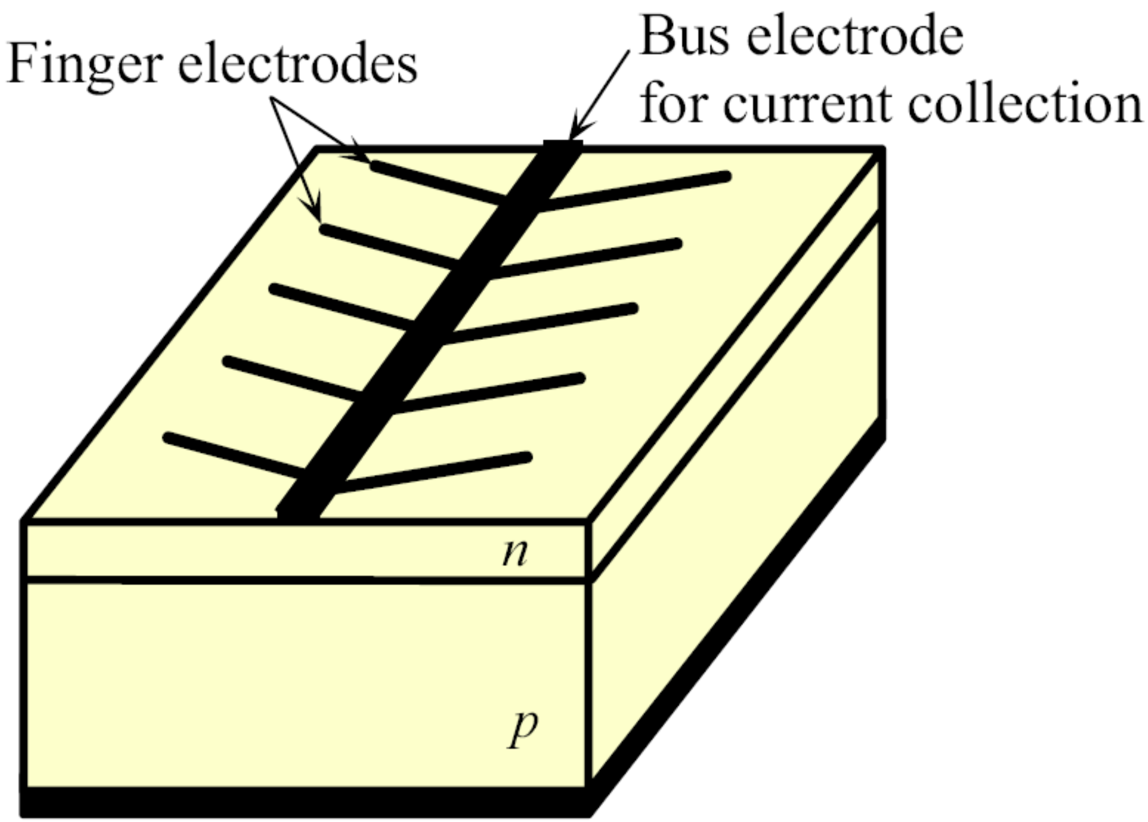
EHPs photogenerated by long-wavelength photons that are absorbed in the neutral p-side diffuse around in this region as there is no electric field. Electrons diffuse a mean distance $\boldsymbol{L_e = \sqrt{D_e \tau_e}}$. Electrons within a distance L_e to the depletion region can readily diffuse and reach this region whereupon they become drifted by E_0 to the n-side. Only those EHPs photogenerated within L_e to the depletion layer can contribute to the photovoltaic effect.

Once an electron diffuses to the depletion region, it is swept over to the n-side by E_0 to give an additional negative charge there. Holes left behind in the p-side contribute a net positive charge to this region.

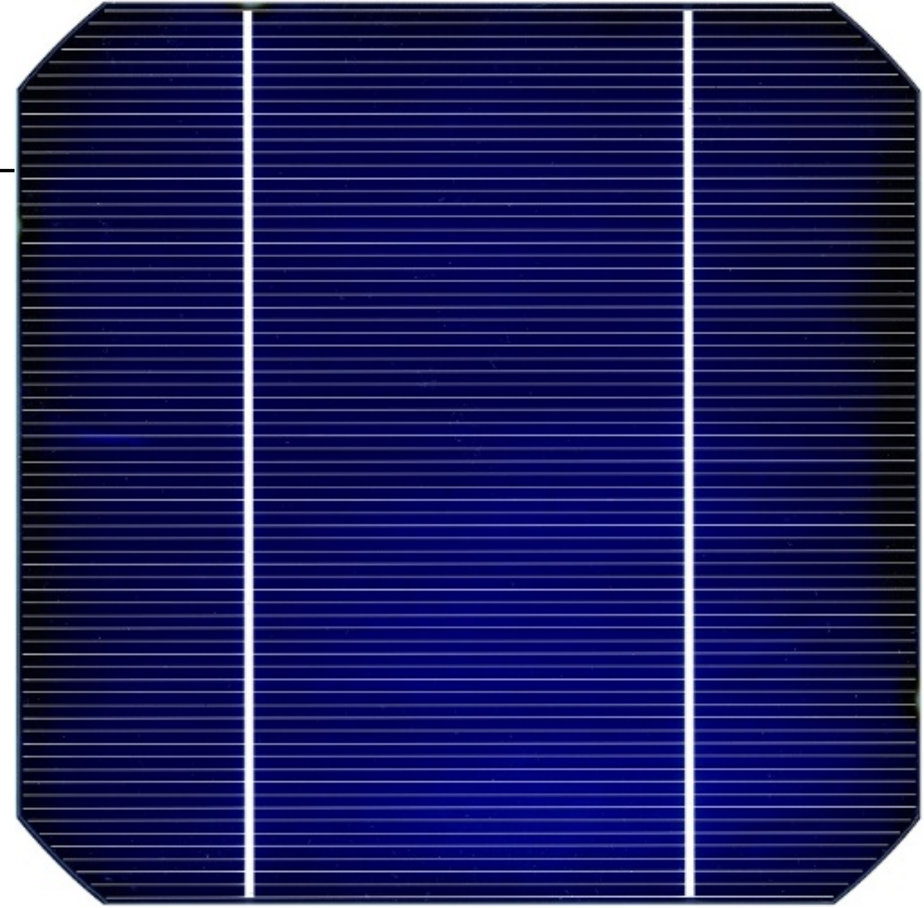
EHPs further away from the depletion region than L_e are lost by recombination.

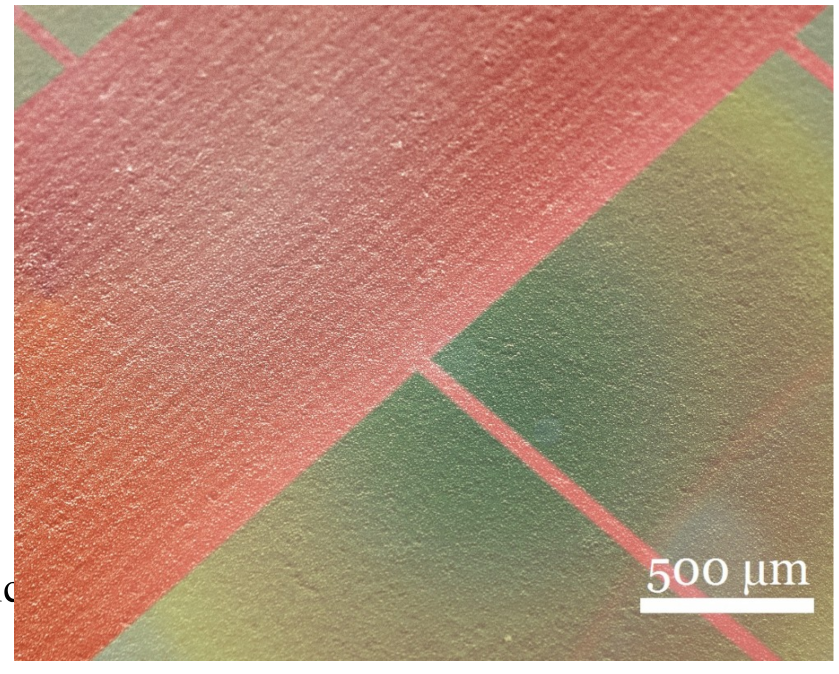
University of Glasgow

Electrodes



Finger electrodes on the surface of a solar cell reduce the series resistance.





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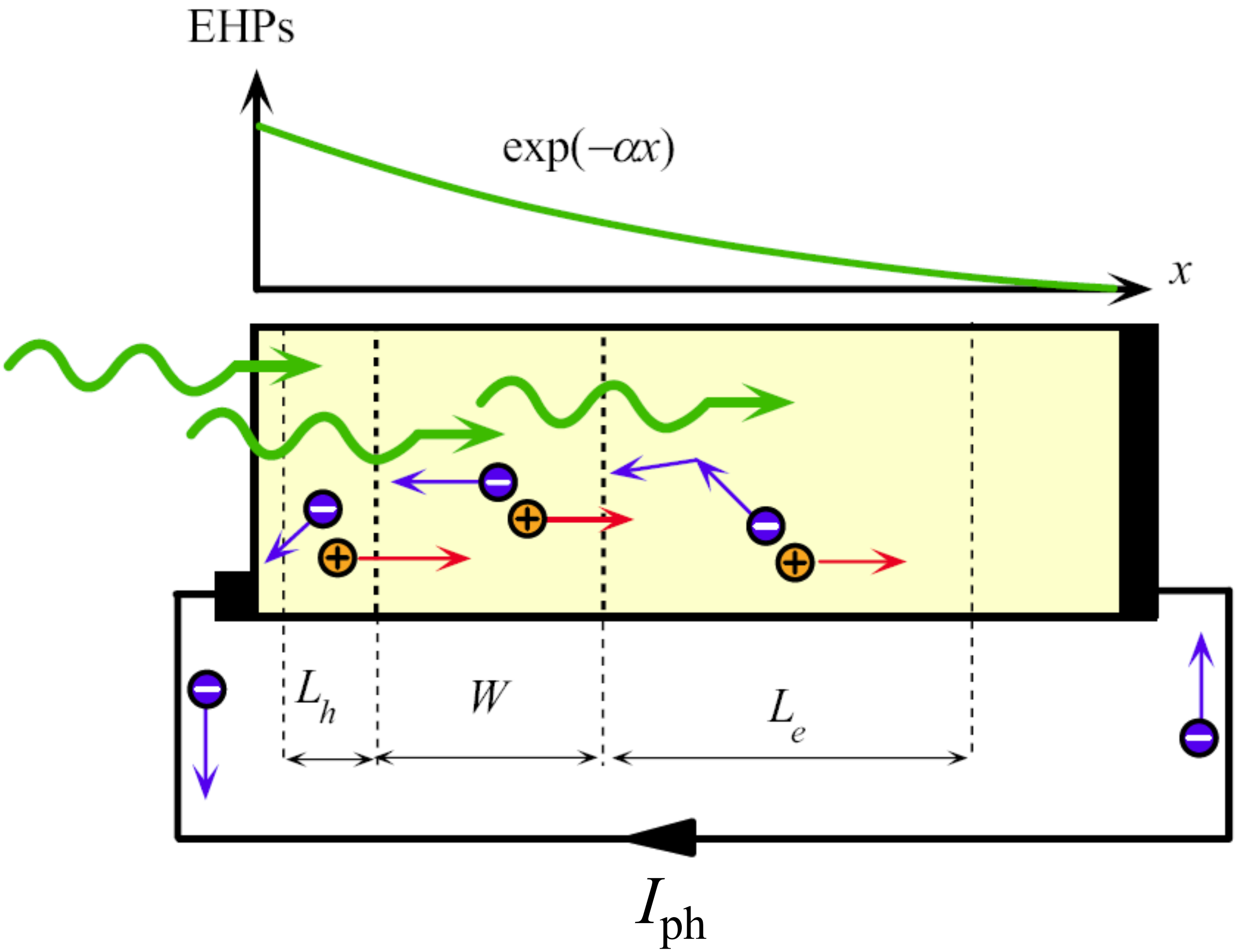
Photovoltaic Device Principles



At long wavelengths, around $1 - 1.2\mu m$, the absorption coefficient α of Si is small and the absorption depth $(1/\alpha)$ is typically greater than $100\mu m$. To capture these long wavelength photons, we therefore need a thick p-side and at the same time a long minority carrier diffusion length L_e. Typically the p-side is $200 - 500\mu m$ and L_e tends to be shorter than this.

