

EE 446/646

Photovoltaic Devices I

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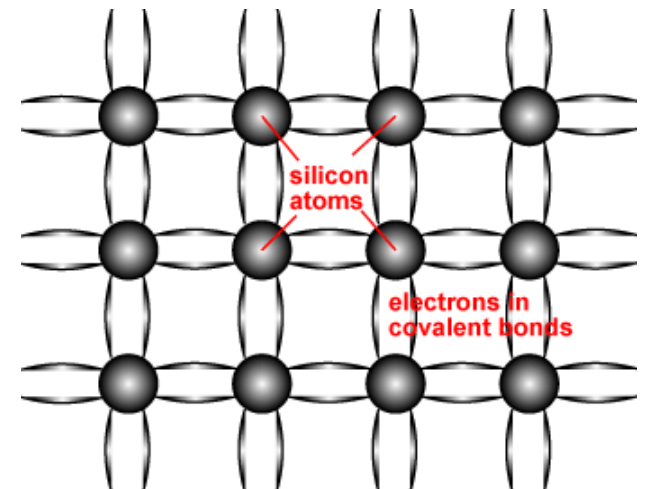
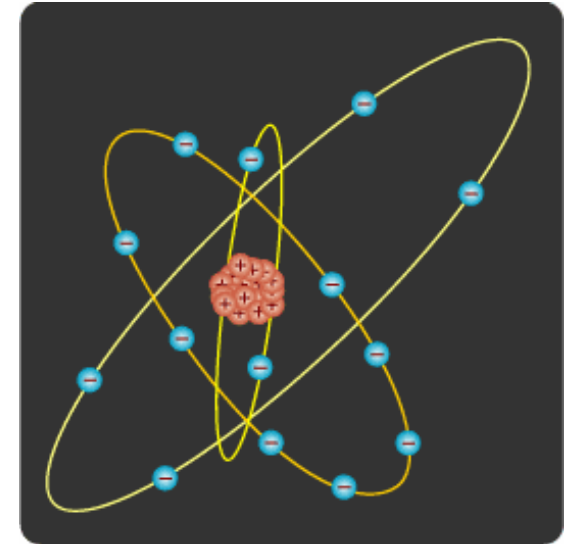
Semiconductors

- Semiconductors are materials from either group IV of the periodic table, or from a combination of group III & V (III-V semiconductors), or II & VI (II-VI semiconductors).
- Silicon (Si) is the most commonly used semiconductor material as it forms the basis for integrated circuit (IC) chips. Most solar cells are also silicon-based.
- Other common semiconductors include Ge, GaAs, and CdTe.

										VIIIA	
										2	He
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										13	Al
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										14	Si
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										16	S
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										17	Cl
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										18	Ar
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IB		IIB									
29	Cu	30	Zn	31	Ga	32	Ge	33	As	34	Se
	63.54		65.37		69.72		72.59		74.922		78.96
47	Ag	48	Cd	49	In	50	Sn	51	Sb	52	Te
	107.870		112.40		114.82		118.69		121.75		127.60
79	Au	80	Hg	81	Tl	82	Pb	83	Bi	84	Po
	196.967		200.59		204.37		207.19		208.980		(210)
										85	At
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											(222)

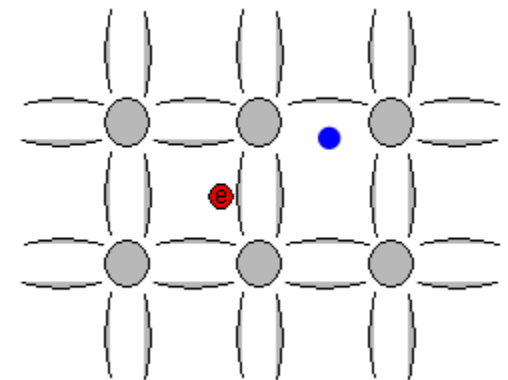
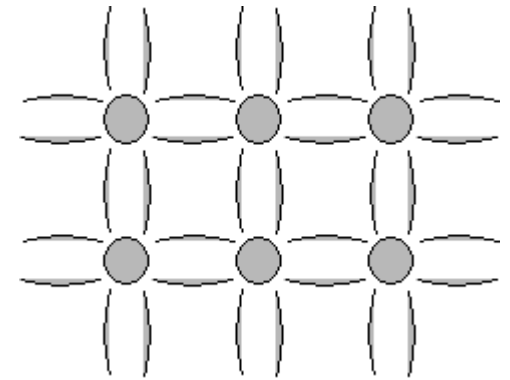
Silicon Atom

- Si - Silicon (14th element) is a "semi-conductor" or a "semi-metal," and has properties of both a metal and an insulator.
- Silicon has 14 electrons. The outermost four electrons, called **valence** electrons, play a very important role in the photoelectric effect.
- These electrons have certain energy levels, based on the number of electrons in the atom, which is different for each element in the periodic table.
- At absolute zero temperature, a silicon atom shares each of its four valence electrons with each of four neighboring atoms. There are no electrons free to roam around (i.e., perfect insulator).



