



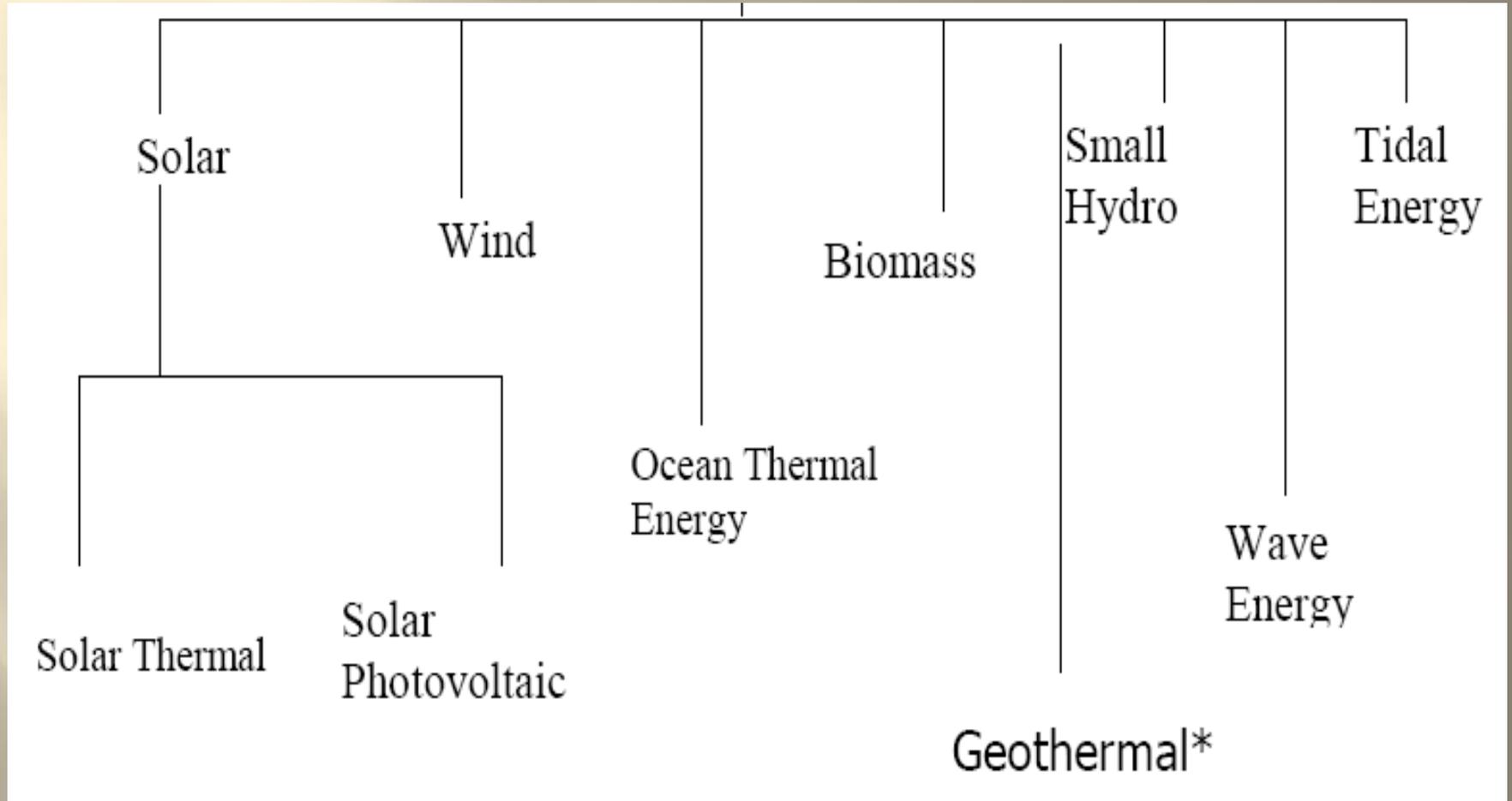
CHEMISTRY 5570

Advanced Analytical Chemistry Lecture 10



Solar Cells

Renewable Energy Options



Solar Cells

PV as Renewable energy source

Absorption of light, photon, creates an electric current thus converts light directly into the electric power, which is the most valuable form of energy.

- There are no moving parts, unlike the conventional energy sources, reduces the need of maintenance
- No fuel is necessary, this eliminate any environmental impact
- Long lifetime
- Modularity, size of the plant can be increased depending on the requirements
- Decentralized power generation

Solar Cells

Photovoltaics (PV) literally means "light-electricity"

Direct conversion of light into electricity based on the photovoltaic effect.

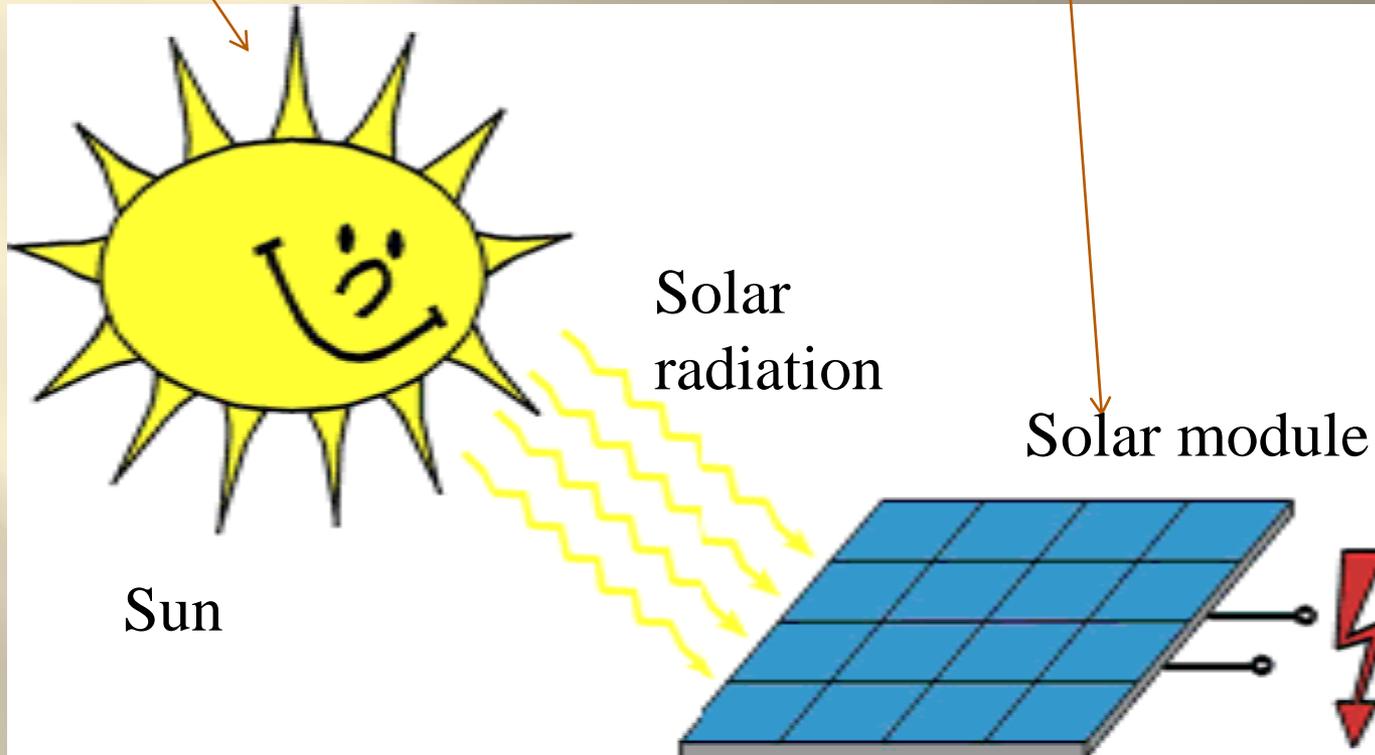
Advanced semiconductor device: solar cells



Solar Cells

Photo

voltaics



Solar Cells

Photovoltaic solar energy

Advantages:

- environmentally friendly
- no noise, no moving parts
- no emissions
- no use of fuels and water
- minimal maintenance requirements
- long lifetime, up to 30 years
- electricity is generated wherever there is light, solar or artificial
- PV operates even in cloudy weather conditions
- modular “custom-made” energy can be sized for any application from watch to a multi-megawatt power plant

Limitations:

- PV cannot operate without light
- high initial costs that overshadow the low maintenance costs and lack of fuel costs
- large area needed for large scale applications
- PV generates direct current special DC appliances or an inverter are needed
- an off-grid applications energy storage is needed

Solar Cells

Solar PV Technologies

Si solar cells

- Monocrystalline Si solar cell
- Multicrystalline Si solar cells

Multi-junction solar cells

- GaAs

Thin film solar cells

- Amorphous Si solar cells
- Microcrystalline, polycrystalline solar cells
- CdTe, CdS, GaAs solar cell
- CIGS (Cu-In-Ga-Diselenide) solar cells

Organic solar cells

- Dye-sensitized solar cells
- Small molecules
- Conducting polymers

Solar Cells

Solar Cell Operation

The basic steps in the operation of a solar cell are:

- Generation of light-generated carriers;
- Collection of the light-generated carriers to generate a current;
- Generation of a voltage across the solar cell; and
- Dissipation of power in the load and in parasitic resistances.

Solar Cells

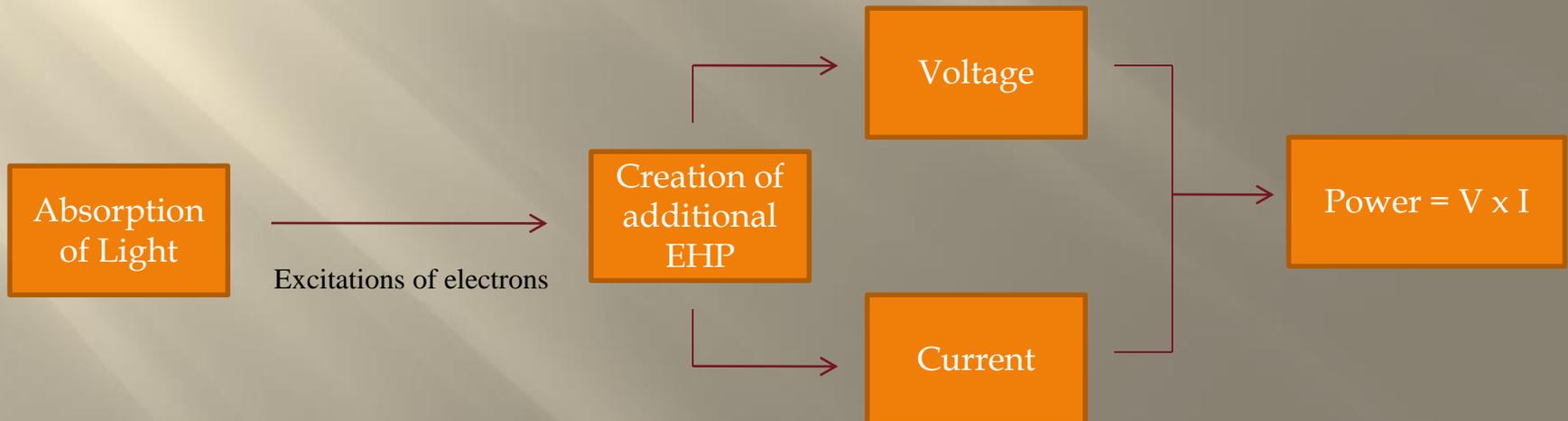
Photovoltaic Effect

Fundamental absorption is from:

- annihilation or absorption of photons by the excitation of an electron from the valence band to the conduction band
- leaves a hole in the valence band

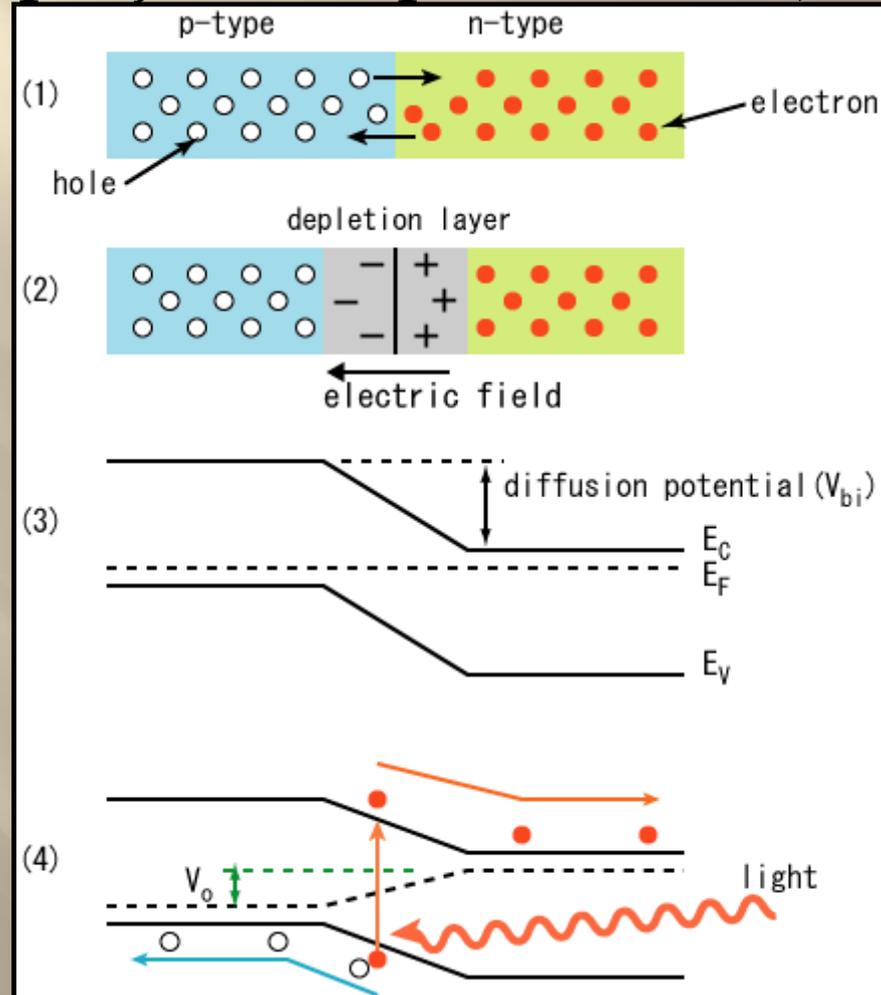
Ideally, each incident photon with $E_{h\nu} > E_G$ will create one electron flowing in the external device.

