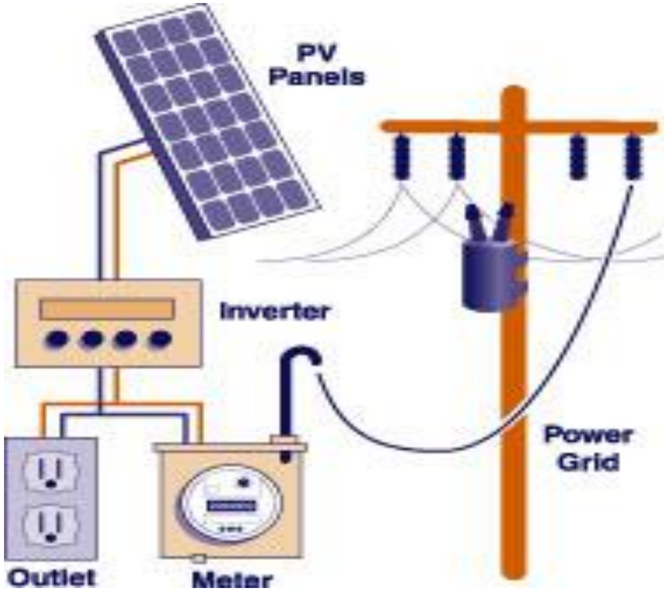
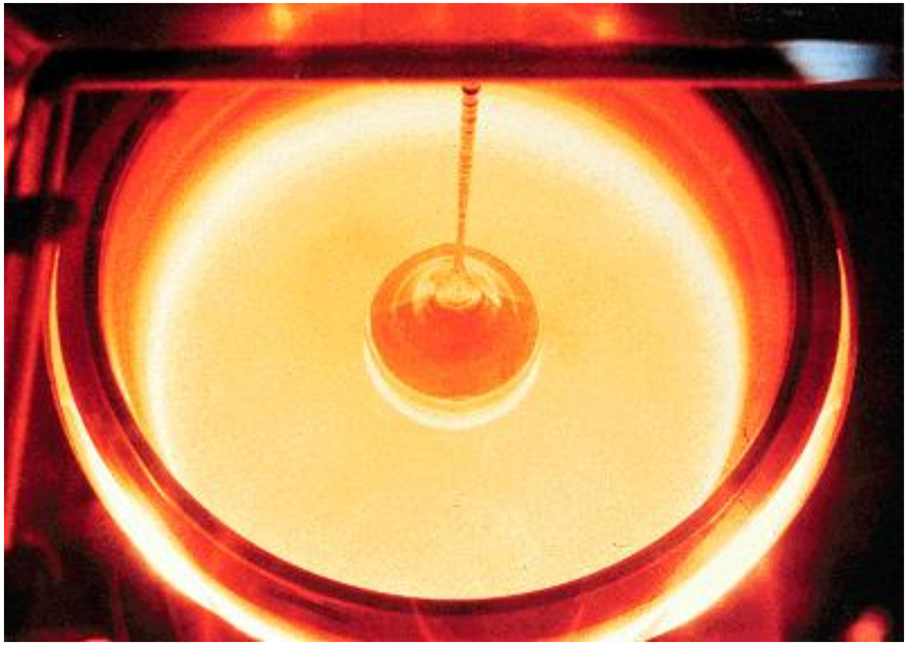
L8 part 2

# Photovoltaic Materials and characteristics





# ENEE5307 Renewable Energy & PV Energy Systems

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BZU-2021

# Introduction

- A material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current is said to be ***photovoltaic*.**
- A photon with short enough wavelength and high enough energy can cause an electron in a photovoltaic material to break free of the atom that holds it.
- If a nearby electric field is provided, those electrons can be swept toward a metallic contact where they can emerge as an electric current.
- The driving force to power photo-voltaics comes from the sun, and it is interesting to note that the surface of the earth receives something like 6000 times as much solar energy as our total energy demand.

# History (1839)

- **In 1839 when a 19-year-old French physicist, Edmund Becquerel, was able to cause a voltage to appear when he illuminated a metal electrode in a weak electrolyte solution .**
- **In 1876,** ***Adams*** and ***Day*** were the first to study the photovoltaic effect in solids .
- They were able to build cells made of selenium that were 1% to 2% efficient.

# History (early 1900s)

- **In 1904, As part of his development of quantum theory, Albert Einstein published a theoretical explanation of the photovoltaic effect, which led to a Nobel Prize in 1923.**
- About the same time, in what would turn out to be a cornerstone of modern electronics in general, and photovoltaics in particular, a Polish scientist by the name **of Czochralski began** to develop a method to grow perfect crystals of silicon.
- By the 1940s and 1950s, the Czochralski process began to be used to make the first generation of single-crystal silicon photo-voltaics, and that technique continues to dominate the photovoltaic (PV) industry today.

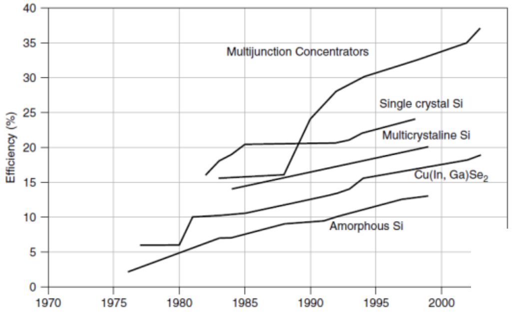
# History (1950s)

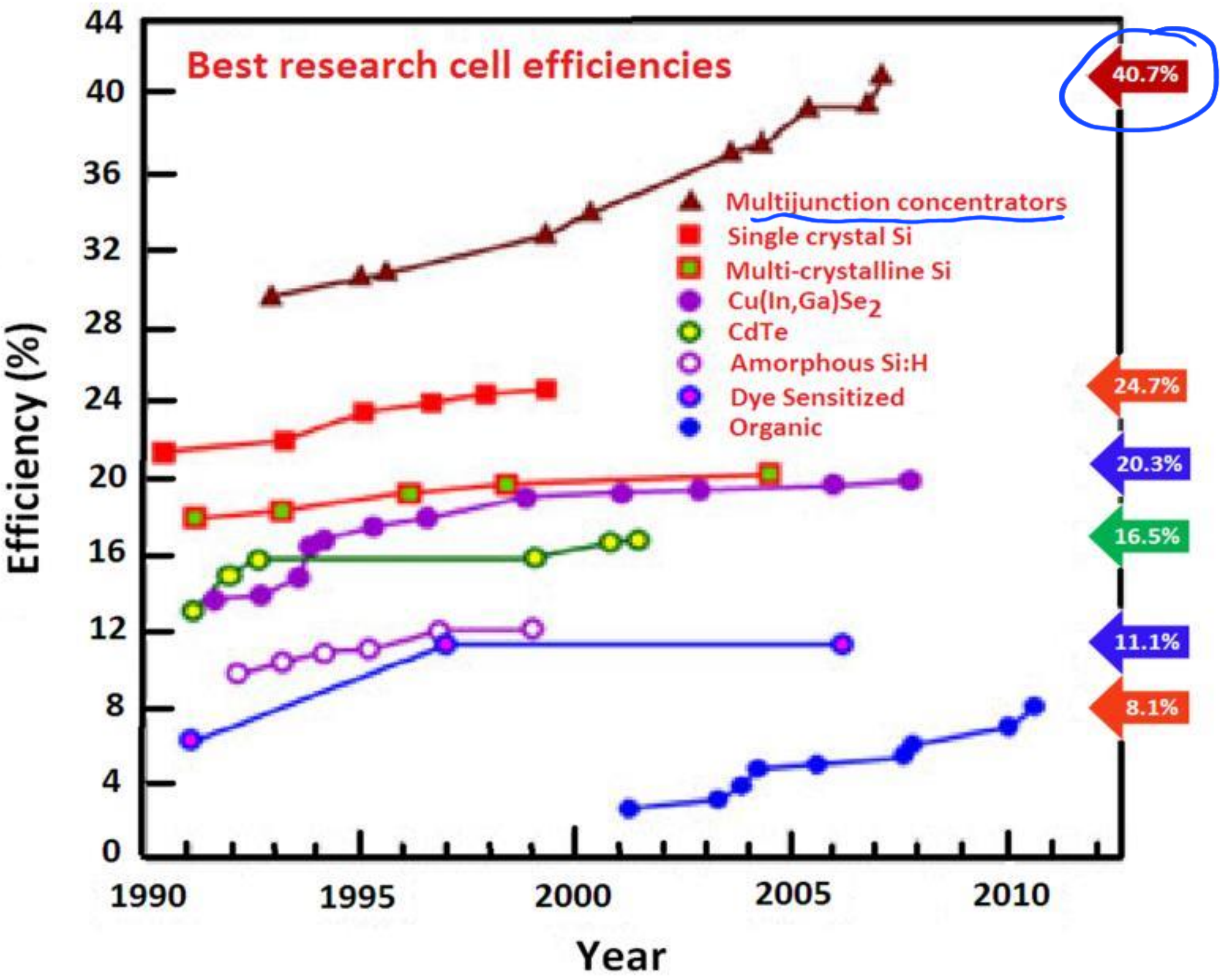
- In the 1950s there were several attempts to commercialize PVs, but their cost was prohibitive.
- The real emergence of PVs as a practical energy source came in **1958** when they were first used in **space** for the Vanguard I satellite.
- For space vehicles, cost is much less important than weight and reliability, and solar cells have ever since played an important role in providing onboard power for satellites and other space craft.
- Spurred on by the emerging energy crises of the 1970s, the development work supported by the space program began to pay off back on the ground

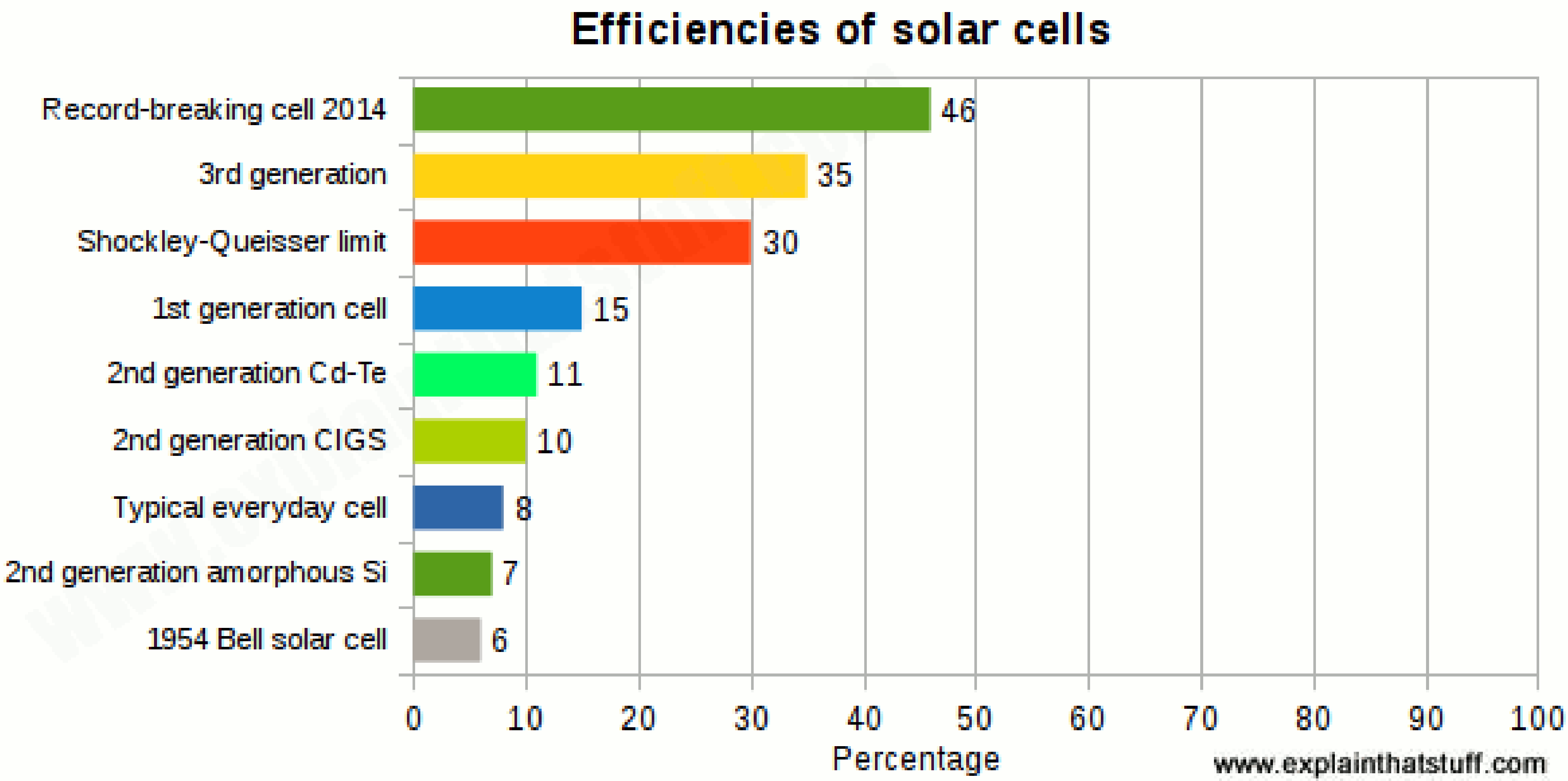
# History (1980s)

- By the late 1980s, higher efficiencies and lower costs brought PVs closer to reality, and they began to find application in many off-grid terrestrial applications such as pocket calculators, highway lights, signs and emergency call boxes, rural water pumping, and small home systems.
- The cost of photovoltaic power did drop dramatically in the 1990s, and it is becoming competitive with other power sources

# Efficiency of PV cells

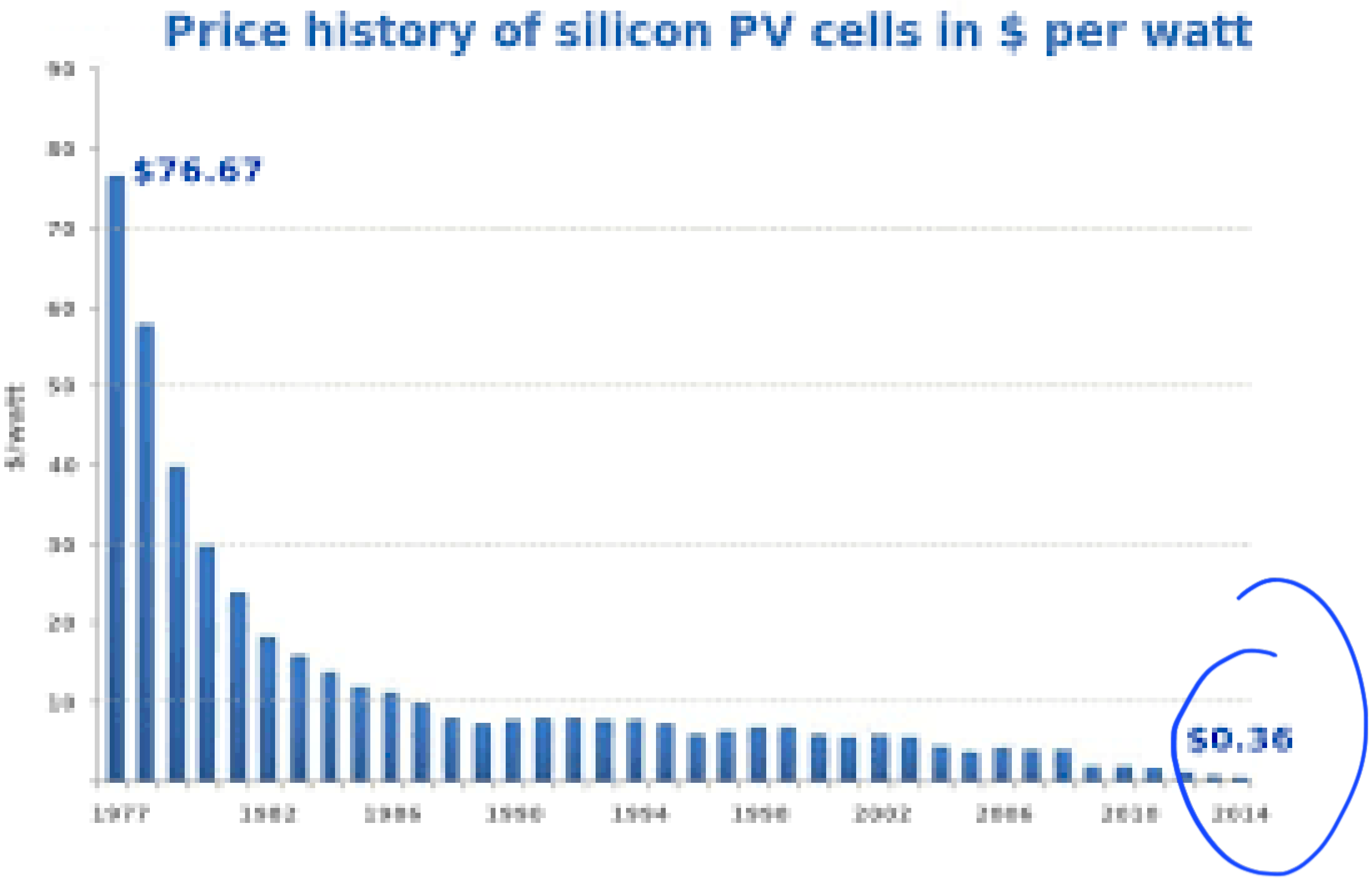






Efficiencies of solar cells

www.explainthatstuff.com

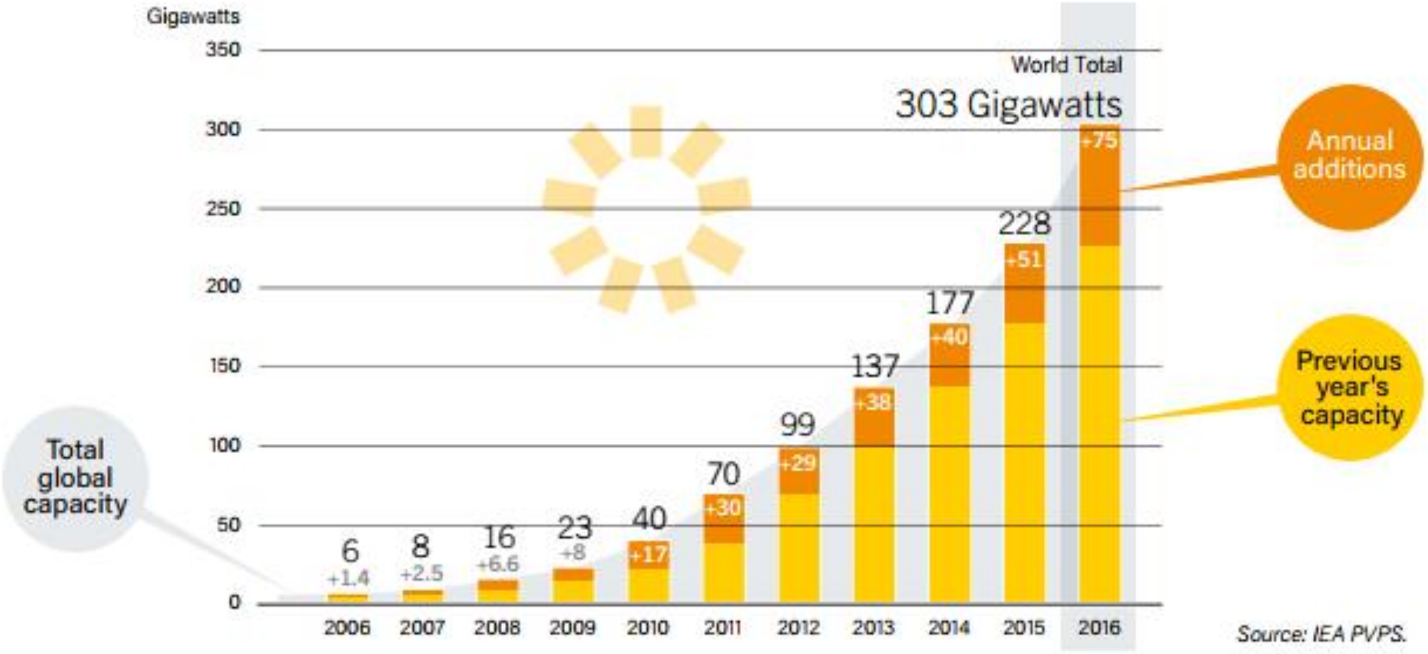


Price history of silicon PV cells in $ per watt

Source: Bloomberg, New Energy Finance & pv.energytrend.com

# Global PV Capacity

**Solar PV Global Capacity and Annual Additions, 2006-2016**



*Source: IEA PVPS.*

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During 2016, at least **75 GW** of solar PV capacity was added worldwide – equivalent to the installation of more than **31,000 SOLAR PANELS EVERY HOUR.**

