PHY 114 A General Physics II
11 AM-12:15 PM TR Olin 101

Plan for Lecture 24 (Chapter 43):

Some topics in the physics of molecules and solids

1. Physics of atoms
2. Physics of molecules
3. Physics of solids

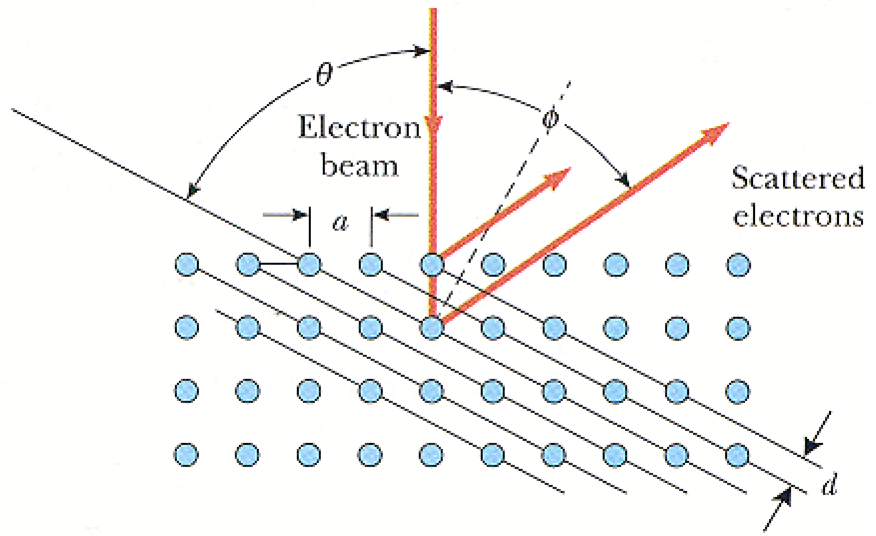
13	03/08/2012	Faraday's law	31.1-31.5	31.12,31.23,31.40	03/20/2012
	03/13/2012	*No class (Spring Break)*			
	03/15/2012	*No class (Spring Break)*			
14	03/20/2012	Induction and AC circuits	32.1-32.6	32.4,32.20,32.43	03/22/2012
15	03/22/2012	AC circuits	33.1-33.9	33.8,33.24,33.71	03/27/2012
16	03/27/2012	Electromagnetic waves	34.1-34.3	34.3,34.10,34.13	03/29/2012
17	03/29/2012	Electromagnetic waves	34.4-34.7	34.22,34.46,34.57	04/03/2012
18	04/03/2012	Ray optics Evening exam	35.1-35.8	35.20,35.27,35.35	04/10/2012
19	04/05/2012	Image formation Evening exam	36.1-36.4	36.8,36.31,36.42	04/10/2012
20	04/10/2012	Image formation	36.5-36.10	36.52,36.54,36.64	04/12/2012
21	04/12/2012	Wave interference	37.1-37.6	37.2,37.19,37.29	04/17/2012
22	04/17/2012	Diffraction	38.1-38.6	38.24,38.30,38.37	04/19/2012
23	04/19/2012	Quantum Physics	40.1-42.10	40.41,41.12,42.10	04/24/2012
24	04/24/2012	Molecules and solids Evening exam	43.1-43.8	43.2,43.40,43.43	05/01/2012
25	04/26/2012	Nuclear reactions Evening exam	45.1-45.4	45.6,45.20,45.30	05/01/2012
26	05/01/2012	Nuclear radiation	45.5-45.7		
	05/08/2012	Final exam 9 AM			

Webassign hint:

2. –/0.334 points My Notes

In the Davisson-Germer experiment, 54.0 eV electrons were diffracted from a nickel lattice. If the first maximum in the diffraction pattern was observed at ϕ = 50.0°, what was the spacing *d* between the planes of atoms causing this diffraction?