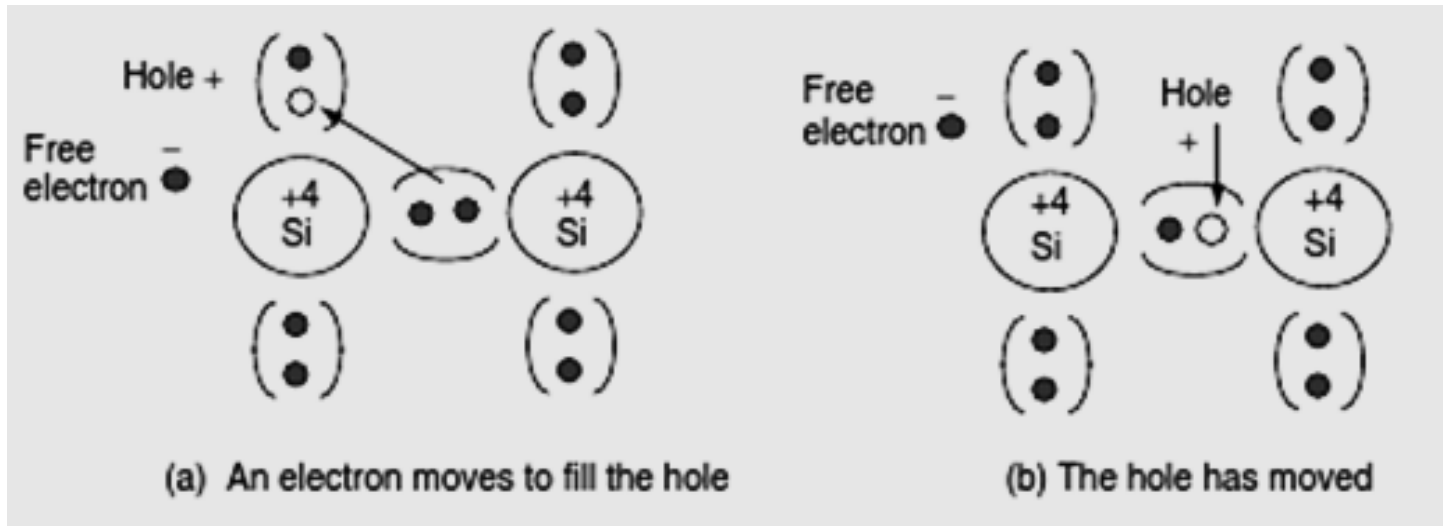
Carriers (holes and electrons)

- As the temperature increases, some electrons will gain enough energy to free themselves from their bond, making them available to flow as electric current.
 - Each **free electron** leaves behind an empty space for an electron.
 - This empty space is called a **hole**, and this can be treated as a mobile positively charged particle through the crystal structure.
 - The free electrons and resulting holes are called “**carriers**”.



Carrier Movement

- Both the negatively charged electron and the positively charged hole left behind are free to move around the crystal”
 - A valence electron can easily move to fill a hole in a nearby atom.
 - Having done so, the hole, in essence, moves to the nucleus from which the electron originated.
 - Thus, electric current in a semiconductor can be created not only by negatively charged electrons, but also by positively charged holes.



Band gap

- There are two distinct energy states for the valence electrons:
 - The lowest energy position - ***bound state***
 - If the electron has enough thermal energy to break free of its bond, then it is in a - ***free state***.
- The electron cannot attain energy values intermediate to these two levels; it is either at a low energy position, or it has gained enough energy to break free and therefore has a certain minimum energy.
 - The minimum energy need for an electron to break free is called the "**band gap**" of a semiconductor.

