PV MATERIALS AND THEIR APPLICATIONS

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MOTIVATION

1. Electronic materials
    1.1 Electronic band structure
    1.2 Metal – Isolator – Semiconductor
    1.3 Definition
    1.4 Doping
    1.5 Intrinsic/Extrinsic
    1.6 Conductivity
    1.7 Direct/indirect band gap
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2. Solar cell – functionality
    2.1 pn-junction
    2.2 pn-junction under radiation
    2.3 Generation and recombination
3. Introduction - Photovoltaics on the world market

Categories of Solids

- There are three categories of solids, based on their **conducting properties**:

  - **conductors**
  - **semiconductors**
  - **insulators**

Electronic Materials

- The goal of electronic materials is to *generate and control* the flow of an electrical current.
- Electronic materials include:

1. Conductors: have low resistance which allows electrical current flow
2. Insulators: have high resistance which suppresses electrical current flow
3. Semiconductors: can allow or suppress electrical current flow

Semiconductors

- Semiconductors are materials that essentially can be conditioned to act as good conductors, or good insulators, or any thing in between.
- Common elements such as **carbon, silicon**, and **germanium** are semiconductors.
- Silicon is the best and most widely used semiconductor.

Definition

- **A semiconductor is a material that has electrical conductivity between that of a conductor and that of an insulator**

- **Its resistivity decreases with increasing temperature**

- **and therefore its conductivity increases.**

SEMICONDUCTORS AND ELECTRONICS

- Semiconductors are materials whose electrical conductivities are higher than those of insulators but lower that those of conductors.
- Silicon, Germanium, Gallium, Arsenide, Indium, Antimonide and cadmium sulphide are some commonly used semiconductors.
- Semiconductors have negative temperature coefficients of resistance, i.e. as temperature increases resistivity decreases.

Semiconductors can be Insulators

- If the material is pure semiconductor material like silicon, *the crystal lattice structure forms an excellent insulator* since all the atoms are bound to one another and are not free for current flow.
- Good insulating semiconductor material is referred to as intrinsic.
- Since the outer valence electrons of each atom are tightly bound together with one another, the electrons are difficult to dislodge for current flow.
- Silicon in this form is a great insulator.
- Semiconductor material is often used as an insulator.

The name "semiconductor" implies that it conducts somewhere between the two cases (conductors or insulators)

Conductivity : σ

$\sigma_{metals} \sim 10^{10}$ /Ω-cm

S/C

$\sigma_{insulators} \sim 10^{-22}$ /Ω-cm

The conductivity (σ) of a semiconductor (S/C) lies between these two extreme cases.

Resistivity vs. Temperature

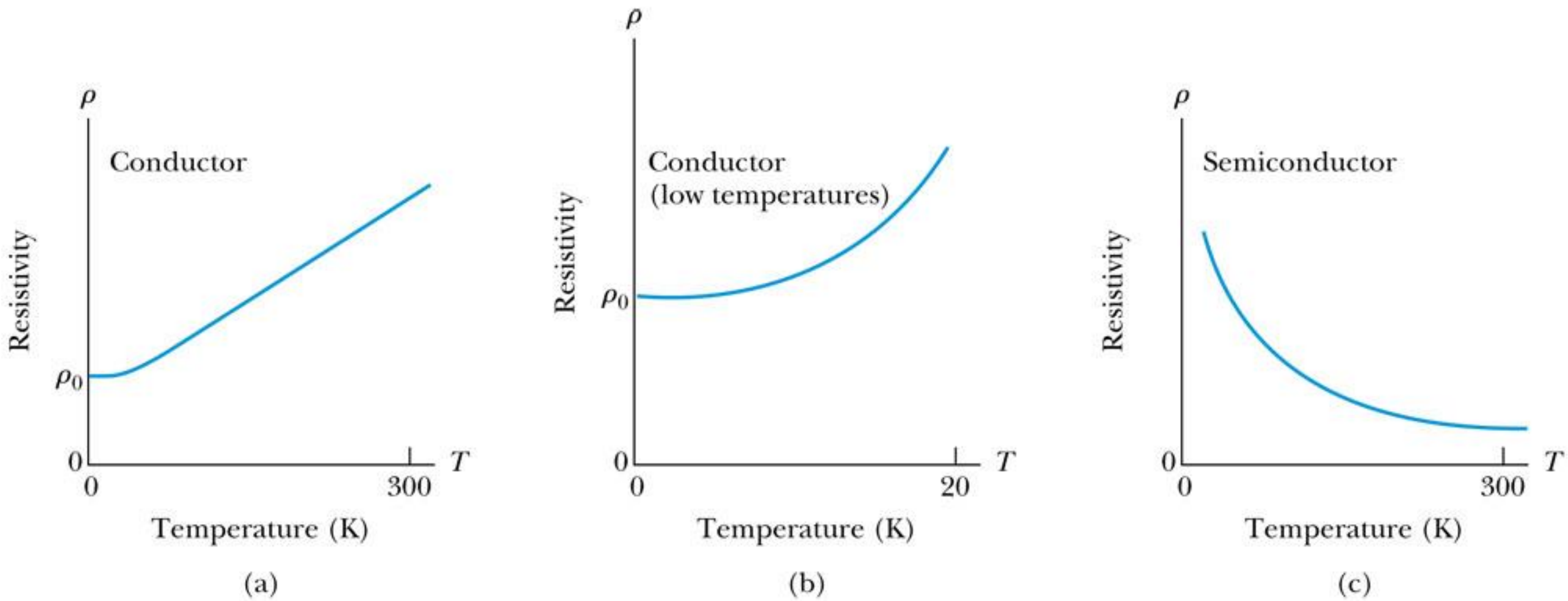
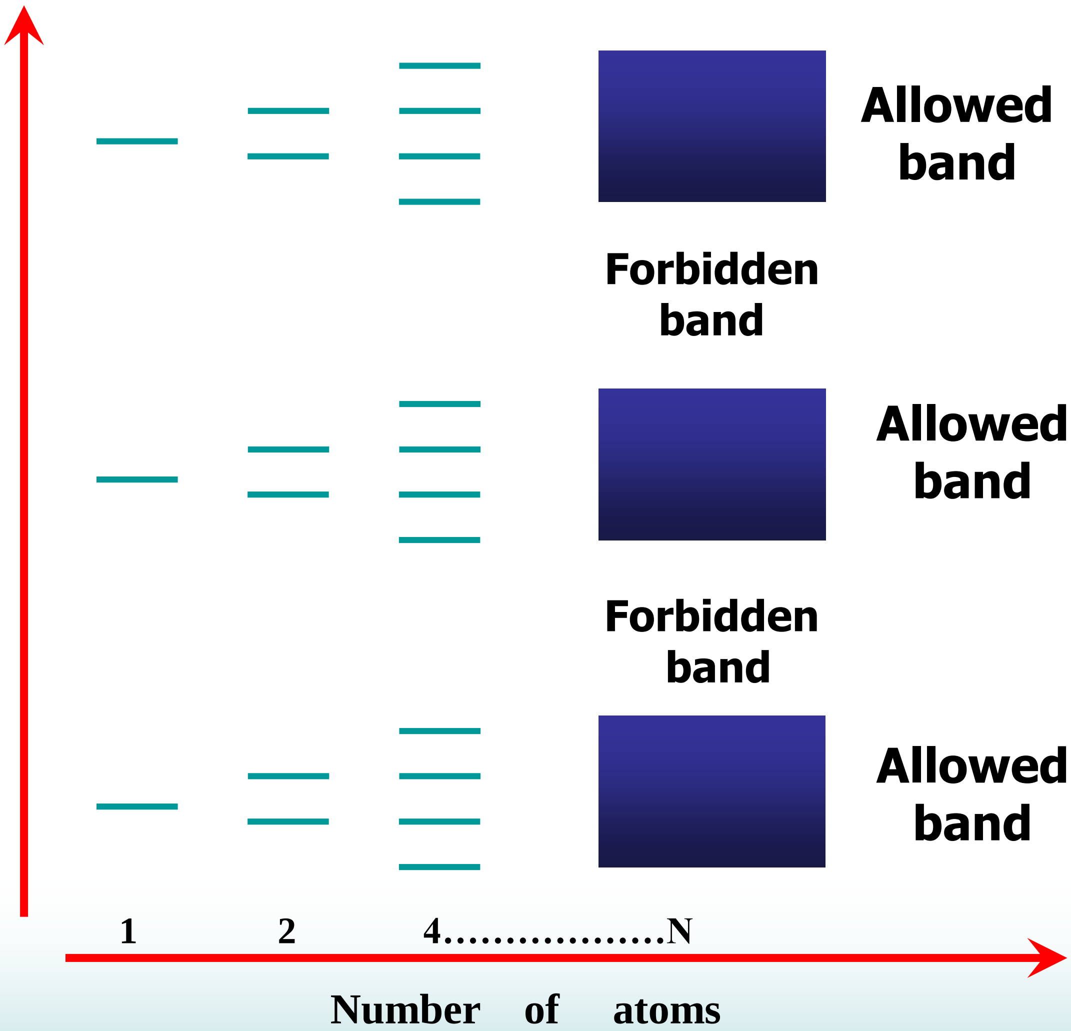


Figure : (a) Resistivity versus temperature for a typical conductor. Notice the linear rise in resistivity with increasing temperature at all but very low temperatures. (b) Resistivity versus temperature for a typical conductor at very low temperatures. Notice that the curve flattens and approaches a nonzero resistance as $T \to 0$. (c) Resistivity versus temperature for a typical semiconductor. The resistivity decreases dramatically as $T \to 0$.

.:: The Band Theory of Solids ::.



- The electrons surrounding a nucleus have certain well-defined energy-levels.
- ***Electrons don't like to have the same energy in the same potential system.***
- The most we could get together in the same energy-level was two, provided thet they had opposite spins. This is called *Pauli Exclusion Principle.*

- The difference in energy between each of these smaller levels is so tiny that it is more reasonable to consider each of these sets of smaller energy-levels as being continuous *bands* of energy, rather than considering the enormous number of discrete individual levels.

- Each ***allowed band*** is seperated from another one by a ***forbidden band***.

- Electrons can be found in ***allowed bands*** but they can not be found in ***forbidden bands***.

.:: Semiconductor, Insulators, Conductors ::.

Full band

All energy levels are occupied by electrons

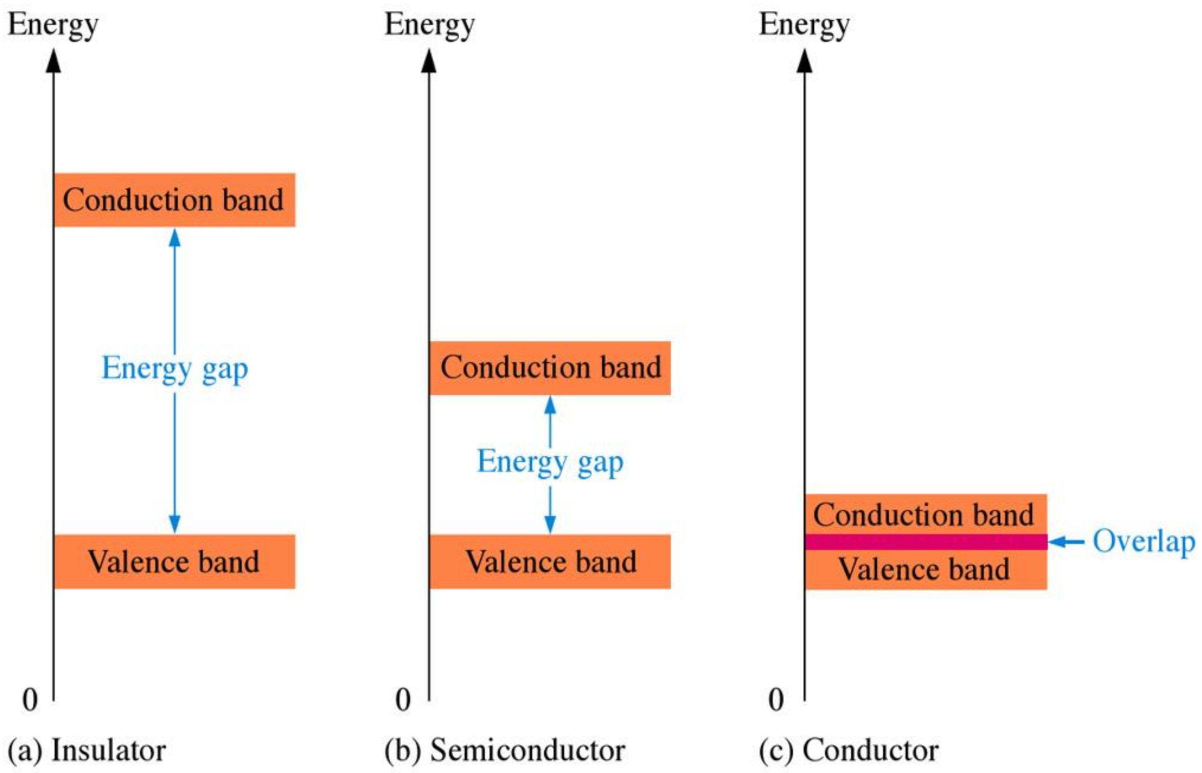
Empty band

All energy levels are empty (no electrons)

Both full and empty bands do not partake in electrical conduction.

1.2 Semiconductors, Conductors and Insulators

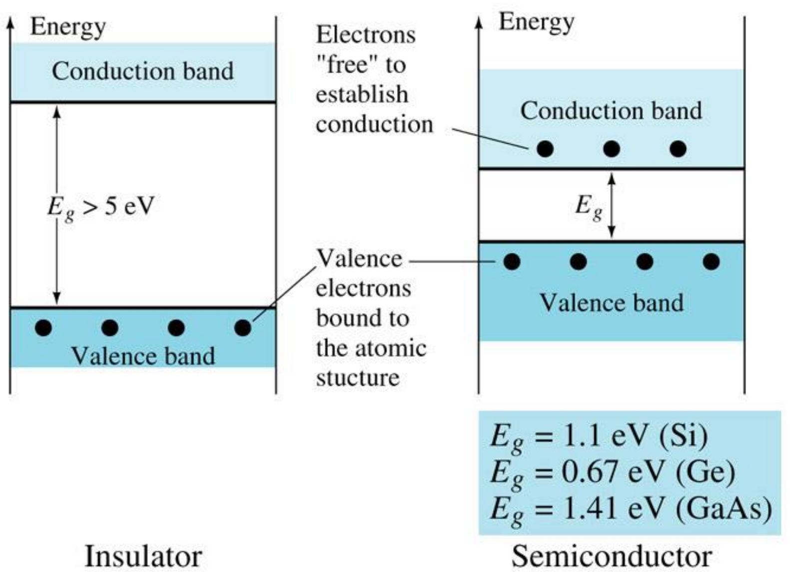
Energy Bands



- **Energy gap-the difference between the energy levels of any two orbital shells**
- **Band-another name for an orbital shell (valence shell=valence band)**
- **Conduction band –the band outside the valence shell**

1.2 Semiconductors, Conductors and Insulators

Energy Bands

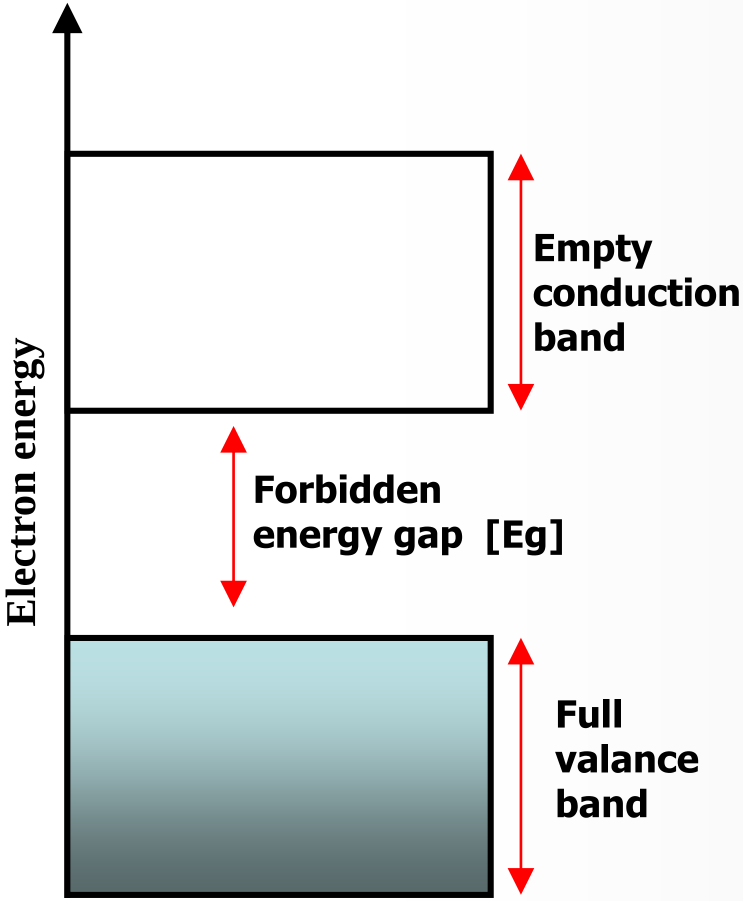


at room temperature 25°

(b)

eV (electron volt) – the energy absorbed by an electron when it is subjected to a 1V difference of potential

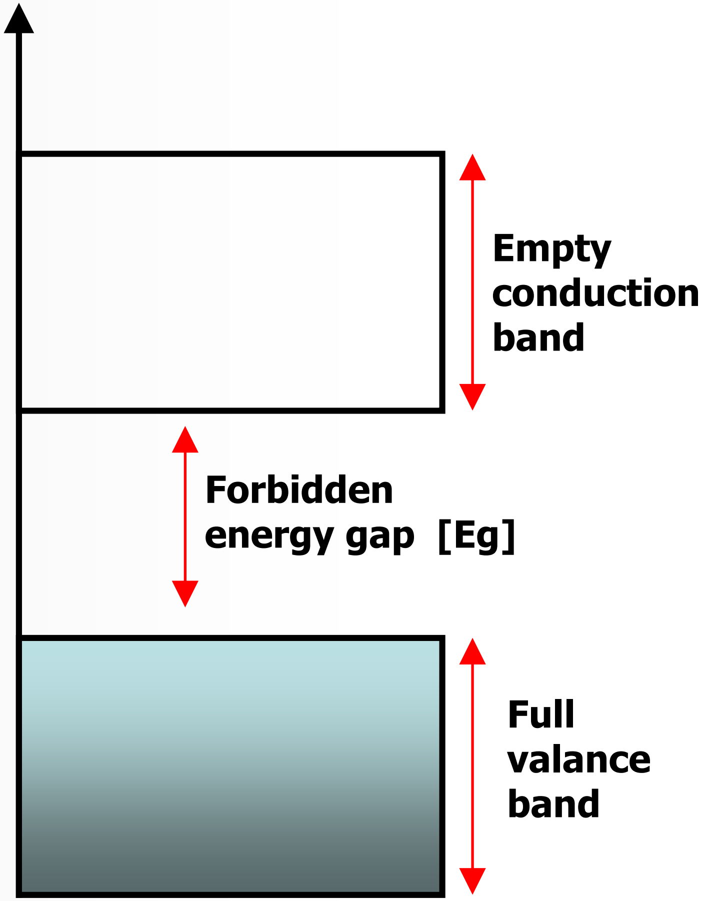
.:: Semiconductor energy bands at low temperature ::.



- **At low temperatures the valance band is *full*, and the conduction band is empty.**
- Recall that a full band can not conduct, and neither can an empty band.
- **At low temperatures**, semiconductors **do not conduct**, they behave like **insulators.**
- The *thermal energy* of the electrons sitting at the top of the full band is much lower than that of the *Eg at low temperatures*.

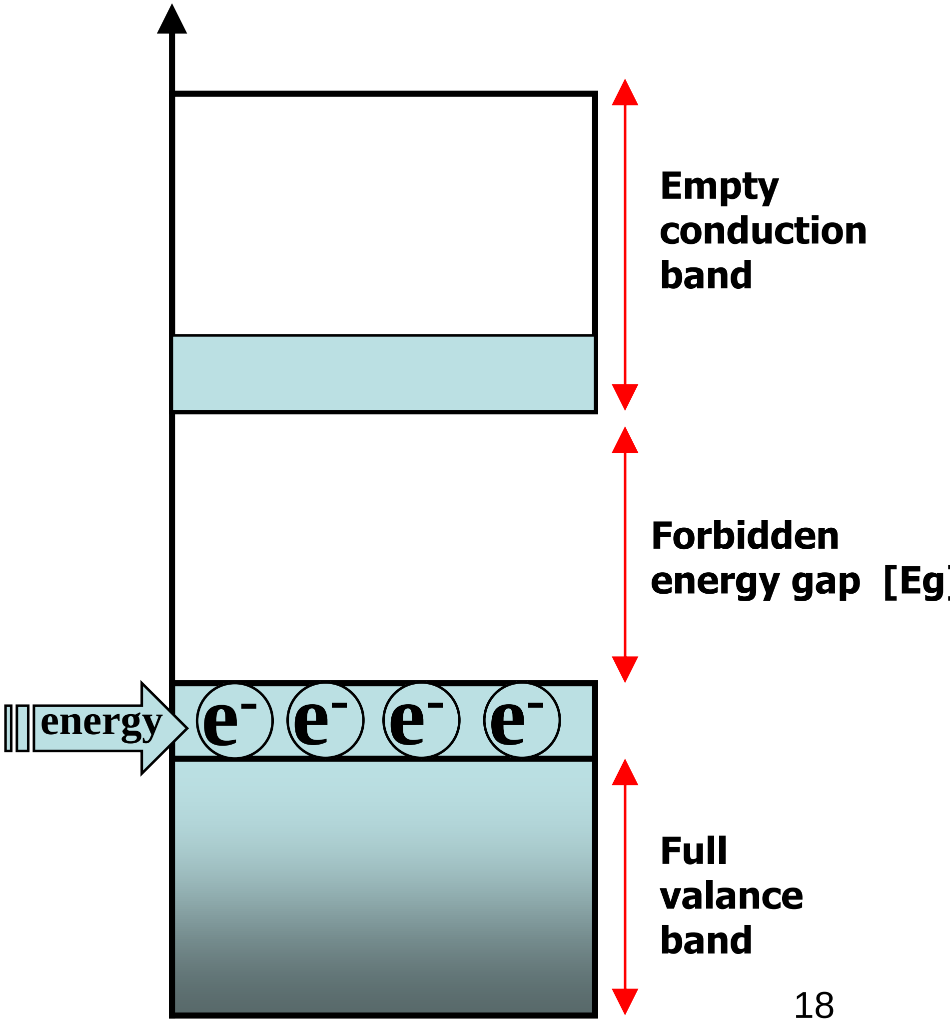
Conduction Electron :

- Assume some kind of energy is provided to the electron (valence electron) sitting at the top of the *valance band*.
- This electron gains energy from the applied field and it would like to move into higher energy states.
- This electron contributes to the ***conductivity*** and this electron is called as a ***conduction electron***.
- At 0^0K, electron sits at the lowest energy levels. The valance band is the highest filled band at zero kelvin.



Semiconductor energy bands at room temperature

- When enough ***energy*** is supplied to the e^- sitting at the top of the valance band, e^- can make a transition to the bottom of the conduction band.
- When electron makes such a transition it leaves behind a ***missing electron state.***
- This missing electron state is called as a ***hole.***
- Hole behaves as a ***positive charge carrier.***
- Magnitude of its charge is the same with that of the electron but with an **opposite sign.**



1.4 Conduction in Semiconductor (Conduction Electron and holes)

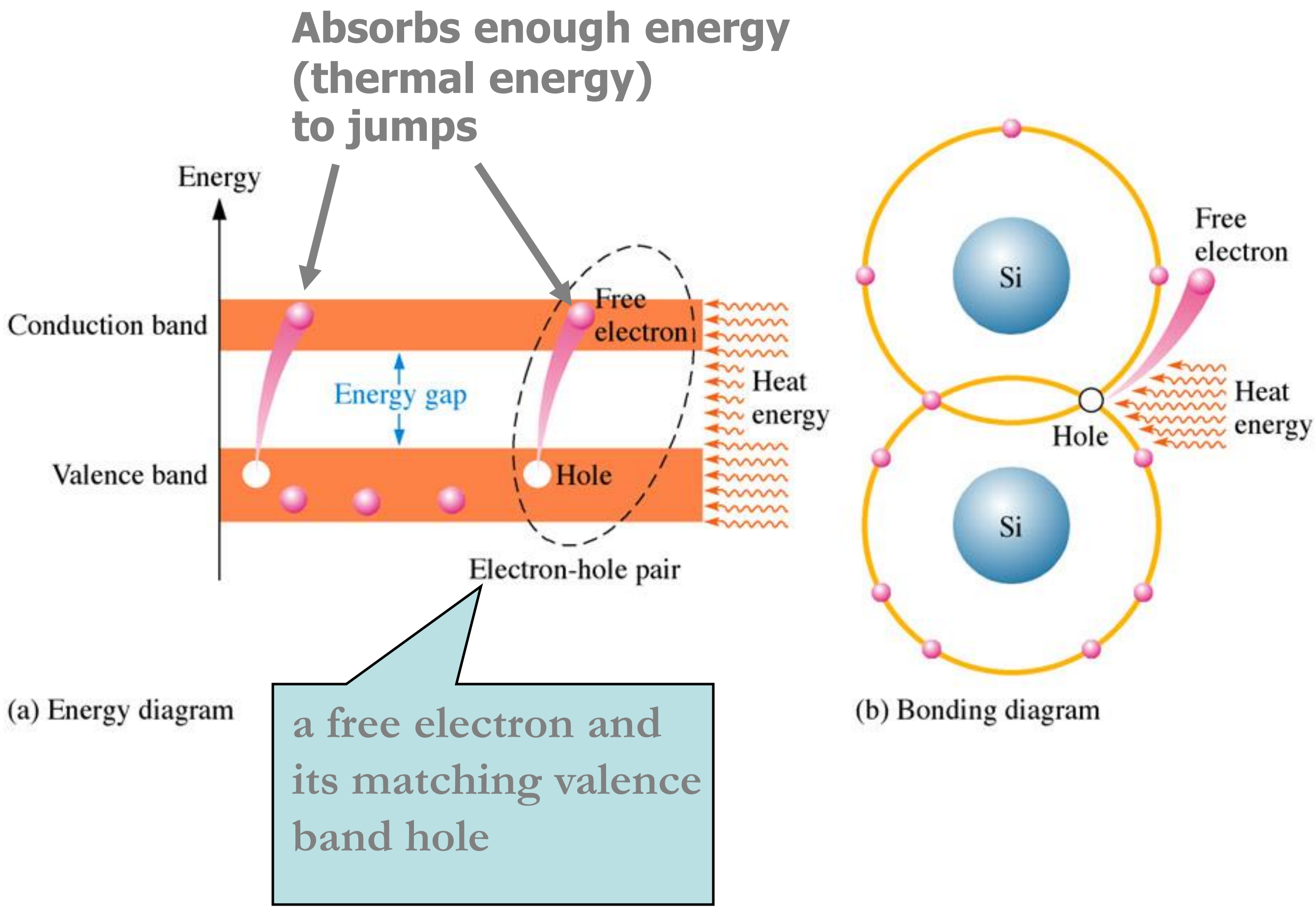
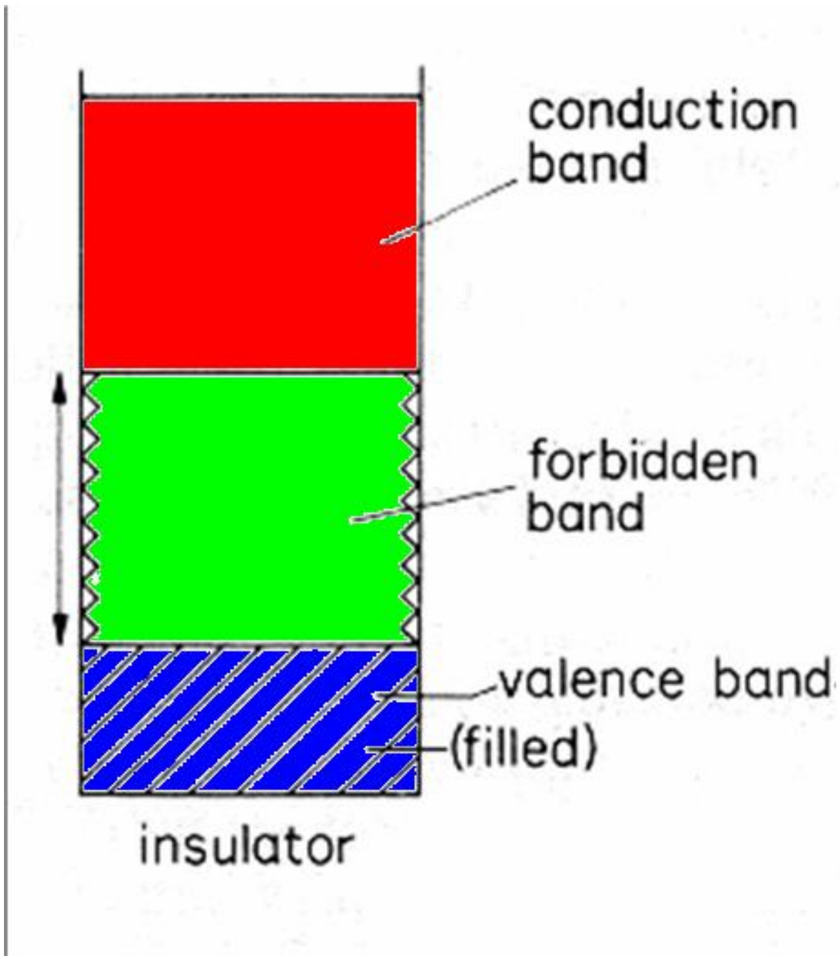
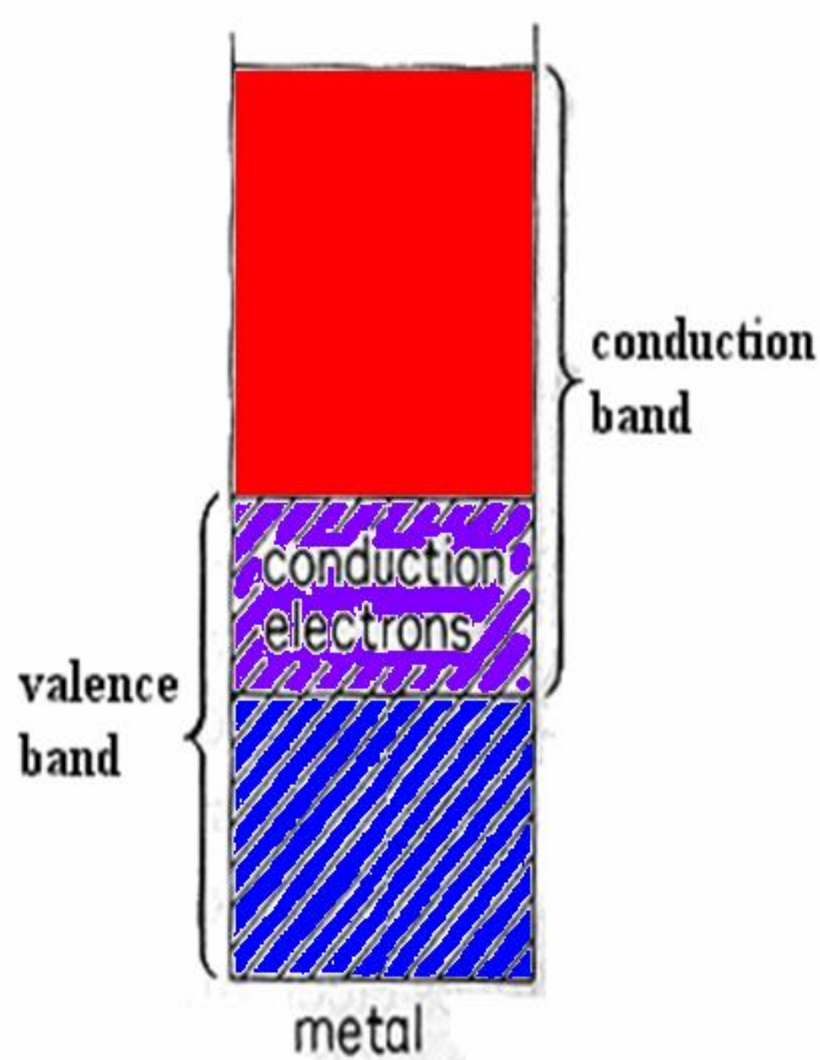


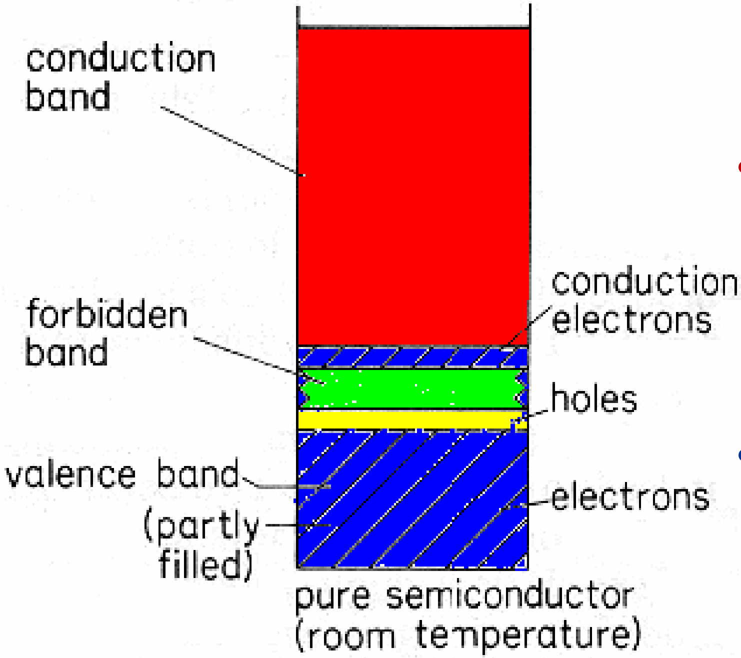
FIGURE Creation of electron-hole pairs in a silicon crystal. Electrons in the conduction band are free.