nm



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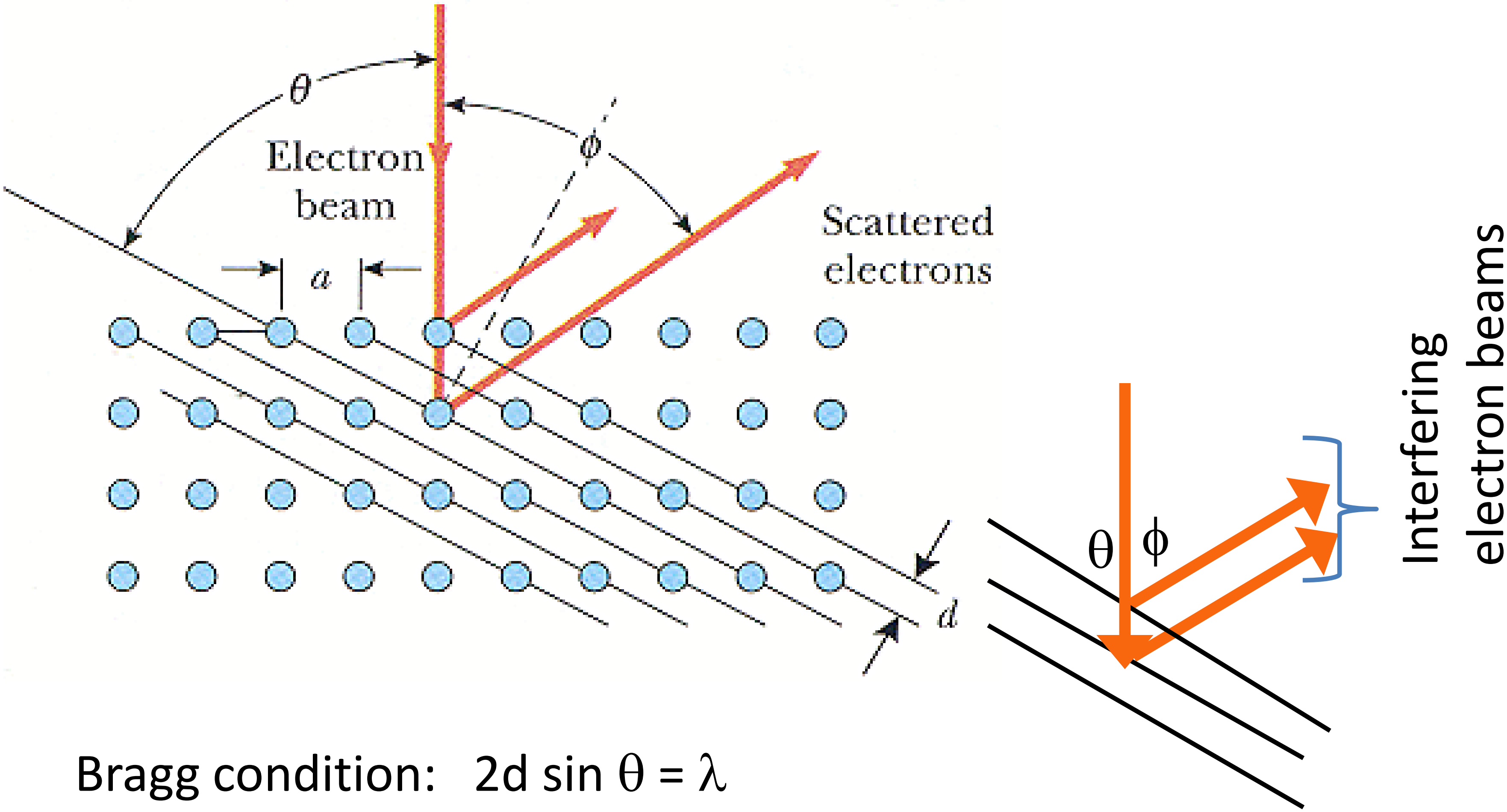
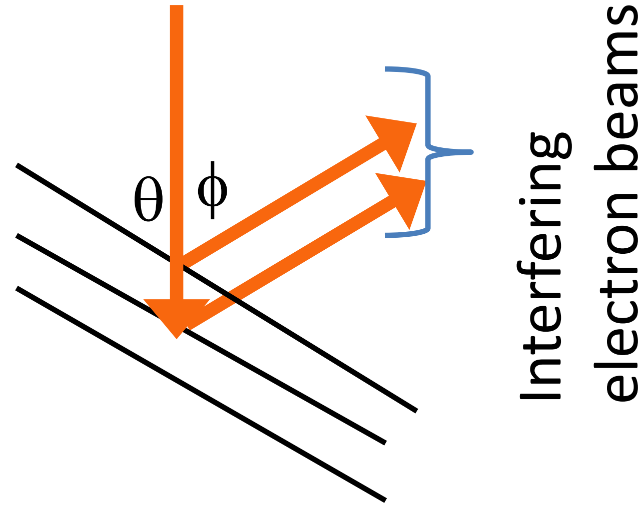
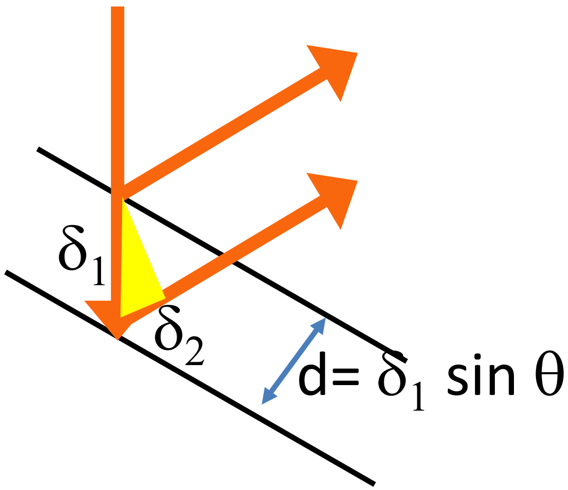


Bragg condition: $2d \sin\theta = \lambda$

Webassign hint -- continued:

Bragg condition: $2d \sin\theta = \lambda$





$$\delta_1 + \delta_2 = 2d \sin\theta = m\,\lambda$$

Some ideas of quantum theory discussed last time:

Matter wave equation – Schrödinger equation:

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial \mathbf{r}^2}+U(\mathbf{r})\right]\Psi(\mathbf{r},t)=-i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t)$$

Stationary-state wavefunctions: $\Psi(\mathbf{r},t)=\psi(\mathbf{r})e^{-iEt/\hbar}$

In this case, the Schrodinger equation becomes:

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial \mathbf{r}^2}+U(\mathbf{r})\right]\Psi(\mathbf{r},t)=E\Psi(\mathbf{r},t)$$