$E_{h\nu} < E_G$: semiconductor is transparent to light



Solar Cells

Conventional p-n junction photovoltaic (solar) cell



Solar Cells

Solar Cells

The photocurrent produces a voltage drop across the resistive load, which forward biases the pn junction.

Ideally, each incident photon with $E_{\text{hv}} > E_{\text{g}}$ will create one electron flowing in the external device.

$E_{\text{hv}} < E_{\text{g}}$: the device is transparent to the incident light.

$E_{\text{hv}} \geq E_{\text{g}}$: photons are absorbed and EHP are photogenerated in the device.

$E_{\text{hv}} > E_{\text{g}}$: energy generated is lost as heat to the device.

Solar Cells

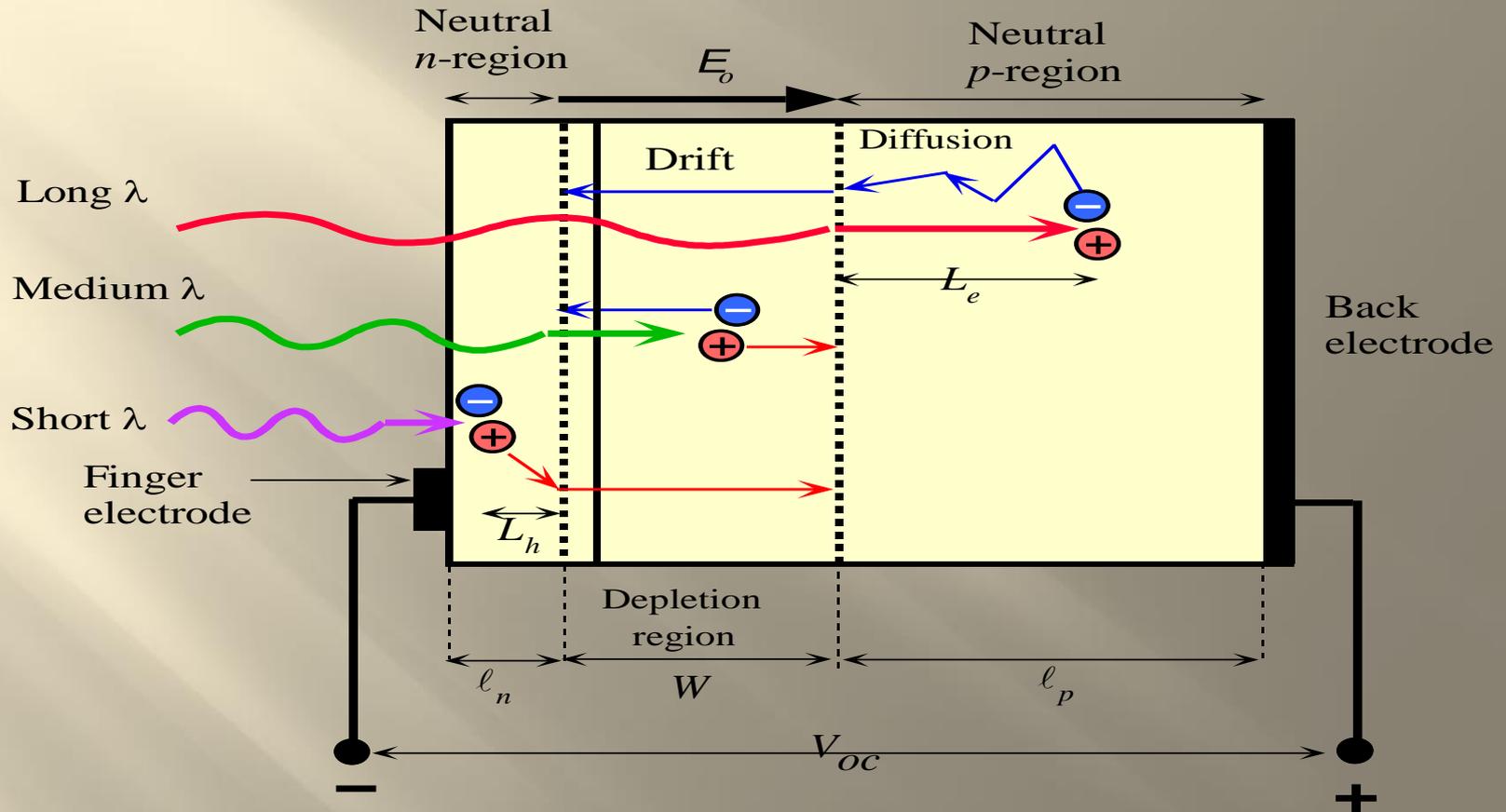
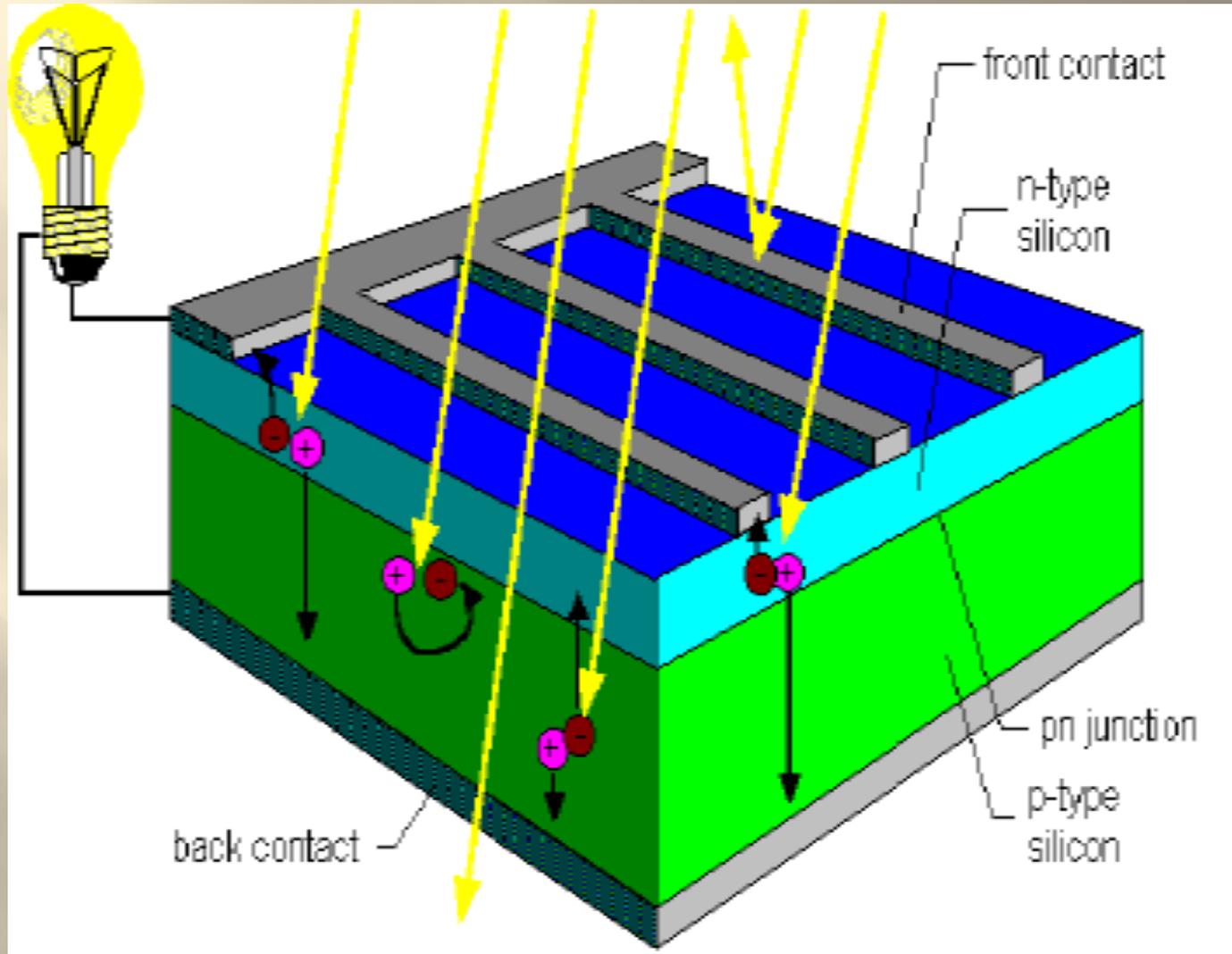


Fig. 6.49: The principle of operation of the solar cell (exaggerated features to highlight principles)

Solar Cells

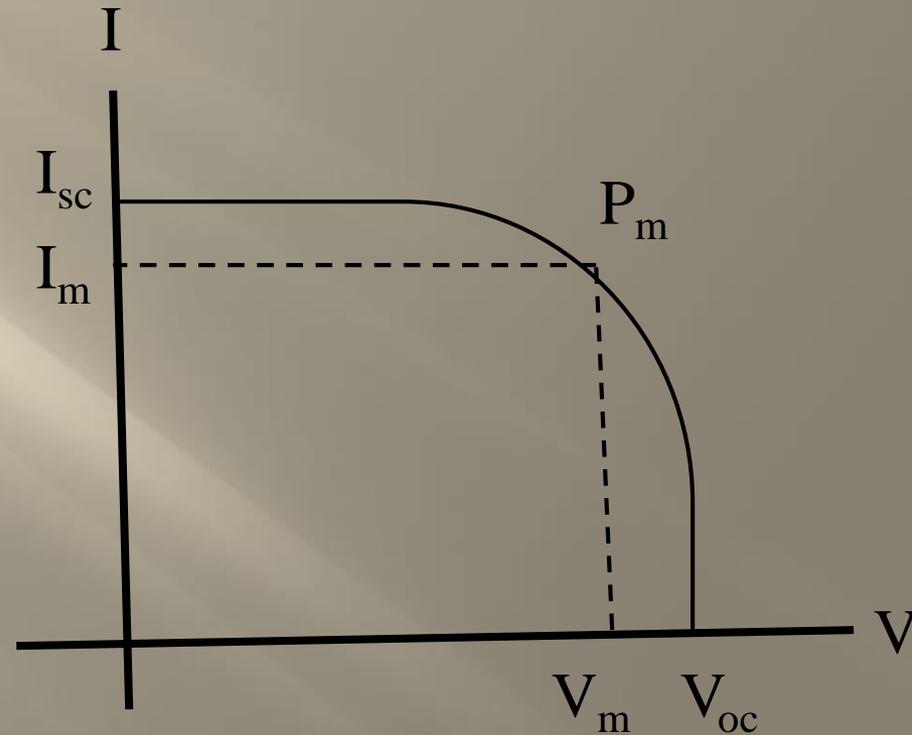


Solar Cells

Solar Cell I-V Curve

Solar cell parameters

- V_{oc} -open circuit voltage
- I_{sc} -short circuit current
- P_m -maximum power point
- I_m , V_m -current and voltage at maximum power point
- FF-Fill factor
- η -Efficiency
- R_s -series resistance
- R_{sh} -shunt resistance

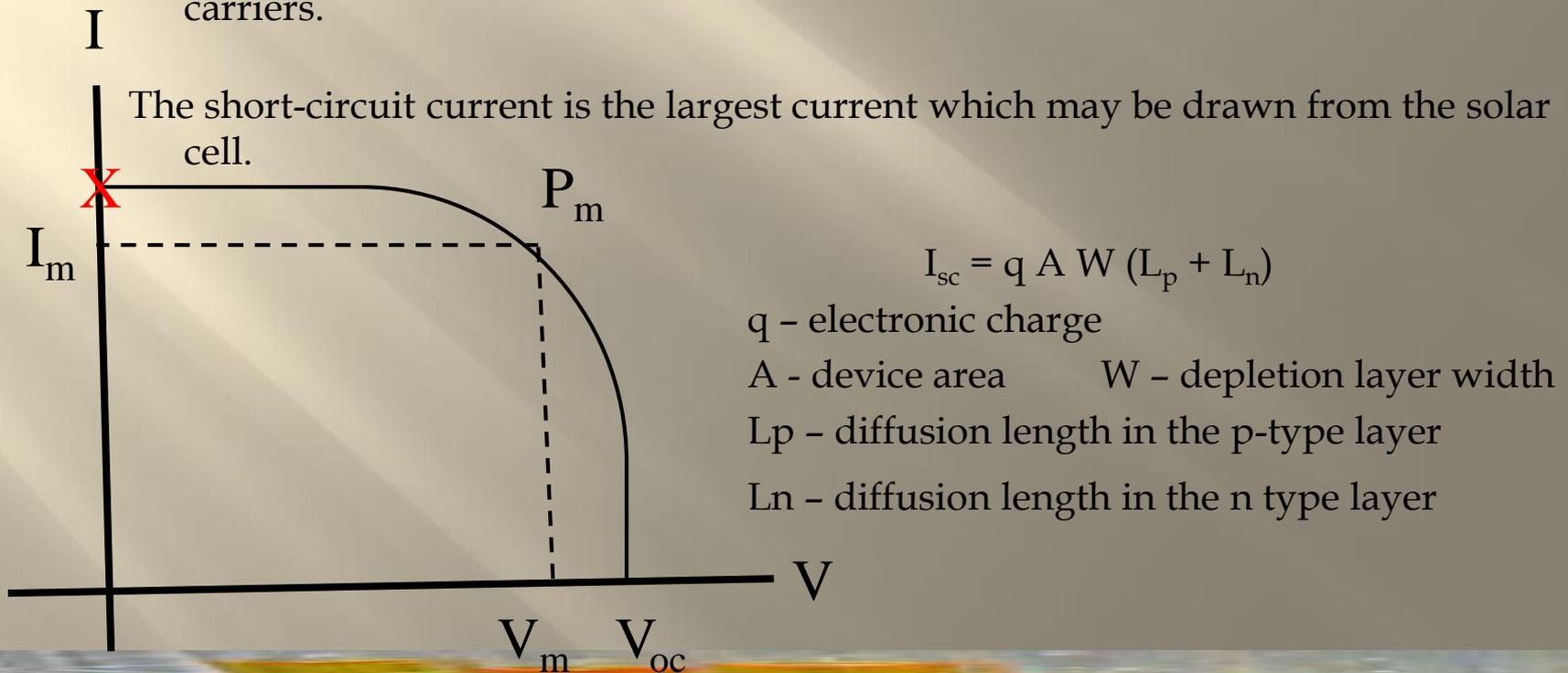


Solar Cells

Short-Circuit Current, I_{sc}

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited).

The short-circuit current is due to the generation and collection of light-generated carriers.