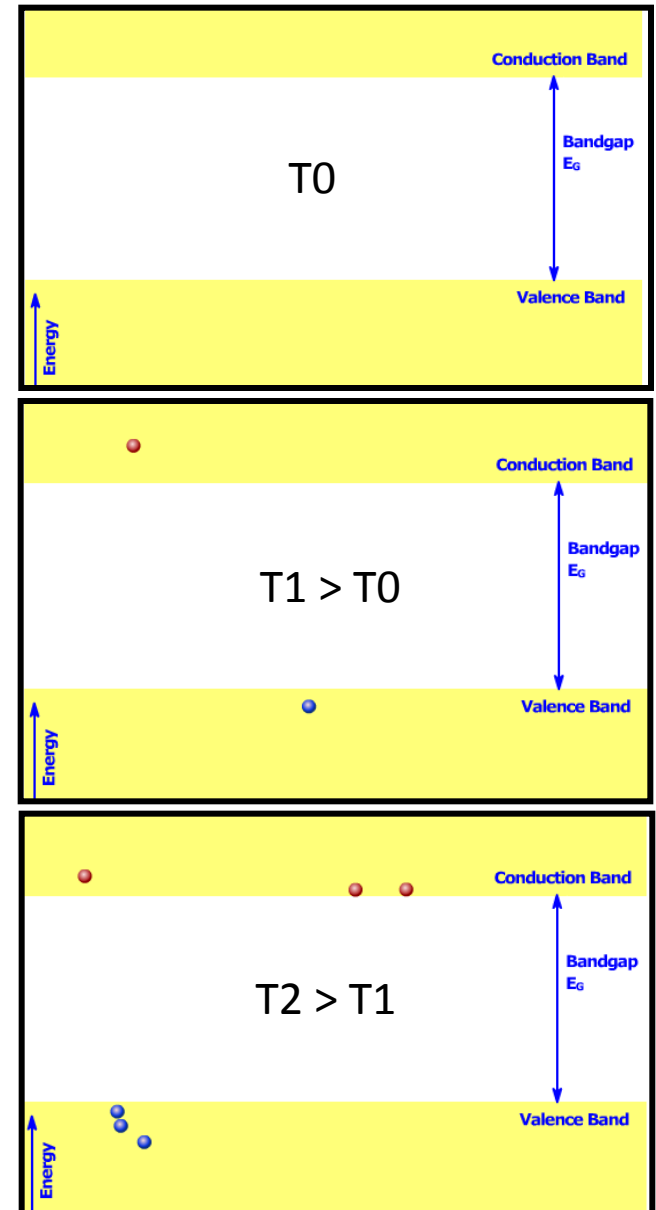
Band Diagram

- The band structure of a semiconductor with the energy of the electrons on the vertical axis and is called a "band diagram".
- The lower energy level of a semiconductor is called the "**valence band**" and the energy level at which an electron can be considered free is called the "**conduction band**".
- The band gap E_g is the distance between the conduction band and valence band.
- The gap between the allowable energy bands is called the "**forbidden band**".



Intrinsic Carrier Concentration

- The thermal excitation of electrons from the valence band to the conduction band creates free carriers in both bands.
- The concentration of these carriers in intrinsic materials (semiconductor with no added impurities) is called **the intrinsic carrier concentration**, n_i .
- n_i is the number of electrons in the conduction band or the number of holes in the valence band in the intrinsic material.
- n_i depends on the band gap and on the temperature of the material.
- At 300 K, the intrinsic carrier concentration of Silicon is around $1 \times 10^{10} / \text{cm}^3$.



Band Gap Energy

- The unit for band-gap energy is electron-volts (eV). One electron-volt is the energy gained an electron when it is placed across an electric potential difference of 1 V (1 J/C):

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joules}$$

- The band-gap E_g 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? 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.
 - Thus, photons with enough energy create hole– electron pairs in a semiconductor.

