Physics 5K Lecture Friday Apr 27, 2012

The Piezoelectric Effect, Ferroelectricity, the Photoelectric Effect, and why Metals Are Shiny

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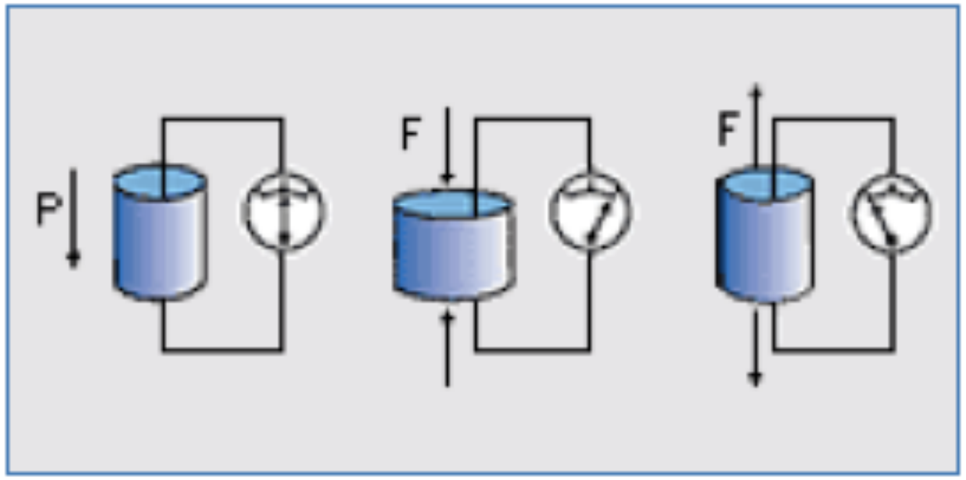
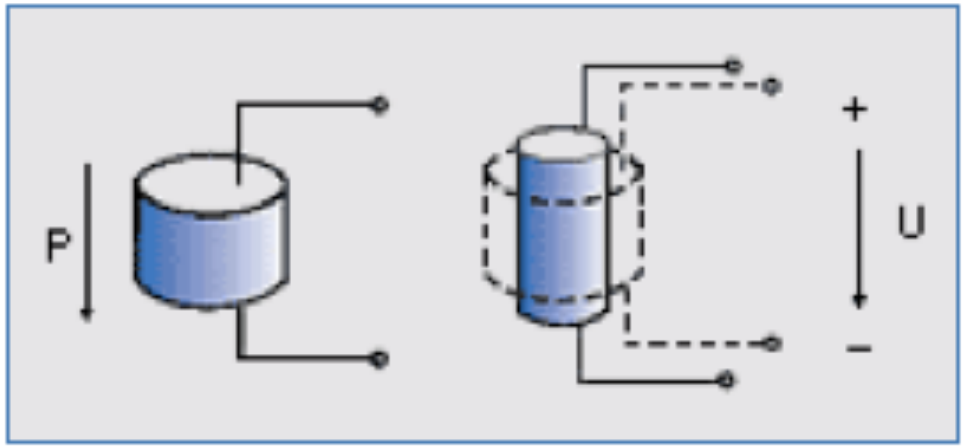
Piezoelectric Effect



The effect of a force on a piezoelectric cylinder

Sqeezing or stretching a piezoelectric crystal produces a voltage difference across it.