Solar Cells

Short-Circuit Current, I_{sc}

The short-circuit current depends on a number of factors :

- The area of the solar cell.
- The number of photons (i.e., the power of the incident light source).
- The spectrum of the incident light. For most solar cell measurement, the spectrum is standardized to the AM1.5 spectrum.
- The collection probability of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base.
- Optical properties (absorption and reflection) of the solar cell.

Solar Cells

Short-Circuit Current dependence on Cell area, Number of photons

Requirement for solar cell area?

Design criteria for area : It should be large

Larger area will intercept more photons → more current

Requirement in terms of solar power/intensity or number of photon in the spectrum?

Larger solar radiation intensity will provide more number of photons → more current

Solar Cells

Short-Circuit Current dependence on The spectrum of the incident light

The air mass represents the proportion of atmosphere that the light must pass through before striking the Earth relative to its overhead path length.

- Solar spectrum standards: AM 0, AM1, AM1.5

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

Where theta is the angle of sun rays

- AM 0 - solar radiation outside the earth atmosphere
- AM 1 - solar radiation when sun is exactly overhead
- AM 1.5 -when sun makes about 48 degree from zenith

Solar Cells

Short-Circuit Current dependence on Absorption probability

- Blue light gets absorbed very close to the surface
- Green light penetrates deeper than the blue light
- Red light gets uniformly absorbed

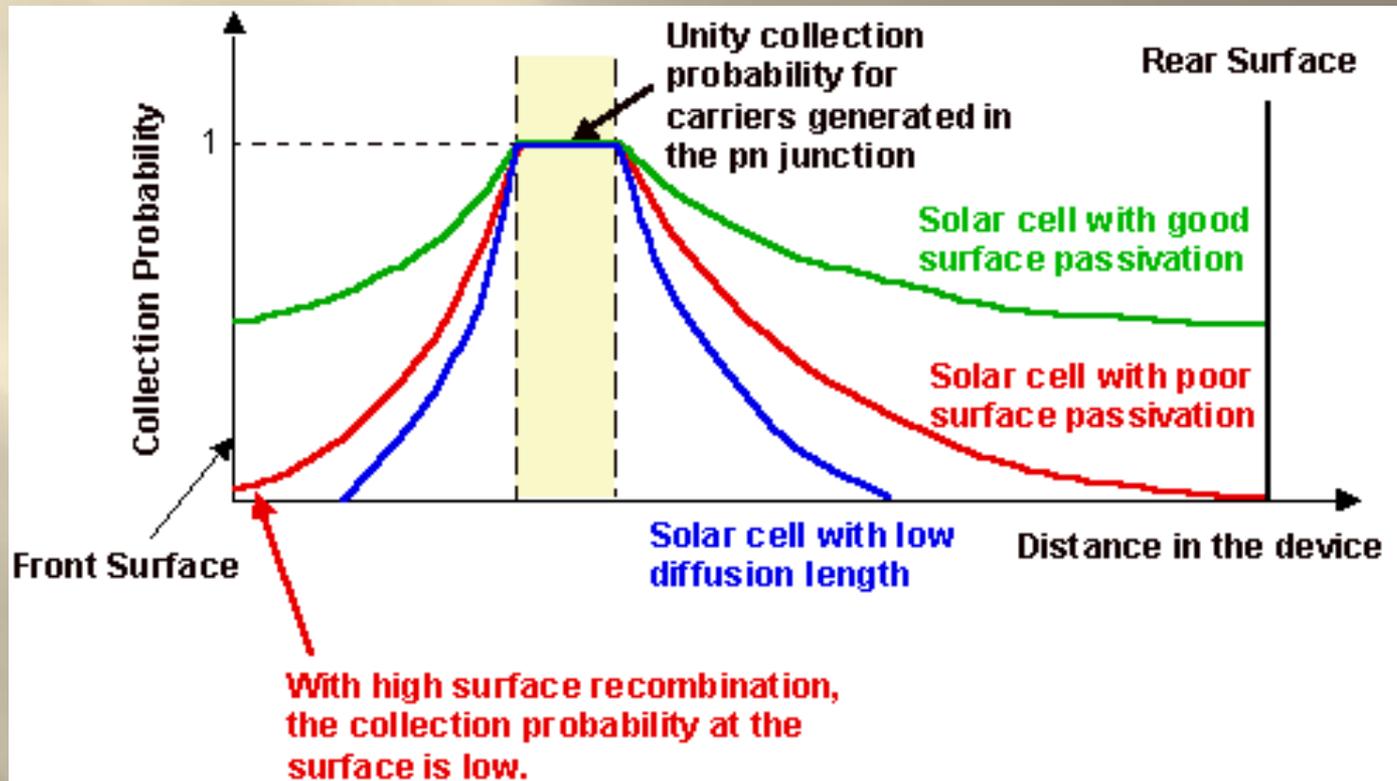
- Penetration depth = $1 / \text{absorption coefficient}$

A non-uniform generation causes a spectral dependence in the light-generated current

Solar Cells

Short-Circuit Current and Collection probability of light generated, EHP

A non-uniform probability \rightarrow spectral dependence of current.



Solar Cells

Short-Circuit Current and Quantum efficiency (QE)

QE is the ratio of number of electrons collected by a solar cell per unit photon of a given energy (wavelength).

External quantum efficiency (EQE) and Internal quantum efficiency (IQE)

EQE is the probability of a incident photon contributing to one electron to the short circuit current

$$EQE(\lambda) = \frac{\Delta J}{q\Delta\Phi_{\lambda}}$$

Where J is current and Φ is the flux of photon

Solar Cells

Short-Circuit Current and Quantum efficiency (QE)

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External quantum efficiency (EQE) and Internal quantum efficiency (IQE)

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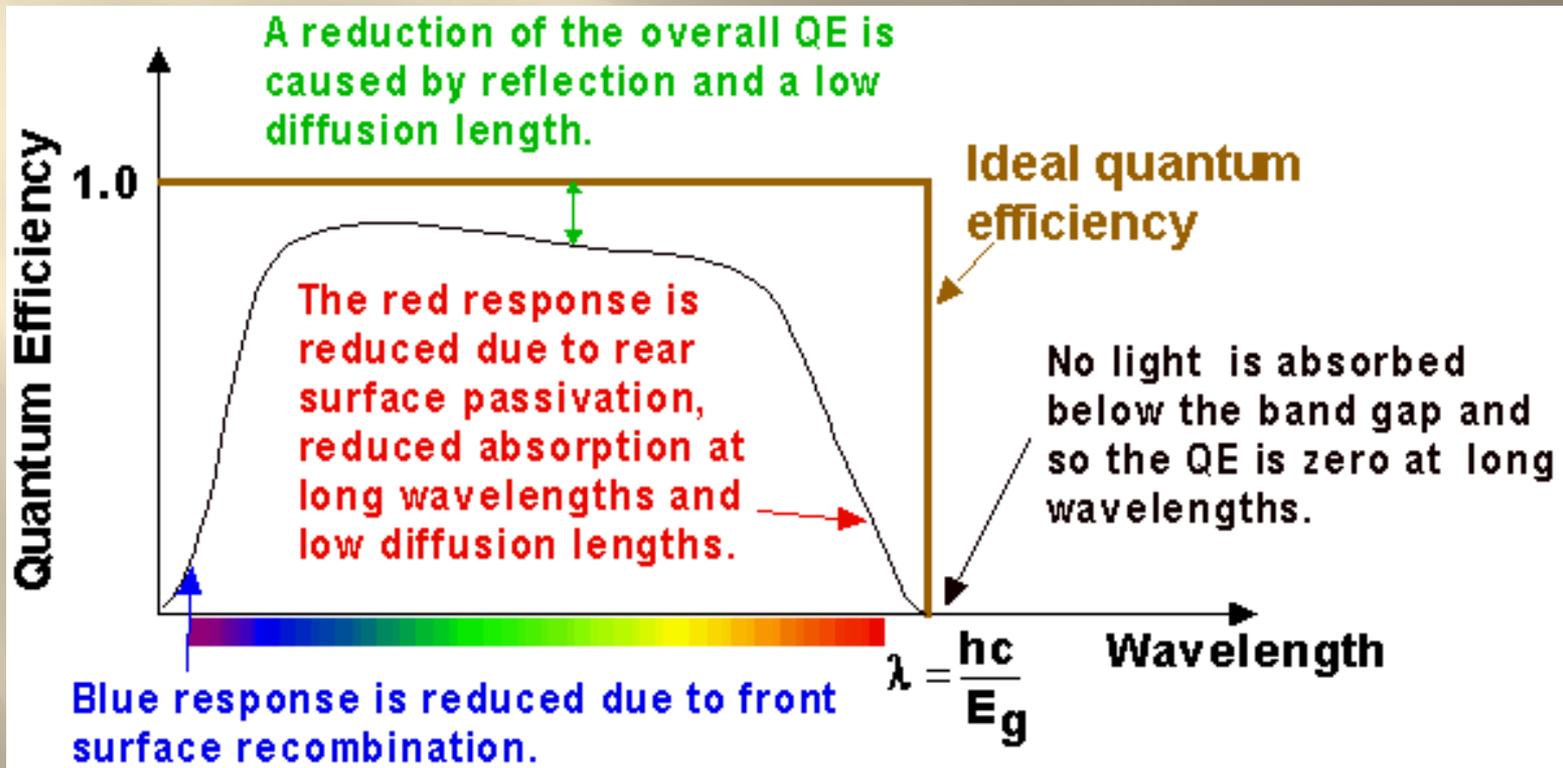
$$IQE(\lambda) = \frac{EQE}{1 - R(\lambda) - T(\lambda)}$$

Where R is reflectance and T is transmittance of the material

Solar Cells

Short-Circuit Current and Quantum efficiency (QE)

QEs are function of wavelength and it depends on many parameters (absorption, reflection, surface properties, recombination)



Solar Cells

Short-Circuit Current and Optical properties of surface

Photons in the spectrum can generate EHP, ideally all the sun light falling on the cell should be absorbed

- Short circuit current is usually reduced due to optical losses

What are optical losses:

- Reflection
- Shadowing due to metal contact
- Partial absorption

Design criteria for small optical losses: minimize optical loss.

Solar Cells

Open Circuit Voltage: Voc

The open-circuit voltage, V_{oc} , is the maximum voltage available from a solar cell, and this occurs at zero current.

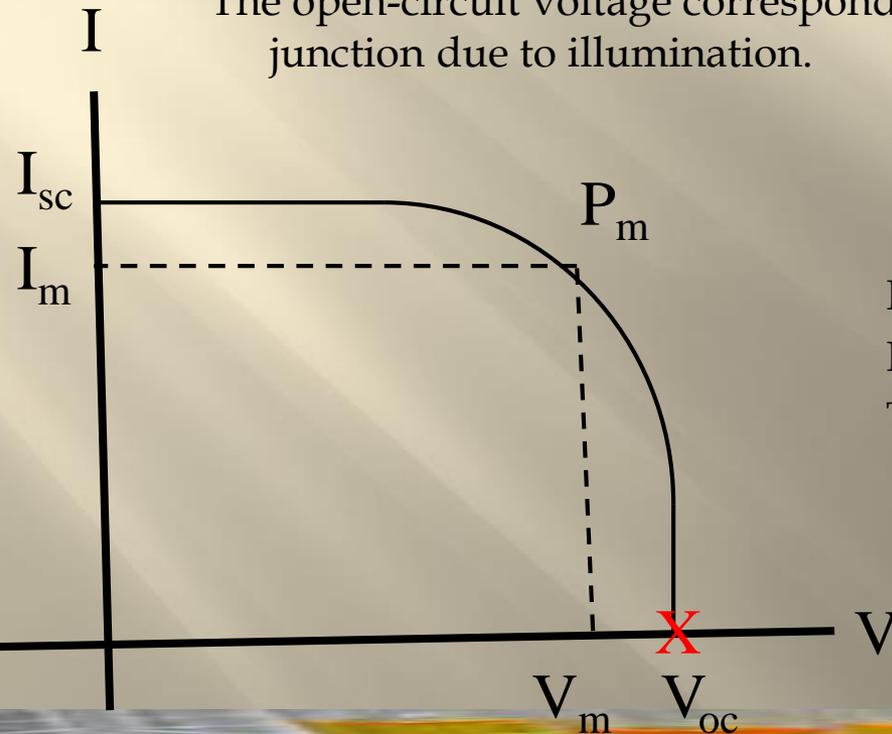
The open-circuit voltage corresponds to the amount of forward bias on the solar cell junction due to illumination.

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{I_L}{I_0} + 1 \right)$$

I_L - light generated current, photocurrent

I_0 - reverse saturated current

T - temperature k - Boltzmann constant

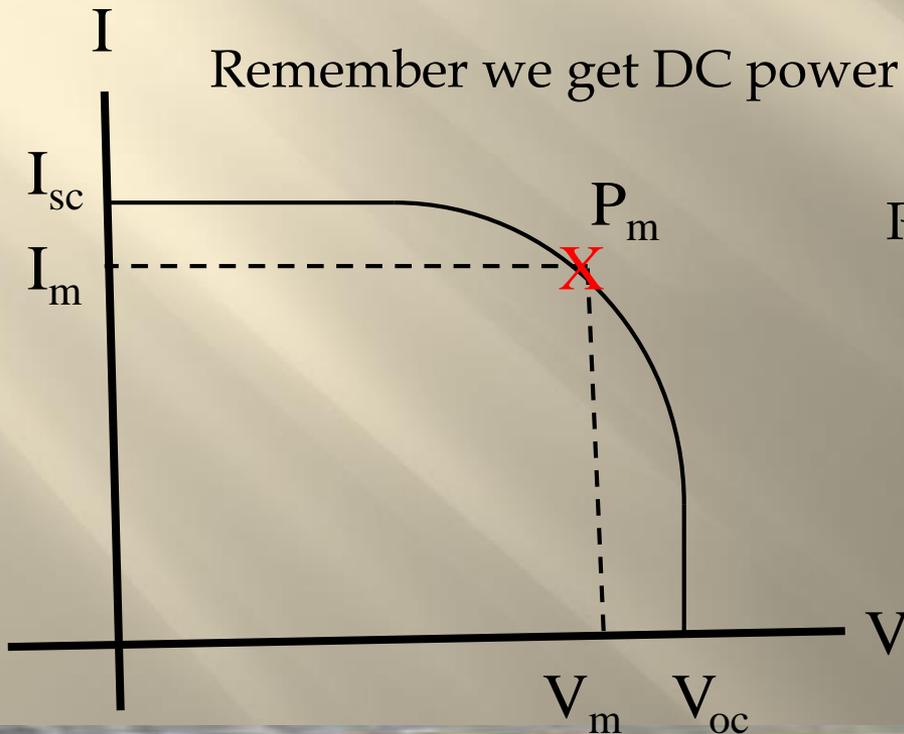


Solar Cells

Maximum power: P_m

Power out of a solar cell increases with voltage, reaches a maximum (P_m) and then decreases again.