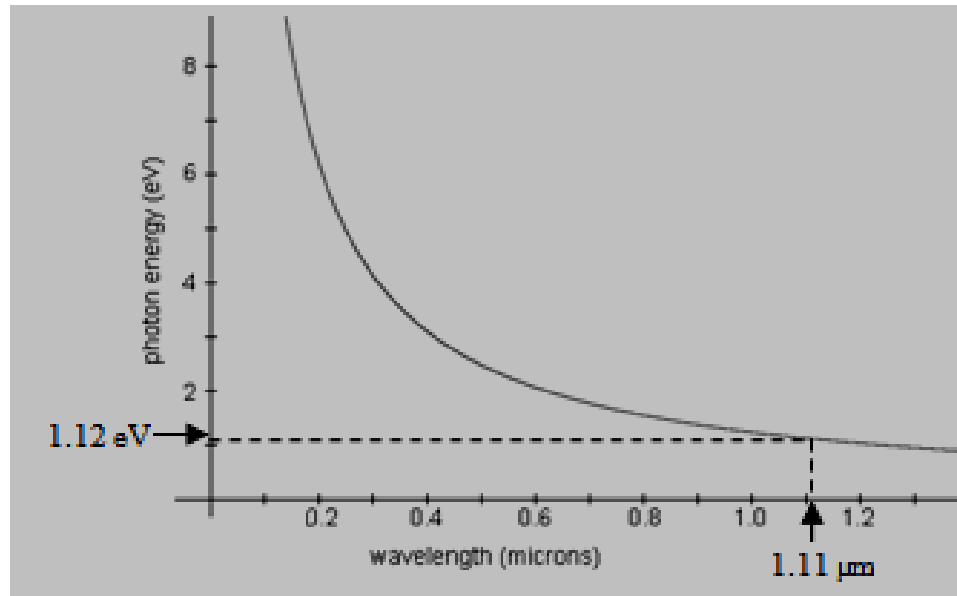
Photon Energy

$$E = \frac{hc}{\lambda}$$

c : speed of light ($= 3 \times 10^8$ m/s),

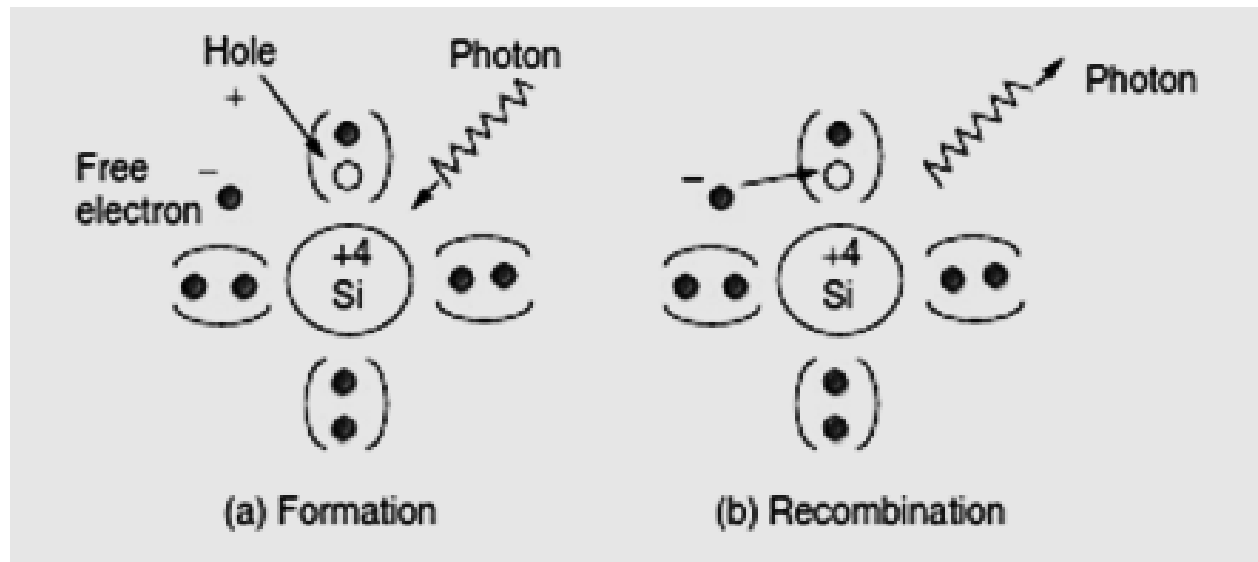
h : Planck's constant ($= 6.626 \times 10^{-34}$ J·s).

- photons with wavelengths longer than $1.11 \mu\text{m}$ have less energy than the band-gap energy of silicon (1.12 eV), so all their energy is wasted as heat within the cell.
- Photons with wavelengths shorter than $1.11 \mu\text{m}$ have more than enough energy to excite an electron.



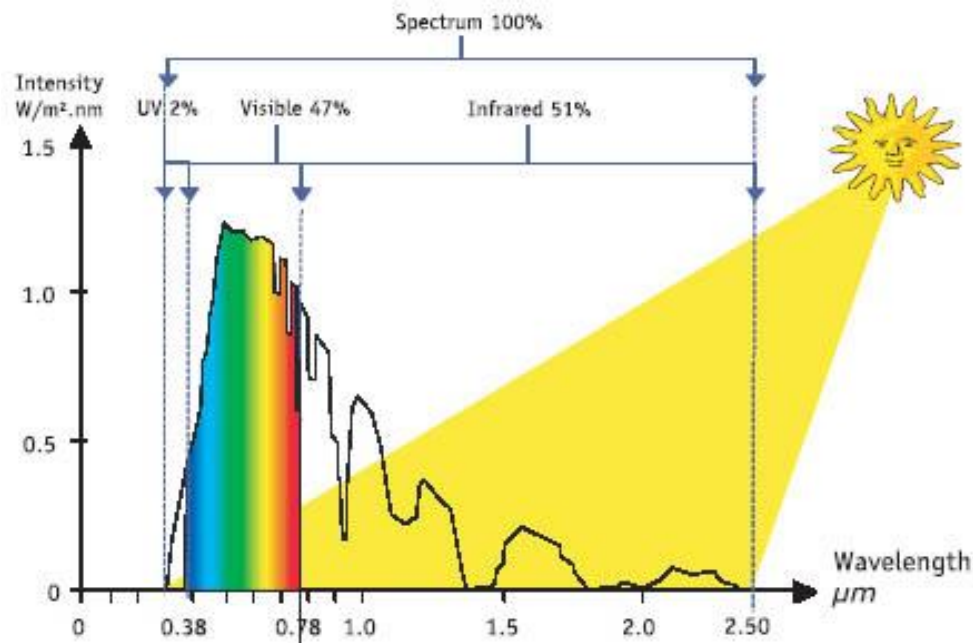
Carrier formation and recombination

- Unless there is some way to sweep the electrons away from the holes, they will eventually recombine, thus losing both the hole and electron.
- When recombination occurs, the energy that had been associated with the electron in the conduction band is released as a photon - this is the basis for light-emitting diodes (LEDs).