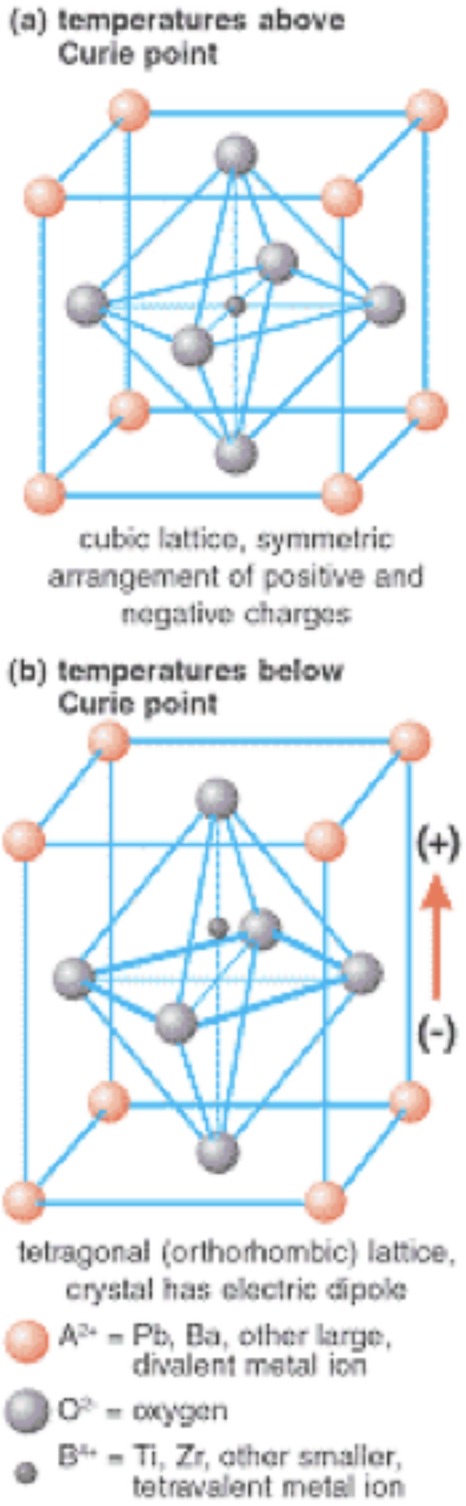


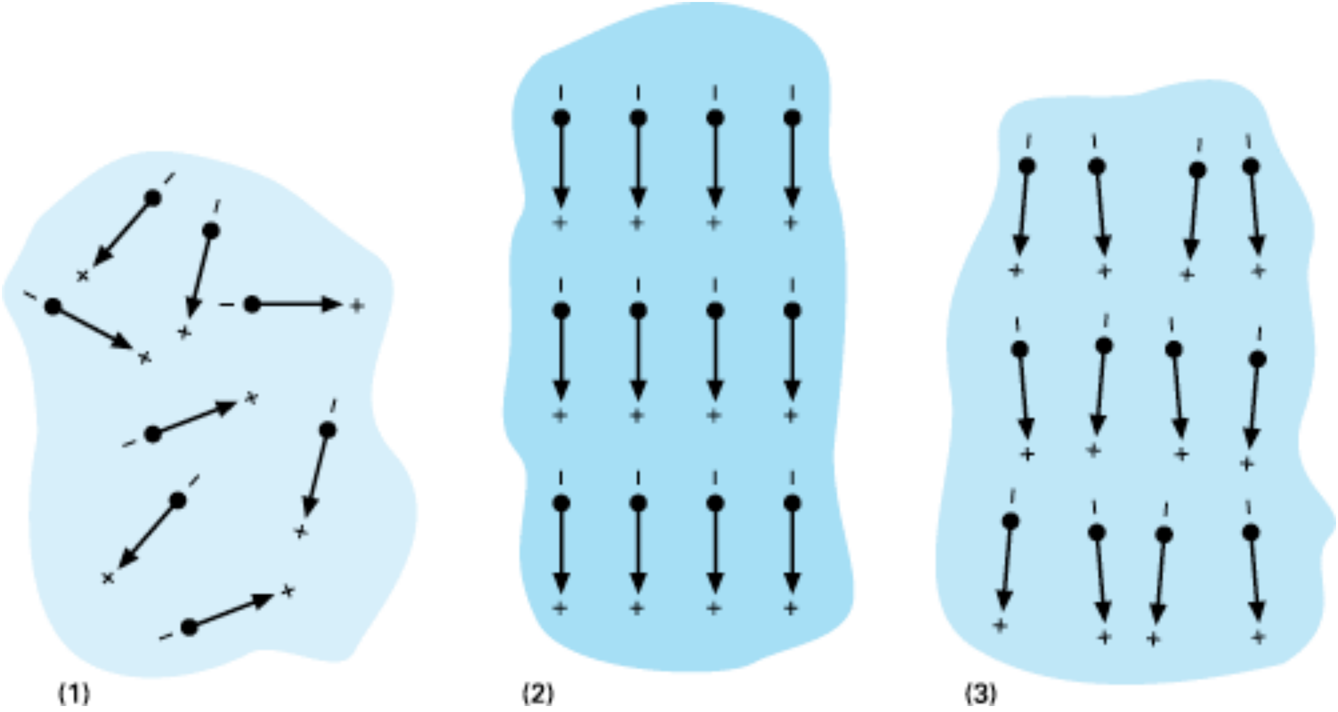
Deformation of a piezoceramic body when a voltage is applied

Applying a voltage across a piezoelectric crystal produces sqeezing or stretching.

The piezoelectric effect was discovered in 1880 by Pierre and Jacques Curie. The Curie point of the now-common piezoelectric material barium titanate $BaTiO_3$ with a perovskite crystal structure is 130° K.

Since the piezoelectric effect exhibited by natural materials such as quartz, tourmaline, Rochelle salt, etc., is small, polycrystalline ferroelectric ceramic materials such as $BaTiO_3$ and Lead Zirconate Titanate (Piezo) have been developed with improved properties. Such ferroelectric ceramics become piezoelectric when poled. Poling means heating and cooling the substance in a strong electric field, in order to align the electric dipole moments.

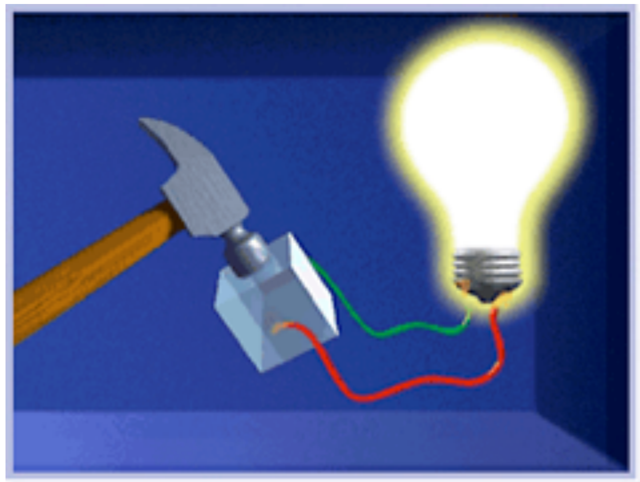




Before Poling Poling After Poling

The piezoelectric effect is used in lots of devices, including

Lighters – pressing the handle causes a spring-loaded hammer to strike a quartz crystal, producing a high enough voltage to cause a spark, igniting the gas