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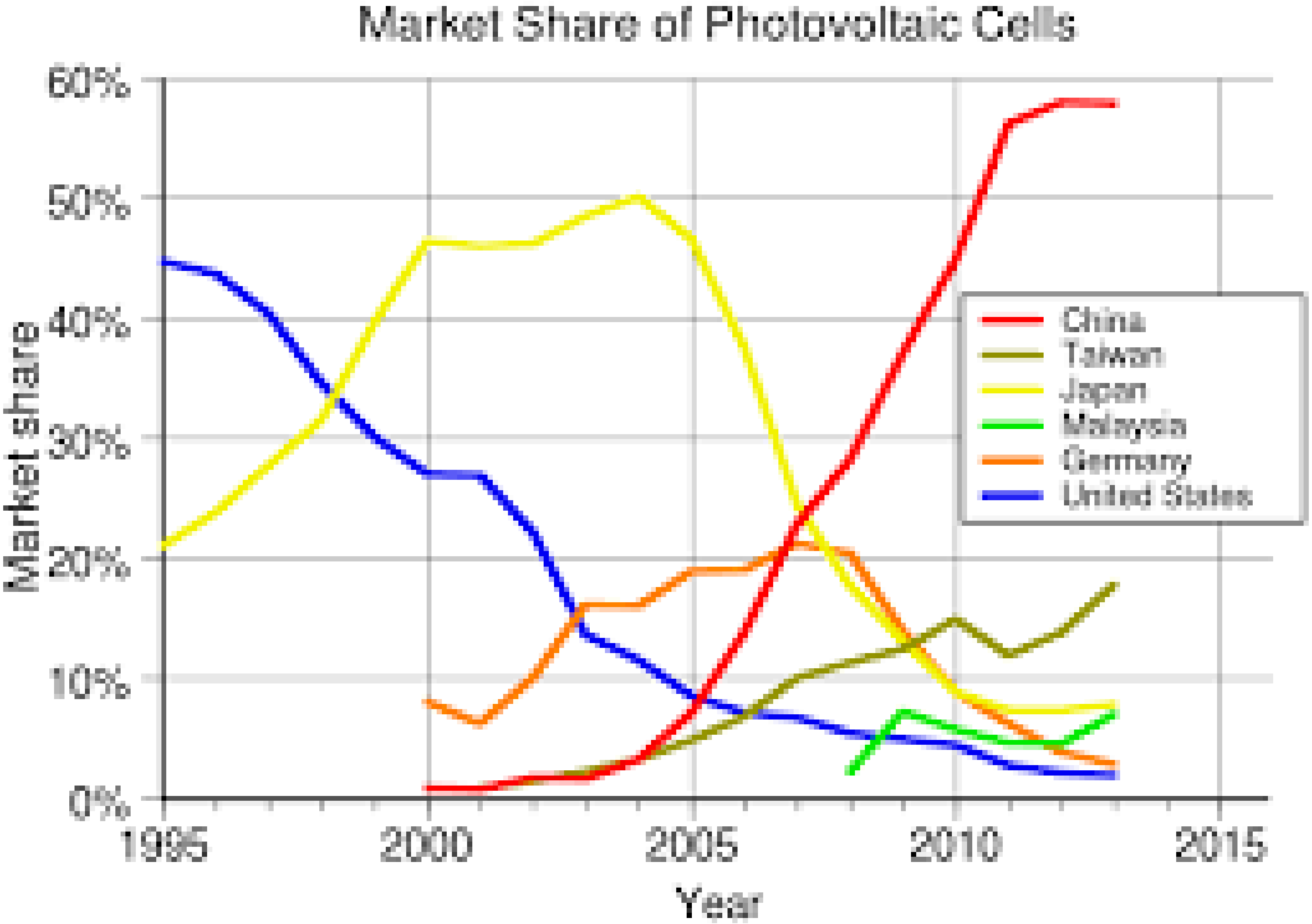
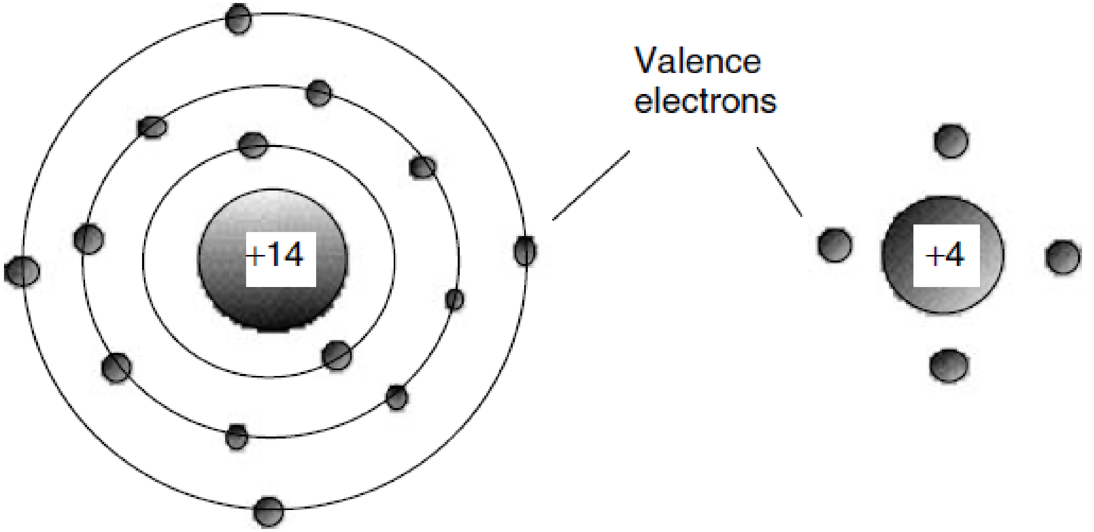
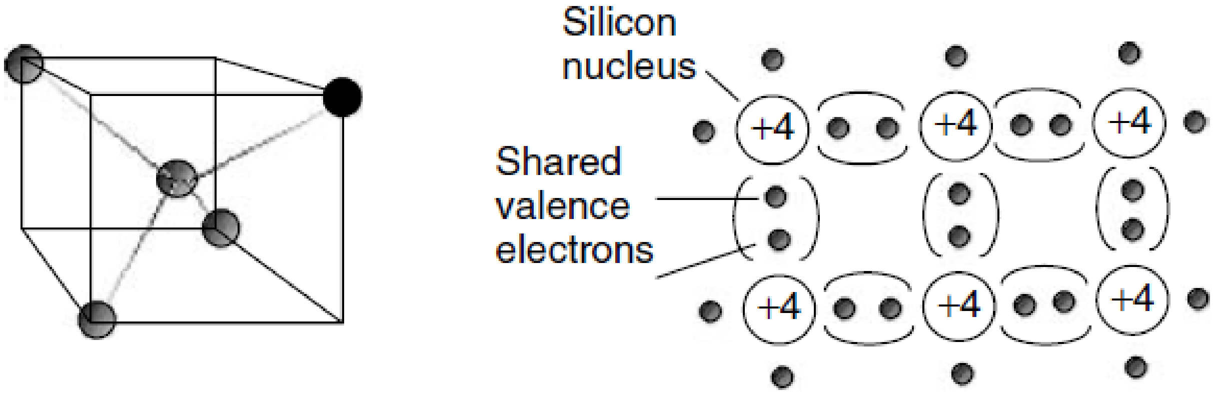

Market Share of Photovoltaic Cells
Market share
60%
50%
40%
30%
20%
10%
0%
1995
2000
2005
2010
2015
Year
China
Taiwan
Japan
Malaysia
Germany
United States

- **Silicon Atom and crystal are shown**



(a) Actual (b) Simplified

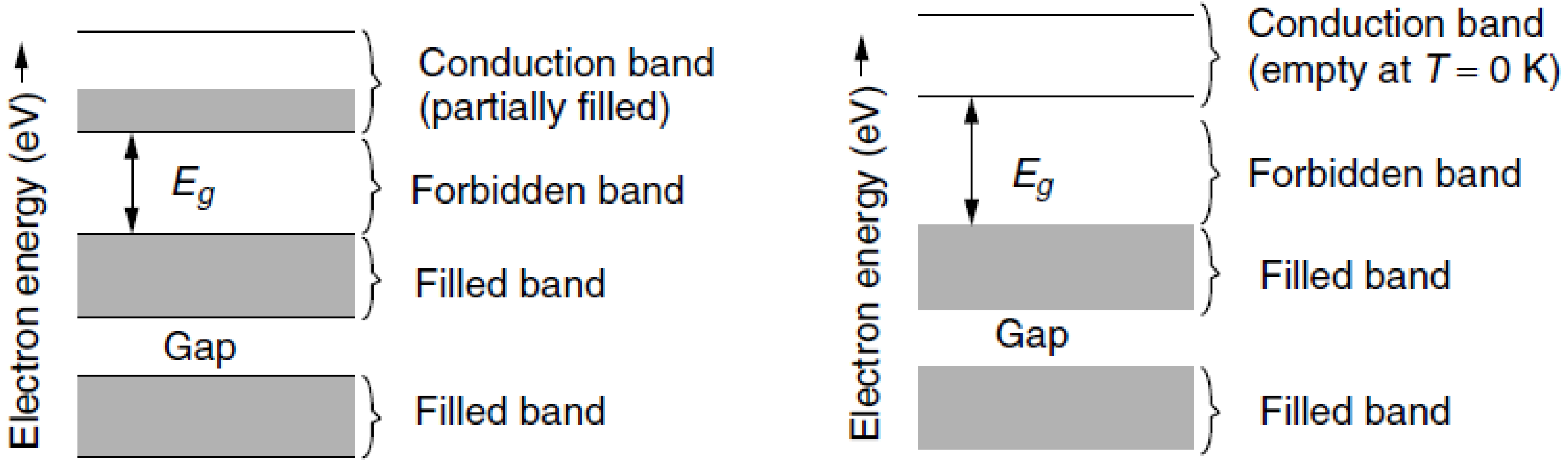


(a) Tetrahedral (b) Two-dimensional version

# Band Gap Energy

- The energy that an electron must acquire to jump across the forbidden band to the conduction band is called the band-gap energy, designated *Eg*.
- **The units for band-gap energy are usually electron-volts (eV), where one electron-volt is the energy that an electron acquires when its voltage is increased by 1 V** (1 eV = 1.6 × 10^−19 J).

# Energy Bands

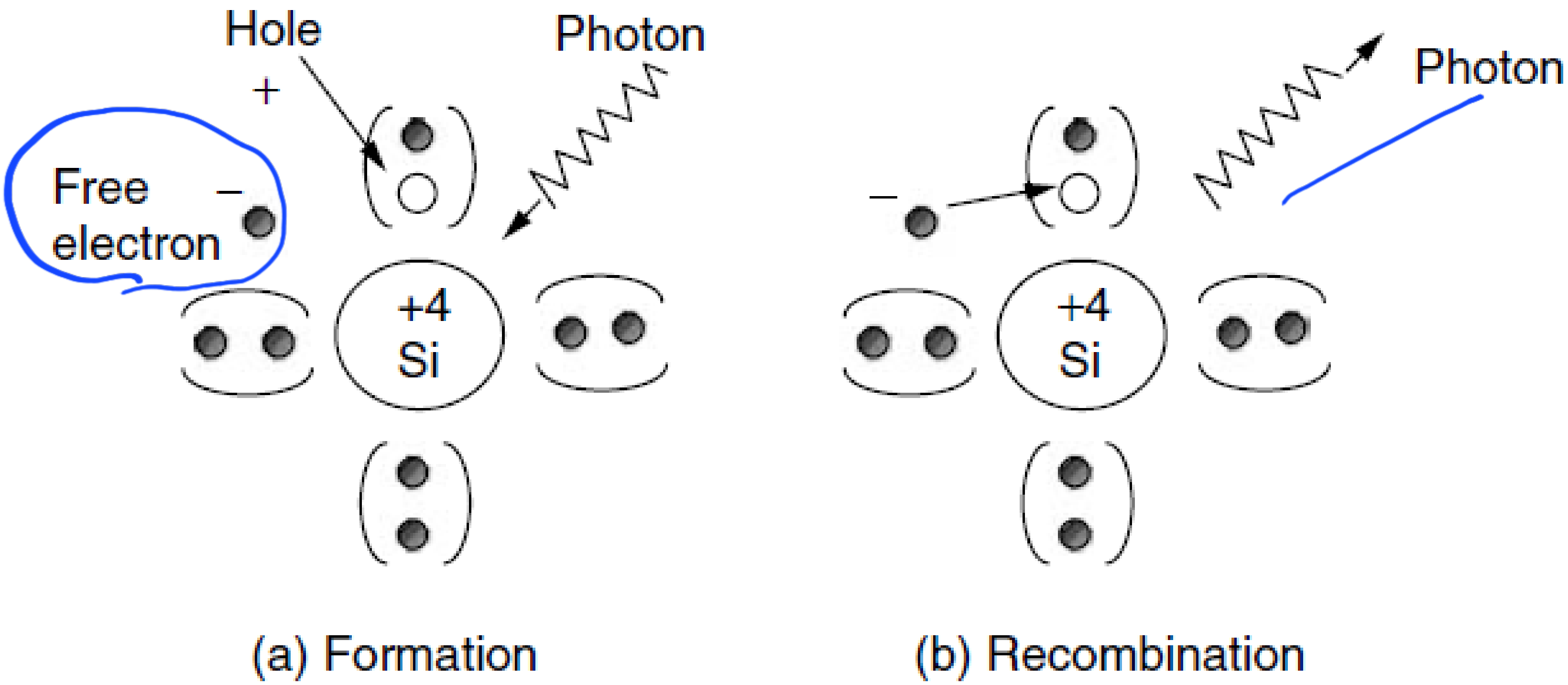


(a) Metals (b) Semiconductors

- Energy bands for (a) metals and (b) semiconductors.
- Metals have partially filled conduction bands, which allows them to carry electric current easily.
- Semiconductors at absolute zero temperature have no electrons in the conduction band, which makes them insulators.

eV – electron volt is a unit of energy equal to approximately $1.6\times10^{-19}$ joules

- **The band-gap *Eg* for silicon is 1.12 eV, which means an electron needs to acquire that much energy to free itself from the electrostatic force that ties it to its own nucleus—that is, to jump into the conduction band.**
- **Where might that energy come from?**
- **We already know that a small number of electrons get that energy thermally.**
- **For photovoltaics, the energy source is photons of electromagnetic energy from the sun.**
- **When a photon with more than 1.12 eV of energy is absorbed by a solar cell, a single electron may jump to the conduction band.**
- **When it does so, it leaves behind a nucleus with a +4 charge that now has only three electrons attached to it.**
- **That is, there is a net positive charge, called a *hole*, associated with that nucleus**



(a) Formation (b) Recombination

A photon with sufficient energy can create a hole–electron pair as in (a).
The electron can recombine with the hole, releasing a photon of energy (b).

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# Photon Energy

- Thus, photons with enough energy create hole–electron pairs in a semiconductor.
- Photons can be characterized by their **wavelengths** or their **frequency** as well as by their **energy**; the three are related by the following:
- $c = \lambda\nu \rightarrow \nu = \frac{c}{\lambda}$
- where *c* is the speed of light (3 × 10^8 m/s),
- *ν* - is the frequency (hertz),
- *λ* - is the wavelength (m), and
- $\boxed{E = h\nu = hc/\lambda}$
- Where *E* is the energy of a photon (J) and *h* is Planck's constant (6.626 × 10^−34 J-s).

$E = hc/\lambda \rightarrow E \propto \lambda$

- **Example: photon to create hole –electron pair in Silicon**

What is the maximum wavelength can a photon have to create hole-electron pairs in Silicon?

What minimum frequency is that?

✓ Si has a band-gap of 1.12 eV (1 eV=1.6x10^-19 J) ✓

micron

***Solution.*** From (8.2) the wavelength must be less than

$$\underline{\lambda} \le \frac{hc}{E} = \frac{6.626 \times 10^{-34}\ \mathrm{J \cdot s} \times 3 \times 10^{8}\ \mathrm{m/s}}{1.12\ \mathrm{eV} \times 1.6 \times 10^{-19}\mathrm{J/eV}} = \underline{1.11 \times 10^{-6}\ \mathrm{m}} = 1.11\ \boxed{\mu\mathrm{m}}$$

and from (8.1) the frequency must be at least

$$\nu \ge \frac{c}{\lambda} = \frac{3 \times 10^{8}\ \mathrm{m/s}}{1.11 \times 10^{-6}\ \mathrm{m}} = \underline{2.7 \times 10^{14}\ \mathrm{Hz}}$$

# Summary

- **For a silicon photovoltaic cell, photons with wavelength greater than 1.11 μm have energy less than the 1.12 eV band-gap energy needed to excite an electron.**
- On the other hand, photons with wavelengths shorter than 1.11 μm have more than enough energy to excite an electron.
- Since one photon can excite *only* one electron, any extra energy above the 1.12 eV needed is also dissipated as waste heat in the cell.
- The band gaps for other photovoltaic materials—gallium arsenide (GaAs), cadmium telluride (CdTe), and indium phosphide (InP), in addition to silicon—are shown later.
- **These two phenomena relating to photons with energies above and below the actual band gap establish a maximum theoretical efficiency for a solar cell. To explore this constraint, we need to introduce the solar spectrum.**

# Solar Spectrum (AM=1.5)

- Photons with wavelengths above 1.11 μm don't have the 1.12 eV needed to excite an electron, and this energy is lost.
- Photons with shorter wavelengths have more than enough energy, but any energy above 1.12 eV is wasted as well.

