MATERIALS SCIENCE

SSP 2412

APPLICATIONS - Semiconductors & Ceramics

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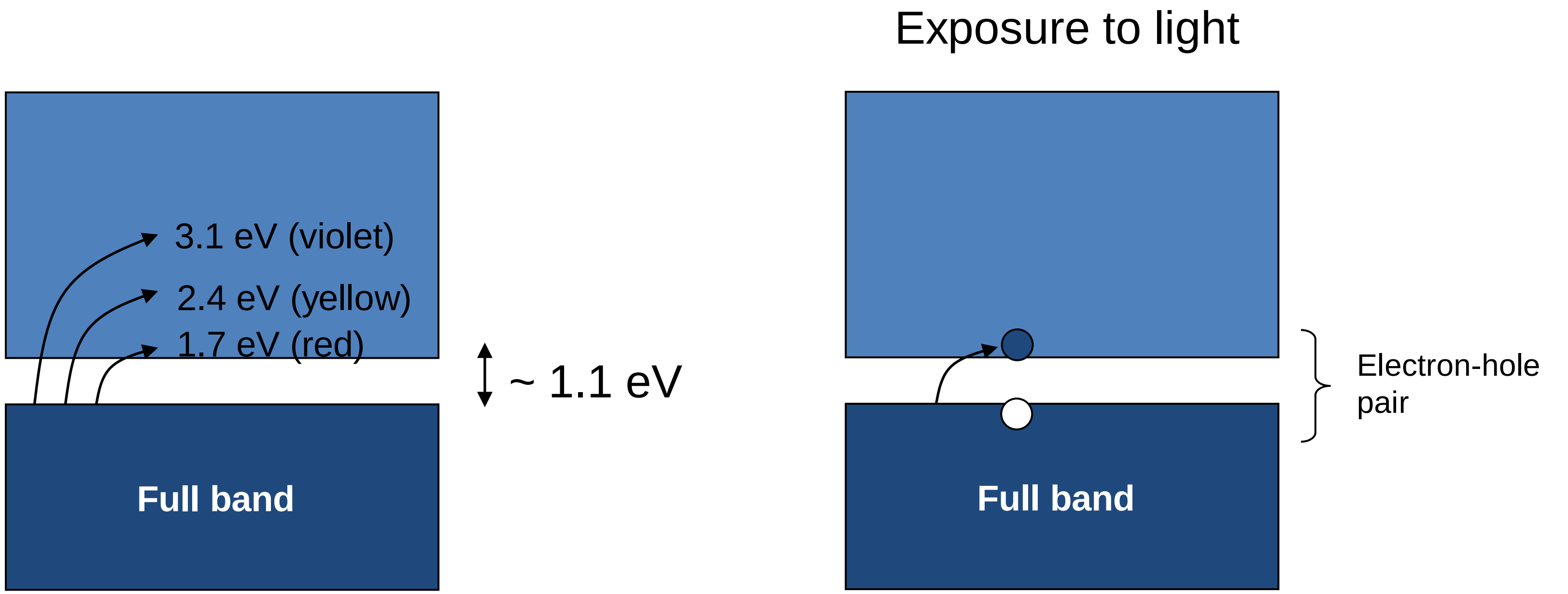
Introduction

Semiconductor devices are electronic components that exploit the electronic properties of semiconductor materials, principally Si, Ge, and GaAs, as well as organic semiconductors. Semiconductor devices are comprised of material with holes in it, which are positive, or p-type, and material with extra electrons, which are negative, or n-type.

1. SOLAR CELLS

Silicon based Solar cells

- Band gap of Si small enough (1.1 eV) for visible light (1.7-3.1 eV) to excite electrons
- Thus visible light will make Si a conductor! So Si is not exposed to light in devices; it is packaged



- In solar cells, Si is exposed to light to create electron hole pairs
- However, electron-hole pairs created will annihilate themselves, as electron will fall back into the hole re-emitting light again
- So, a p-n junction is used which will prevent the re-emission process, and will result in a net current

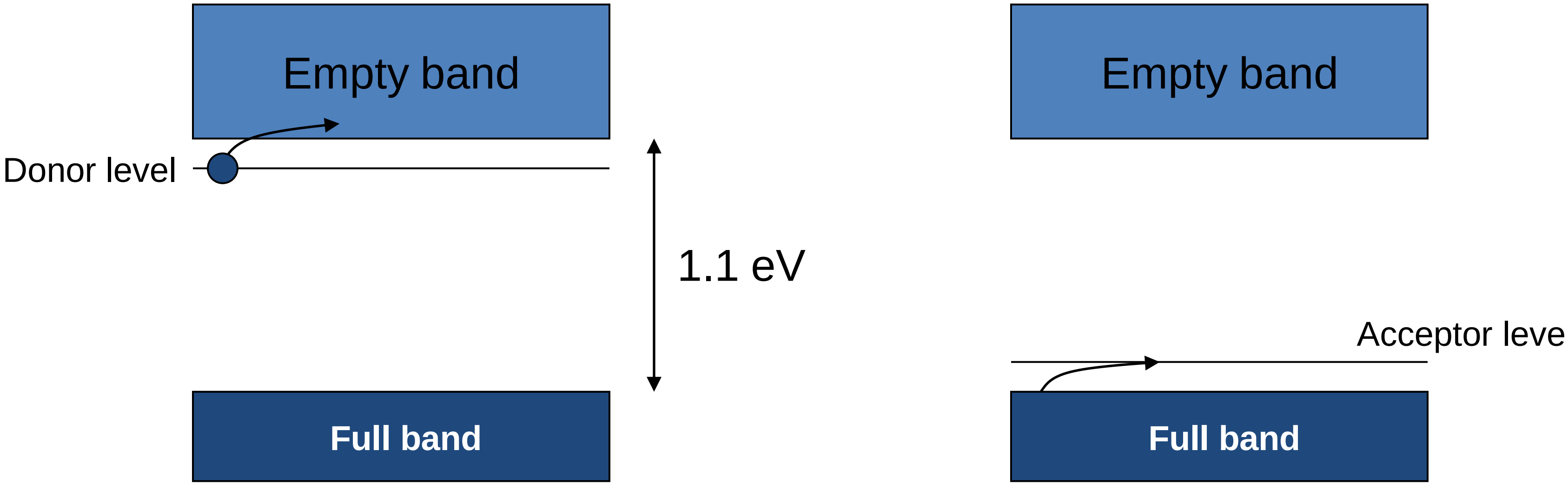
Impurities in Si

- Impurities are added to Si in a controlled manner (by a process called “doping”) to create donor and acceptor levels

B	C	N
Al	Si	P
Ga	Ge	As
3 valence electrons	4 valence electrons	5 valence electrons

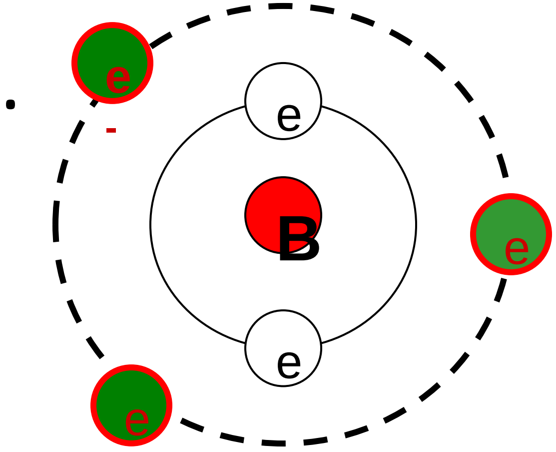
Phosphorous impurity

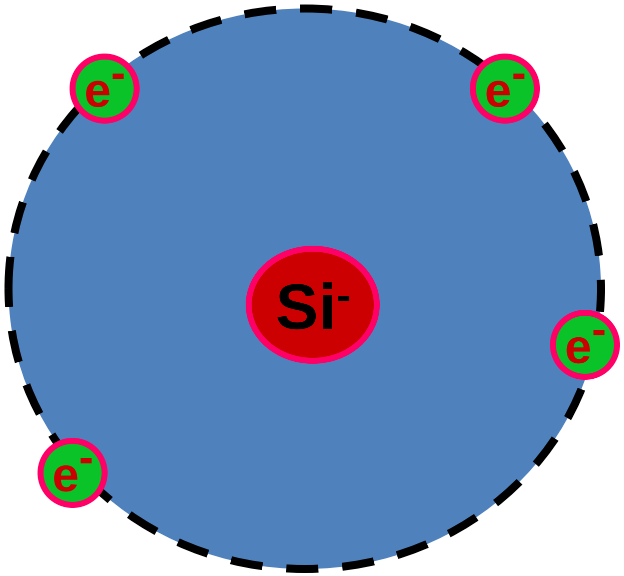
Aluminum impurity



Both impurities result in levels that are about 0.03 eV from the main band; thus room temperature thermal energy is sufficient to excite electrons to and from these levels