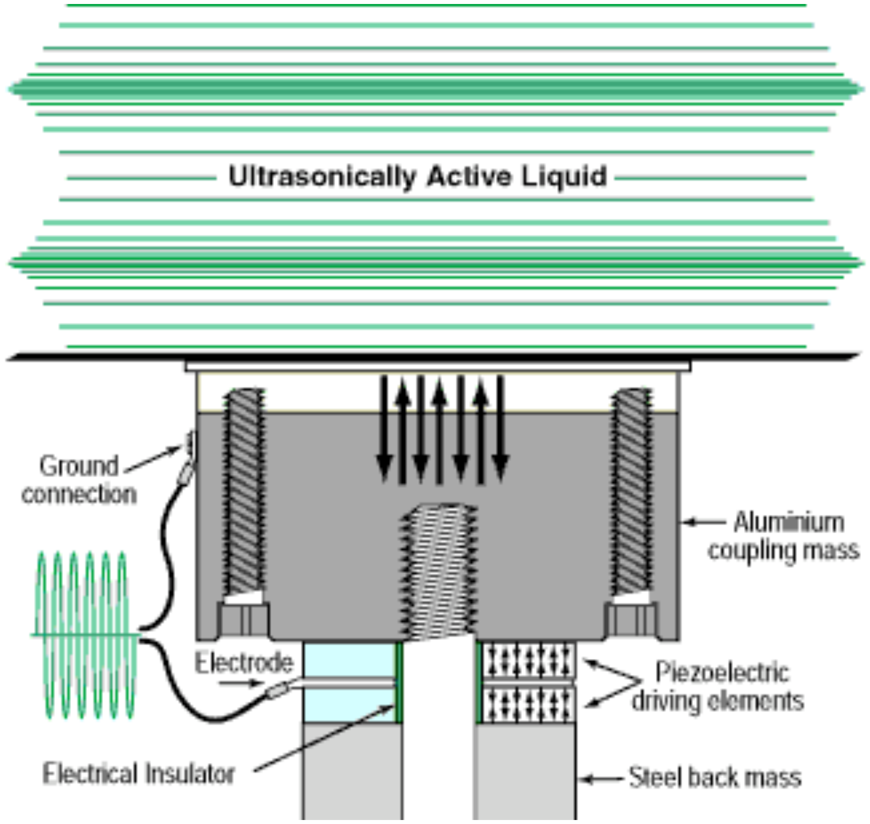
Piezoelectric (“Crystal”) microphones

Guitar pickup

Inkjet printers, particularly Epson’s, use piezoelectric crystals to control the inkflow

Quartz clocks and wristwatches – the oscillation frequency of the quartz crystal is determined by its size and shape; counting the voltage oscillations tells the time

Sound generators - tweeters in stereo loudspeakers, watch beepers, sonar, ultrasonic cleaners, etc.



Computer keybards

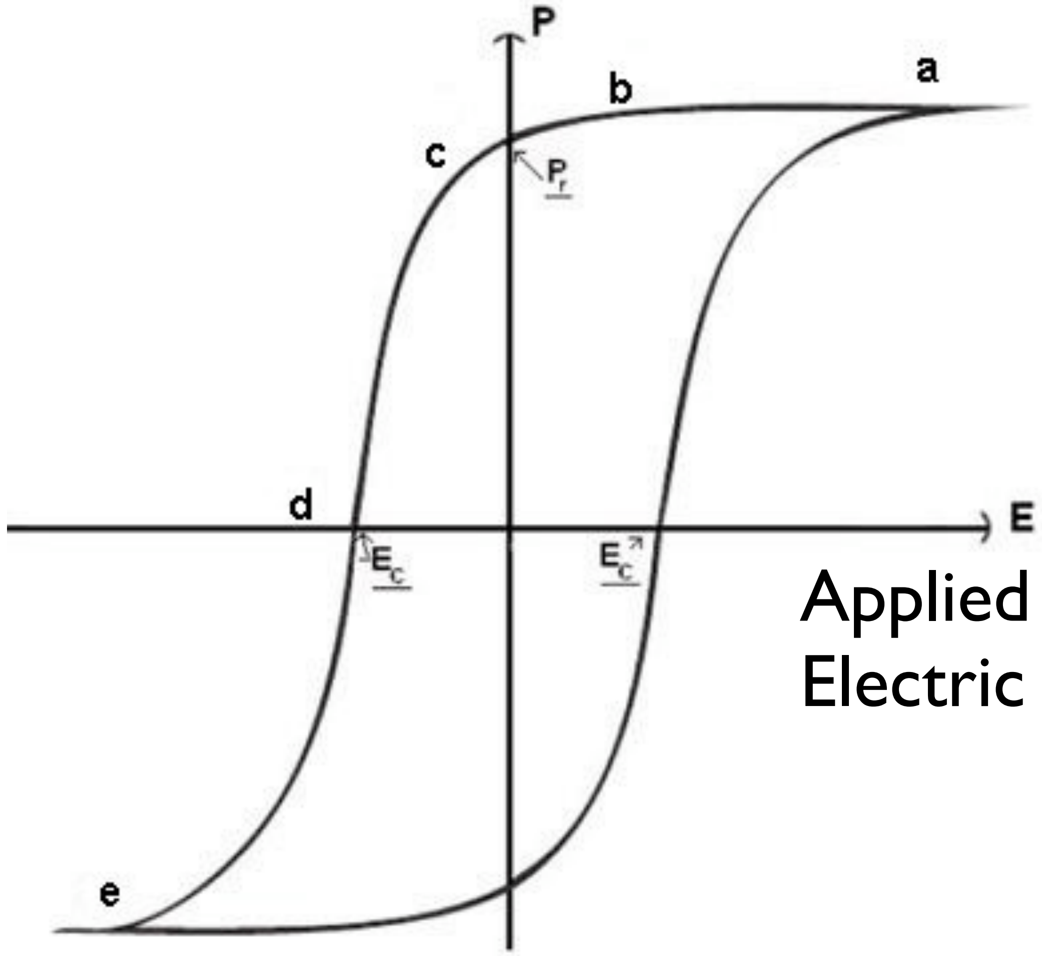
Ferroelectricity

When the field is removed (a→ c), the polarization of a ferroelectric material does not disappear as in a dielectric. The polarization that remains after a material has been fully polarized and then had the field removed is called the remanent polarization (P_r).

Only after a field is applied in the opposite direction to the original polarizing field does the polarization diminish significantly. There is a specific field which results in zero net polarization (d). This is called the coercive field (E_C).