Remember we get DC power from a solar cell

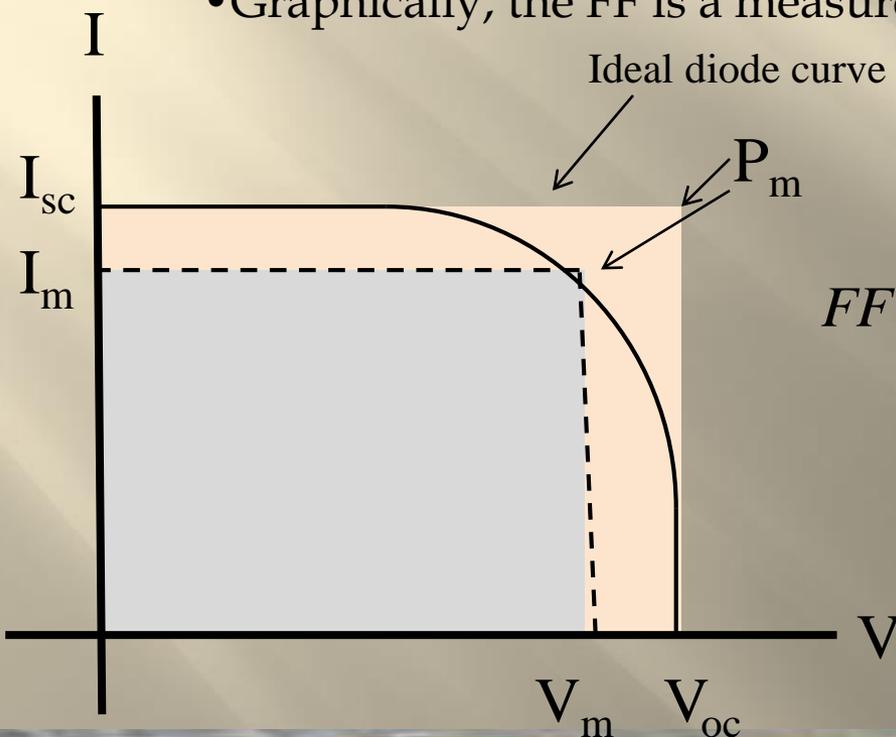


$$P_m = I_m \times V_m$$

Solar Cells

Fill Factor: FF

- The FF is defined as the ratio of the maximum power from the actual solar cell to the maximum power from an ideal solar cell
- Graphically, the FF is a measure of the "squareness" of the solar cell.



$$FF = \frac{\text{Max power from real cell}}{\text{Max power from ideal cell}} = \frac{V_m I_m}{V_{oc} I_{sc}}$$

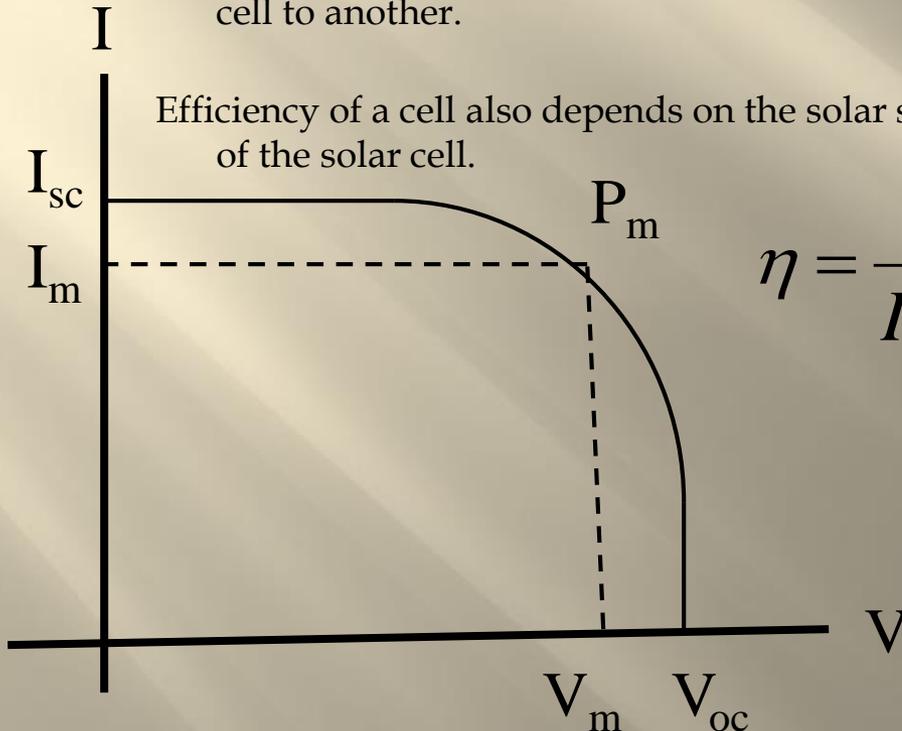
Solar Cells

Efficiency: η

Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun.

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another.

Efficiency of a cell also depends on the solar spectrum, intensity of sunlight and the temperature of the solar cell.



$$\eta = \frac{\text{Max Cell Power}}{\text{Incident light Intensity}} = \frac{V_m I_m}{P_{in}}$$

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

Solar Cells

- Efficiency is limited due to several factors.
 - The energy of photons decreases at higher wavelengths.
 - Radiation with higher wavelength causes only heating up of solar cell and does not produce any electrical current.
 - Each photon can cause only production of one electron-hole pair.
 - The highest efficiency of silicon solar cell is around 23%, some other semi-conductor materials up to 30%, which is dependent on wavelength and semiconductor material.
 - Self losses are caused by metal contacts on the upper side of a solar cell, solar cell resistance and due to solar radiation reflectance on the upper side (glass) of a solar cell.
 - Other non-ideal parameters.

Solar Cells

Non-Idealities

- Bulk defects – dislocations and stacking faults, due to lattice mismatch with the substrate.
- Surface recombination defects – EHP generated by the absorption of light can recombine before they cross the junction, therefore not contributing to the power output of the solar cell.
- Bulk recombination defects – EHP generated further away from the junction have a large probability of recombining before they reach the device terminals.
- Insufficient photon energy: $h\nu < E_g$
- Excessive photon energy : $h\nu > E_g$
- Solar cell is too thin – some of the light of the appropriate energy is not coupled into the cell and is passed through the device.
- Open circuit Voltage (V_{OC}) losses – recombination of EHP in trap levels in the depletion region that lowers V_{OC} .
- Fill Factor losses – related to V_{OC} , series resistance, and shunt resistance.
- Reflection losses.

Solar Cells

Minimizing optical losses

There are a number of ways to reduce the optical losses:

Top contact coverage of the cell surface can be minimized.

Anti-reflection coatings can be used on the top surface of the cell.

Reflection can be reduced by surface texturing.

The solar cell can be made thicker to increase absorption.

The optical path length in the solar cell may be increased by a combination of surface texturing and light trapping.

Solar Cells

Anti-Reflection Coating

Prevents incident light from reflecting off of the device.

The AR coating needs to have the correct refractive index for the material system and be transparent.

Deposited as noncrystalline or amorphous layer which prevents problems with light scattering at grain boundaries.

A double layer AR coating reduces the reflection of usable sunlight to $\sim 4\%$.

Solar Cells

Choice of ARC

The thickness of a ARC is chosen such that the reflected wave have destructive interference → this results in zero reflected energy.

The thickness of the ARC is chosen so that the wavelength in the dielectric material is one quarter the wavelength of the incoming wave (destructive interference).

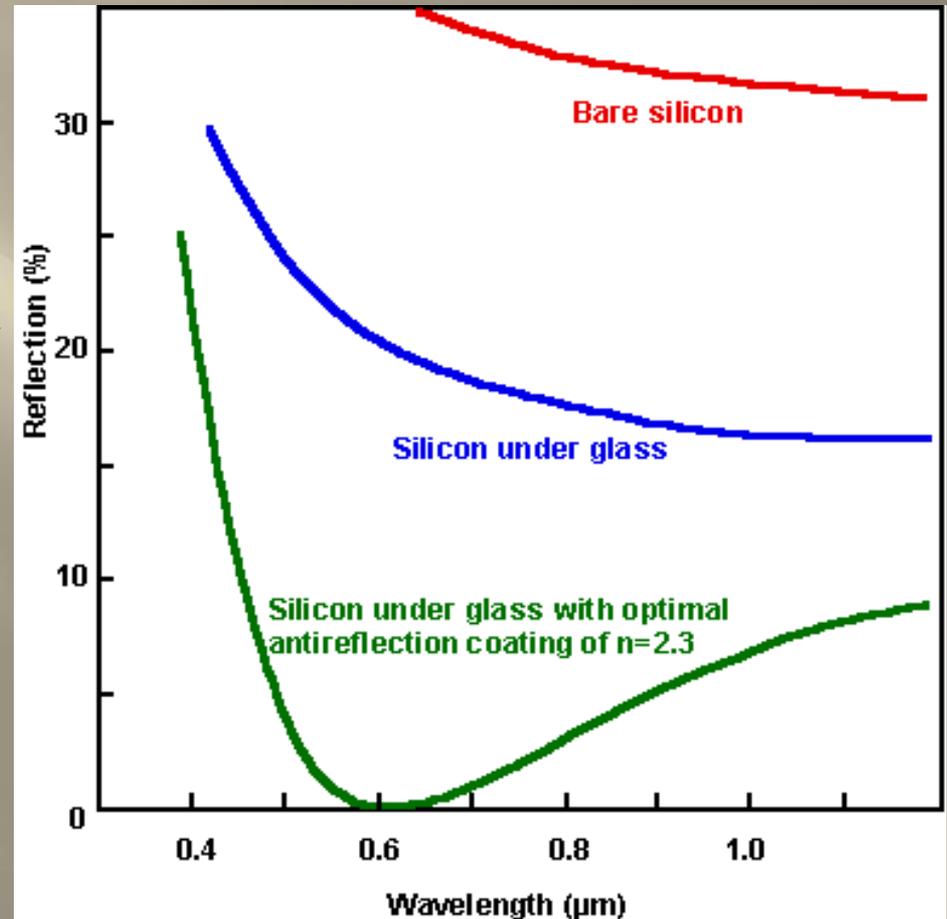
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Reflection from various combination

Index of refraction is also a function of wavelength, minimum reflection is obtained for one wavelength.

Multilayer structure reduces the reflection losses.

More than one ARC can be used, but expensive.



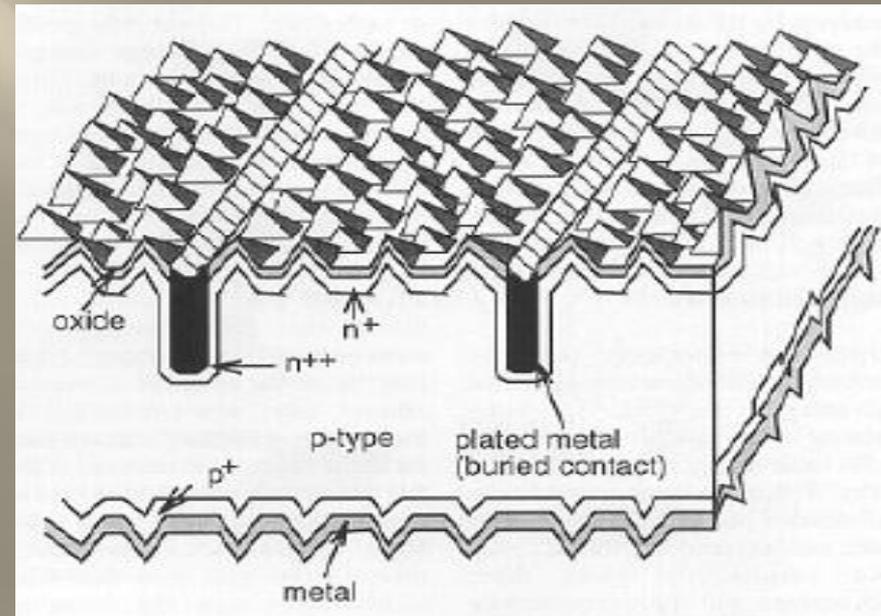
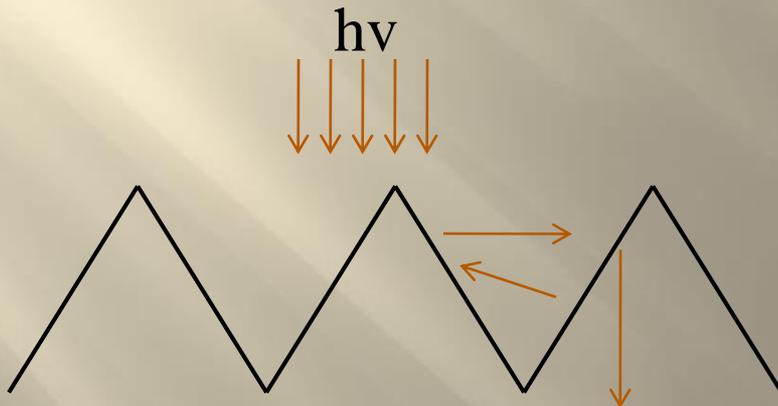
Solar Cells

Si Technology

Textured top layer

Incident light will:

- Become trapped
- Bounced around in the texture
- Absorbed in the device



Solar Cells

Surface texturing

Any rough surface decreases the reflection by increasing the chances of the reflected rays bouncing back on the surface

Surface texturing can be obtained by selective etching → a process by which material is removed by chemical reaction

Selective etching is based on the concept of different orientation properties in different direction in crystals