An np junction solar cell in short circuit. Photogenerated carriers within the volume $L_h + W + L_e$ give rise to a photocurrent I_{ph}. The variation in the photogenerated EHP concentration with distance is also shown where α is the absorption coefficient at the wavelength of interest.

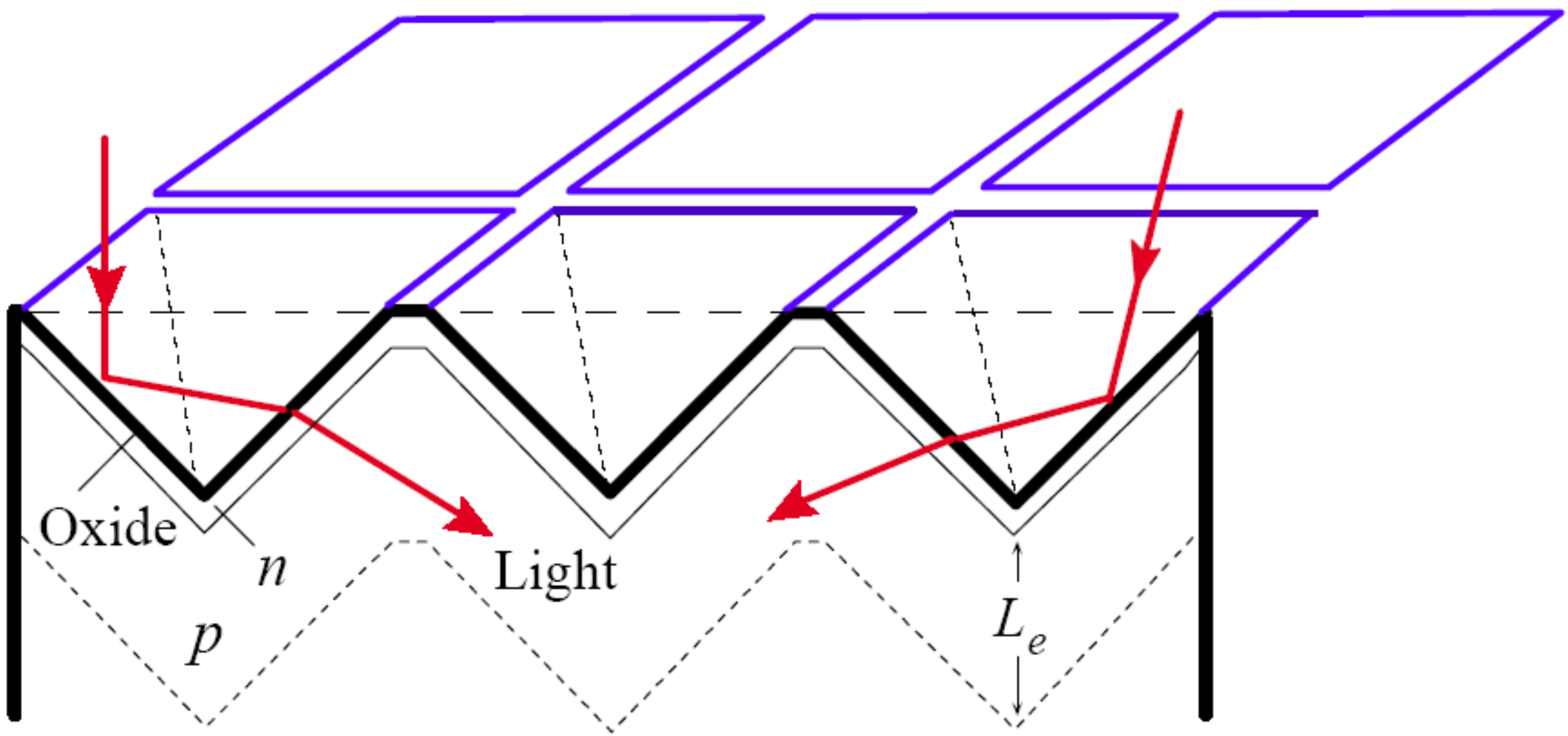
Photovoltaic Device Principles

It is important to have **the minority carrier diffusion length L_e large**. This is the reason for choosing this side of a Si pn junction to be p-type which make electrons the minority carriers **(electron diffusion length in Si is longer than the hole diffusion length)**.

Same ideas apply to EHPs photogenerated by shortwavelength photons absorbed in the n-side. Those holes photogenerated within a diffusion length L_h can reach the depletion layer and become swept across to the n-side. EHPs beyond L_h are lost by recombination as lifetime in n-side is very short (due to heavy doping). The n-side is made thin and sometimes **shorter than L_h** (<0.2μm).

Photogeneration of EHPs that contribute to photovoltaic effect occur in volume covering $L_h + W + L_e$. If the terminals of the device are shorted then excess electron in the n-side can flow through the external circuit to neutralize the excess hole in the p-side. C**urrent due to flow of the photogenerated carriers is called the photocurrent**.

Photovoltaic Device Principles



A thin antireflection coating on the surface reduces reflections and allows more light to enter the device. An inverted pyramid textured surface in this case substantially reduces reflection losses and increases absorption probability in the device.

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Losses:

1) Limitations of the photovoltaic action itself

2) Crystal surfaces and interfaces contain a high concentration of recombination centers which facilitate the recombination of photogenerated EHPs near the surface of the n-side

3) The antireflection coating is not perfect, which reduces the total collected photons by a factor of about 0.8-0.9.

Upper limit to a photovoltaic device that uses a single crystal of Si is about 24-26% at room temperature.

Ideal Solar Cells

Short Circuit Solar Cell Current:

$$I_{sc} = -I_{ph} = -K\mathcal{I}$$

Photocurrent generated by light

Light intensity

Constant that depends on the particular device

The photocurrent I_{ph} flows even when there is no voltage across the device.

The photocurrent does not depend on the voltage across the pn junction because there is always some internal field to drift the photogenerated EHP.

Ideal Solar Cells

Diode Current:

If R is not a short circuit, then a positive voltage V appears across the pn junction as a result of the current passing through it. This voltage reduces the built-in potential of the pn junction and leads to minority carrier injection and diffusion (just as in a normal diode).

Id is therefore due to the normal pn junction behaviour and it is given by the diode characteristics:

$$I_d = I_0(e^{V/\eta V_t} - 1)$$

where I_o is the reverse saturation current and is the ideality factor: 1 - 2

Ideal Solar Cells

Total Current in Solar Cell

$$I = \underbrace{-I_{ph}}_{I_{sc}} + \underbrace{I_o\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]}_{I_d}$$

In an open circuit, the net current is **zero**. This means that the photocurrent I_{ph} develops just enough photovoltaic voltage V_{oc} (open circuit voltage) to generate a diode current $I_d = I_{ph}$.