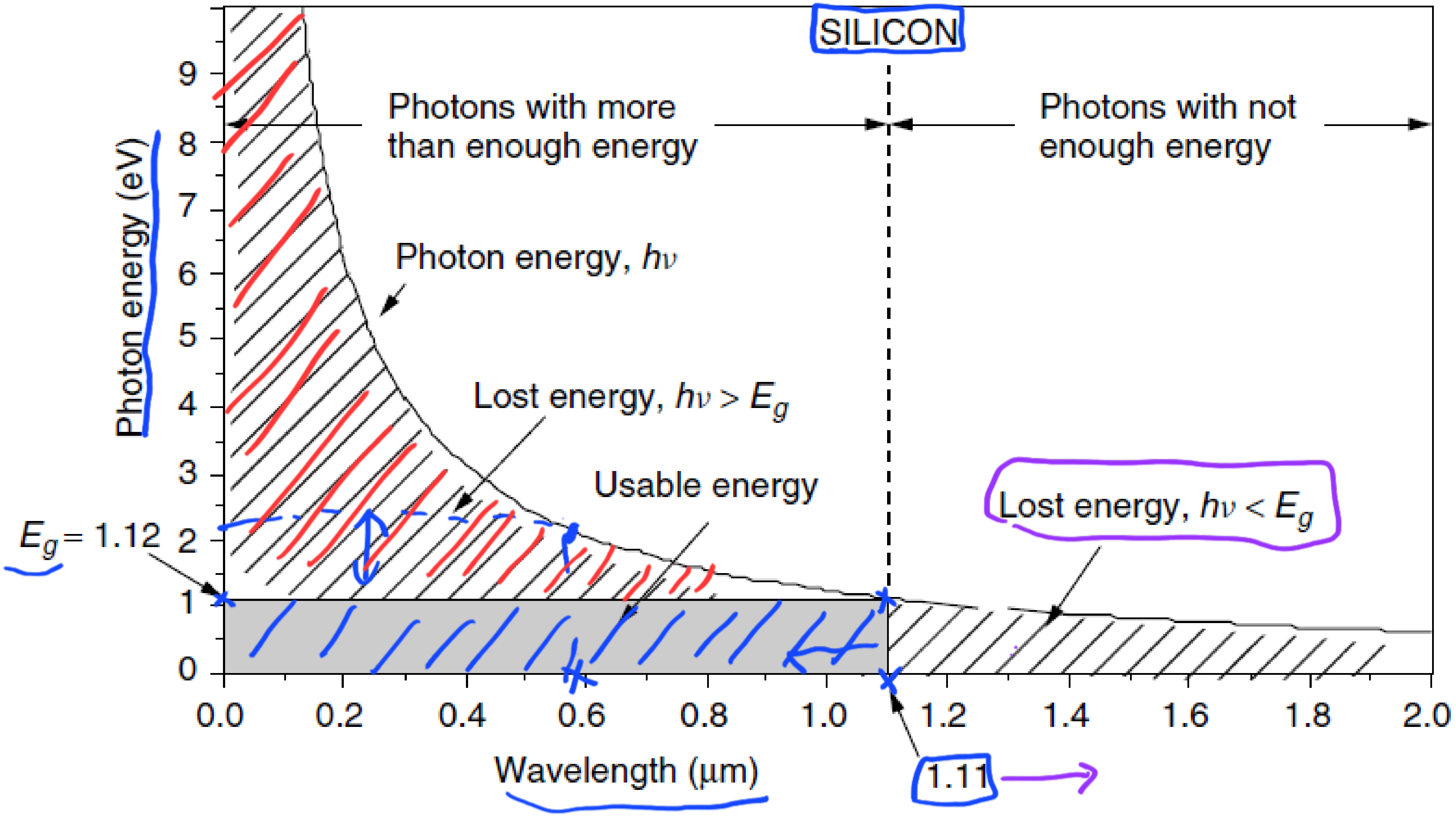
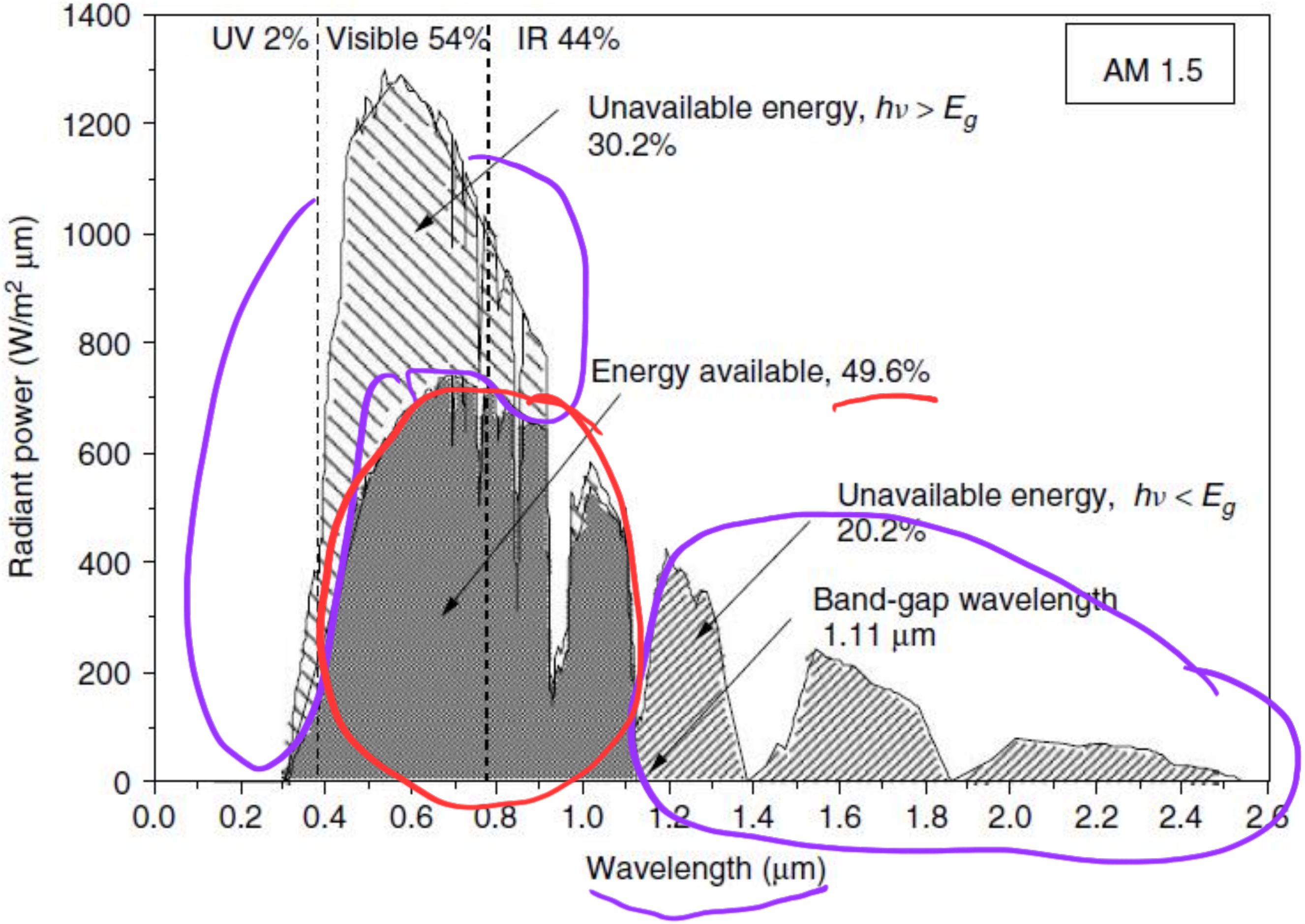


**TABLE 8.2 Band Gap and Cut-off Wavelength Above Which Electron Excitation Doesn't Occur**

| Quantity | Si | GaAs | CdTe | InP |
|---|---|---|---|---|
| Band gap (eV) | 1.12 | 1.42 | 1.5 | 1.35 |
| Cut-off wavelength (μm) | 1.11 | 0.87 | 0.83 | 0.92 |



- Photons with wavelengths longer than 1.11 μm don't have enough energy to excite electrons (20.2% of the incoming solar energy);
- Those with shorter wavelengths can't use all of their energy, which accounts for another 30.2% unavailable to a silicon photovoltaic cell.

# Photovoltaic Efficiency

- The remaining 49.6% represents the maximum possible fraction of the sun’s energy that could be collected with a silicon solar cell.
- 1) **That is, the constraints imposed by silicon’s band gap limit the efficiency of silicon to just under 50%.**
- There are other constraints to PV efficiency, mainly black-body radiation losses and recombination. 2)
- Cells in the sun get hot, which mean their surface radiate energy proportional to the fourth power of their temperature
- This accounts for 7% losses
- 3) Hole saturation effects in silicon can result in another 10% losses …(see main reference book)

# Photovoltaic Efficiency

- Notice that the efficiencies of Si PV cells are well below the 49.6% due to other factors such as:

- ✓ 1. Recombination of holes and electrons before they can contribute to current flow.
- ✓ 2. Photons that are not absorbed in the cell either because they are reflected off the face of the cell, or because they pass right through the cell, or because they are blocked by the metal conductors that collect current from the top of the cell.
- ✓ 3. Internal resistance within the cell, which dissipates power.

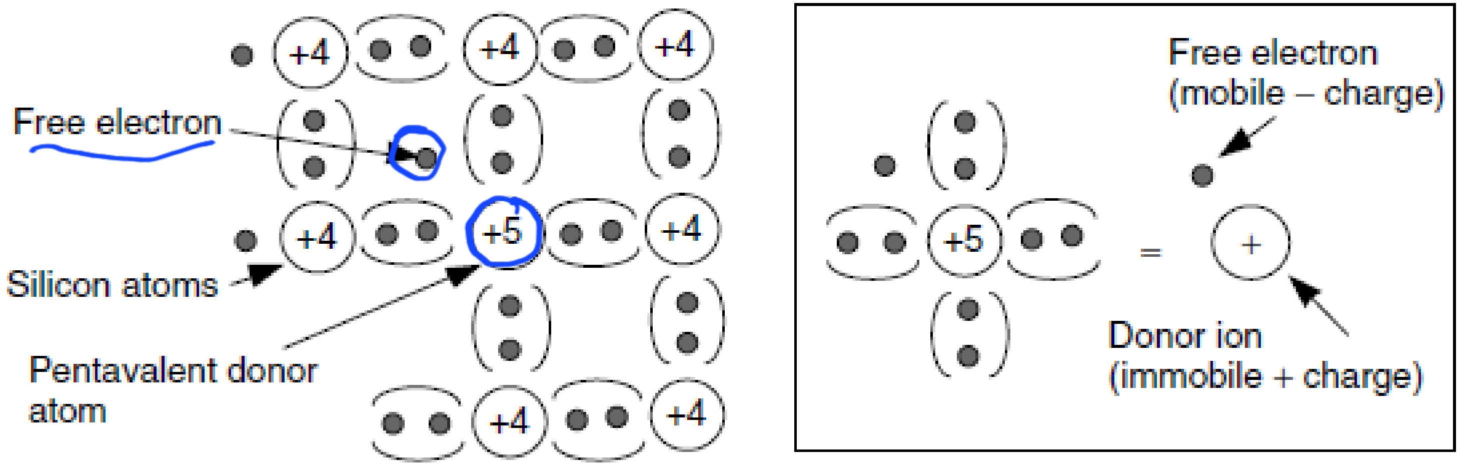
# The p-n Junction (reminder)

- As long as a solar cell is exposed to photons with energies above the bandgap energy, hole–electron pairs will be created.
- The problem is, of course, that those electrons can fall right back into a hole, causing both charge carriers to disappear.
- **To avoid that recombination, electrons in the conduction band must continuously be swept away from holes.**
- In PVs this is accomplished by creating a built-in electric field within the semiconductor itself that pushes electrons in one direction and holes in the other.

# Electric Field

- To create the electric field, two regions are established within the crystal.
- On one side of the dividing line separating the regions, pure (intrinsic) silicon is purposely contaminated with very small amounts of a trivalent element from column III of the periodic chart;
- On the other side, pentavalent atoms from column V are added.

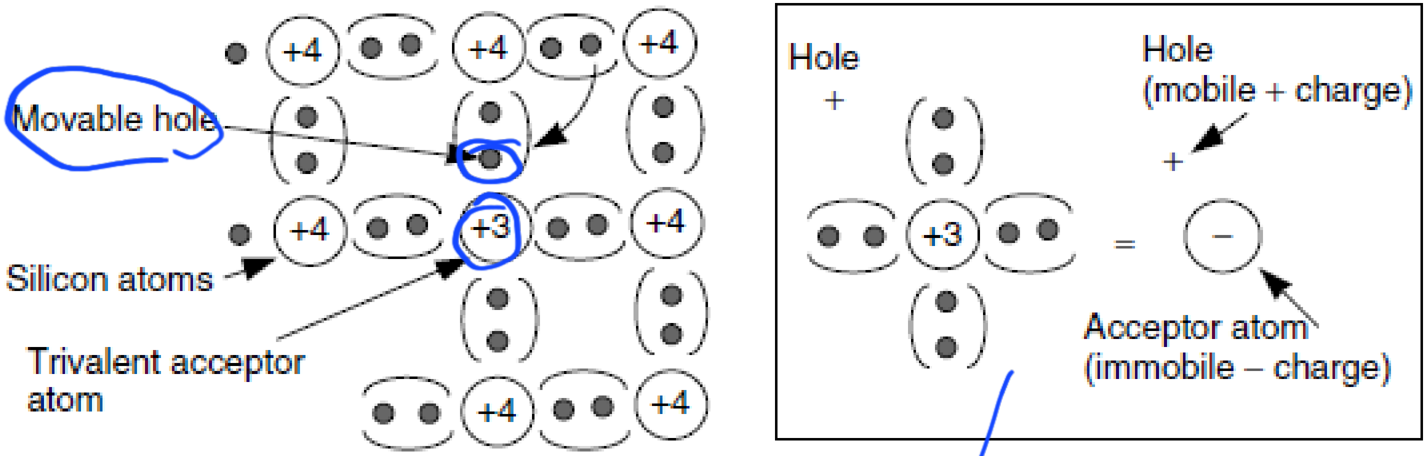
n - type



(a) The donor atom in Si crystal

(b) Representation of the donor atom

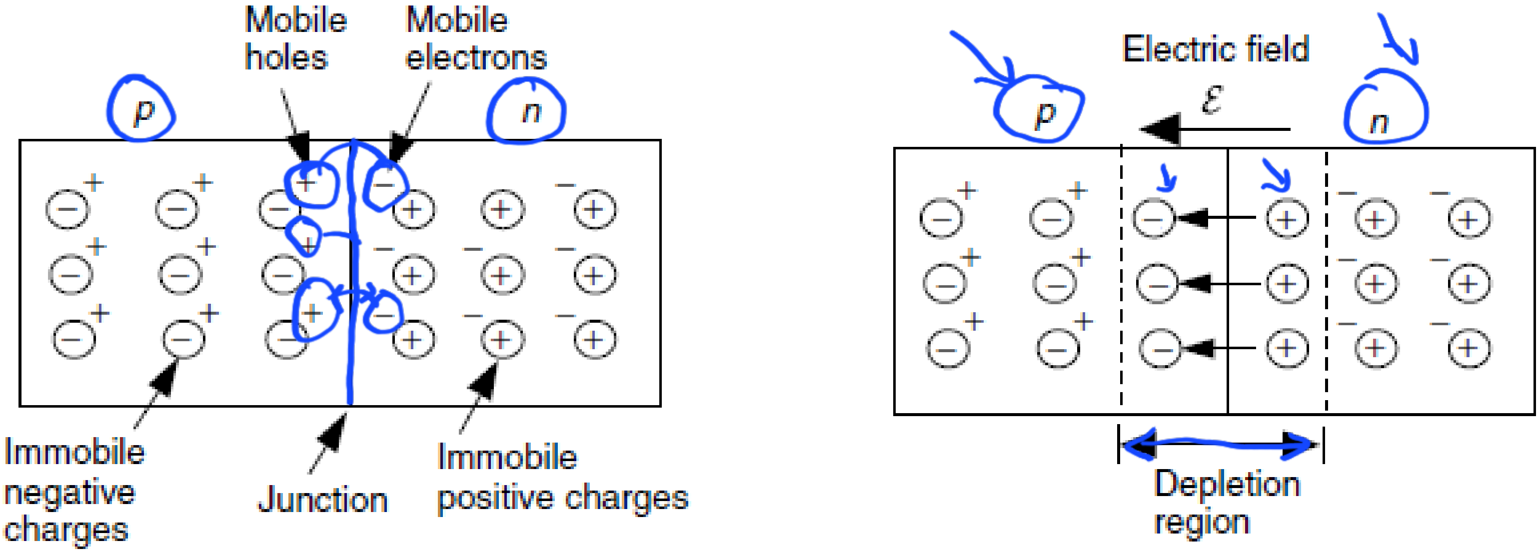
An *n*-type material.
(a) The pentavalent donor.
(b) The representation of the donor as a mobile negative charge with a fixed, immobile positive charge



(a) An acceptor atom in Si crystal

(b) Representation of the acceptor atom

In a *p*-type material, trivalent acceptors contribute movable, positively charged holes leaving rigid, immobile negative charges in the crystal lattice.



(a) When first brought together

(b) In steady-state

(a) When a *p*–*n* junction is first formed, there are mobile holes in the *p*-side and mobile electrons in the *n*-side.

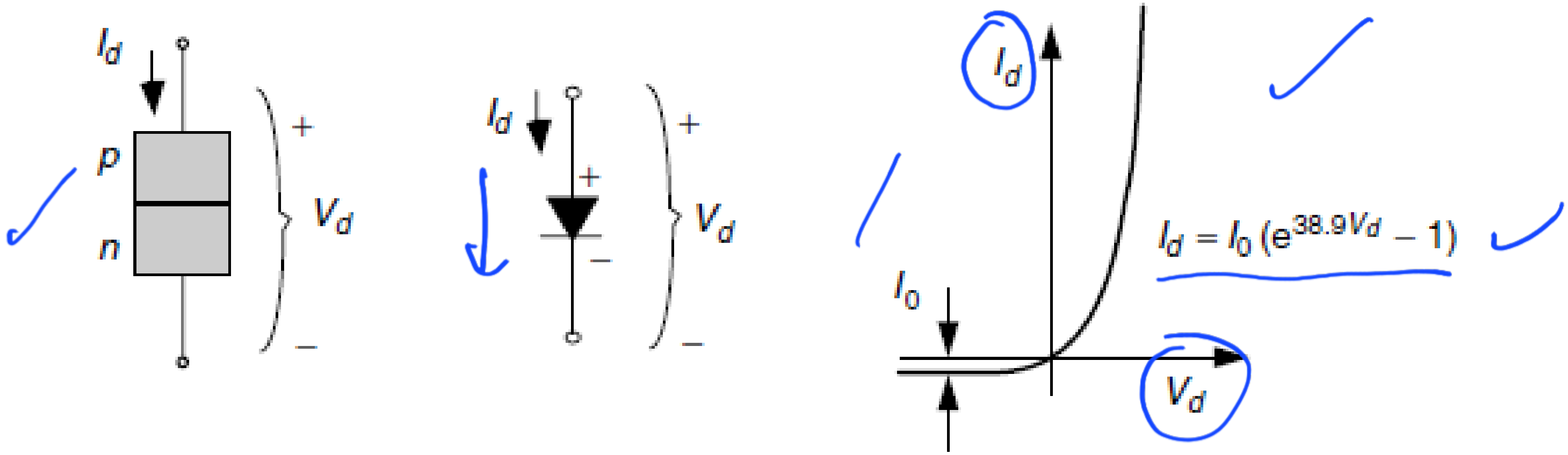
(b) As they migrate across the junction*, an electric field builds up that opposes, and quickly stops, diffusion.