Finally, if a sufficiently strong electric field is applied in the reverse direction, the polarization will reach its maximum value in the opposite direction (e).

Electric Polarization



Applied Electric Field

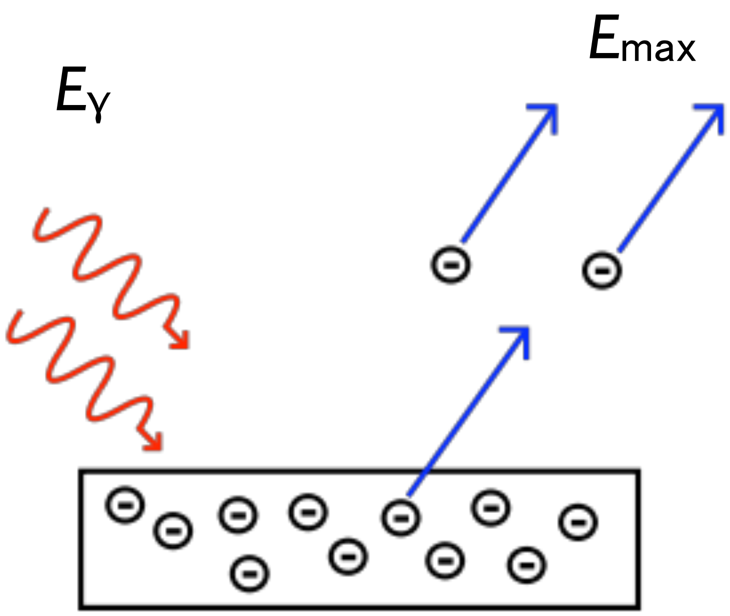
Hysteresis loop for a ferroelectric material.

Ferromagnetism is a similar magnetic phenomenon, first seen in iron -- hence the name, from ferrum, the Latin word for iron.

Photoelectric Effect

Experimental results on photoelectric emission

1. For a given metal and frequency of incident radiation, the rate at which photoelectrons are ejected is directly proportional to the intensity of the incident light.
2. For a given metal, there exists a certain minimum frequency of incident radiation below which no photoelectrons can be emitted. This frequency is called the threshold frequency.
3. Above the threshold frequency, the maximum kinetic energy of the emitted photoelectron is independent of the intensity of the incident light but depends on the frequency of the incident light.



Einstein's theory of the Photoelectric Effect:

Energy of photon = Energy needed to remove an electron + Kinetic energy of the emitted electron

Equivalent equation, with h = Planck's constant, ν = photon frequency, ϕ = work function of metal, and E_{max} = maximum kinetic energy of ejected electron :

$E_\gamma = h\nu = \phi + E_{max}$, or $E_{max} = h\nu - \phi$, $\Rightarrow$ $\nu_{threshold} = \phi / h$

Some work functions: Cu 4.7 eV, Al 4.1 eV, Na 2.3 eV

Einstein’s theory of the Photoelectric Effect (1905):

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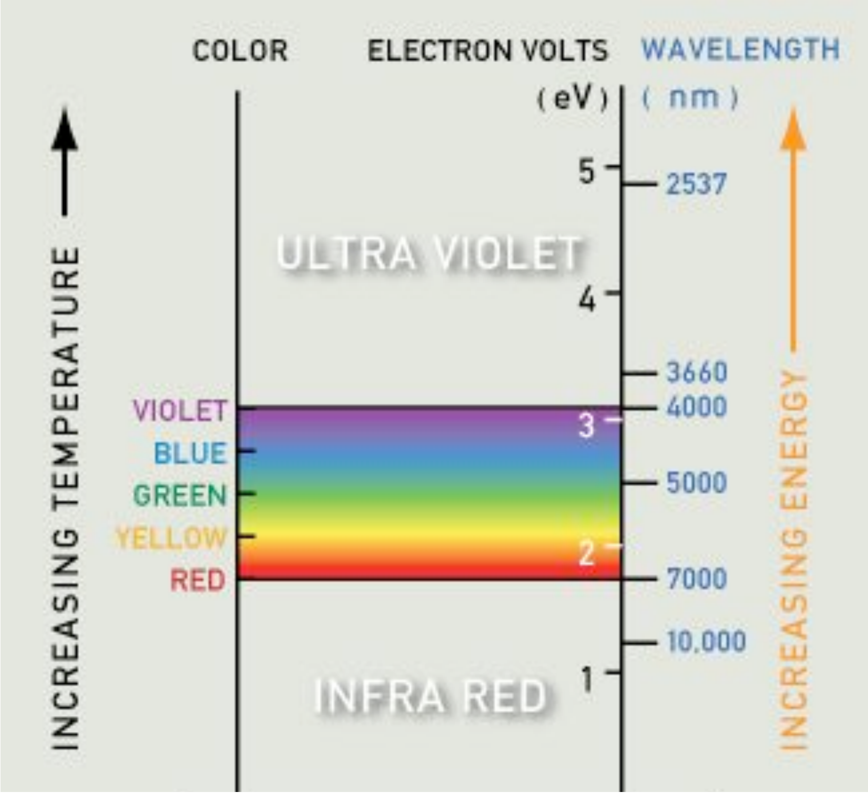
Significance:

In order to derive the observed spectrum P(ν) of black body radiation of frequency ν, Planck (1900) proposed that light is emitted in quanta of energy $E(\nu) = h\nu$, thus introducing a new fundamental constant of nature h = Planck’s constant = 6.626×10^{-34} J-s = 4.136×10^{-15} eV-s.

IN DIESEM HAUSE
LEHRTE
MAX PLANCK
DER ENTDECKER
DES ELEMENTAREN
WIRKUNGSQUANTUMS h
VON
1889 1928

A plaque for Max Planck, commemorating his discovery of the Planck constant, in front of Humboldt University, Berlin. English translation: "Max Planck, discoverer of the elementary quantum of action h, taught in this building from 1889 to 1928."