ENERGY BANDS IN INSULATORS & CONDUCTORS



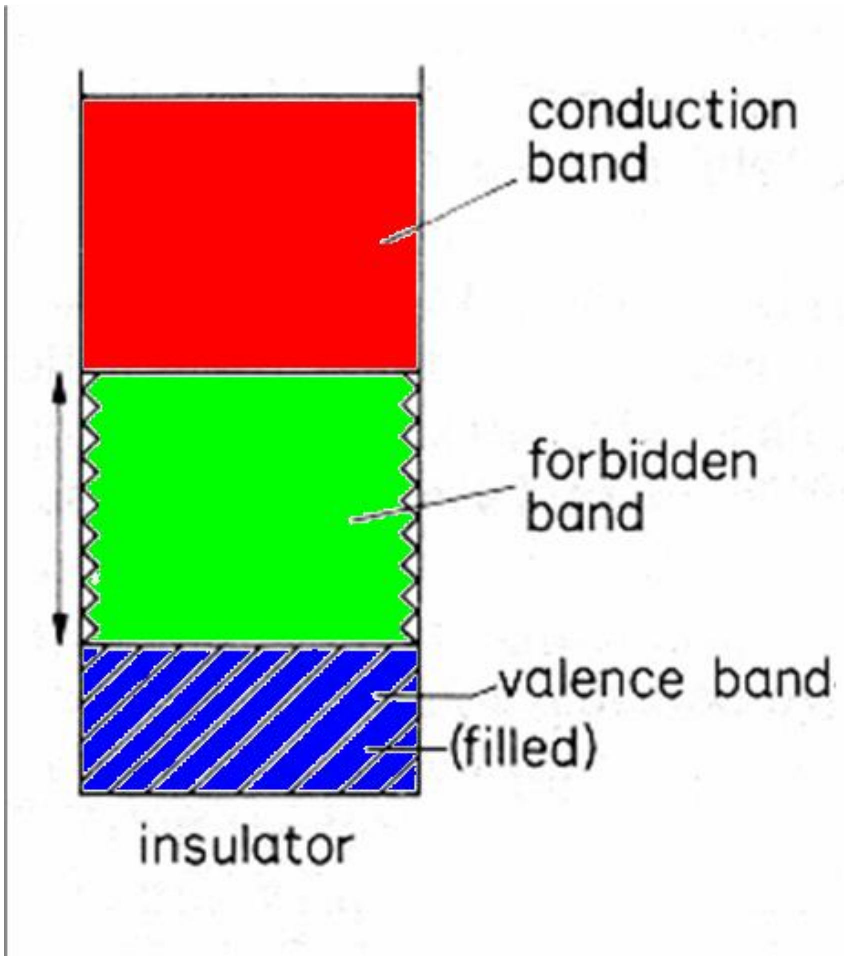


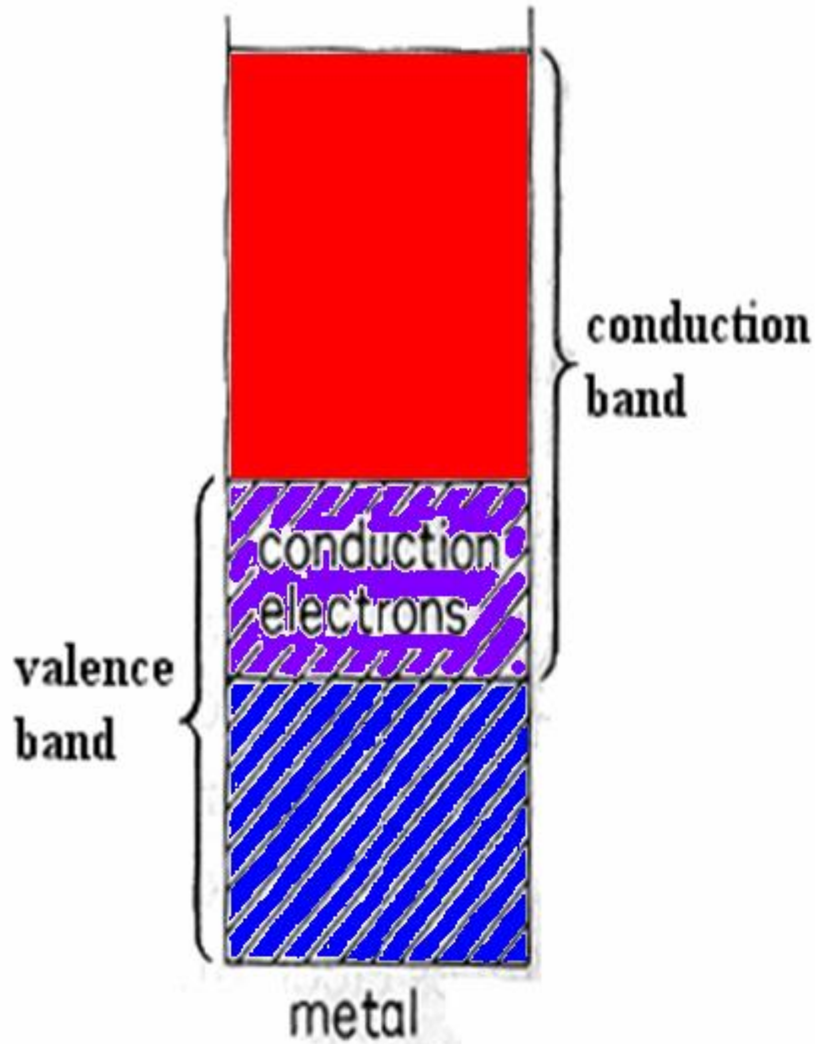
ENERGY BANDS IN SEMICONDUCTORS



- Forbidden band small for semiconductors.
- Less energy required for electron to move from valence to conduction band.
- A vacancy (hole) remains when an electron leaves the valence band.
- Hole acts as a positive charge carrier.

ENERGY BANDS IN INSULATORS & CONDUCTORS





Conductivity

$$\sigma_i = n_i e(\mu_e + \mu_h) = C \cdot e(\mu_e + \mu_h) \cdot T^{\frac{3}{2}} \exp\left(-\frac{E_G}{2kT}\right)$$

- **σ_i depends strongly on the temperature and the charge carrier densities**
- **extrinsic conductivity depends additionaly on excitation of dopants into the conduction band.**

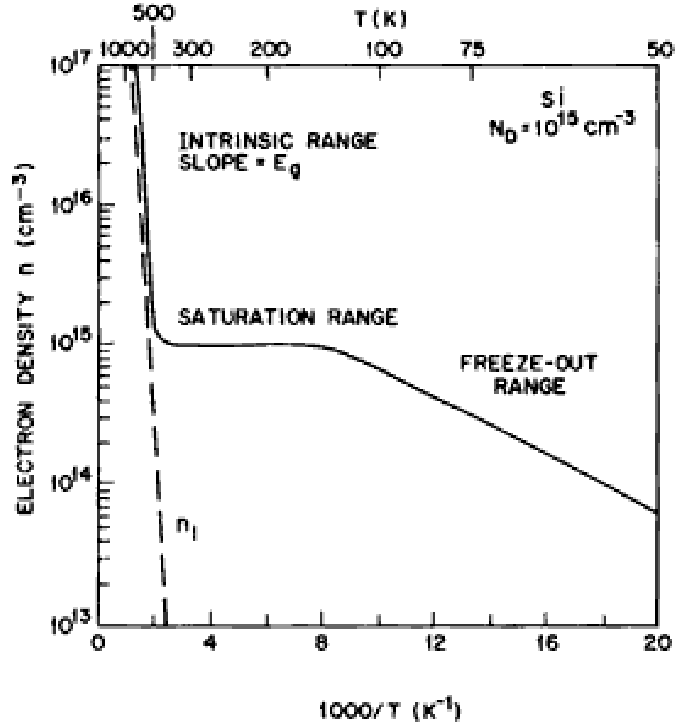
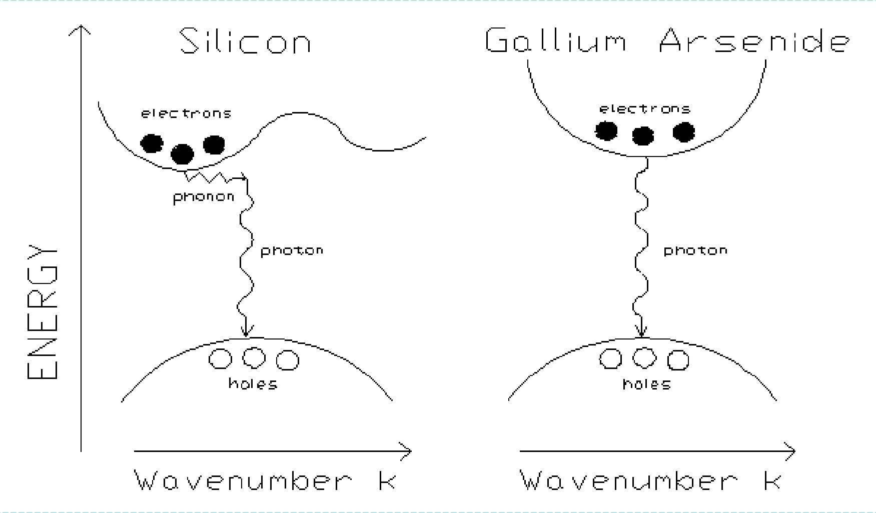


Fig. 16 Electron density as a function of temperature for a Si sample with donor impurity concentration of 10^{15} cm^{-3}. (After Smith, Ref. 5.)

Direct/indirect band gap



Indirect and direct band gap

Material	c-Si	a-Si:H	GaAs
Band gap	1,12 eV (indirekt)	1,8 eV („direct“)	1, 43 eV (direct)
Absorption coefficient (hν = 2,2) [cm^{-1}]	$6*10^3$	$2*10^4$	$5*10^4$

Indirect:

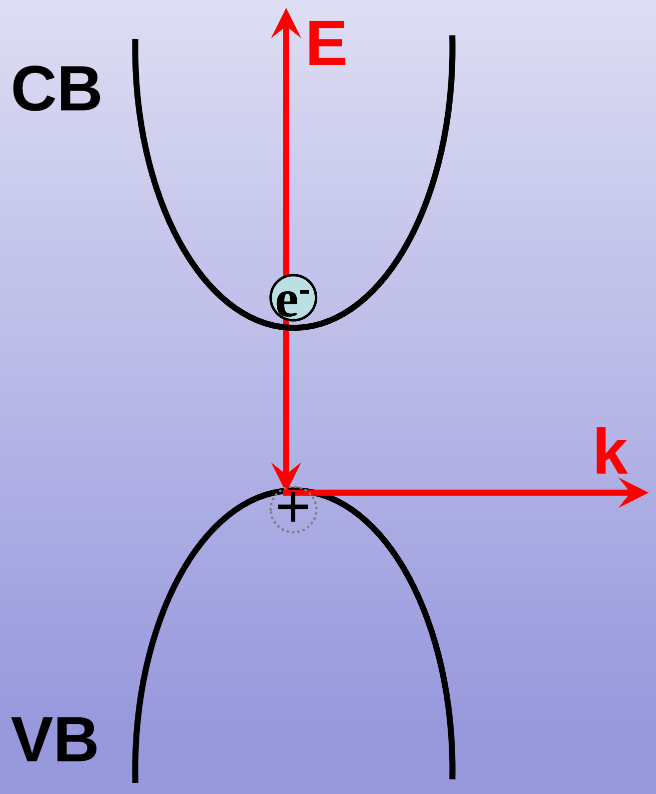
- need a photon, a phonon, and a charge carrier → happens more seldom
  → longer absorption length
- recombination at grain boundarys and point defects

Direct:

- need just the right photon for band transition
- higher transition probability

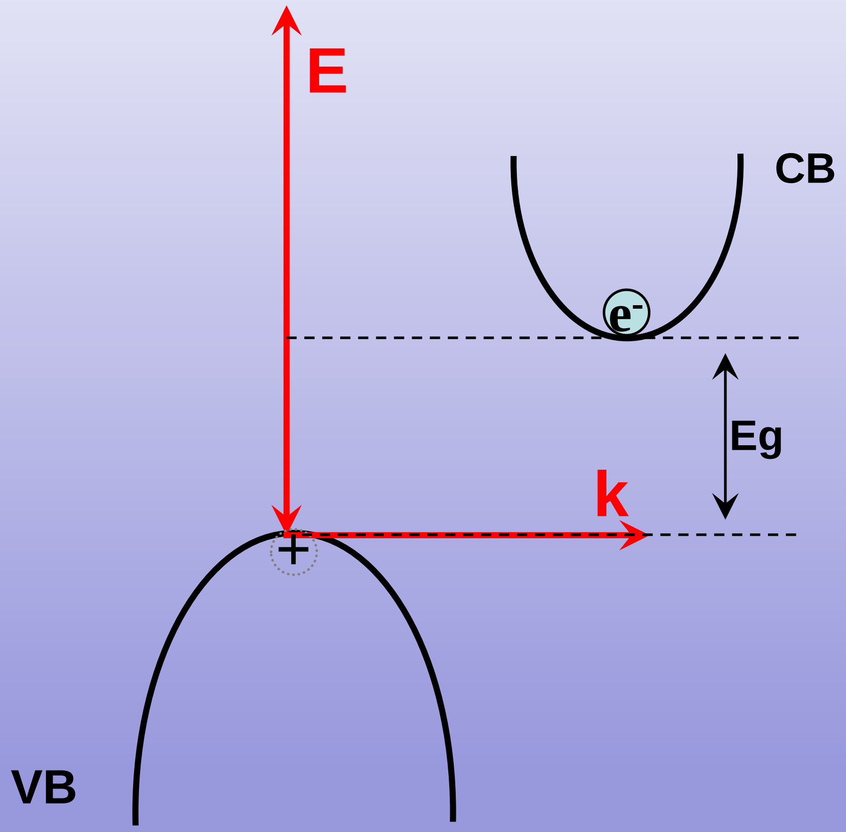
Direct an indirect-band gap materials :

Direct-band gap s/c's (e.g. GaAs, InP, AlGaAs)



- **For a *direct-band gap material*, the minimum of the conduction band and maximum of the valance band lies at the same momentum, k, values.**
- When an electron sitting at the bottom of the CB recombines with a hole sitting at the top of the VB, there will be no change in momentum values.
- **Energy is conserved by means of emitting a photon, such transitions are called as radiative transitions.**

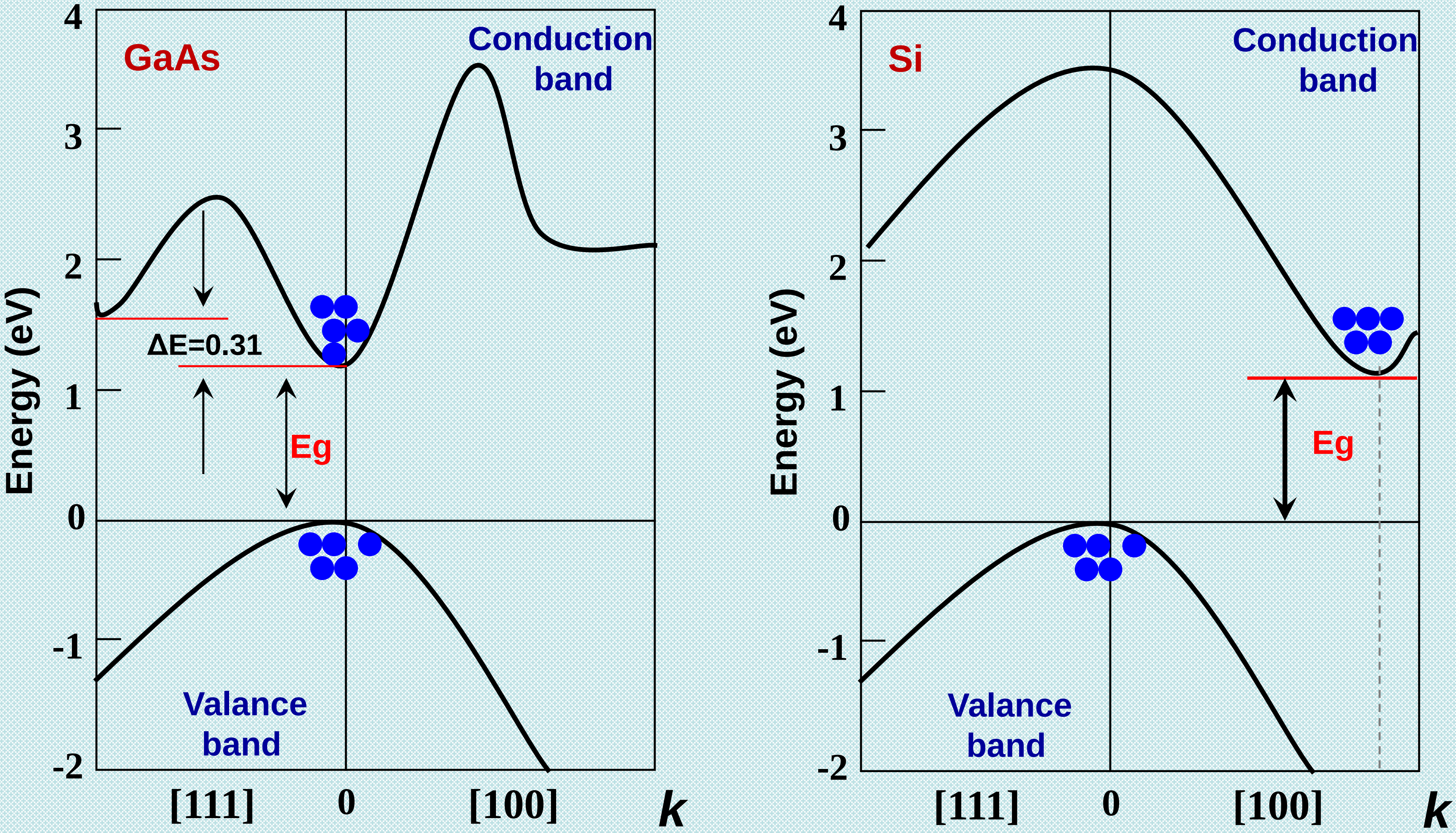
Indirect-band gap s/c's (e.g. Si and Ge)



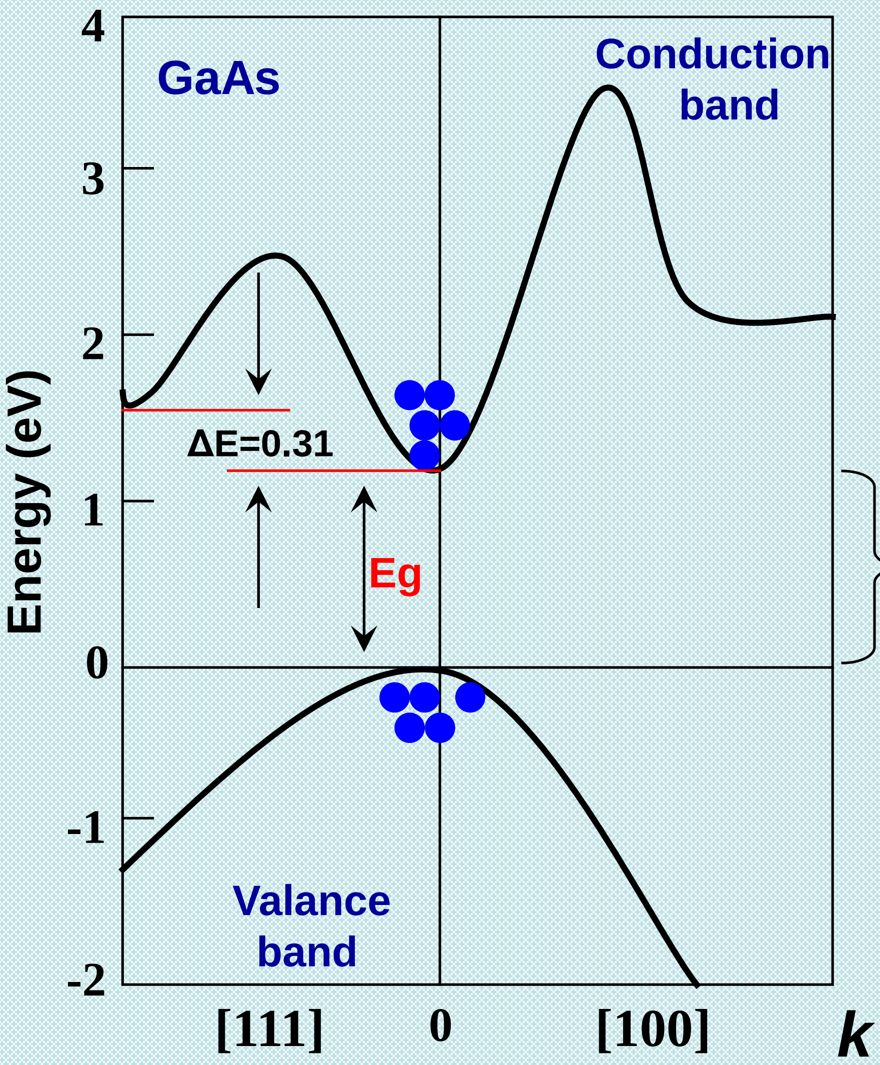
- **For an** **indirect-band gap** **material; the minimum of the** **CB** **and maximum of the** **VB** **lie at different k-values**.
- When an e^- and hole recombine in an indirect-band gap s/c, phonons must be involved to conserve momentum.

Phonon

- **Atoms vibrate about their mean position at a finite temperature.These vibrations produce vibrational waves inside the crystal.**
- **Phonons are the quanta of these vibrational waves. Phonons travel with a velocity of sound .**
- **Their wavelength is determined by the crystal lattice constant. Phonons can only exist inside the crystal.**



Energy band structures of *GaAs* and *Si*



Band gap is the smallest energy separation between the valence and conduction band edges.

The smallest energy difference occurs at the same momentum value

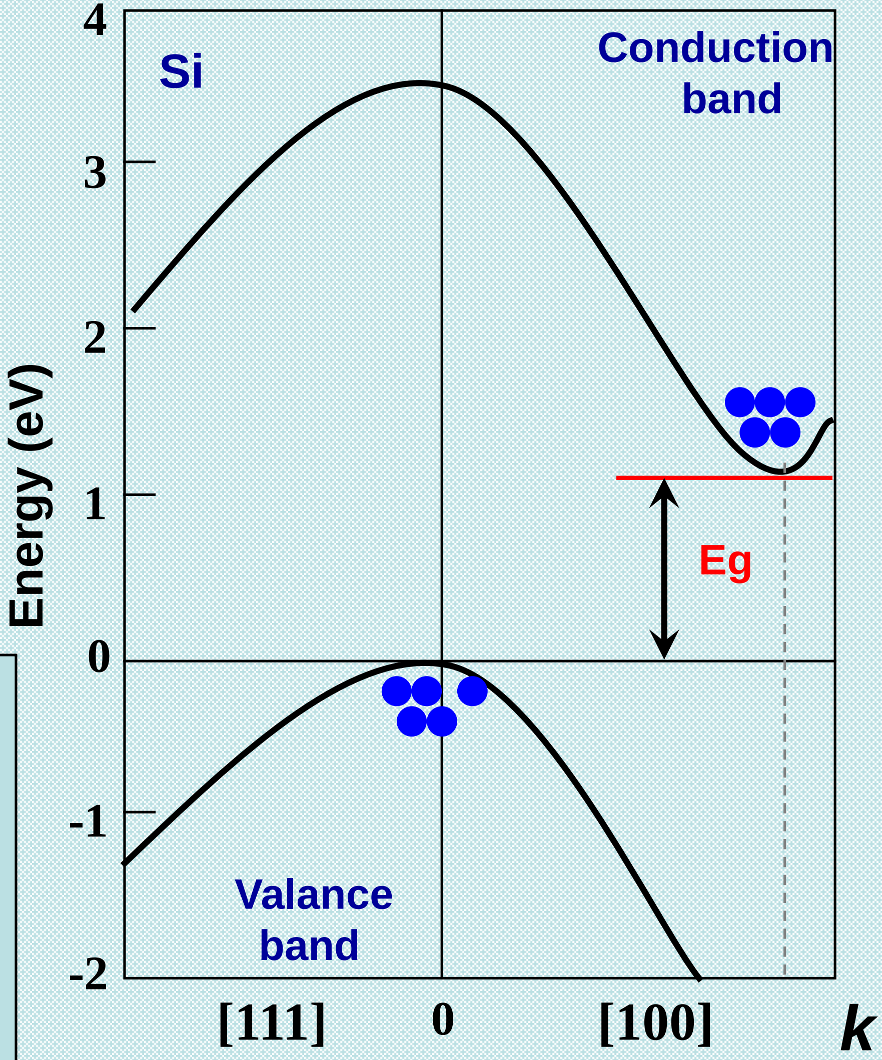
Direct band gap semiconductor

Energy band structure of *GaAs*

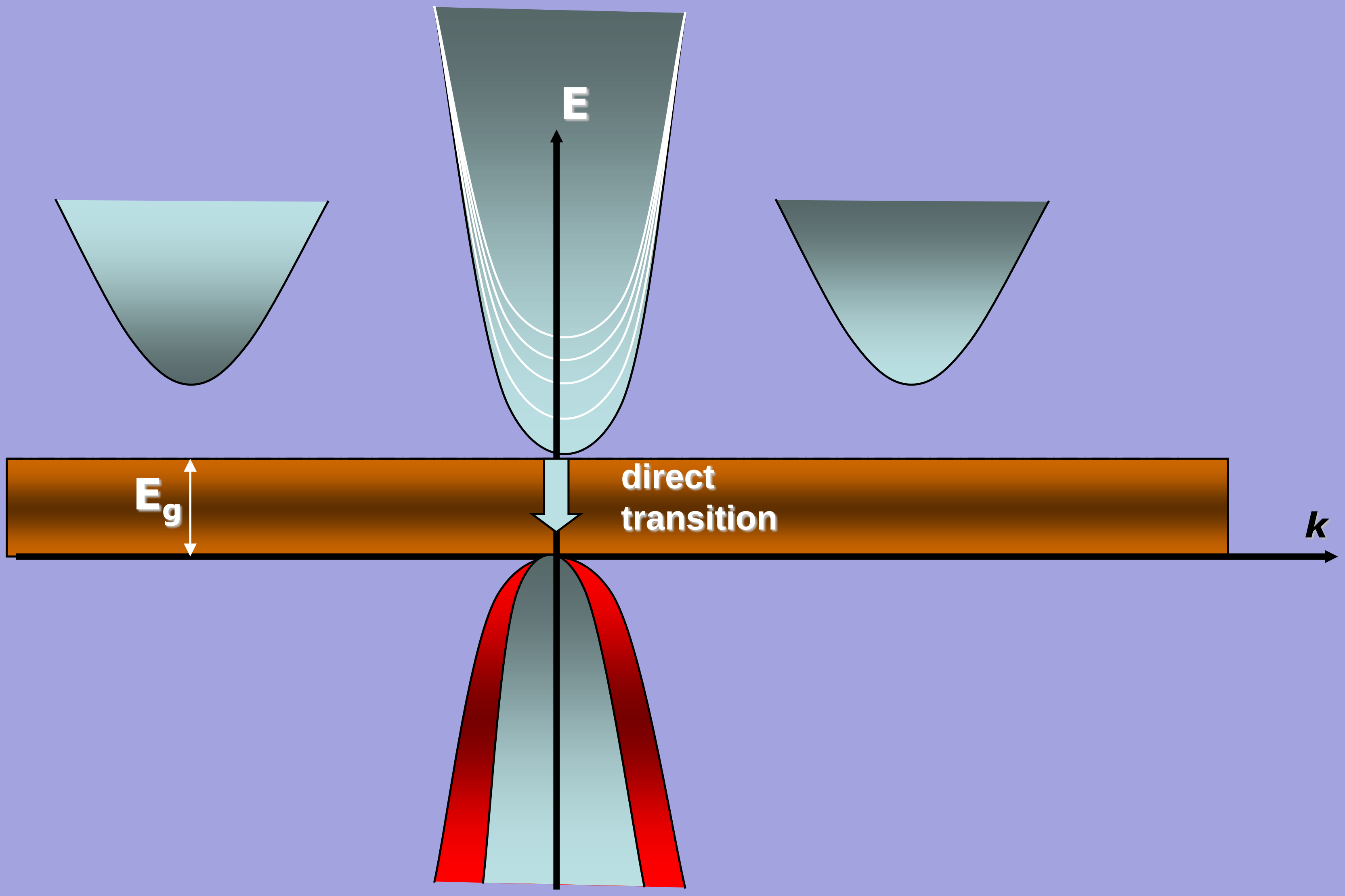
The smallest energy gap is between the top of the VB at k=0 and one of the CB minima away from k=0