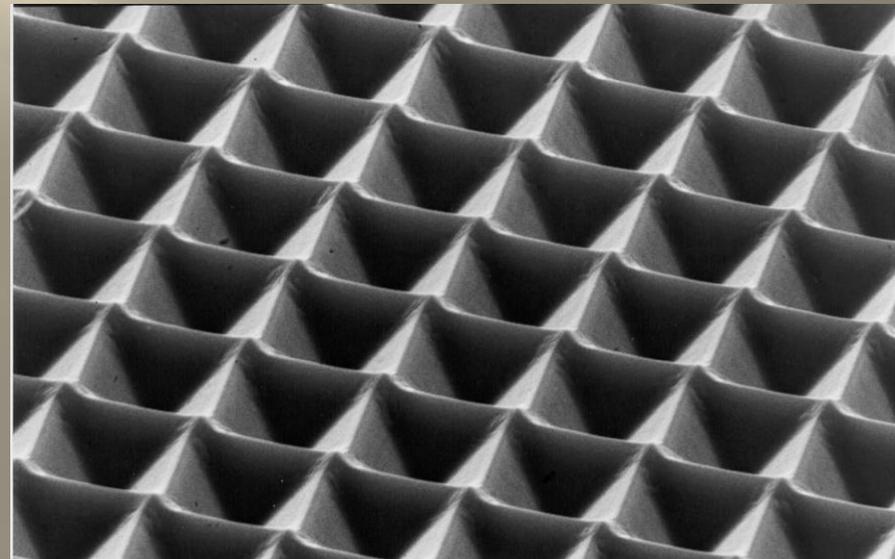
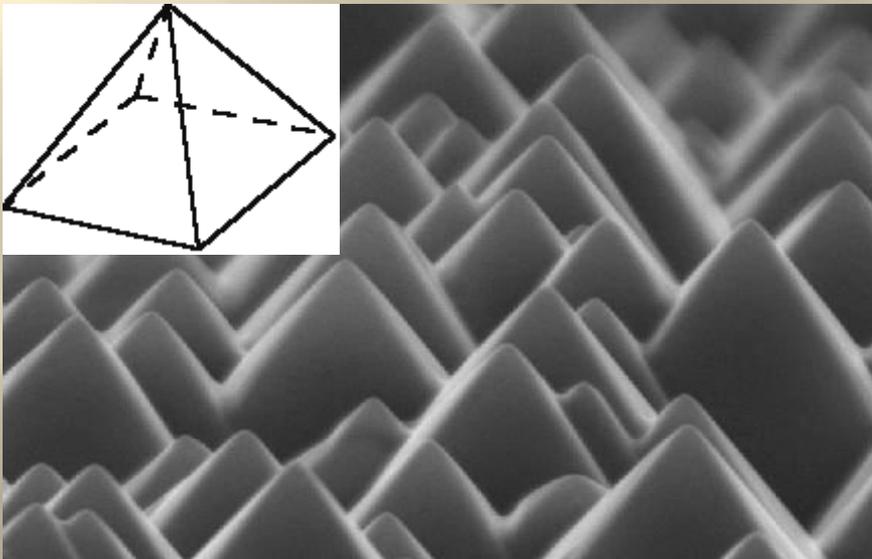
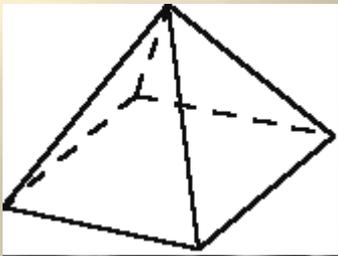
Etching rate are different in $\langle 100 \rangle$ dir than in $\langle 111 \rangle$ dir

Solar Cells

Surface texturing

Chemical etching in KOH results in pyramid formation on the Si surface \rightarrow etching is faster in $\langle 100 \rangle$ direction than in $\langle 111 \rangle$ direction

Using photolithography, inverted pyramids can be obtained, which are even more effective



Solar Cells

Light trapping

Rear side reflector or rear side texturing is used to increase the optical path length in solar cell

Increased optical path is required for thin solar cell (thin solar cell have higher V_{oc} . It saves expensive Si)

Total internal reflection (TIR) condition are used to increase the optical path length

Solar Cells

Current loss due to recombination

Recombination of carriers reduces both short circuit current as well as open circuit voltage.

Recombination areas

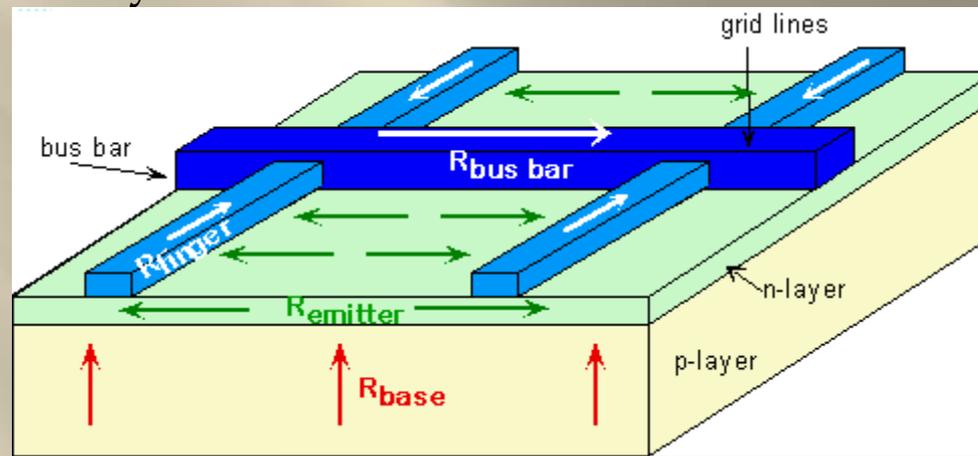
- Surface recombination
- Bulk recombination
- Depletion region recombination

Design criteria: The carrier must be generated within a diffusion length of the junction, so that it will be able to diffuse to the junction before recombining.

Solar Cells

Resistive Losses

Resistive effects (series and shunt resistance) in solar cells reduce the efficiency of the solar cell by dissipating power in the resistances. Both the magnitude and impact of series and shunt resistance depend on the geometry of the solar cell and solar cell area



Contributing factors to R_s :

1. the movement of current through the emitter and base of the solar cell
2. the contact resistance between the metal contact and the silicon
3. resistance of the top and rear metal contacts

Solar Cells

Resistance

There are electrodes attached to the n-side which allow illumination and form an array of electrodes.

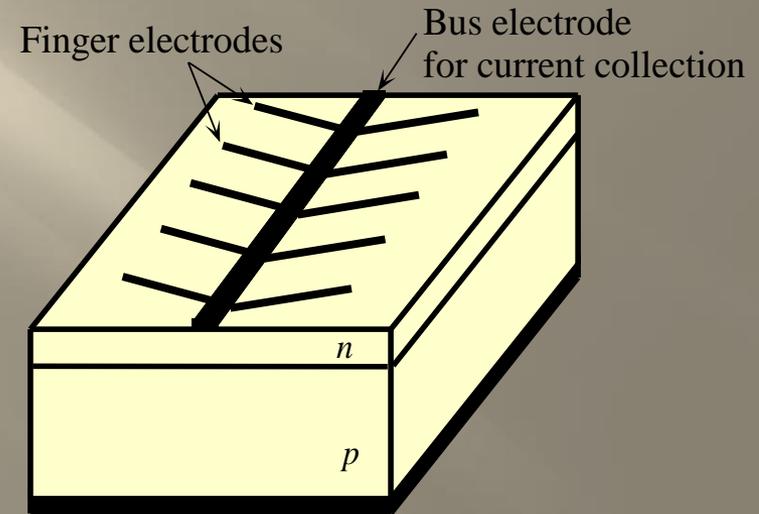
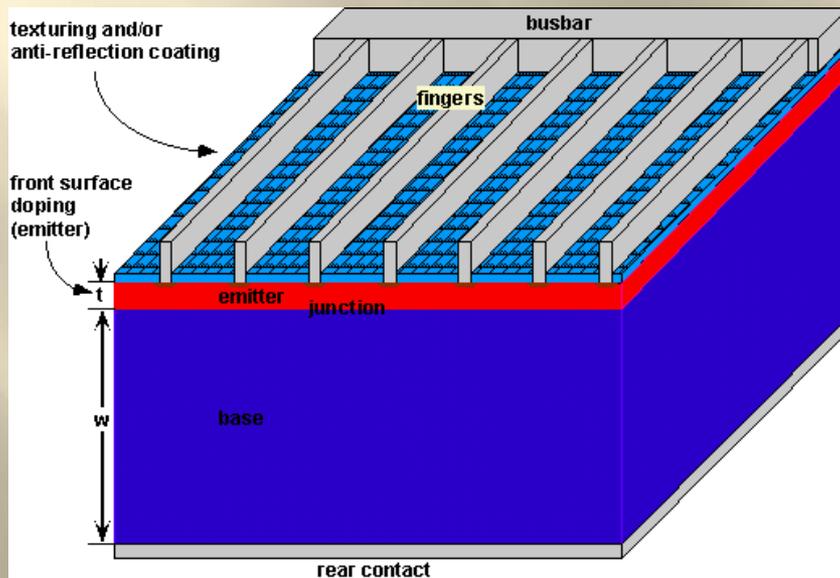
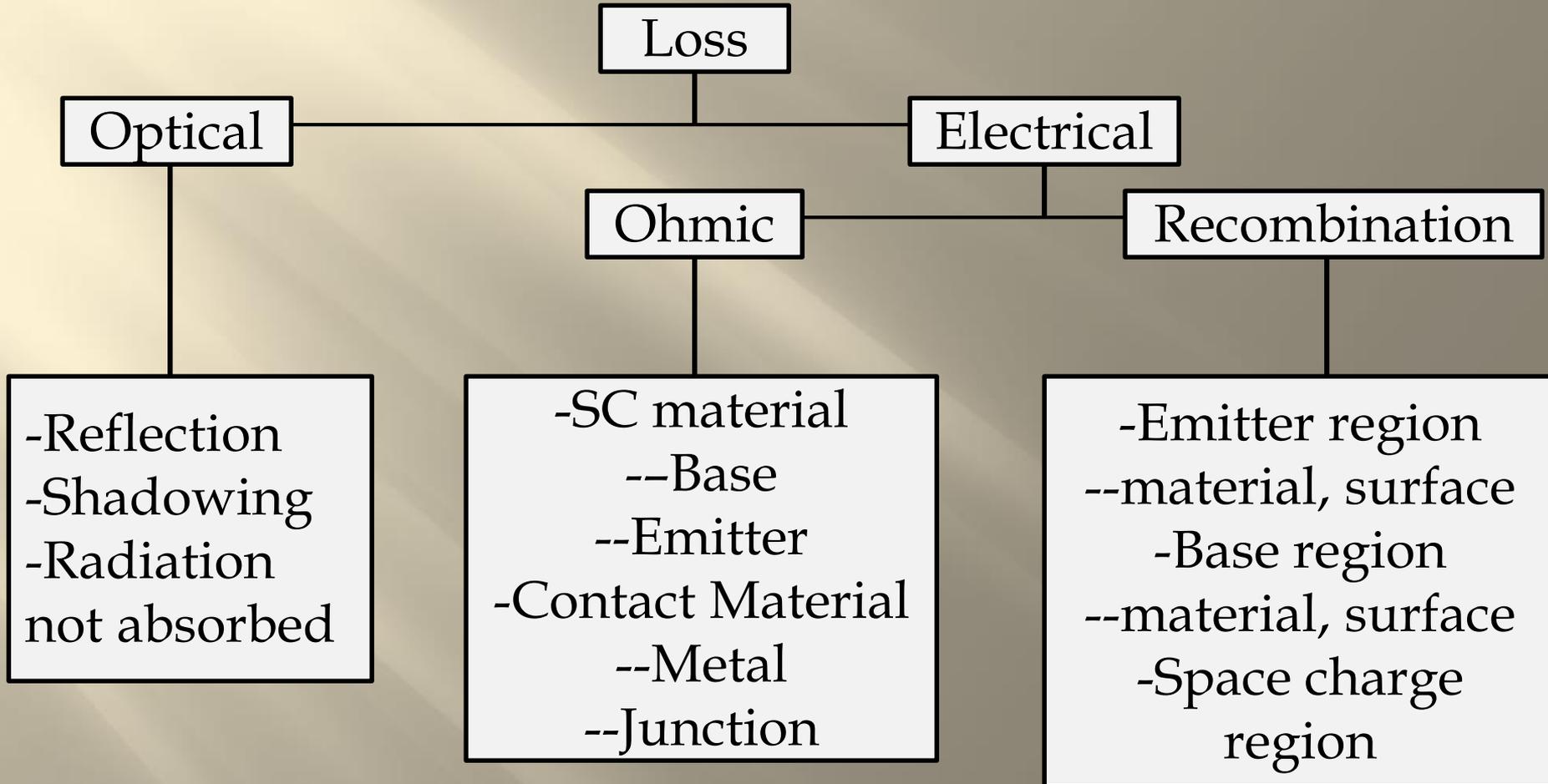


Fig. 6.50: Finger electrodes on the surface of a solar cell reduce the series resistance

Solar Cells

Summary of losses in Solar cell



Solar Cells

Challenge

To provide the world with 10 TW of solar electricity by 2030

Need to grow the industry by $\sim 35\%$ /year.

so far it has

Not run out of essential materials.

problem?

Make enough money in 2 years to double the factory size.

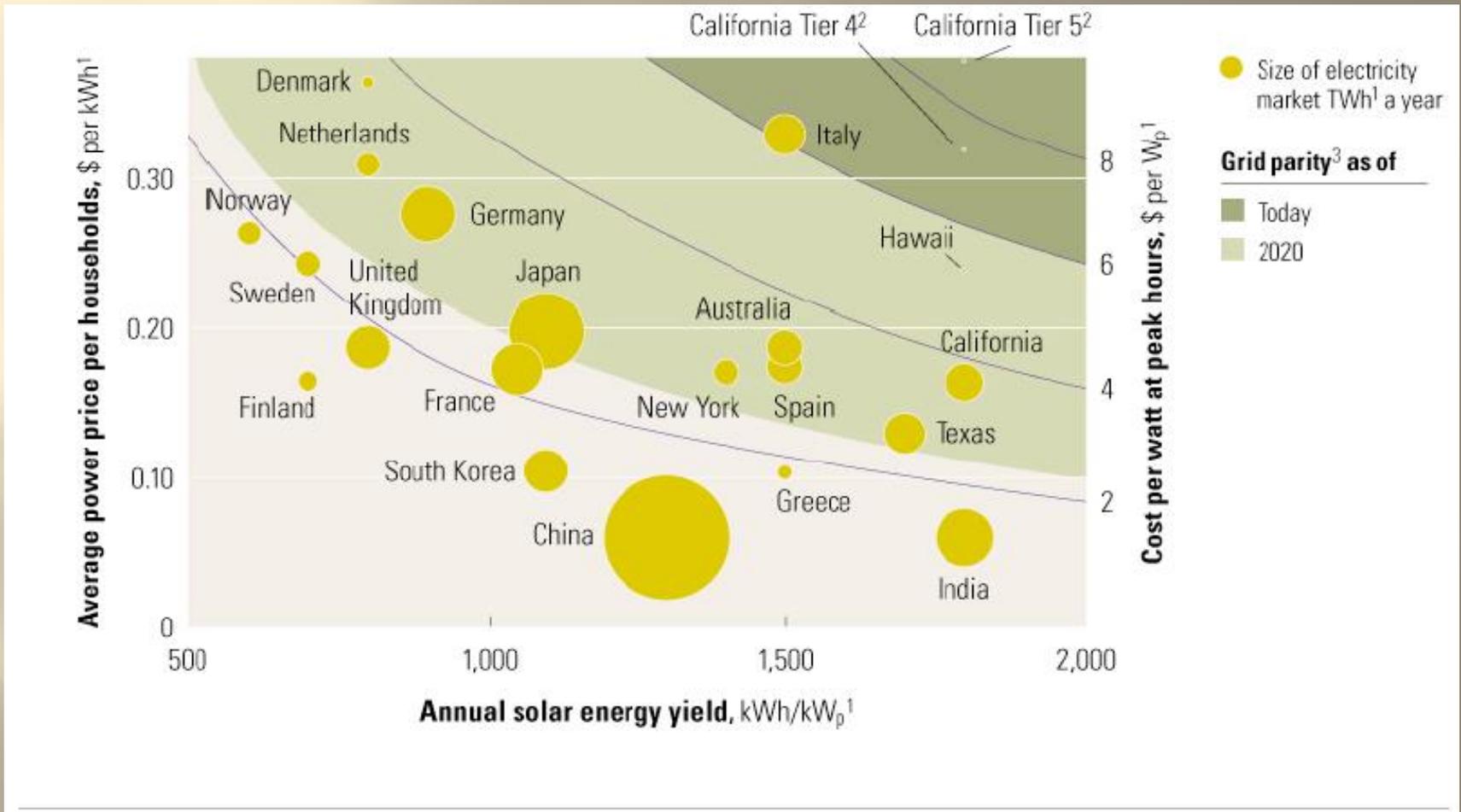
profits must be made

Get energy payback within two years so that we generate more power than we use.

