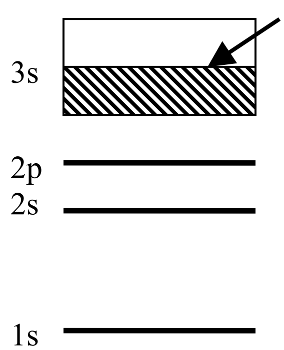
Conductors

- Only free electrons near the **Fermi surface** (energy $\varepsilon \approx \varepsilon_F$) can conduct.
- To conduct electrons must acquire energy to **jump** from the **valence** to the **conduction** band. In electronic devices, energy is usually supplied by a battery.
- # of **conduction electrons**, N_c, is less than # of **free electrons**, N_f.
- # of **conduction electrons**, N_c, depends on temperature.

Example I: Solid sodium (Na), Z = 11, $1s^2 2s^2 2p^6 3s^1$. For a Na atom, the single valence electron is in the **half-filled** $3s$ subshell. The $3s$ subshell is both the **valence** and **conduction** bands.

Band Structure of Solid Sodium (Na)

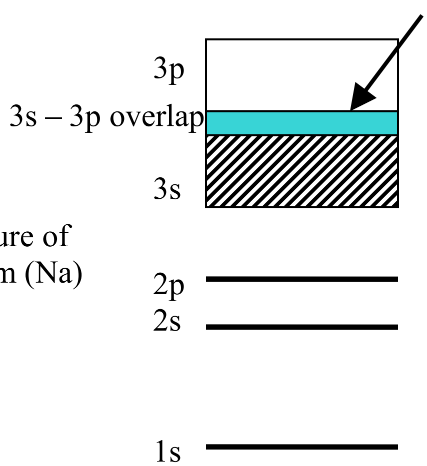


ε_F - Fermi Energy

- The 3s band is the Valence Band and Conduction Band
- Electrons near Fermi surface (ones with energy $\varepsilon \approx \varepsilon_F$) can conduct in the 3s conducting band

Example II: Solid Magnesium (Mg), Z = 12, $1s^2 2s^2 2p^6 3s^2$. For an Mg atom, the two valence electrons are in the **filled** $3s$ subshell. For many elements, in order to conduct, the electrons near the **Fermi surface** in the **filled valence band** would have to cross a **band gap** to reach the **conduction band**. However, for magnesium the $3s$ **valence band** overlaps with the $3p$ **conducting band**, and there is no **gap**. Hence Mg is a conductor.

Band Structure of Solid Sodium (Na)