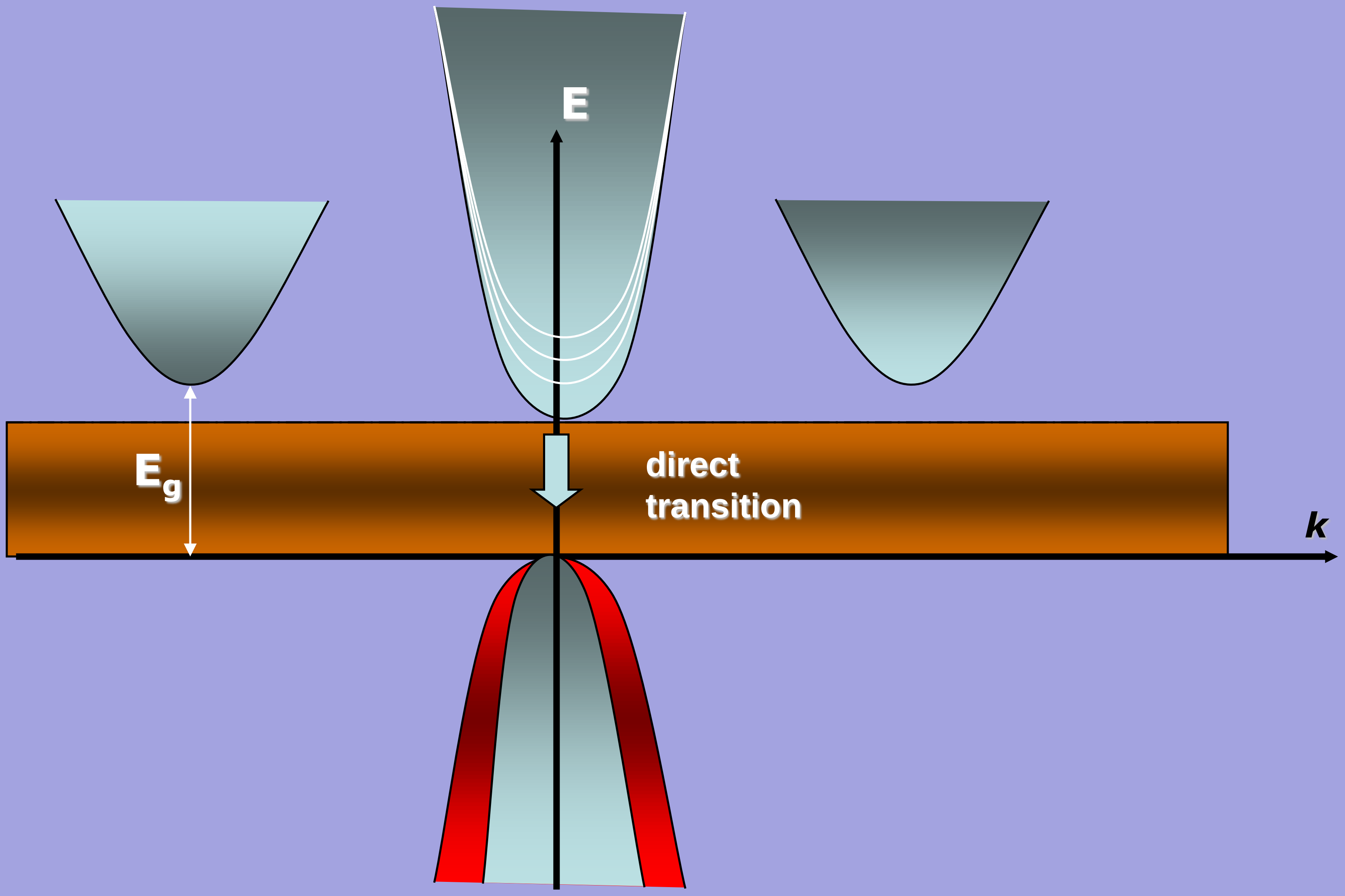
Indirect band gap semiconductor

- **Band structure of AlGaAs?**
- **Effective masses of CB satellites?**
- **Heavy- and light-hole masses in VB?**



Energy band structure of ***Si***


E
E
g
direct
transition
k


E
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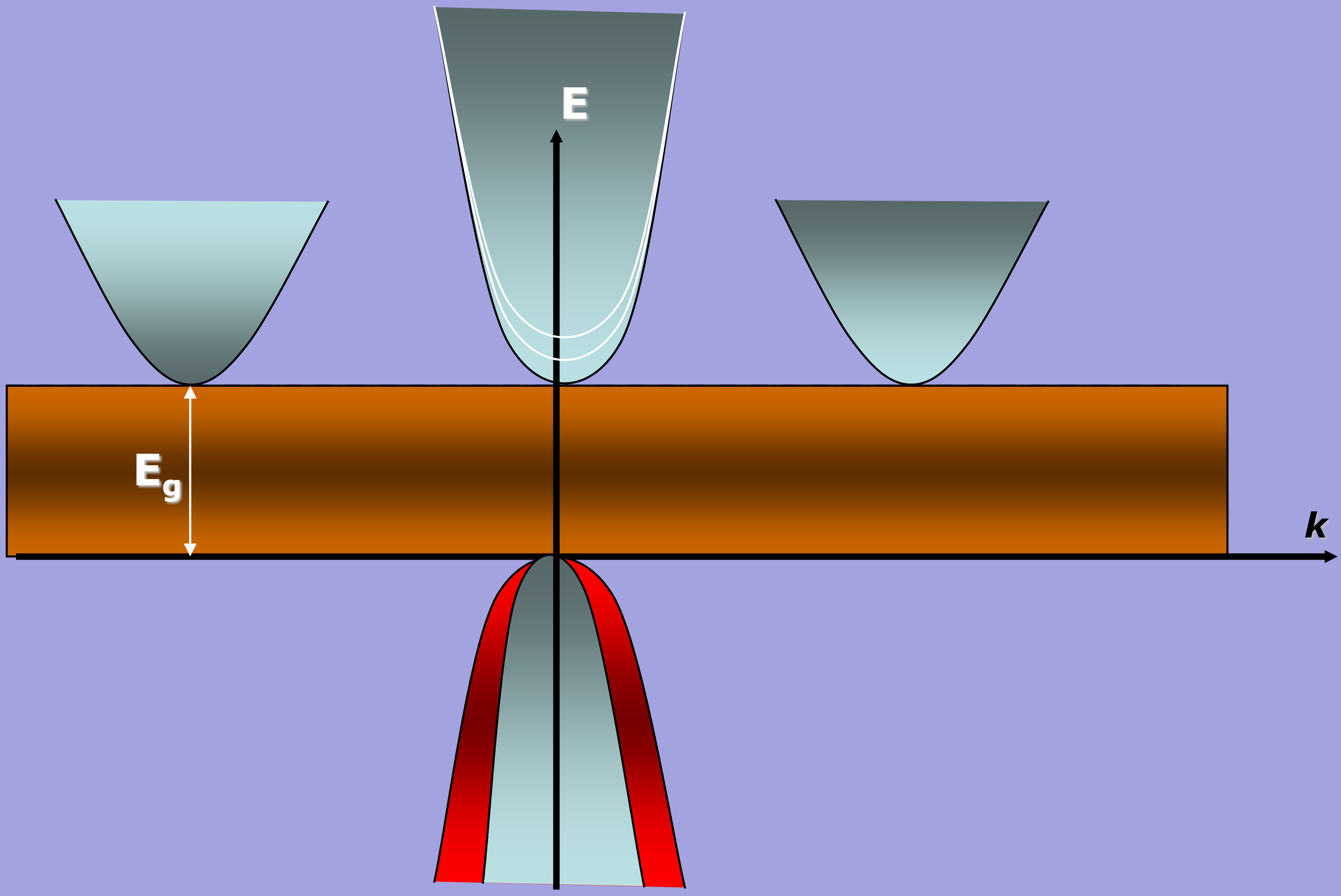
E
E
g
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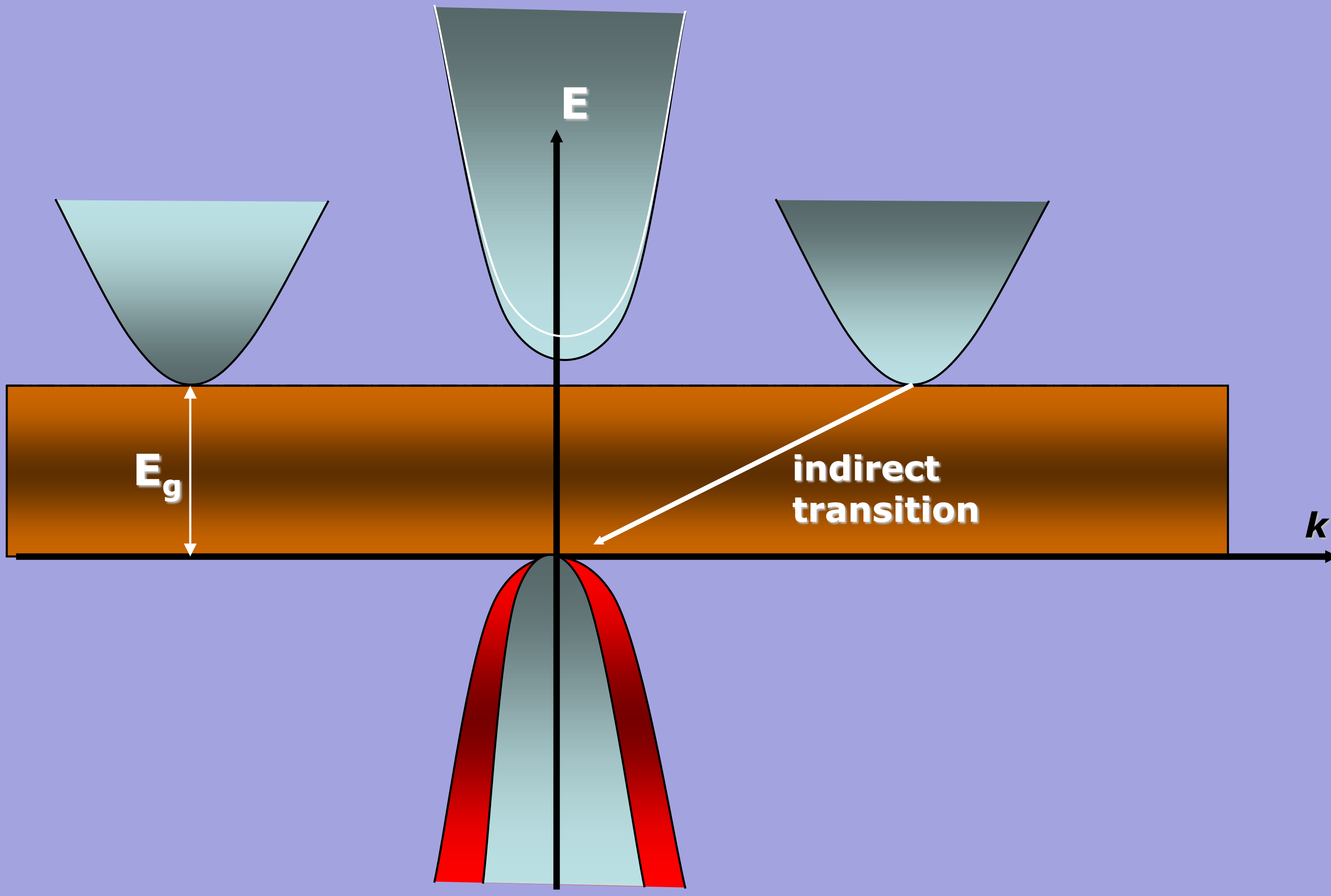
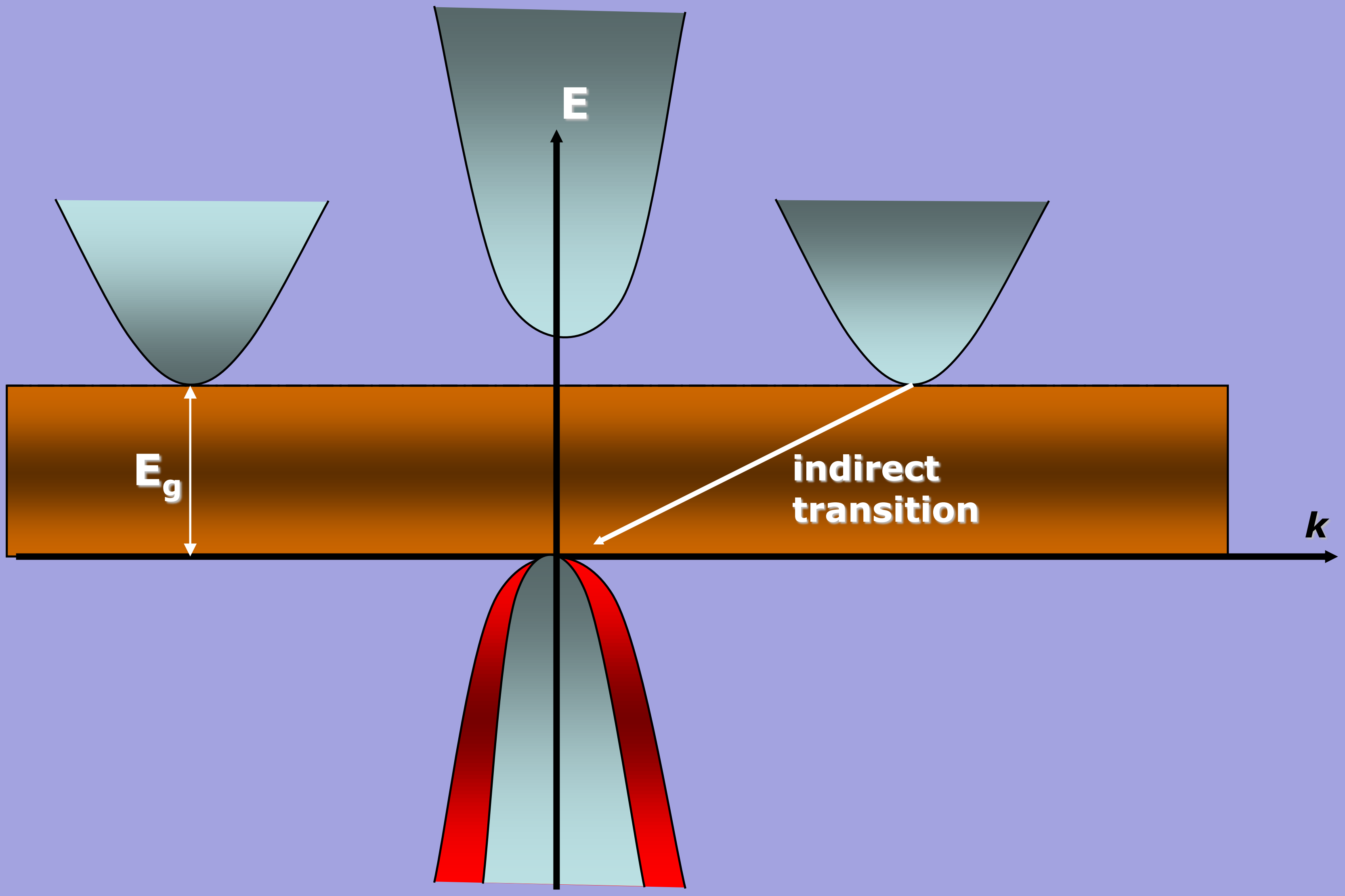
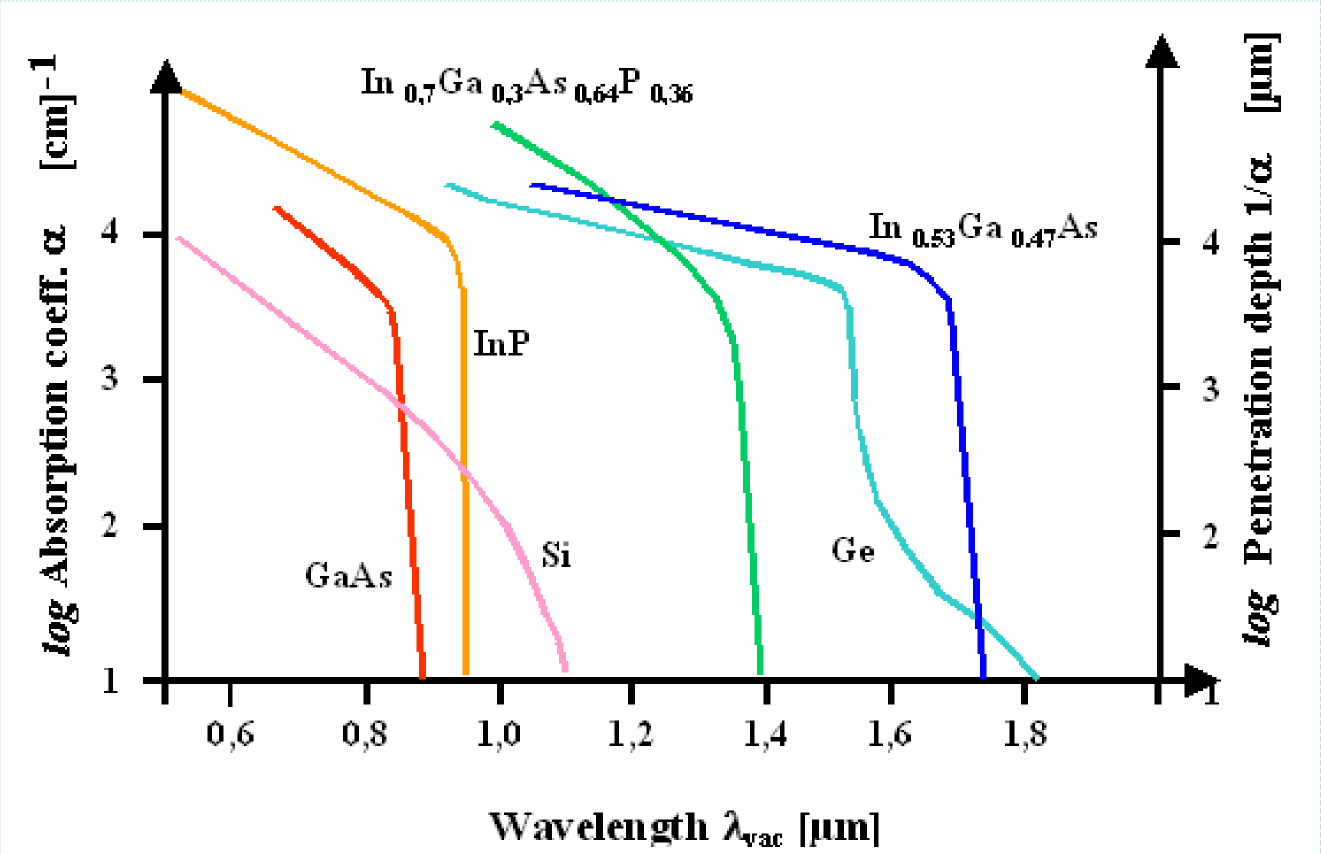

E
E$_g$
indirect
transition
k


E
E_g
indirect
transition
k

Absorptioncoefficient



2.5 Intrinsic/Extrinsic

Intrinsic	Extrinsic
pure semiconductor	doped semiconductor
$n = p$	$n \neq p$
self conduction	Self conduction + conduction because of doping
Conductivity depends on T	Conductivity depends on T and on additional charge carriers (dopant)
$E_F \sim E_V + \frac{E_G}{2}$	Change in E_F

At thermal equilibrium

T>0

INTRINSIC SEMICONDUCTOR

- Both silicon and germanium are tetravalent, i.e. each has four electrons (valence electrons) in their outermost shell.
- Both elements crystallize with a diamond-like structure, i.e. in such a way that each atom in the crystal is inside a tetrahedron formed by the four atoms which are closest to it.
- Each atom shares its four valence electrons with its four immediate neighbours, so that each atom is involved in four covalent bonds.
-

INTRINSIC SEMICONDUCTOR

- At zero Kelvin all of the four valence electrons of each atom in the silicon crystal form part of the covalent bond with the four neighboring atoms.
- The valence band is completely full and the conduction band completely empty.
- The semiconductor behaves as a
- perfect insulator because there are
- no conducting electrons present.

•

Doping

- To make the semiconductor conduct electricity, other atoms called impurities must be added.
- "Impurities" are different elements.
- This process is called doping.

Doping

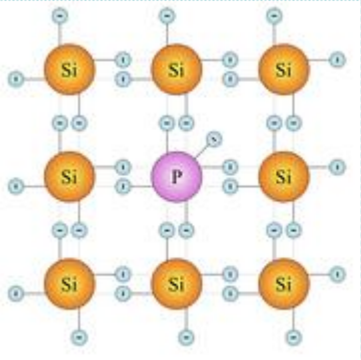
Doping: Change in carrier concentration → change in electrical properties

Donor - doping

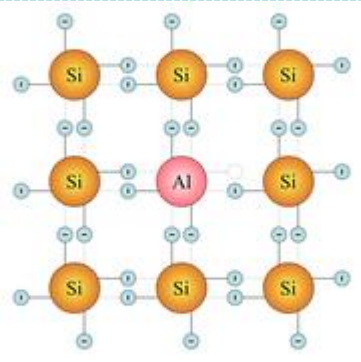
- add an extra electron
- number of e^- > number valence e^-
- n – type dopant
- E_D right under conduction band E_C

Acceptor - doping

- add an extra hole
- number of e^- < number valence e^-
- p – type dopant
- E_A right above valence band E_V

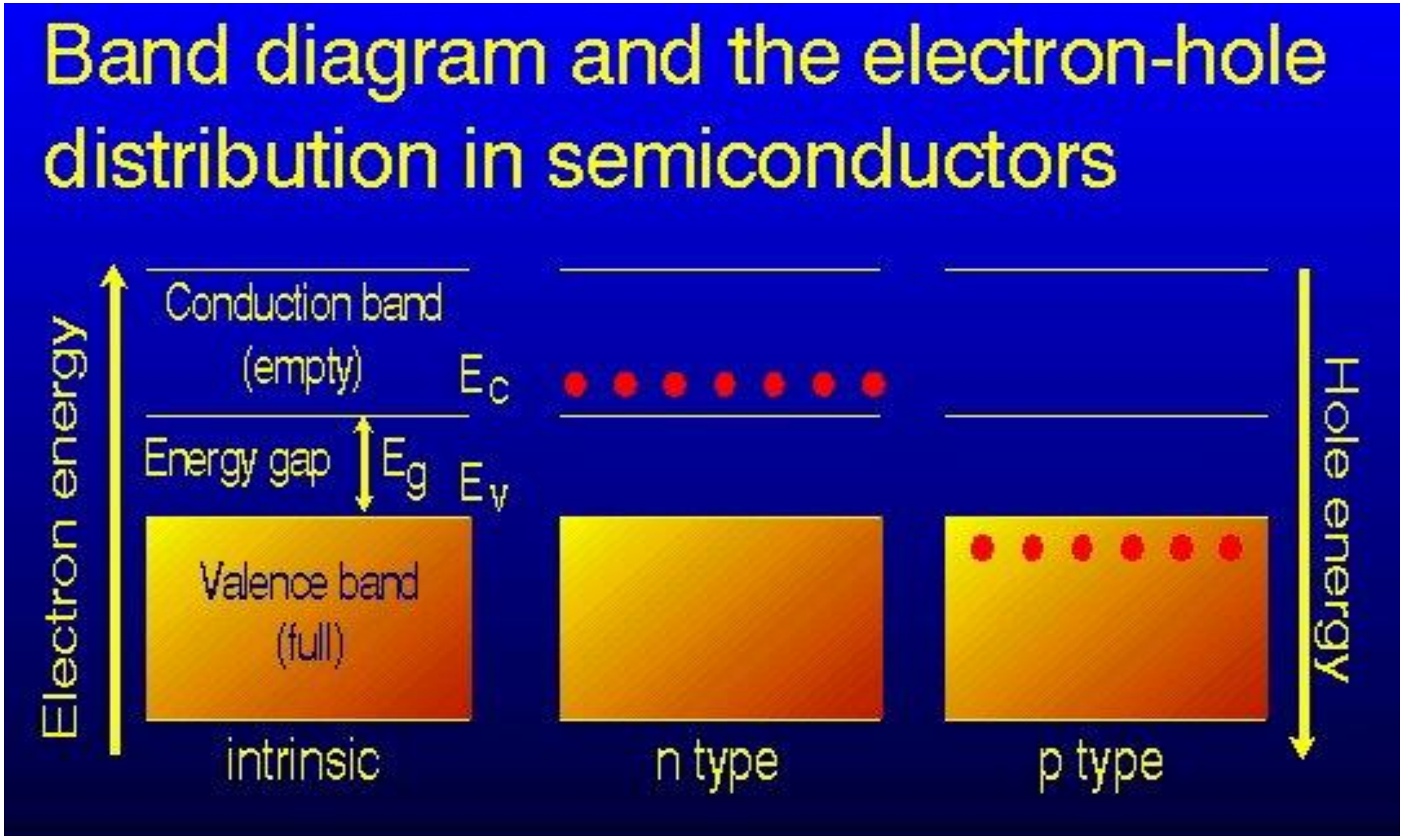


n-type doping



p-type doping

2.4 Doping



Band diagram and the electron-hole distribution in semiconductors
Electron energy
Conduction band
(empty)
E_c
Energy gap
E_g
E_v
Valence band
(full)
intrinsic
n type
p type
Hole energy

Types of Semiconductor Materials

- The silicon doped with extra electrons is called an “N type” semiconductor.
  - “N” is for negative, which is the charge of an electron.
- Silicon doped with material missing electrons that produce locations called holes is called “P type” semiconductor.
  - “P” is for positive, which is the charge of a hole.

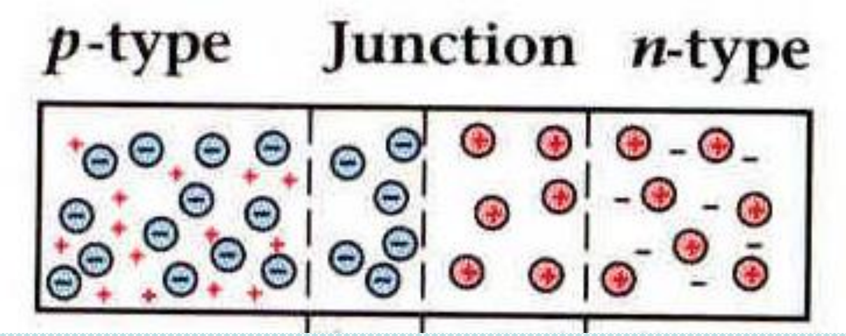
In Summary

- In its pure state, semiconductor material is an excellent insulator.
- The commonly used semiconductor material is silicon.
- Semiconductor materials can be doped with other atoms to add or subtract electrons.
- An N-type semiconductor material has extra electrons.
- A P-type semiconductor material has a shortage of electrons with vacancies called holes.
- The heavier the doping, the greater the conductivity or the lower the resistance.
- By controlling the doping of silicon the semiconductor material can be made as conductive as desired.

P-N JUNCTION DIODE

- On its own a p-type or n-type semiconductor is not very useful. However when combined very useful devices can be made.
- **The p-n junction can be formed by allowing a p-type material to diffuse into a n-type region at high temperatures.**
- **The p-n junction has led to many inventions like the diode, transistors and integrated circuits**.

P-N JUNCTION DIODE



Free electrons on the n-side and free holes on the p-side can initially diffuse across the junction. Uncovered charges are left in the neighbourhood of the junction.

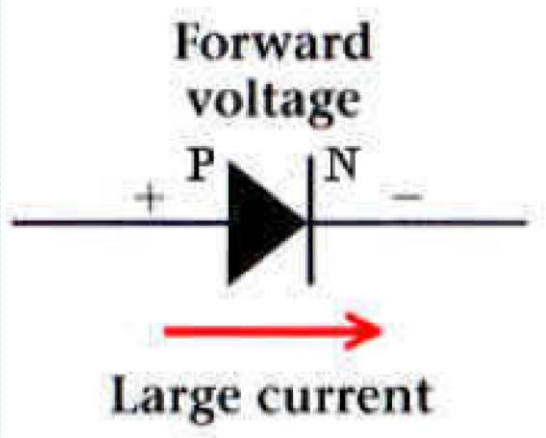
This region is depleted of mobile carriers and is called the **DEPLETION REGION** (thickness 0.5 – 1.0 µm).