In his 1905 Photoelectric effect paper, Einstein postulated that photons are absorbed only in energy units $h\nu$, and thus that they only exist in these quanta of electromagnetic energy, or “photons”. Einstein continued to work on photons, predicting in 1917 the phenomenon of “stimulated emission” -- the basis of the laser.

Band Theory of Solids

When atoms combine to form substances, the outermost shells, subshells, and orbitals merge, providing a greater number of available energy levels for electrons to assume. When large numbers of atoms are close to each other, these available energy levels form a nearly continuous *band* wherein electrons may move as illustrated in Figure 2.20

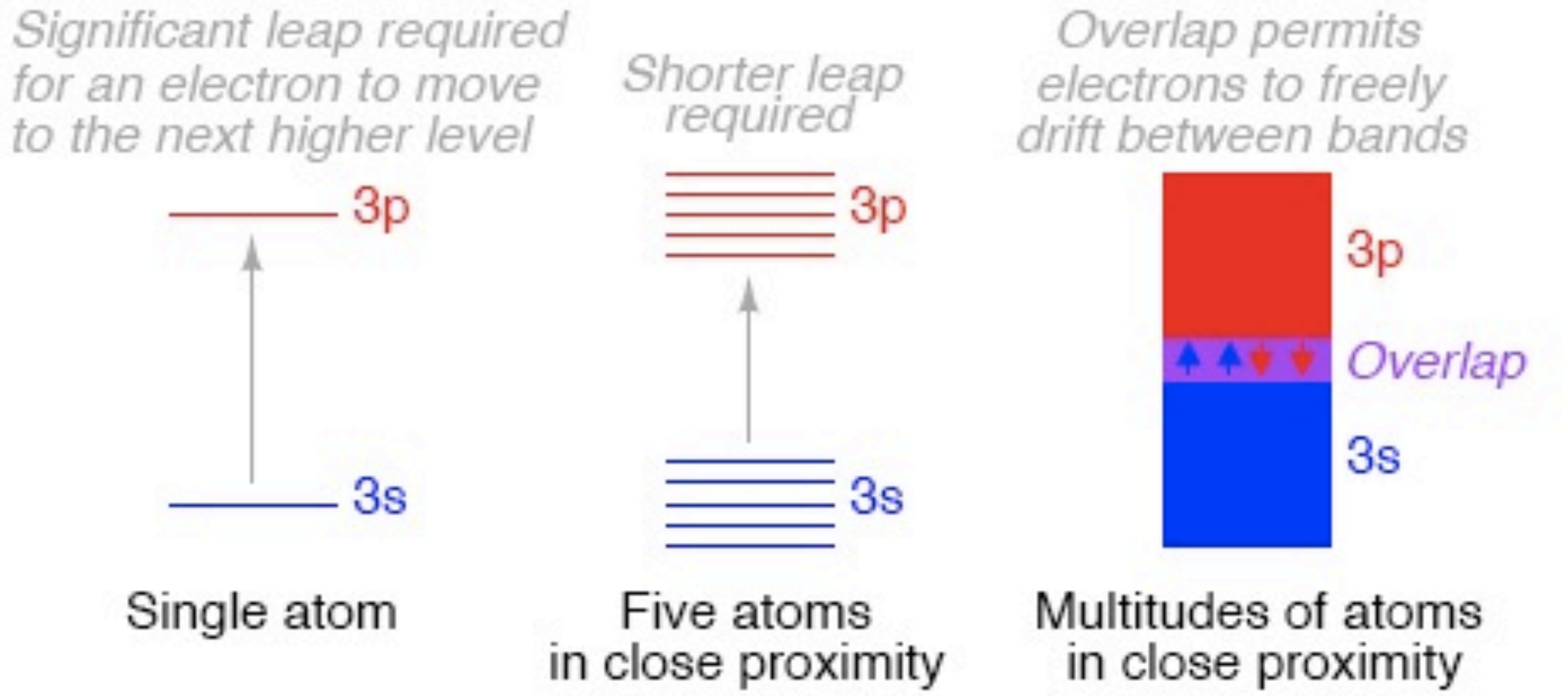


Figure 2.20: *Electron band overlap in metallic elements.*

It is the width of these bands and their proximity to existing electrons that determines how mobile those electrons will be when exposed to an electric field. In metallic substances, empty bands overlap with bands containing electrons, meaning that electrons of a single atom may move to what would normally be a higher-level state with little or no additional energy imparted. Thus, the outer electrons are said to be "free," and ready to move at the beckoning of an electric field.

From *Lessons In Electric Circuits, Volume III – Semiconductors*
By Tony R. Kuphaldt - Fifth Edition, last update July 02, 2007

Band overlap will not occur in all substances, no matter how many atoms are close to each other. In some substances, a substantial gap remains between the highest band containing electrons (the so-called *valence band*) and the next band, which is empty (the so-called *conduction band*). See Figure 2.21. As a result, valence electrons are "bound" to their constituent atoms and cannot become mobile within the substance without a significant amount of imparted energy. These substances are electrical insulators.