Ideal Solar Cells

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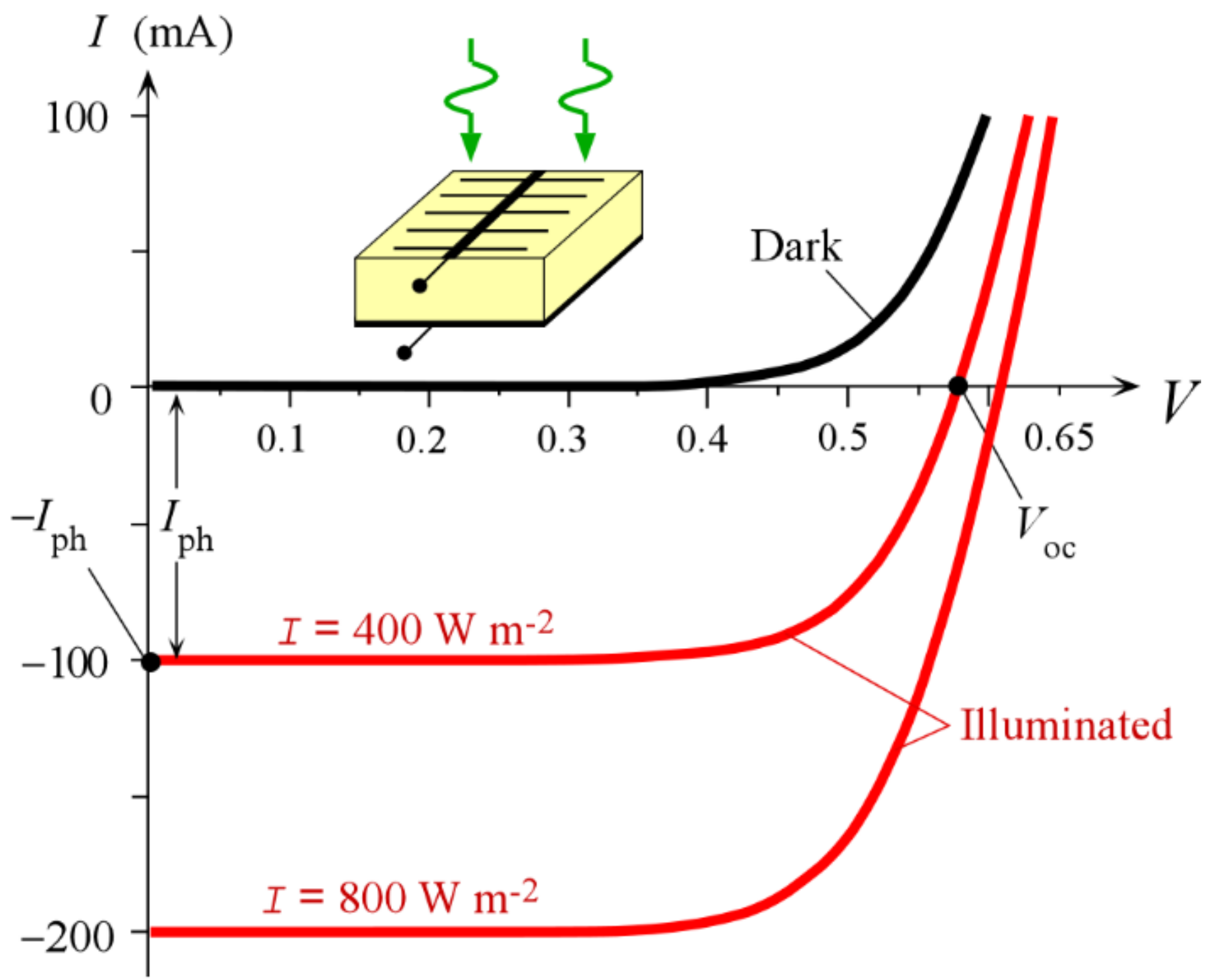
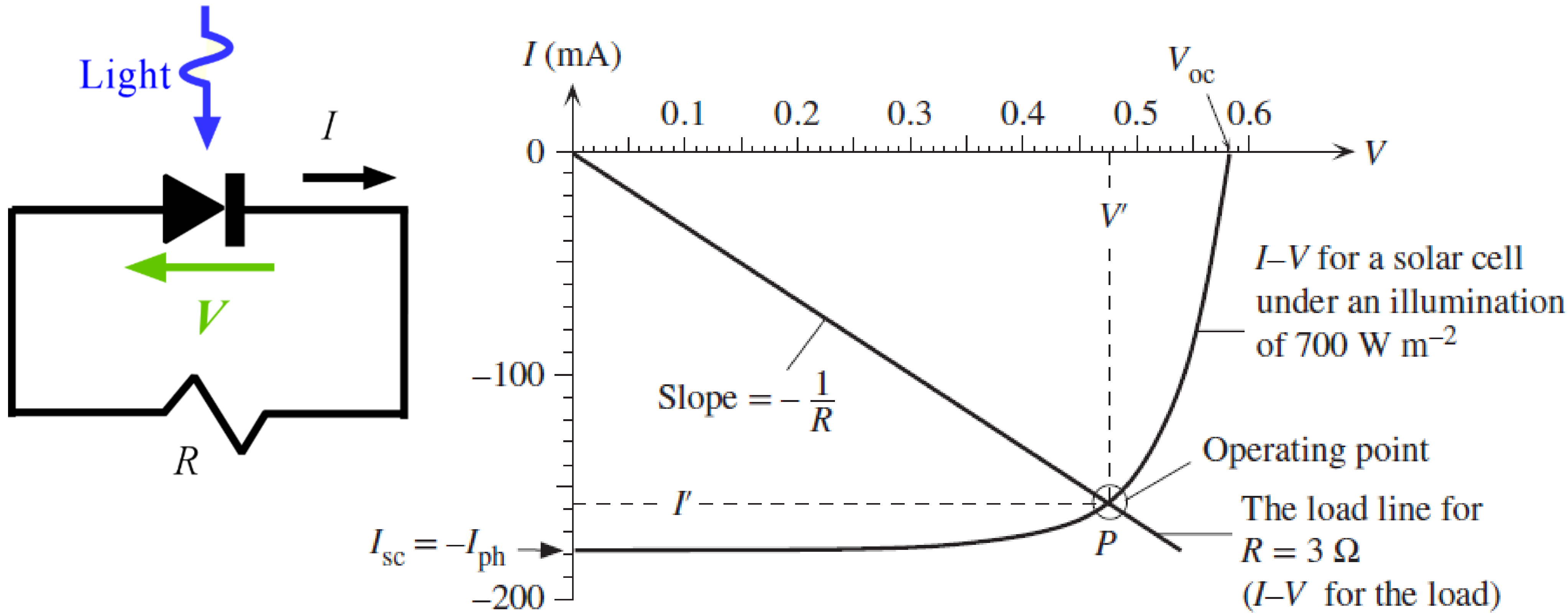


Typical I–V characteristics of a Si solar cell. The *I–V* curves for positive current require an external bias voltage. Photovoltaic operation is always in the negative current region. *I-V* characteristics in the dark and under illumination at intensities corresponding to 400 and 800 W m^{-2}

Ideal Solar Cells

Solar Cell Characteristics & Load Line



(a) When a solar cell drives a load R, R has the same voltage as the solar cell but the current through it is in the opposite direction to the convention that current flows from high to low potential. (b) The current I' and voltage V' in the circuit of (a) can be found from a load line construction. Point P is the operating point (I', V'). The load line is for $R = 3\ \Omega$.

Ideal Solar Cells

When the solar cell is connected to a load, the load has the same voltage as the solar cell and carries the same current. But the current through R is now in the **opposite** direction to the convention that current flows from high to low potential.

The load line

$$I = -\frac{V}{R}$$

The actual current I' and voltage V' in the circuit must satisfy both the I vs V characteristics of the solar cell and the load.

Ideal Solar Cells

The Power

The power delivered to the load is $P_{out} = I'V'$, which is the area of the rectangle bound by the I and V axes and the dashed lines.

Maximum power is delivered to the load when this rectangular area is maximized. Therefore it makes sense to compare the maximum power output $I_m V_m$ with $I_{sc} V_{oc}$.

Definition of Fill Factor

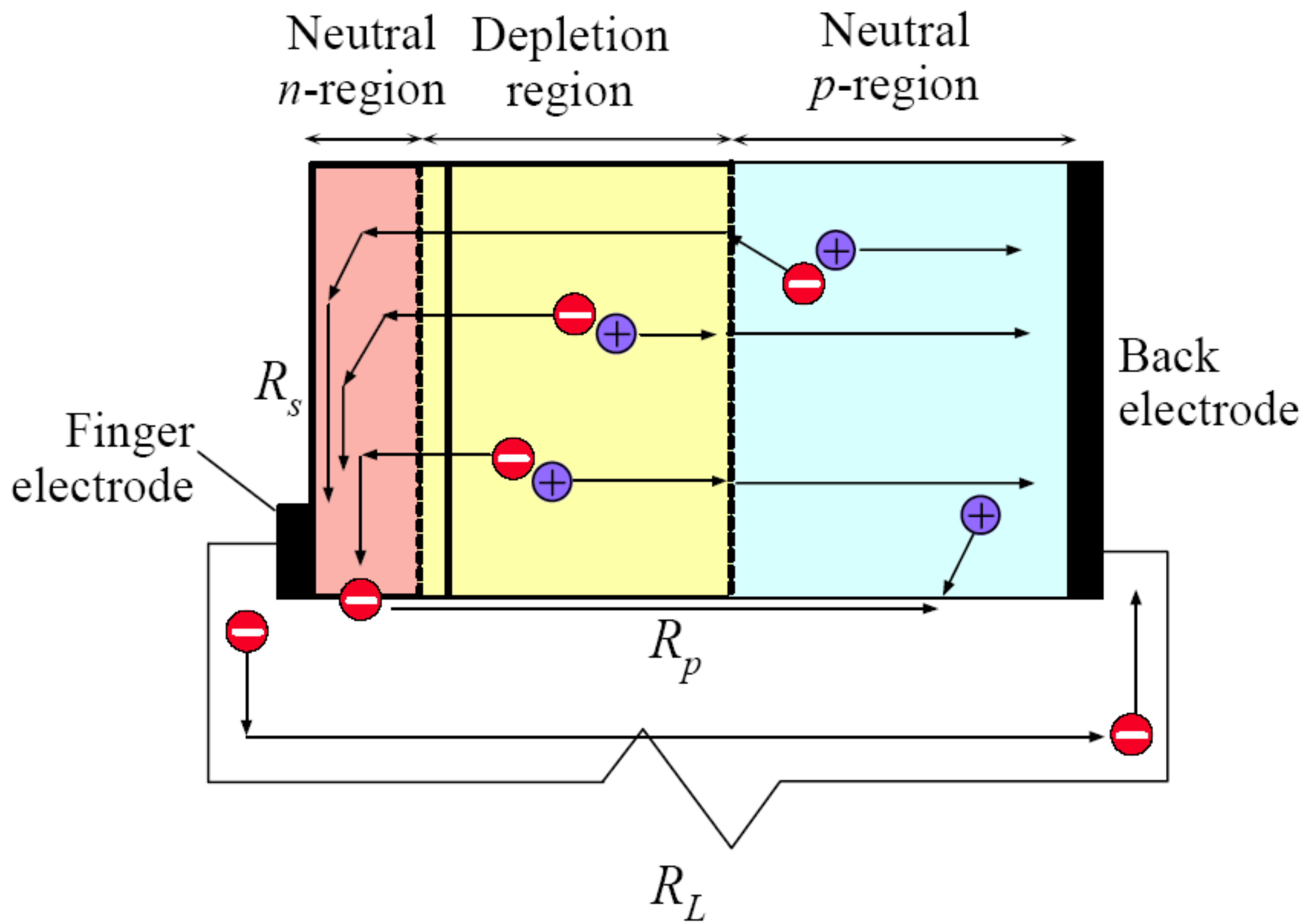
$$\mathrm{FF} = \frac{I_m V_m}{I_{sc} V_{oc}}$$

The FF is a measure of the closeness of the solar cell *I-V* curve to the rectangular shape (the ideal shape).

Practical Solar Cells

Series Resistance:

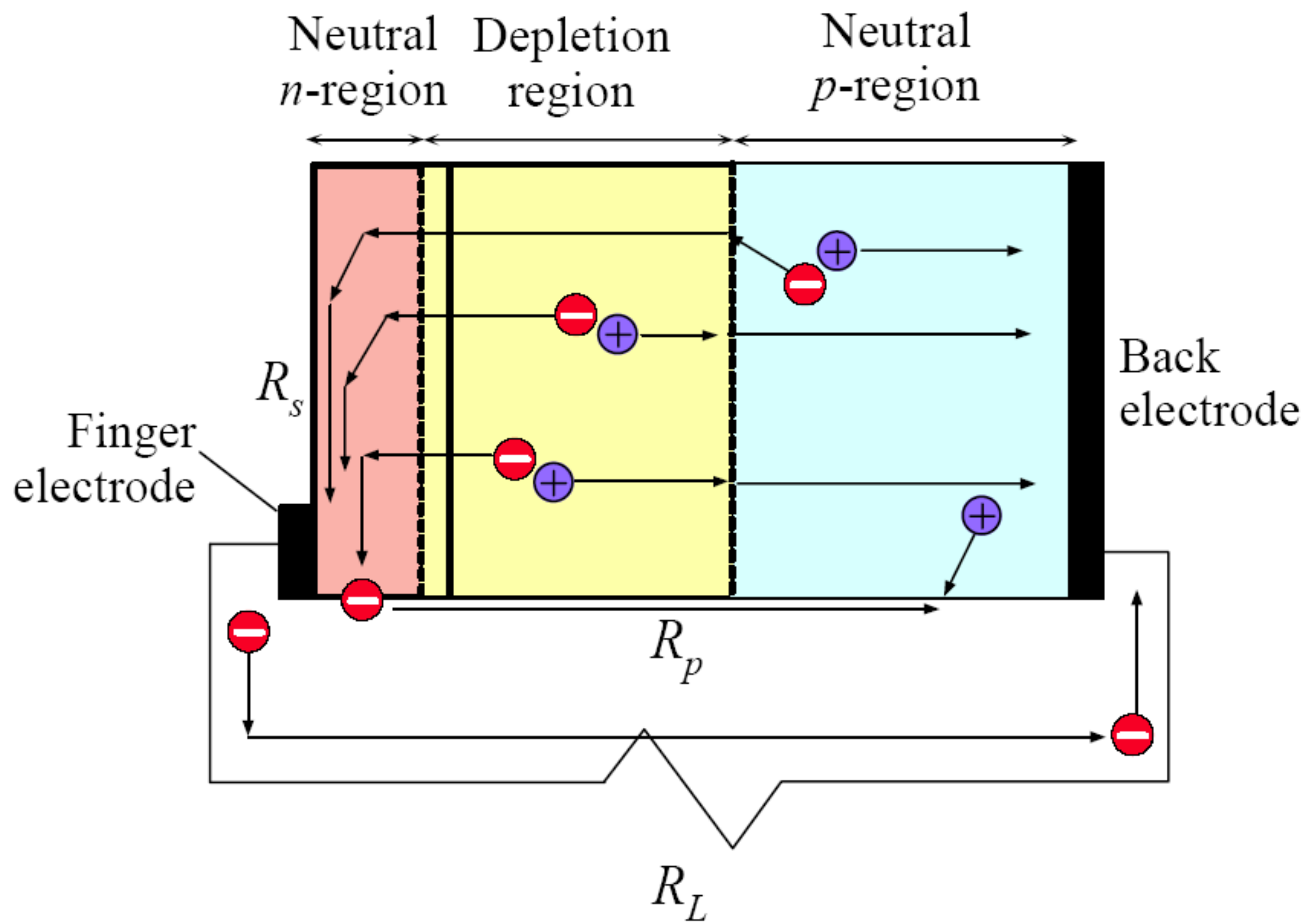
Photogenerated electrons have to traverse a surface semiconductor region to reach the nearest finger electrode. All these electron paths in the n-layer surface region to finger electrodes introduce an effective **series resistance R_s** into the photovoltaic circuit.



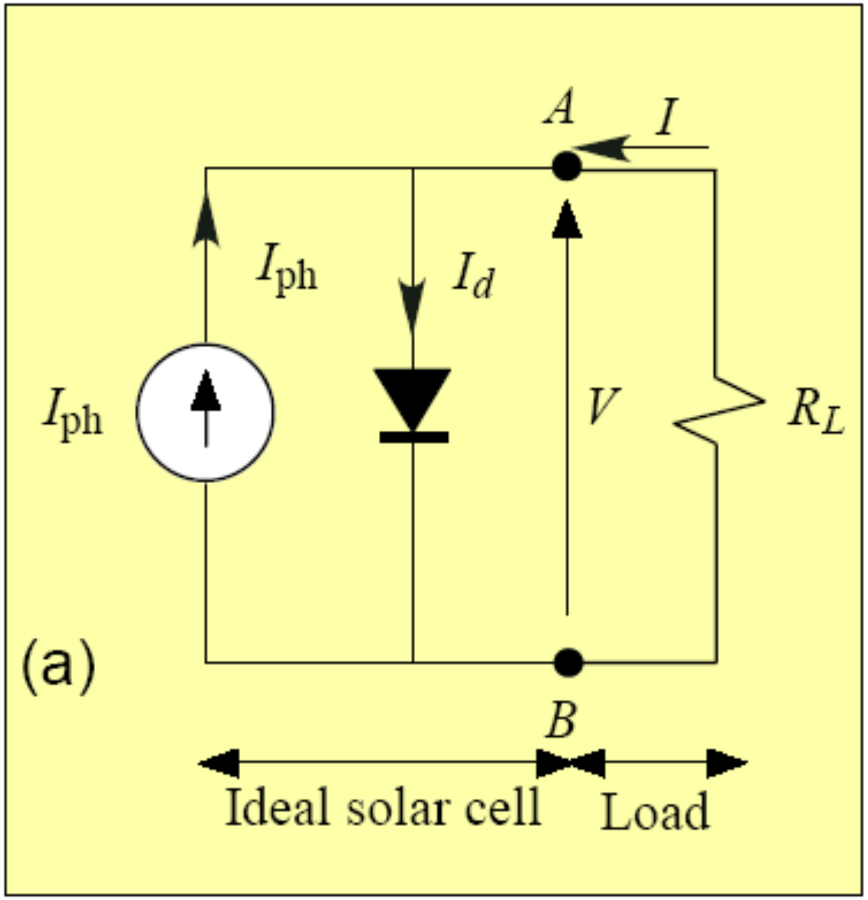
Practical Solar Cells

Shunt Resistance:

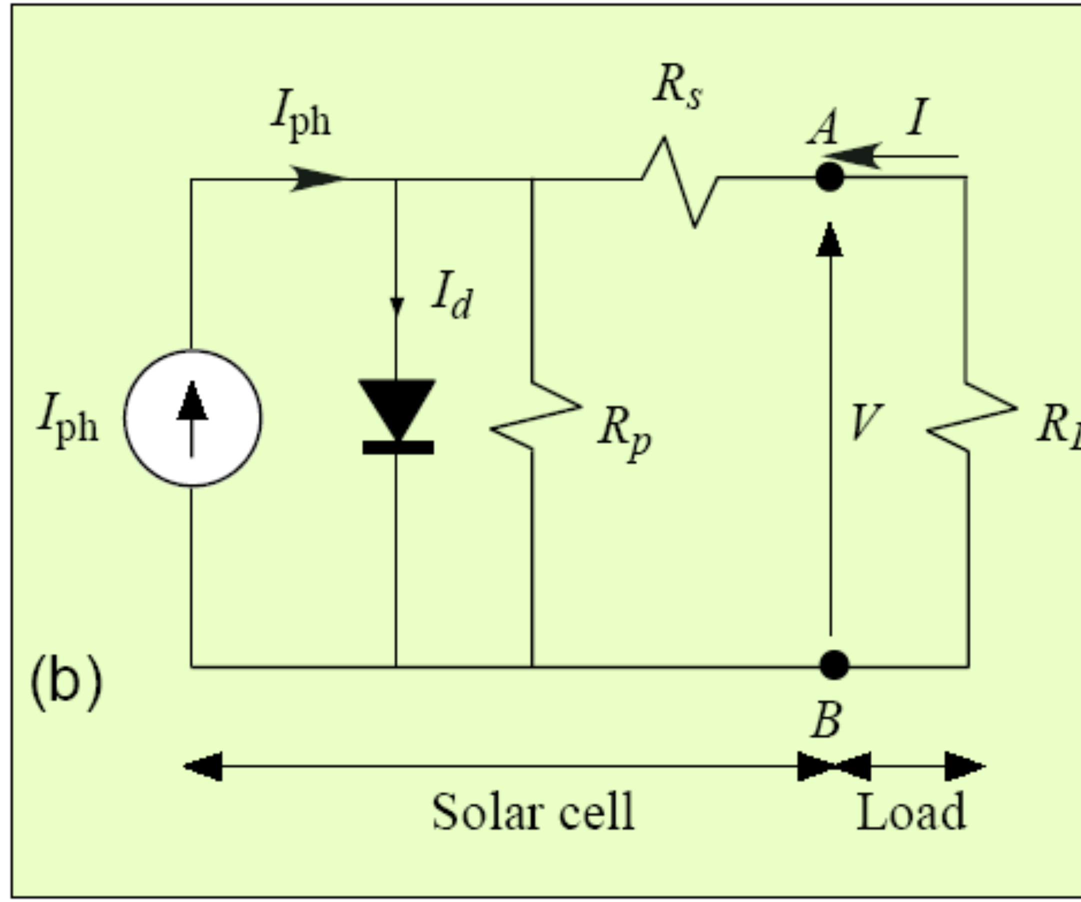
Photogenerated carriers can also flow through the crystal surfaces (edges of the device) or through grain boundaries in polycrystalline devices instead of flowing though R_L . These effects that prevent photogenerated carriers from flowing in external circuit can be represented by a **shunt resistance R_p** that diverts photocurrent away from R_L. Typically R_p is less important than R_s.



Equivalent Circuit of a Solar Cell



Ideal *pn* junction



Parallel and series resistances R_s and R_p.

In reality, of course, the solar cell current is negative, as explained in slide 18 which represents a current that is flowing out into the load

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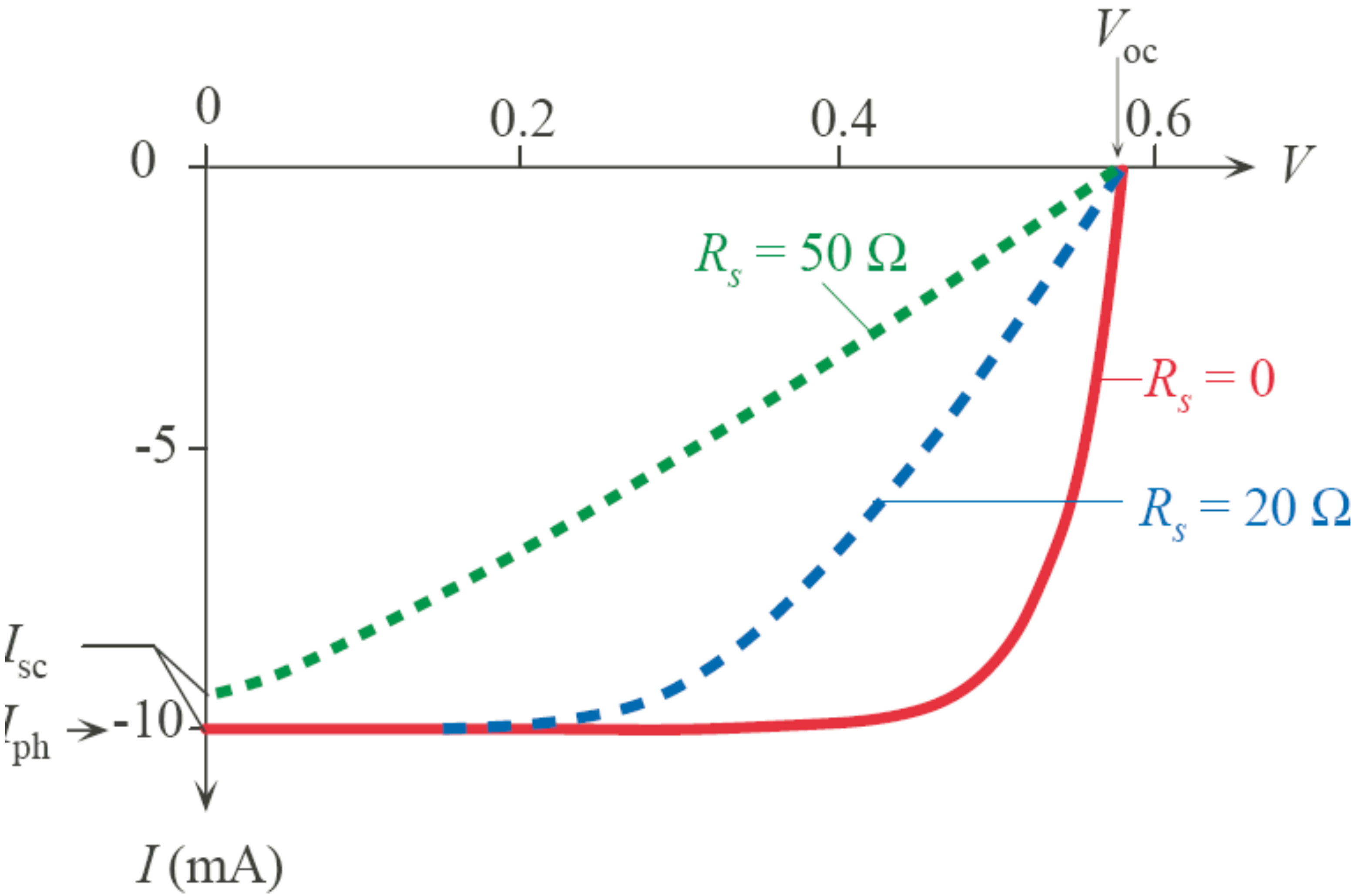
Series Resistance



The series resistance severely deteriorates solar cell performance. It broadens the I–V curve and reduces the maximum available power and hence the overall efficiency of the solar cell. The example is a Si solar cell with $\eta \approx 1.5$ and $I_o \approx 3 \times 10^{-6}$ mA. Illumination is such that the photocurrent $I_{ph} = 10$ mA.