P-N JUNCTION DIODE

- The diffusion of electrons and holes stop due to the barrier p.d (p.d across the junction) reaching some critical value.
- The barrier p.d (or the contact potential) depends on the type of semiconductor, temperature and doping densities.
- At room temperature, typical values of barrier p.d. are:
- Ge ~ 0.2 – 0.4 V
- Si ~ 0.6 – 0.8 V

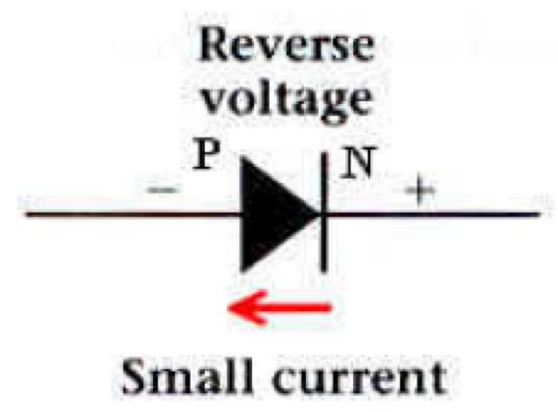
FORWARD BIAS P-N JUNCTION

- **When an external voltage is applied to the P-N junction making the P side positive with respect to the N side the diode is said to be forward biased (F.B).**



- **The barrier p.d. is decreased by the external applied voltage. The depletion band narrows which urges majority carriers to flow across the junction.**
- **A F.B. diode has a very low resistance**

REVERSE BIAS P-N JUNCTION



- When an external voltage is applied to the PN junction making the P side negative with respect to the N side the diode is said to be Reverse Biased (R.B.).
- The barrier p.d. increases. The depletion band widens preventing the movement of majority carriers across the junction.
- A R.B. diode has a very high resistance.
-

REVERSE BIAS P-N JUNCTION

- Only thermally generated minority carriers are urged across the p-n junction. Therefore the magnitude of the reverse saturation current (or reverse leakage current) depends on the temperature of the semiconductor.
- **When the PN junction is reversed biased the width of the depletion layer increases, however if the reverse voltage gets too large a phenomenon known as diode breakdown occurs.**
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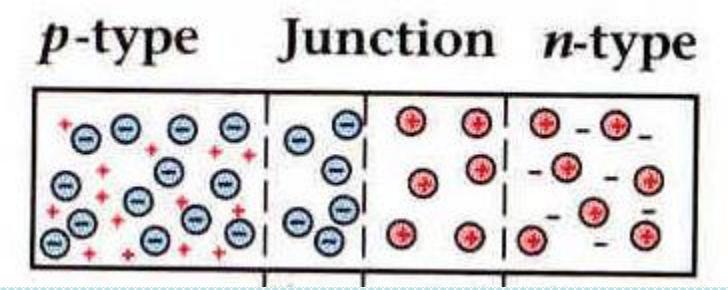
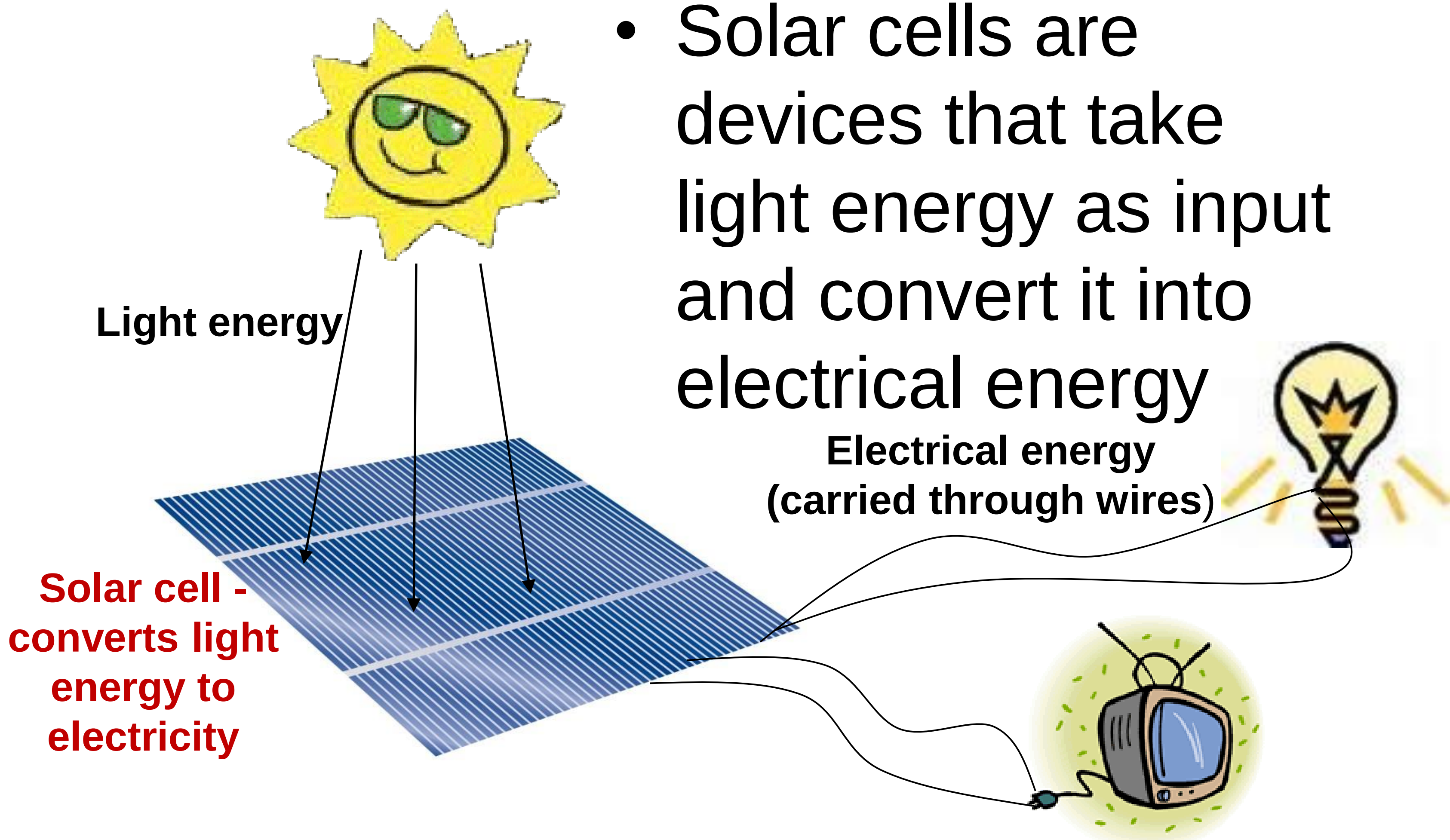


- **Solar Cell Technology**

Solar Cells are Converters of Energy…

- Solar cells are devices that take light energy as input and convert it into electrical energy

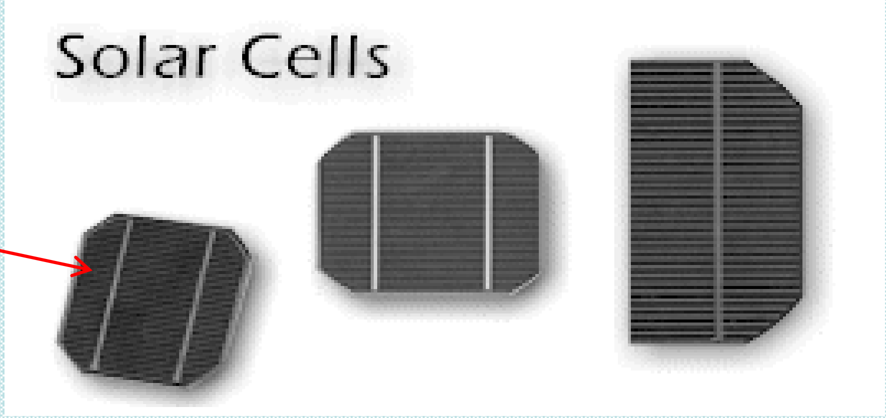


Sources: http://www.econedlink.org/lessons/EM189/images/cartoon_tv.gif
http://emmagoodegg.blogs.com/thebeehive/images/lightbulb.jpg, http://www.torpedowire.com/solar.htm, http://www.uoregon.edu/~stiedeke/a3/assignment03/a3/assignment_images/cartoon-sun.jpg

What is a Solar Cell?

- **It is also known as Photovoltaic cell (PV cell)**
- **A device that converts light energy (solar energy) directly to electricity.**
- **The term solar cell is designated to capture energy from sunlight, whereas PV cell is referred to an unspecified light source.**
- **It is like a battery because it supplies DC power.**
- **It is not like a battery because the voltage supplied by the cell changes with changes in the resistance of the load.**

Made from a single crystalline silicon wafer



What is Solar Energy?

- Energy produced by the sun
- **Clean, renewable source of energy**
- Harnessed by solar collection methods such as solar cells
- Converted into usable energy such as electricity

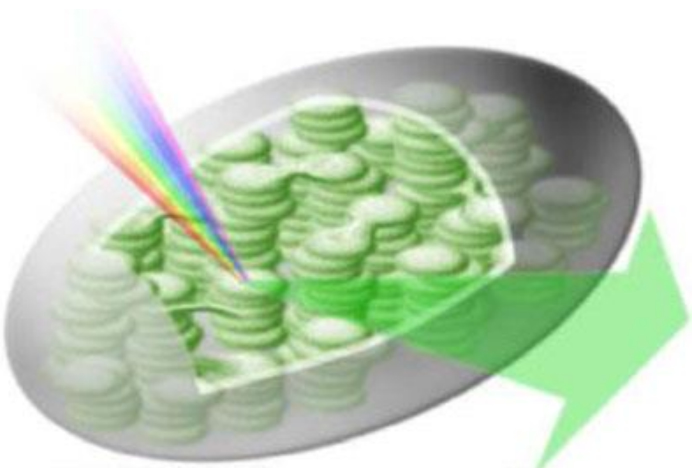
Photovoltaic (solar) panel

Set of solar panels

Sun and electrical power lines

…But Not All Energy is Converted

- Like chloroplasts in plants, solar cells can only absorb specific wavelengths of light.
- In both, light that isn't absorbed is either transmitted through or reflected back.
- Whether a certain wavelength of lights gets absorbed depends on its energy.



Chlorophyll molecules absorb blue and red light, but reflect green light

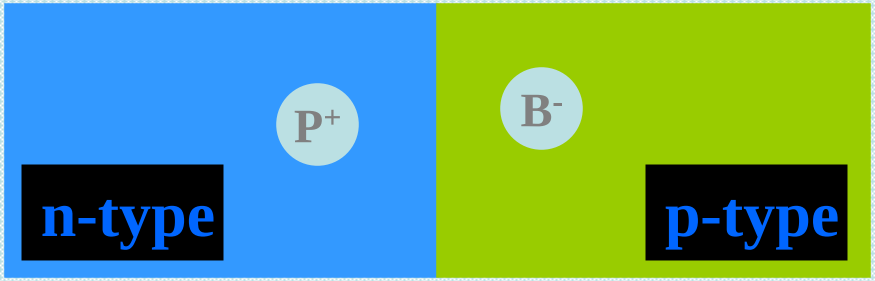
Source: http://ebiomedia.com/prod/cyclops/images/image004.jpg

Applications of Solar Cells

- Renewable energy
- Can be powered for remote locations
- It’s free, limitless, and environmentally friendly…

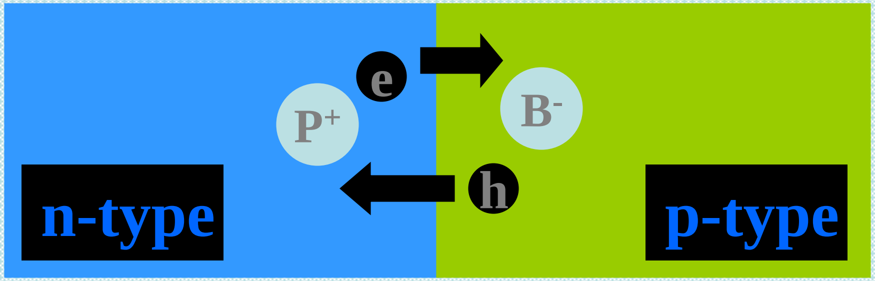
Physics of Solar Cells

- Semiconductor material can be p-type (hole carriers) or n-type (electron carriers)



- N-type has impurities with an extra electron (phosphorus)
- P-type has impurities with one fewer electron (boron)
- Put them together: p-n junction
- ***A solar cell is a very large p-n junction (or diode)***

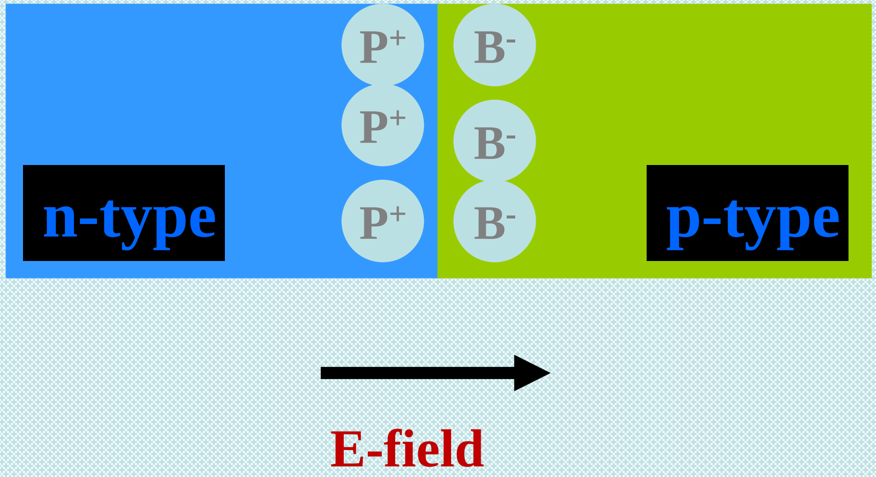
Basic Physics of Solar Cells



- The holes from the p-type side diffuse to the n-type side.
- The electrons diffuse to the p-type side.
- This leaves behind charged ions (missing electrons or holes).

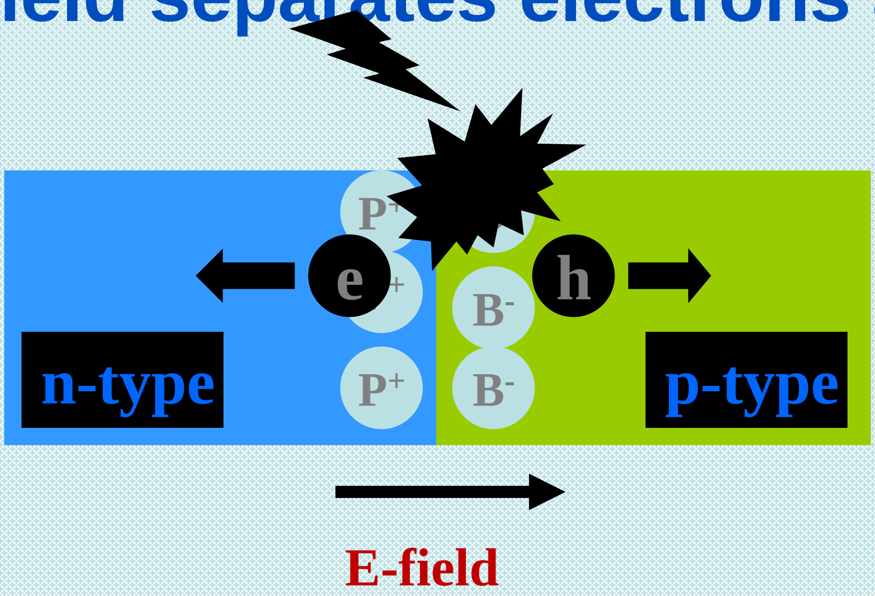
Built-In Electric Field

- The charged atoms (ions) create an electric field.
- This electric field makes it easy for current to flow in one direction, but hard to flow in the opposite direction.



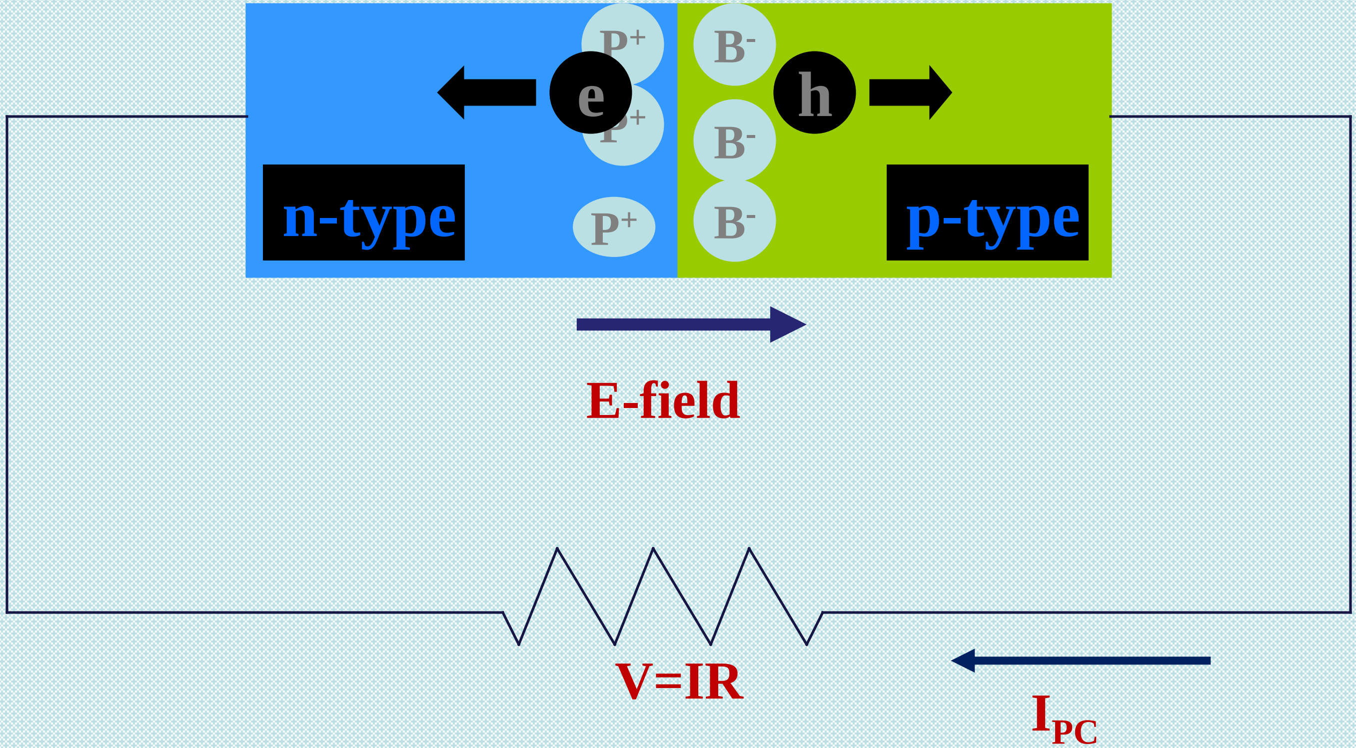
Generating Charges From The Sun

- Light breaks silicon bonds and creates "free" electrons and holes "missing electrons"
- Holes are positive charges
- Built-in field separates electrons and holes



Generating Charges From The Sun

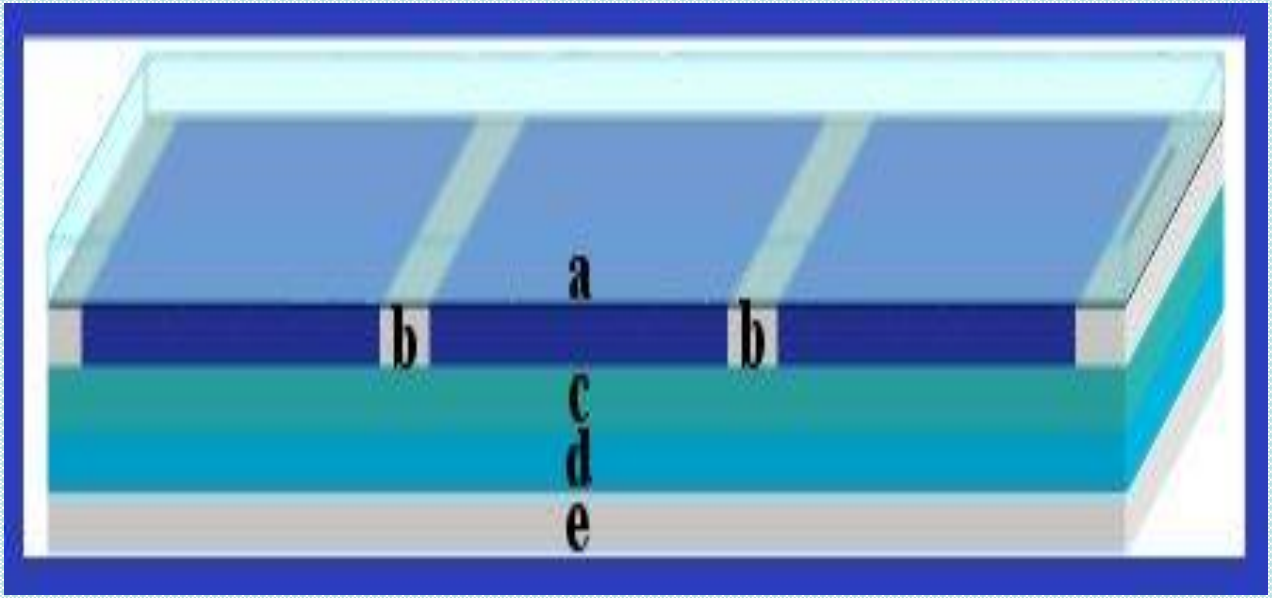
- Connect diode to a circuit
- Photocurrent goes through resistor
- Causes a voltage drop



Construction of Solar cells

- They are constructed by layering special materials called semiconductors into thin, flat sandwiches.
- These are linked by electrical wires and arranged on a panel of a stiff, non-conducting material such as glass. The panel itself is called a **module.**
- Modules are then interconnected, in series or parallel, or both, to create an **array** with the desired peak DC voltage and current.

http://www.specmat.com/Overview%20of%20Solar%20Cells.htm



a. Encapsulate

b. Contact Grid

c. Antireflective Coating

d. N-type Silicon

e. P-type Silicon

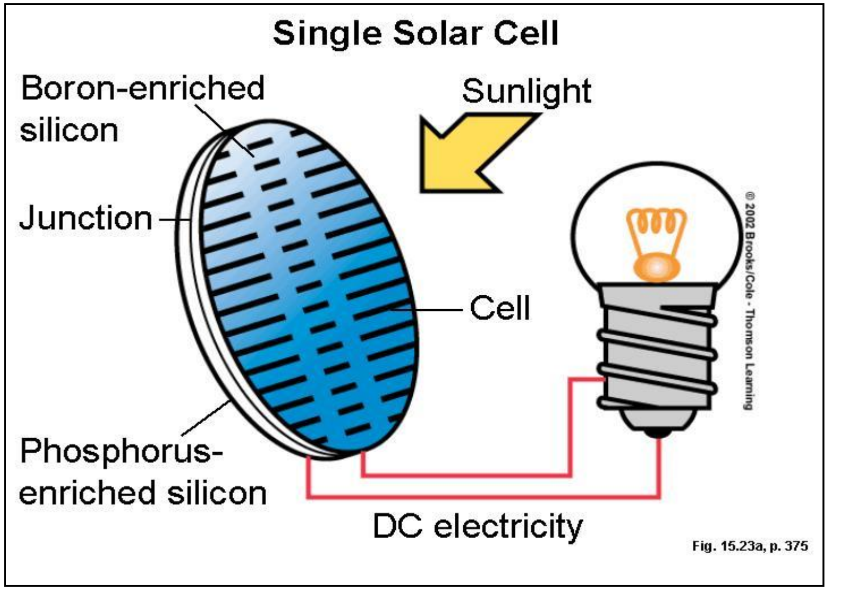
f. Back Contact

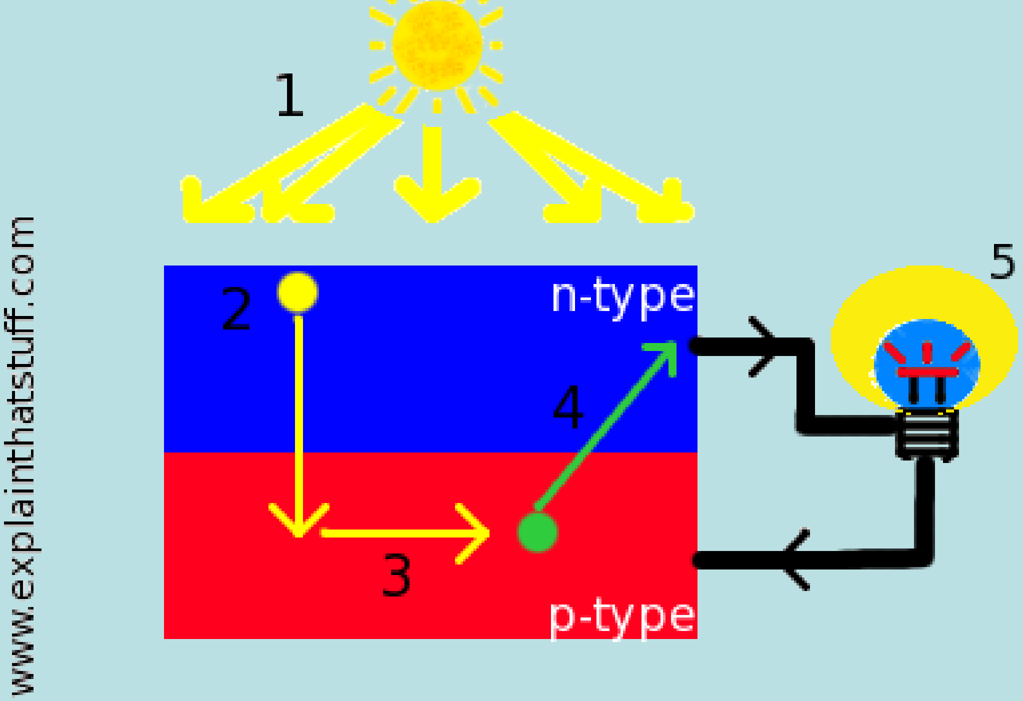
How Solar cells work

- Function 1: Photogeneration of charge carriers (electrons and holes) in a light-absorbing material
- Function 2: Separation of the charge carriers to a conductive medium such as a metal contact or a wire in order to transmit the electricity
  - ✓ **It supplies a voltage and a current to a resistive load (light, battery, motor).**
  - ✓ **Power = Current x Voltage**

Photovoltaics

- **<u>Photo</u>+<u>voltaic</u> = convert <u>light</u> to <u>electricity</u>**





1. A solar cell is a sandwich of n-type silicon (blue) and p-type silicon (red).
2. When sunlight shines on the cell, photons (light particles) bombard the upper surface.
3. The photons (yellow dot) carry their energy down through the cell.
4. The photons give up their energy to electrons (green dot) in the lower, p-type layer.
5. The electrons use this energy to jump across the barrier into the upper, n-type layer and escape out into the circuit.
6. Flowing around the circuit, the electrons make the lamp light up.

http://www.explainthatstuff.com/solarcells.html

Mechanism of generation

• Mechanism of generation

The solar cell is composed of a P-type semiconductor and an N-type semiconductor. Solar light hitting the cell produces two types of electrons, negatively and positively charged electrons in the semiconductors.

Negatively charged (-) electrons gather around the N-type semiconductor while positively charged (+) electrons gather around the P-type semiconductor. When you connect loads such as a light bulb, electric current flows between the two electrodes.

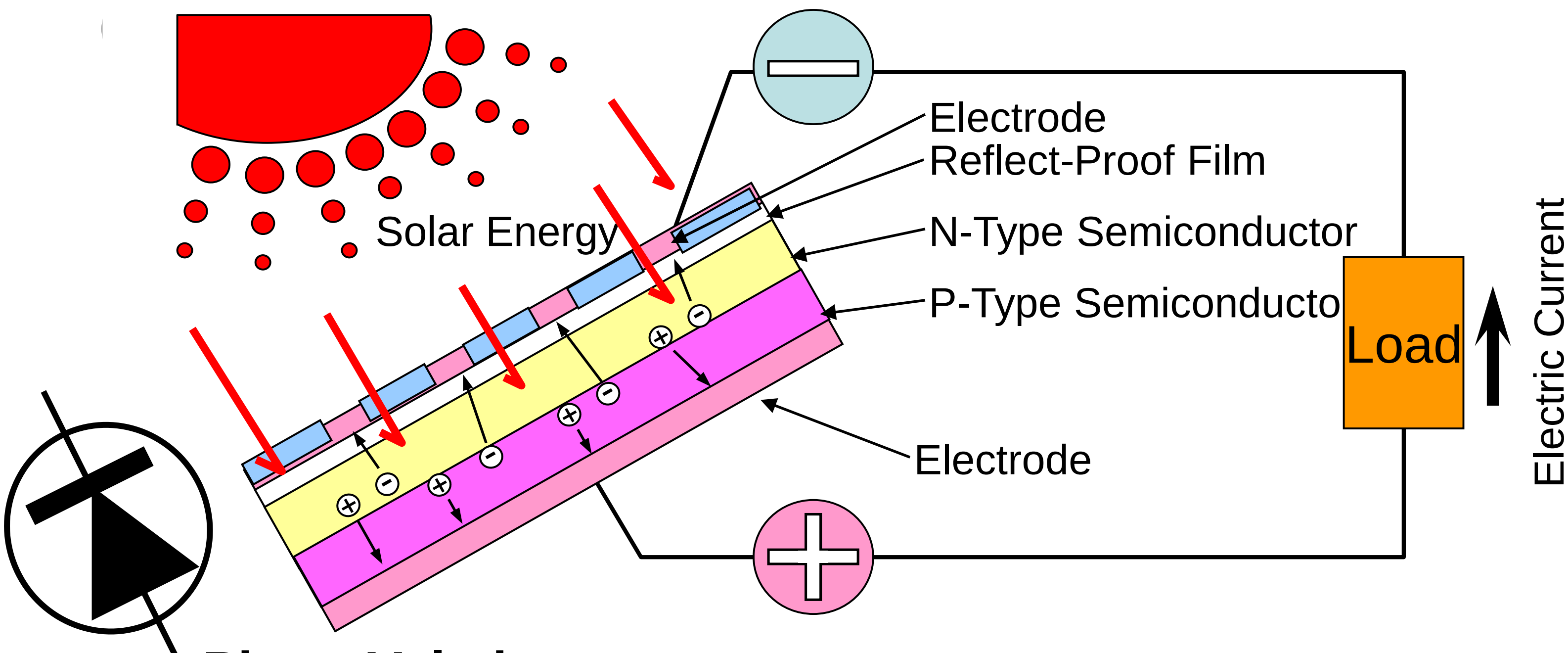
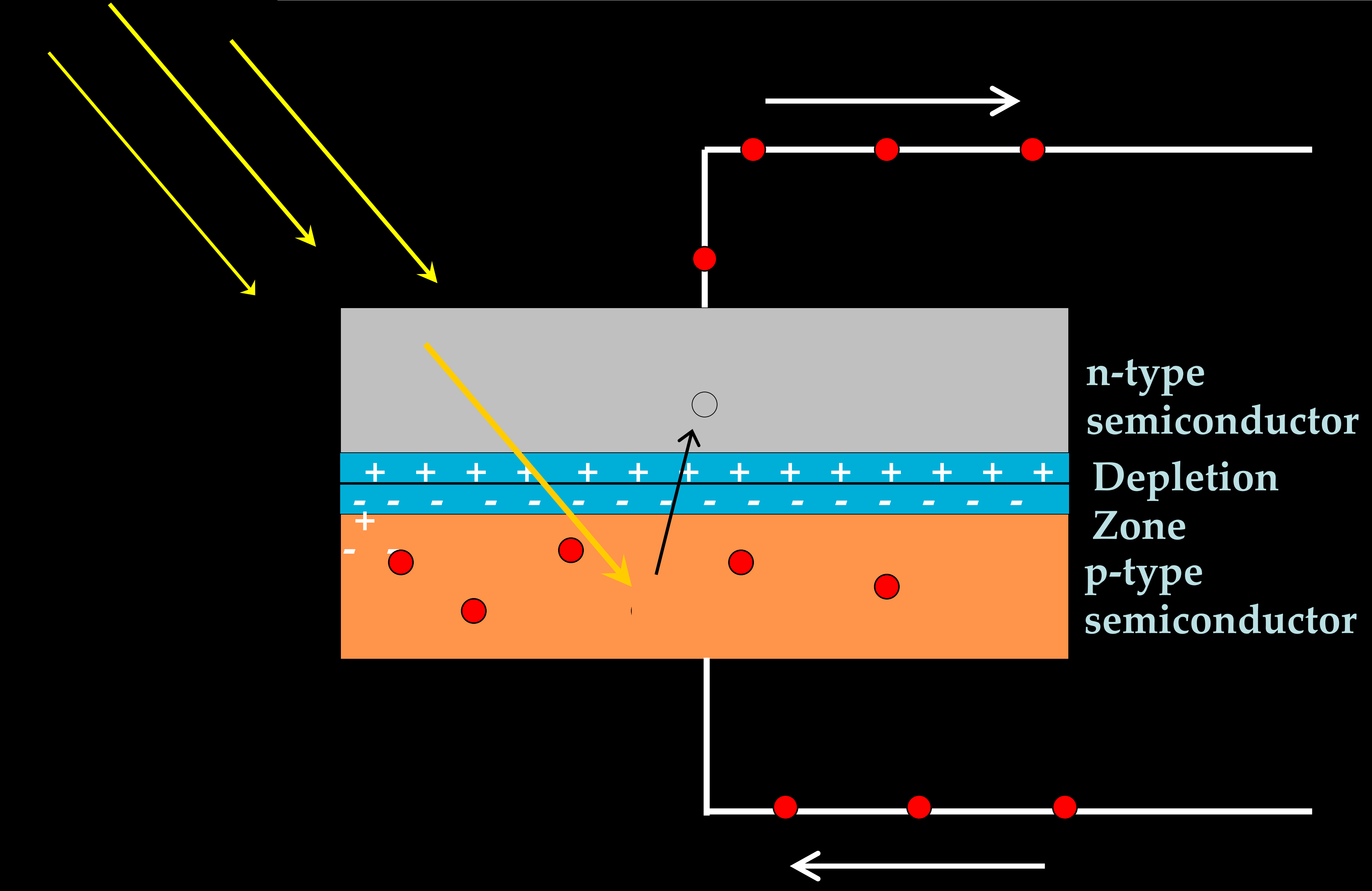
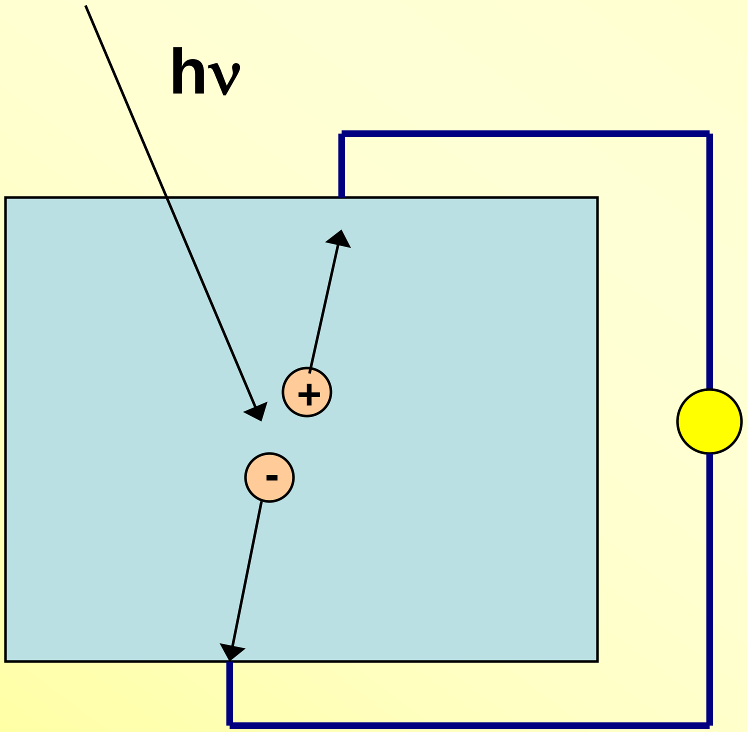