Here Planck's constant: $h=6.63\times10^{-34}\,J$

$$\hbar\equiv\frac{h}{2\pi}=1.05\times10^{-34}\,J$$

$$\text{Example -- free particle -- } U(r)=0: \quad \Psi(\mathbf{r},t)=\psi(\mathbf{r})e^{-iEt/\hbar}$$

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\right]\Psi(x,t)=E\Psi(x,t)$$

$$\Psi(x,t)=\Psi_0\sin(kx)e^{-iEt/\hbar}$$

$$E=\frac{\hbar^2k^2}{2m} \quad \text{Note: This is consistent with de Broglie's } \lambda=\frac{h}{p}$$

$$k=\frac{2\pi}{\lambda} \;\Rightarrow\; \lambda=\frac{h}{\sqrt{2mE}} \quad \text{or} \quad E=\frac{h^2}{2m\lambda^2}$$

Example: Suppose we want to create a beam of electrons (m=9.1x10^{-31}kg) for diffraction with λ=1x10^{-10}m. What is the energy E of the beam?

$$E=\frac{h^2}{2m\lambda^2}=\frac{\left(6.6\times10^{-34}J\right)^2}{2\cdot9.1\times10^{-31}kg\cdot\left(10^{-10}m\right)^2} \quad =2.4\times10^{-17}J=150eV$$

Recall de Broglie's relation between wavelength and momentum:

$$\lambda = \frac{h}{p} \qquad h = 6.6 \times 10^{-34} J$$

Which has the larger de Broglie wavelength:

A. An electron with a velocity of 100 m/s (mass = 9.1×10^{-31} kg)
B. A baseball with a velocity of 100 m/s (mass = 1 kg)

Another example -- electron bound to a proton:

(H atom) $U(r) = -\frac{Ze^2}{4\pi\varepsilon_0 r}$

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial \mathbf{r}^2} + U(\mathbf{r})\right]\Psi(\mathbf{r},t) = -i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t)$$

Stationary-state wavefunctions: $\Psi(\mathbf{r},t) = \psi(\mathbf{r})e^{-iEt/\hbar}$

$$\text{Solutions:} \quad E_n = -\frac{Z^2e^2}{8\pi\varepsilon_0 a_0}\frac{1}{n^2} = -13.6\frac{Z^2}{n^2}\,\text{eV} \qquad n = 1,2,3\cdots$$

$$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{me^2} = 0.0529\,\text{nm}$$

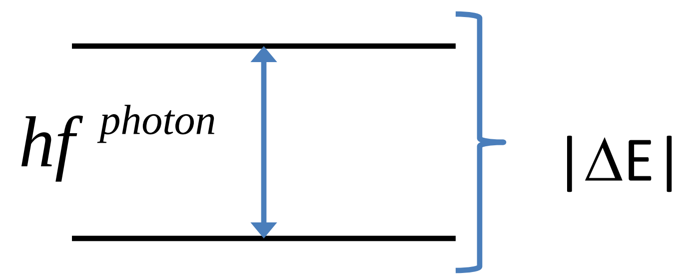
Quantum theory for electromagnetic radiation

The transition between bound quantum states can correspond to the emission (production) or absorption (consumption) of electromagnetic quanta:

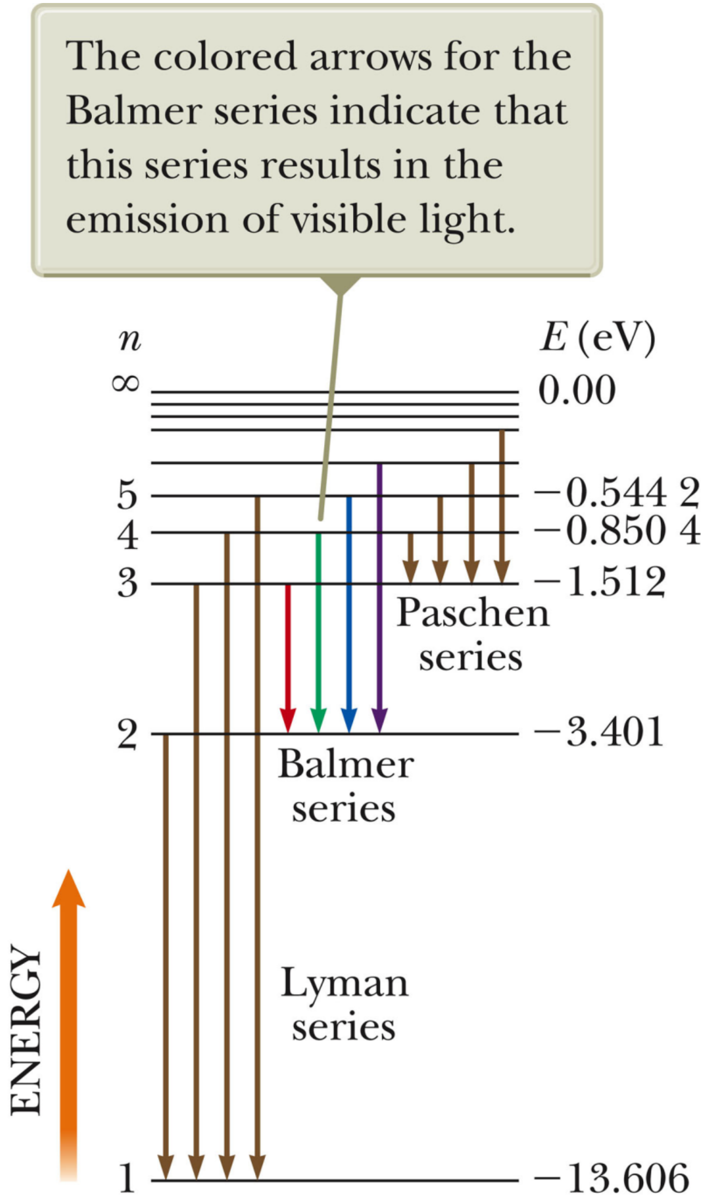
Coupling of states of matter with EM radiation :