1 year payback is not here yet

Solar Cells

The grid parity cost depends on location



Solar Cells

Requirement for ideal solar cell material

Bandgap between 1.1 to 1.7 eV

Direct band structure

Consisting of readily available, non-toxic material

Easily reproducible deposition techniques, suitable for large area production

Good PV conversion efficiency

Long-term stability

Solar Cells

Factors to consider when comparing technologies

Efficiency (and its effect on balance of system costs)

Cost

Throughput of equipment

Availability of necessary elements

Toxicity

Does it require direct (not diffuse) sunlight?

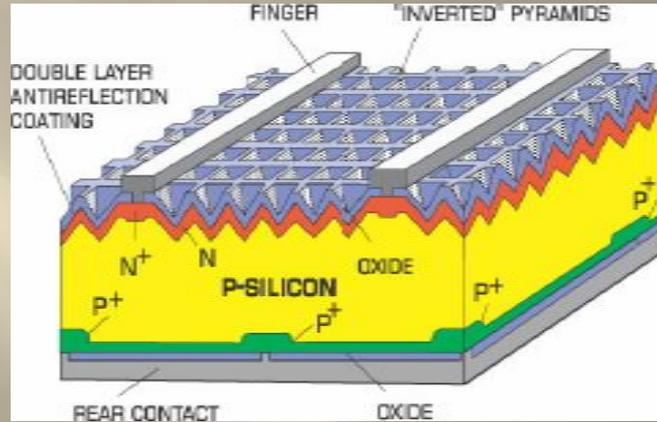
Aesthetics

There might be different winners for various applications.

Solar Cells

Three generations of solar cells

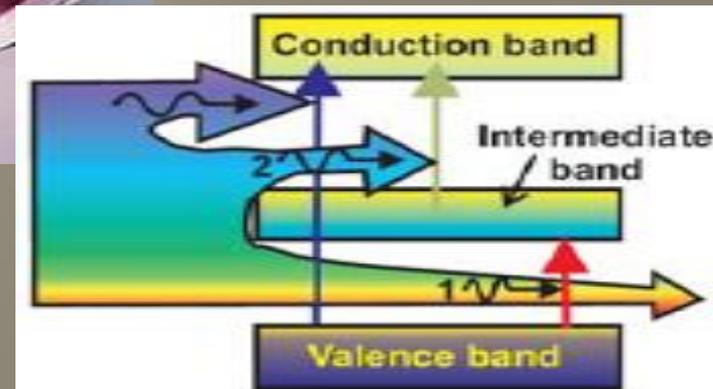
I. Wafer based Si



II. Thin films

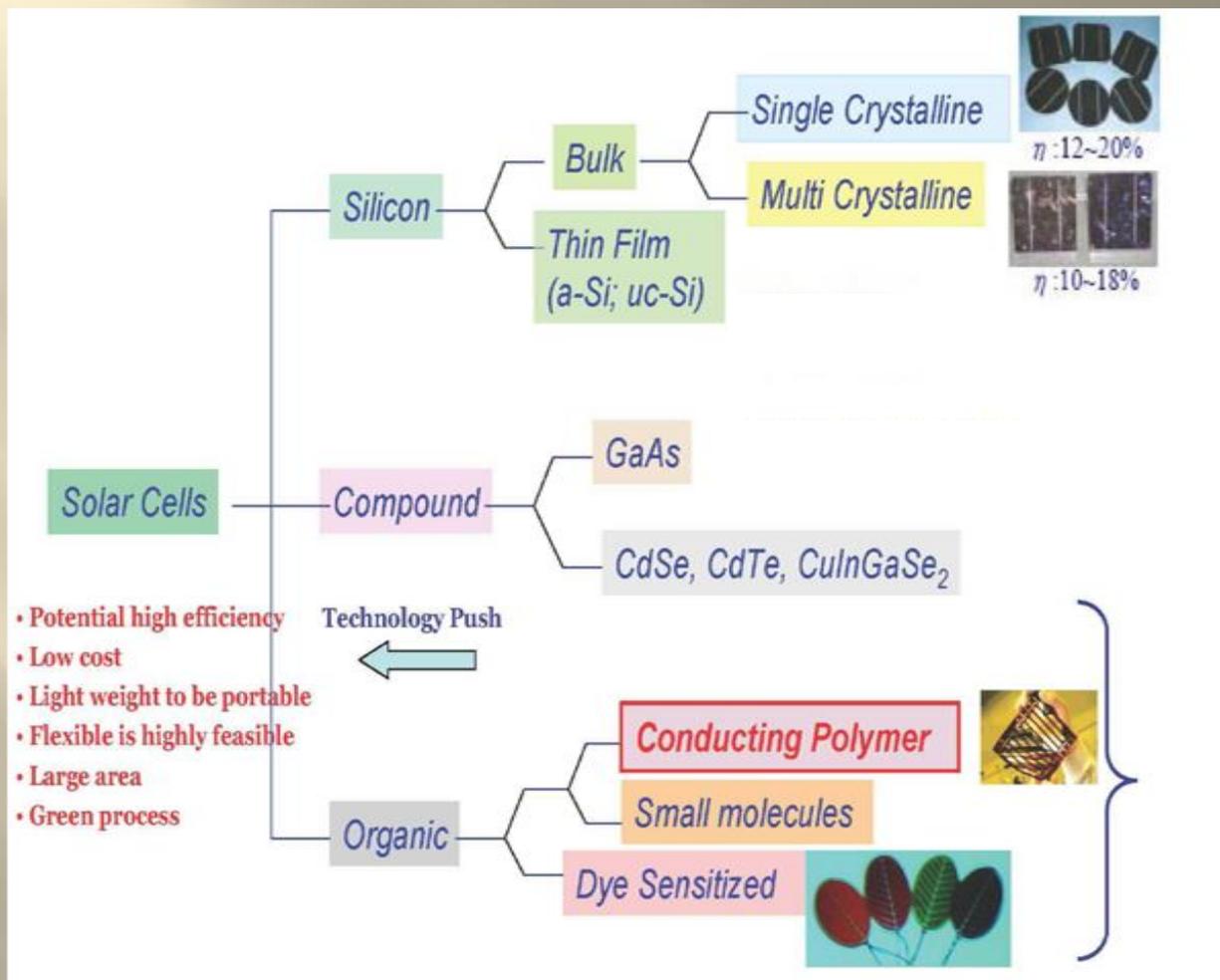


III. Cheap and efficient



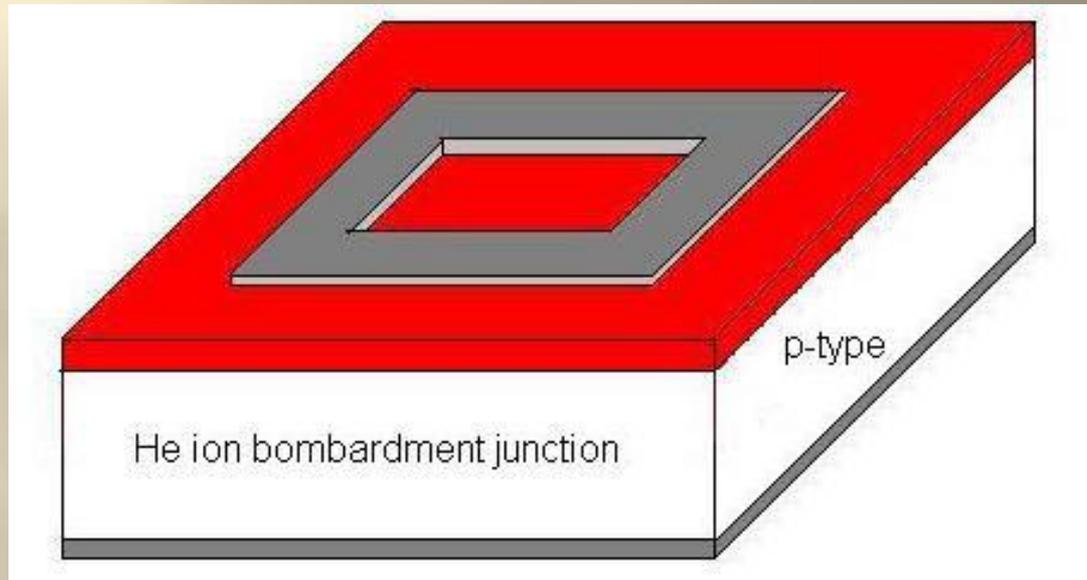
Solar Cells

Solar Cell Research



Solar Cells

Early Si solar cells

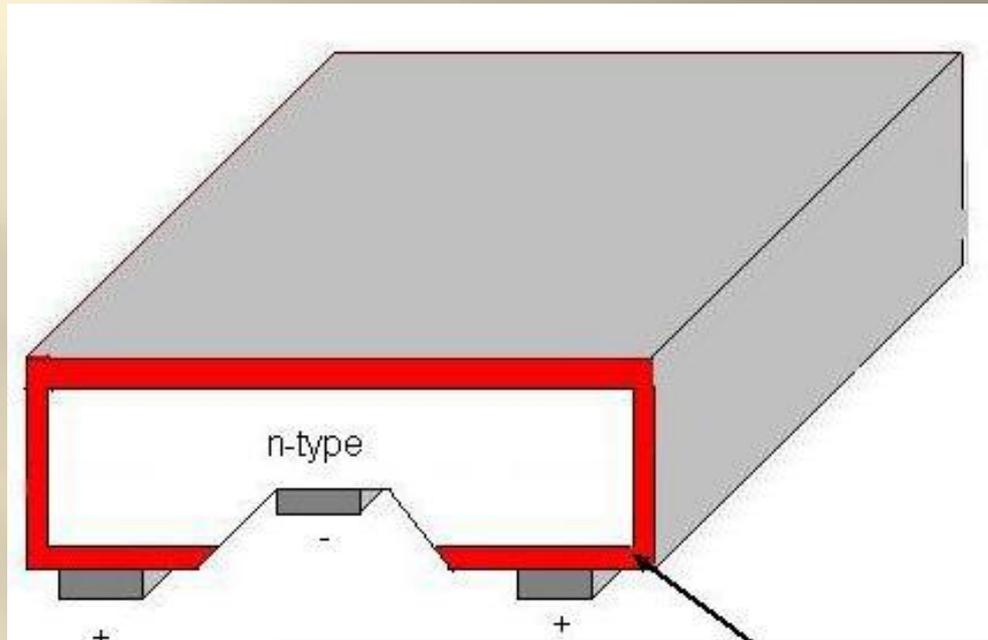


Cell reported in 1941,
Grown junction,
Efficiency much less than one percent

Cell reported in 1952,
Implanted junction
Efficiency about one percent

Solar Cells

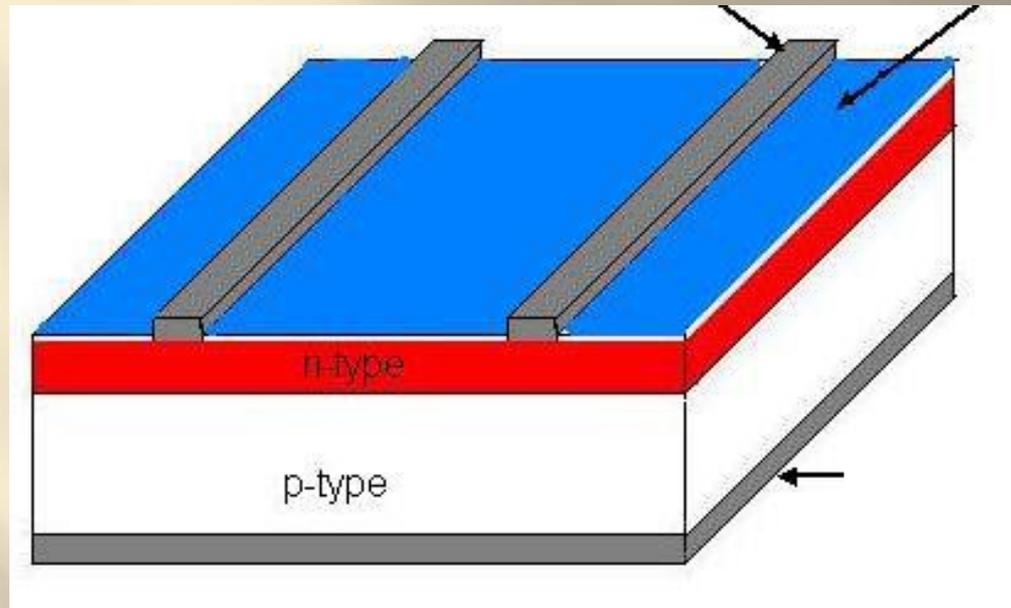
Early Si solar cells



Cell reported in 1954, Bell Labs
High temperature diffused junction
Single crystal
6% cell efficiency