Photo Voltaic cell

Physics of Photovoltaic Generation



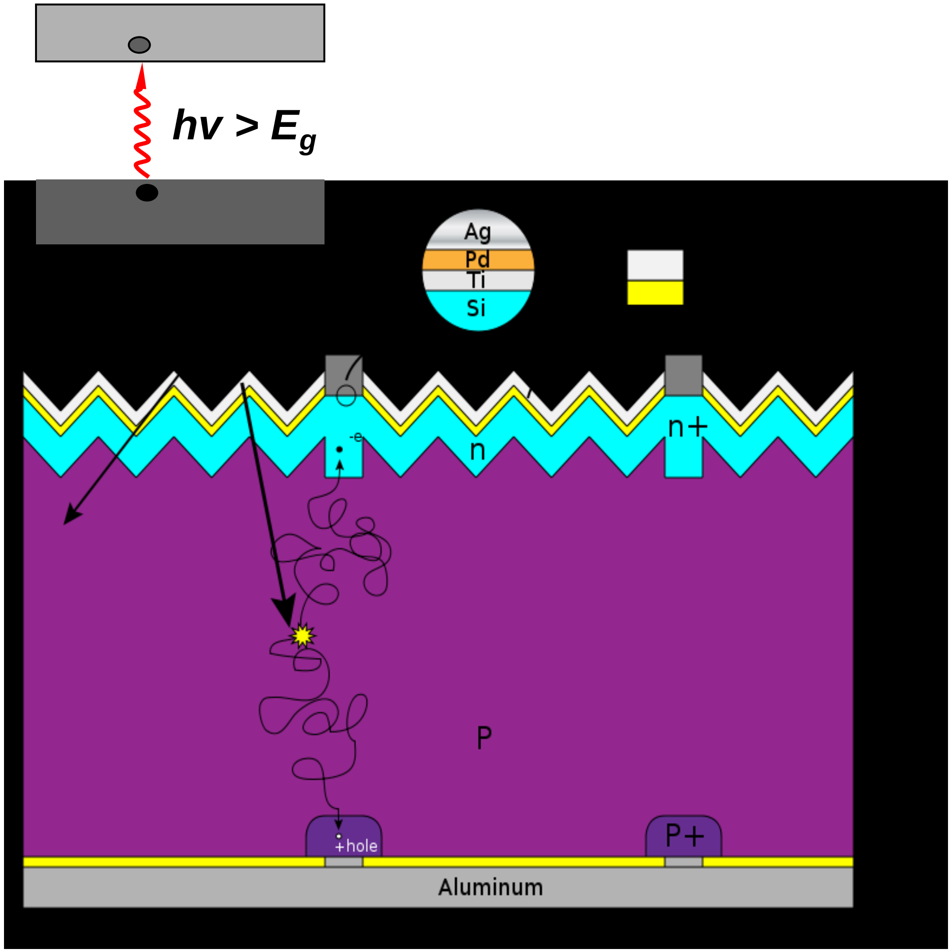
Solar Cell and Photoelectric Effect

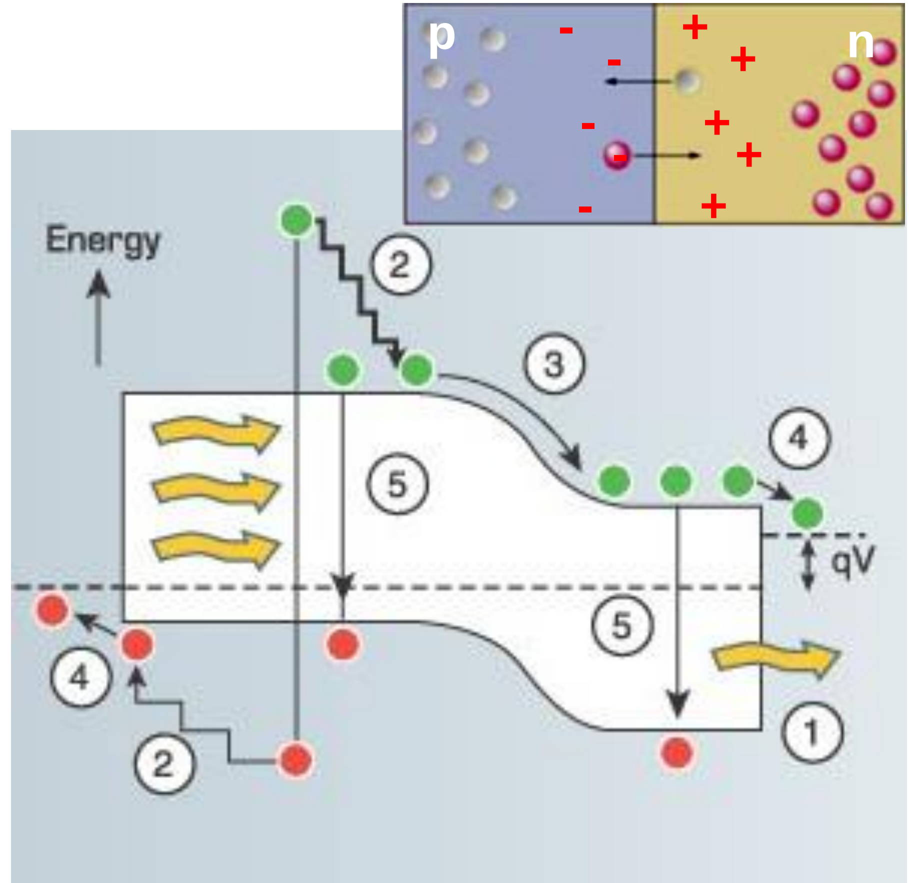


1. **Light absorption**
2. **Generation of „free“ charges**
3. **effective separation of the charges**

Result: wearless generation of electrical Power by light absorption

How Solar Cells Work

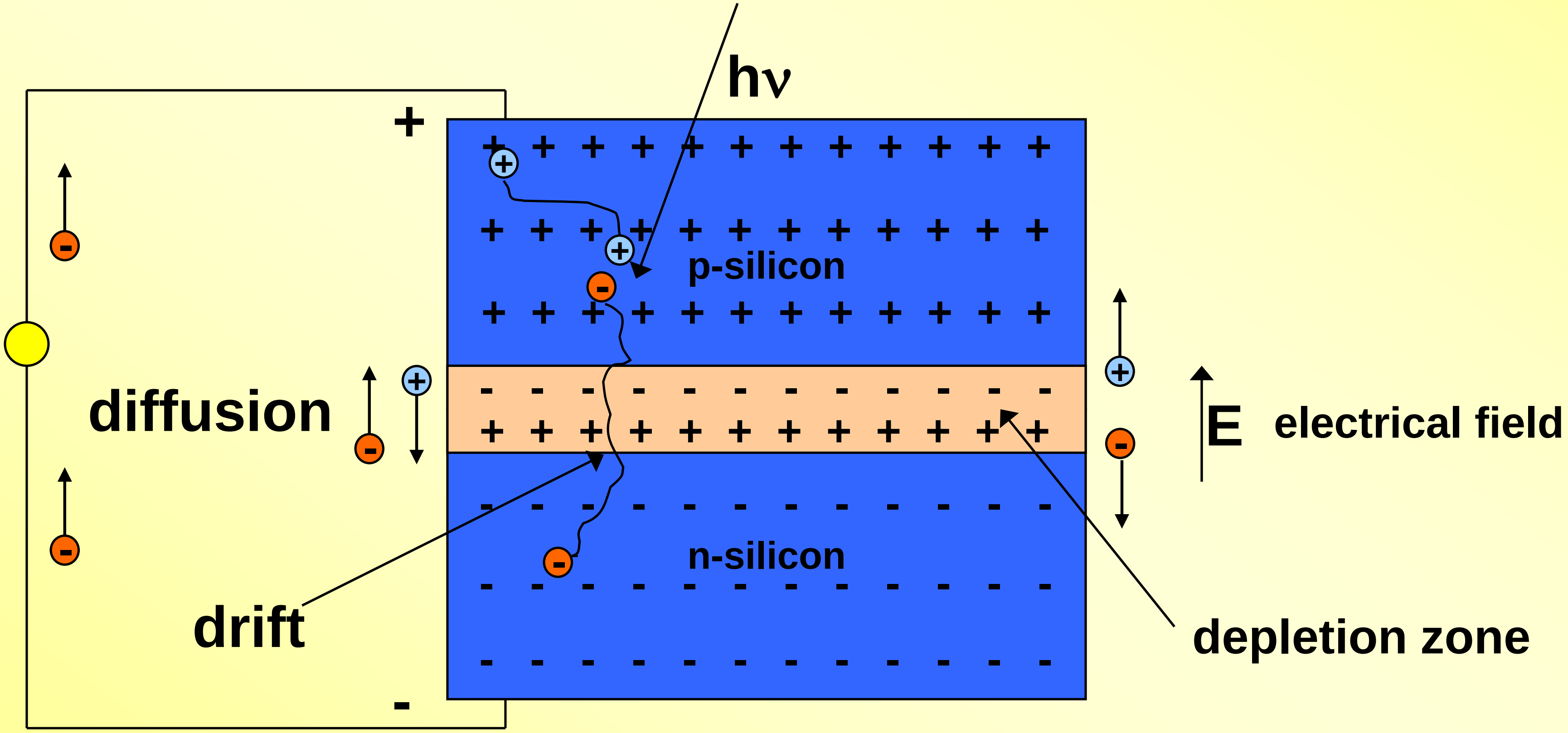




- Photons in sunlight hit the solar panel and are absorbed by semiconducting materials to create electron hole pairs.
- Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity.

p/n–junction with irradiation

crystal view



Charge carrier separation within p/n–junction

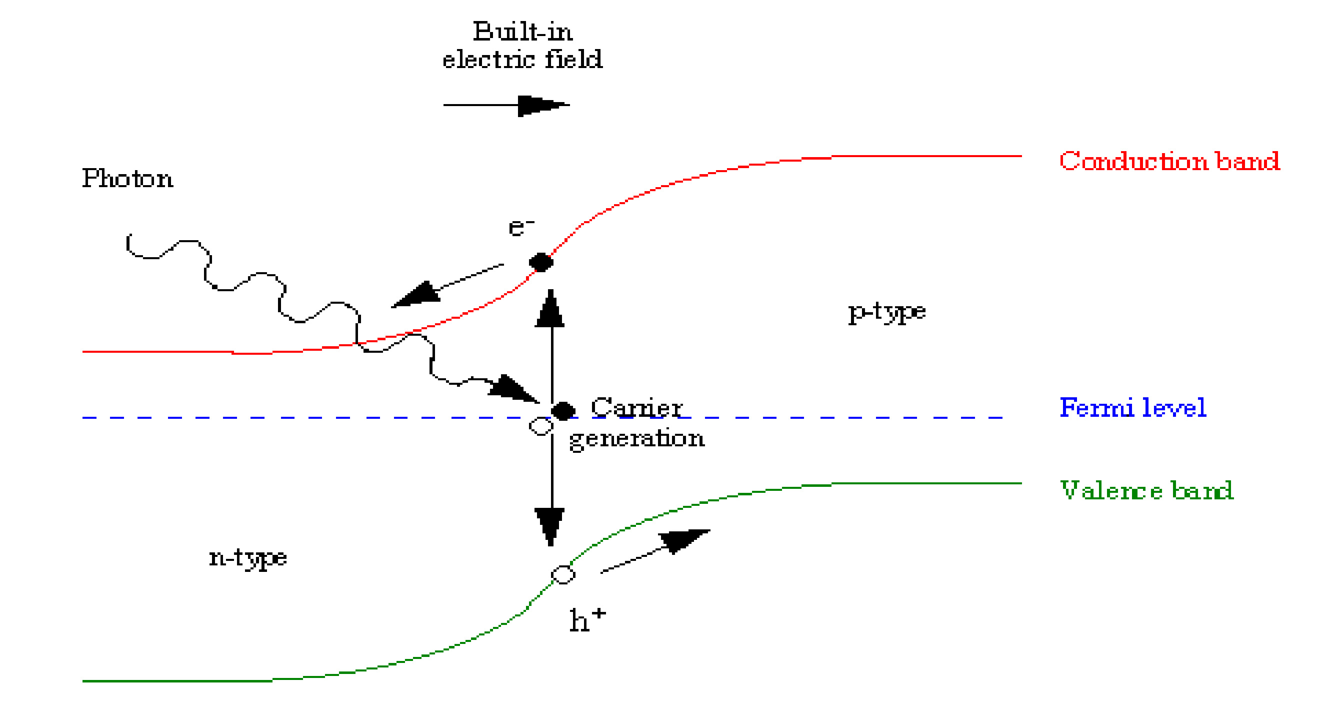
diffusion:

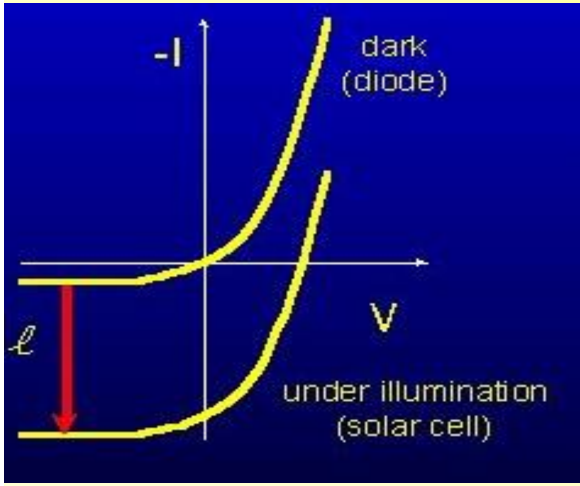
from zones of high carrier concentration to zones of low carrier concentration (following a gradient of electrochemical potential)

drift:

driven by an electrostatic field established across the device

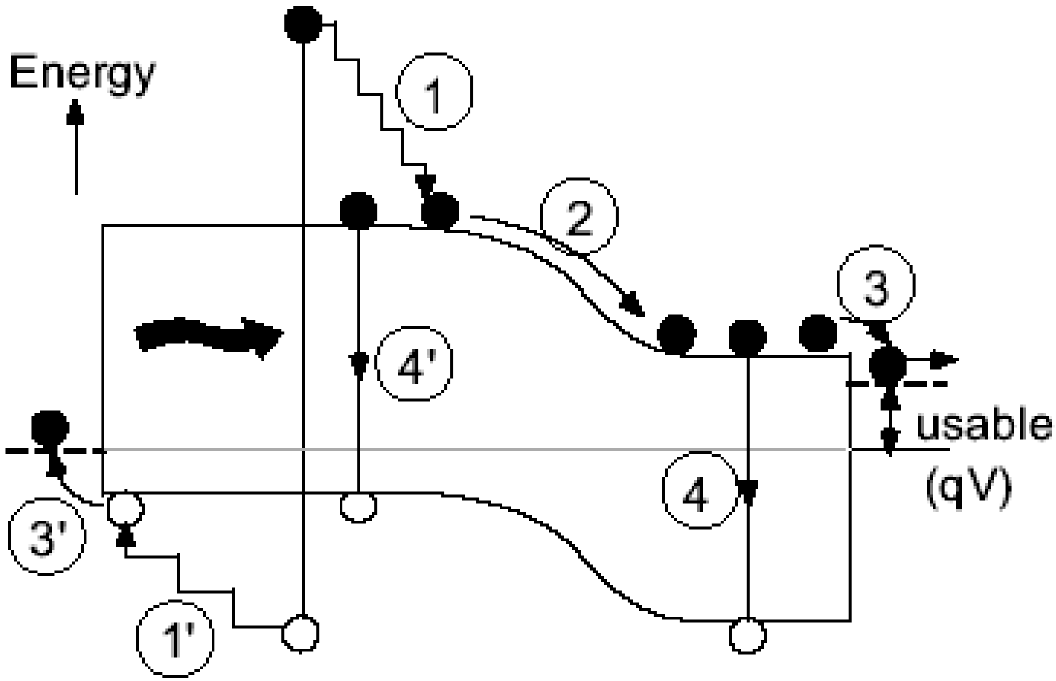
Solar cell – Working Principle





- **Operating diode in fourth quadrant generates power**

Efficiency Losses in Solar Cell



1 = Thermalization loss

2 and 3 = Junction and contact voltage loss

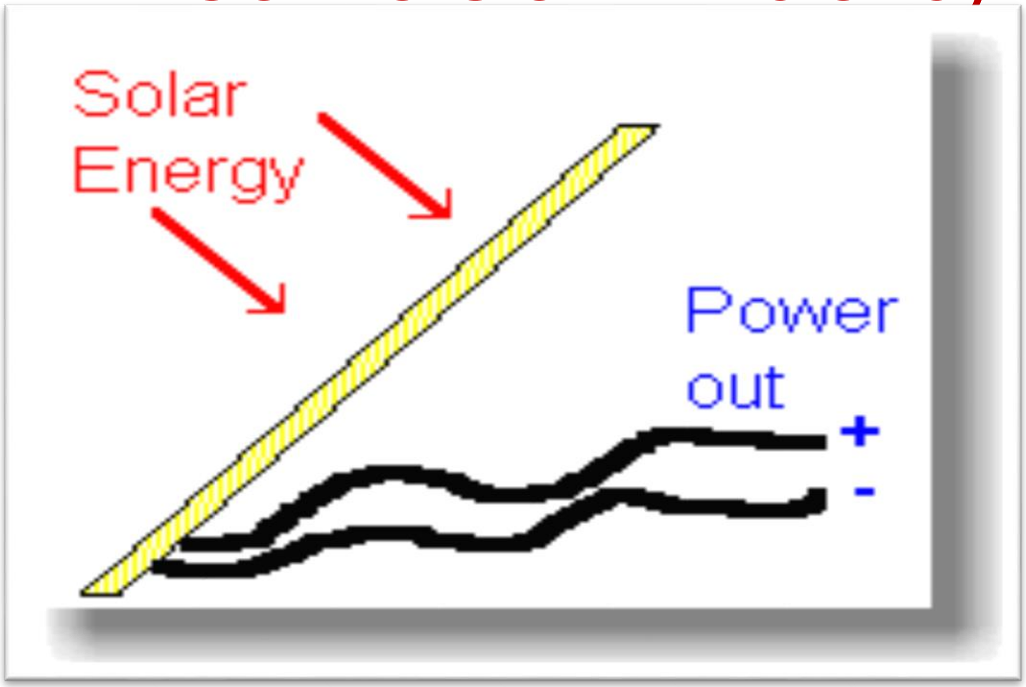
4 = Recombination loss

Efficiency

- A solar cell's *energy conversion efficiency* (η, "eta"), is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell is connected to an electrical circuit. This term is calculated using the ratio of P_m, divided by the input light *irradiance* under "standard" test conditions (*E*, in W/m²) and the *surface area* of the solar cell (A_c in m²).

$$\eta = \frac{P_m}{E \times A_c}$$

Conversion Efficiency



- **The conversion efficiency of a PV cell is the proportion of sunlight energy that the cell converts into electrical energy.**

- **This is very important because improving this efficiency is vital to making PV energy competitive with more traditional sources of energy, such as fossil fuels.**

- **The first PV cells were converting light to electricity at 1 to 2 percent efficiency.**

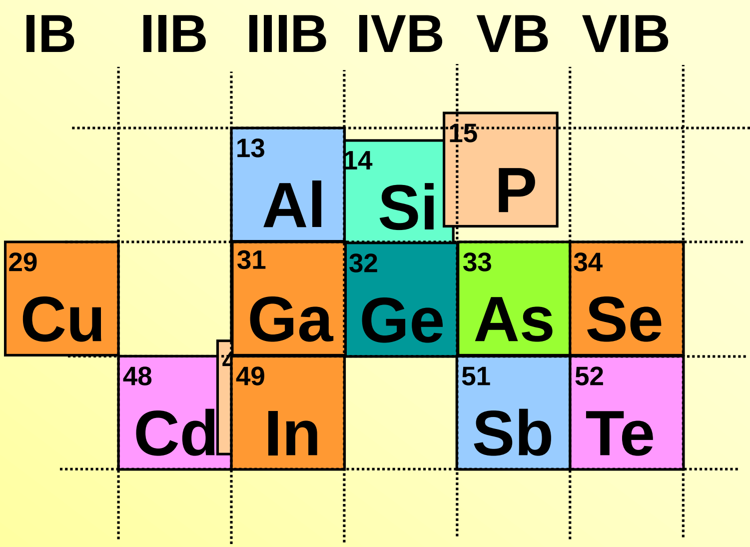
- ***Today's PV devices convert up to 17 percent of the radiant energy that strikes them into electric energy. (40% NREL) NATIONAL RENEWABLE ENERGY LABORATORY***

Materials

<u>Definition of semiconductor:</u>

This is a matter of electron configuration

Extract of periodic table:



Silicon (Si)

Germanium (Ge)

Gallium-Arsenide (GaAs)

Cadmium-Telluride (CdTe)

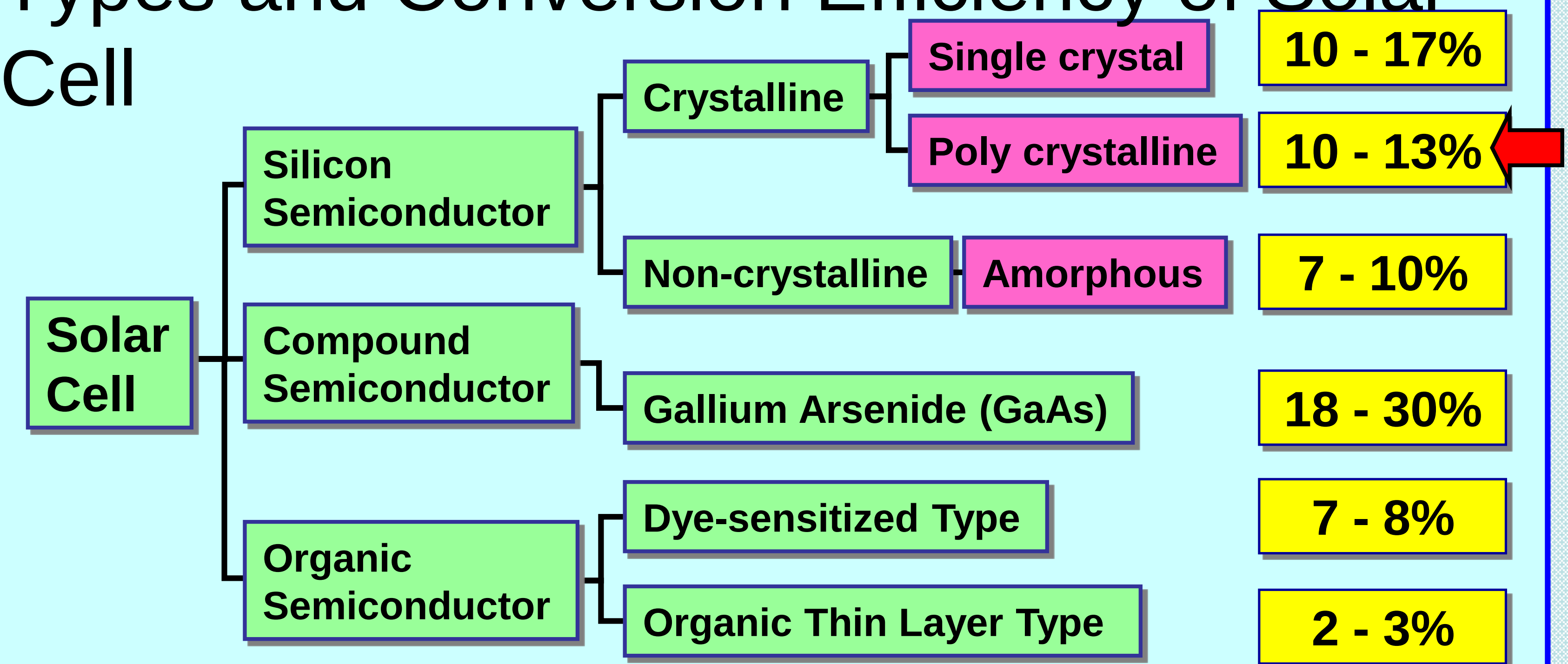
Indium-Phosphorus (InP)

Aluminium-Antimon (AlSb)

Copper, Indium, Gallium, Selenide (CIS)

Various type of PV cell

- Types and Conversion Efficiency of Solar Cell



$$\left(\text{Conversion Efficiency} = \frac{\text{Electric Energy Output}}{\text{Energy of Insolation on cell}} \times 100\% \right)$$

Solar Cells : Technology Options

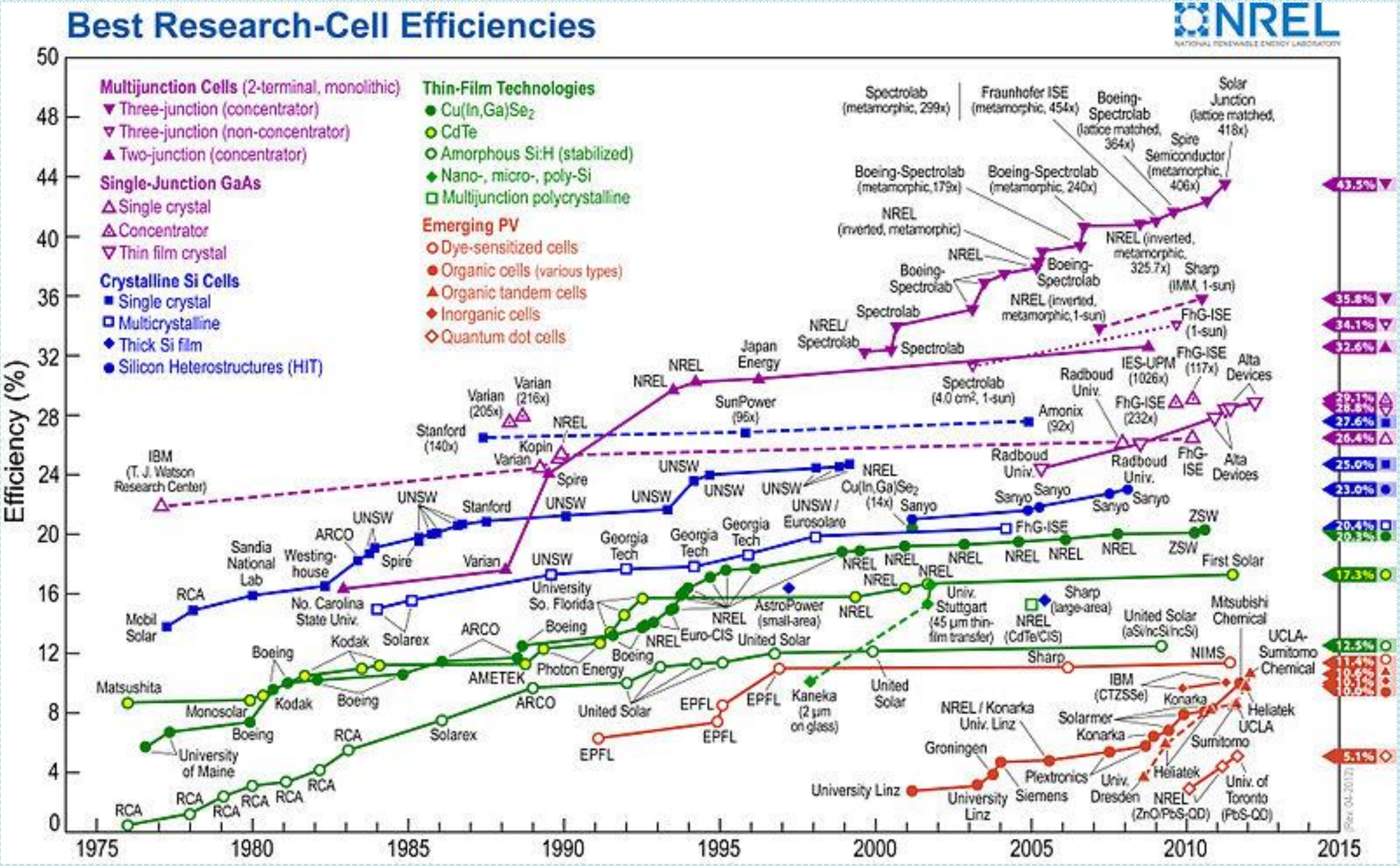
- Crystalline Silicon solar cells
  - Single, Multi, Ribbon

- Thin Film solar cells
  - Silicon, a-Si, m-Si, CdTe, CIGS

- Concentrating solar cells
  - Si, GaAs

- Dye, Organic, nano materials & other emerging solar cells

Solar Cell Best Efficiencies: World



HIGHEST SOLAR CELL EFFICIENCIES (WORLD)

TECHNOLOGY	AREA SQ. CM.	EFF. %	GROUP
Si SINGLE CRYSTAL	4.00	24.7	UNSW
Si MULTI CRYSTAL	1.00	20.3	FhG-ISE
a-Si SINGLE JUNCTION	1.00	12.7	SANYO
a-Si TRIPLE JUNCTION	0.27	13.5	USSC
a-Si/µc-Si(nc-Si)	1.20	10.1	Kaneka
CdTe	1.00	17.3	First Solar
CIGS	1.00	19.6	NREL
Si FILMS	4.01	16.6	Stuttgart University
DYE	1.00	11.0	Sharp
Organic	1.0	10.0	Mitsubishi
GaAs (500 x)	0.4	40.7	SPECTROLAB
Si/GaAs (20 x)	0.4	42.8	Delaware Univ,