$$hf^{\,photon} = \frac{hc}{\lambda^{photon}} = \left| E_{final} - E_{initial} \right| = \left| \Delta E \right|$$

$$\lambda^{photon} = \frac{hc}{\Delta E} \approx \frac{1234}{\Delta E_{12}(eV)}\, nm$$



Energy level diagram for H atom



$$E_n = -\frac{Z^2 e^2}{8\pi\varepsilon_0 a_0}\frac{1}{n^2}$$

$$= -13.6\frac{Z^2}{n^2}\,\text{eV} \qquad n = 1,2,3\cdots$$

Radiation produced by "emission" or the transition from $n_1 \rightarrow n_2$

Examples (for $Z = 1$):

$$E_2 - E_1 = (-3.401) - (-13.606) = 10.205eV$$

$$\lambda_{12}^{\ photon} = \frac{hc}{\Delta E_{12}} \approx \frac{1234}{\Delta E_{12}(eV)} nm = 120nm$$

$$E_3 - E_1 = (-1.512) - (-13.606) = 12.094eV$$

$$\lambda_{13}^{\ photon} = \frac{hc}{\Delta E_{13}} \approx \frac{1234}{\Delta E_{13}(eV)} nm = 100nm$$

$$E_\infty - E_1 = (-0.000) - (-13.606) = 13.606eV$$

$$\lambda_{1\infty}^{\ photon} = \frac{hc}{\Delta E_{1\infty}} \approx \frac{1234}{\Delta E_{1\infty}(eV)} nm = 90nm$$

Physics of molecules – H_2

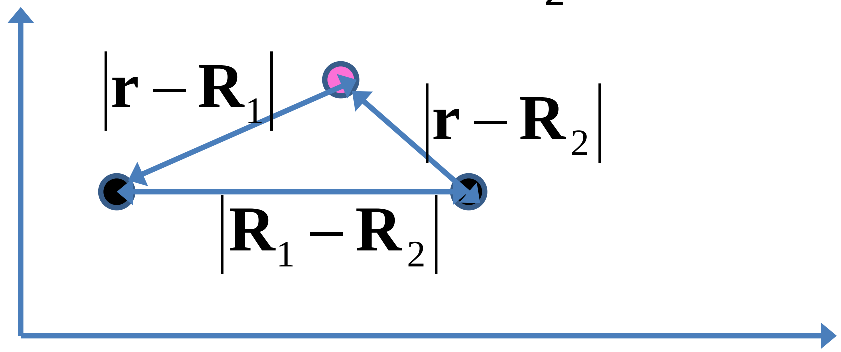
Recall for H atom:

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial \mathbf{r}^2}-\frac{Ze^2}{4\pi\varepsilon_0 r}\right]\psi(\mathbf{r})=E\,\psi(\mathbf{r})$$

$$\text{For ground state:}\quad E_1=-\frac{Z^2e^2}{8\pi\varepsilon_0 a_0}$$

$$\psi_1(\mathbf{r})=\frac{1}{\sqrt{\pi a_0^3}}e^{-r/a_0}$$

Physics of molecules – H_2 -- continued

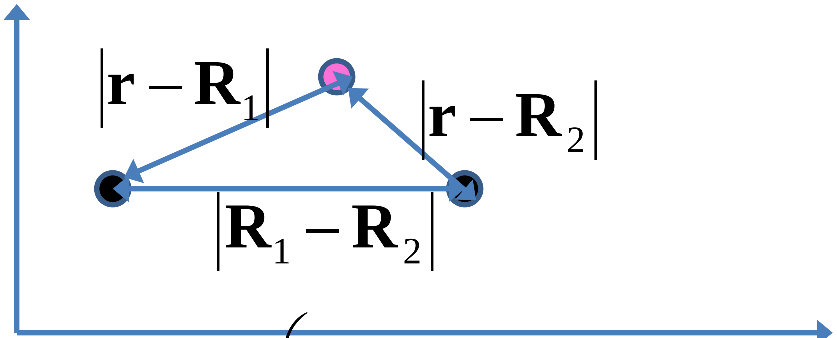


$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial \mathbf{r}^2}-\frac{Ze^2}{4\pi\varepsilon_0|\mathbf{r}-\mathbf{R}_1|}-\frac{Ze^2}{4\pi\varepsilon_0|\mathbf{r}-\mathbf{R}_2|}\right]\psi(\mathbf{r})=E\,\psi(\mathbf{r})$$