Solar Cells

Early Si solar cells



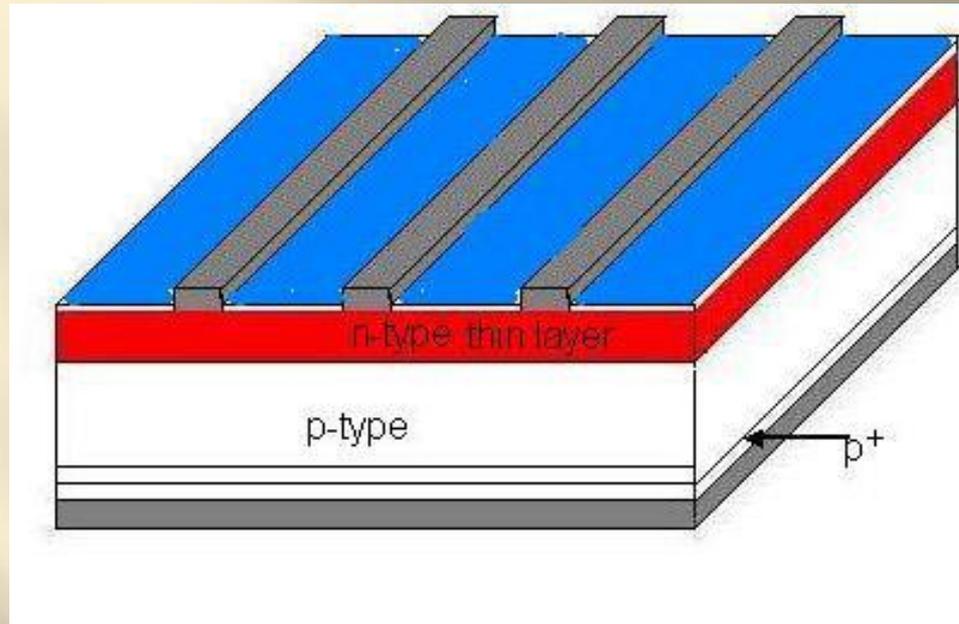
In 1960s solar cell were used only for space craft applications

Cell design as shown here

Cell efficiencies up to 15%

Solar Cells

Early Si solar cells



In 1970 cell design was changed (COMSAT labs)

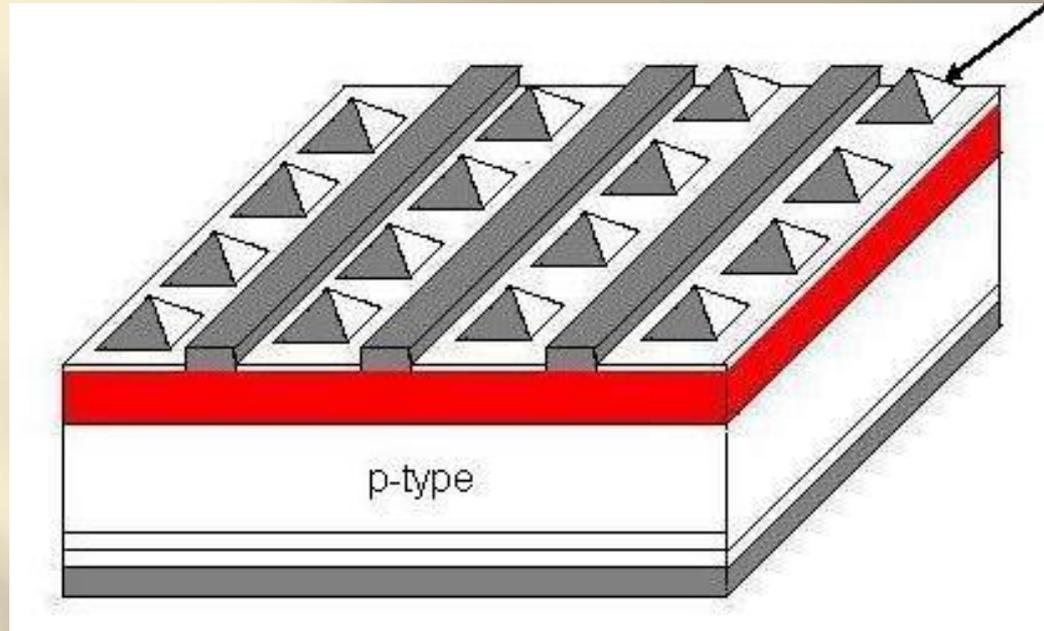
Thinner emitter and closed spaced metal fingers (improved blue response)

Back surface field

so called "violet cell" due to lower wavelength reflection

Solar Cells

Early Si solar cells



Further improvement in cell efficiencies have been obtained due to anisotropic texturing

These approaches improved the current collection ability of solar cells

Solar Cells

Si for PV

Solar energy (PV) is a very fast growing market where the basic technology depends on availability of pure Si. This material is today in high demand.

Most analysts assume that silicon will remain the dominant PV material for at least a decade.

Solar Cells

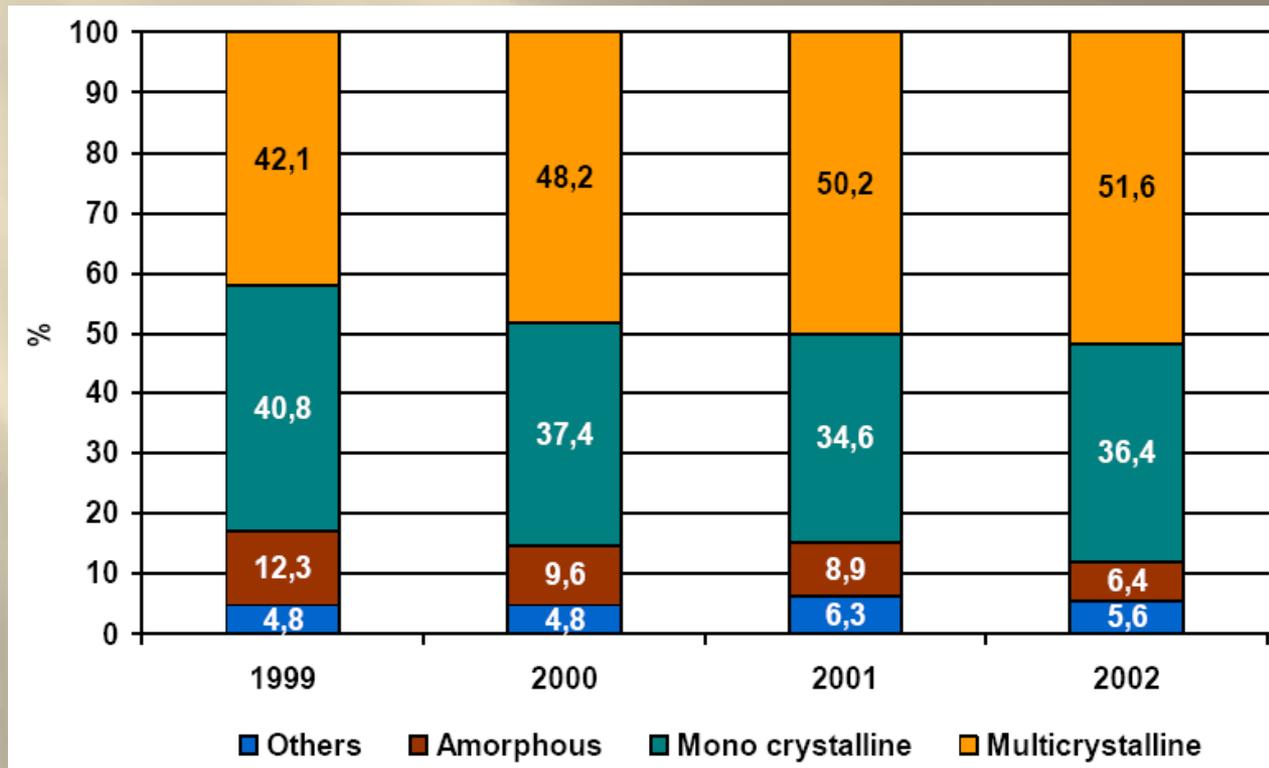
Why Silicon?

- At the time being it is almost the only material used for solar cell mass production
- Easily found in nature, Silicon oxide forms 1/3 of the Earth's crust
- It is non-poisonous, environment friendly, its waste does not represent any problems
- It is fairly easy formed into mono-crystalline form
- Its electrical properties with endurance of 125°C
- Si is produced with 99.9999999% purity in large quantities

Solar Cells

Contribution of Si in PV market

- Others include CdTe, CIGS, C-Si/a-Si (4.5%)
- Over 90% of solar cell are made of Si



Solar Cells

Metallurgical grade (MG) Si

MG-Si is material with 98-99% purity,

Produced in about 1 million tons per year

Produced in countries which cheap electricity and quartz deposits (USA, Europe, Brazil, Australia, Norway)

Average price is 2 to 4 \$/kg

MG-Si is produced by reduction of SiO_2 with C in arc furnace at 1800 °C



Application in producing chlorosilane for electronic grade Si production, production of Al and Steel

Typical impurities are iron, aluminium, calcium and magnesium

Solar Cells

What is the best material for PV?

According to solid state physics Si is not the best material

- 90% absorption of spectrum requires 100 μm of Si while only 1 μm of GaAs \rightarrow Si indirect bandgap material
- Larger thickness also demand for higher quality material, generated carrier needs to diffuse longer
- Diffusion length should be double of wafer thickness, at least 200 μm
- Si still is material of choice due to well developed micro-electronics industry

Solar Cells

Multicrystalline silicon solar cells: today's most popular technology

15-18 % efficiency

\$500/m²

	Price (\$/W)
Module	\$3.00
Inverter	\$0.50
Retro fit installation	\$4.00
TOTAL	\$7.50



Average cost over 30 yrs of PV cell electricity
in CA including 6 % interest payments:

\$0.28/kW-hr

Average grid electricity in CA:
Peak rates in CA:

\$0.13/kW-hr

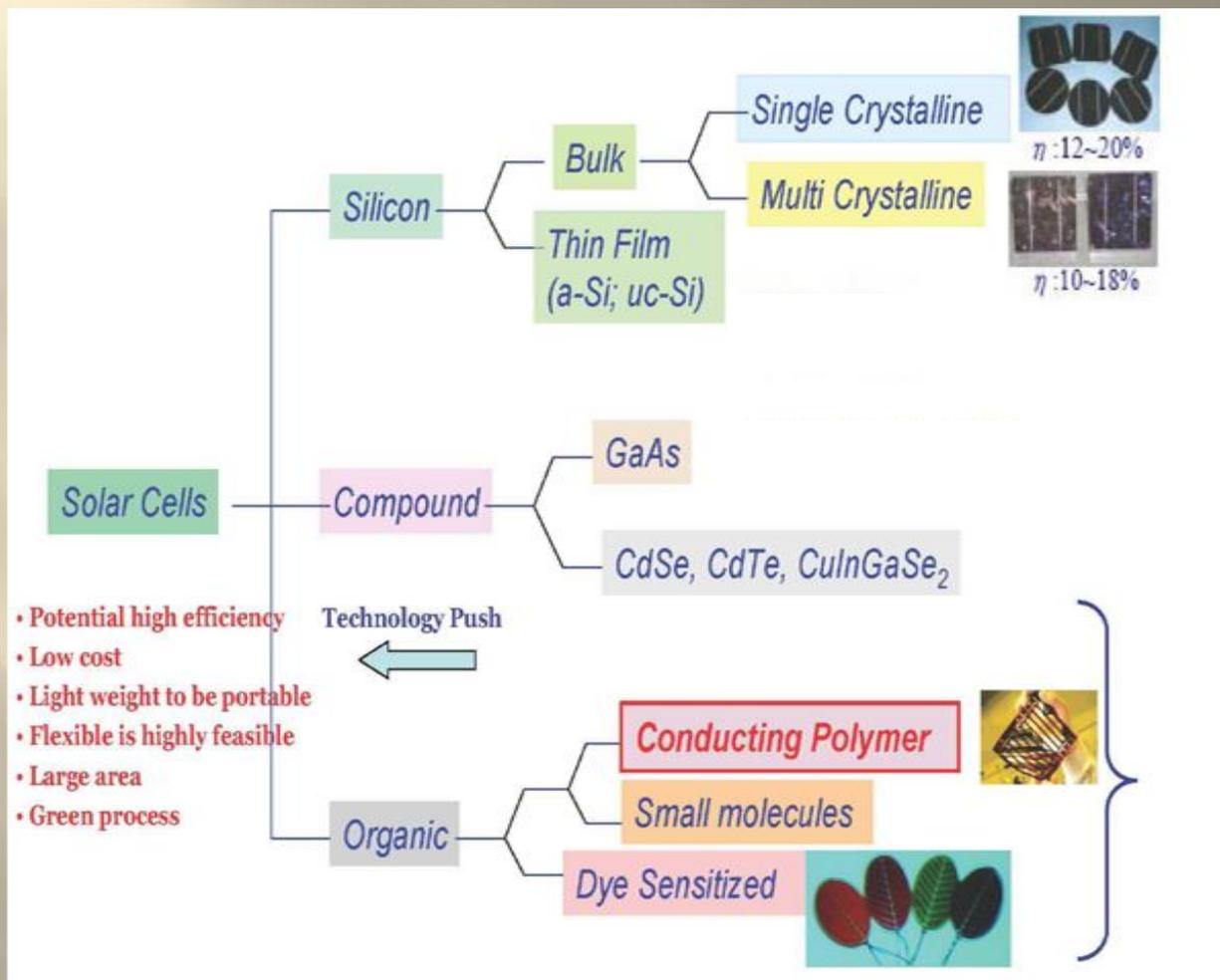
\$0.29/kW-hr

actually lower if
the interest is deducted
from taxes

will rise over
30 years

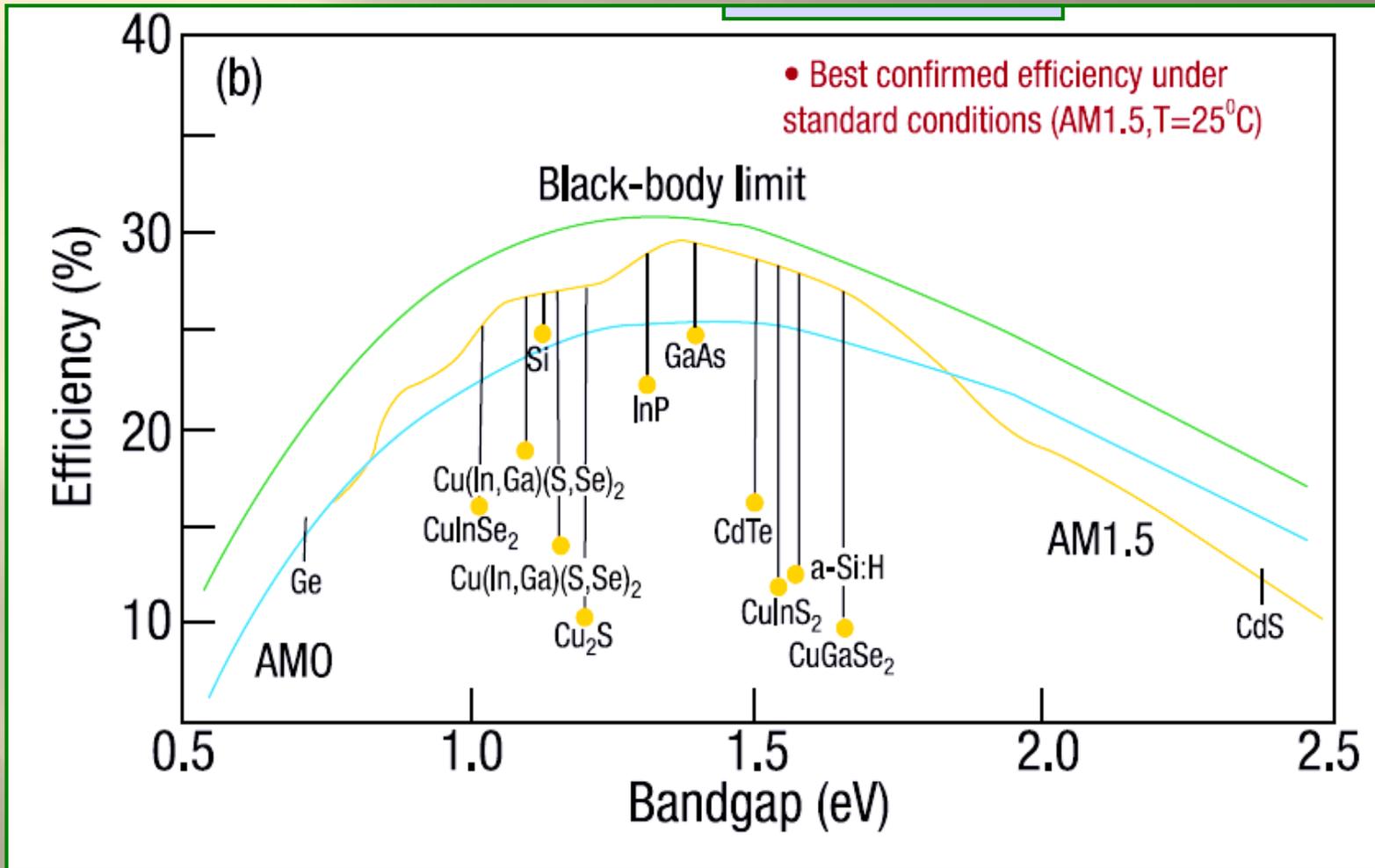
Solar Cells

Solar Cell Research



Solar Cells

Efficiency limits



Solar Cells

Triple-junction cells

New World Record:

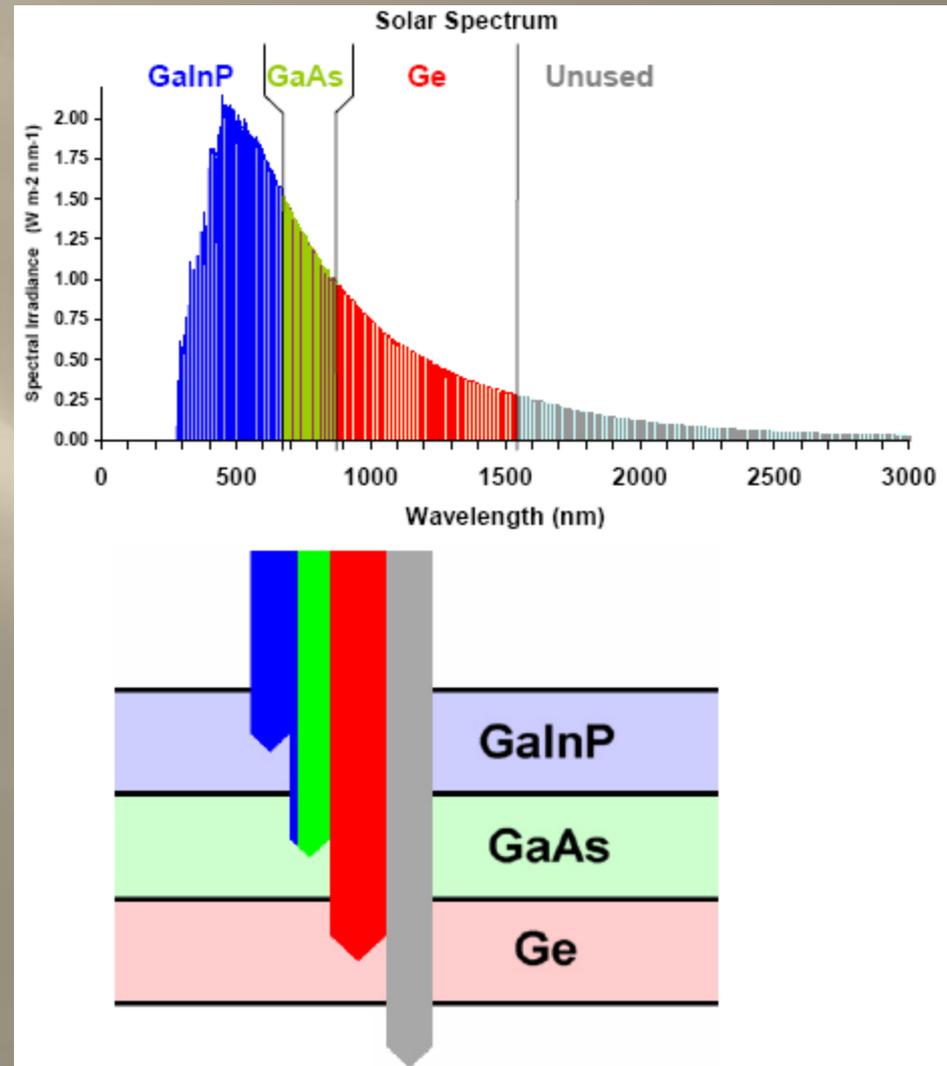
~46%

The cells are in series;
current is passed through
device.

The current is limited by
the layers that produces the
least current.

The voltages of the cells add.

The higher band gap must
see the light first.



Solar Cells

Schematic of Multijunction Cell

$\text{Ga}_{0.50}\text{In}_{0.50}\text{P}$: Top Cell

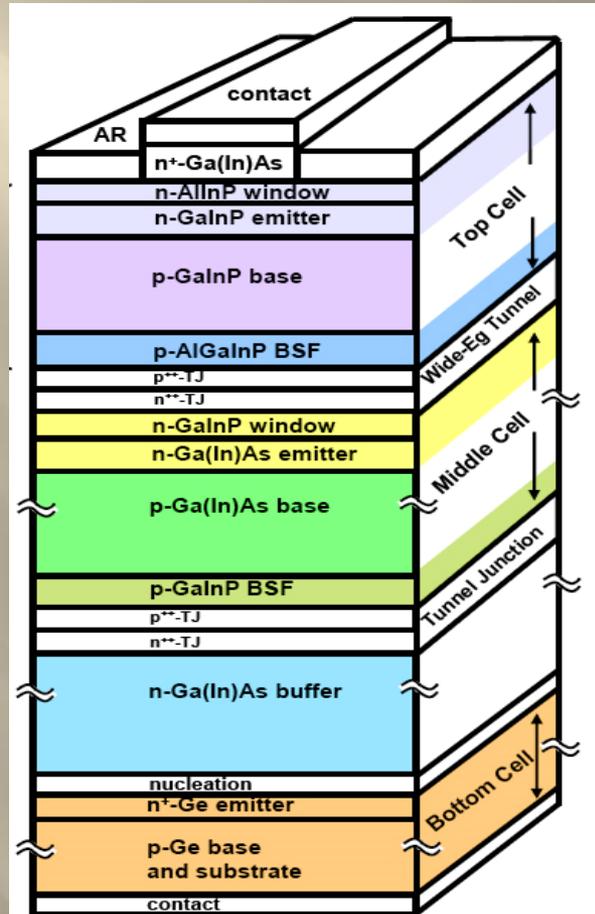
1.8 eV = 689 nm

$\text{Ga}_{0.99}\text{In}_{0.01}\text{As}$: Middle Cell

1.4 eV = 866 nm

Ge substrate: Bottom Cell

0.67 eV = 1850 nm



- World record efficiency: 46 %

- Highest Efficiency Device GaInP/GaInAs/Ge by Spectrolab (A Boeing Company)

- 37% cells can be purchased for \$50,000/m²

- These complex structures are grown very slowly under high vacuum

R.R. King; Spectrolab Inc., AVS 54th International Symposium, Seattle 2007

Solar Cells

Cost Estimate

The cost of multijunction solar cells is approximately \$50,000/m² (\$5/cm²). 500X concentration (added technology) reduces this to \$100/m².

If the tracker and concentration cost \$200/m².

The sun gives us 1000 W/m², but this is reduced to 850 W/m² direct sunlight.

The best commercially available cells are 37% efficient at 25°C, but this decreases to 30% at typical operating temperatures. If the optical system is 75% efficient, then we are at $0.30 \times 0.75 \times 850 \approx 200$ W/m² of electrical power.

At \$200/m² the capital cost would be \$1.50/W.

Although this calculation is wildly optimistic.

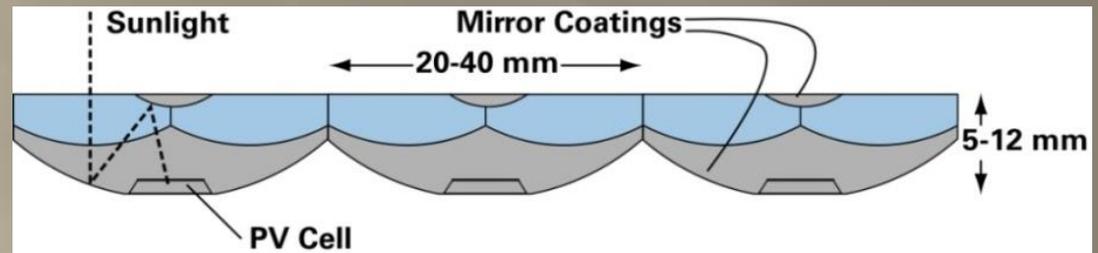
Solar Cells

Concentrating Light

It is possible to track the sun and concentrate the light by 500X



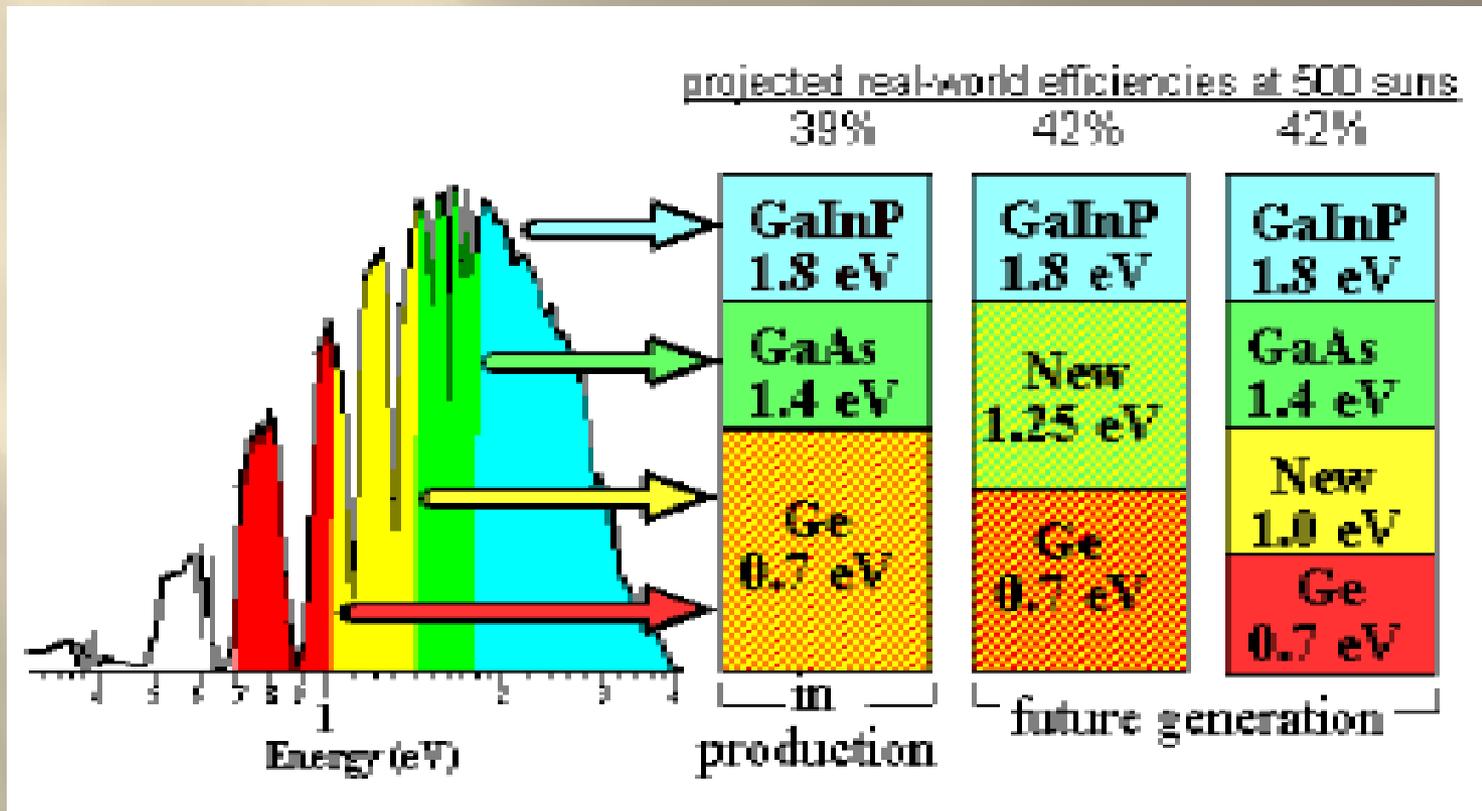
Dish Shape



Sol Focus

Solar Cells

Splitting the Spectrum



Assignment

- ▣ Thanks to:
 - Source: NREL Solar Radiation Data Manual
 - Sarah Kurtz, NREL
- ▣ Outline of research paper Due 10-12-20