Solar Cell Best Efficiencies: India

TECHNOLOGY	AREA SQ. CM.	EFF. %	Group
SINGLE CRYSTAL	64.00	19.7	CEL
MULTI CRYSTAL	100.00	16.8	Tata BP
a-Si SINGLE JUNCTION	1.00	12.0	IACS
a-Si MULTI JUNCTION	1.00	11.5	IACS
a-Si/μc-Si(nc-Si)	1.00	9.0	IACS
CdTe	1.00	12.0	NPL
CIGS	0.41	13.0	IISC
Si FILMS	0.98	8.7	Jadavpur
Dye Sensitized	1.00	9.5	Amrita
Organic cells	1.00	6.2	NPL

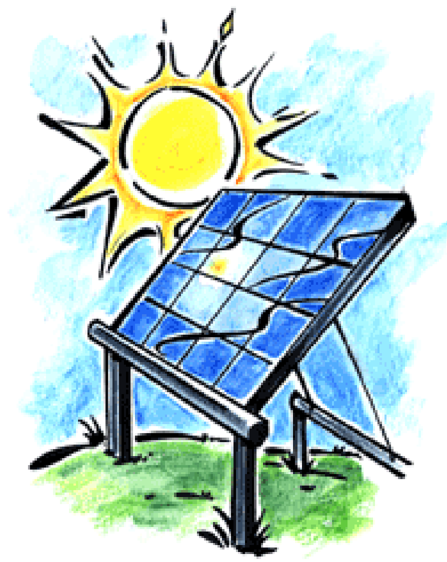
Crystalline Silicon Solar Module Efficiency

TYPICAL IN PRODUCTION

	INTERNATIONAL	INDIAN
• SINGLE CRYSTAL	15 – 20.4 %	14 – 17 %
• MULTI CRYSTAL	13 – 16%	13 – 16%

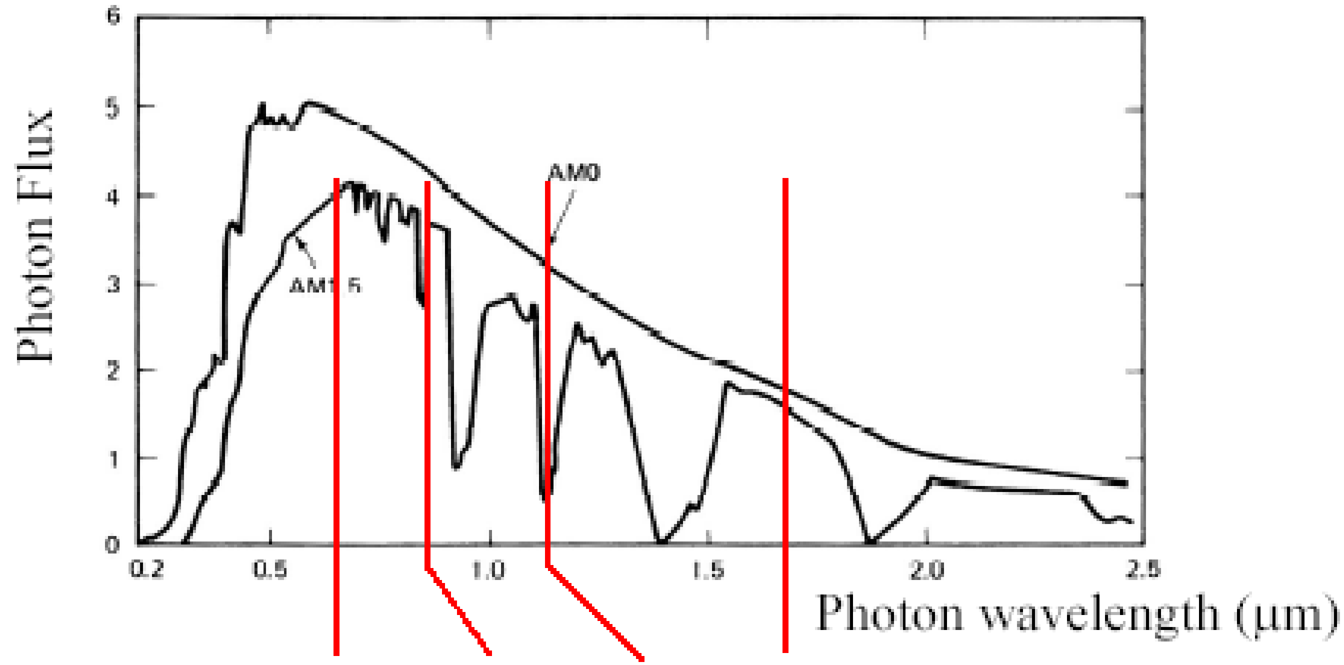
Silicon-Based Solar Cell Attributes

- Expensive
  - Made in high vacuum at high heat
  - High manufacturing costs
- Need TLC
  - Fragile, rigid, thick
- Long return on investment
  - Takes 4 years to produce energy savingsequivalent to cost of production



Source: http://www.powerhousekids.com/stellent2/groups/public/documents/pub/phk_ee_re_001505-2.gif

Theoretical Efficiency of Photovoltaic Cell



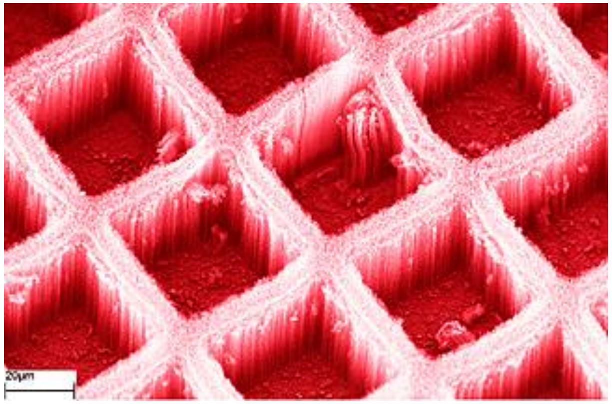
Material	a-Si	GaAs	c-Si	Ge
Band gap	1.7eV	1.45eV	1.1eV	.7eV
Max Efficiency	26%	29%	27%	13%

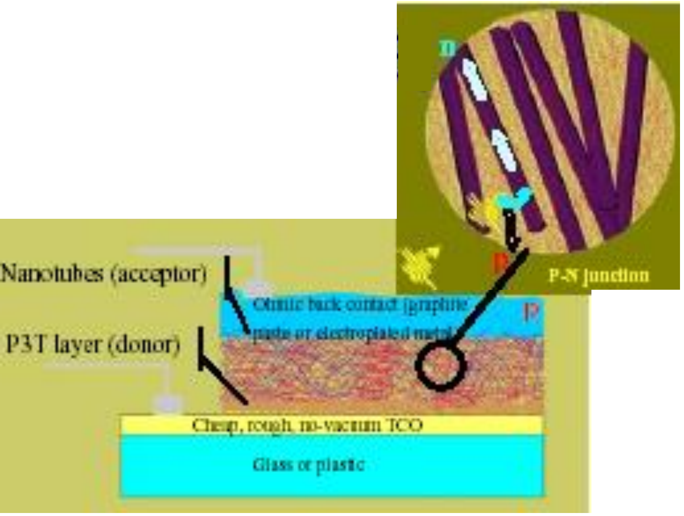
High band gap PV cell provides higher voltage
Typical efficiency of commercial PV is around 12%

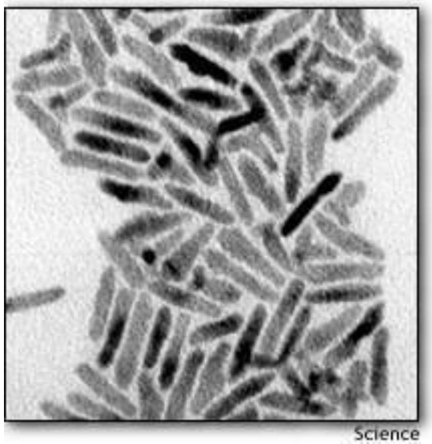
Types of Photovoltaic Cell

- **First Generation PV Cell:**
  - **Single crystalline silicon**
  - **Multi-junction cell (different band-gap materials)**
- Second Generation PV Cell:
  - Thin film silicon (amorphous silicon)
  - CdTe (Cadmium Telluride)
  - $CuInSe_2$ (Copper Indium Diselenide)

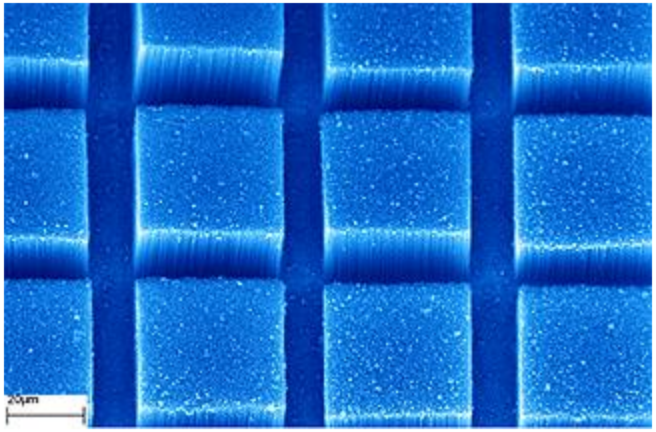
- Third Generation PV Cell
  - Ultra-High Efficiency concepts (>80%)
  - Ultra-low Cost
    - Polymer cells with quantum dots or nanostructures





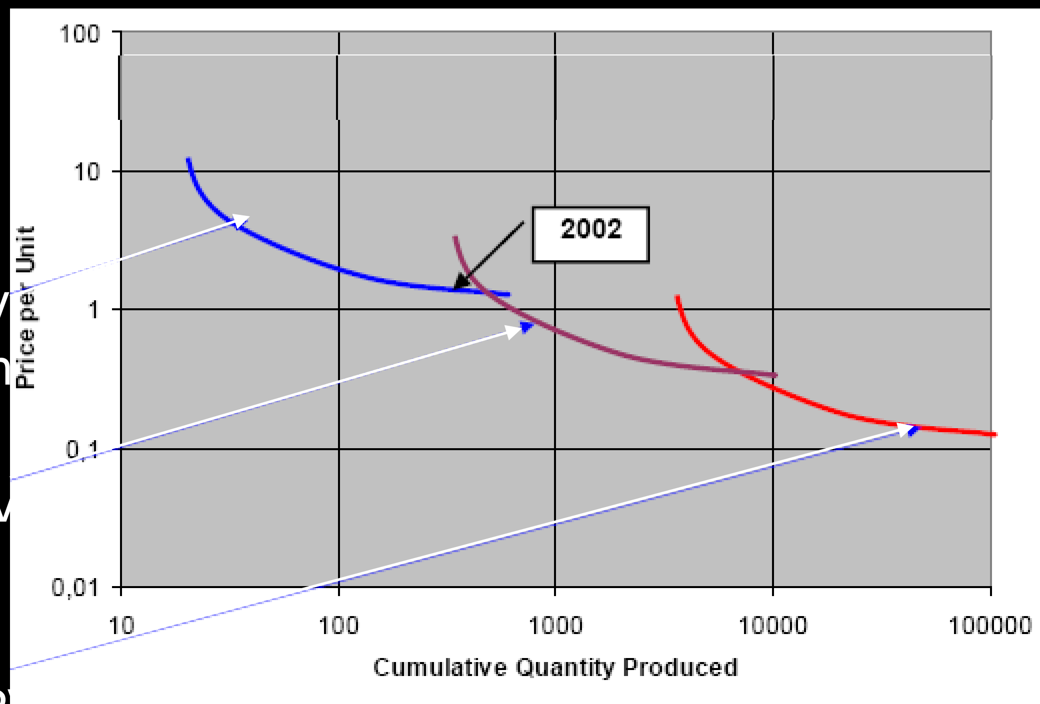


CdTe rods in polymer



Carbon nanotube on Si for more efficient solar powe

Photovoltaic Roadmap



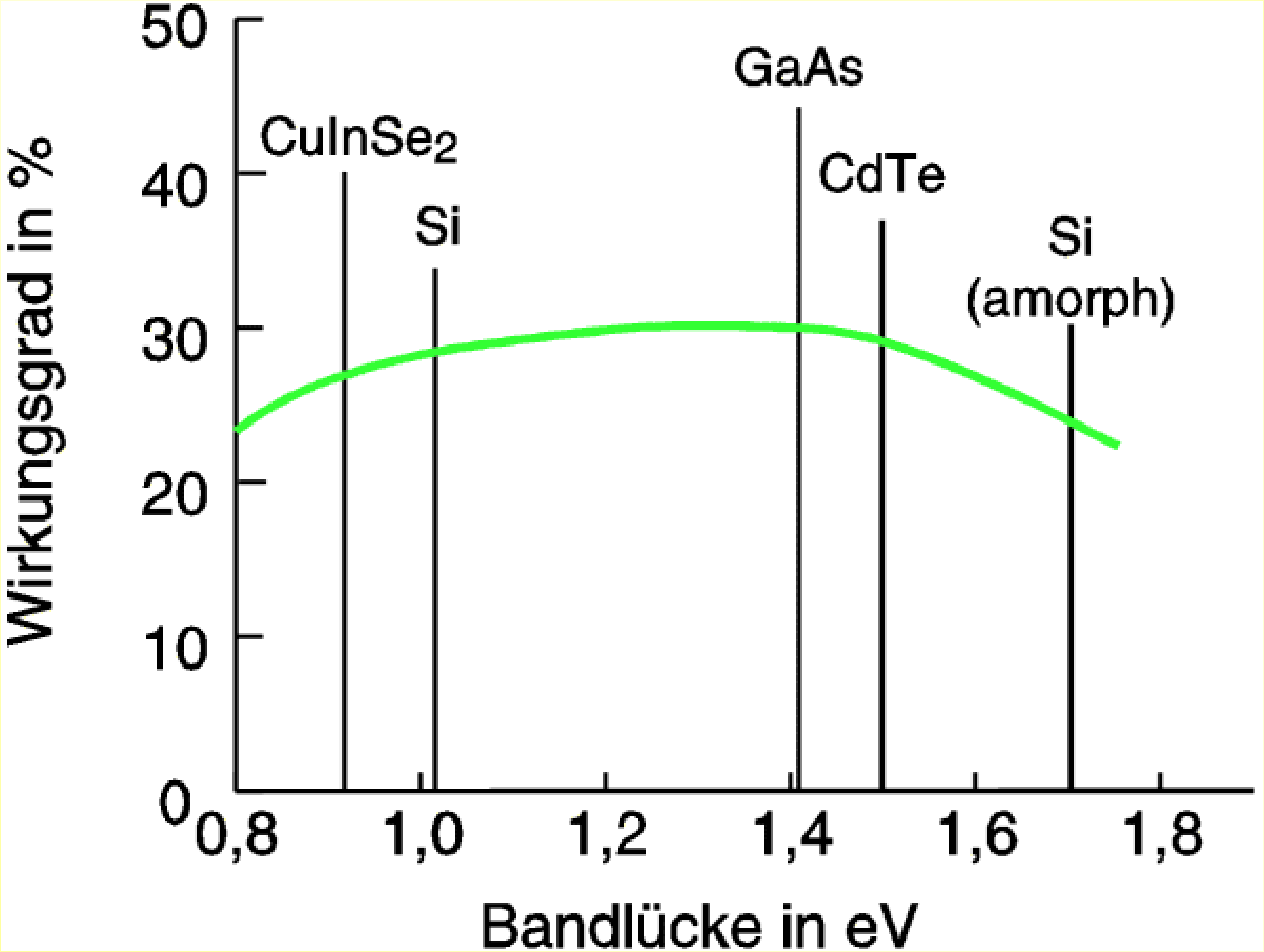
1st Generation PV
Crystalline Silicon

2nd Generation PV
Thin Film

3rd Generation PV
Ultra-High
Efficiency
Ultra-Low Cost

Source: European Commission meeting Dec. 2

Efficiency of different solar cells (Theory / Laboratory)

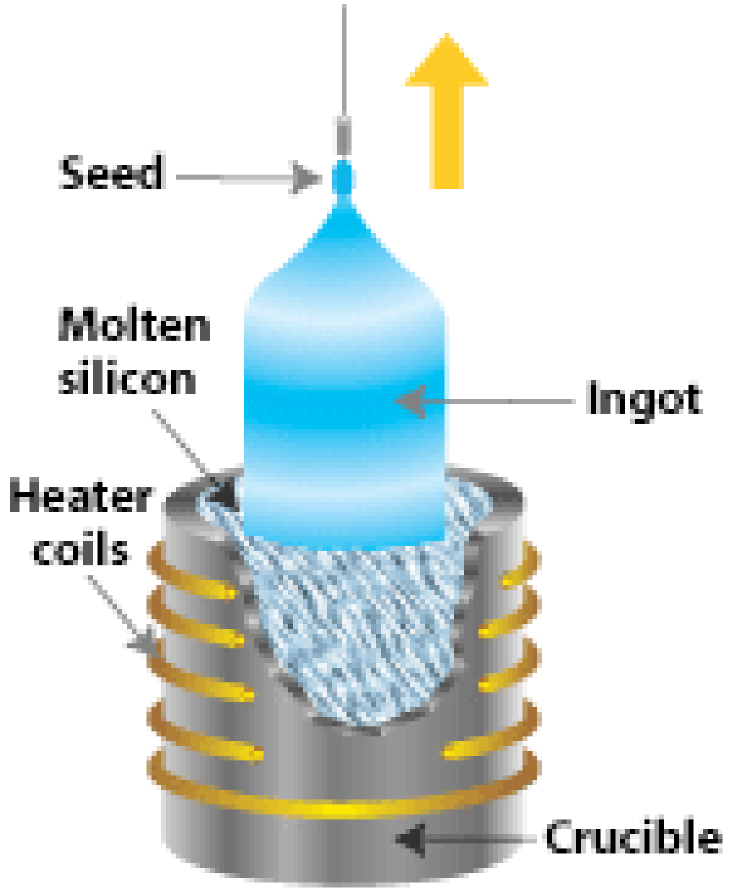


SILICON

- Silicon is the most popular PV material
- Most cells are made from left over computer chip manufacturing
- Silicon must be refined to almost 100% purity
- The uniform molecular structure of silicon makes it efficient for electron transport
- Silicon wafers are cut from ingots

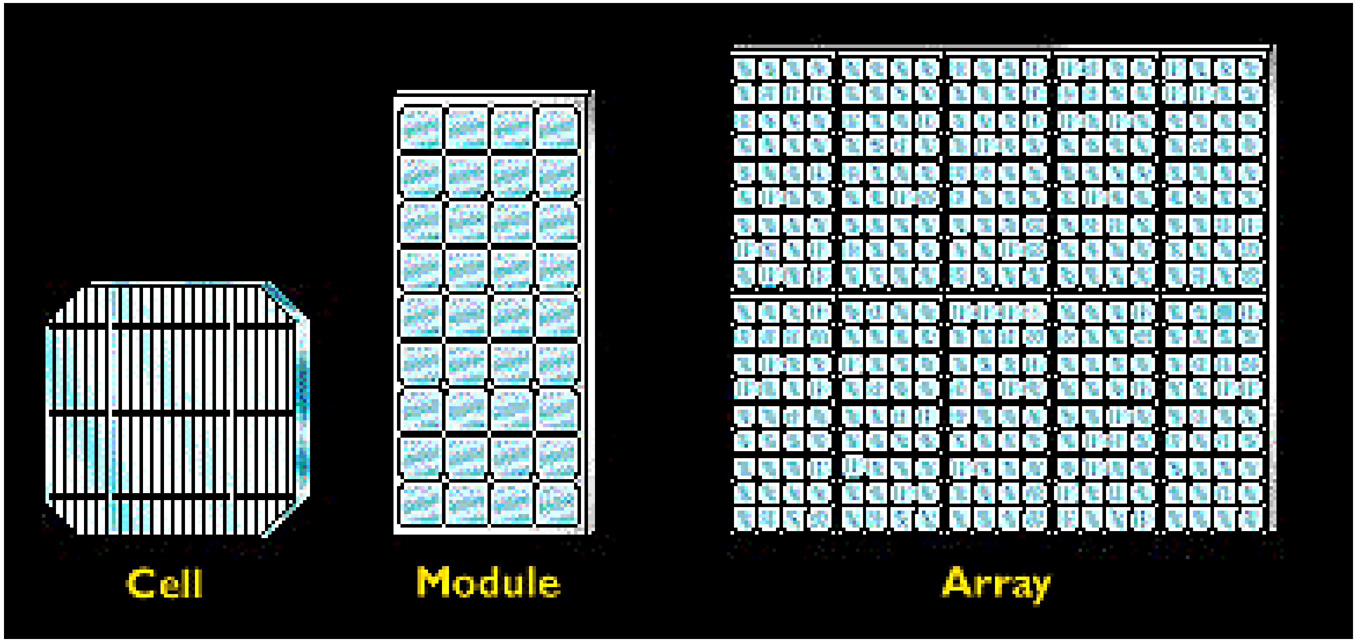
CZOCHRALSKI PROCESS

- This is the process of creating an ingot.
- A small single silicon rod (seed) is placed in an inert gas at high temps.
- When the seed is rotated up and out silicon adheres to it to form an ingot.



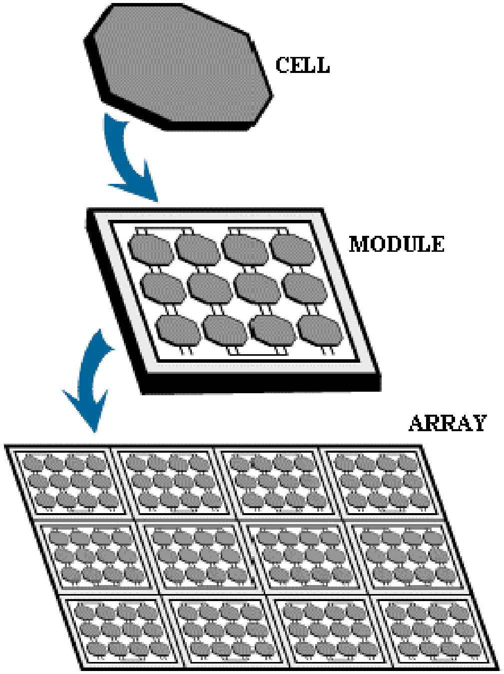
CELLS -> MODULES

- Wafers 5 inches square and .012 inches thick are sliced from the ingot.
- They are then processed into cells and soldered together to achieve the desired voltage.
- Cells arrayed in series are called modules.



Solar Cells

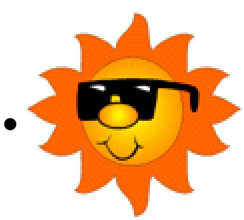
- **What are Solar Cells?**
  - Thin wafers of silicon;
    - similar to computer chips,
    - much bigger,
    - much cheaper.



Solar Cells

- **Silicon is abundant (sand);**
  - **non-toxic, safe**

- **Light carries energy <u>into</u> the cell;**
  - **cells <u>convert</u> sunlight energy into electric current, they *do not* store energy.**

- **Sunlight is the "fuel".** 

TECHNOLOGY

- PV cells exhibit voltage or current when exposed to light.
- The light liberates electrons which move through the cell creating current.
- The larger area there is the more current.
- Single crystal silicon cells are the most efficient at 15-24% sunlight-to-electricity conversion rate.
- They are also the most expensive to produce at $6.50/ watt.

Introduction - Photovoltaics on the world market

• *In 2007 the photovoltaic market grew over 40% with ~ 2.3 GW of newly installed capacity“* (EPIA)

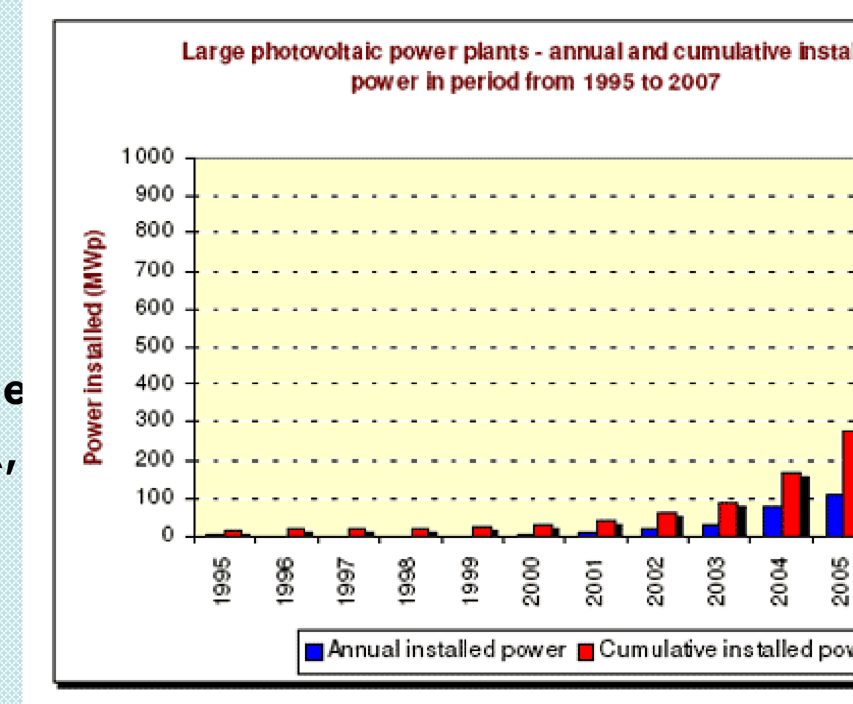
• Germany has the first position on the world market with 50% global market share

• power Installed by region:
  80% Europe
  16% North America
  4% Asia

• Most dynamic market is Spain

• Seven Countries hosting the majority of large power plants: RoW, Italy, Japan, Korea, USA, Spain, Germany

• the cumulative power quadrupled



Annual installed power grew significantly from 2004

• Installed PV world wide 7300MW$_P$

• Annual growth predicted ~ 25%

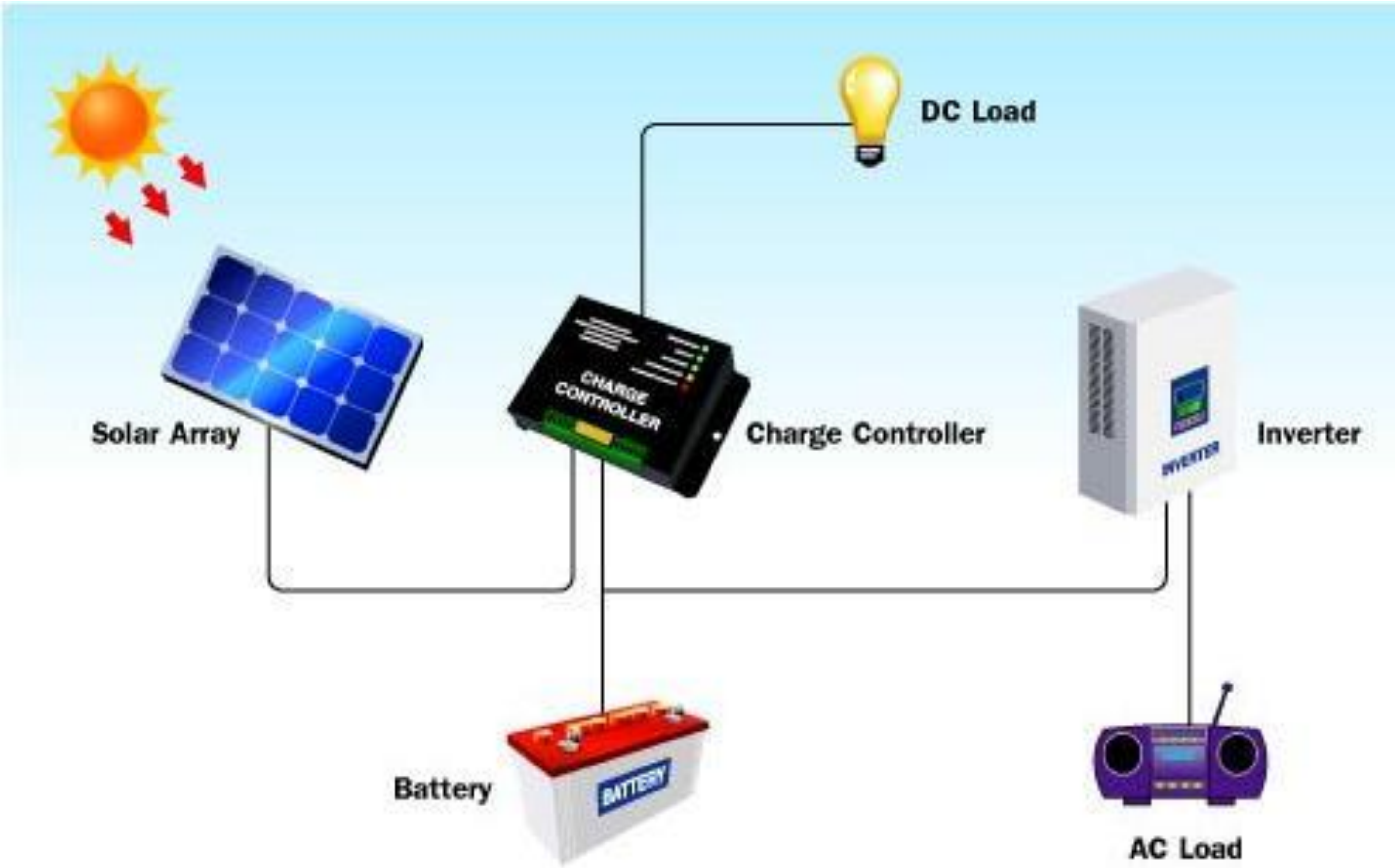
• Turnover by modules (2030) ~100billion €/a

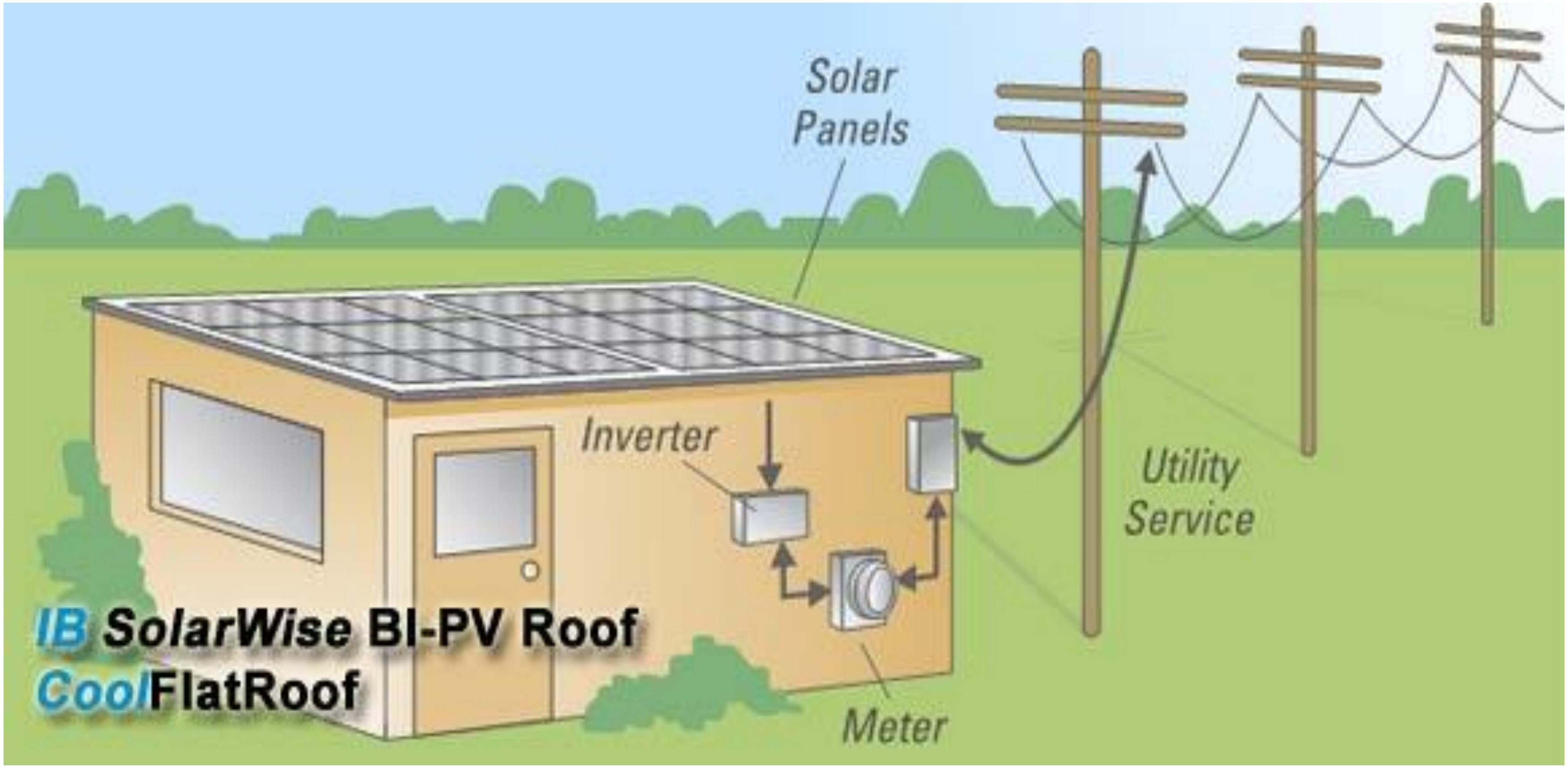
Advantages and Disadvantages

- Advantages
  - All chemical and radioactive polluting byproducts of the thermonuclear reactions remain behind on the sun, while only pure radiant energy reaches the Earth.
  - Energy reaching the earth is incredible. By one calculation, 30 days of sunshine striking the Earth have the energy equivalent of the total of all the planet's fossil fuels, both used and unused!
- Disadvantages
  - Sun does not shine consistently.
  - Solar energy is a diffuse source. To harness it, we must concentrate it into an amount and form that we can use, such as heat and electricity.
  - Addressed by approaching the problem through:

    1) collection, 2) conversion, 3) storage.