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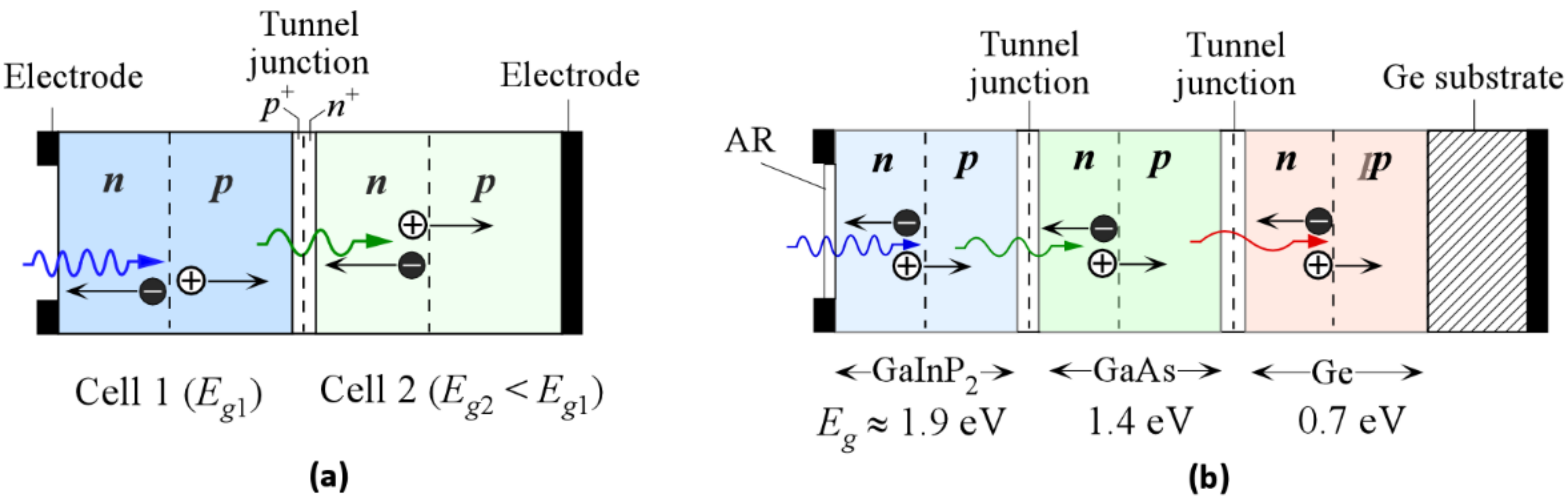
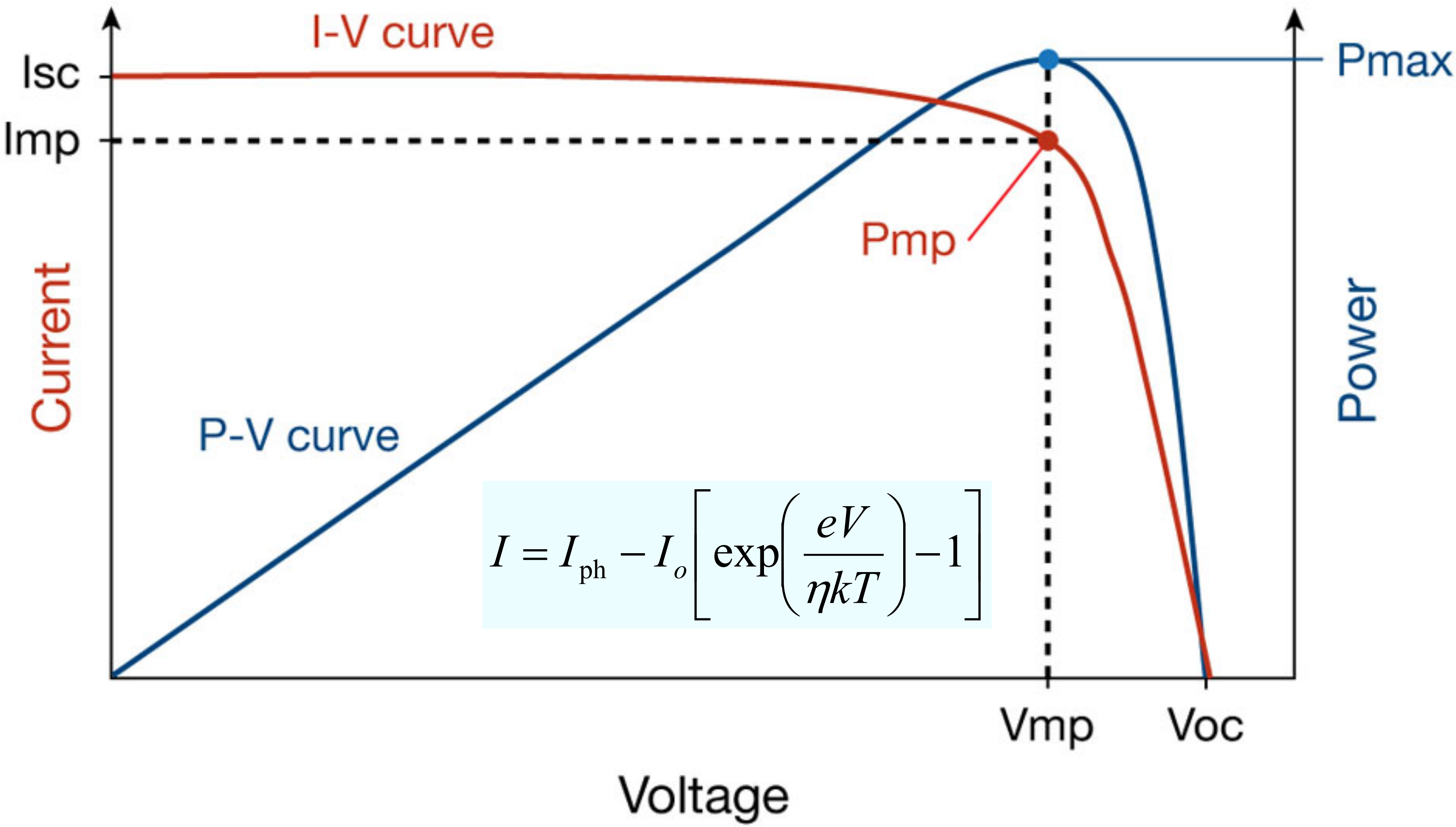
Multijunction Solar Cells



Tandem or cascaded cells use two or more cells in tandem or in cascade to increase the absorbed photons from the incident light. (a) The first cell is made from a wider bandgap (E_{g1}) material and only absorbs photons with $h\upsilon > E_{g1}$. The second cell with bandgap E_{g2} absorbs photons that pass the first cell and have $h\upsilon > E_{g2}$. (b) Tandem solar cell with three individual cells connected by tunnel junctions, and with an efficiency above 30 percent. The structures are grown layer by layer on a suitable substrate, e,g. Ge in this case.

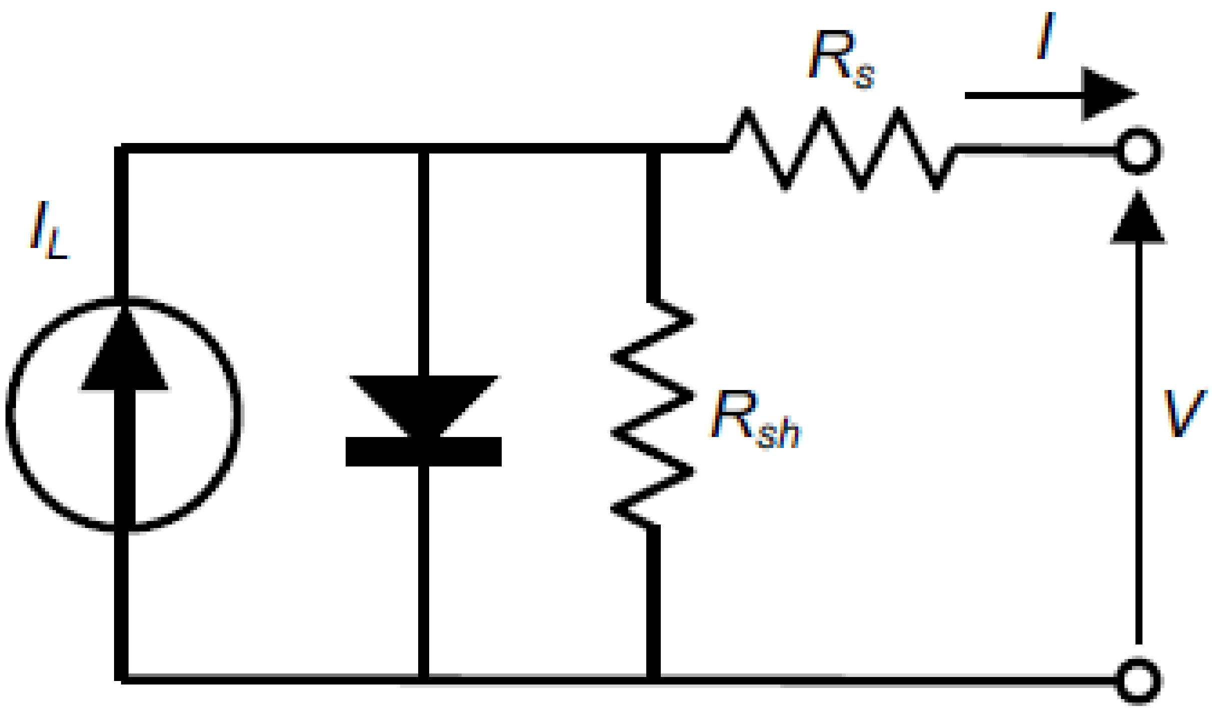
Equivalent Circuit of a Solar Cell

I-V curve is most often shown reversed with the output curve in the first quadrant and represented by:



$$I = I_{ph} - I_o\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]$$

General Model of Solar Cell

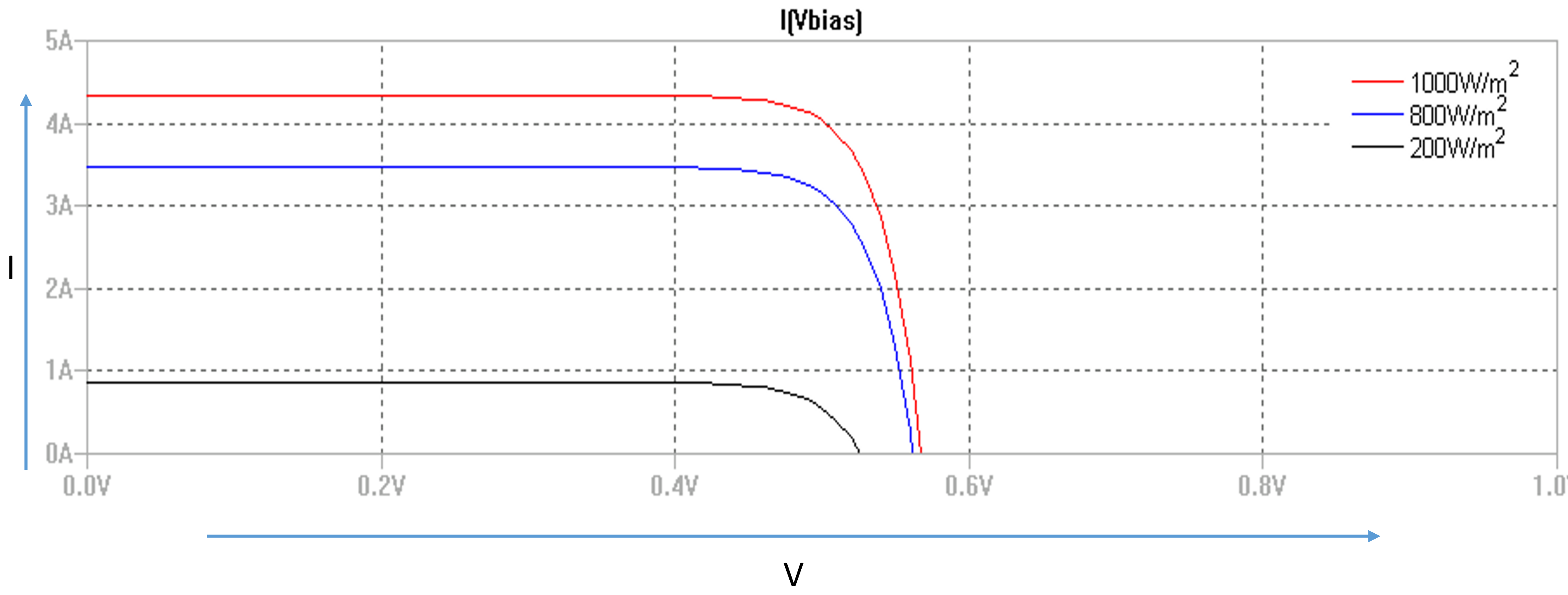


Write down the new expression for the current, *I*:

$$I = I_L - I_o\left[\exp\left(\frac{V + IR_s}{\eta kT/q}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$

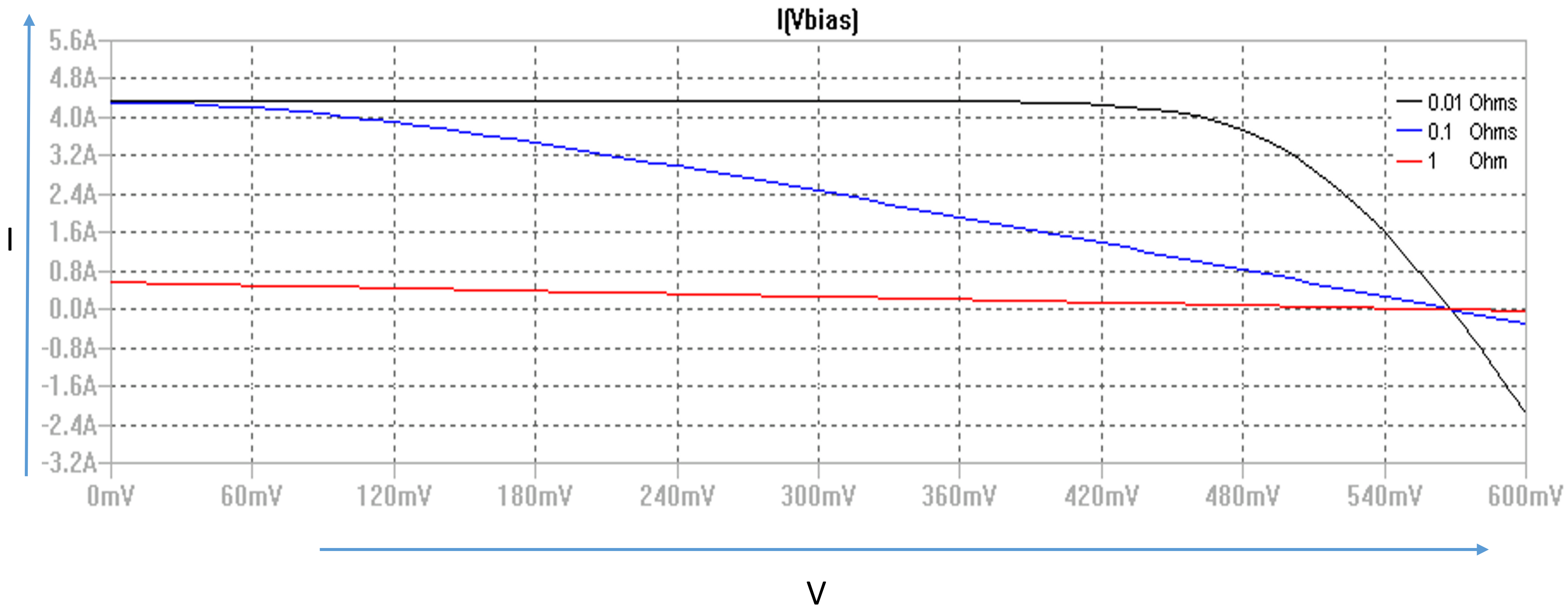
Effect of Illumination

Ideal solar cell with area=126.6 cm^2 $J_{sc} = 34.3\ mA/cm^2$, $J_0 = 10\ pA/cm^2$



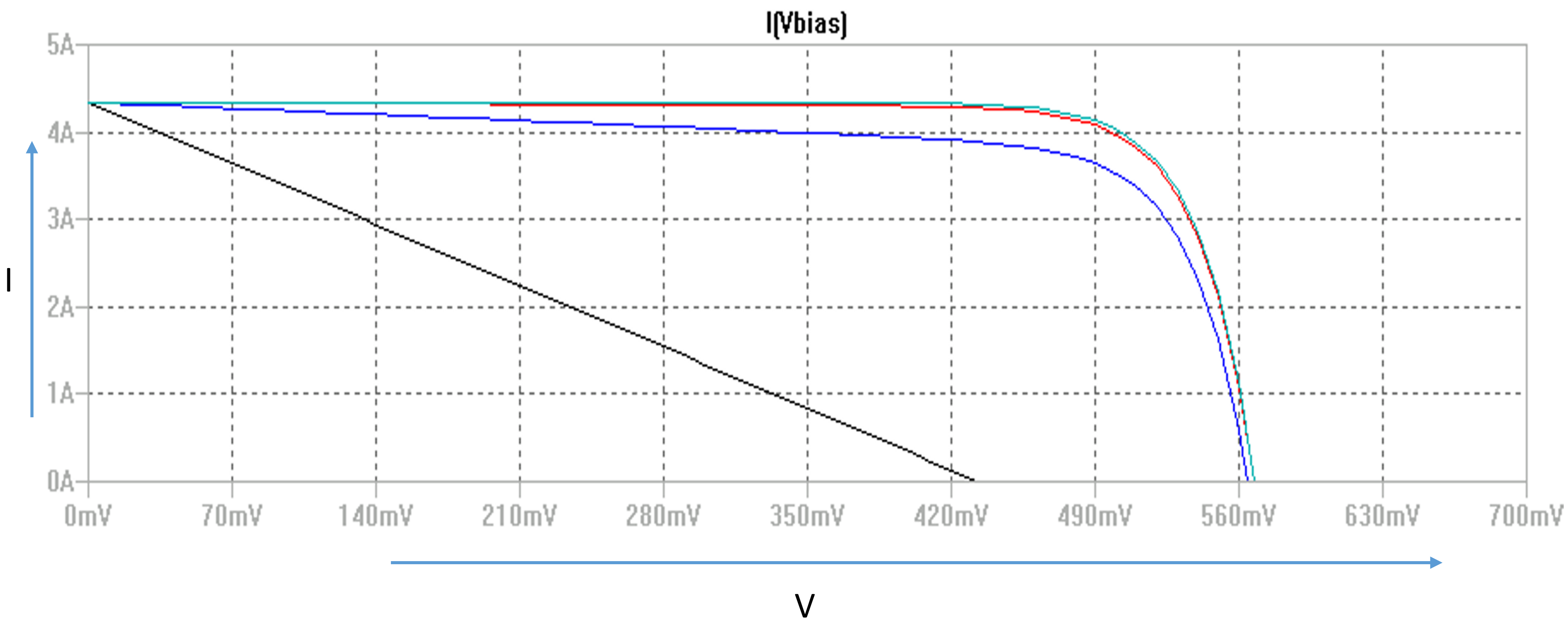
Effect of Series Resistance

Ideal solar cell with area=126.6 cm^2 $J_{sc} = 34.3\ mA/cm^2$, $J_0 = 10\ pA/cm^2$, $R_{sh} = 10\ k\Omega$ and varying the Series Resistance.



Effect of Shunt Resistance

Ideal solar cell with area=126.6 cm^2 $J_{sc} = 34.3\ mA/cm^2$, $J_0 = 10\ pA/cm^2$, $R_s = 1\ \mu\Omega$ and varying the Shunt Resistance from 0.1 Ω, 1 Ω, 10 Ω, 10000 Ω



Total Current Solar Cell

- This consists of two components, which are the photogenerated current and the diode current.

- Photocurrent generated by light and depends on light intensity.

- In an open circuit, the net current is zero. This means that the photocurrent I_{ph} develops just enough photovoltaic voltage V_{oc} (open circuit voltage) to generate a diode current $I_d = I_{ph}$.