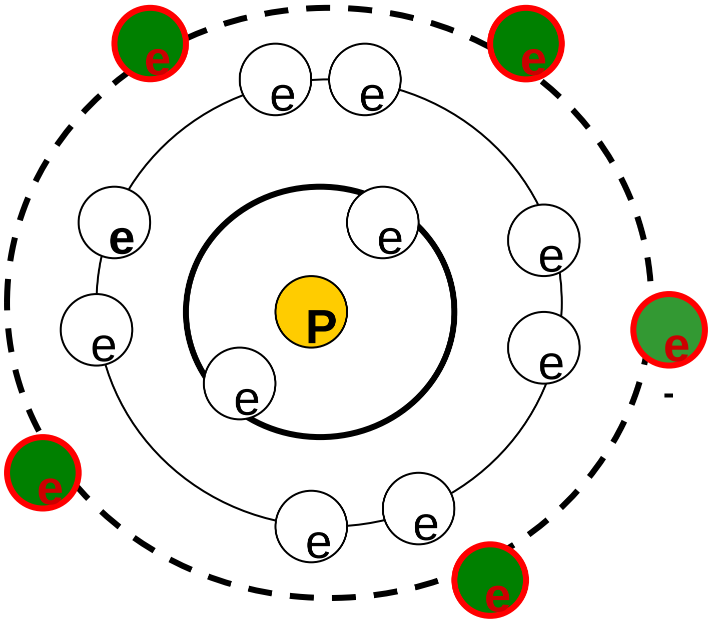
p- type

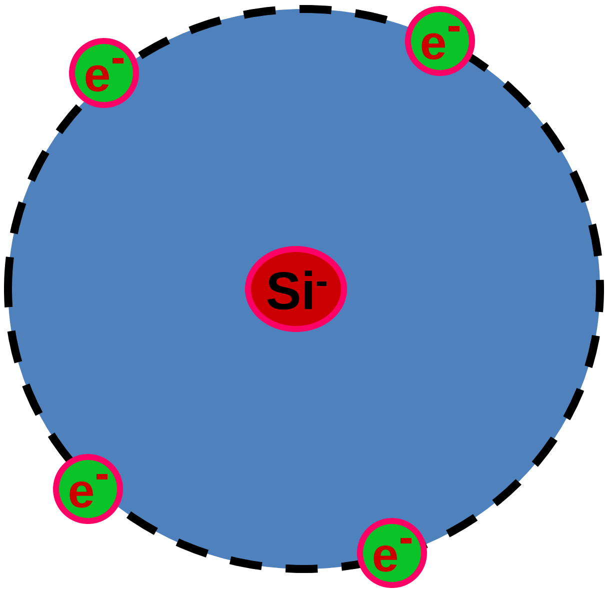




Boron with 3 valence e$^-$, accepts – acceptor – p type

n - type



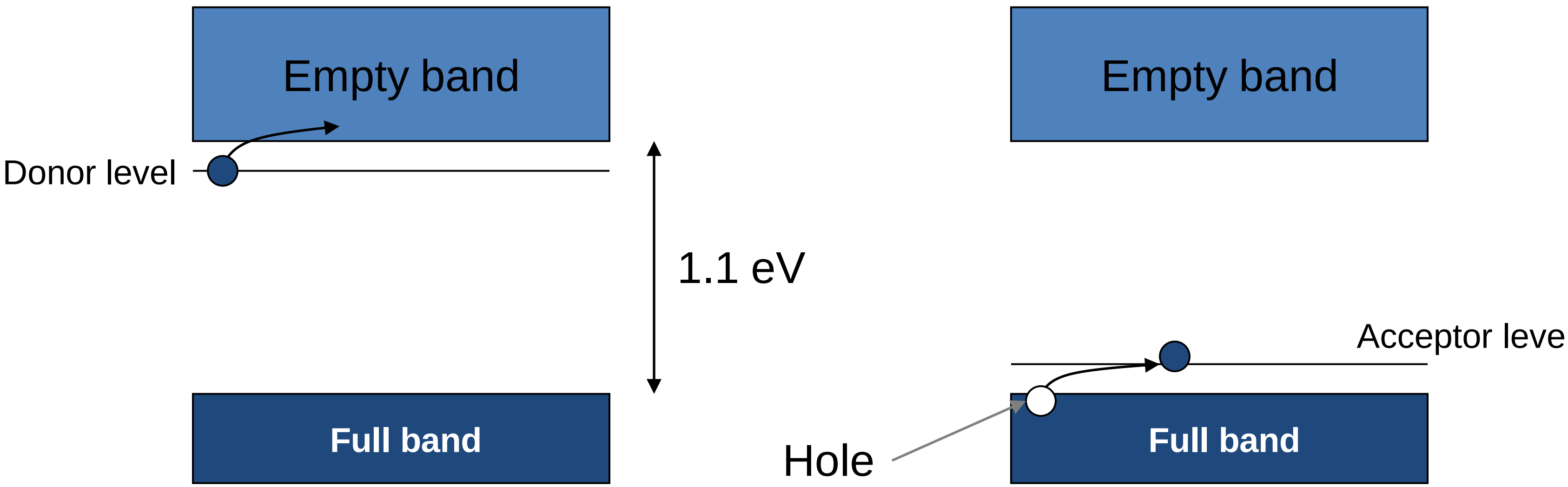


Phosphorus with 5 valence gives - donor – n-type

Impurities in Si: band picture

Phosphorous impurity

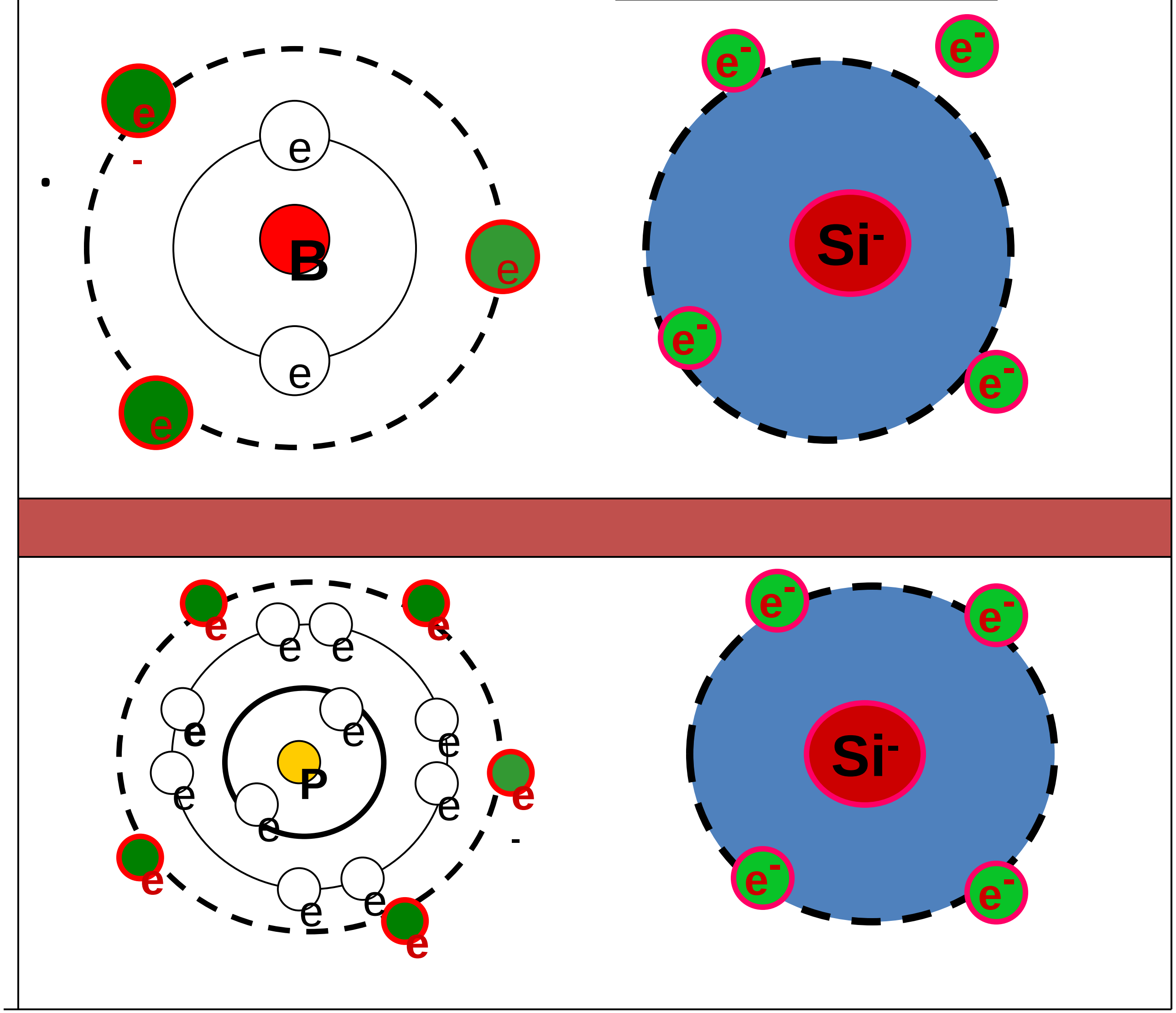
Aluminum impurity



n-type semiconductor (charge carriers are negatively charged)

p-type semiconductor (charge carriers are positively charged)

p-n junction

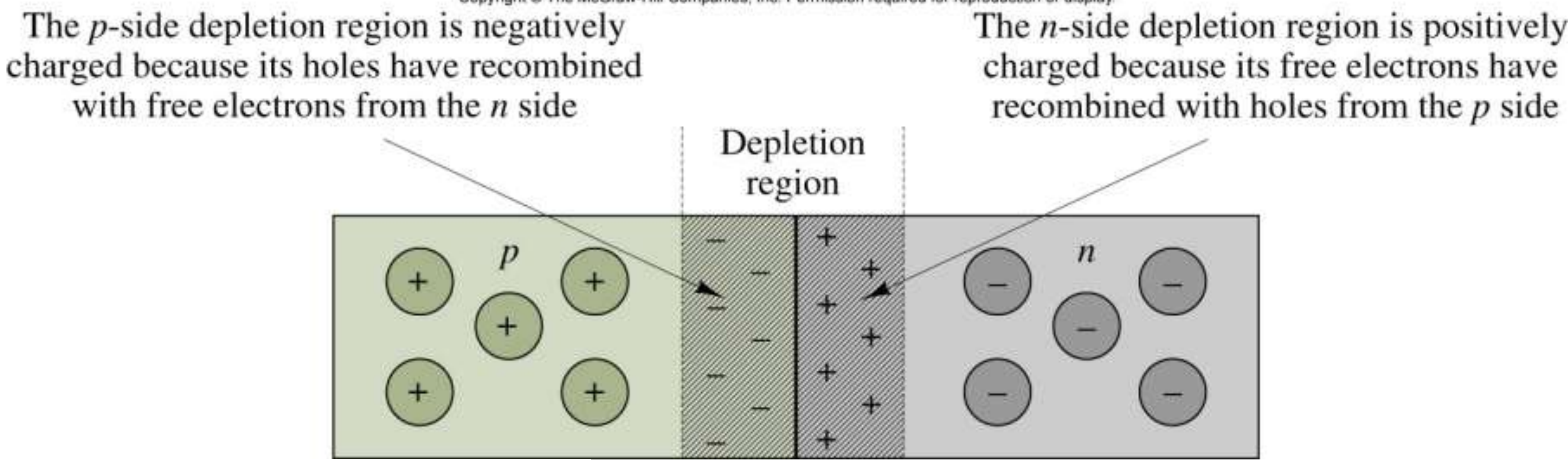


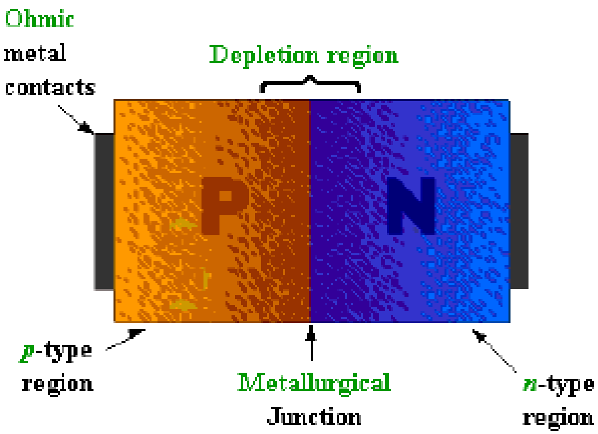
p-type

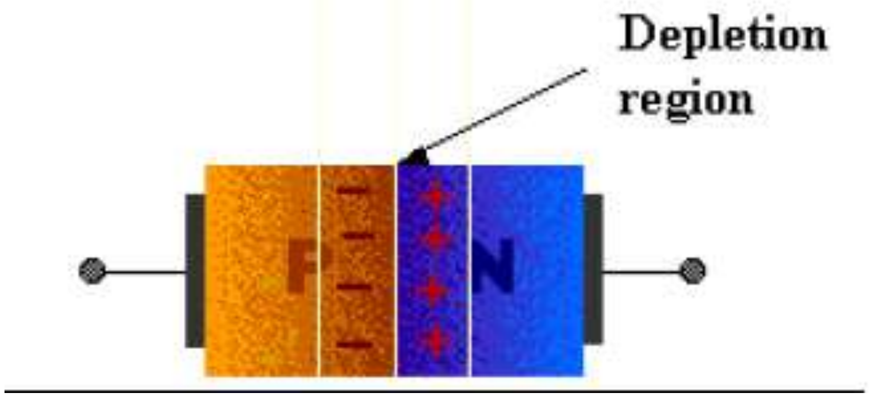
p-n Junction

n-type

PN Junction Diode



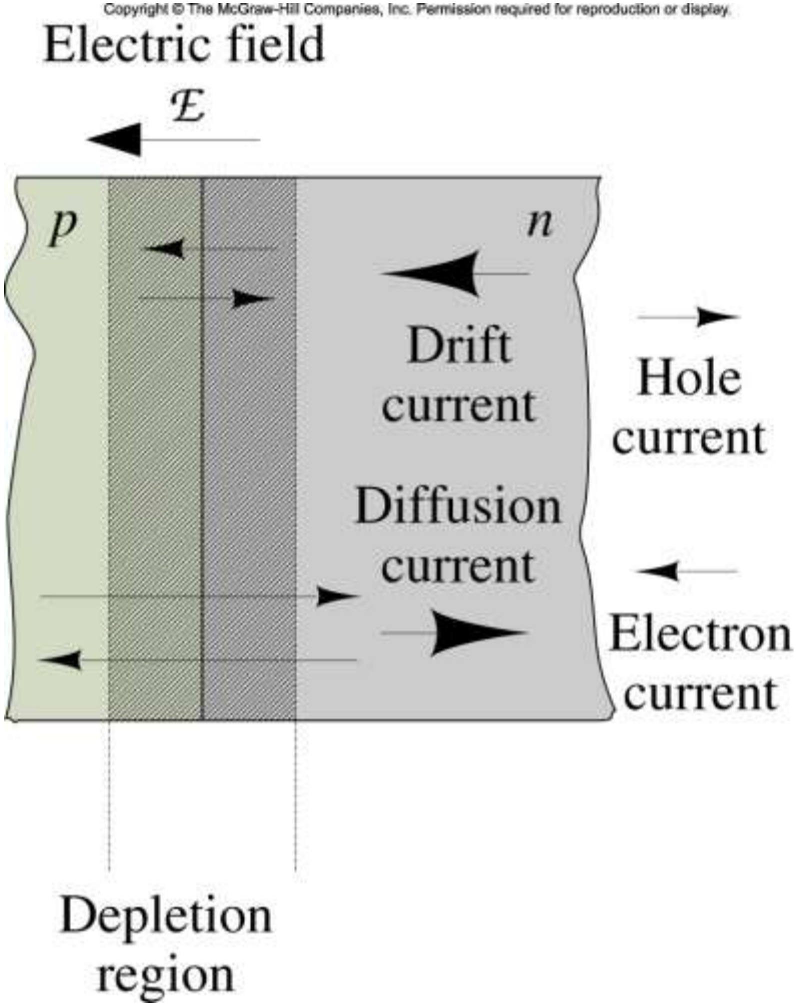


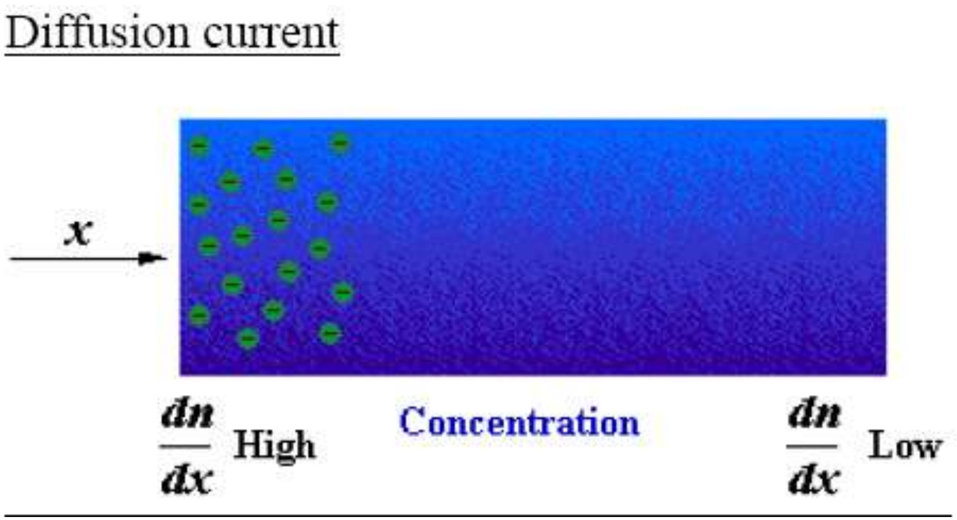


The p-n junction rectifier

- When a p-type and a n-type Si are joined together, we have a p-n junction
- A p-n junction has high electron conductivity along one direction, but almost no conductivity along the other! Why?
- Electrons can cross the p-n junction from the n-type Si side easily as it can jump into the holes
- However, along the other direction, electrons have to surmount a ~ 1.1 eV barrier (which is impossible at room temperature in the dark)