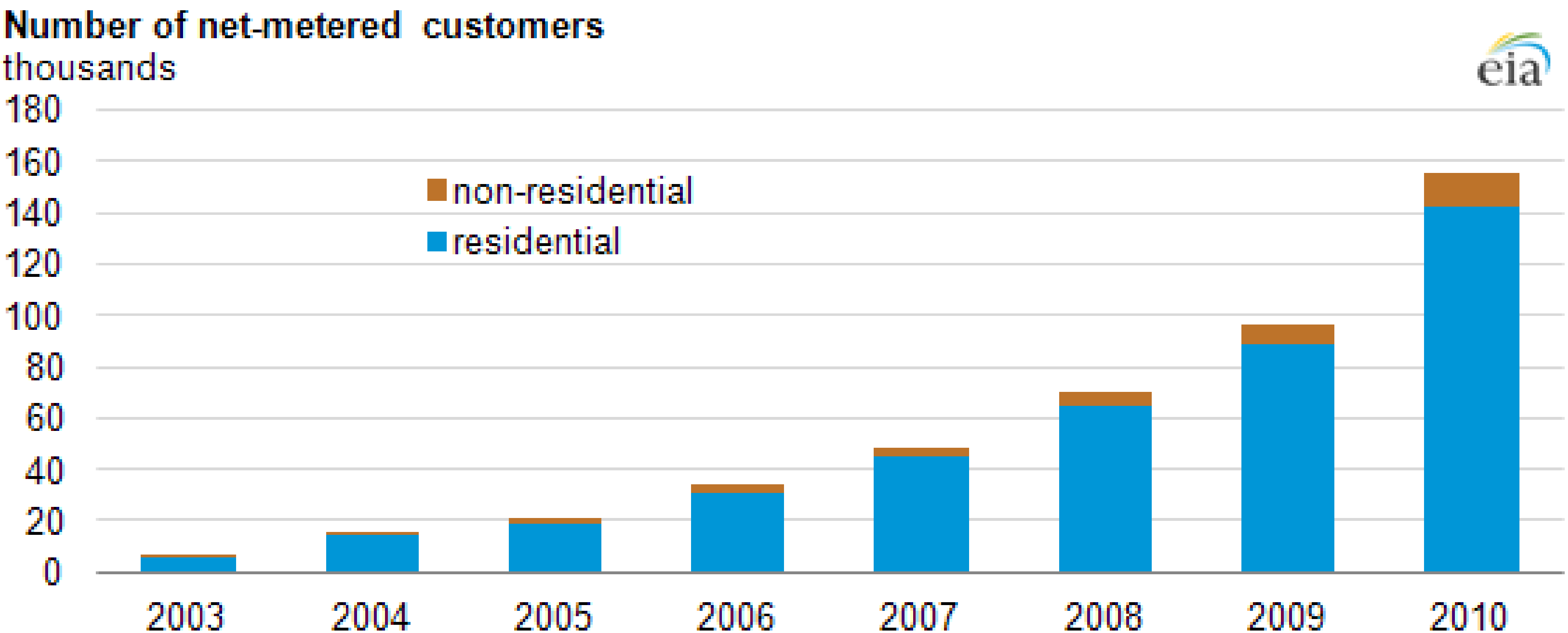
PV System Components



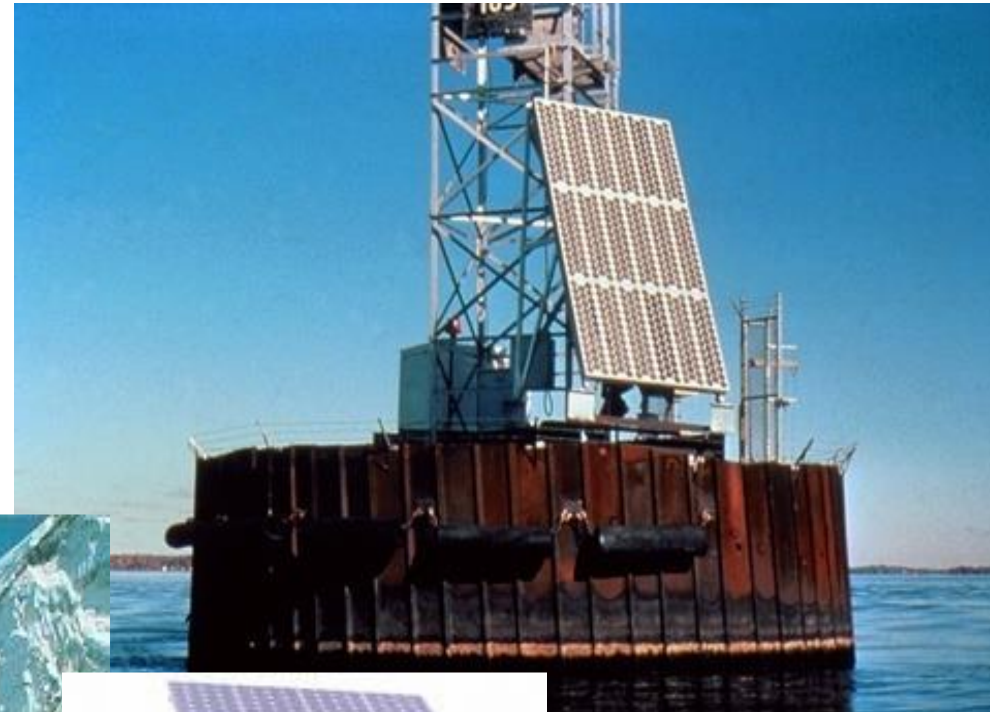


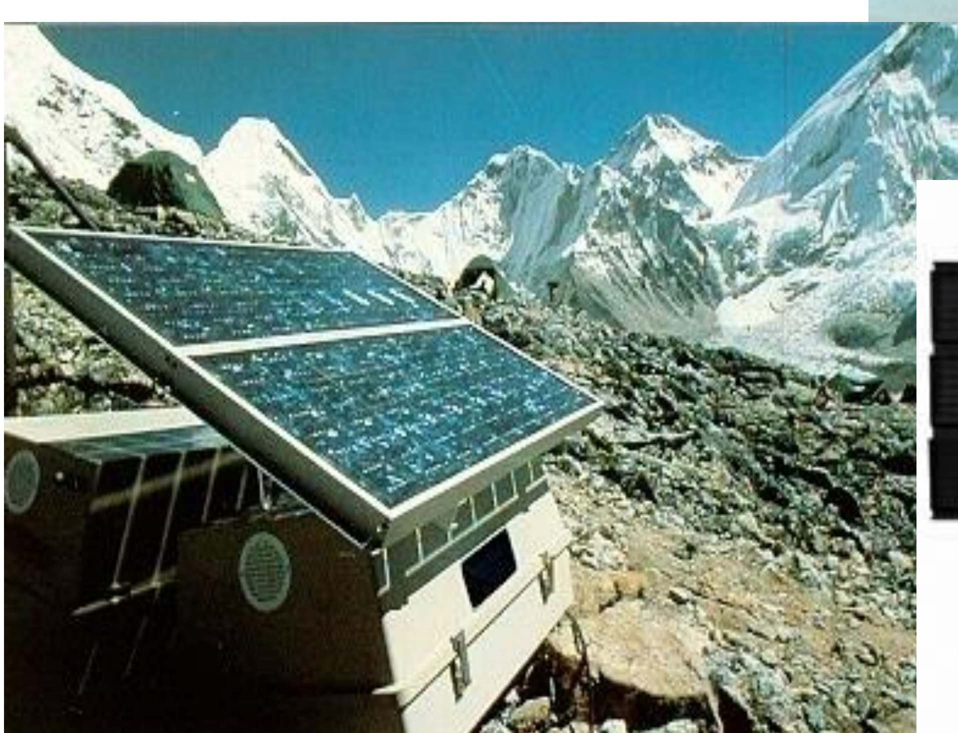
Net Metering

Net Metering Participation

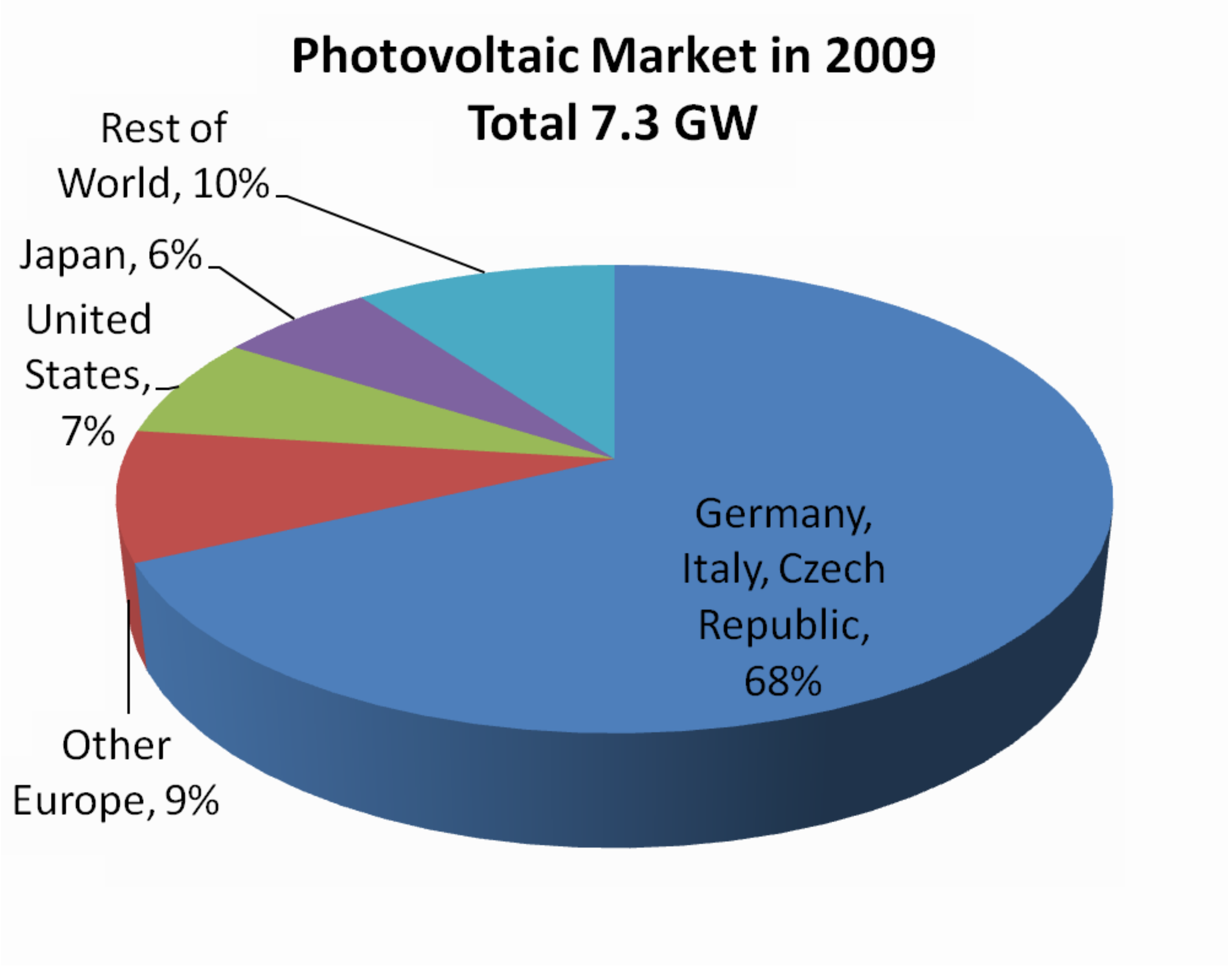


PV Array Fields



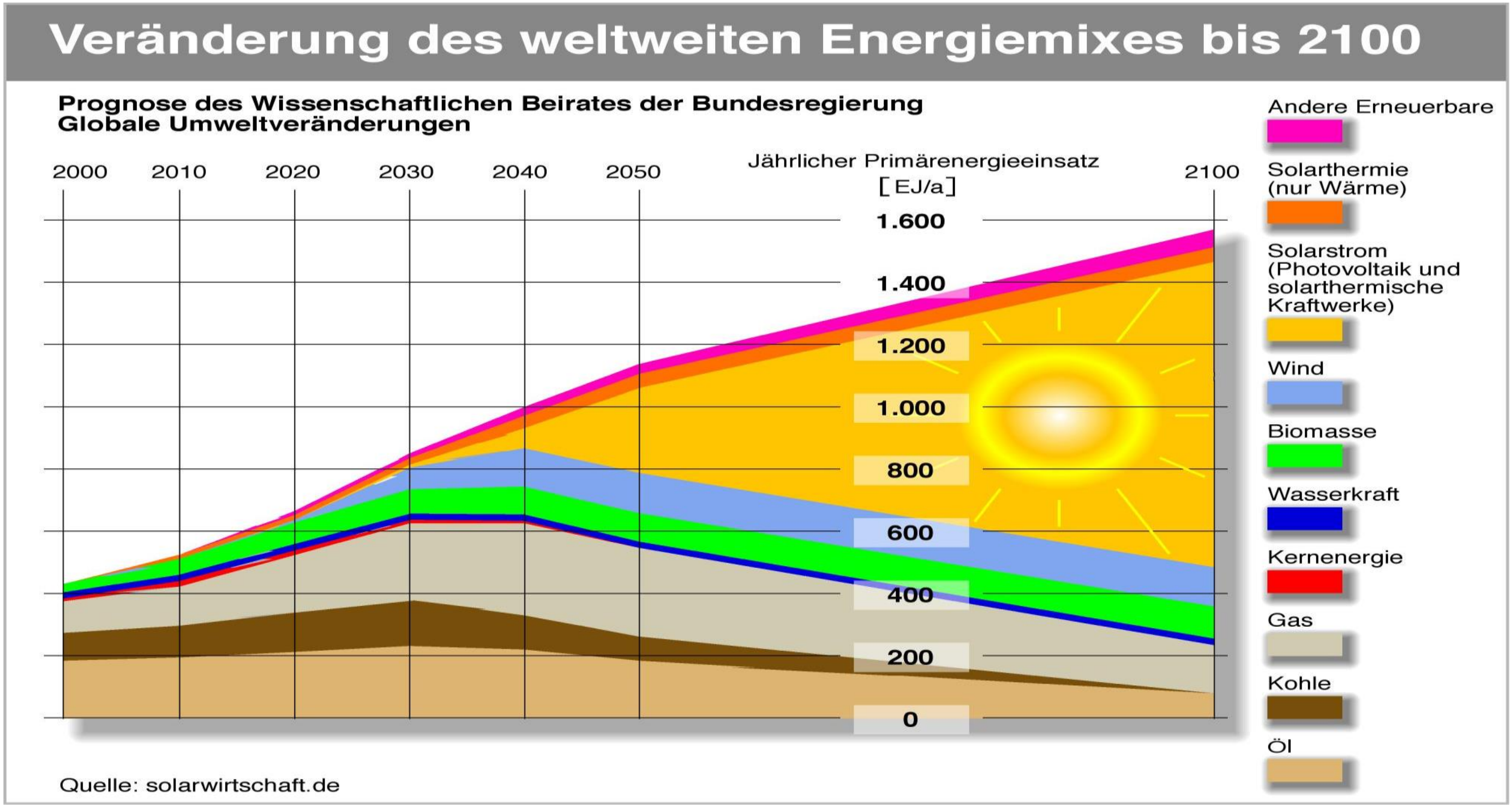



BRIDGE
CLOSED
AHEAD

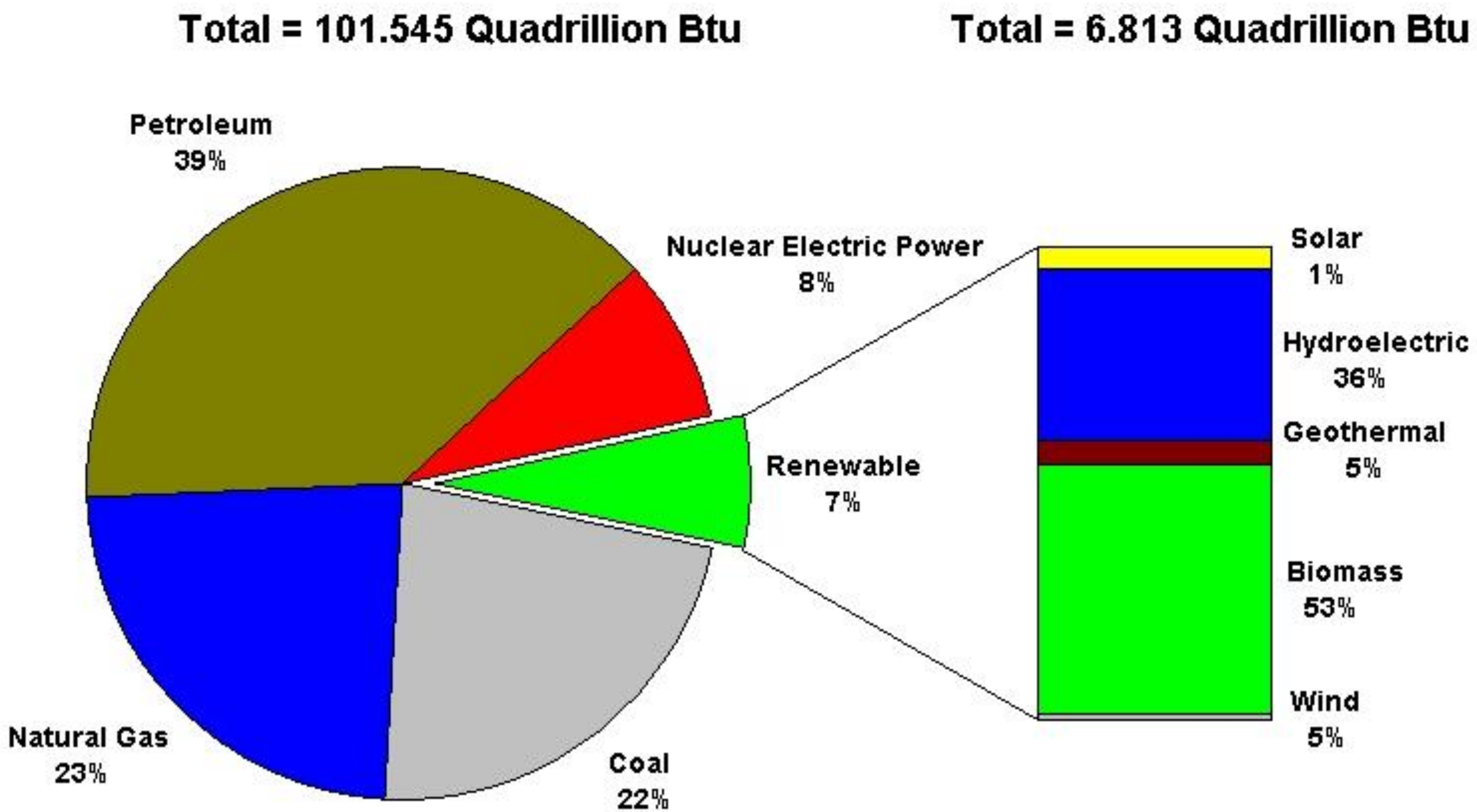


Source: Solarbuzz, a part of The NPD Group

Future Energy Mix



Renewable Energy Consumption in the US Energy Supply, 2007



http://www.eia.doe.gov/cneaf/solar.renewables/page/trends/highlight1.html

Top 10 PV Cell Producers

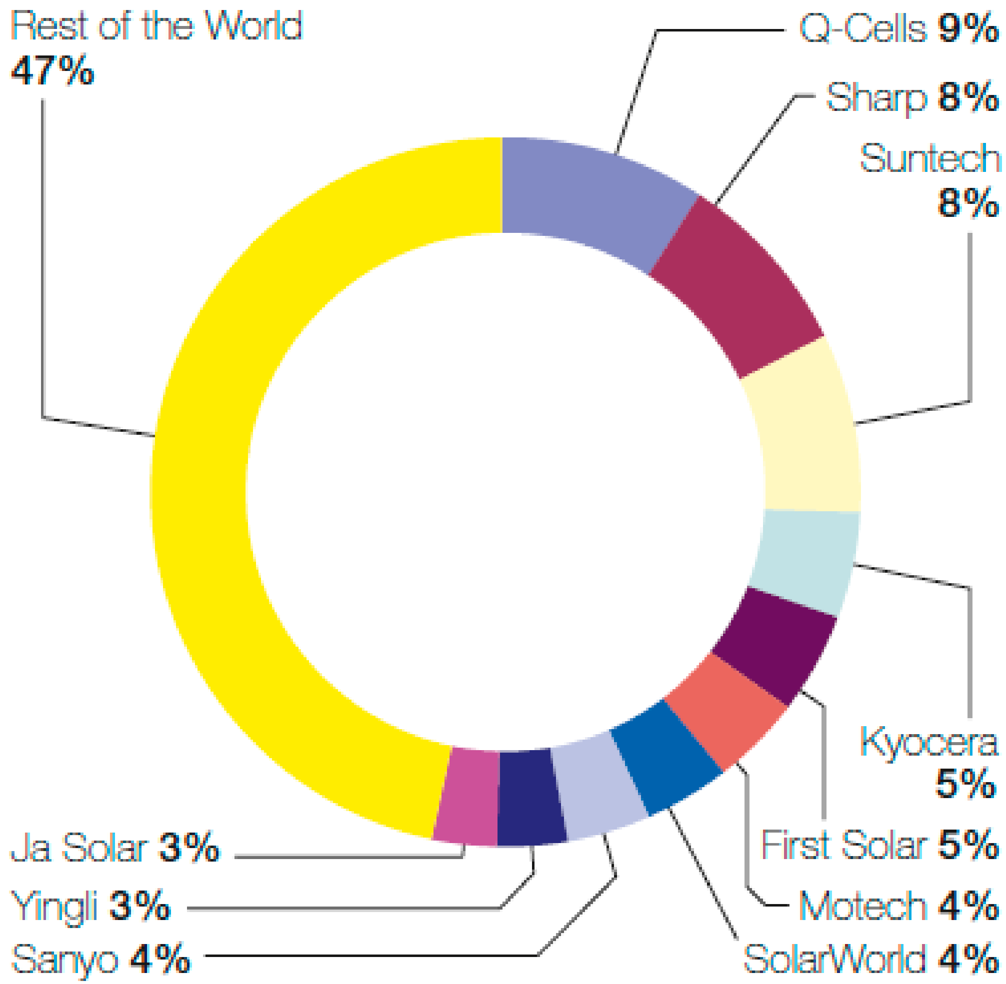
Top 10 produce 53% of world total

Q-Cells, SolarWorld - Germany

Sharp, Kyocera, Sharp, Sanyo – Japan

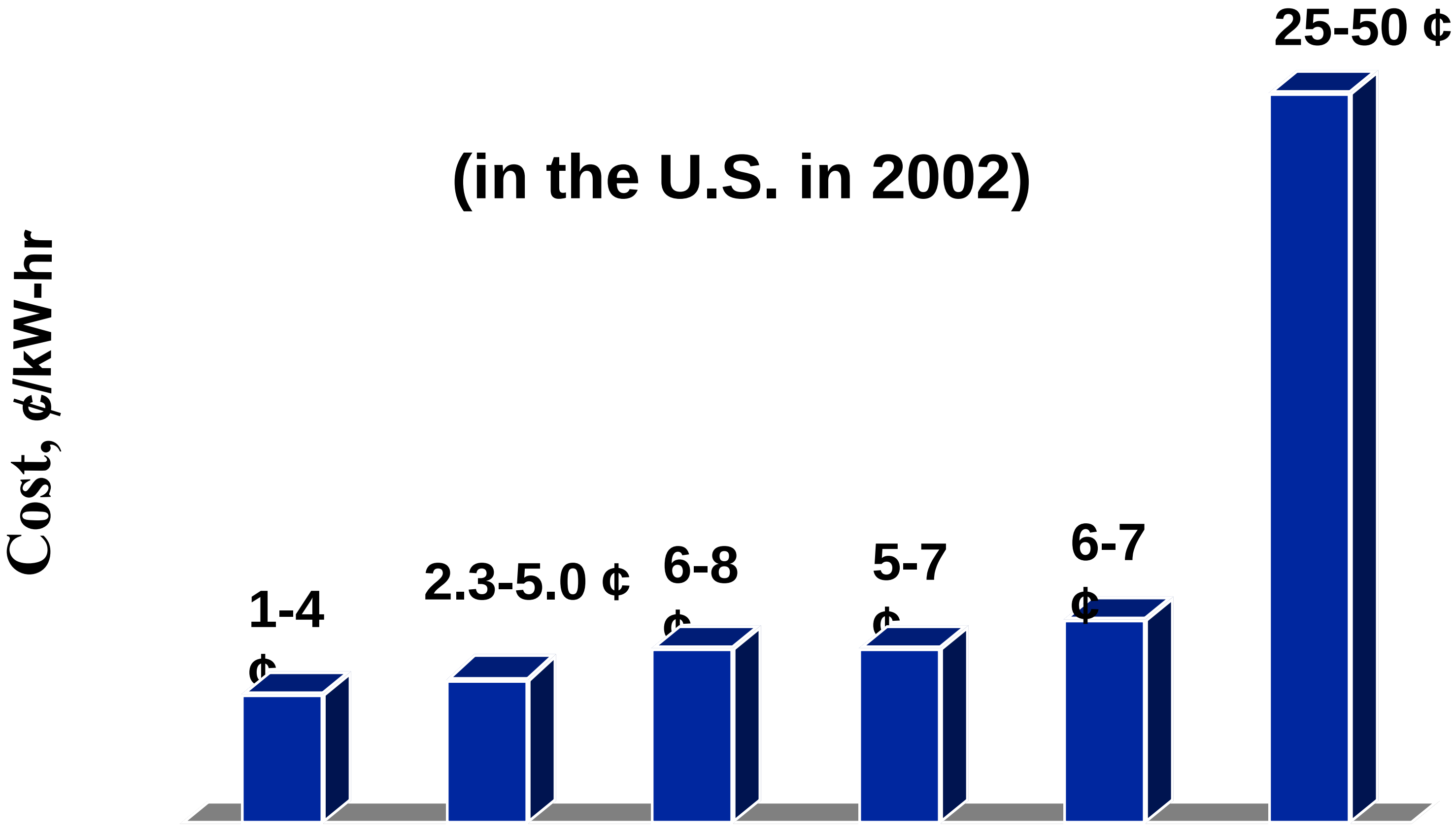
Suntech, Yingli, JA Solar – China

Motech - Taiwan

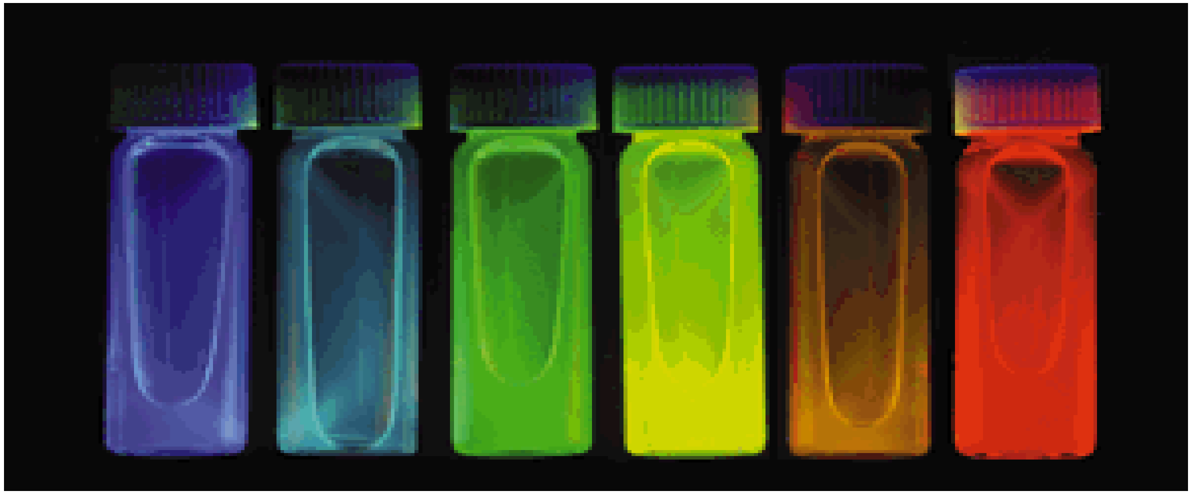


Source : Photon International

Production Cost of Electricity



Future Generation
– Printable Cells

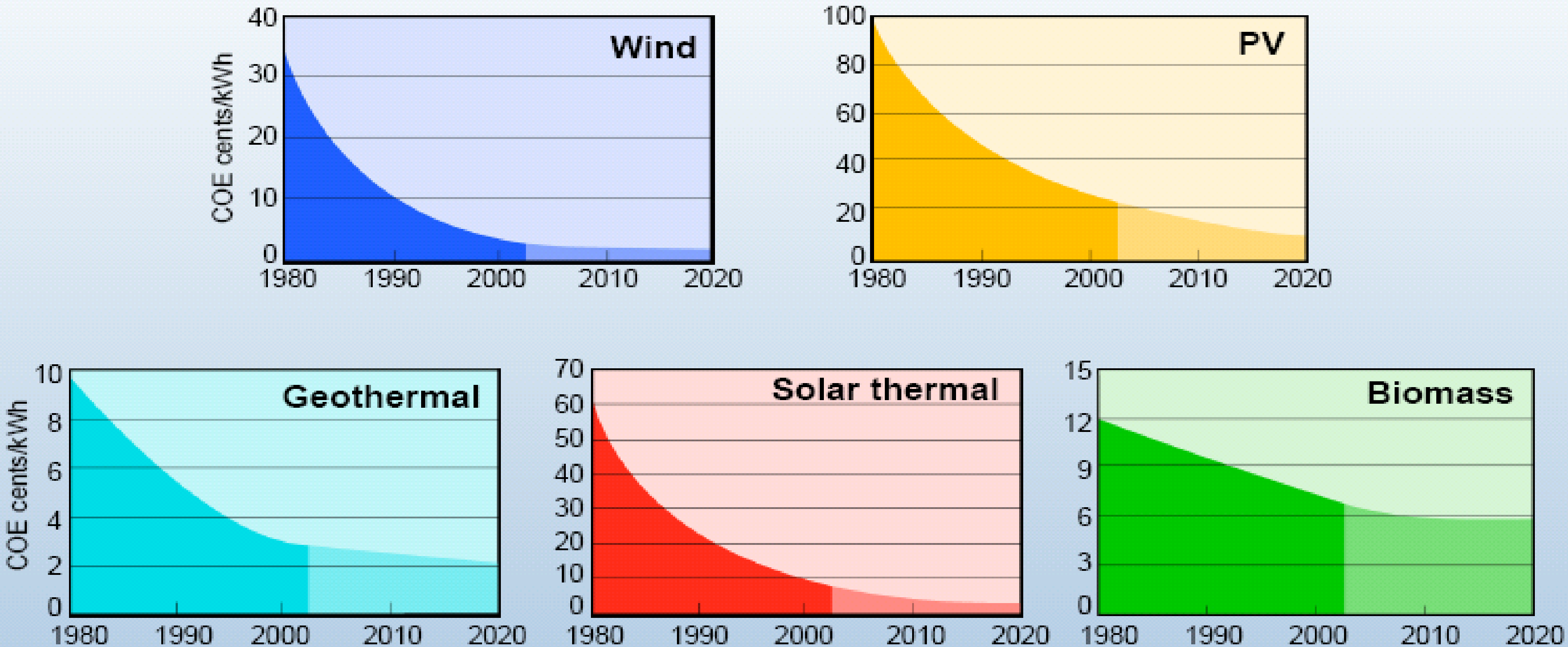


Solution Processible Semiconductor

Organic Cell
Nanostructured Cell

Renewable Energy Cost Trends

Levelized cents/kWh in constant $2000[1]