Materials that fall within the category of *semiconductors* have a narrow gap between the valence and conduction bands. Thus, the amount of energy required to motivate a valence electron into the conduction band where it becomes mobile is quite modest. (Figure 2.22)

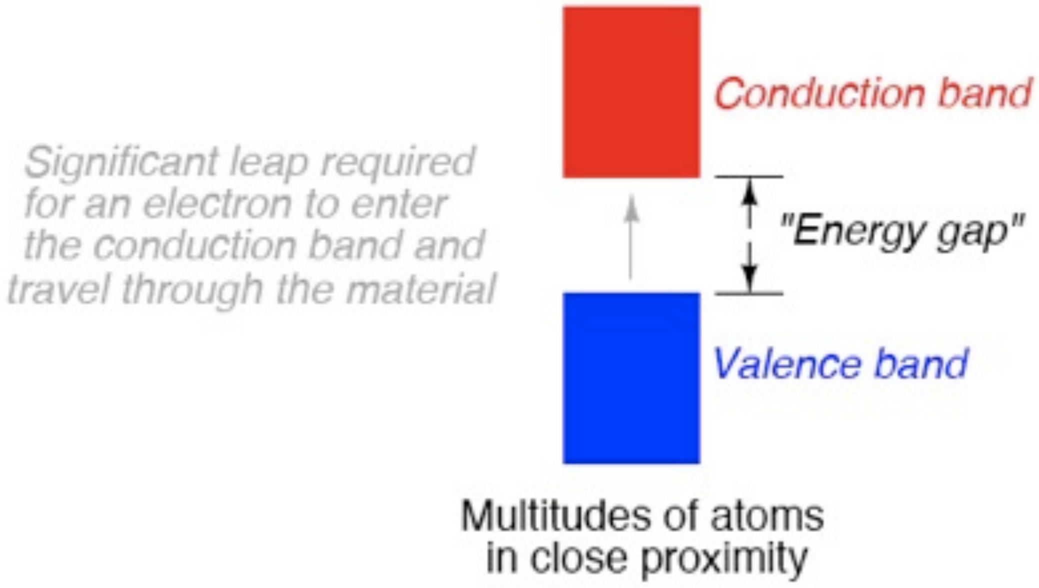


Figure 2.21: *Electron band separation in insulating substances.*

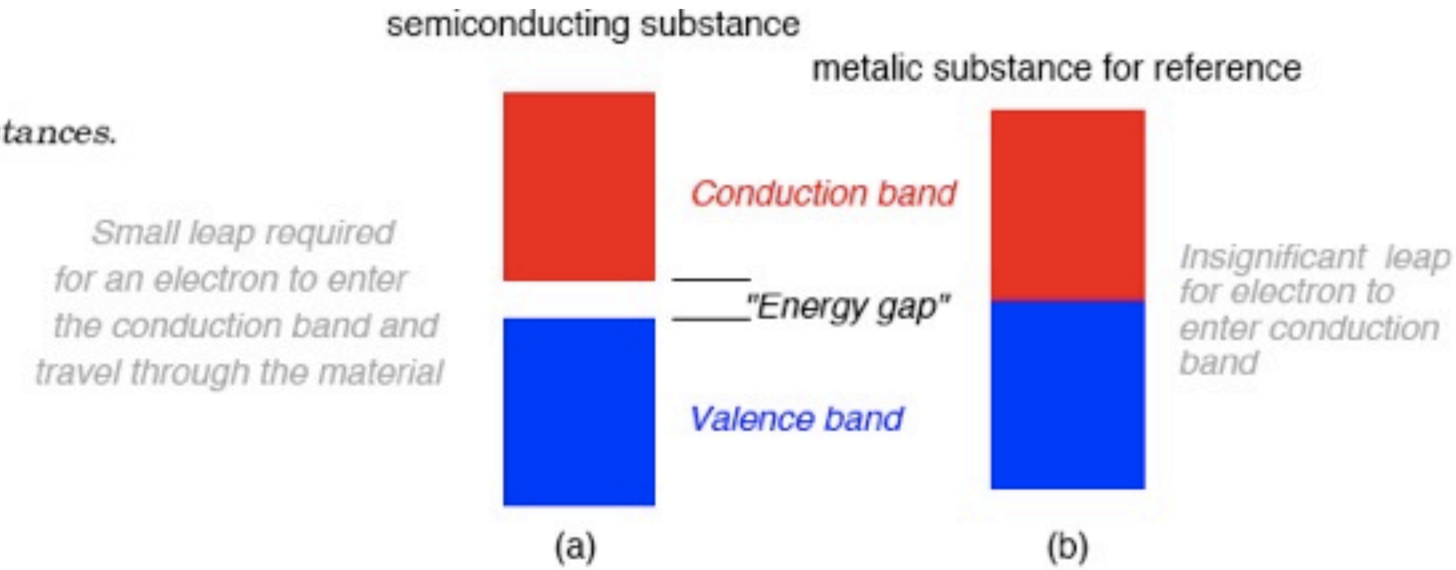


Figure 2.22: *Electron band separation in semiconducting substances, (a) multitudes of semiconducting close atoms still results in a significant band gap, (b) multitudes of close metal atoms for reference.*