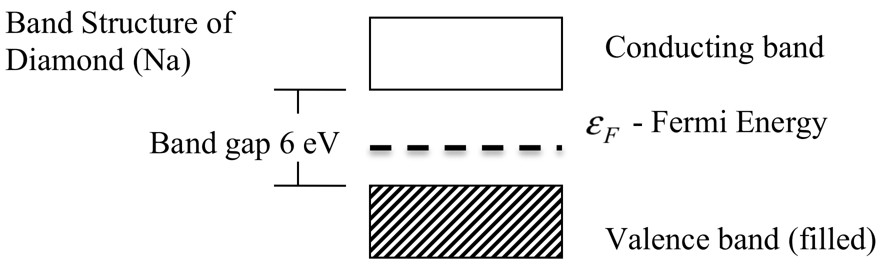
ε_F - Fermi Energy

Conducting band

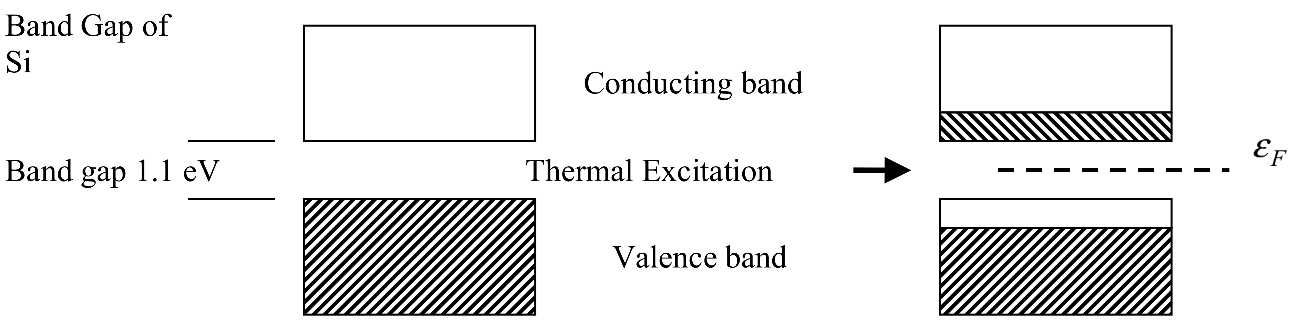
Valence band (filled)

- Electrons near Fermi surface (ones with energy $\varepsilon \approx \varepsilon_F$) in the **3s valence band** can conduct into the **3p conducting band** since there is **no band gap**.

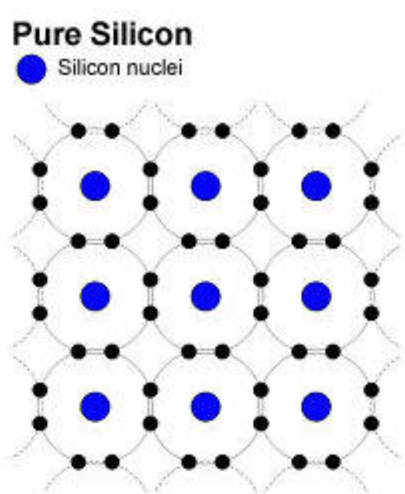
Insulators (diamonds, rubber….) **LARGE BAND GAP** (> 5 eV) between **valence** and **conduction** bands prevent conduction, even when voltages are applied.



Semiconductors (Germanium, Ge, Silicon, Si,….) **RELATIVELY SMALL BAND GAP** ($\approx 1\,\text{eV}$) between **valence** and **conduction** bands allows conduction at sufficiently high temperature.



- At low temperature <<< $273^\circ K$, electrons do not conduct.
- At room temperature ($300^\circ K$) thermal excitations ($kT \approx 0.025\,\text{eV}$) induce a small number of electrons to enter the conduction bands. On application of a voltage these electrons can conduct.
- Silicon and Germanium are the most common intrinsic (pure) semiconductors.

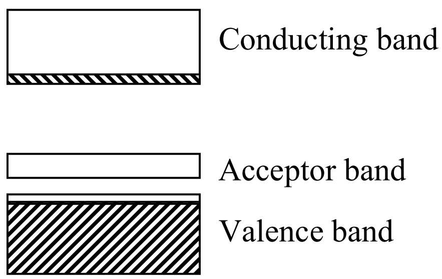


Microscopic Illustration of Silicon

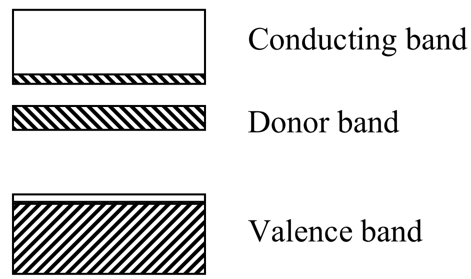
Consider Silicon (Si) with Z = 14, with electronic configuration, $1s^2 2s^2 2p^6 3s^2 3p^2$, with **four electrons**, $3s^2 3p^2$, in the n = 3 shell. The four electrons of an atom is shared with its four silicon neighbors, which contribute one electron each. In this way the silicon is said to form "metallic" bonds, where the electrons that binds the nuclei may also move throughout the solid.