- As the diffusion process continues, the electric field countering that movement increases until eventually (actually, almost instantaneously) all further movement of charged carriers across the junction stops.
- This is a pn junction (Diode)

# The *p–n* Junction Diode

- Anyone familiar with semiconductors will immediately recognize that what has been described thus far is just a common, conventional *p–n* junction diode.
- :

$$\boxed{I_d = I_0(e^{qV_d/kT} - 1)}$$



(a) *p–n* junction diode

(b) Symbol for real diode

(c) Diode characteristic curve

- where Id is the diode current in the direction of the arrow (A), Vd is the voltage across the diode terminals from the p-side to the n-side (V), I0 is the reverse saturation current (A), q is the electron charge (1.602 × 10^−19C), k is Boltzmann’s constant (1.381 × 10^−23 J/K), and T is the junction temperature (K).

$$\frac{qV_d}{kT} = \frac{1.602 \times 10^{-19}}{1.381 \times 10^{-23}} \cdot \frac{V_d}{T(\mathrm{K})} = \boxed{11,600\frac{V_d}{T(\mathrm{K})}}$$

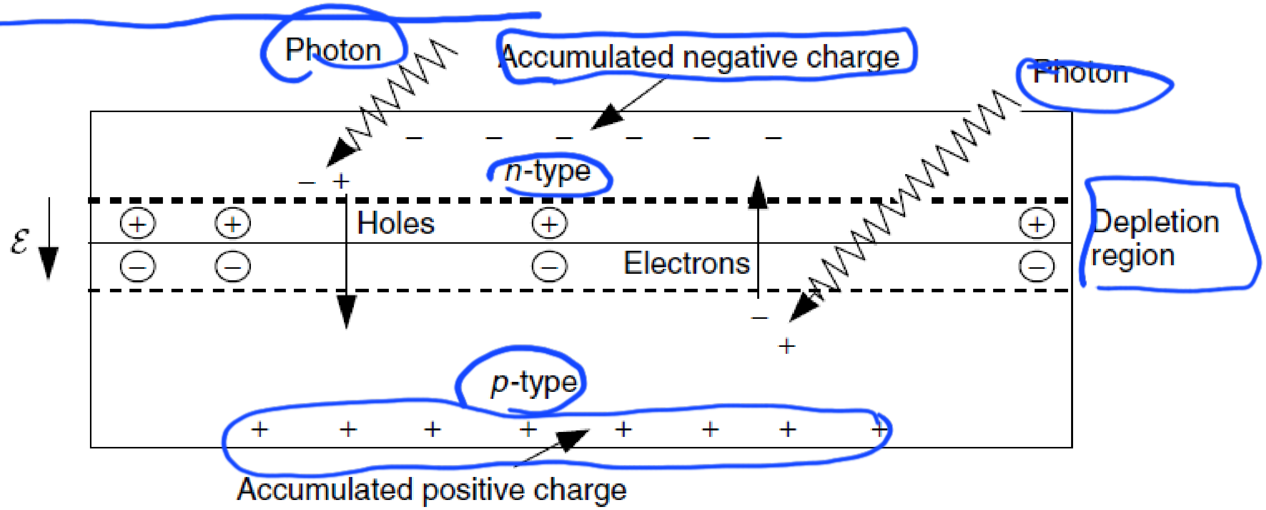
- A junction temperature of 25◦C is often used as a standard, which results in the following diode equation:

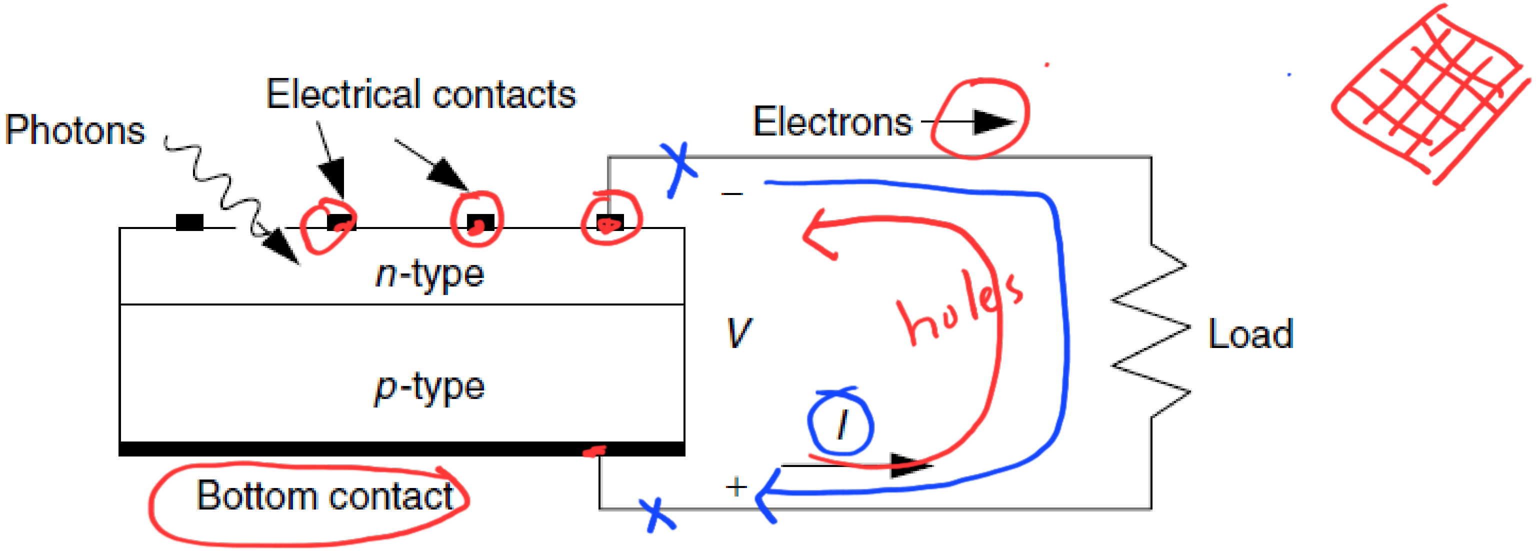
$$\frac{1}{38.9} = \underset{\uparrow \atop V_T}{25.7\,\mathrm{mV}}$$

$$I_d = I_0\left(e^{\boxed{38.9}V_d} - 1\right) \qquad \text{(at } 25^\circ\text{C)}$$

# A GENERIC PHOTOVOLTAIC CELL

- Let us consider what happens in the vicinity of a p–n junction when it is exposed to sunlight.
- As photons are absorbed, hole-electron pairs may be formed.
- When photons create hole–electron pairs near the junction, the electric field in the depletion region sweeps holes into the p-side and sweeps electrons into the n-side of the cell.





- If electrical contacts are attached to the top and bottom of the cell, electrons will flow out of the n-side into the connecting wire, through the load and back to the p-side as shown above.
- Since wire cannot conduct holes, it is only the electrons that actually move around the circuit. When they reach the p-side, they recombine with holes completing the circuit.
- Conventional current I is in the opposite direction.

## Photovoltaic Effect

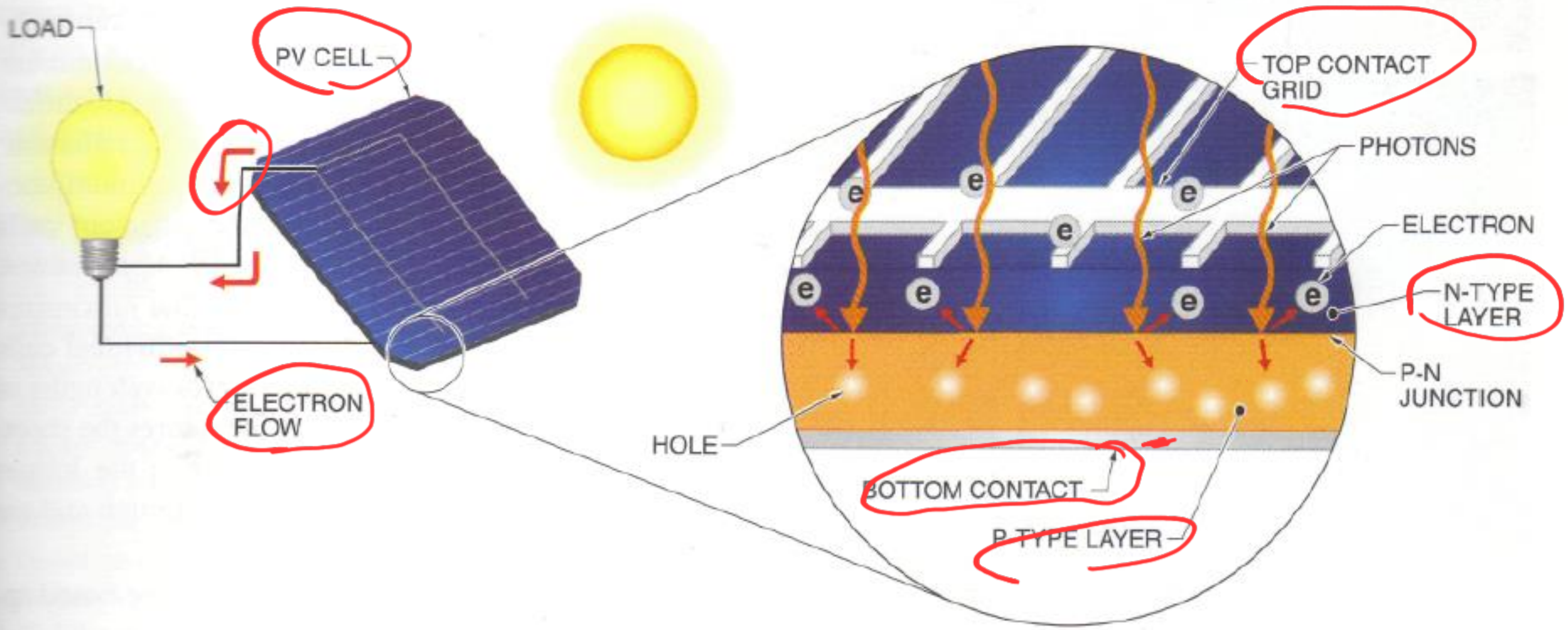
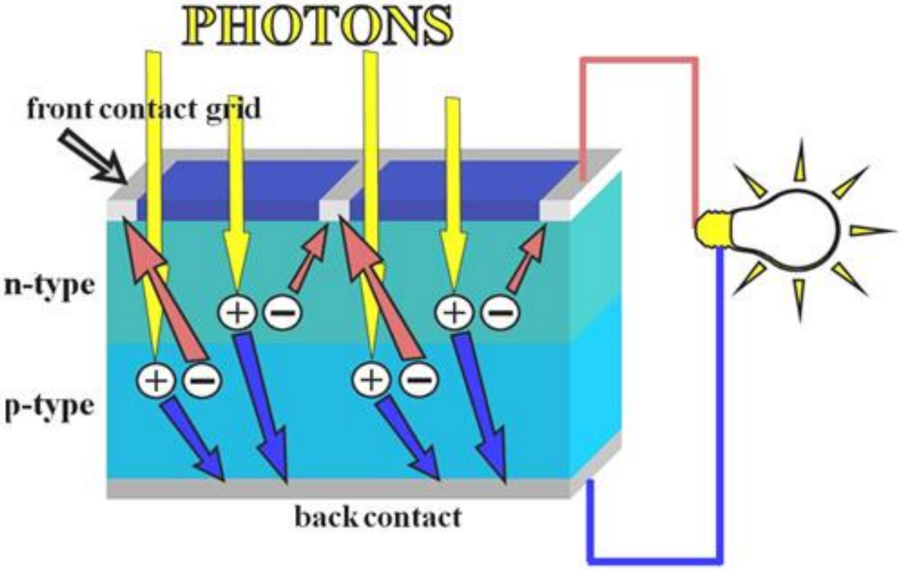


**Figure 5-3.** *The photovoltaic effect produces free electrons that must travel through conductors in order to recombine with electron voids, or "holes."*



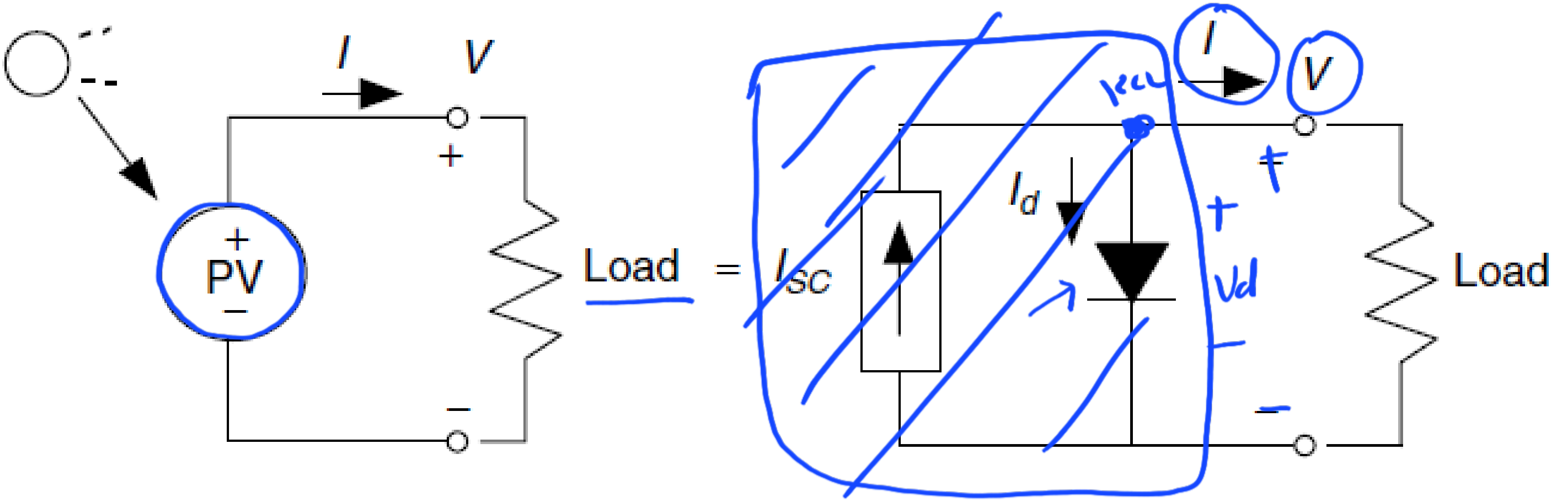
# Can you turn the PV cell off?

- The process of electrons and holes being separated by photon energy, and doing work before recombining , occurs continuously while PV cells are exposed to light
- **There is no way of turning off a PV device other than completely covering the top surface with no light reaching the cells**

- See animations:
- https://www.youtube.com/watch?v=PROhNDen3nk

- https://www.youtube.com/watch?v=UJ8XW9AgUrw

# The Simplest Equivalent Circuit for a Photovoltaic Cell



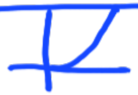
A simple equivalent circuit for a photovoltaic cell consists of a current source driven by sunlight in parallel with a real diode.

$I_{sc}$

$I_d$ ?

$I$

$\rightarrow$ KCL $\rightarrow$

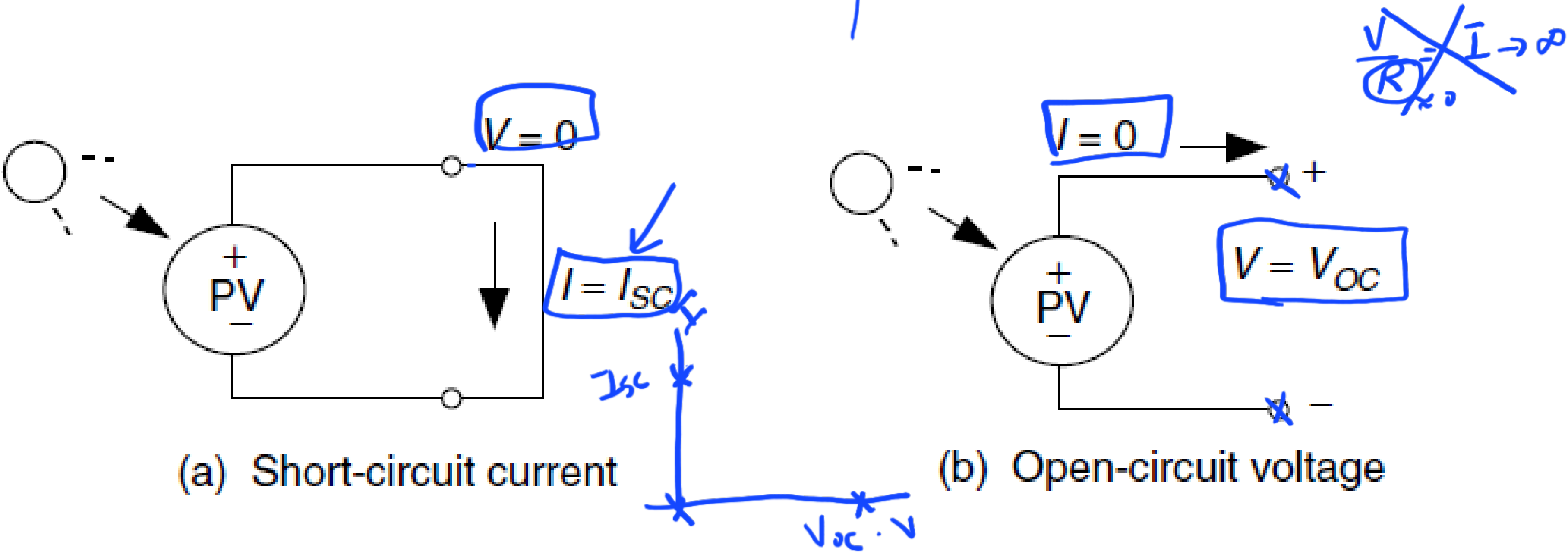


? = const

$$\boxed{I} + I_d = \boxed{I_{sc}}$$

$$\leftarrow I = I_{sc} - I_d$$

$V = V_d$



(a) Short-circuit current

(b) Open-circuit voltage

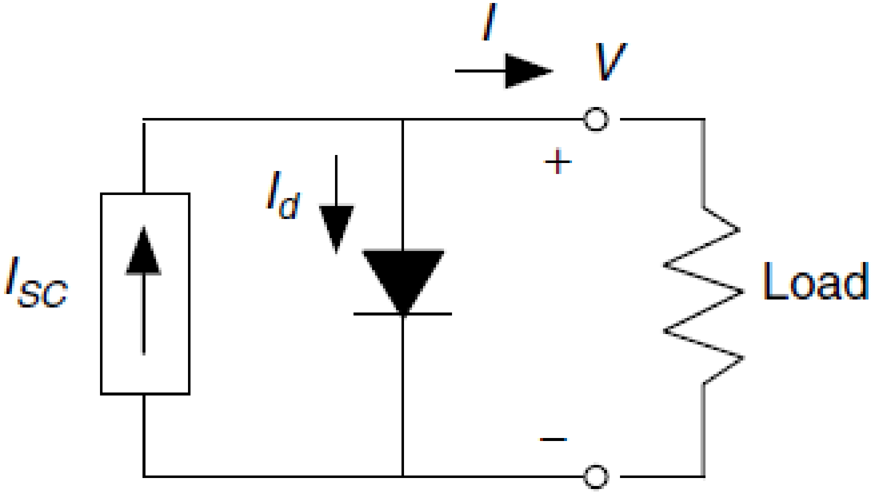
**There are two conditions of particular interest for the actual PV and for its equivalent circuit**

**(1) the current that flows when the terminals are shorted together (the short-circuit current, *Isc*) and**

**(2) the voltage across the terminals when the leads are left open (the open-circuit voltage, *Voc*)**

- When the leads of the equivalent circuit for the PV cell are shorted together, no current flows in the (real) diode since $Vd = 0$, so all of the current from the ideal source flows through the shorted leads.
- Since that short-circuit current must equal $Isc$, the magnitude of the ideal current source itself must be equal to $Isc$.
- Now we can write a voltage and current equation for the equivalent circuit of the PV cell shown.
- Start with
- $\underline{I = Isc - Id}$