Drift and diffusion currents in a *pn* junction





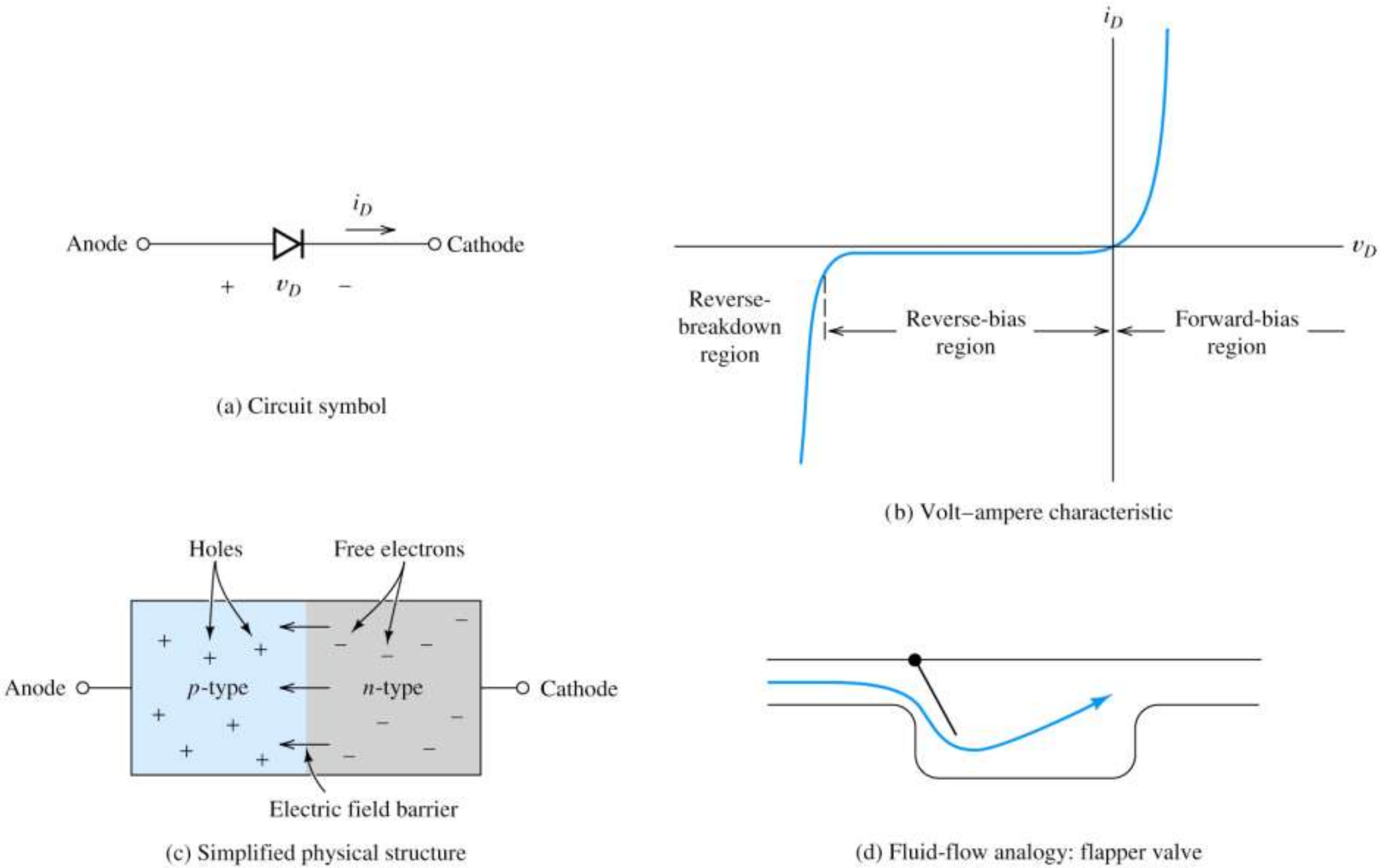
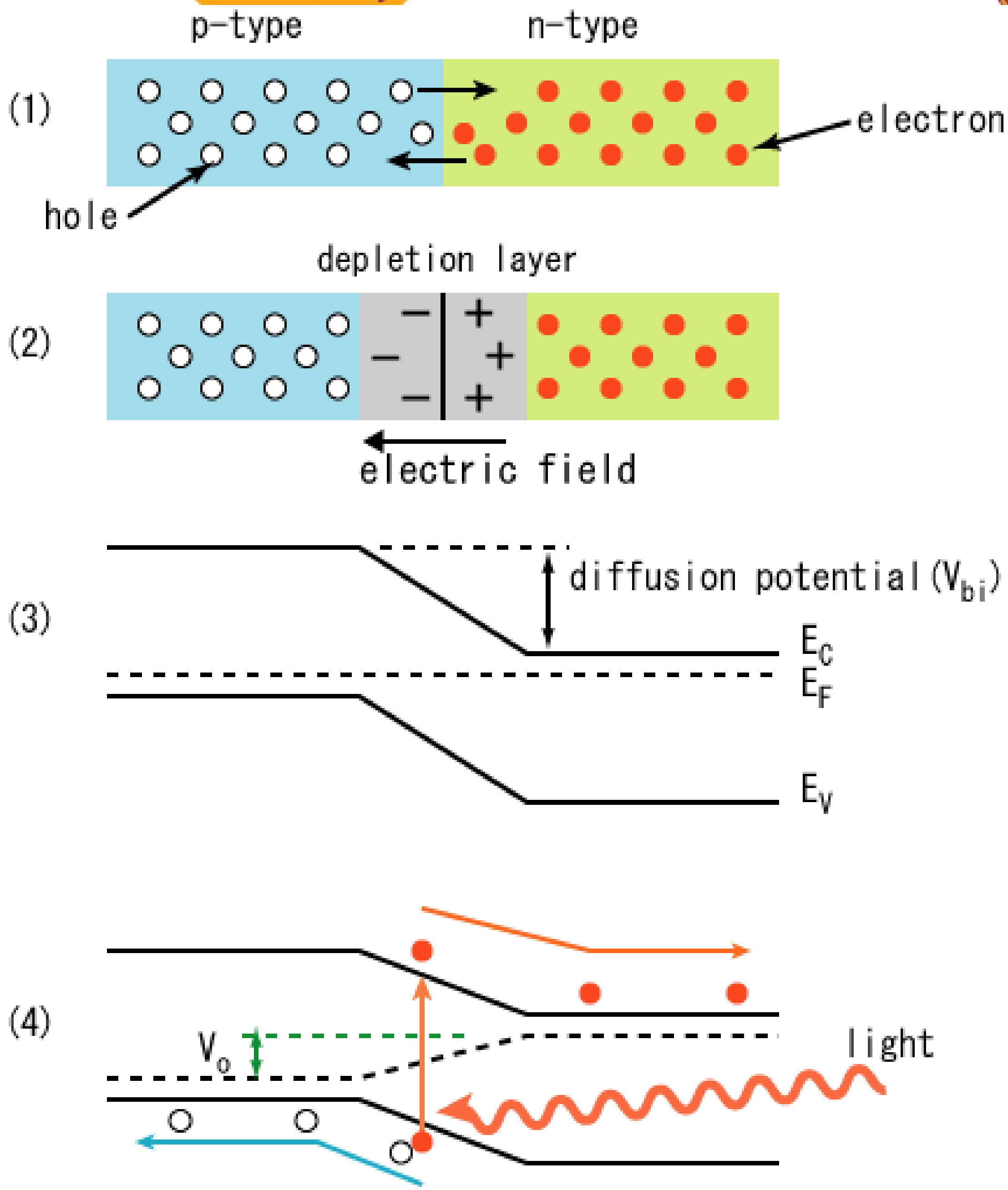


Figure 10.1 Semiconductor diode.

p-n junction solar cell



How Does SC Work?

- Solar cells are usually made of two thin pieces of **silicon**, the substance that makes up sand and the second most common substance on earth.
- One piece of silicon has a small amount of boron added to it, which gives it a tendency to attract electrons. It is called the **p-layer** because of its positive tendency.
- The other piece of silicon has a small amount of phosphorous added to it, giving it an excess of free electrons. This is called the **n-layer** because it has a tendency to give up negatively charged electrons.

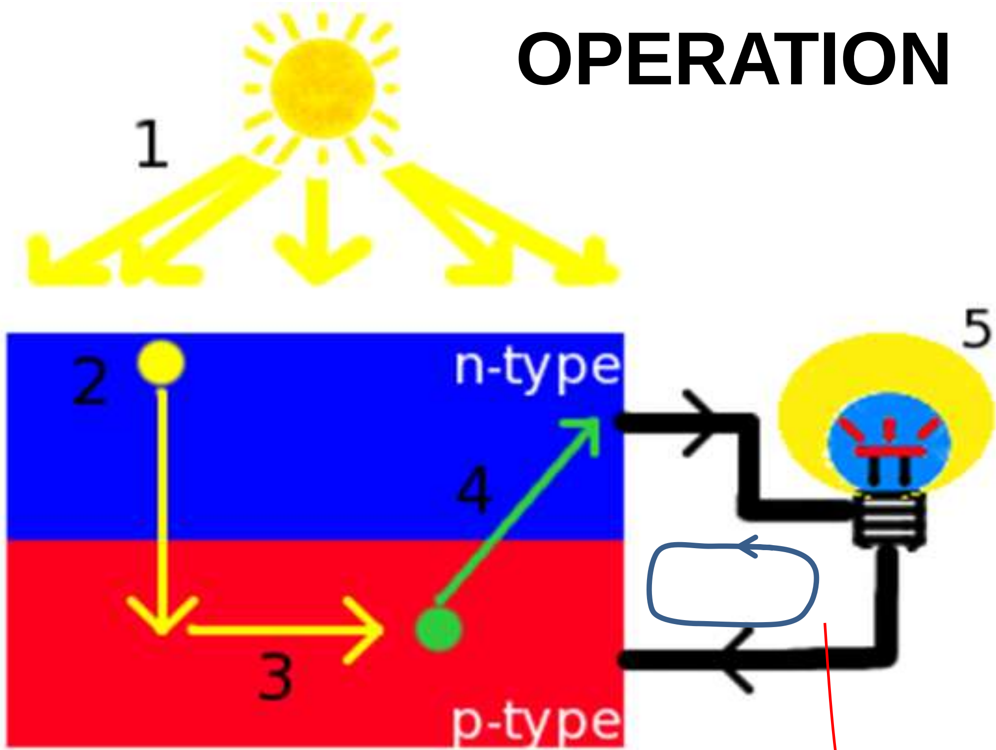
Steps 1, 2 & 3

1. Sunlight is composed of **photons**, or bundles of radiant energy. When photons strike a PV cell, they may be reflected or absorbed, or transmitted through the cell. Only the absorbed photons generate electricity. When the photons are absorbed, the energy of the photons is transferred to electrons in the atoms of the solar cell.

2. When the two pieces of silicon are placed together, some electrons from the n-layer flow to the p-layer and an electric field forms between the layers. The p-layer now has a negative charge and the n-layer has a positive charge.

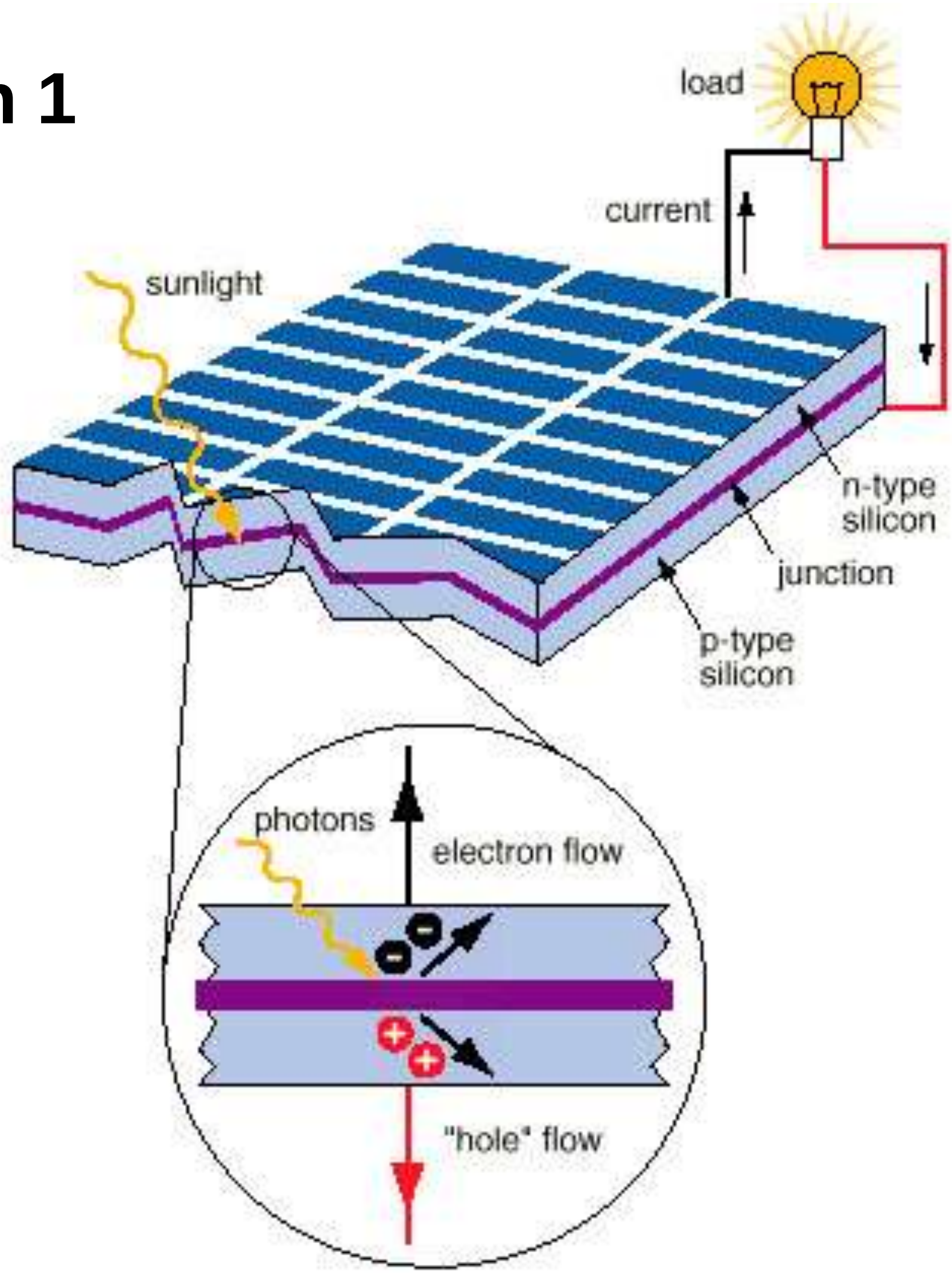
3. When the PV cell is placed in the sun, the radiant energy energizes the free electrons. If a circuit is made connecting the layers, electrons flow from the n-layer through the wire to the p-layer. The PV cell is producing electricity—the flow of electrons. If a load such as a light bulb is placed along the wire, the electricity will do work as it flows.