Impurity Semiconductors are **doped**, which means impurities (boron, arsenic, gallium…) are introduced to alter the band structure resulting in enhanced conduction.

p - type

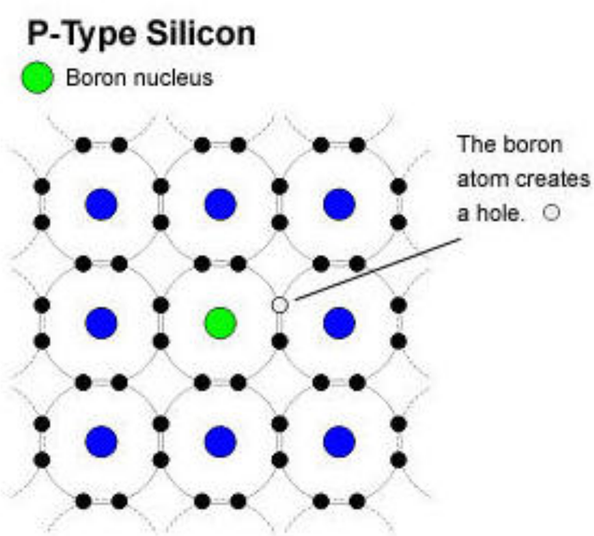


n - type



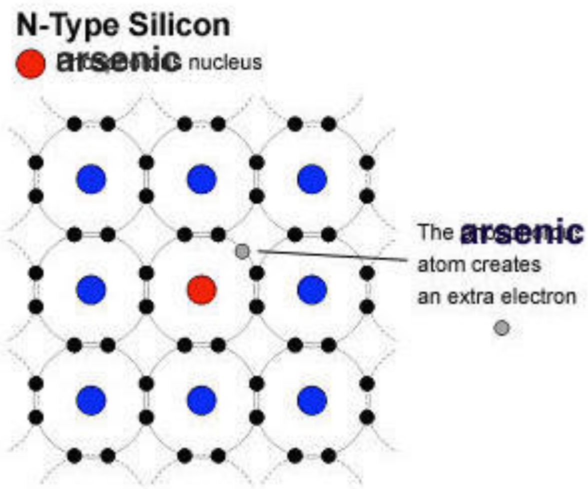
- Impurity with high electron affinity such as B, Al, and Ga giving an **acceptor band**
- Free electrons near **Fermi surface** can be thermally excited to **acceptor band** leaving **positively charged conducting holes**

- Impurity such as P, As, and Sb donates electrons giving a **donor band**
- **Donor band** is near the **conducting band** reducing the **effective band gap**



Microscopic Illustration of p-type semiconductor:

Boron has Z = 5, with configuration $1s^2 2s^2 2p^1$, and **three** electrons in the valence shell $2s^2 2p^1$, which is one fewer than in Silicon. When a Boron atom is introduced as an impurity in Silicon, it is missing one electron, which creates a vacancy (a hole) in the "bond network". When a "neighboring" electron moves to fill a vacancy, it creates a "virtual" positive hole currents. In solid-state physics the holes are quasi-particle with a mass, m_n, which is usually greater than the mass of the electron. The vacancy creates a **acceptor band**, which accepts electrons from the valence band, leading to currents.



<u>Microscopic Illustration of n-type semiconductor:</u>

Arsenic (As) has Z = 33, with configuration: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^3$, with **five electrons**, $4s^2 4p^3$, in the n = 4 valence shell., and **three** electrons in the valence shell, which is one more than in Silicon. When an As atom is introduced as an impurity in Silicon, has an extra electron, which creates a donor band that can easily moves into the conduction band.