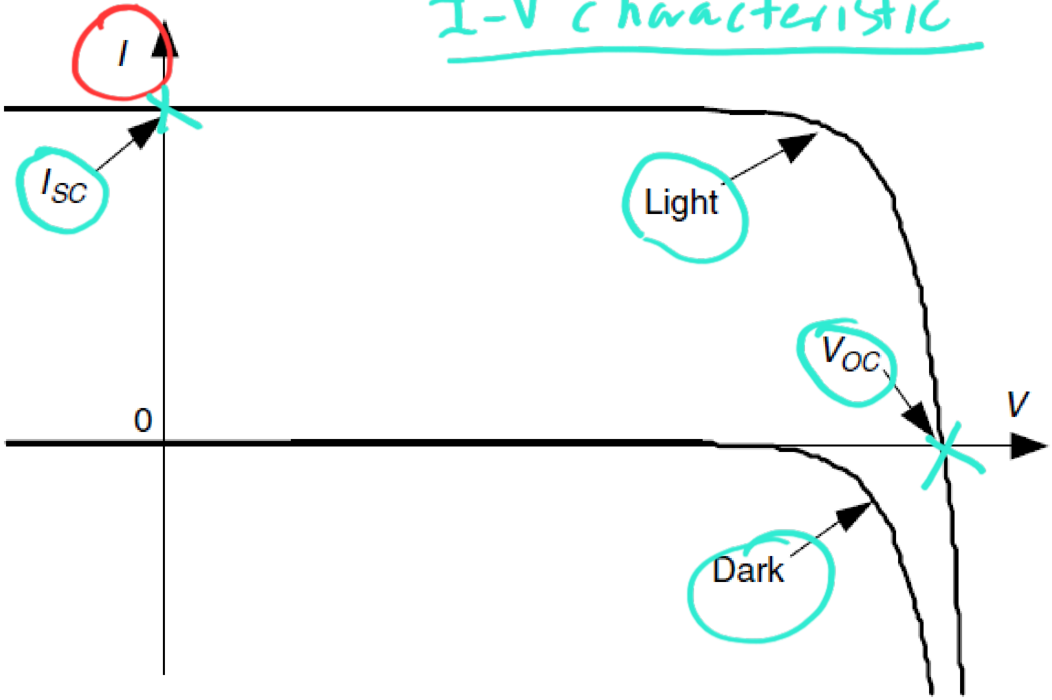
$$\underline{I} = \underline{I_{SC}} - \underline{I_0 \left(e^{qV/kT} - 1\right)}$$

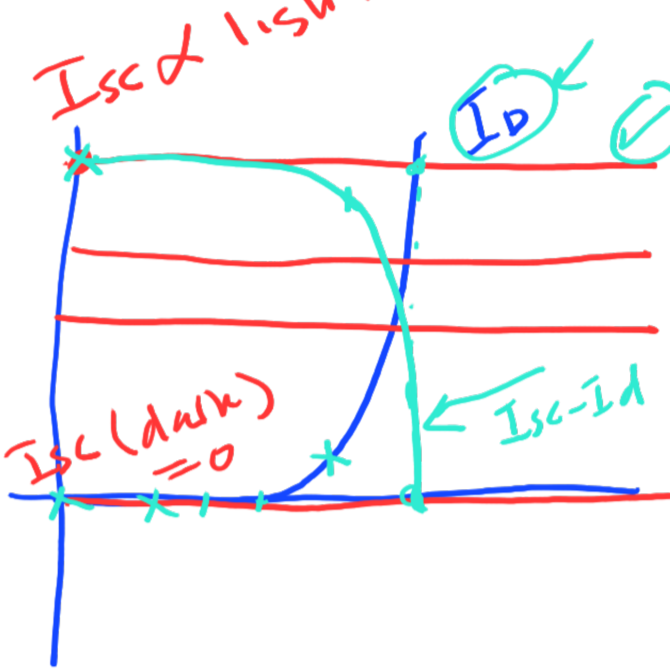


$$I = I_{SC} - I_0\left(e^{qV/kT} - 1\right)$$

- It is interesting to note that the second term above is just the diode equation with a negative sign.
- That means that a plot of I is just *ISC* added to the diode curve turned upside-down.
- Figure below shows the current–voltage relationship for a PV cell when it is dark (no illumination) and light (illuminated)

I-V characteristic





- When the leads from the PV cell are left open, *I* = 0 and we can solve for the open-circuit **voltage *Voc***:

$$\boxed{V_{OC} = \boxed{\frac{kT}{q}} \ln\left(\frac{I_{SC}}{I_0}+1\right)}$$

✓

- And at 25◦C,

$$\boxed{I = I_{SC} - I_0\left(e^{38.9\ \mathrm{V}} - 1\right)}$$

$$\underline{V_{OC}} = \boxed{0.0257} \ln\left(\frac{\underline{I_{SC}}}{\underset{\uparrow\ \text{constant}}{\underline{I_0}}}+1\right)$$

# Short circuit current:  Isc

- In both of these equations, short-circuit current, *Isc*, is directly proportional to solar insolation, which means that we can now quite easily plot sets of PV current–voltage curves for varying sunlight.
- Also, quite often laboratory specifications for the performance of photovoltaics are given per cm^2 of junction area, in which case the currents in the above equations are written as current densities.
- Both of these points are illustrated in the following example.

**Example 8.3 The $I$–$V$ Curve for a Photovoltaic Cell.** Consider a 100-cm$^2$ photovoltaic cell with reverse saturation current $I_0 = 10^{-12}$ A/cm$^2$. In full sun, it produces a short-circuit current of 40 mA/cm$^2$ at 25°C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

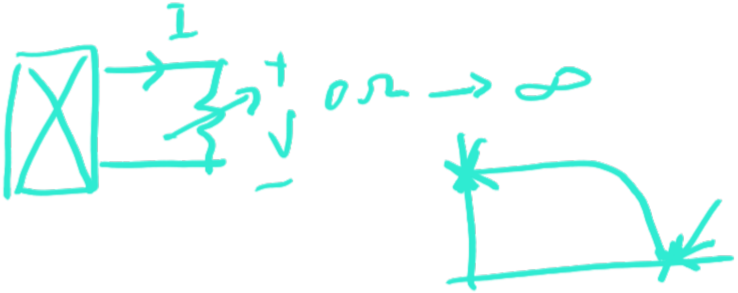
***Solution.*** The reverse saturation current $I_0$ is $10^{-12}$ A/cm$^2$ × 100 cm$^2$ = $1 \times 10^{-10}$ A. At full sun $I_{SC}$ is 0.040 A/cm$^2$ × 100 cm$^2$ = 4.0 A.

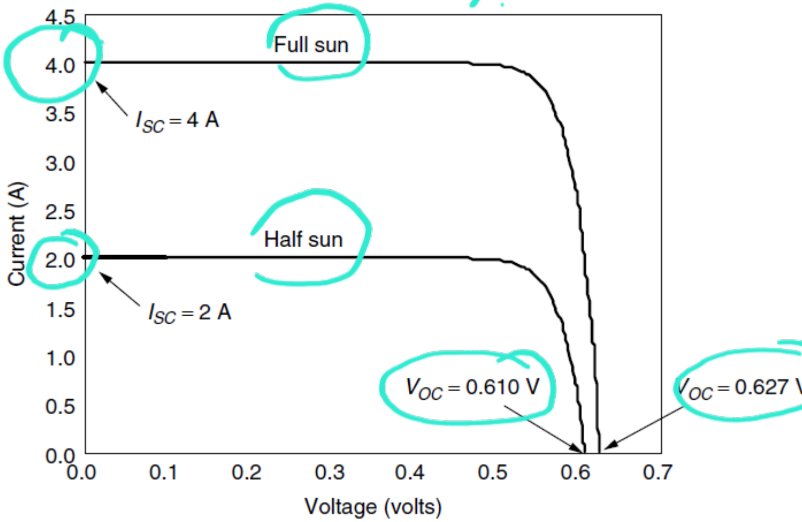
$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4.0}{10^{-10}} + 1\right) = 0.627 \text{ V}$$

Since short-circuit current is proportional to solar intensity, at half sun $I_{SC} = 2$ A and the open-circuit voltage is

50%

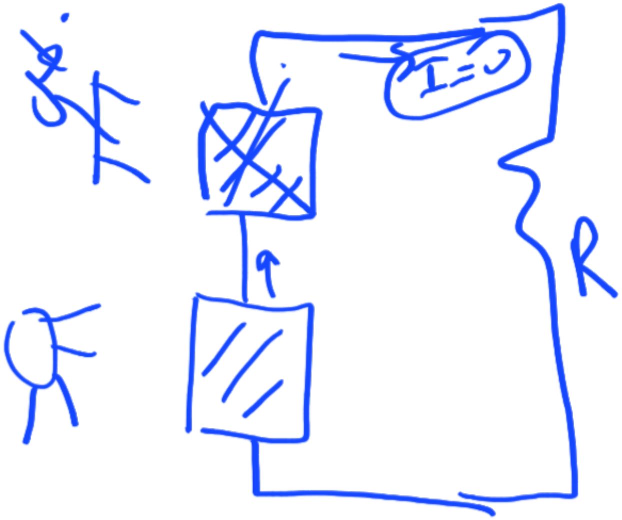
$$V_{OC} = 0.0257 \ln\left(\frac{2}{10^{-10}} + 1\right) = 0.610 \text{ V}$$

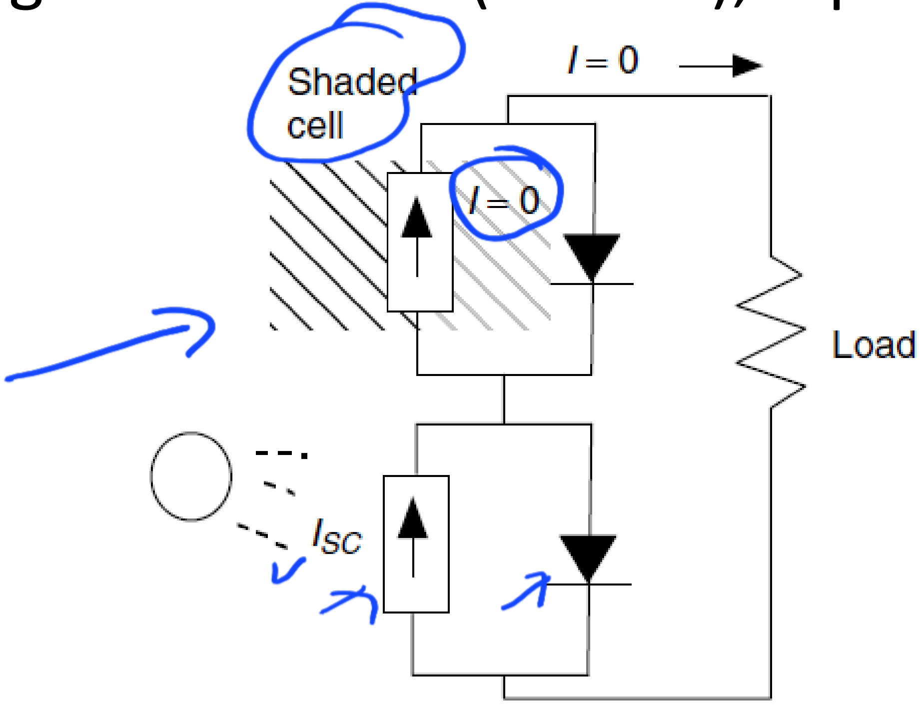




# A More Accurate Equivalent Circuit for a PV Cell

- There are times when a more complex PV equivalent circuit than the one shown in previously is needed.
- For example, consider the impact of shading on a string of cells wired in series (Figure below shows two such cells).
- If any cell in the string is in the dark (shaded), it produces no current.





- In our simplified equivalent circuit for the shaded cell, the current through that cell's current source is zero and its diode is back biased so it doesn't pass any current either (other than a tiny amount of reverse saturation current).
- This means that the simple equivalent circuit suggests that no power will be delivered to a load if any of its cells are shaded!
- This is not correct , a more complex model can deal with this problem

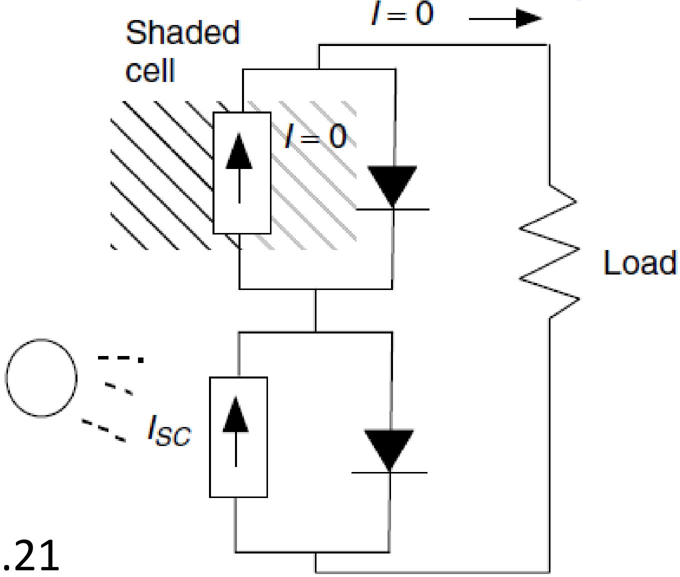


Fig. 8.21

The simple equivalent circuit of a string of cells in series suggests no current can flow to the load if any cell is in the dark (shaded).

# A More Accurate Equivalent Circuit for a PV Cell

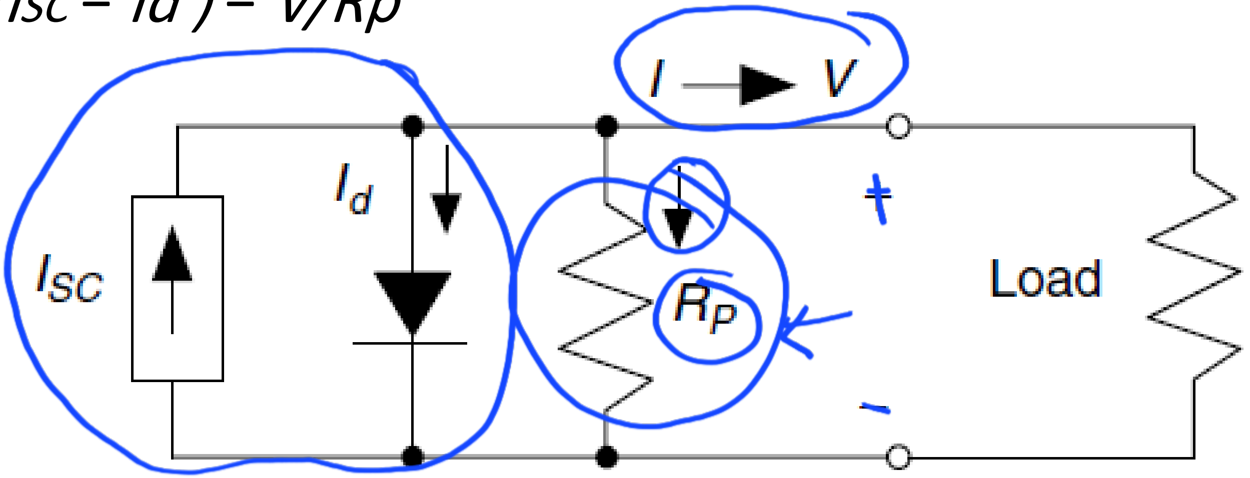
- While it is true that PV modules are very sensitive to shading, the situation is not quite as bad as that.
- So, we need a more complex model if we are going to be able to deal with realities such as the shading problem.
- A PV equivalent circuit that includes some parallel leakage resistance *Rp* is shown
- The ideal current source *Isc* in this case delivers current to the diode, the parallel resistance, and the load:

$$I = (I_{SC} - I_d) - V/R_p$$

$$I = I_{sc} - I_d - \boxed{I_{R_p}}$$

$$\downarrow$$

$$= \frac{V}{R_p}$$



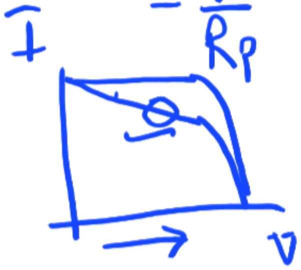
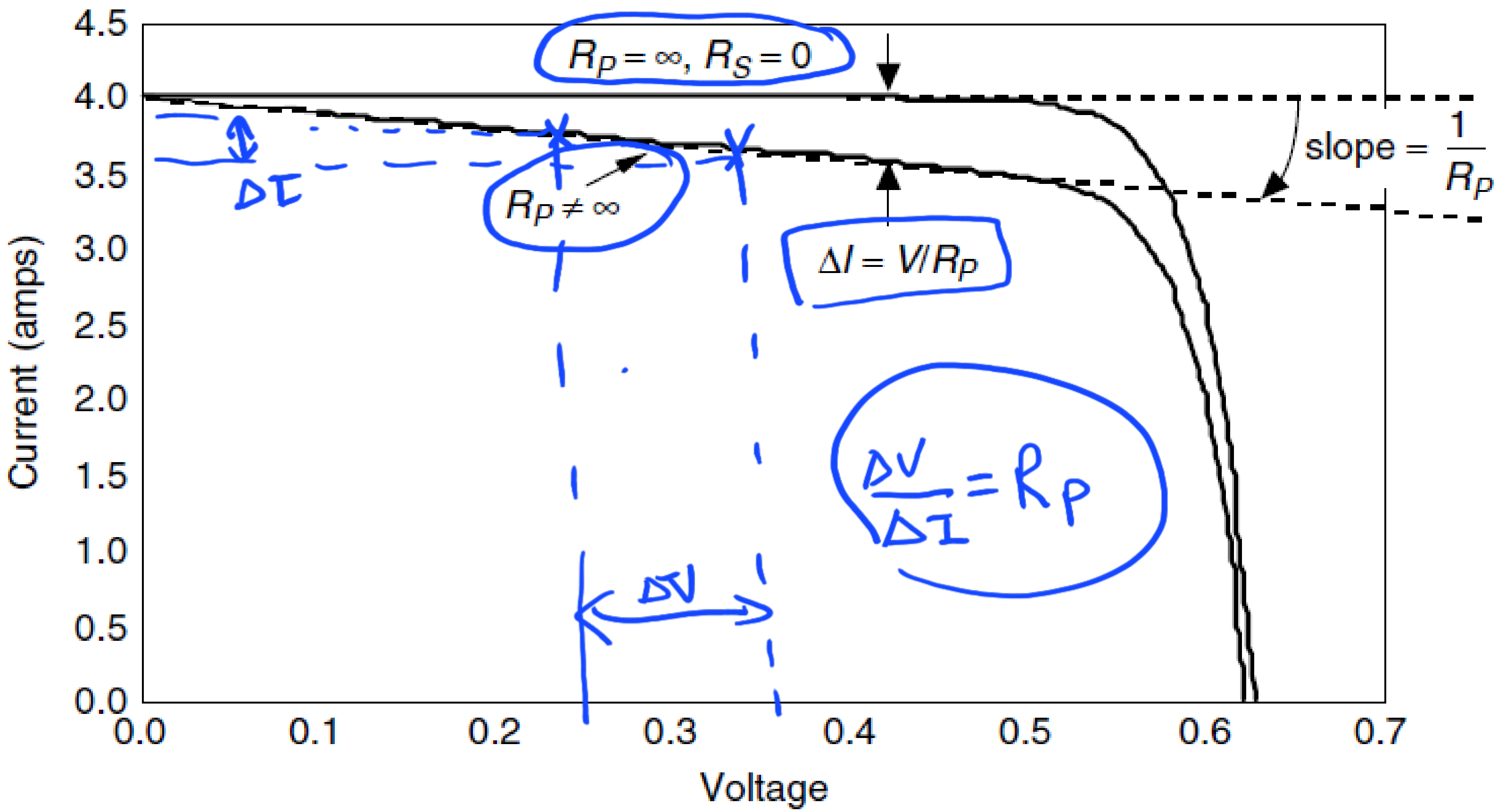


Figure 8.22



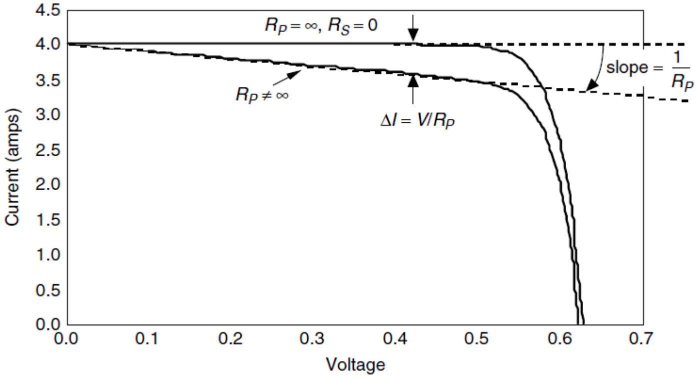
Modifying the idealized PV equivalent circuit by adding parallel resistance causes the current at any given voltage to drop by $V/R_P$.