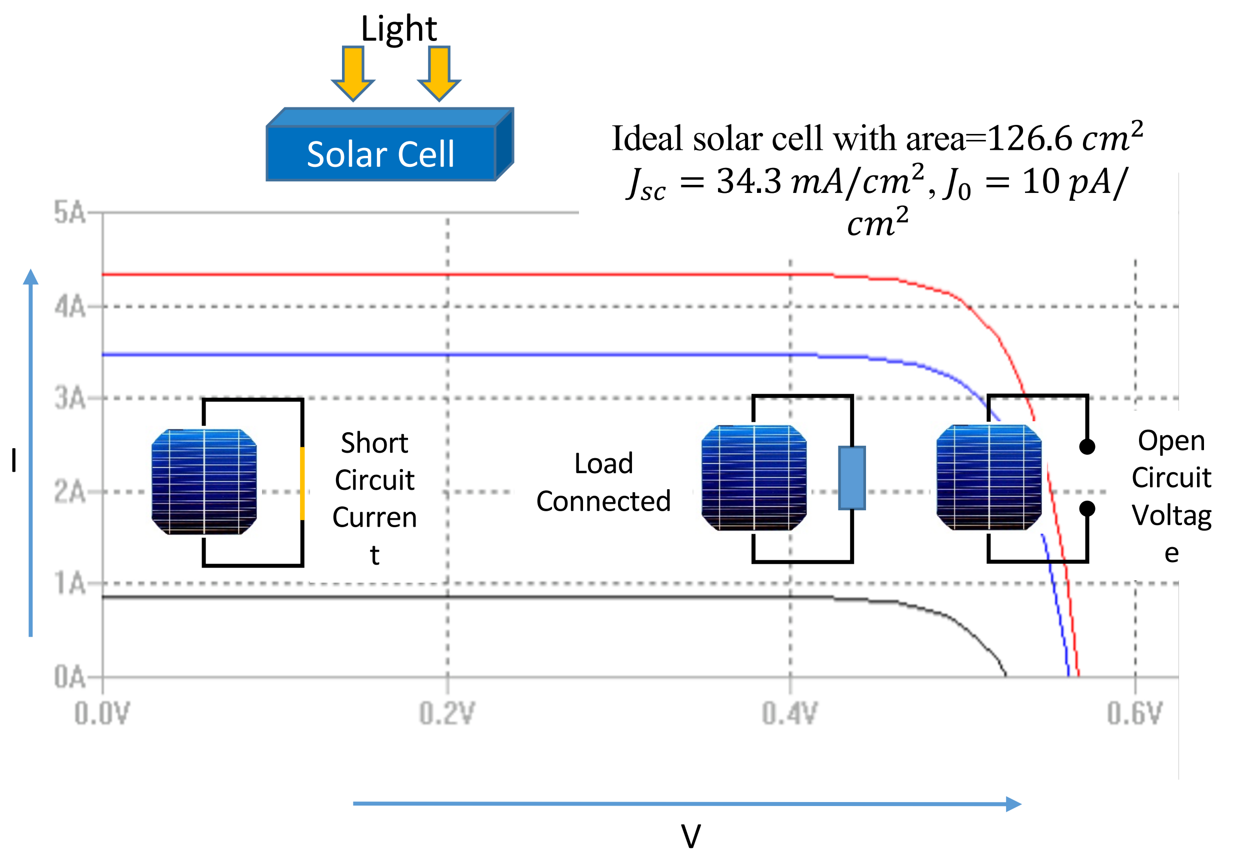
$$I = \underbrace{I_{ph}}_{I_{sc}} - \underbrace{I_o\left[\exp\left(\frac{eV}{\eta KT}\right) - 1\right]}_{I_d}$$

I-V Characterisitics

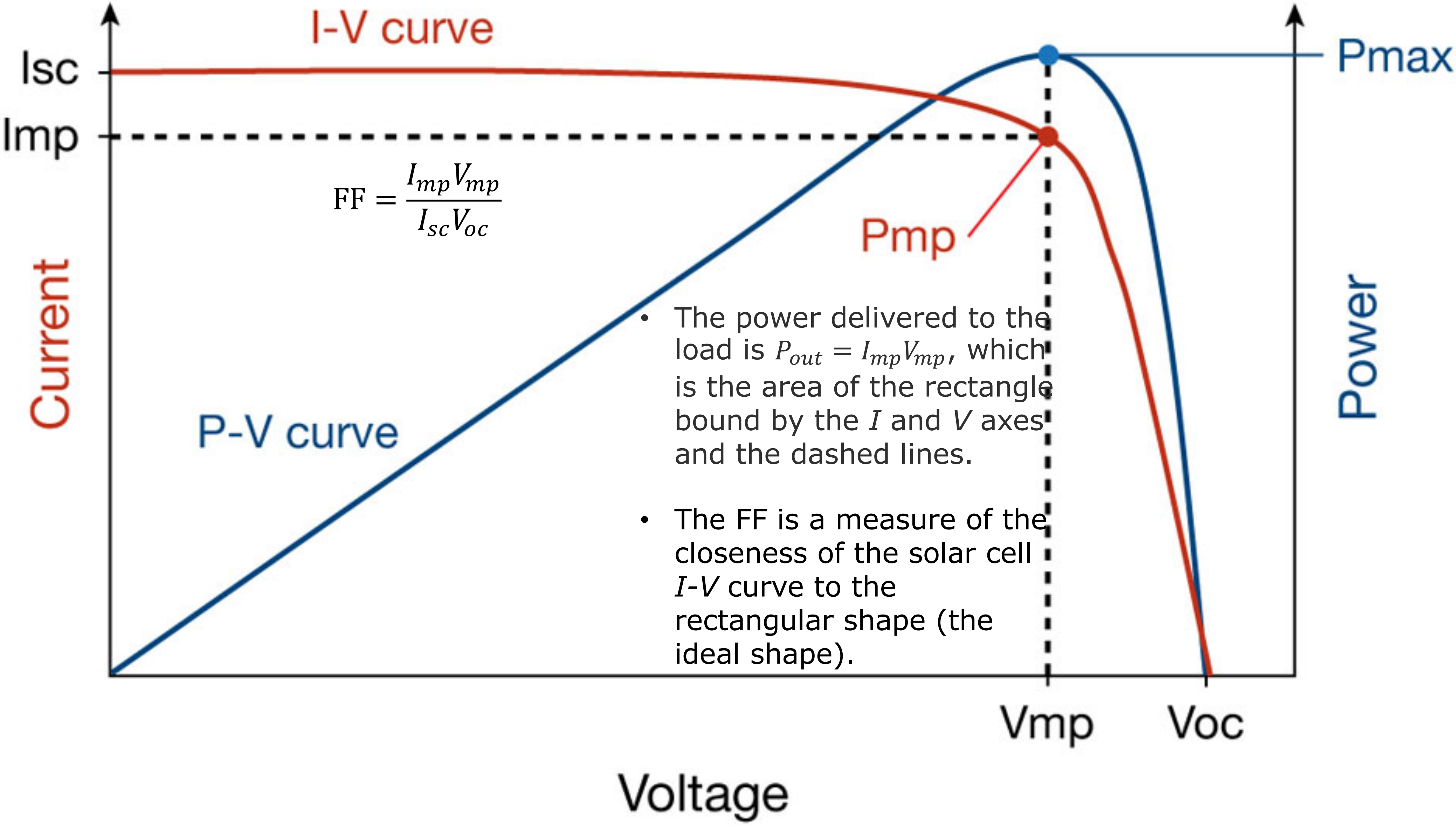
- Typical I–V characteristics of a Si solar cell. The *I–V* curves under illumination at intensities corresponding to 400, 800 and 1000 W m^{-2}

- Short circuit current increases with an increase in illumination.

- Load: Anything in an electrical circuit that, when the circuit is turned on, draws power from that circuit.



I-V Characterisitics



$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}$$

- The power delivered to the load is $P_{out} = I_{mp}V_{mp}$, which is the area of the rectangle bound by the I and V axes and the dashed lines.
- The FF is a measure of the closeness of the solar cell I-V curve to the rectangular shape (the ideal shape).

Revision Question - Power from a Solar Cell

Consider the solar cell with an efficiency of 20%. This cell has an area of 3 cm x 3 cm and is illuminated with light of intensity $700\ W/m^2$.

What is the maximum power generated by this cell?

a. 4.2 W　　b. 0.13 W　　c. 0.18 W　　d. 1260 W

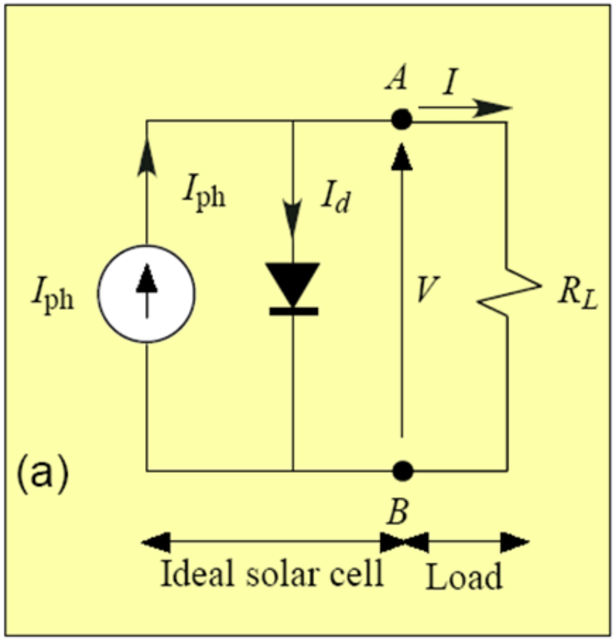
Revision Question - Solution

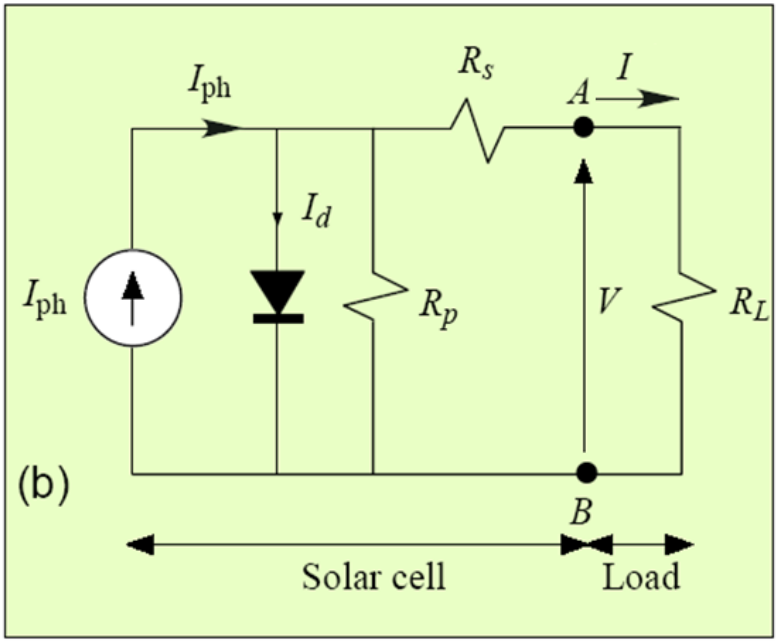
The correct answer is

a. 4.2 W   b. 0.13 W   c. 0.18 W   d. 1260 W

Ideal vs Practical Solar Cells

- Small signal equivalent circuit of an ideal and practical solar cell.