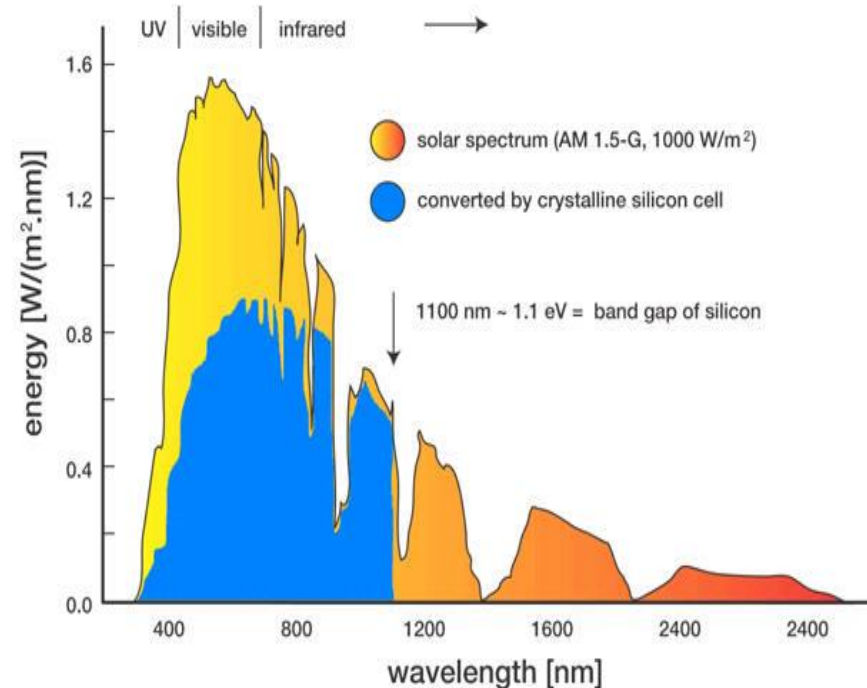
Solar Spectrum

- The solar spectrum at sea level contains nearly 2% of ultra-violet light ($\lambda \leq 0.38 \mu\text{m}$), 47% visible light ($0.38 \mu\text{m} \leq \lambda \leq 0.78 \mu\text{m}$), and 51% infrared light ($0.78 \mu\text{m} \leq \lambda \leq 2.5 \mu\text{m}$).
- The maximum power density is nearly $1.3 \text{ W/m}^2.\text{nm}$, or $1,300 \text{ W/m}^2.\mu\text{m}$, and this occurs at a wavelength of approximately $0.5 \mu\text{m}$.
- The **photon flux**, or number of photons striking one square meter each second, is determined by dividing the power density by the photon energy. For example, at the above maximum power density, the photon flux is nearly equal to $2 \times 10^{21} \text{ photons/m}^2/\text{sec}$.



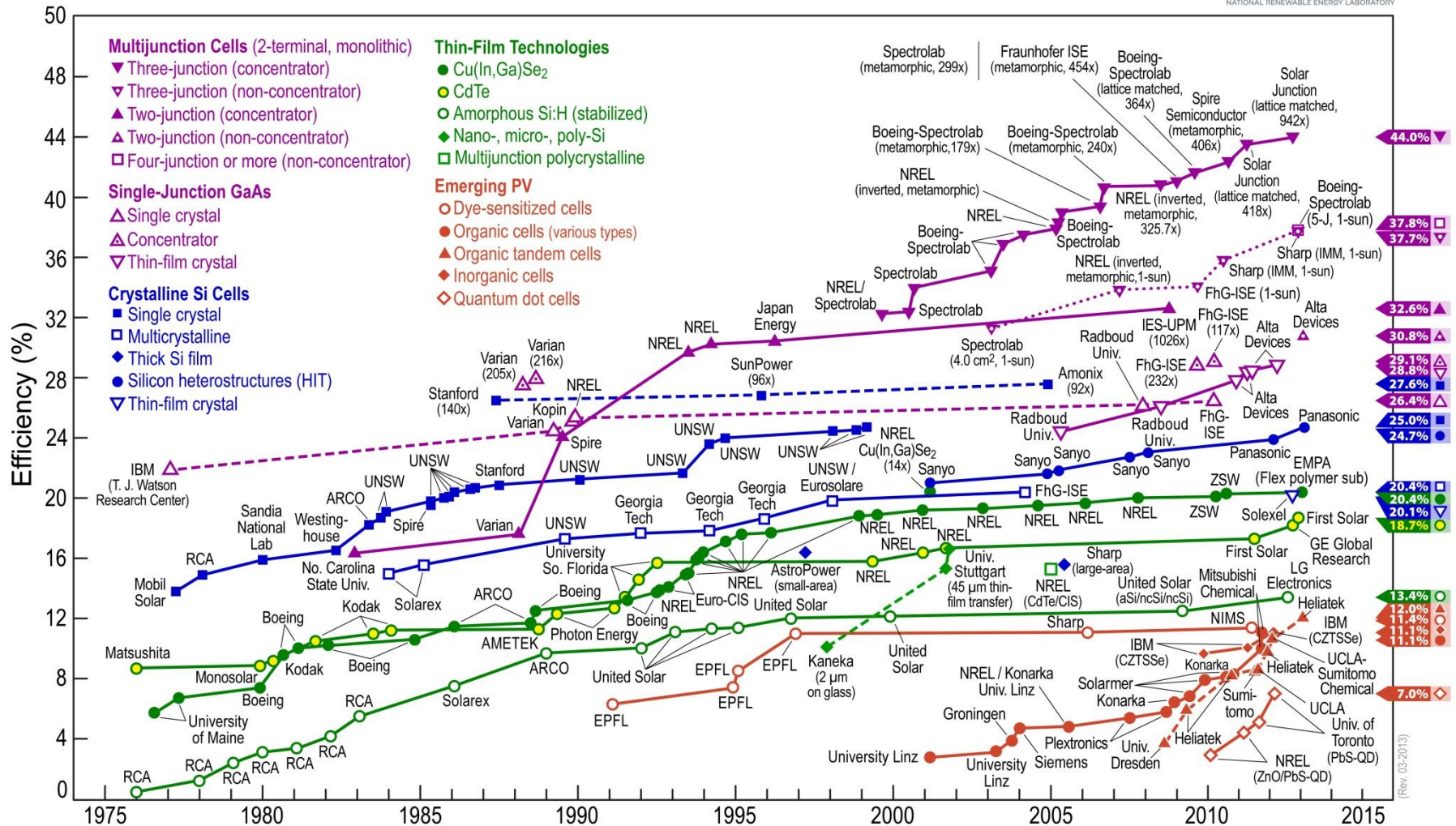
Theoretical Maximum Efficiency of c-Si Cells

- Knowing the solar spectrum and the band-gap of silicon, one can estimate the maximum theoretical efficiency of a silicon cell.
 - Nearly 20% of the sun's energy cannot be used to generate electron-hole pairs due to photons having less energy than the band-gap.
 - In addition, nearly 30% of the sun's energy is lost due to excess energy in photons with wavelengths shorter in $1.11 \mu\text{m}$.
 - Therefore the maximum theoretical efficiency of c-Si cells cannot exceed 50%.