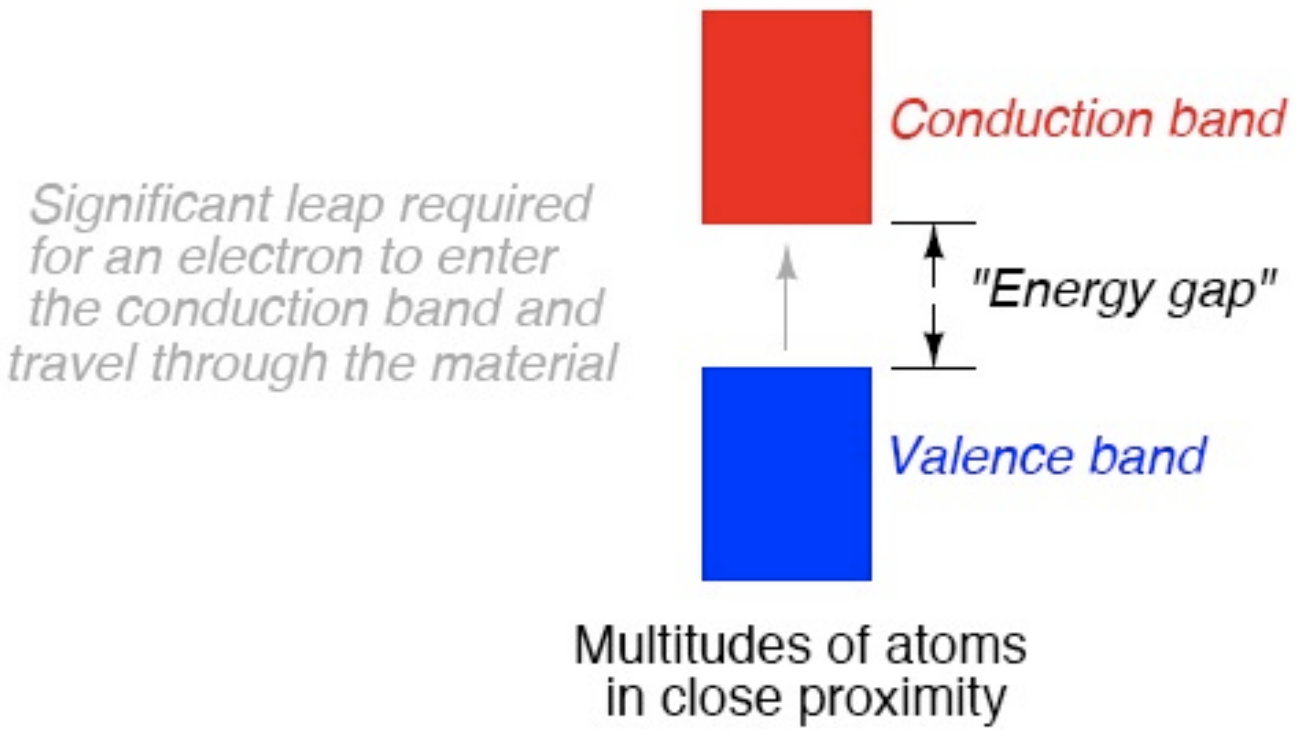
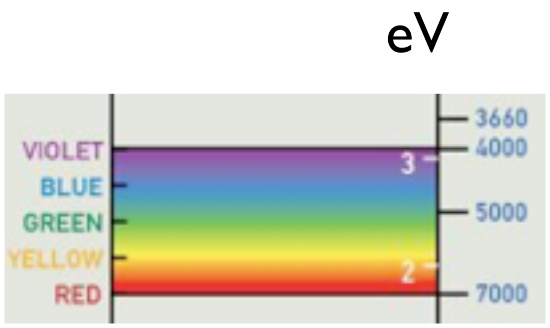
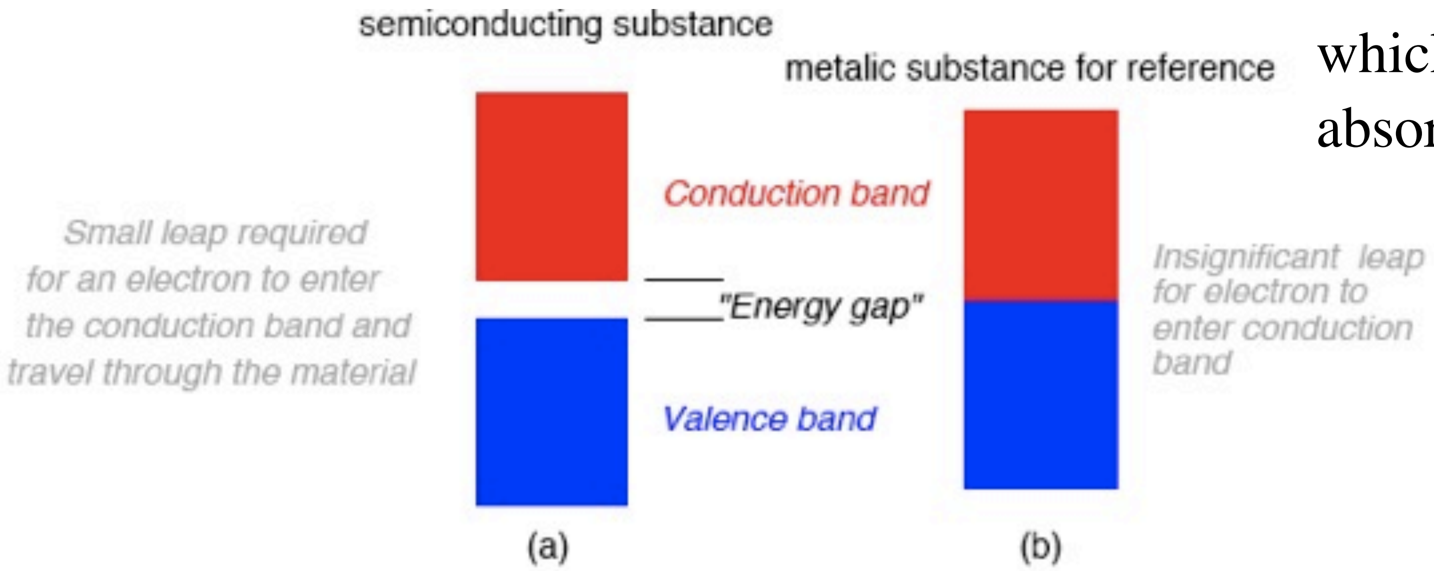


Figure 2.21: *Electron band separation in insulating substances.*



If the Energy gap is larger than the energy of visible light (~3.2 eV), then the insulator will be transparent. Glass is an example. A very small percentage of impurity atoms in the glass can give it color by providing specific available energy levels which absorb certain colors of visible light.

Another example: Ruby is aluminum oxide with a small amount (about 0.05%) of chromium, which gives it its characteristic red color by absorbing green and blue light.