- Real solar cell includes **series resistance R_s** and **shunt resistance R_p** that diverts photocurrent away from R_L.

- The total current can be determined using Kirchhoff's Current Law.

$$I = I_{ph} - I_o\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]$$

$$I = I_L - I_o\left[\exp\left(\frac{V + IR_s}{\eta kT / q}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$

Effect of Resistance on Solar Cell Performance

Will the solar cell's short circuit current increase, decrease or stay the same when the series resistance increases ?

$$I = I_L - I_o\left[\exp\left(\frac{V + IR_s}{\eta kT / q}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$

Select one of the options below:

a. Increase b. Decrease c. Stay the Same d. Don't know

Effect of Resistance on Solar Cell Performance

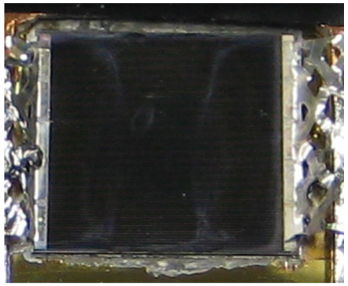
As the series resistance increases, the short circuit current will decrease (a)

a. Decrease   b. Increase   c. Stay the Same   d. Don't know

From the solar cell equation, it is clear that increasing the series resistance results in a greater voltage drop across that resistor, which leads to a reduction in the short circuit current and the output power.

Multi-junction Solar Cells

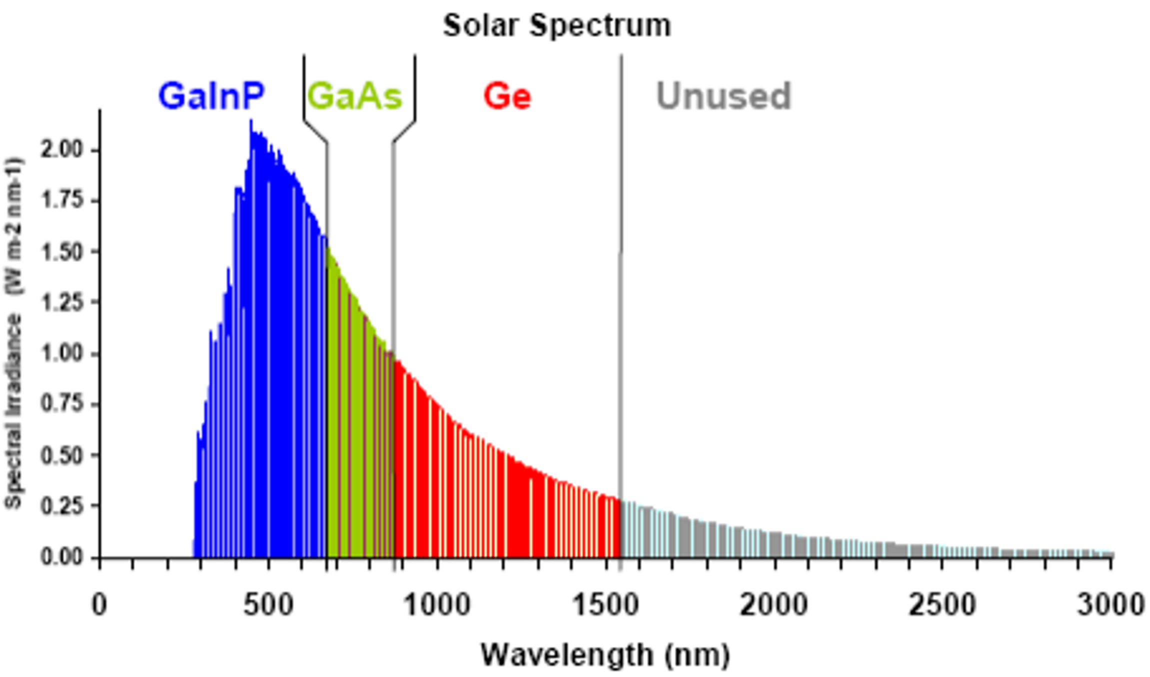
- Multijunction cells aim to increase the amount of absorbed photons from the incident light.



- For example, the first cell is made from a wide bandgap material to absorb photons with $hv > E_{g1}$.

- The second cell with bandgap E_{g2} absorbs photons that pass the first cell and have $hv > E_{g2}$, and so on.

- Such cells have efficiencies exceeding 30%.



Solar PV Panels

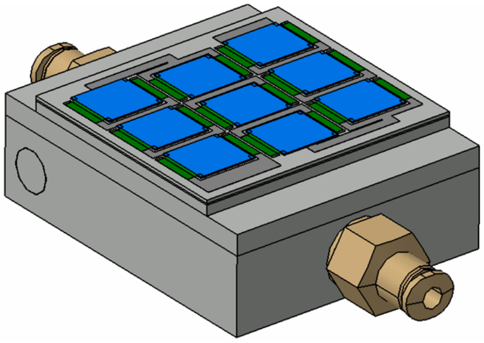
- Since each solar PV cell generates a small amount of power (approx. 1W), they are assembled and packaged into a complete panel or “module”.
- Cells are arranged in series and parralel. Bypass diodes are used to avoid “hotspots”.
- Most panel configurations are either 36, 42 or 72 cells.

https://www.pxfuel.com/en/search?q=solar+power+station

Concentrated Photovoltaics

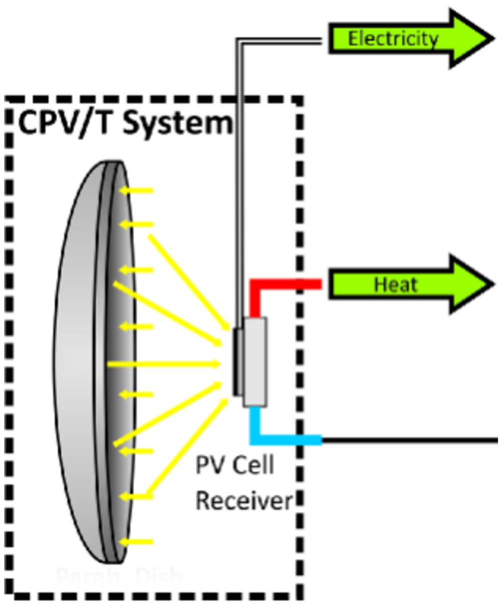
Among the obstacles to widespread use of solar electricity is the cost.

- In tackling the cost problem, we can:
    - Use less photovoltaic material.
    - Package more cells in a module.
    - Use less expensive optics.



Make use of excess heat generated from Concentrated PV (CPV) systems to drive an auxiliary system.

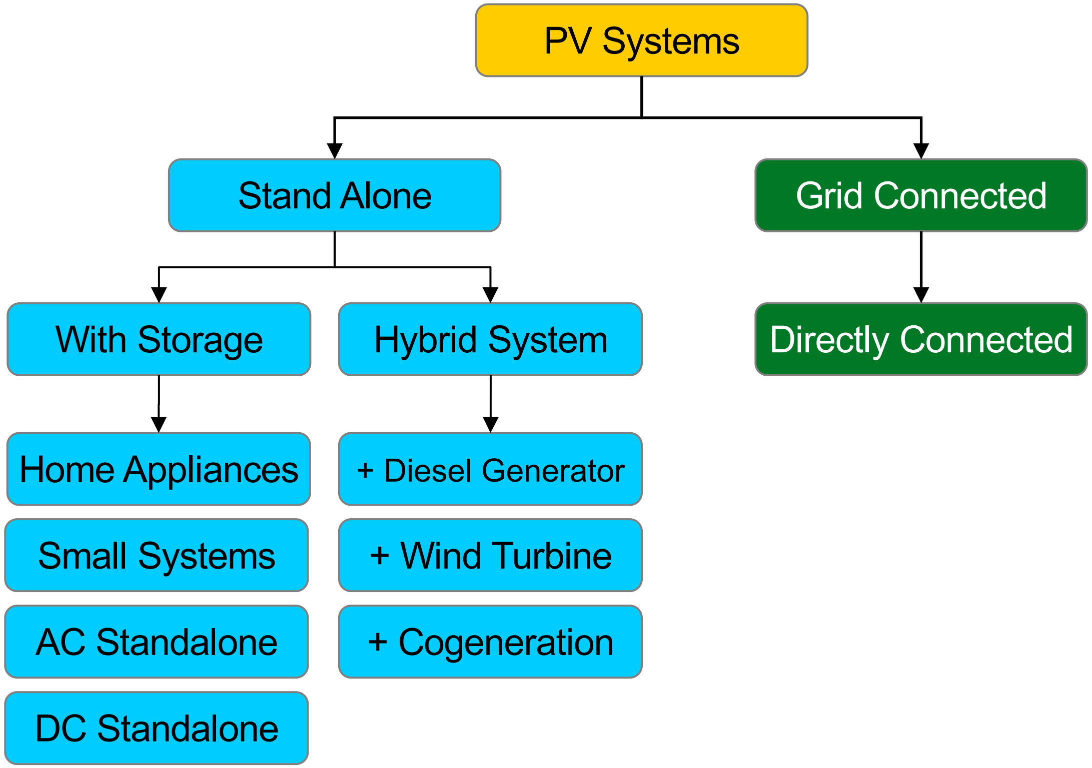
- Overall CPV system acts as a Combined Heat and Power system.
- Excess heat can be used for water desalination, space heating, cooling, storage, … etc.



PV System Types

PV systems can be dvided into two broad groups:

1. **Grid Connected:** PV Systems that directly feed electricity to the national grid.
2. **Stand-alone (autonomous):** Very first application of PV, in case there was no electricity supply from national grid. Main components include PV Modules, Charge Controllers, Battery Bank, Inverter and Loads.



Balance of Systems (BoS)

Typical components in a PV System include:

Batteries, Inverters, Charge controllers,

Bypass/Blocking diode(s),

Cables and connectors,

Over-current protection and disconnectors,

Combiner boxes, Grounding hardware,

Lightning protection,

Mounting and stainless fastening hardware,

Other essential system and associated components.

Autonomous PV System

Self-sufficient and not backed up by another generating source. They normally include batteries.

Areas of application:

Isolated facilities (cottages, fish farms, hunting lodges, etc.).

Telecommunication systems (transmitters, repeaters, base stations).

Street lighting, bus stops, parking lots, various signaling.

Mobile Units, camping cottages, campers and boats.

Systems for automatic acquisition and tracking data.

https://k2-systems.com/en/news/details/swiss-transmission-mast-produces-own-solar-power

Telecomms Tower in Switzerland

Autonomous PV System

The first step in designing a solar PV system is to find out the total power and energy consumption of all loads that need to be supplied by the solar PV system as follows:

The daily energy use will be:

<Number of appliances × Power consumption × operation time (hrs) per day >

https://commons.wikimedia.org/wiki/File:Solar_water_pump.jpg