Trend of PV cell efficiencies

Best Research-Cell Efficiencies

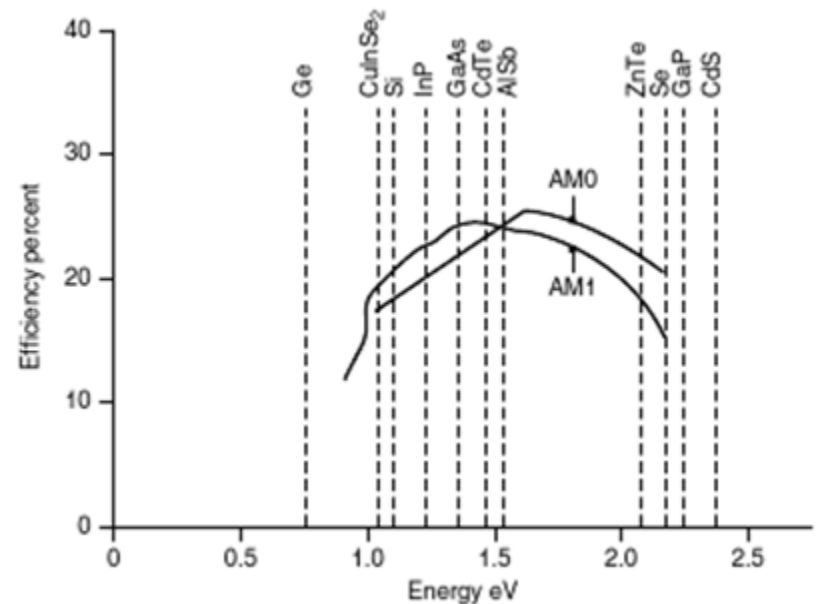


Trade-off between material with small band gap versus one with large band gap

- With a smaller band gap,
 - more solar photons have the energy needed to excite electrons, which is good since it creates the charges that will enable current to flow. However, a small band gap gives those charges a lower voltage.
- With a higher band gap,
 - fewer photons have enough energy to create the current-carrying electrons and holes, which limits the current that can be generated. On the other hand, a high band gap gives those charges a higher voltage.
- In summary, low band gap gives more current with less voltage while high band gap results in less current and higher voltage.
 - Since power is the product current and voltage, there must be some middle-ground band gap, usually estimated to be between 1.2 eV and 1.8 eV, which will result in the highest power and efficiency.

Impact of band gap on theoretical maximum efficiency of photovoltaics

Notice that the efficiencies are roughly in the 20 – 25% range (instead of 50%). Factors that contribute to the drop in theoretical efficiency are listed below.



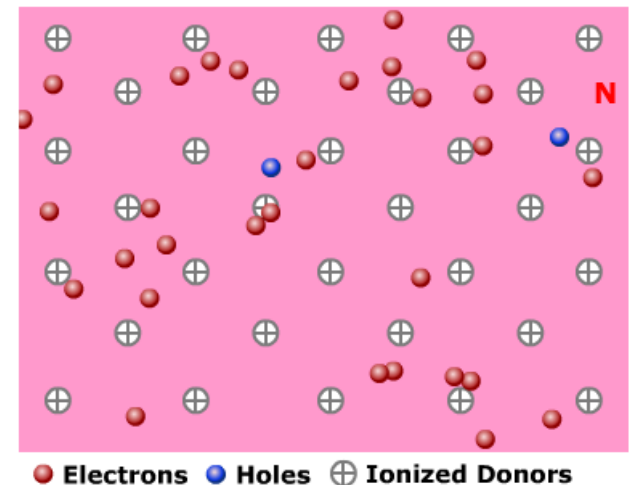
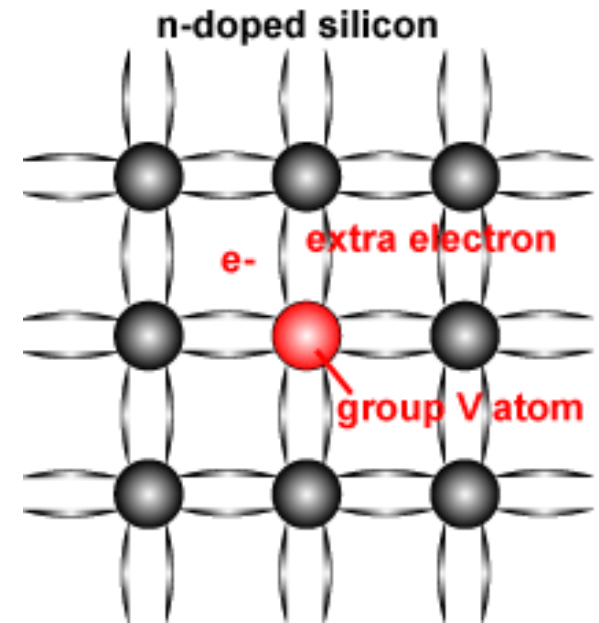
1. Only about half to two-thirds of the full band-gap voltage appears across the terminals of the solar cell.
2. Some holes and electrons recombine before they contribute to current flow.
3. Some photons are not absorbed in the cell either because they are reflected off the face of the cell, or because they pass right through the cell, or because they are blocked by the metal conductors that collect current from the top of the cell.
4. There is an internal resistance within the cell, which dissipates power.