<u>Optical Properties of Solids</u>

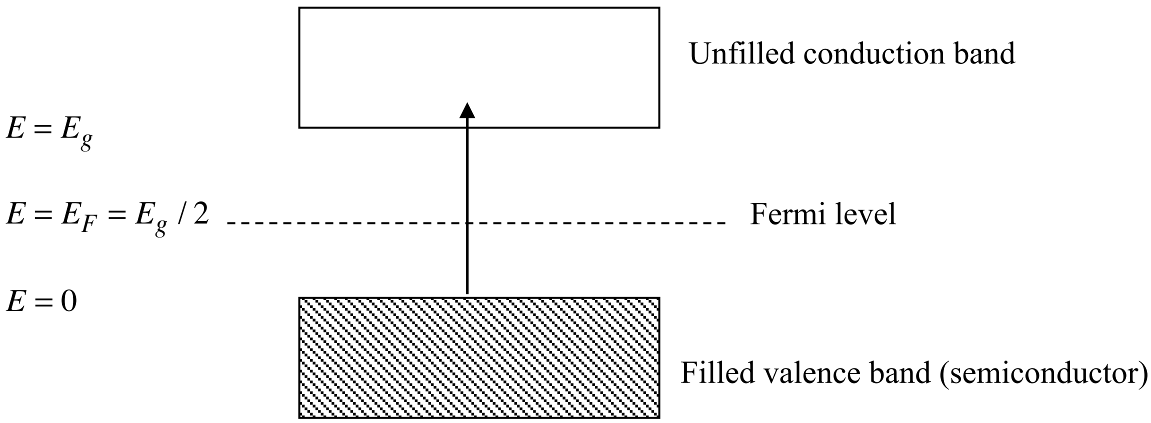
Note that the energy of a photon in the visible region is 1 to 3 eV.

1. <u>Conductor</u> free electron near the Fermi surface can absorbed visible light without leaving their valence band. Characteristic metal luster is due to the re-radiation of absorbed light.
2. <u>Insulators</u> free electrons can absorb only photons with energy equal to or greater than the band, which at $\approx 6\,\text{eV}$ is too large for visible light. This is why diamonds are **transparent**. Other insulators are not transparent due to structural irregularities.
3. <u>Semiconductor</u> relatively small band gap ($\approx 1\,\text{eV}$) is comparable to that of visible light photons, so electrons can absorbed light and jump to the conduction band. This is why semiconductor is opaque (dull color).

<u>Hint for Problem 18 of Chapter 11</u>

The Fermi-Dirac factor is expressed in equation 9.34 as $F_{FD} = \dfrac{1}{\exp\left[\beta\left(E - E_F\right)\right] + 1}$. In a semiconductor or insulator, with and energy gap E_g between the valence and conduction bands, we can take the Fermi energy, E_F, to be halfway between the two bands, so that $E_F = E_g / 2$. (A) Show that for a typical semiconductor or insulator at room temperature the Fermi-Dirac factor is approximately equal to $\exp\left(-E_g / 2kT\right)$. (B) Use the result in (A) to compute the Fermi-Dirac factor for a typical insulator with $E_g = 8.0eV$ and T = 300 K. (C) Repeat for a semiconductor, silicon with $E_g = 1.1eV$ at T = 293 K. (D) Your results in C will still be small, but still large enough to explain why there are some conduction. Explain.

The diagram below explains the basic premise of the problem, where the valence band of a semiconductor is completely filled, but the conduction band is completely unfilled.



In terms of electronics, we are interested in the electrons near the top of the filled valence band that can conduct by crossing the energy gap. Students will do well by looking at the class notes, where I discussed why electrons inside the band (i.e. not near the top) **cannot conduct** due to Pauli exclusion principle. The probability of an electron crossing the gap is related to the Fermi-Dirac distribution equation 9.34, $F_{FD} = \dfrac{1}{\exp\left[\beta\left(E - E_F\right)\right] + 1}$.

Hence from the diagram it should be clear that $E \approx E_g = 2E_F$. Using this we have

$F_{FD} \approx \dfrac{1}{\exp\left[\dfrac{T_F}{T}\right] + 1}$ where $T_F = \dfrac{E_F}{k_B}$ is the Fermi temperature. Now you **must argue** that at room temperature, say T = 300 K, $F_{FD} \approx \exp\left(-\dfrac{E_g}{2K_B T}\right)$. Use this result to do part B, C, D.