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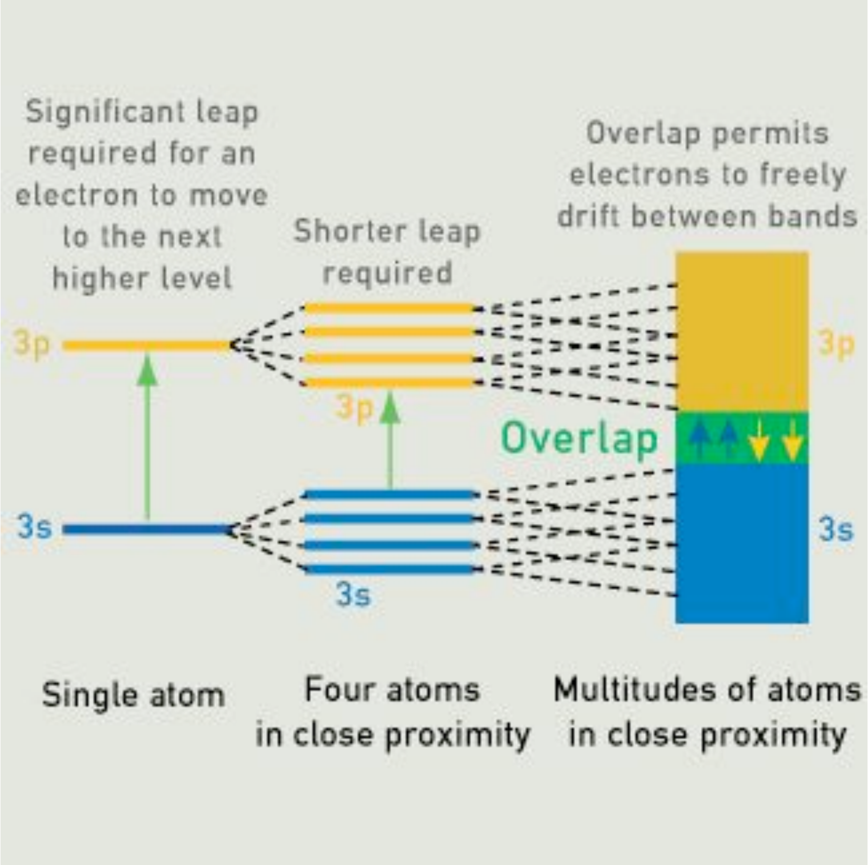
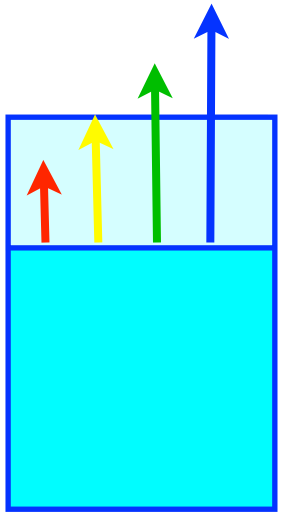
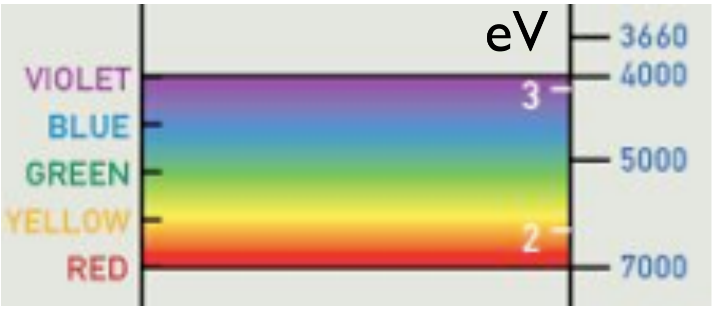


Metals reflect light because the oscillating electric field of the light makes the free electrons in the metals oscillate.

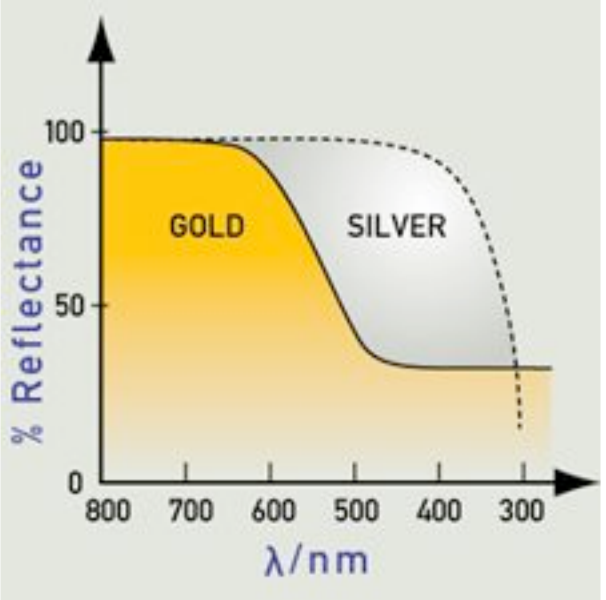


Empty Conduction Band Levels

Filled Conduction Band Levels



(Note: the actual situation is more complicated since the work function of Cu is 4.7 eV.)



Metals are colored because the absorption and re-emission of light are dependent on wavelength. Gold and copper have low reflectivity at short wavelengths, and yellow and red are preferentially reflected, as the color here suggests. Silver has good reflectivity that does not vary with wavelength, and therefore appears close to white.

Transmitted color of gold: gold is so malleable that it can be beaten into gold leaf less than 100 nm thick, revealing a bluish-green color when light is transmitted through it. Gold reflects yellow and red, but not blue or blue-green. There's gold leaf letters in the UCSC sign at the main entrance.