The need to add impurities

- As long as a solar cell is exposed to photons with energies higher the band gap energy, hole– electron pairs will be created.
- The problem is, that those electrons can fall right back into holes, causing both charge carriers to disappear.
- To avoid this recombination, electrons in the conduction band must continuously be swept away from holes.
- 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.
- 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 an element from column III of the periodic chart (such as boron).
 - On the other side, atoms from column V are added (such as phosphorus).
 - Impurity ratio of 1/1,000,000 is typical.

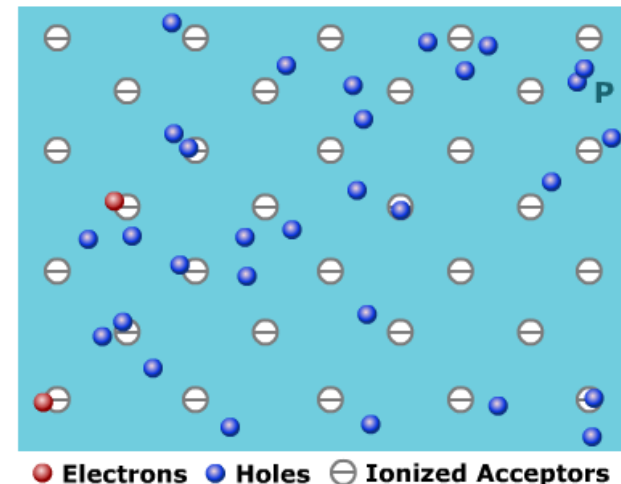
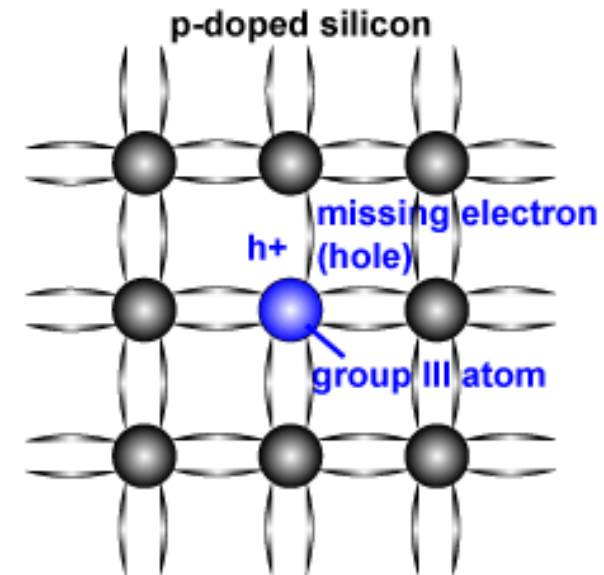
n-type material

- The pentavalent impurity forms covalent bonds with four adjacent silicon atoms.
 - Four of its five electrons are now tightly bound,
 - the fifth electron is left on its own to roam around the crystal.
- each donor atom can be represented as a single, fixed, *immobile positive charge plus a freely roaming negative charge*.
- Pentavalent elements donate electrons- so they are called **donor atoms**.
- Since there are now negative charges that can move around the crystal, a semiconductor doped with donor atoms is referred to as an "**n-type material**."
- In doped materials, there is always more of one type of carrier than the other.
- The type of carrier with the higher concentration is called a "**majority carrier**", while the lower concentration carrier is called a "**minority carrier**."



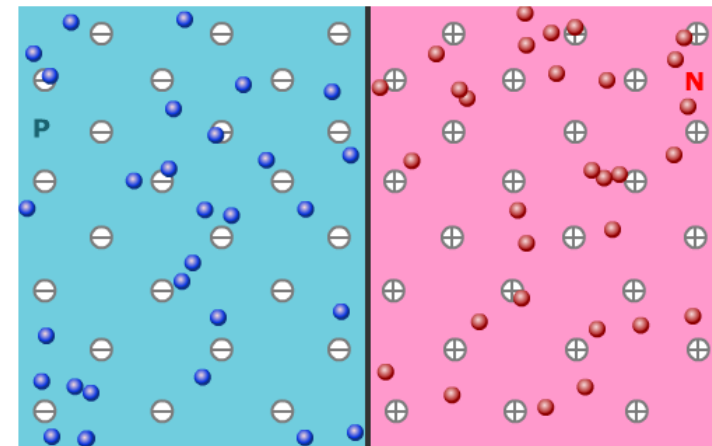
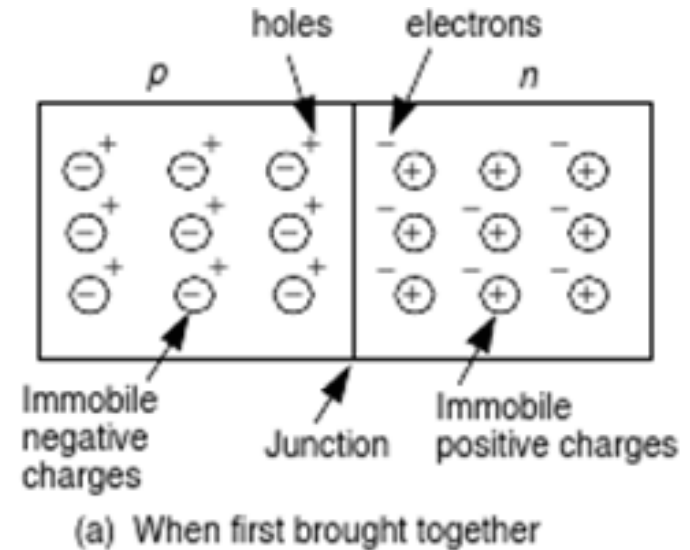
p-type material