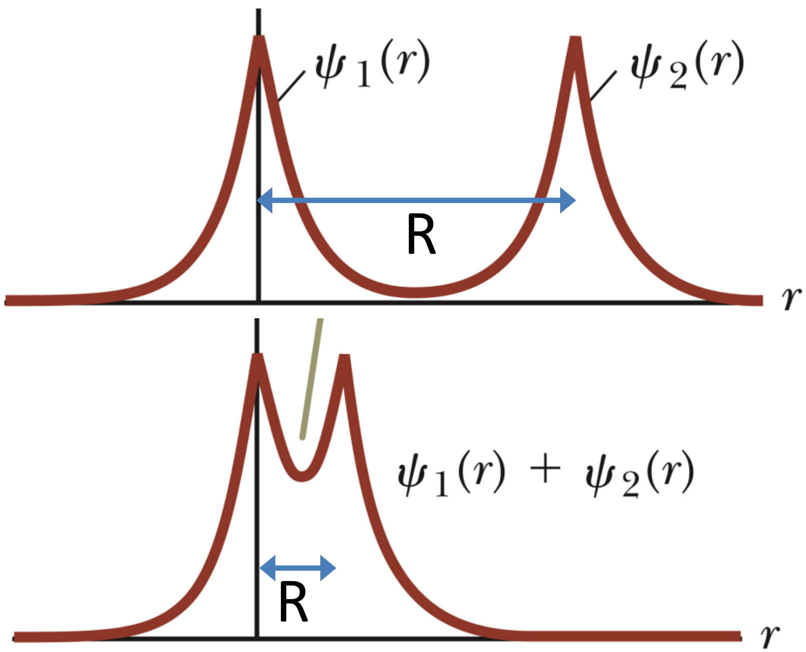
Approximate solutions :

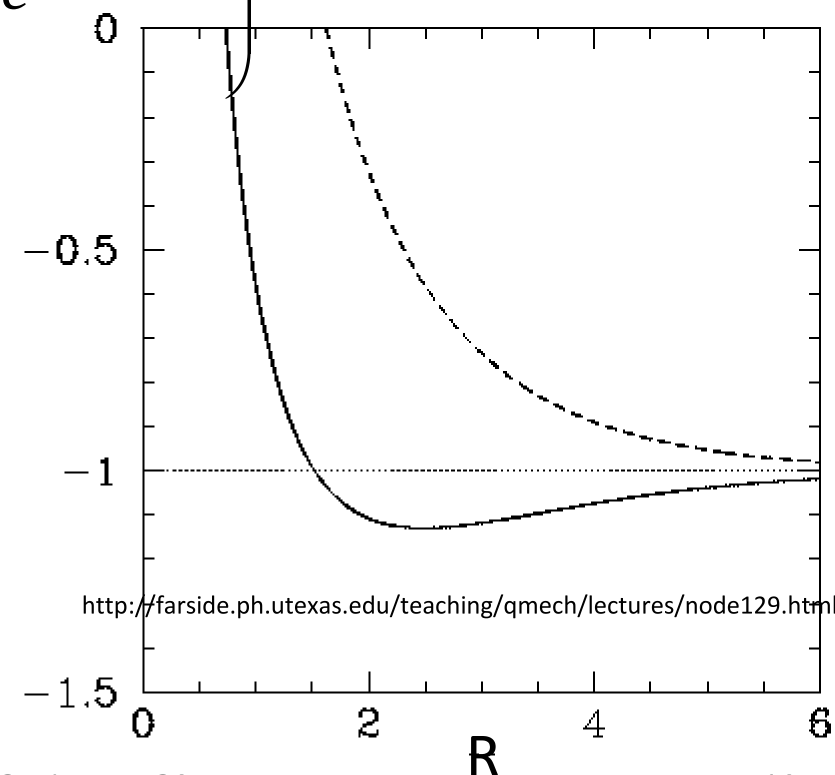
$$\psi_{approx}(\mathbf{r})=C\left(\frac{1}{\sqrt{\pi a_0^3}}e^{-|\mathbf{r}-\mathbf{R}_1|/a_0}\pm\frac{1}{\sqrt{\pi a_0^3}}e^{-|\mathbf{r}-\mathbf{R}_2|/a_0}\right)$$

Physics of molecules – H_2 -- continued



$$\psi_{approx}(\mathbf{r}) = C\left(\frac{1}{\sqrt{\pi a_0^3}} e^{-|\mathbf{r}-\mathbf{R}_1|/a_0} \pm \frac{1}{\sqrt{\pi a_0^3}} e^{-|\mathbf{r}-\mathbf{R}_2|/a_0} \right)$$