OPERATION

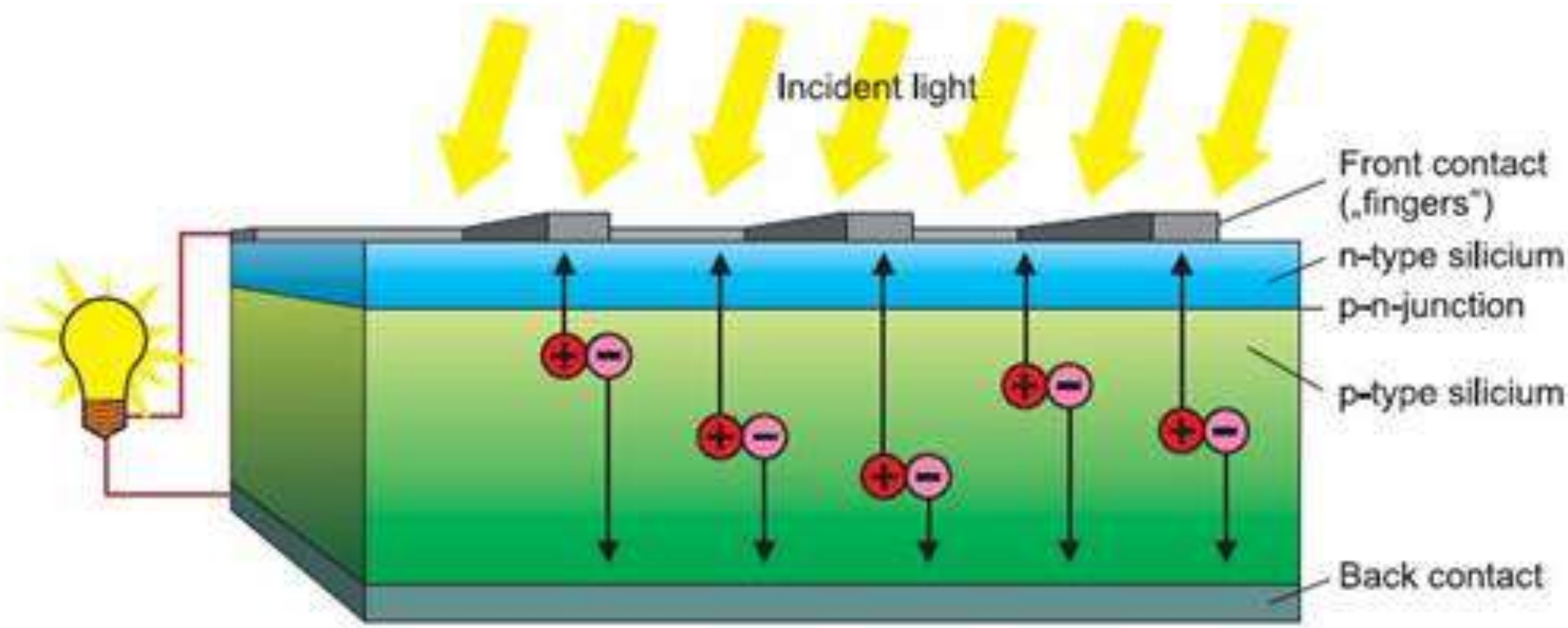


1. A solar cell is a sandwich of n-type silicon (blue) and p-type silicon (red).
2. When sunlight shines on the cell, photons (light particles) bombard the upper surface.
3. The photons (yellow dot) carry their energy down through the cell.
4. The photons give up their energy to electrons (green dot) 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. Current flow is anti-clockwise

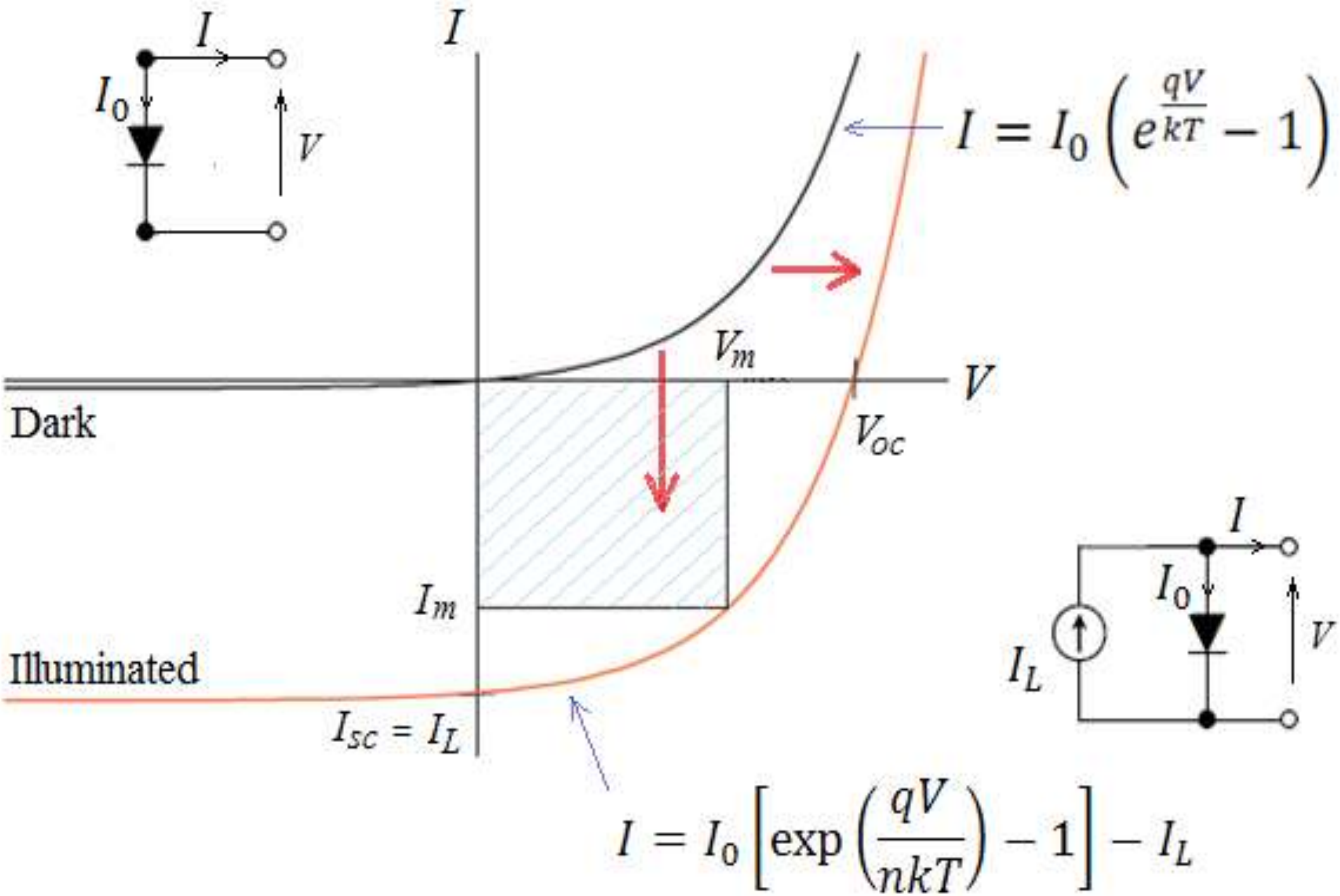
Design 1


load
current
sunlight
n-type
silicon
junction
p-type
silicon
photons
electron flow
"hole" flow

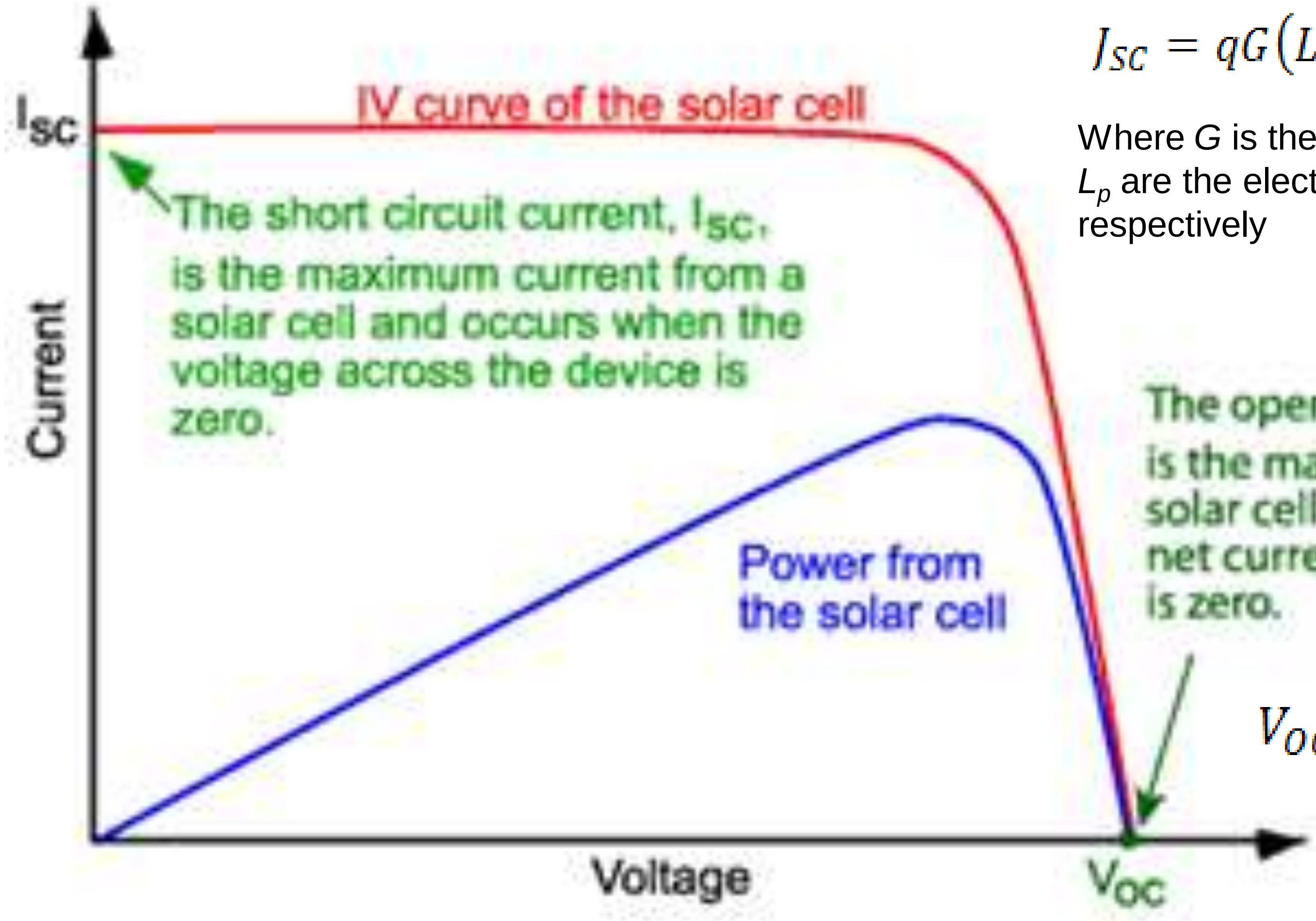
Design 2


Incident light
Front contact
(„fingers")
n-type silicium
p-n-junction
p-type silicium
Back contact

Equivalent Circuit



IV Characteristics

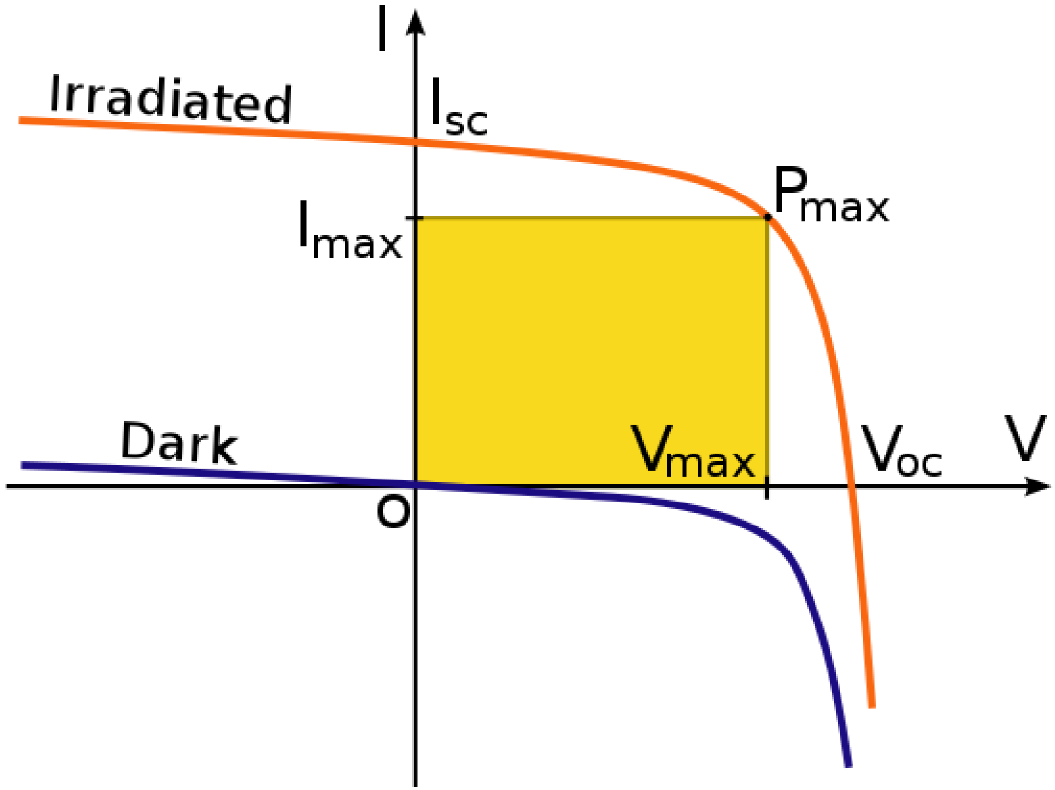


$$J_{SC} = qG\left(L_n + L_p\right)$$

Where G is the generation rate, and L_n and L_p are the electron and hole diffusion lengths respectively

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

IV Characteristics



$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}}$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