# $I = (I_{SC} - I_d) - V/R_p$

- The term in the parentheses is the same current that we had for the simple model.
- So, what the equation tells us is that at any given voltage, the parallel leakage resistance causes load current for the ideal model to be decreased by $V/R_p$ as is shown I
- For a cell to have losses of less than 1% due to its parallel resistance, $R_P$ should be greater than about

$$R_P > 100\ V_{OC}/I_{SC}$$

- Consider a large cell, with $I_{SC}$ around 7 A and $V_{OC}$ about 0.6 V, which says its parallel resistance should be greater than about 9 .



End of L9

24/3

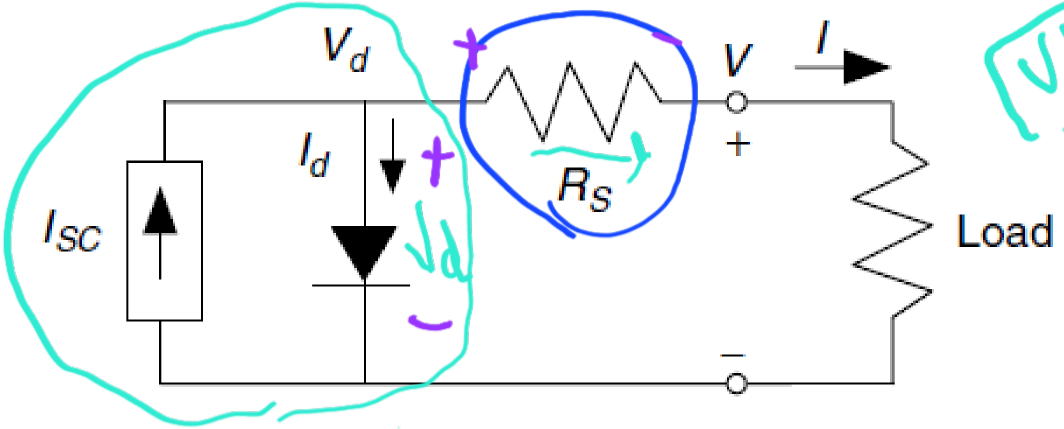
L10 14/4 covered Project & review

# Series Resistance

Start

L11
19/4

- An even better equivalent circuit will include series resistance as well as parallel resistance.
- Before we can develop that model, consider Fig. below in which the original PV equivalent circuit has been modified to just include some series resistance, *Rs*.
- Some of this might be contact resistance associated with the bond between the cell and its wire leads, and some might be due to the resistance of the semiconductor itself



$$\boxed{V_d = IR_s + V}$$

# Effect of Rs

- To analyze effect of series resistance, start with the simple equivalent circuit

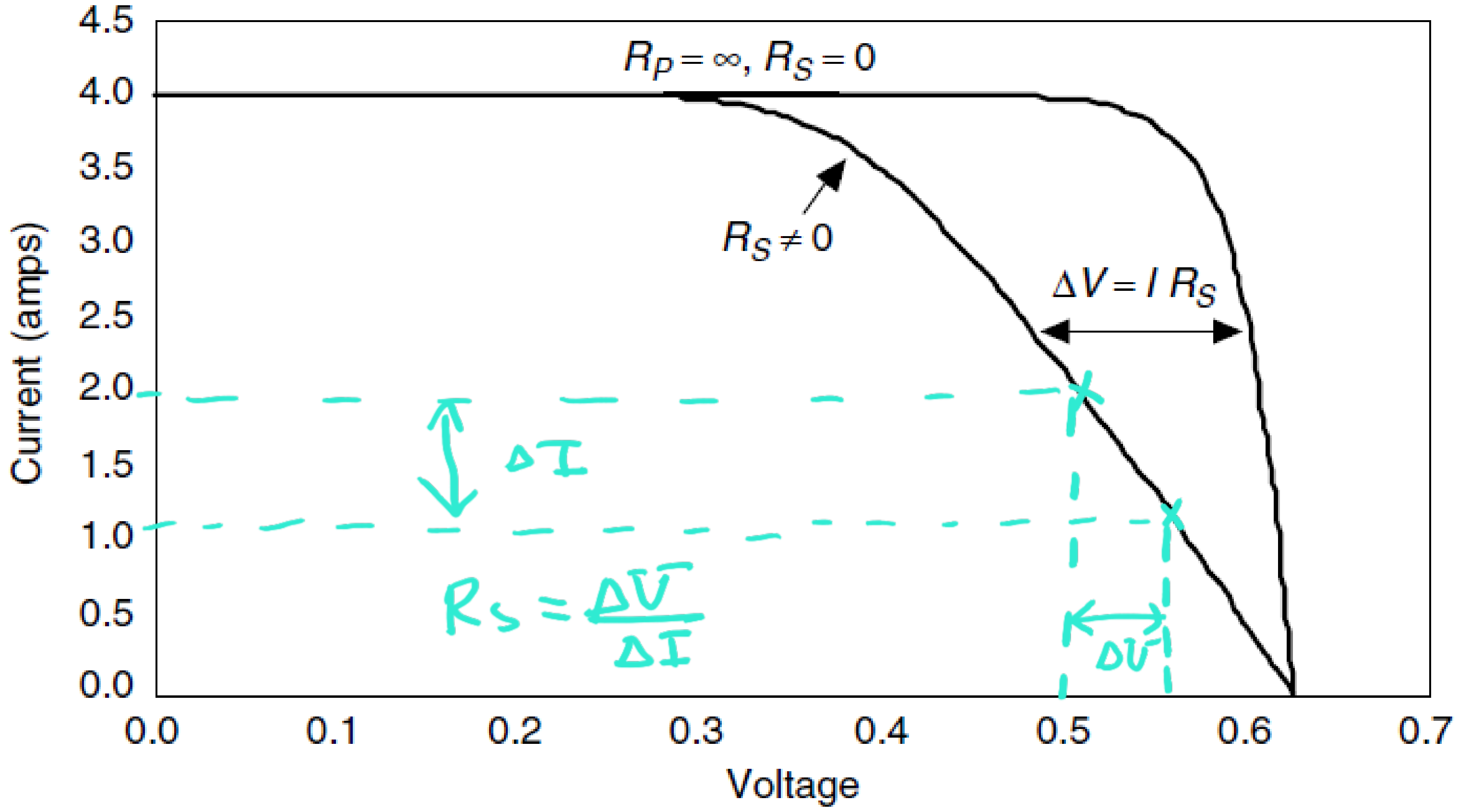
$$I = I_{SC} - I_d = I_{SC} - I_0\left(e^{q\boxed{V_d}/kT} - 1\right)$$

- and then add the impact of *RS*

$$V_d = V + \boxed{I \cdot R_S}$$

$$I = I_{SC} - I_0\left\{\exp\left[\frac{q\boxed{(V + I \cdot R_S)}}{kT}\right] - 1\right\}$$

- Equation above can be interpreted as the original PV $I - V$ curve with the voltage at any given current shifted to the left by $\Delta V = IRs$ as shown in Fig. 8.25.



Adding series resistance to the PV equivalent circuit causes the voltage at any given current to shift to the left by $\Delta V = I R_S$.

- Rs must be as small as possible to avoid high losses and voltage drop across it

# Generalized PV cell equivalent Circuit

- Finally, let us generalize the PV equivalent circuit by including both series and parallel resistances as shown in Fig. 8.26. We can write the following equation for current and voltage:

KCL

$$I = I_{SC} - I_0\left\{\exp\left[\frac{q(V+\boxed{I\cdot R_S})}{kT}\right]-1\right\} - \overset{=\frac{V_d}{R_P}}{\boxed{\left(\frac{V+I\cdot R_S}{R_P}\right)}}$$

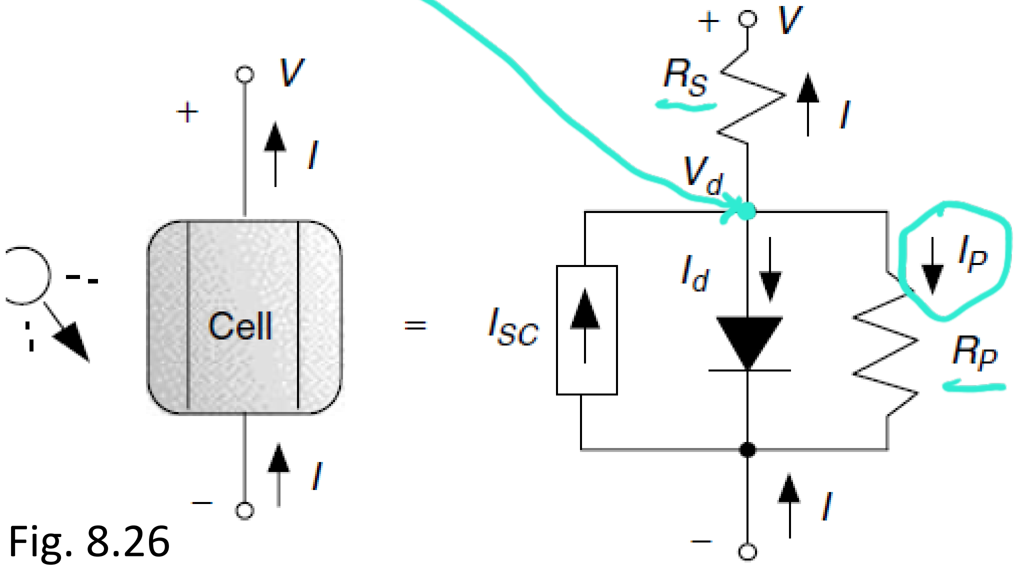


Fig. 8.26

A more complex equivalent circuit for a PV cell includes both parallel and series resistances. The shaded diode reminds us that this is a “real” diode rather than an ideal one.

- Under the standard assumption of a 25◦C cell temperature

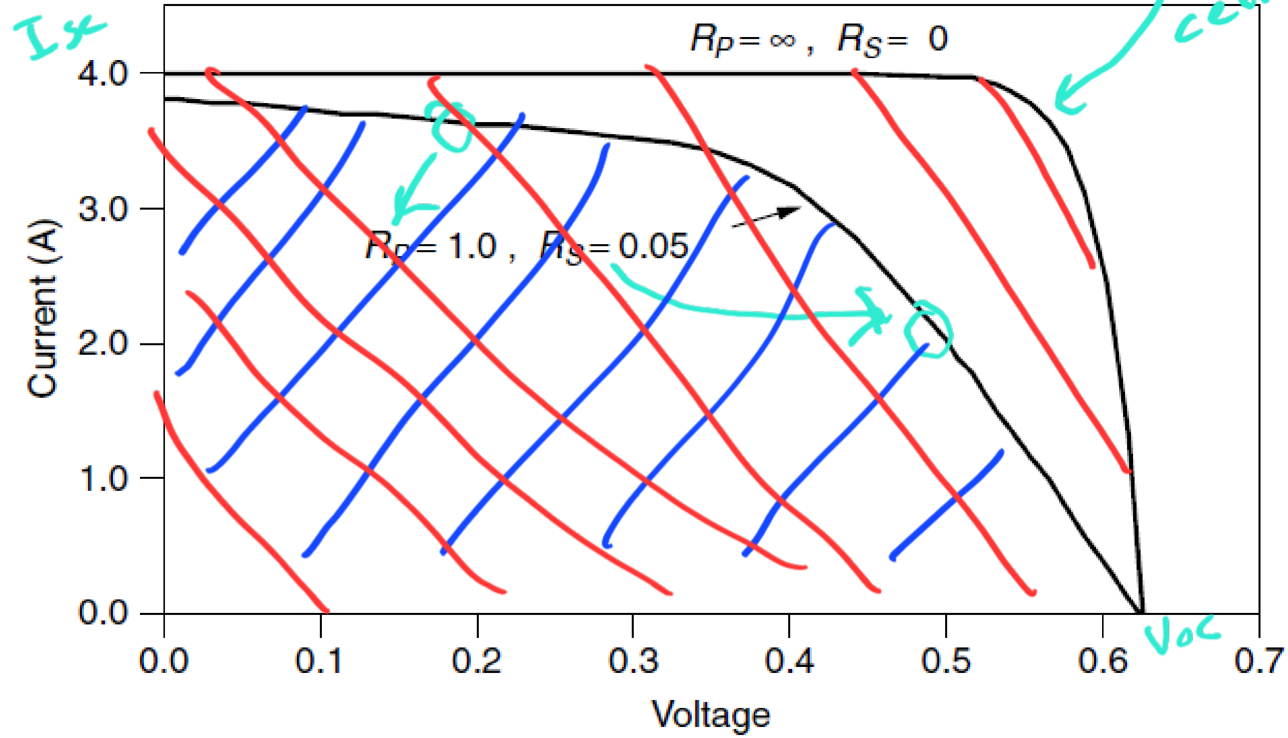
$$I = I_{SC} - I_0\left[e^{38.9(V+IR_S)} - 1\right] - \frac{1}{R_P}(V + IR_S) \qquad \text{at } 25^\circ\text{C}$$

- Unfortunately, this is a complex equation for which there is no explicit solution for either voltage *V* or current *I* .
- A spreadsheet solution, however, is fairly straightforward and has the extra advantage of enabling a graph of *I* versus *V* to be obtained easily.
- The approach is based on incrementing values of diode voltage, *Vd* , in the spreadsheet.
- For each value of *Vd* , corresponding values of current *I* and voltage *V* can easily be found.

$$I_{SC} = I + I_d + I_P$$

$$\boxed{I = I_{SC} - I_0(e^{38.9V_d} - 1) - \frac{V_d}{R_P}}$$

- Voltage across an individual cell then can be found from $V = V_d - I\,R_S$
- for an equivalent circuit with $\boxed{R_S = 0.05}$ and $\boxed{R_P = 1}$ is shown



# PV Modules and Arrays

- The primary component common to all PV systems is the PV array which consists of individual modules that are connected to produce desired voltage, current, and power output
- Modules and arrays produce **DC power** ,which can be used to charge batteries, directly power DC loads, or converted to AC power by inverters to power AC loads or to interface with electric utility grid

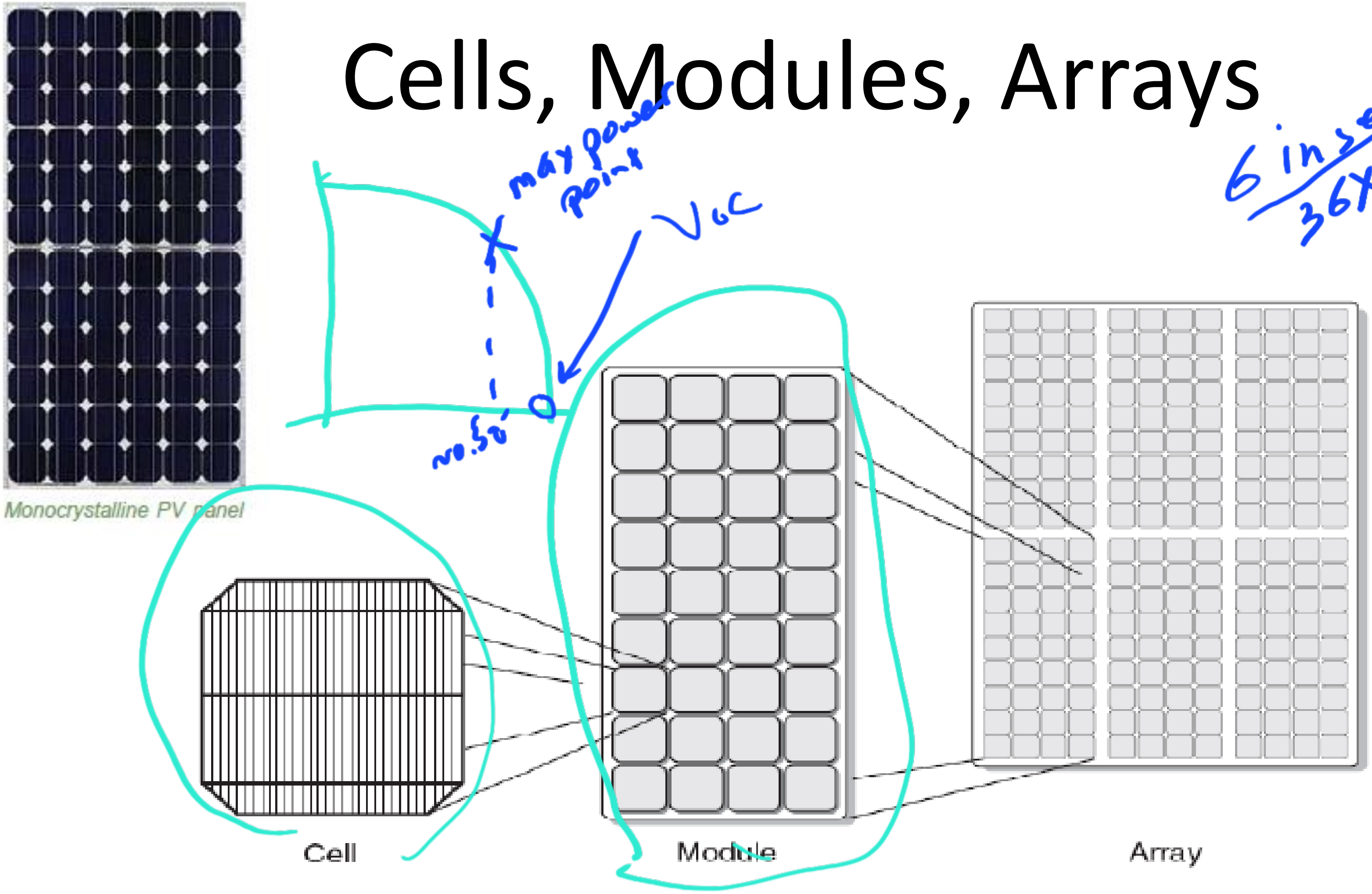
# PV Modules and Arrays

- The voltage of PV modules varies somewhat with **temperature**, and the current varies proportionately to **solar irradiance**, so power output is rarely constant
- PV systems usually require means to store or condition power so it can be used effectively by electrical loads

# Cells, Modules, Arrays

6 in series

36x6 = 216V



**Source:** [ABS Energy Research, 2009 or [Dr. Harald Schutzeeichel, 2009]

# Cell Materials

- Crystalline Silicon is most common base raw material for silicon cell production is at least 99.9% pure polysilicon, a product refined from quartz and silica sands
- Various grades of polysilicon can be used in PV cell production and affect the quality and efficiency of cells
- Crystalline silicon (C-Si) cells currently offer the **best ratio of performance to cost** and utilize many of the raw materials and process used by semiconductor industry

# Cell Materials

- Gallium Arsenide (GaAs) cells are more efficient than C-Si cells , but the high cost and toxicity have limited their use to space applications so far → [illegible]
- Multi-junction cell: a cell that maximizes efficiency by using layers of individual cells that each respond to different wavelengths of solar energy; the top layer captures the short wave while longer wave lengths is absorbed by the lower layer

# Cell Materials

- Thin-Film PV devices: module based approach to cell design
- A thin film module is a module –like PV device with its entire substrate coated in thin layers of semiconductor material using chemical vapor deposition techniques and then laser-scribed to delineate individual cells and make electrical connection between them
- Amorphous Silicon (a-Si) ; copper indium, gallium selenide (CIGS) and cadmium telluride (CdTe) are among competing thin film technologies