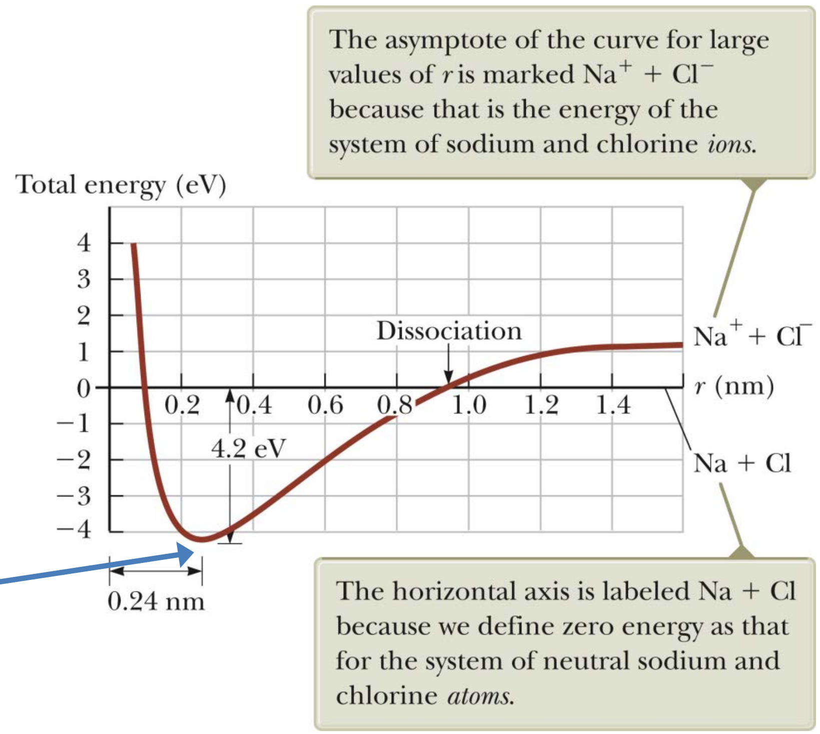




http://farside.ph.utexas.edu/teaching/qmech/lectures/node129.html

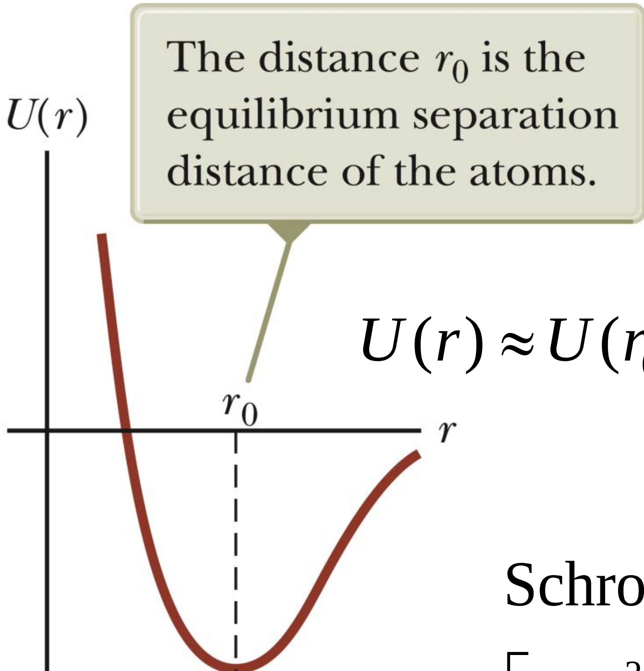
Physics of molecules – continued

Energy diagram for NaCl molecule as a function of ion separation

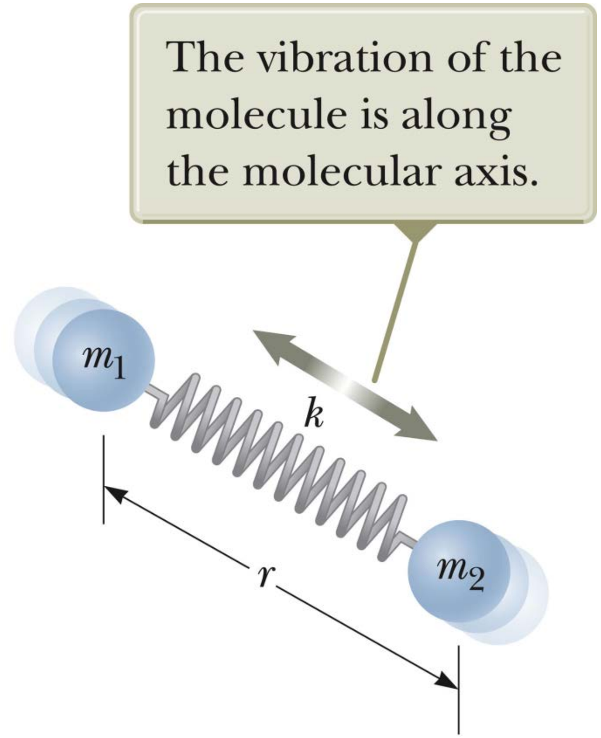


Stable equilibrium

Physics of molecules – continued
Vibration about equilibrium point



$$U(r) \approx U(r_0) + \frac{1}{2}k(r - r_0)^2$$



Schrodinger equation for vibrating nuclei

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + \frac{1}{2}kx^2\right]\psi(\mathbf{r}) = E\,\psi(\mathbf{r})$$