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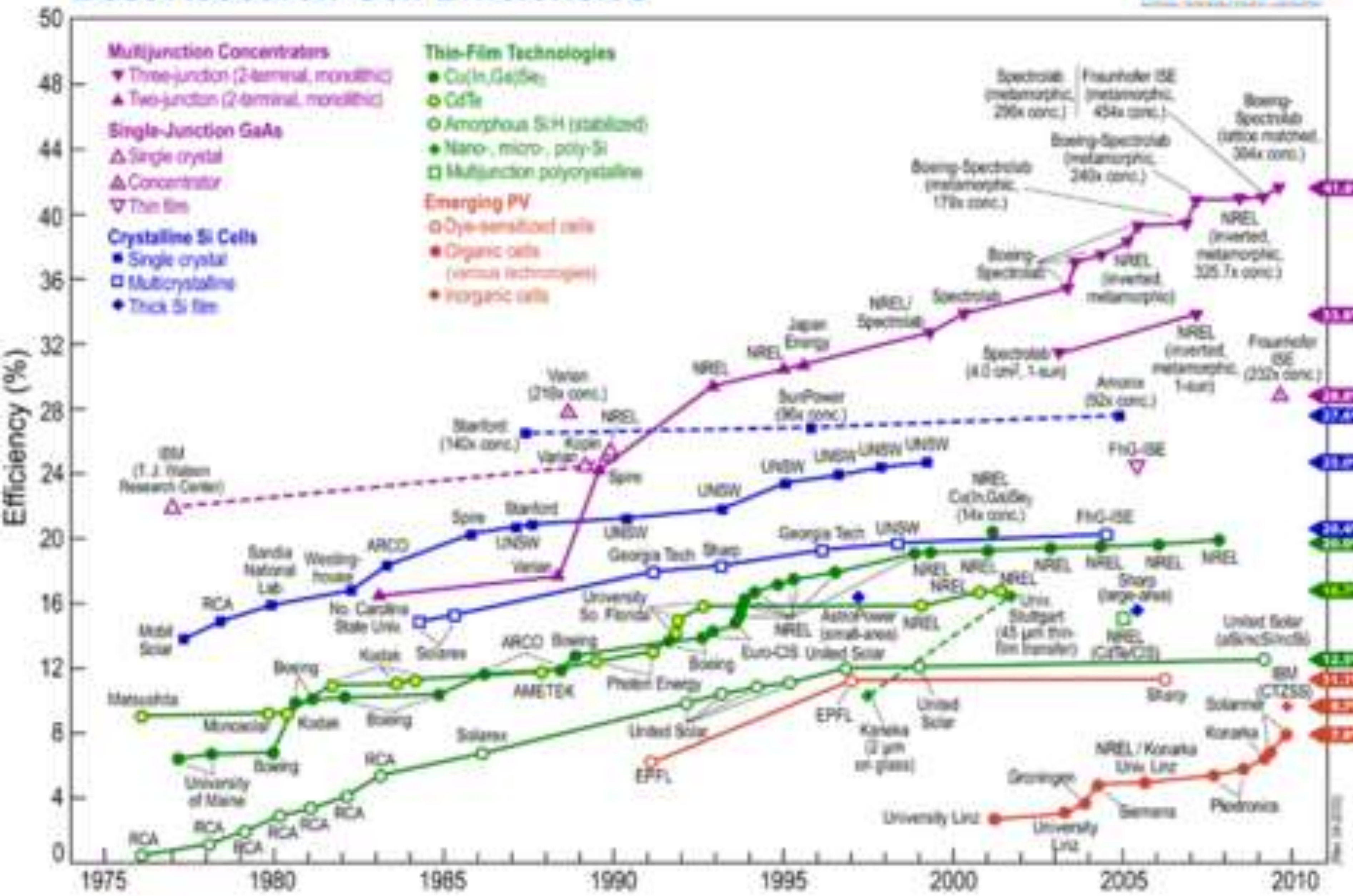
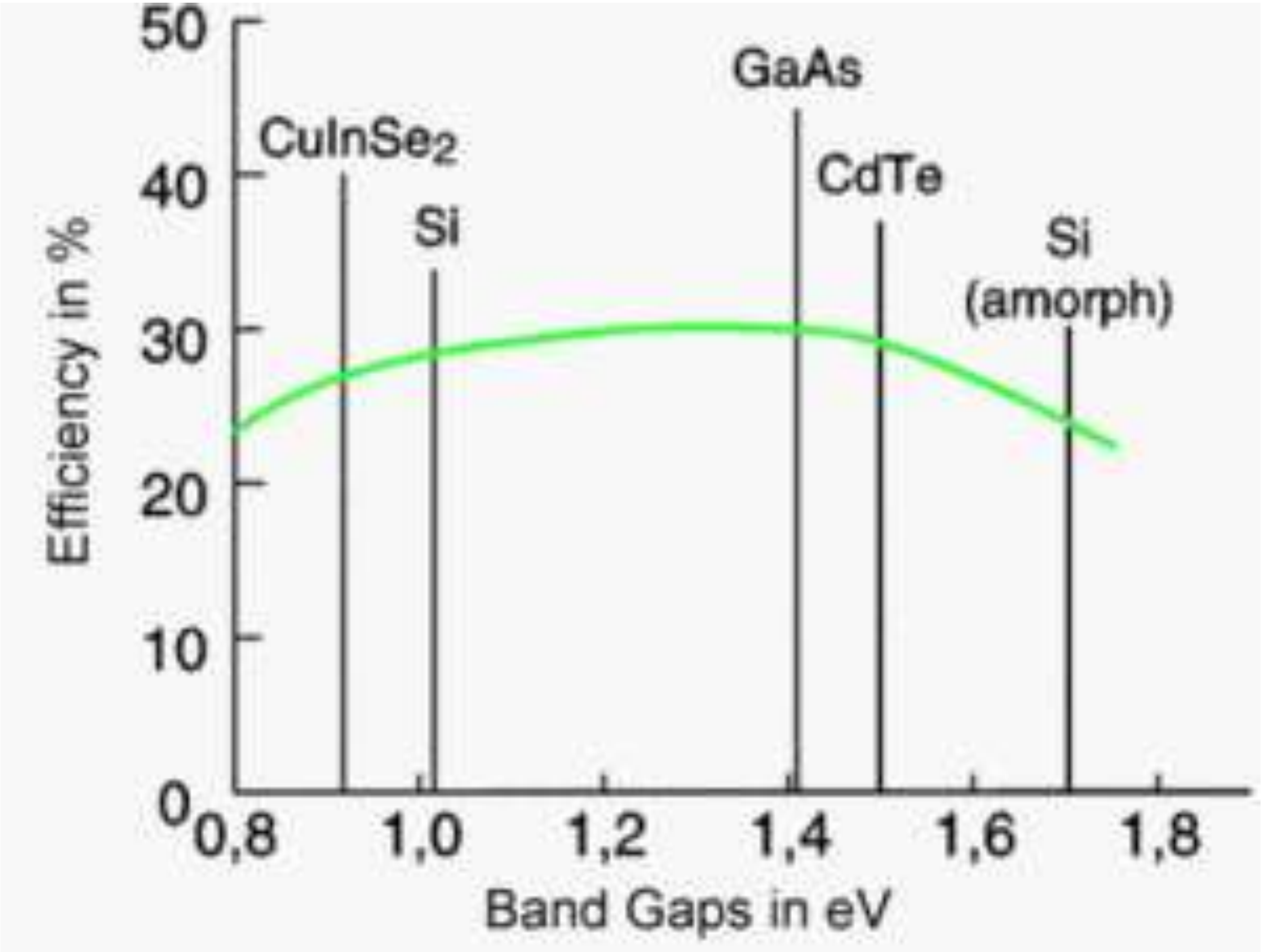
Best Research-Cell Efficiencies



Theore. Eficiency of Solar Cells



Basic structure of solar cell

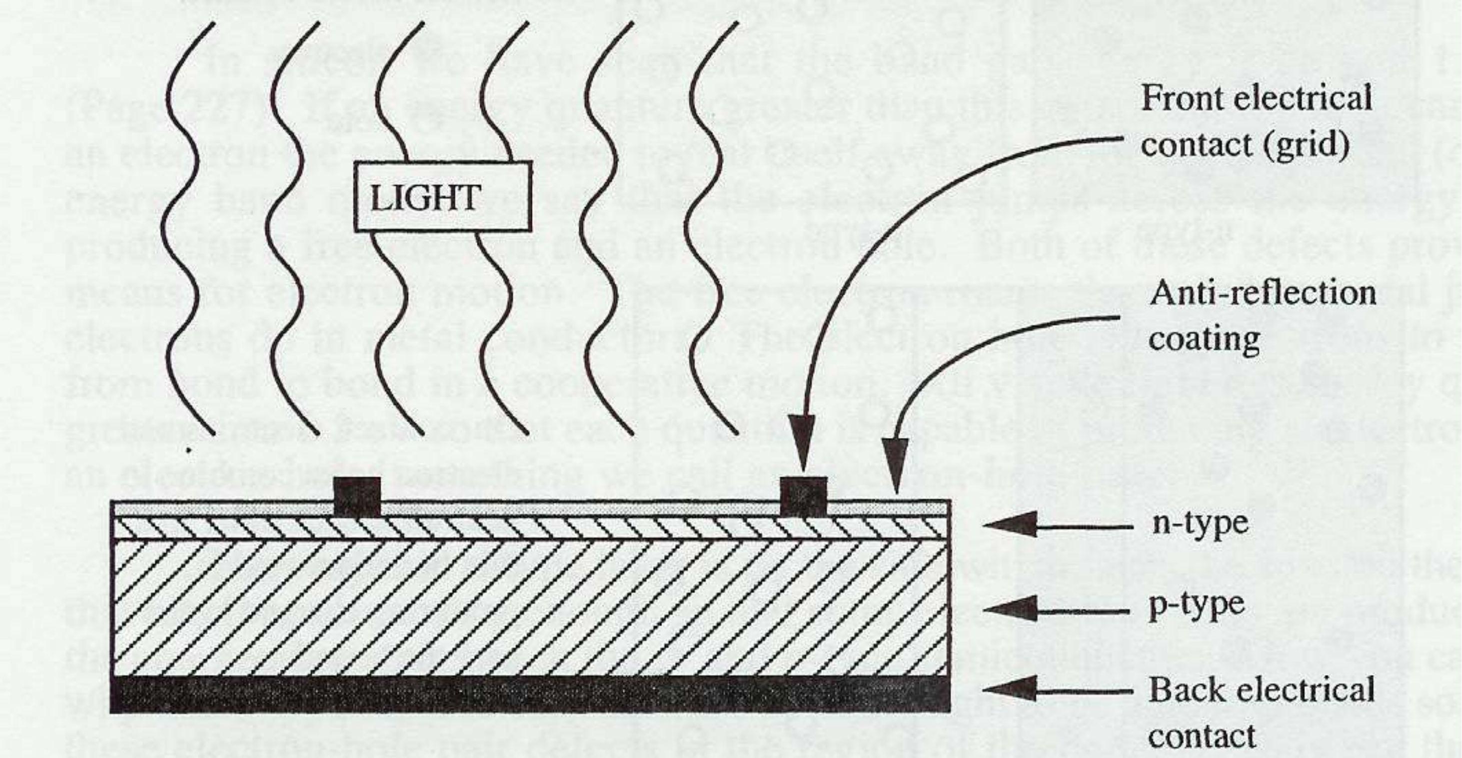


Diagram of cross-section of a solar cell.

- Anti-reflective coating prevents reflection at top surface to increase efficiency
- Top and bottom contacts help collect the electron and hole currents generating electricity in an external circuit

Prospects of solar cells

- Today, only 0.1% of all energy produced come from solar energy; maximum demonstrated efficiency is 30 %
- We want large pieces of crystalline Si to make solar cells ➔ counter to the trend of miniaturization, and difficult to produce large crystalline Si
- Although large, high efficiency amorphous Si solar cells have been demonstrated, production of these is slow
- Lack of sunshine in some parts of the world, and unpredictability in others
- Solar cells produce DC, but AC current required for transmission to large distances
- At present, the most promising applications are in rural and remote areas
- However, this is a very "clean" source of energy, and research is continuing …

a-Si Solar Cell

Amorphous Silicon, a-Si: The efficiency of amorphous solar cells is typically between 6 and 8%. The Lifetime of amorphous cells is shorter than the lifetime of crystalline cells. Amorphous cells have current density of up to 15 mA/cm2, and the voltage of the cell without connected load of 0.8 V, which is more compared to crystalline cells.