- Thin-Film modules are less costly to produce and use less raw materials than C-Si and may not be as durable in the field

# Photo-Electrochemical Cell

- A cell that relies on chemical process to produce electricity from light, rather than using semiconductors
- Photo-Electrochemical cells include dye-sensitized cells ,and polymer (plastic) cells and are sometimes called organic cells
- Engineering challenges in developing these cells are considerable, some are expected to impact commercial markets in the next decade

# Solar Cell Construction

- Materials
  - Crystalline Silicon
  - Gallium Arsenide (more expensive)
- Grown into large single-crystal ingots

سبائك

- Sawed into thin wafers

عملية نشر للطبقات

- 2 wafers are bonded together (p-n junction)
- Wafers grouped into panels or arrays

http://en.wikipedia.org/wiki/Solar_panel

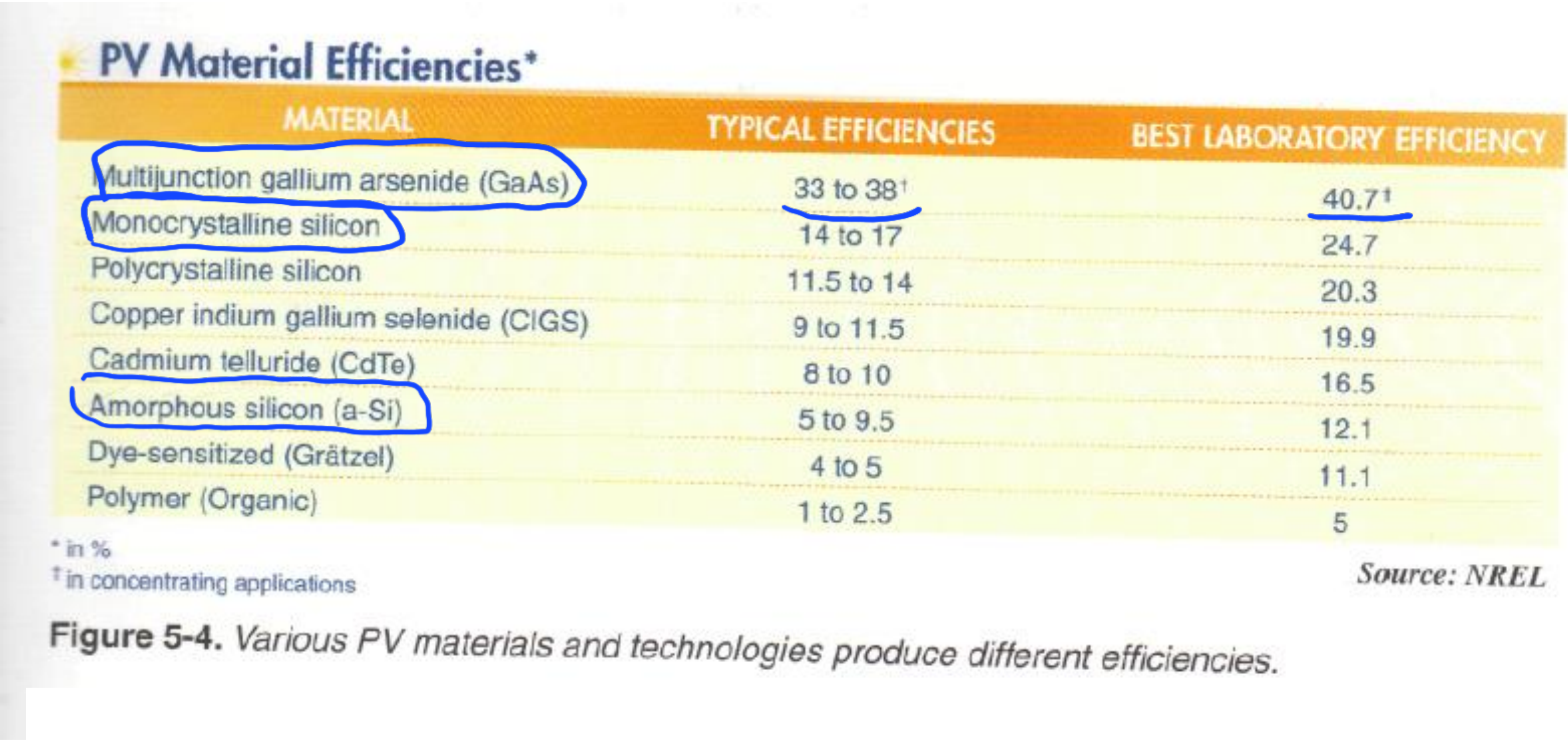
# Wafer Manufacturing

- The manufacture of commercial silicon modules involves fabricating silicon wafers, transforming the wafers into cells, and assembling cells into modules.
- A *wafer* is a thin, flat disk or rectangle of base semiconductor material.
- Wafers are 180 μm to 350 μm thick and are made from p-type silicon.
- Crystalline silicon cell wafers are produced in three basic types:

1) Monocrystalline , 2) polycrystalline, and 3) ribbon silicon.

- Each type has advantages and disadvantages in terms of efficiency, manufacturing , and costs.

# PV Materials Efficiencies



## PV Material Efficiencies*

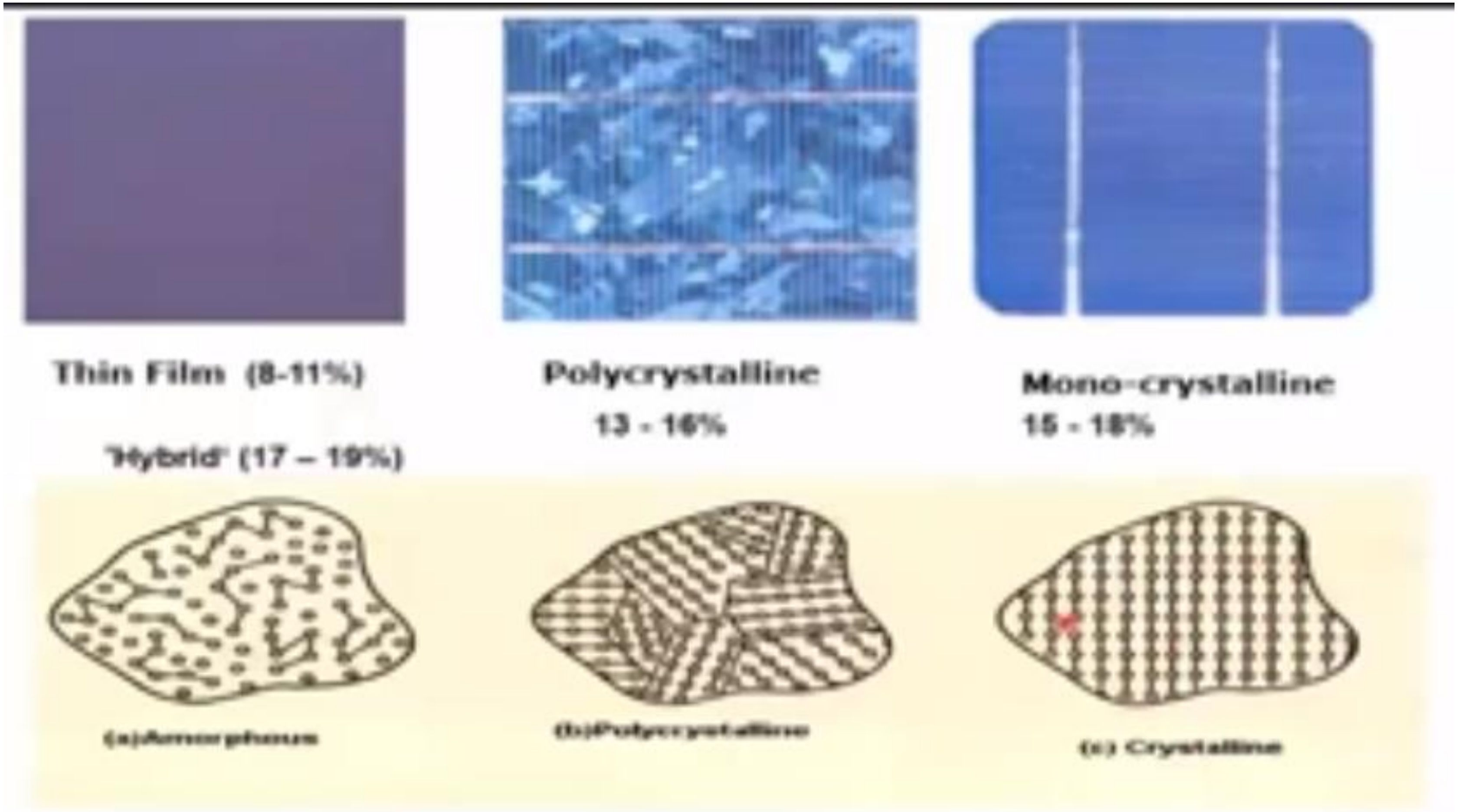
| MATERIAL | TYPICAL EFFICIENCIES | BEST LABORATORY EFFICIENCY |
|---|---|---|
| Multijunction gallium arsenide (GaAs) | 33 to 38[†] | 40.7[†] |
| Monocrystalline silicon | 14 to 17 | 24.7 |
| Polycrystalline silicon | 11.5 to 14 | 20.3 |
| Copper indium gallium selenide (CIGS) | 9 to 11.5 | 19.9 |
| Cadmium telluride (CdTe) | 8 to 10 | 16.5 |
| Amorphous silicon (a-Si) | 5 to 9.5 | 12.1 |
| Dye-sensitized (Grätzel) | 4 to 5 | 11.1 |
| Polymer (Organic) | 1 to 2.5 | 5 |

[*] in %

[†] in concentrating applications

*Source: NREL*

**Figure 5-4.** *Various PV materials and technologies produce different efficiencies.*


Thin Film (8-11%)
"Hybrid" (17 – 19%)
Polycrystalline
13 - 16%
Mono-crystalline
15 - 18%
(a)Amorphous
(b)Polycrystalline
(c) Crystalline

# Mono-crystalline Silicon

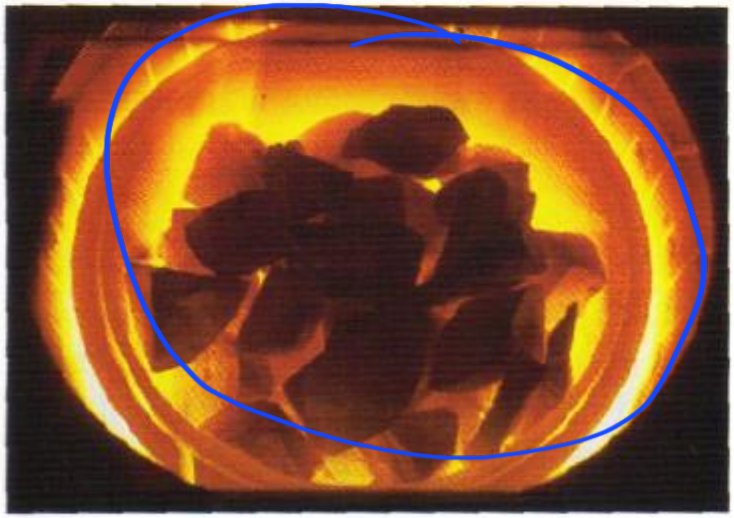
- A *mono-crystalline wafer is* a silicon wafer made from a single silicon crystal grown in the form of a cylindrical ingot. See **Figure** next slide.
- Chunks of highly pure polysilicon are melted in a crucible, along with boron.
- A small seed crystal is dipped into the molten bath and slowly rotated and withdrawn.
- Over a period of many hours, the seed crystal grows into a large cylindrical crystal up to 40" in length and 8" in diameter

*wafer (رقاقة)* ingot (سبيكة)

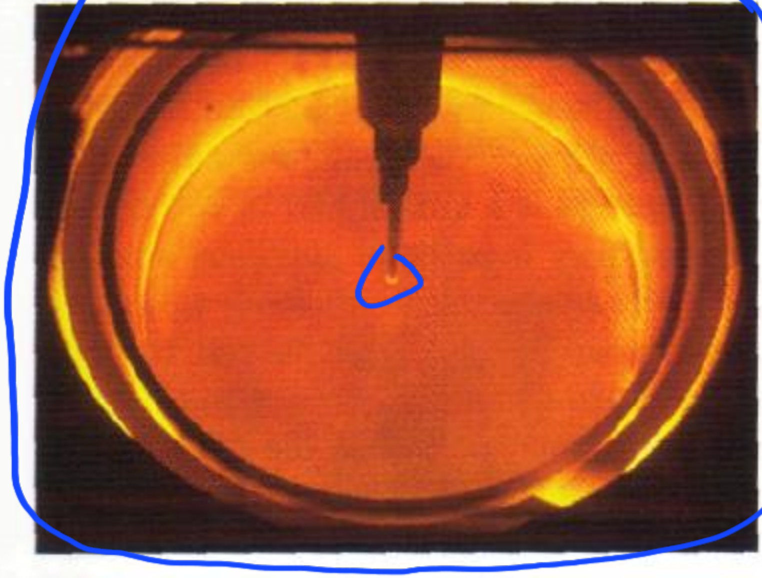
## Monocrystalline Ingots

1)

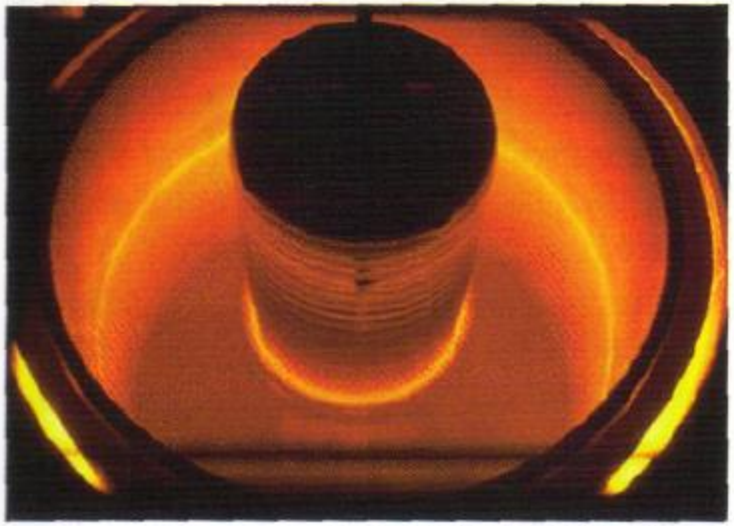
2)



3)



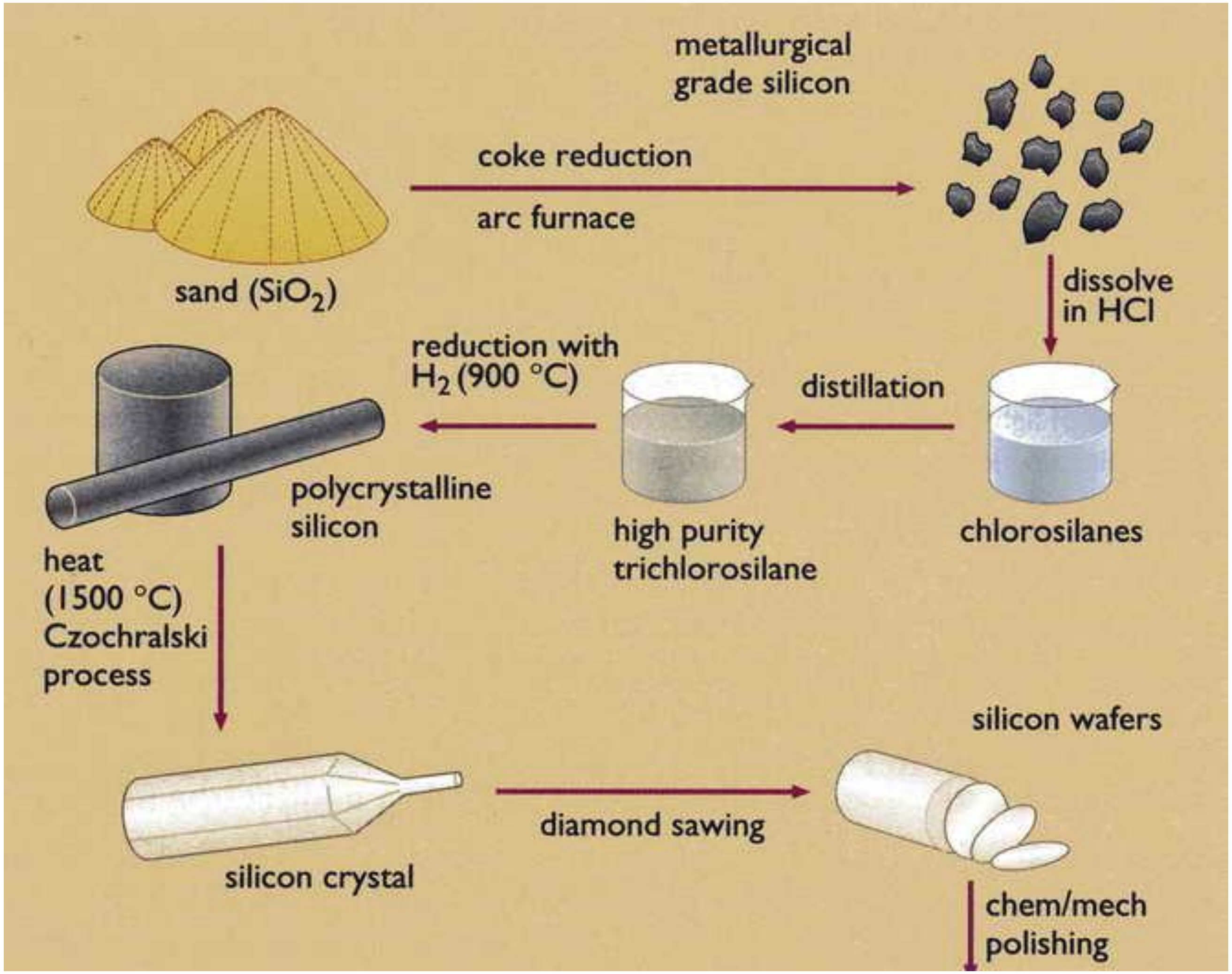
4)