- Since each of the trivalent impurity atoms has only three electrons, only three of the covalent bonds are filled, which means that a positively charged hole appears next to its nucleus.
- An electron from a neighboring silicon atom can easily move into the hole, so these impurities are referred to as **acceptors** since they accept electrons.
- The filled hole now means there are four negative charges surrounding a nucleus. All four covalent bonds are now filled creating *a fixed, immobile net negative charge at each acceptor atom*.
- Meanwhile, each acceptor has created a positively charged hole that is free to move around in the crystal, so this type of the semiconductor is called a **“p-type material”**.
- Holes are the majority carriers in a p-type material.



Forming a p-n junction

- Initially, mobile electrons and holes drift by diffusion across the junction.
- when an electron crosses the junction it fills a hole, leaving an immobile positive charge behind in the n-region.
- Similarly, when a hole crosses the junction, it is filled by an electron, while leaving an immobile negative charge behind in the p-region.
- These exposed immobile charged atoms in the p and n regions near the junction create an electric field that works against the continued movement of electrons and holes across the junction.
- As the diffusion process continues, the electric field increases until the movement comes to a near stop.

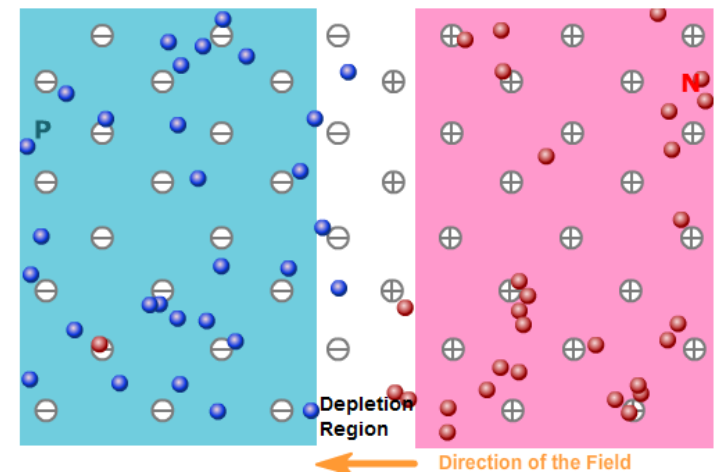
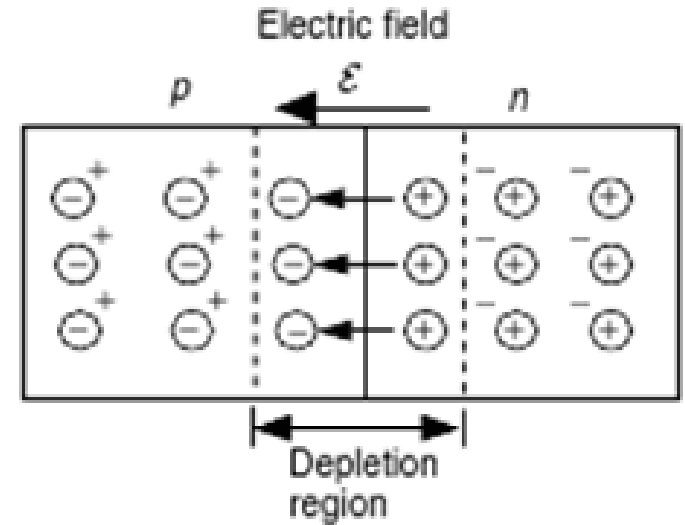


Depletion region

- The immobile charges creating the electric field in the vicinity of the junction form what is called a **depletion region**, meaning that the mobile charges are depleted from this region.
- The arrow of the electric field points in the direction that holds the mobile positive holes in the p-region, while it repels the electrons back into the n-region.
- The electric field creates an electrical potential difference across the p-n junction:

$$V = Ed$$

where d is the width of the depletion region.



Diffusion and drift currents

- Even at thermal equilibrium, some carriers may have sufficient energy to cross this region by diffusion, resulting in what is referred to as a **diffusion current**, and become minority carriers before recombining.
- Minority carriers which reach the edge of the depletion region are swept across it by the electric field, resulting in what is referred to as **drift current**.
- At equilibrium, the electron drift current and the electron diffusion current exactly balance out. Similarly, the hole drift current and the hole diffusion current also balance each other out. The net current through the junction is zero.