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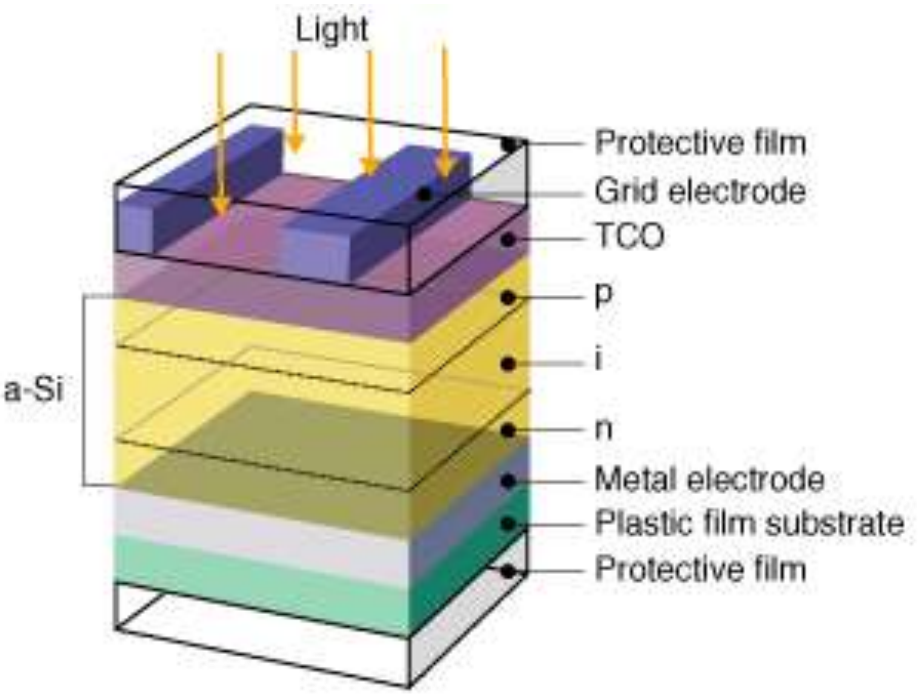
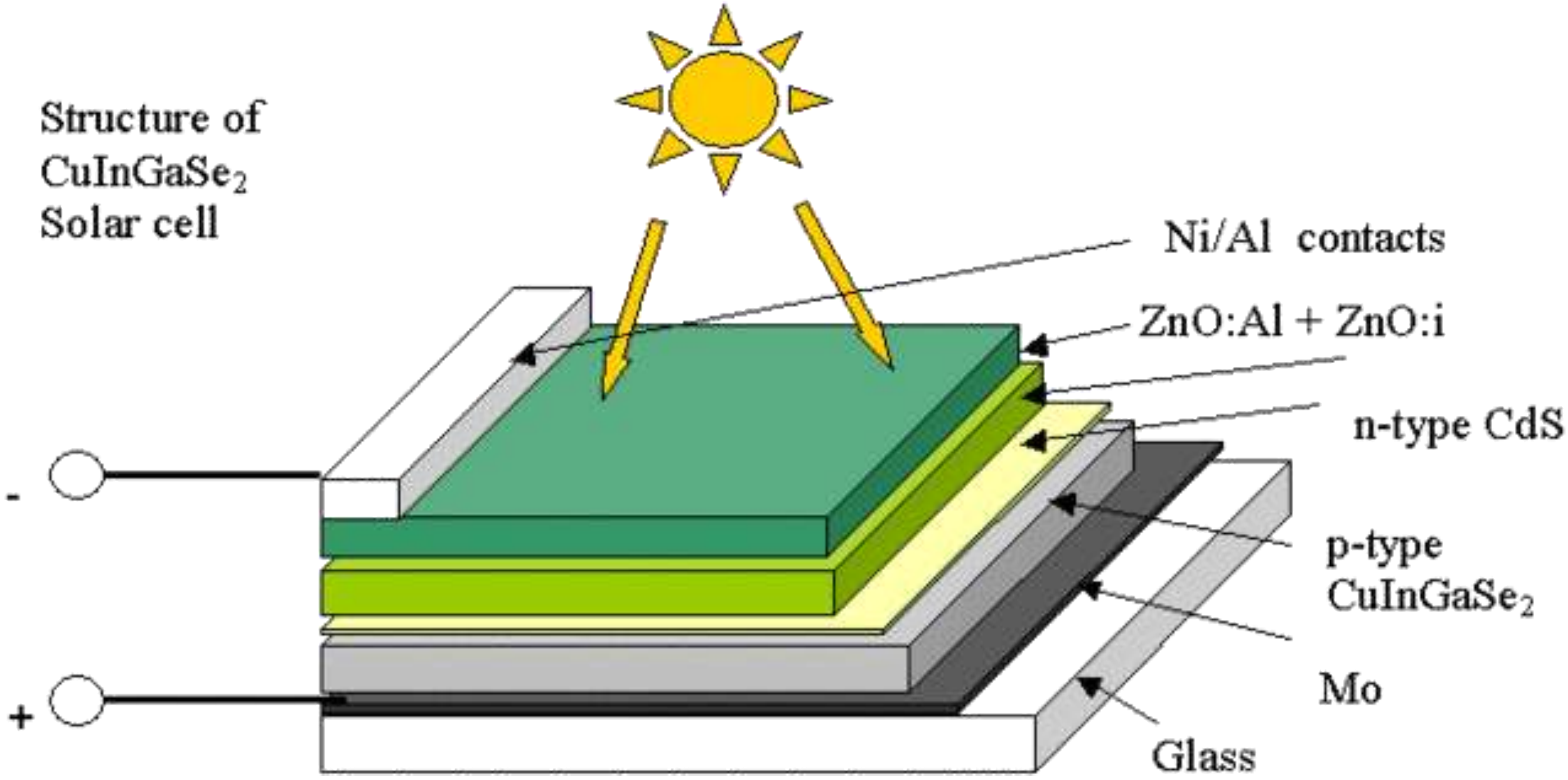


Amorton Film Configuration

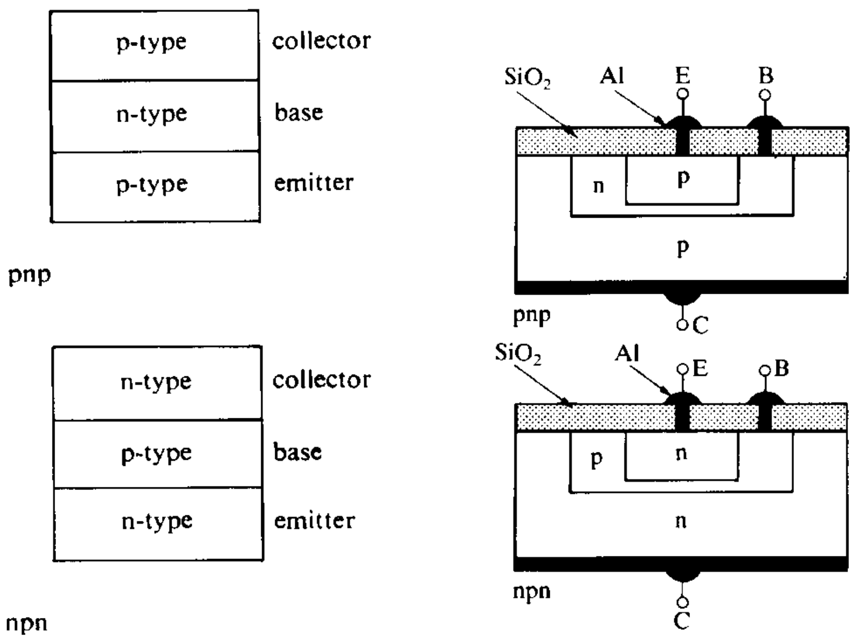
CIGS: Copper indium gallium selenide (CIGS), has an extremely high absorption that allows 99 percent of available light to be absorbed in the first micron of the material. CIGS is mainly used in the form of polycrystalline thin films. The best efficiency achieved as of 2005 was 19.5%.



Transistors: Introduction

- A transistor is a device with three separate layers of semiconductor material stacked together
  - The layers are made of *n*–type or *p*–type material in the order *pnp* or *npn*
  - The layers change abruptly to form the *pn* or *np* junctions
  - A terminal is attached to each layer

(*The Art of Electronics*, Horowitz and Hill, 2nd Ed.)



(a) *schematic construction* (b) *practical construction*

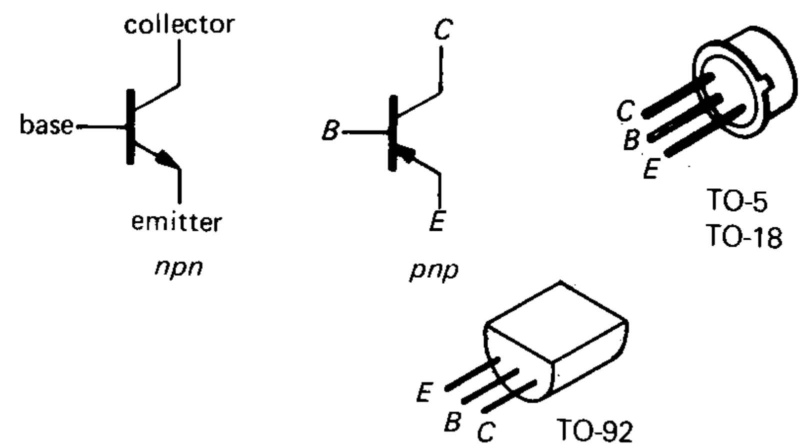
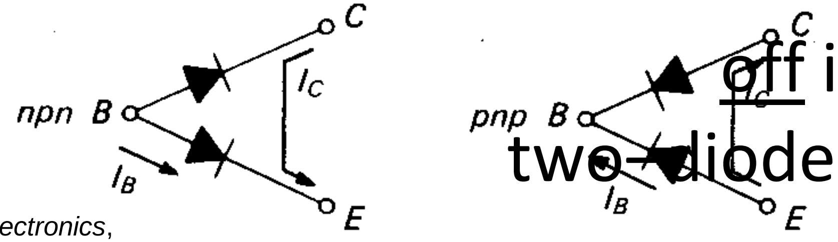


Figure 2.1. Transistor symbols, and small transistor packages.

(*Introductory Electronics*, Simpson, 2nd Ed.)

Introduction to Transistors

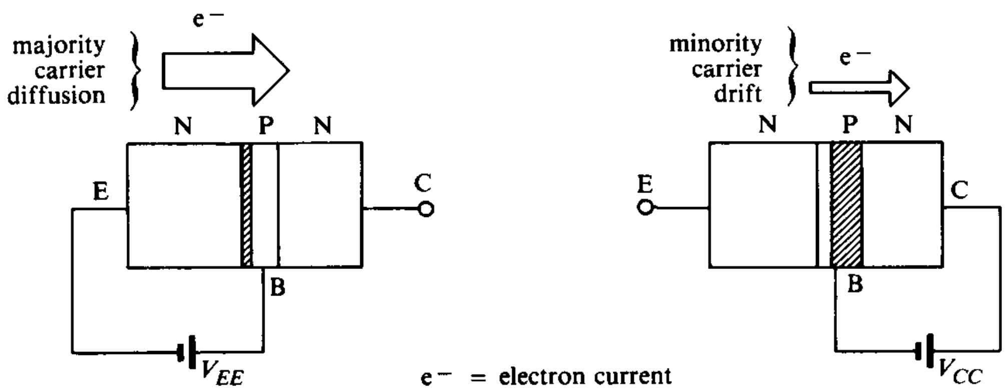
- Thus when a transistor is off it behaves like a two-diode circuit
- A transistor operates (or turns on) when the base–emitter junction is forward biased and the base–collector junction is reversed biased (“biasing”)



(*The Art of Electronics*, Horowitz and Hill, 2nd Ed.)

Figure 2.2. An ohmmeter’s view of a transistor’s terminals.

(Lab 4–1)



(a) Forward biasing the emitter-base junction

(b) Reverse biasing the collector-base junction

Figure 4.3 Biasing the two PN junctions in an NPN transistor

(*Electronic Devices and Circuits*, Bogart, 1986)

Transistor Biasing (*npn* Transistor)

- Electrons are constantly to the emitter by voltage V_{EE}
- These electrons can:
  1. Recombine with holes in the base, giving rise to I_B
  2. Diffuse across base and be swept (by electric field at base–emitter junction) into collector, then diffuse around and eventually recombine with holes injected into collector, giving rise to I_C

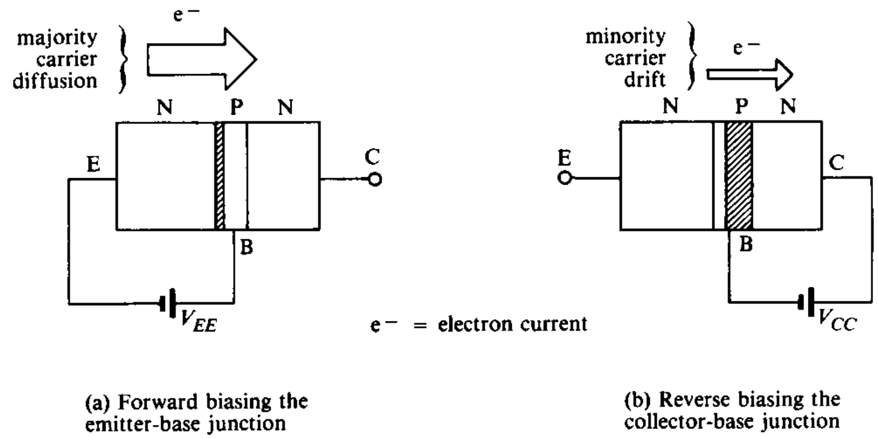


Figure 4.3 Biasing the two PN junctions in an NPN transistor

- Since the base region is designed so thin, process 2 dominates (no time for #1 to occur as often)
  - In an actual *npn* transistor, 98 or 99% of the electrons that diffuse into the base will be swept into the collector

Current Flow Inside a Transistor

- Current flow for an *npn* transistor (reverse for *pnp*):
  - From conservation of current ($I_E = I_B + I_C$) we can obtain the following relating the currents:

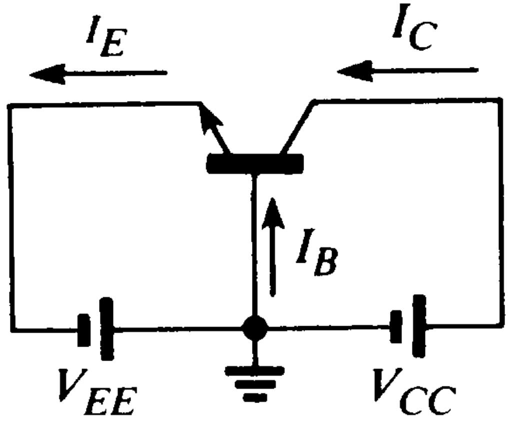
$$I_C = \beta I_B \qquad I_E = (\beta + 1) I_B$$

(and thus $I_C \approx I_E$)

where $\beta \approx 20 - 200$ (depends on emitter current)

- β increases as I_E increases (for very small I_E) since there is less chance that recombination will occur in the base
- β *decreases* slightly (10–20%) as I_E increases beyond several mA due to increased base conductivity resulting from larger number of charge carriers in the base
- Thus β is <u>not</u> a constant for a given transistor!
- An average value of 100 is typically used

(*Electronic Devices and Circuits*, Bogart, 1986)

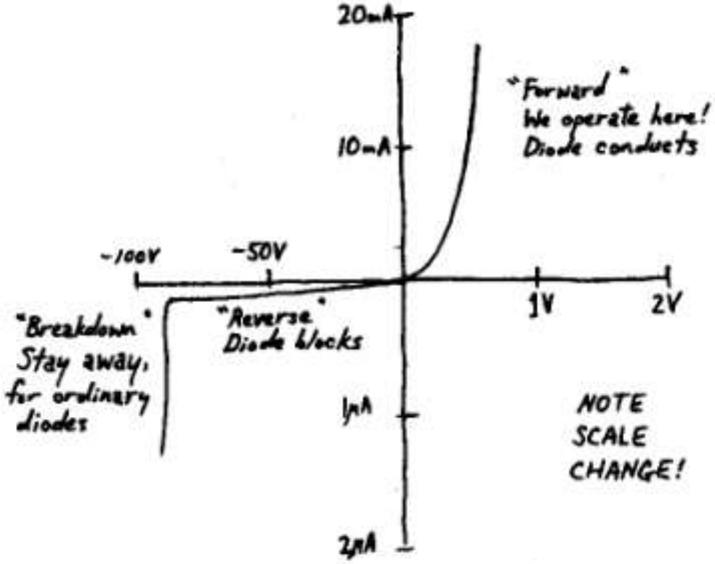


(Lab 4–5)

Transistor Current Amplification

- If the "input" current is I_B and the "output" current is I_C, then we have a current *amplification* or *gain*
  - Happens because base–emitter junction is forward-biased
  - Forward bias ensures that the base–emitter junction conducts (transistor is turned on)
  - Reverse bias ensures that most of the large increase in the base–emitter current shows up as collector current

Thus small gains in I_B result in large gains in I_E and hence I_C



(*Student Manual for The Art of Electronics*, Hayes and Horowitz, 2nd Ed.)