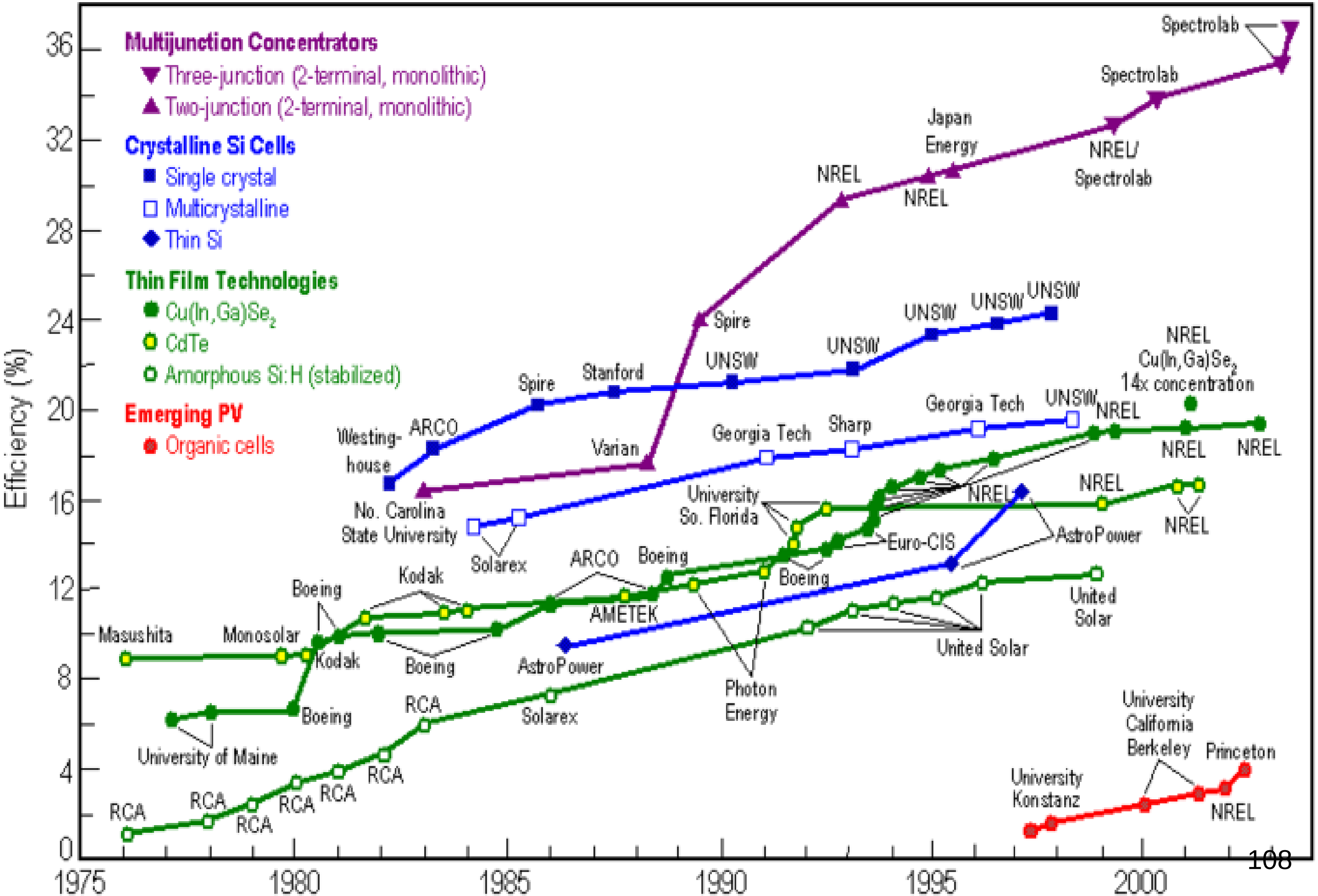
Source: NREL Energy Analysis Office (www.nrel.gov/analysis/docs/cost_curves_2002.ppt)
[1]These graphs are reflections of historical cost trends NOT precise annual historical data.
Updated: October 2002

NREL National Renewable Energy Laboratory

Solar electricity prices are today, around 30 cents/kWh, but still 2-5 times average Residential electricity tariffs

Best Research-Cell Efficiencies

www.nrel.gov/ncpv/thin_film/docs/kaz_best_research_cells.ppt

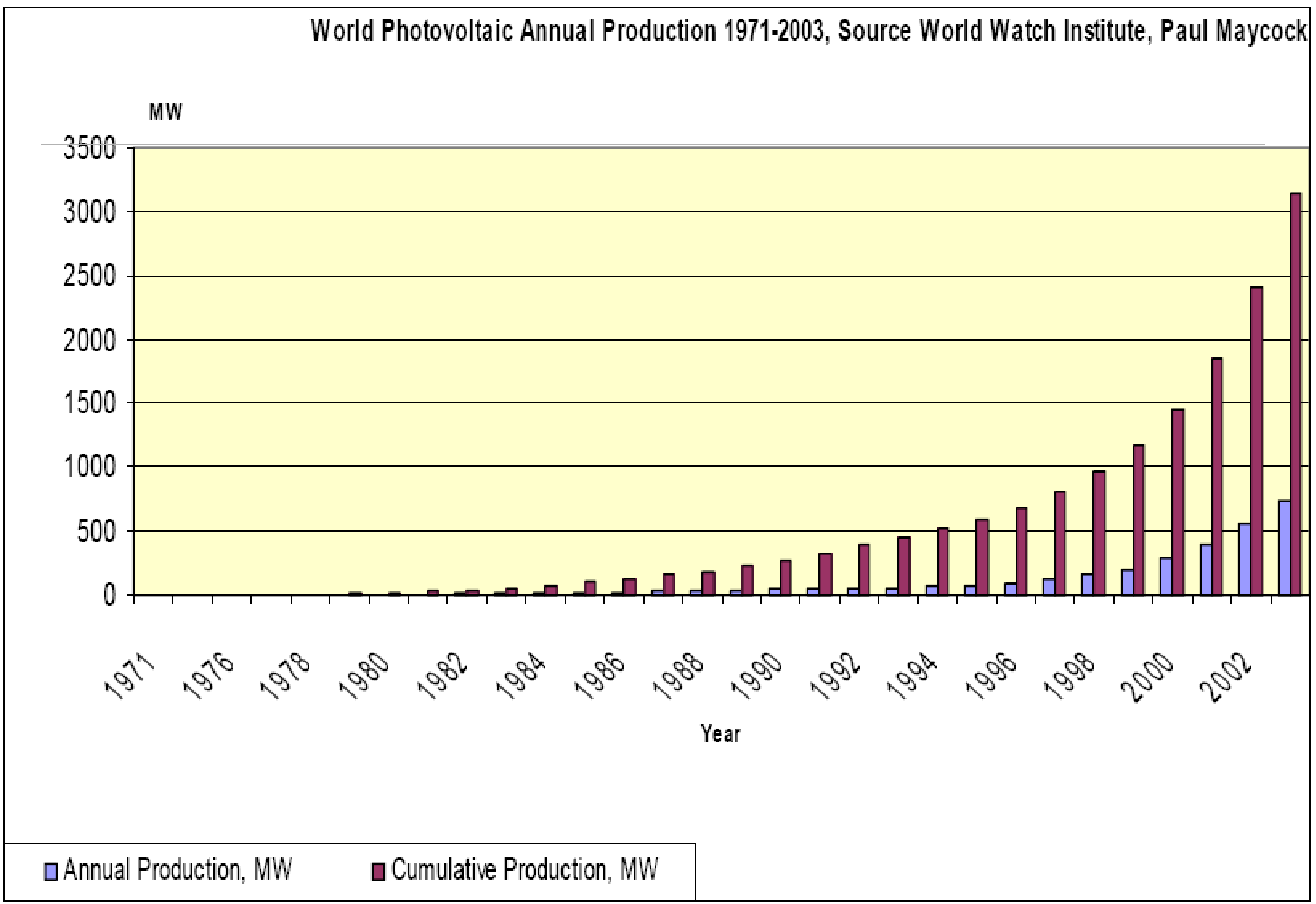


- Clean
- Sustainable
- Free
- Provide electricity to remote places

Advantages of Solar Energy

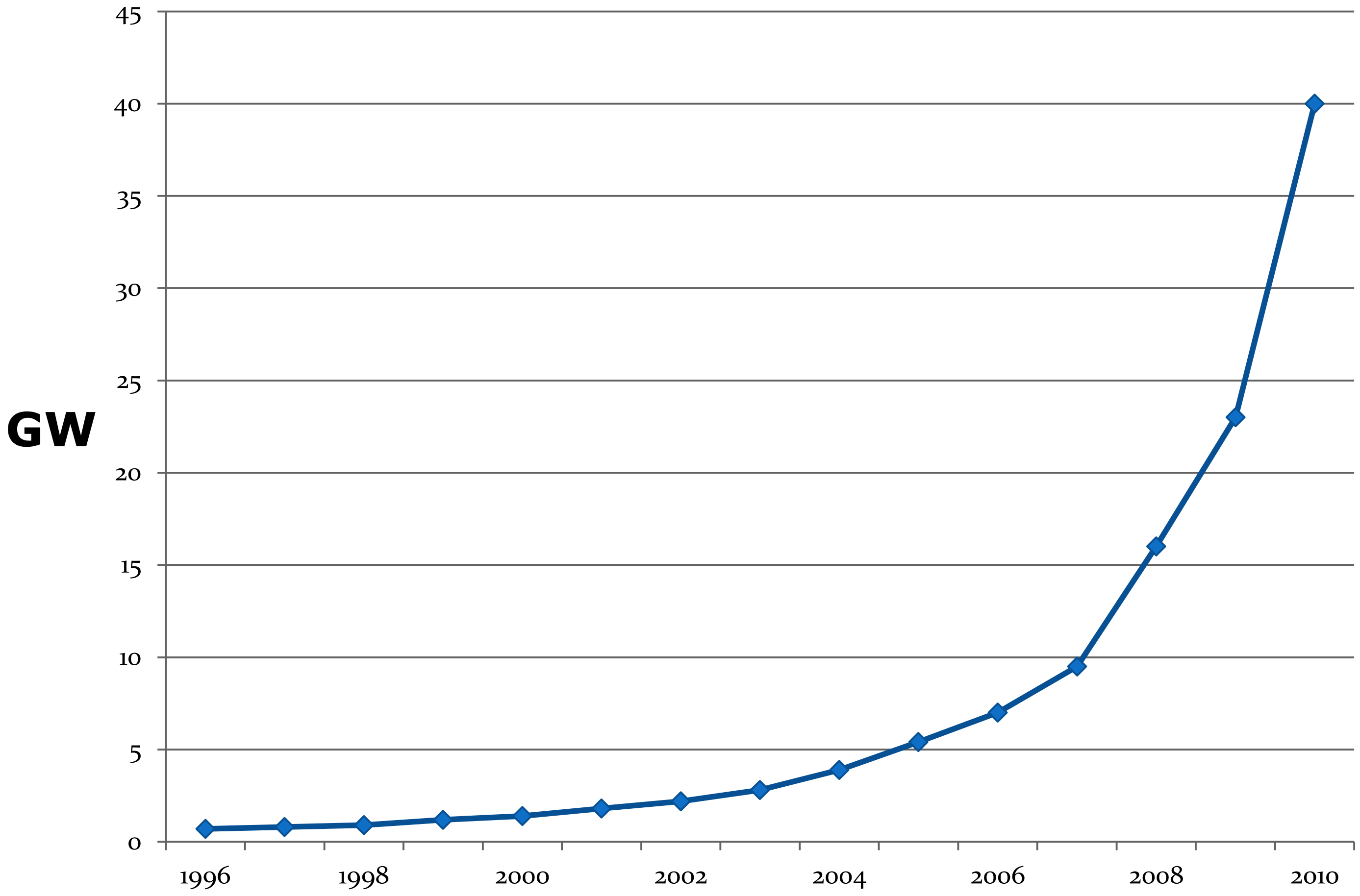
Disadvantages of Solar Energy

- Less efficient and costly equipment
- Part Time
- Reliability Depends On Location
- Environmental Impact of PV Cell Production

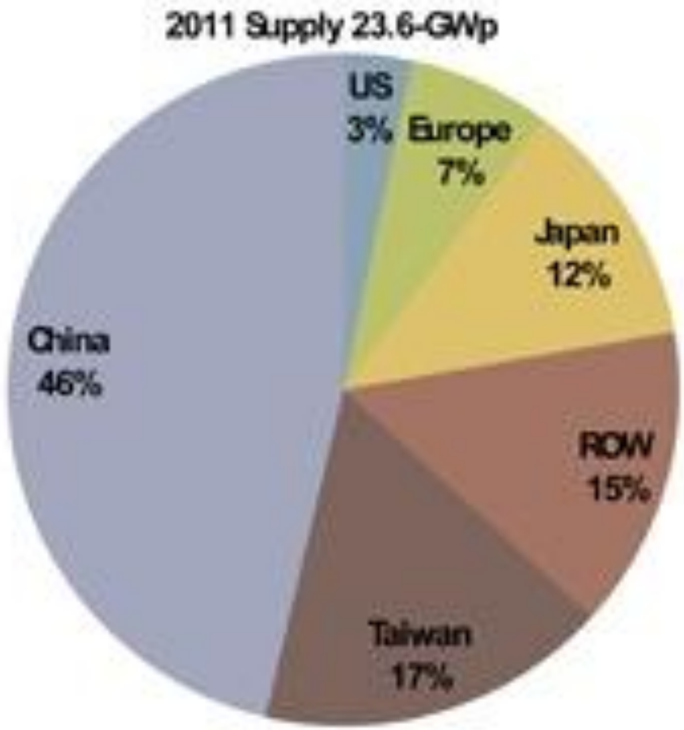


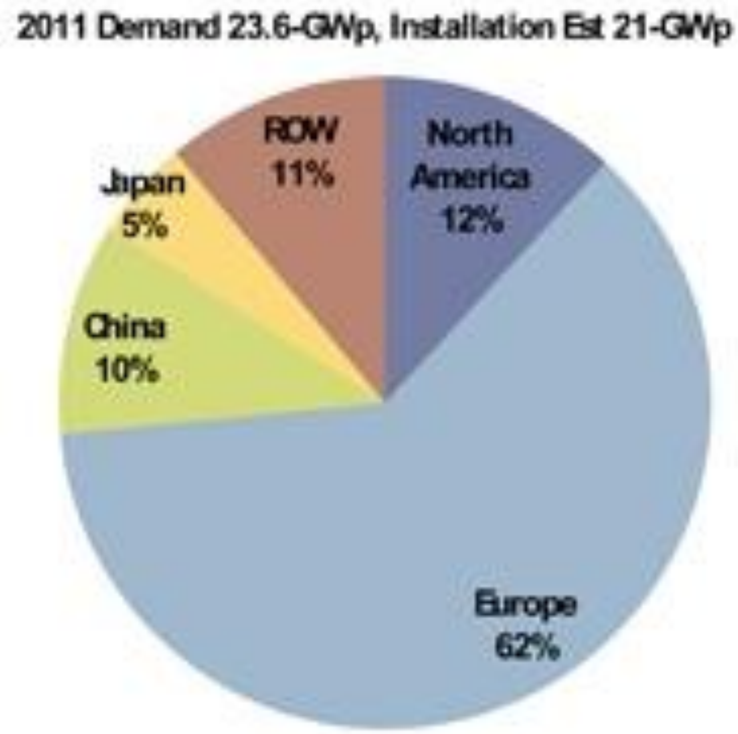
30% increase in global manufacturing of solar cells every year

World PV Production Growth

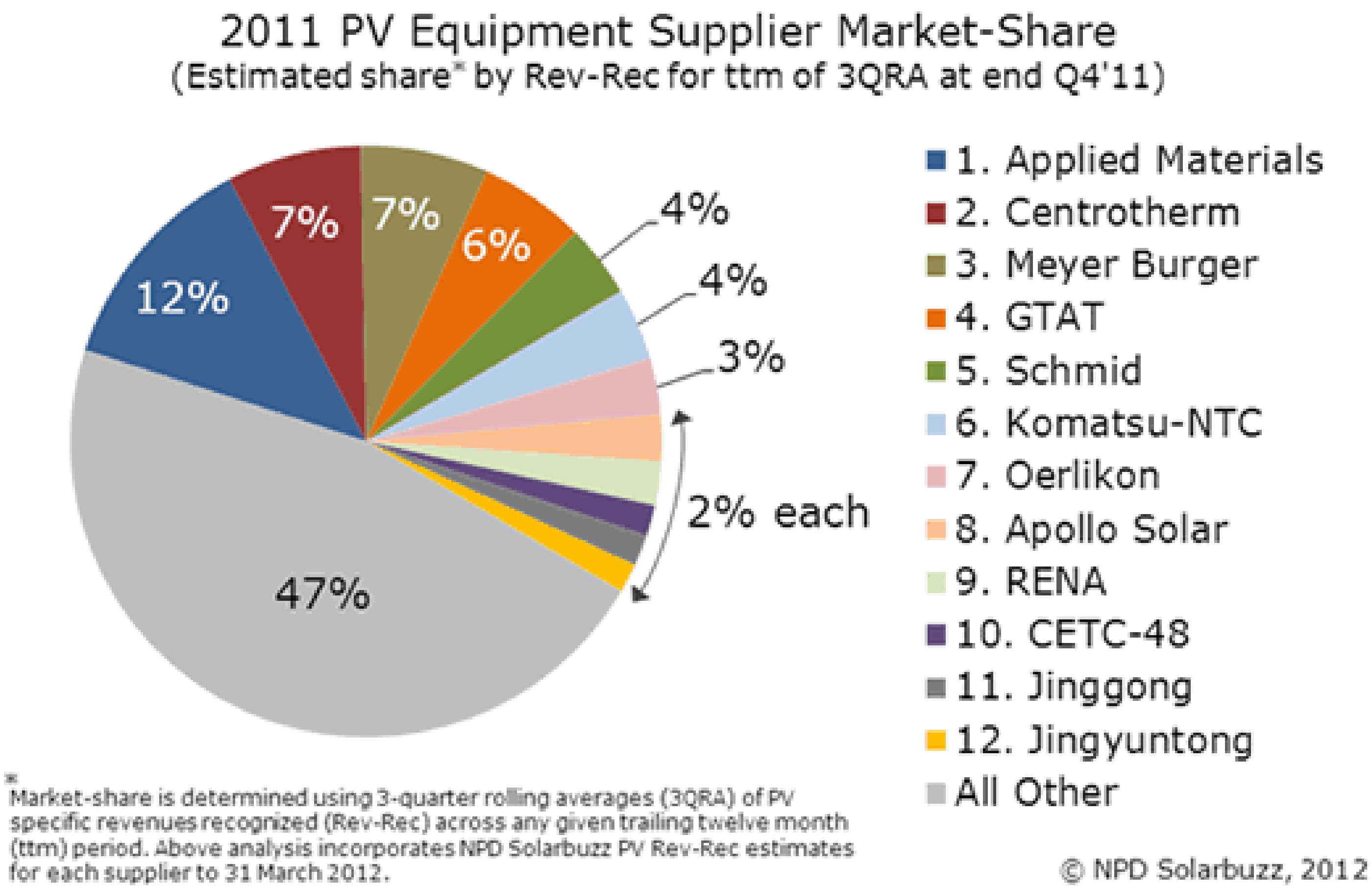


World PV Market and Production: 2011





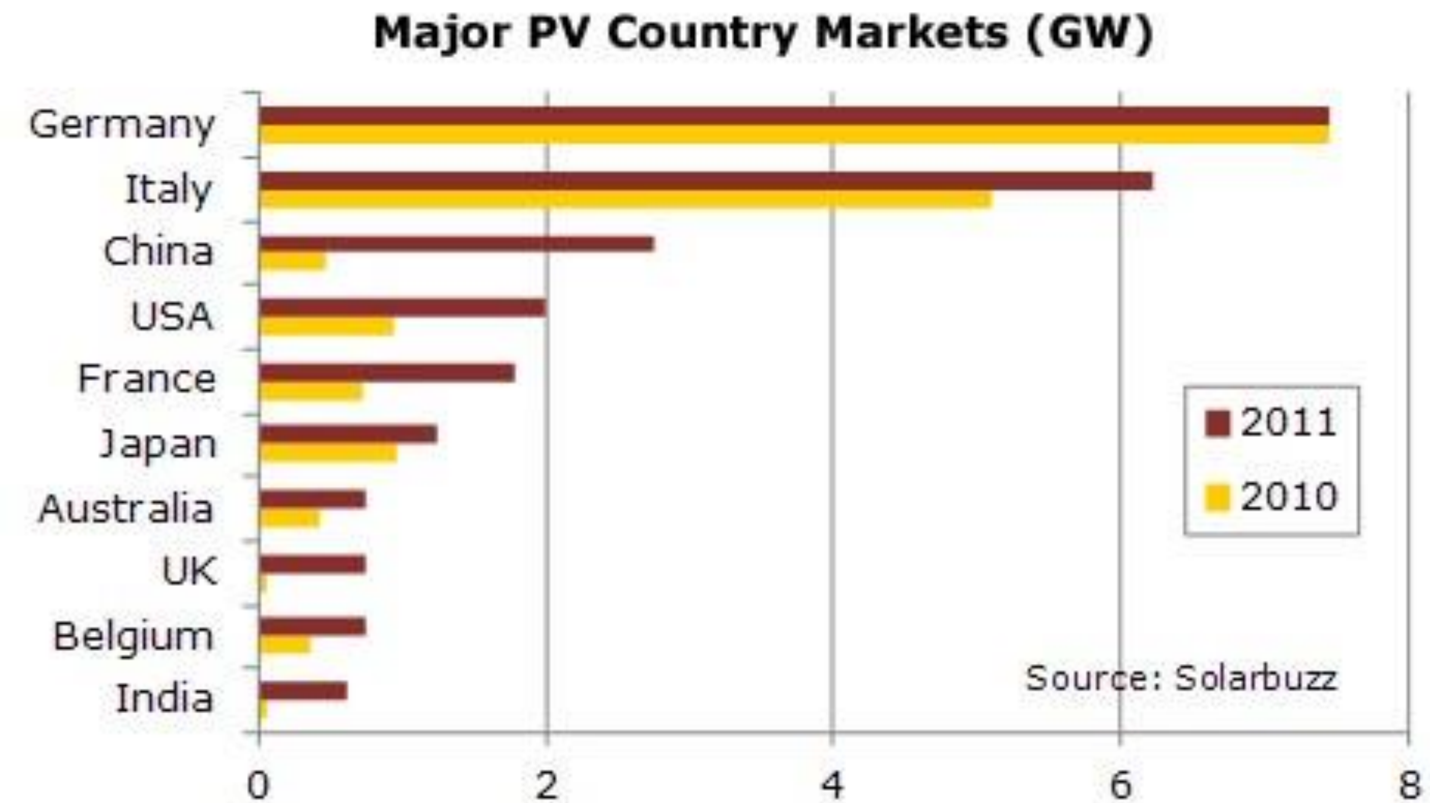
World: 2011 PV Equipment Suppliers



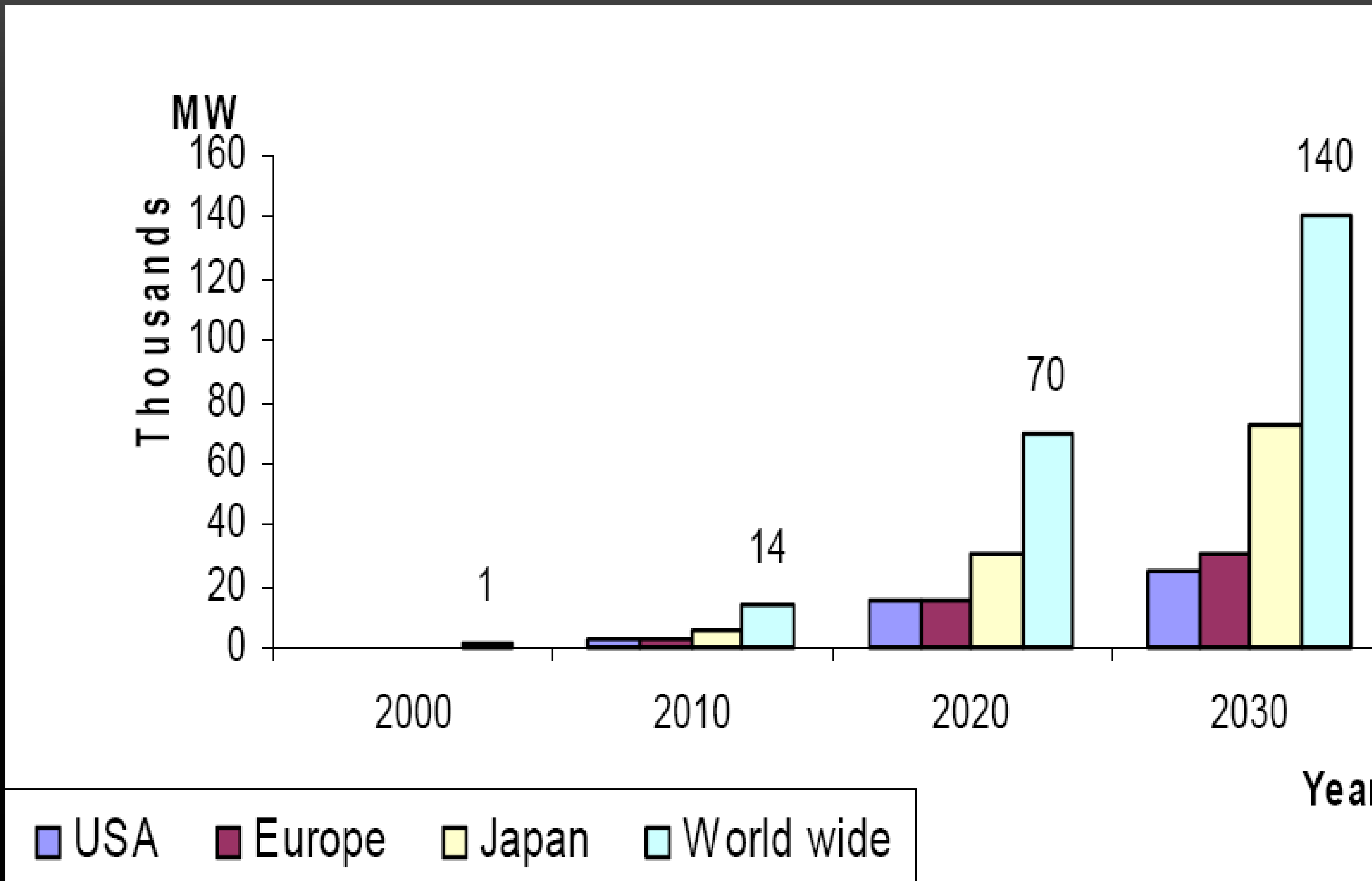
World Top 10 PV Plants: 2011

Location	Capacity MWp	Technology
Perovo. Ukraine	100	c-si
Sarnia, Canada	92	CdTe
Montalto di Castro, Italy	84	c-Si
Finsterwalde, Germany	83	c-Si
Ohotnikovo, Ukraine	80	c-Si
Senftenberg, Germany	78	c-Si
Lieberose, Germany	71	CdTe
Rovigo, Italy	70	c-Si
Olmedilla de Alarcón, Spain	60	c-Si
Boulder City, USA	55	CdTe

Major PV Markets : 2010 & 2011



Expected Future of Solar Electrical Capacities



Photovoltaics

Solar Panel Use Today

- Large companies like Google, Walmart, and Microsoft use solar energy to partially p
fa

Solar panels on Microsoft building

Solar panels being tested on Walmart store

Sources: http://i.n.com.com/i/ne/p/2006/IMG_5396_550x367.jpg
http://www.solarwall.de/assets/images/Walmart_SW.jpg

Important Summary Questions

- What are clean and renewable energy sources?
- What are current and projected global energy demands?
- How do newer, nanotechnology-influenced solar cells work, and how do they differ from traditional solar cells?

Future Reality ?

If the PV market growth continues at rate of 20% and panel lasts 50yrs, there will be 100 TW of energy provide by PV cells on the ground

↓

Within 50 years, photovoltaic will supply more than half of the world's supply energy

Global Scenario

- Solar Electric Energy demand has grown consistently by 20-25% per annum over the past 20 years (from 26 MW back in 1980 to 127MW in 1997)

- At present solar photovoltaic is not the prime contributor to the electrical capacities but the pace at which advancement of PV technology and with the rising demand of cleaner source of energy it is expected by 2030 solar PV will have a leading role in electricity generation

- Research is underway for new fabrication techniques, like those used for microchips. Alternative materials like cadmium sulfide and gallium arsenide ,thin-film cells are in development

Conclusions

- Solar power source is abundant
- Many types of PV cells are in development to meet to PV Roadmap for future needs
- PV cells' efficiency can be increased and underdevelopment
- Solar power from PV cell are safe and potentially growing