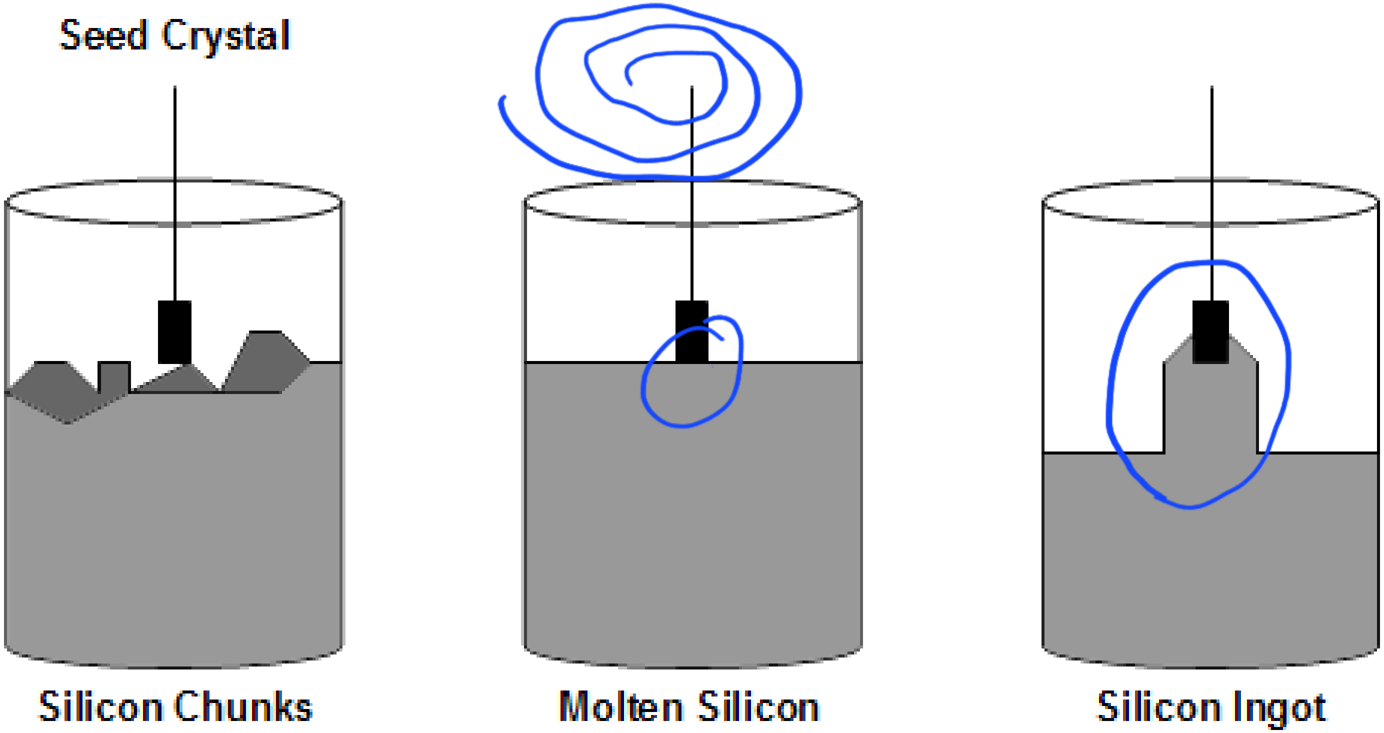
*SolarWorld Industries America*

**Figure 5-5.** *Monocrystalline silicon wafers are sawn from grown cylindrical ingots.*

# Creating Silicon Wafers



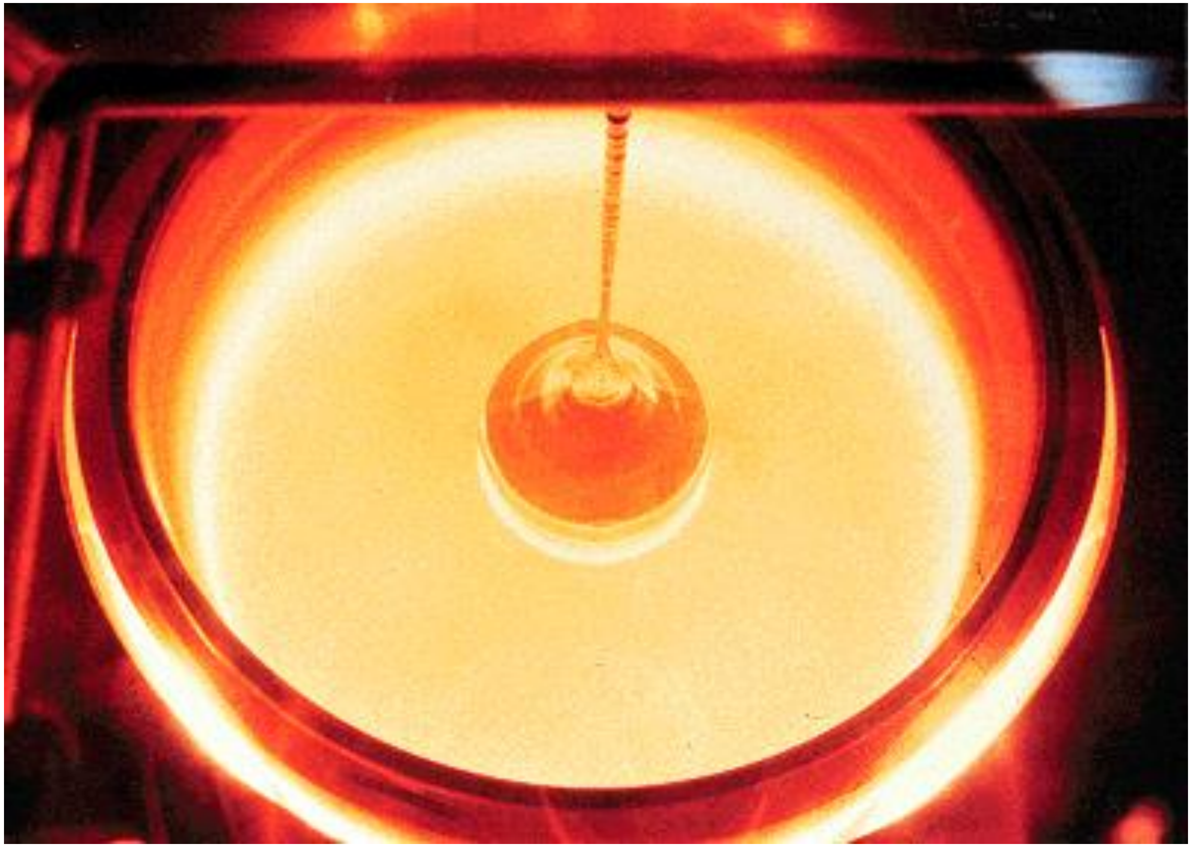
# Growing Silicon Ingots



Czochralski Process

http://en.wikipedia.org/wiki/Czochralski_process

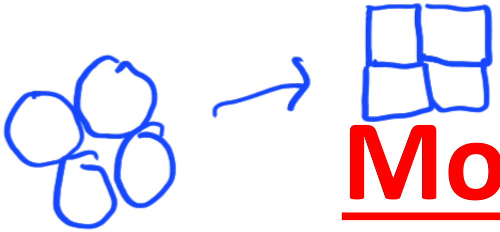
# Drawing a Silicon Ingot



http://www.answers.com/topic/silicon

# Silicon Ingots & Wafers

http://www.sumcosi.com/english/products/products2.html



# Monocrystalline Silicon

- Because the ingot is round, the edges are often cropped to a more rectangular or square shape, which allows cells to be packed more closely in a module.
- Individual wafers are then cut from the ingot using diamond wire saws.
- Commercial monocrystalline cells have efficiencies on the order of 14% to 17%, with some laboratory samples having efficiencies as high as about 25%.

# Polycrystalline Silicon

- *A polycrystalline wafer (رقاقة)* is a silicon wafer made from a cast silicon ingot (سبيكة)that is composed of many silicon crystals.
- Molten silicon is poured into a crucible to form an ingot, which is slowly and carefully cooled over several hours.
- During cooling, many silicon crystals form and grow as the molten material solidifies.
- The cast ingot is then sectioned with wire saws to form square or rectangular wafers.

# Polycrystalline Silicon

- Polycrystalline wafers can sometimes be distinguished from monocrystalline wafers by their square corners and the grain boundaries appearing on the wafer surface.
- While polycrystalline cells have slightly lower efficiencies (11.5% to 14%) than monocrystalline cells, their lower manufacturing costs and denser packing in modules makes them competitive with monocrystalline modules.

## Polycrystalline Ingots

*DOE/NREL, John Wohlgemuth—Solarex*

**Figure 5-6.** *Polycrystalline silicon wafers are sawn from cast rectangular ingots.*

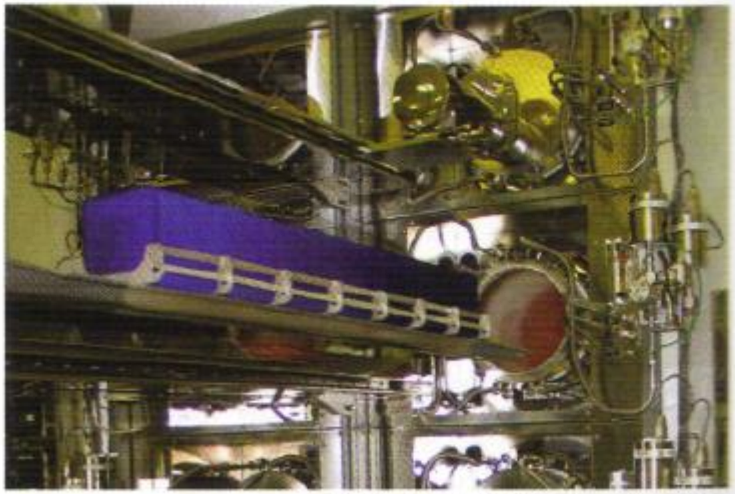
# Ribbon Silicon

- A *ribbon wafer* is a silicon wafer made by drawing a thin strip from a molten silicon mixture.
- The melted material is pulled between parallel dies where it cools and solidifies to form a continuous multicrystalline ribbon.
- The ribbon is then cut at specific intervals to form rectangular-shaped wafers.
- While cells produced from ribbon silicon wafers have slightly lower efficiencies (11% to 13%) than other silicon cells, this process is less expensive because there is less material waste and it does not require ingot sawing.

# Cell Fabrication

- Once a crystalline silicon wafer is produced, it must go through additional processing to become a functional PV cell.
- **Etching:** first the wafers are dipped in a sodium hydroxide solution to etch the surface and remove imperfections introduced during the sawing process.
- The textured surface increases surface area, allows subsequent coatings to adhere better, and minimizes reflected sunlight.

- **Phosphorous Diffusion**: After the wafers are cleaned they are placed on racks and into a diffusion furnace, where phosphorous gas penetrates the outer surfaces *of the cell, creating a thin n-type semiconductor* layer surrounding the original p-type semiconductor material. See **Figure** 5-8.



*SolarWorld Industries America*

**Figure 5-8.** *Diffusion of phosphorous gas creates a thin n-type semiconductor layer over the entire surface of a p-type wafer.*

قص الاطراف

- **Edge Abrasion** : the edge of the wafer is then abraded to remove the n-type material.
- **Coating**: Antireflective coatings are then applied to the top surface of the cell to further reduce reflected sunlight and improve cell efficiency.
- **Electrical Contacts:** After the coatings dry, grid patterns are screen printed on the top surface of the cell with silver paste to provide a point for electron collection and the electrical connection to other cells.
- These grid lines generally include two or more main strips across the cell, with finer lines emanating from the main strips across the cell surface.
- The configuration of these grid patterns is a critical part of cell design,

# Electrical Contacts

- The configuration of these grid patterns is a critical part of cell design, because they must be of sufficient size and distribution to be able to efficiently collect and conduct current away from the cell, but must be minimized to avoid covering much of the cell surface, which lowers the effective cell surface area exposed to sunlight.
- Finally, the entire back surface of the cell is coated with a thin layer of metal, typically aluminum, which alloys with the silicon and neutralizes the n-type semiconductor layer on the back surface.
- This results in the bottom surface of the cell being the positive connection, while the top surface is negative

# Testing

- After cells are produced, each is electrically tested under simulated sunlight and sorted according to its current output.
- This sorting *process largely eliminates problems with* current mismatch among series-connected cells and allows manufacturers to produce modules that are of the same physical size but have different power ratings.

## Cell Fabrication

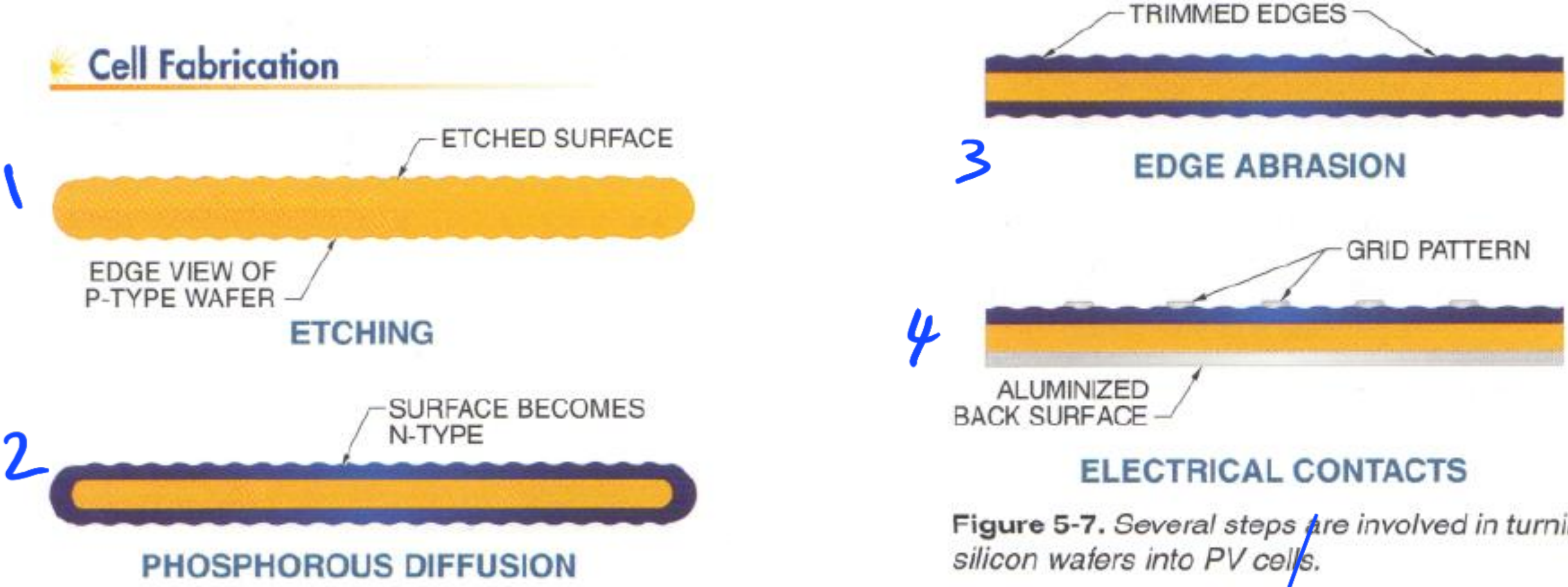
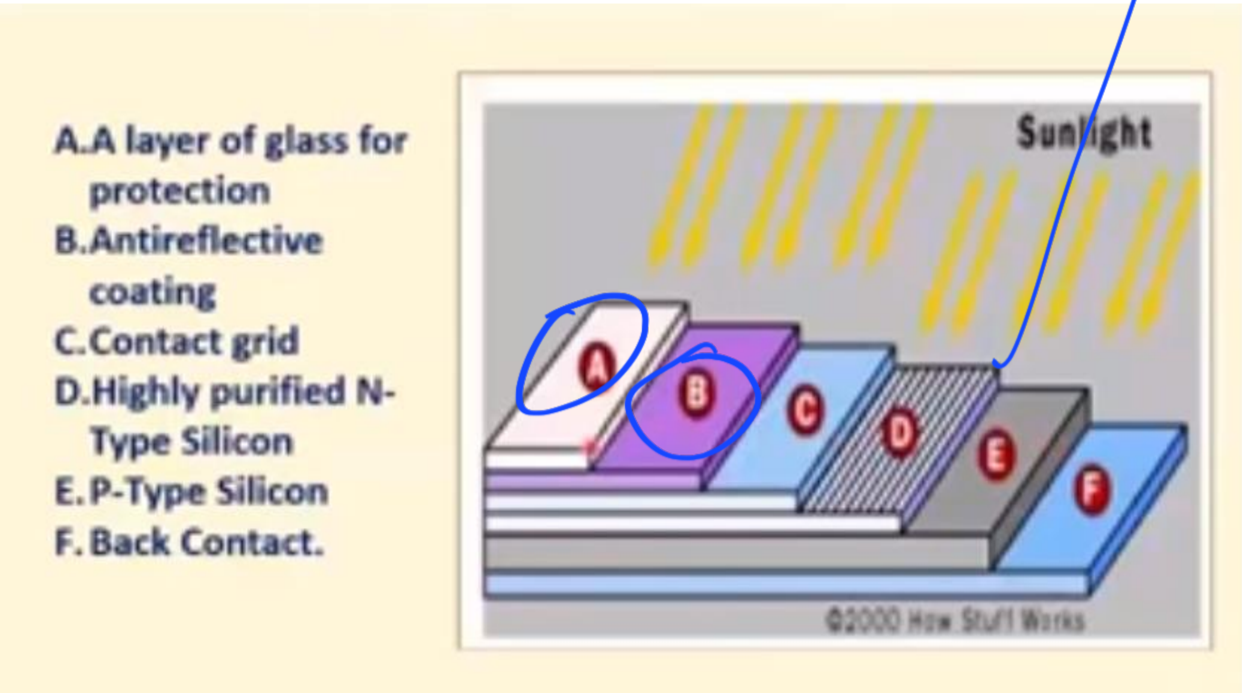
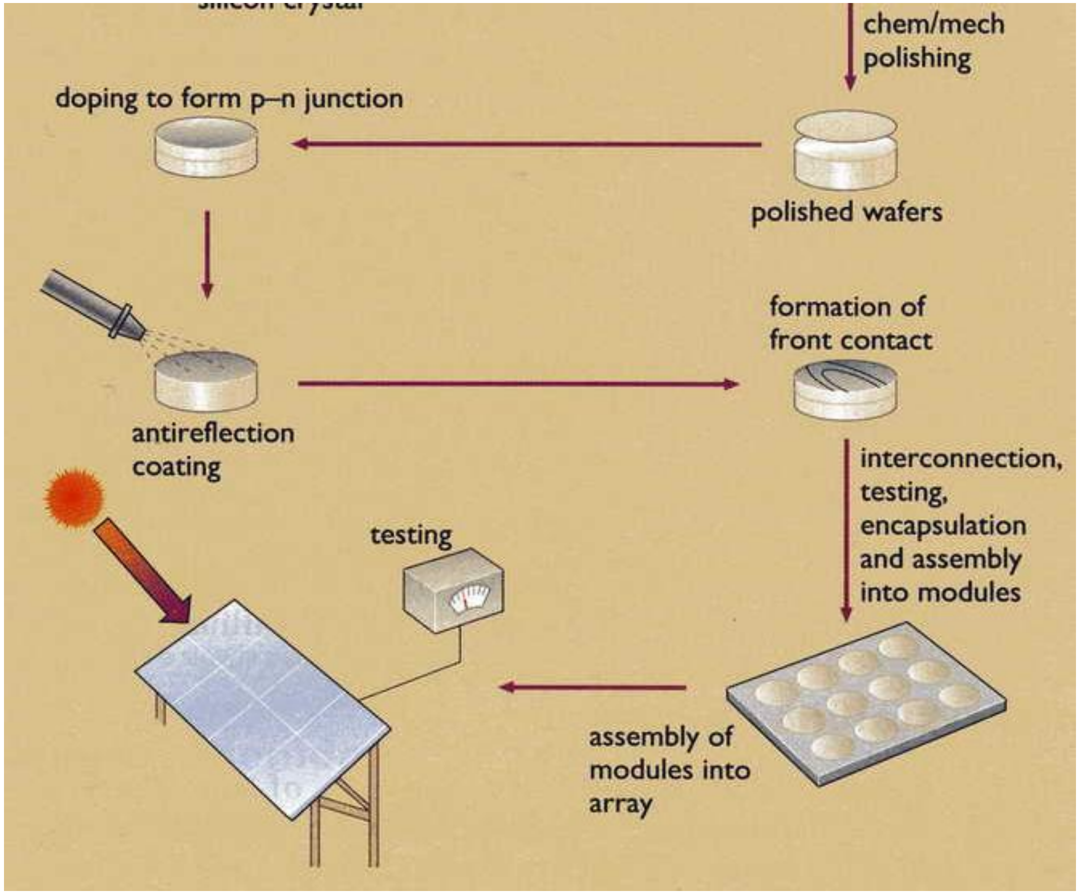


**Figure 5-7.** *Several steps are involved in turning silicon wafers into PV cells.*



A. A layer of glass for protection
B. Antireflective coating
C. Contact grid
D. Highly purified N-Type Silicon
E. P-Type Silicon
F. Back Contact.

# Creating PV Cells



# How Solar Cells are Made
# see movie book CD

First Exam material Ends Here

L11-PV model
19/4/202