Figure N3.9: Diode *I-V* curve (reverse current is exaggerated by change of scale in this plot)

Ceramics

Ceramics

A wide-ranging group of materials whose ingredients are clays, sand and felspar.

Clays

Contain some of the following:

- Silicon & Aluminium as silicates
- Potassium compounds
- Magnesium compounds
- Calcium compounds

Sand contains Silica and Feldspar or Aluminium Potassium Silicate.

Types of Ceramics

- Whitewares
- Refractories
- Glasses
- Abrasives
- Cements

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Comparison metals v ceramics

Metals	Ceramics
Crystal structure	Crystal structure
Large number of free electrons	Captive electrons
Metallic bond	Ionic/covalent bonds
Good electrical conductivity	Poor conductivity
Opaque	Transparent (in thin sections)
Uniform atoms	Different-size atoms
High tensile strength	Poor tensile strength[a]
Low shear strength	High shear strength
Good ductility	Poor ductility (brittle)
Plastic flow	None
Impact strength	Poor impact strength
Relatively high weight	Lower weight
Moderate hardness	Extreme hardness
Nonporous	Initial high porosity
High density	Initial low density

Bonded Clay Ceramics

Made from natural clays and mixtures of clays and added crystalline ceramics.

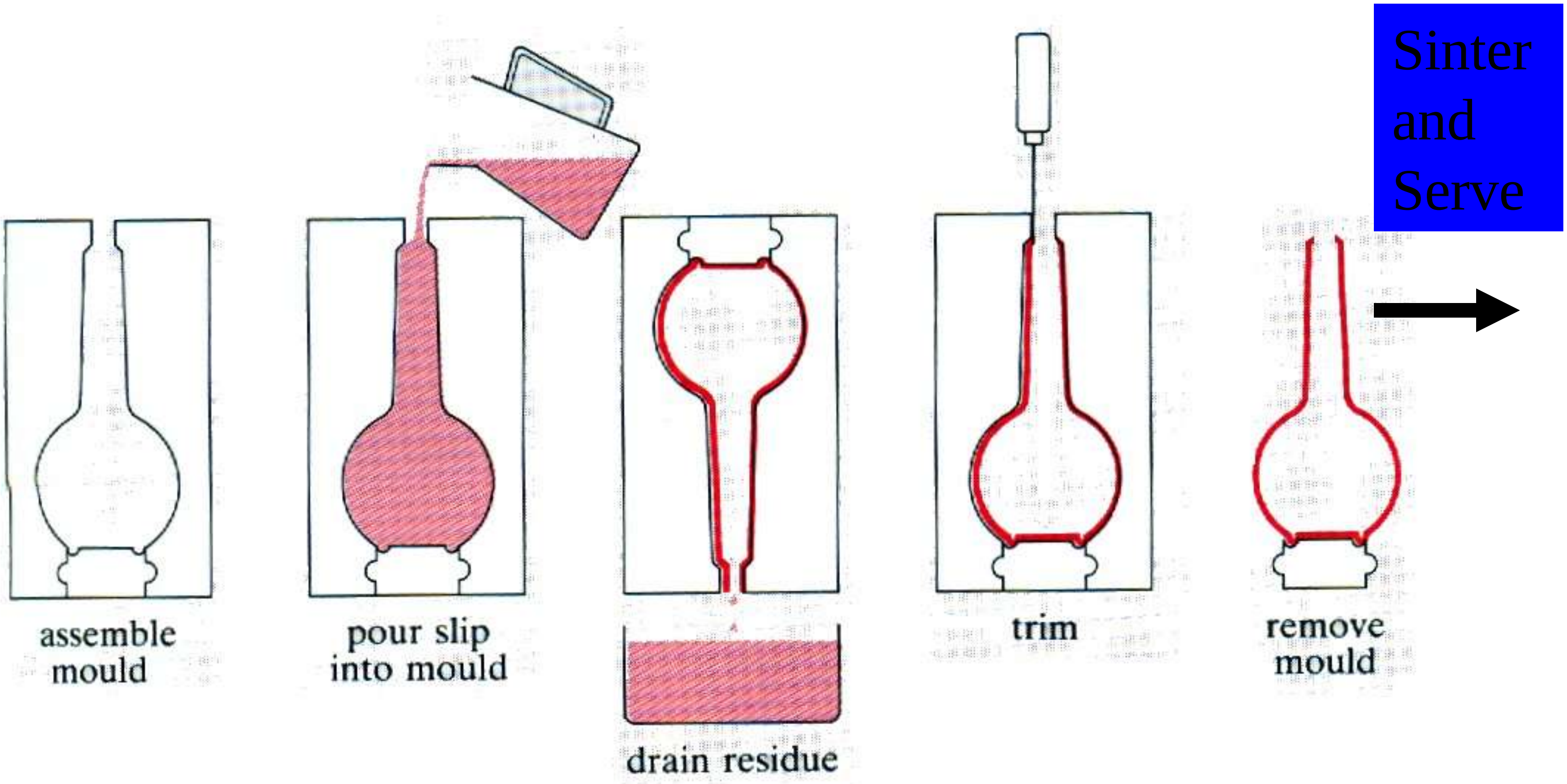
These include:

- Whitewares
- Structural Clay Products
- Refractory Ceramics

Whitewares

- Crockery
- Floor and wall tiles
- Sanitary-ware
- Electrical porcelain
- Decorative ceramics

Slip Casting



Refractories

Firebricks for furnaces and ovens. Have high Silicon or Aluminium oxide content.

Brick products are used in the manufacturing plant for iron and steel, non-ferrous metals, glass, cements, ceramics, energy conversion, petroleum, and chemical industries.

Refractories

- Used to provide thermal protection of other materials in very high temperature applications, such as steel making (T_m=1500°C), metal foundry operations, etc.

- They are usually composed of alumina (T_m=2050°C) and silica along with other oxides: MgO (T_m=2850°C), Fe_2O_3, TiO_2, etc., and have intrinsic porosity typically greater than 10% by volume.

- Specialized refractories, (those already mentioned) and BeO, ZrO_2, mullite, SiC, and graphite with low porosity are also used.

Amorphous Ceramics (Glasses)

- Main ingredient is Silica (SiO_2)
- If cooled very slowly will form crystalline structure.
- If cooled more quickly will form amorphous structure consisting of disordered and linked chains of Silicon and Oxygen atoms.
- This accounts for its transparency as it is the crystal boundaries that scatter the light, causing reflection.
- Glass can be tempered to increase its toughness and resistance to cracking.

Glass Types

Three common types of glass:

- *Soda-lime glass* - 95% of all glass, windows containers etc.
- *Lead glass* - contains lead oxide to improve refractive index
- *Borosilicate* - contains Boron oxide, known as Pyrex.

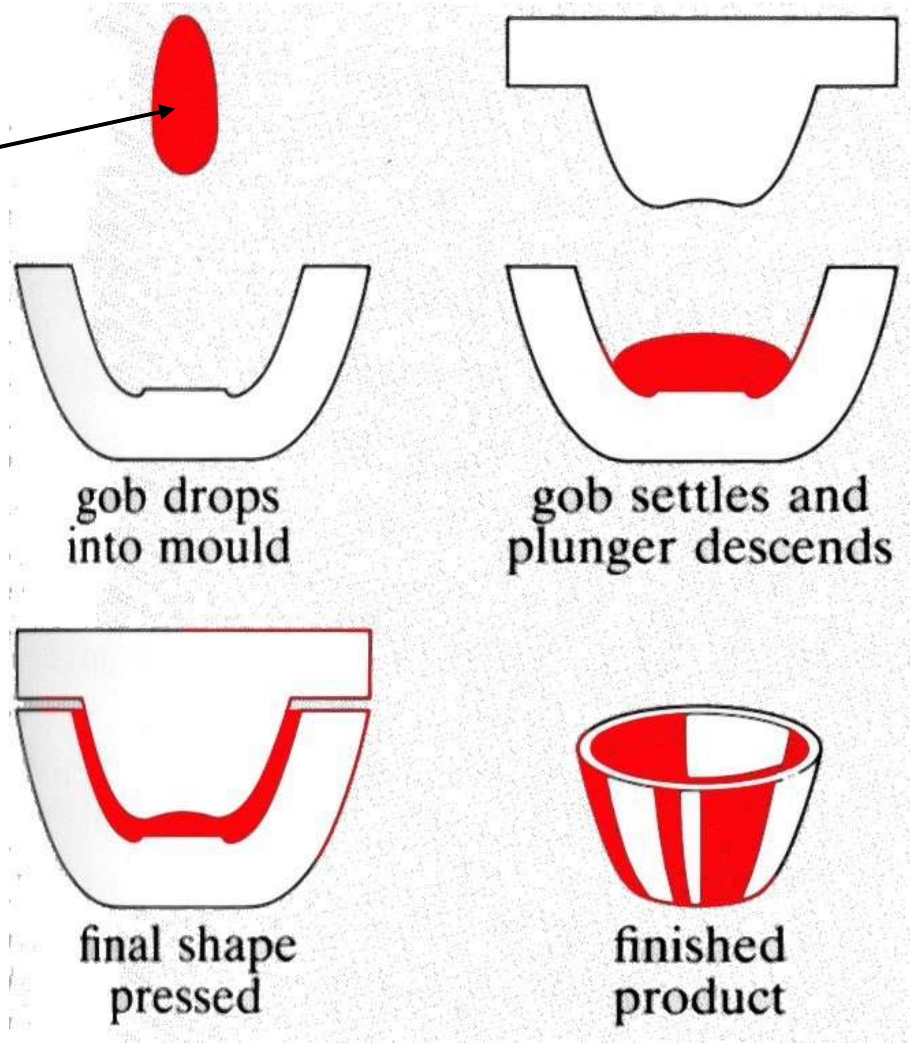
Glasses

- Flat glass (windows)
- Container glass (bottles)
- Pressed and blown glass (dinnerware)
- Glass fibres (home insulation)
- Advanced/specialty glass (optical fibres)

Glass Containers

Pressed Glass Processing

Softened Gob



Blow Molding

Softened glass

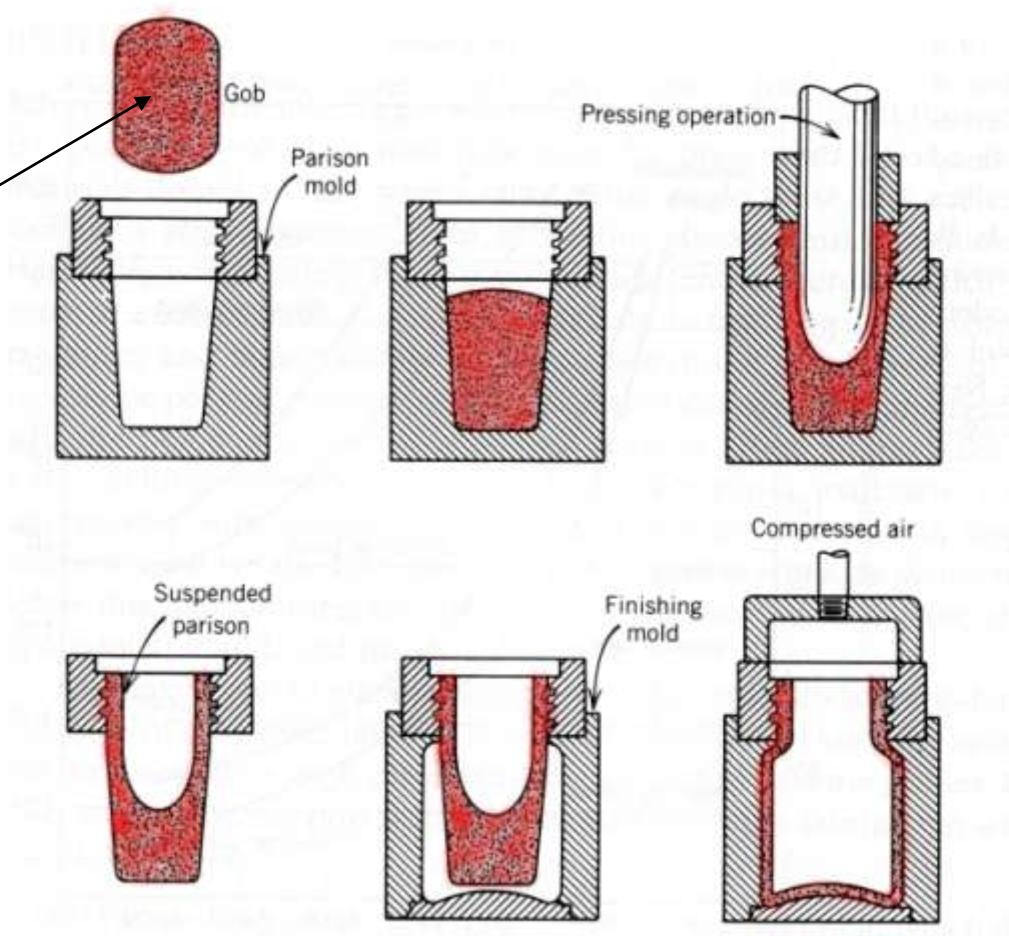
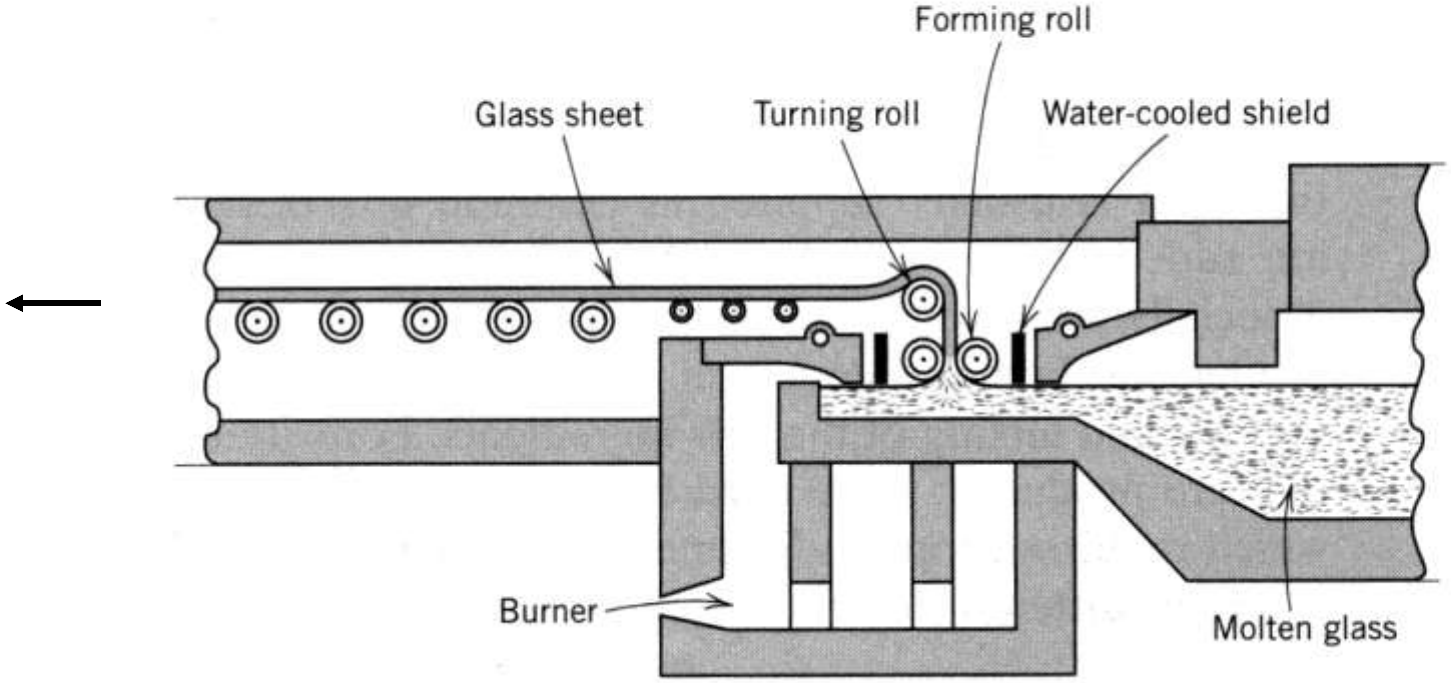


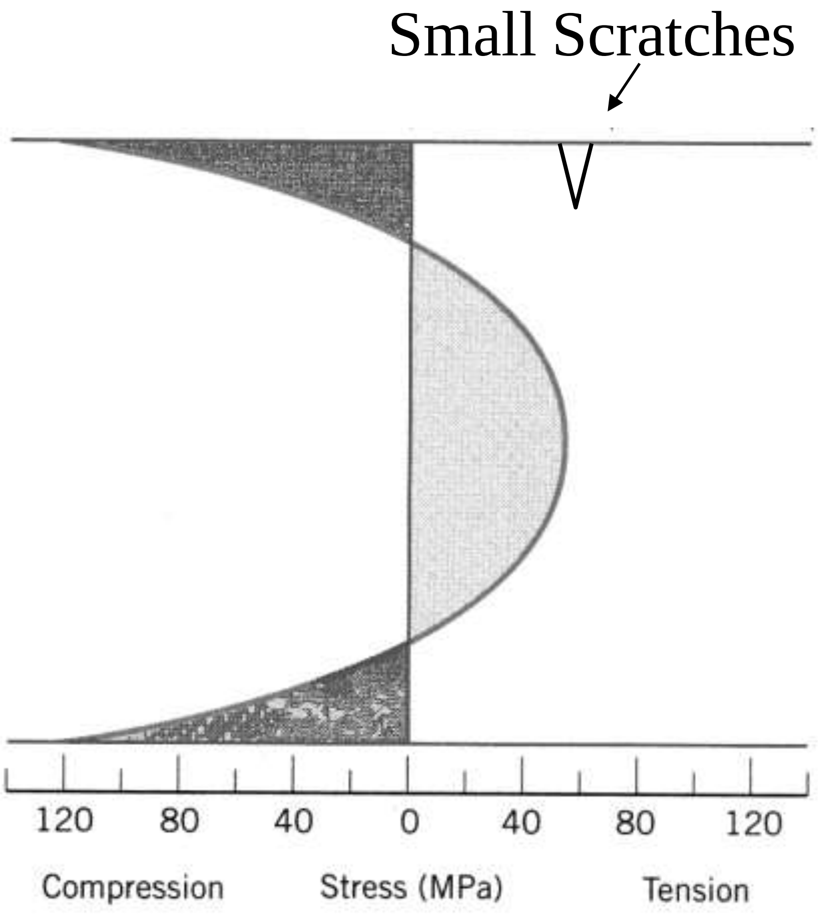
Plate Glass Drawing Processes



Tempered Glass

The strength of glass can be enhanced by inducing compressive residual stresses at the surface.

The surface stays in compression - closing small scratches and cracks.



Hardening Processes

- Tempering:
  - Glass heated above T_g but below the softening point
  - Cooled to room temp in air or oil
  - Surface cools to below T_g before interior
  - when interior cools and contracts it draws the exterior into compression.
- Chemical Hardening:
  - Cations with large ionic radius are diffused into the surface
  - This strains the “lattice” inducing compressive strains and stresses.

Armoured Glass

- Many have tried to gain access with golf clubs and baseball bats but obviously the glass remains intact ! From time to time a local TV station intends to show videos of those trying to get at the cash!!

Crystalline Ceramics

Good electrical insulators and refractories.

- Magnesium Oxide is used as insulation material in heating elements and cables.
- Aluminium Oxide
- Beryllium Oxides
- Boron Carbide
- Tungsten Carbide.
- Used as abrasives and cutting tool tips.

Abrasives

- Natural (garnet, diamond, etc.)
- Synthetic abrasives (silicon carbide, diamond, fused alumina, etc.) are used for grinding, cutting, polishing, lapping, or pressure blasting of materials

Cements

- Used to produce concrete roads, bridges, buildings, dams.

Advanced Ceramics

- Advanced ceramic materials have been developed over the past half century
- Applied as thermal barrier coatings to protect metal structures, wearing surfaces, or as integral components by themselves.
- Engine applications are very common for this class of material which includes silicon nitride (Si_3N_4), silicon carbide (SiC), Zirconia (ZrO_2) and Alumina (Al_2O_3)
- Heat resistance and other desirable properties have lead to the development of methods to toughen the material by reinforcement with fibers and whiskers opening up more applications for ceramics

UTM

Advanced Ceramics

- *Structural:* Wear parts, bioceramics, cutting tools, engine components, armour.
- *Electrical:* Capacitors, insulators, integrated circuit packages, piezoelectrics, magnets and superconductors
- *Coatings:* Engine components, cutting tools, and industrial wear parts
- *Chemical and environmental:* Filters, membranes, catalysts, and catalyst supports

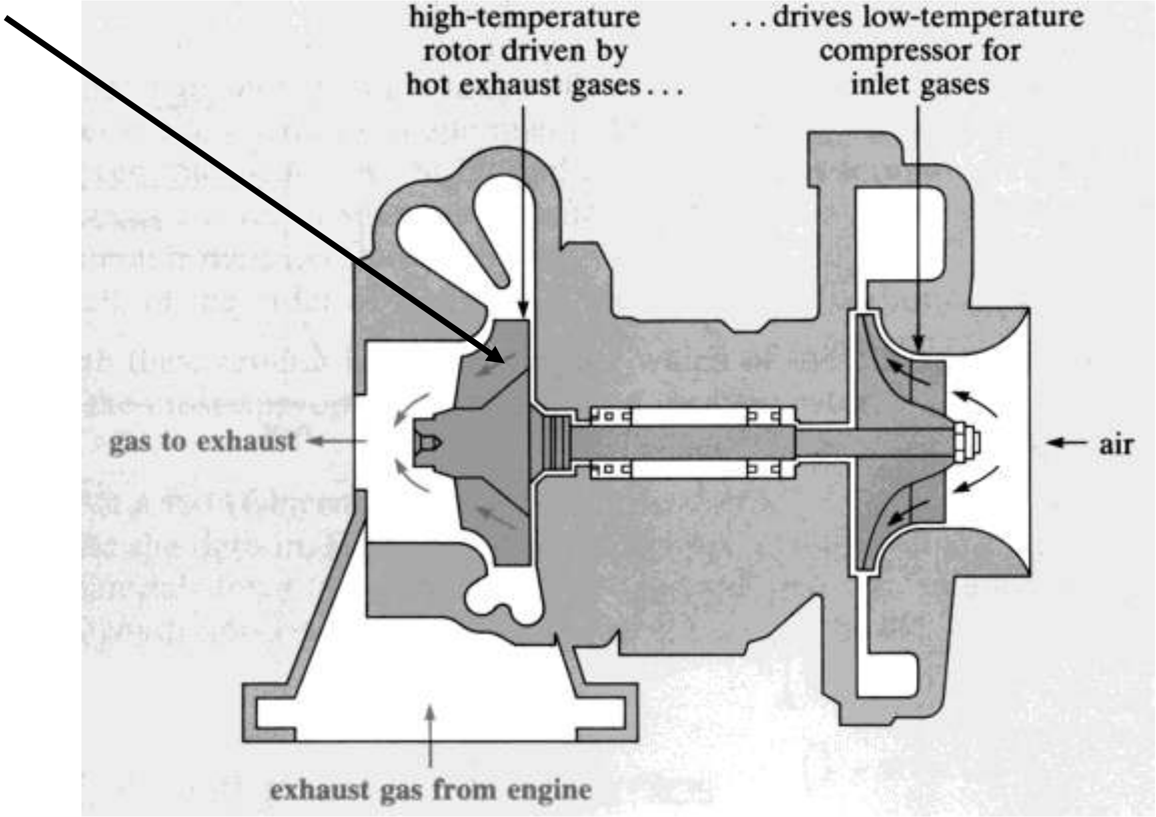
Engine Components

Rotor (Alumina)

Gears (Alumina)

Turbocharger

Ceramic Rotor



Ceramic Brake Discs

Silicon Carbide

General Components made from Silicon Carbide

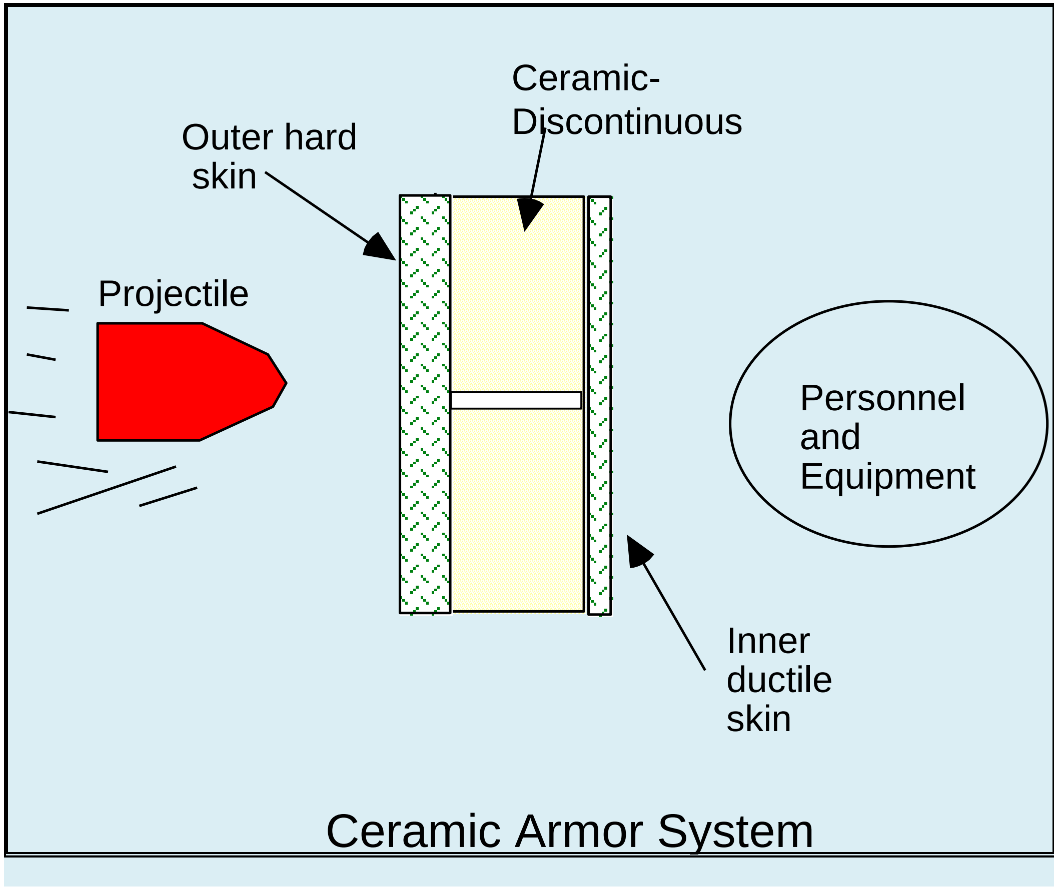
Chosen for its heat and wear resistance

Ceramic Armour

- Ceramic armour systems are used to protect military personnel and equipment.
- Advantage: low density of the material can lead to weight-efficient armour systems.
- Typical ceramic materials used in armour systems include alumina, boron carbide, silicon carbide, and titanium diboride.
- The ceramic material is discontinuous and is sandwiched between a more ductile outer and inner skin.
- The outer skin must be hard enough to shatter the projectile.

- Most of the impact energy is absorbed by the fracturing of the ceramic and any remaining kinetic energy is absorbed by the inner skin, that also serves to contain the fragments of the ceramic and the projectile preventing severe impact with the personnel/equipment being protected.
- Alumina ceramic/Kevlar composite system in sheets about 20mm thick are used to protect key areas of Hercules aircraft (cockpit crew/instruments and loadmaster station).
- This lightweight solution provided an efficient and removable/replaceable armour system. Similar systems used on Armoured Personnel Carrier’s.

Ceramic - Composite Armor



Silicon Carbide

Body armour and other components chosen for their ballistic properties.