Here $m = \dfrac{m_1 m_2}{m_1 + m_2}$ $\quad x = r - r_0$

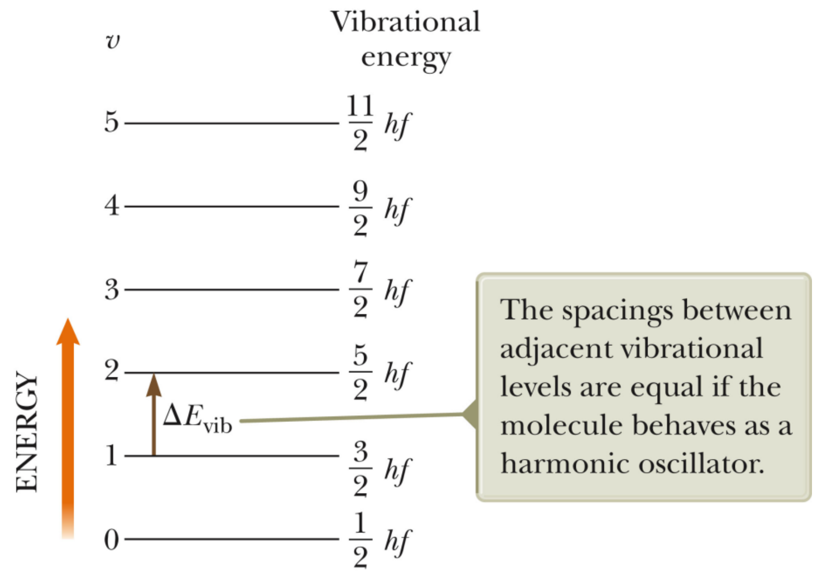
Physics of molecules – continued

Vibration about equilibrium point

Solution to Schrodinger equation for vibrating nuclei

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}+\frac{1}{2}kx^2\right]\psi(\mathbf{r})=E\,\psi(\mathbf{r})$$

$$E_\nu = hf_0\left(\frac{1}{2}+\nu\right) \qquad f_0 \equiv \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$



Given that $f_0=6\text{x}10^{13}$ cycle/s for a vibrating CO molecule, if this vibration were to couple to EM radiation, what would be the wavelength of light?

A. $5\text{x}10^{-6}$m B. $2\text{x}10^{5}$m C. $1\text{x}10^{-47}$m

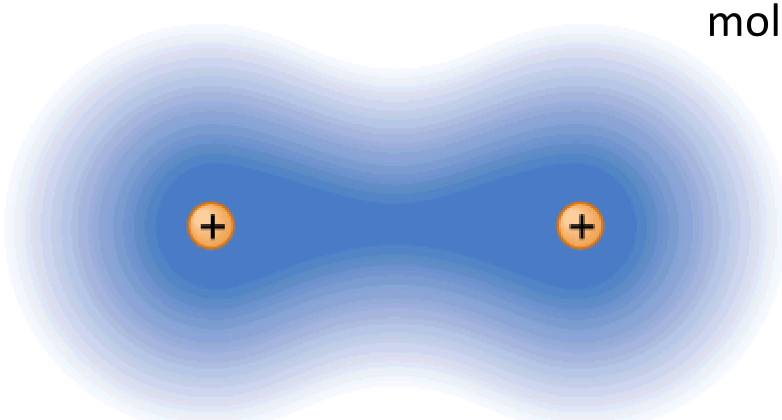
Physics of molecules and solids

$$E\psi(\mathbf{r}) = \left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial \mathbf{r}^2} + U(\mathbf{r})\right]\psi(\mathbf{r})$$

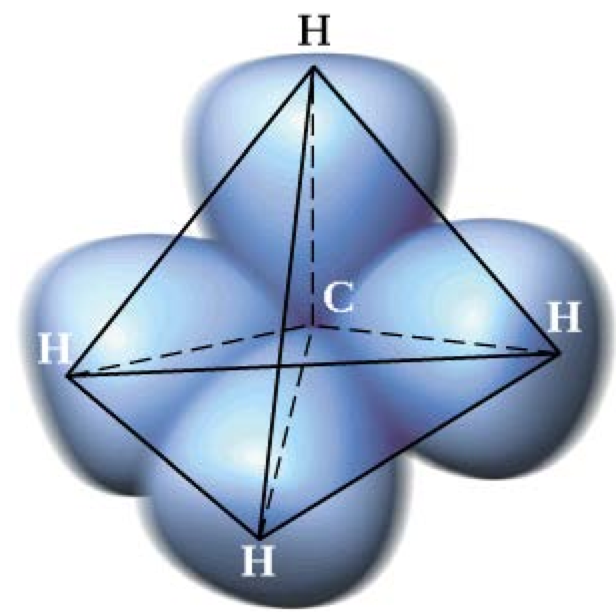
effective potential for electron in molecule or solid

Example: electron density associated with

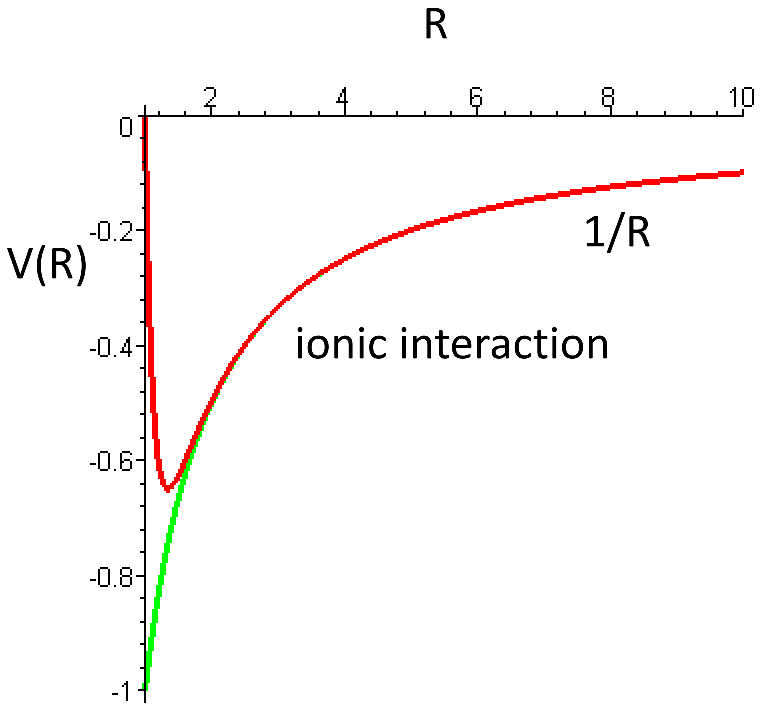
H_2 molecule:

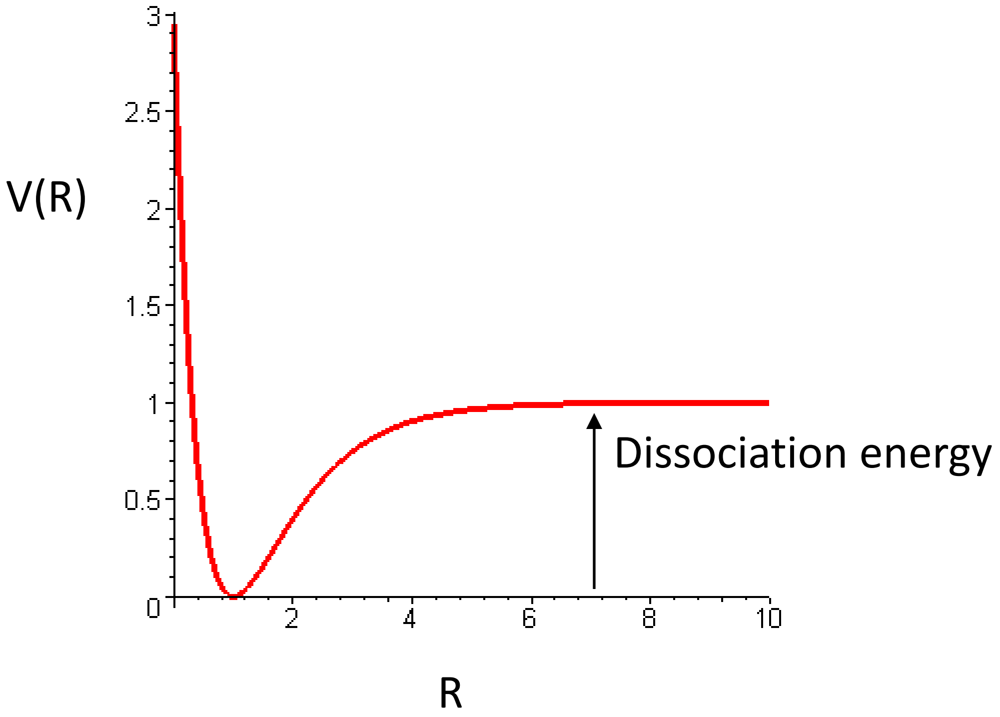


CH_4 molecule:



Molecular binding of nuclei due to electron "glue":





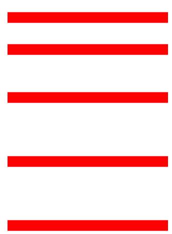
effective potential for
electron in molecule or solid

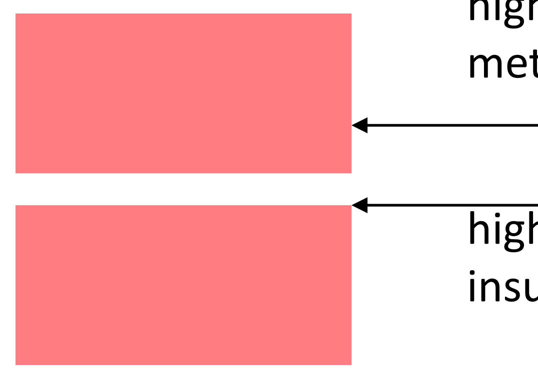
Physics of solids

$$E\psi(\mathbf{r}) = \left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial \mathbf{r}^2} + U(\mathbf{r}) \right]\psi(\mathbf{r})$$

$$U(\mathbf{r}) = \sum_i u\left(\left|\mathbf{r} - \mathbf{R}_i\right|\right)$$

Energy spectrum of atom or
molecule :

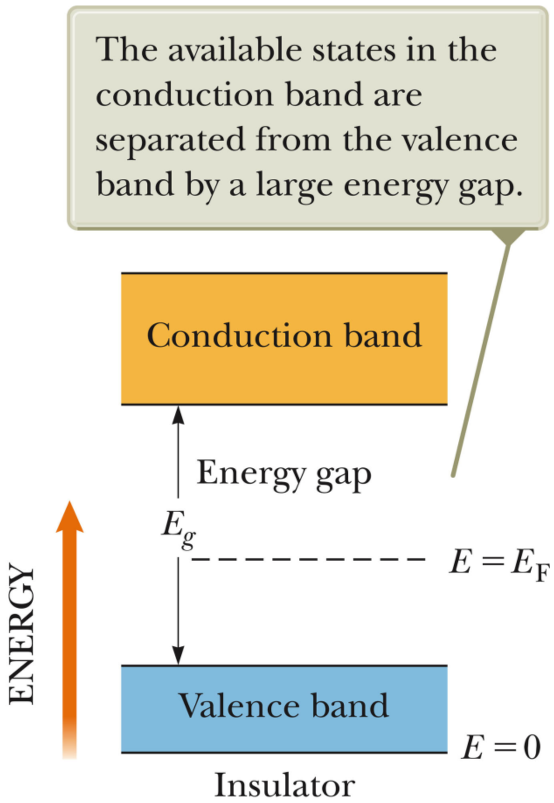




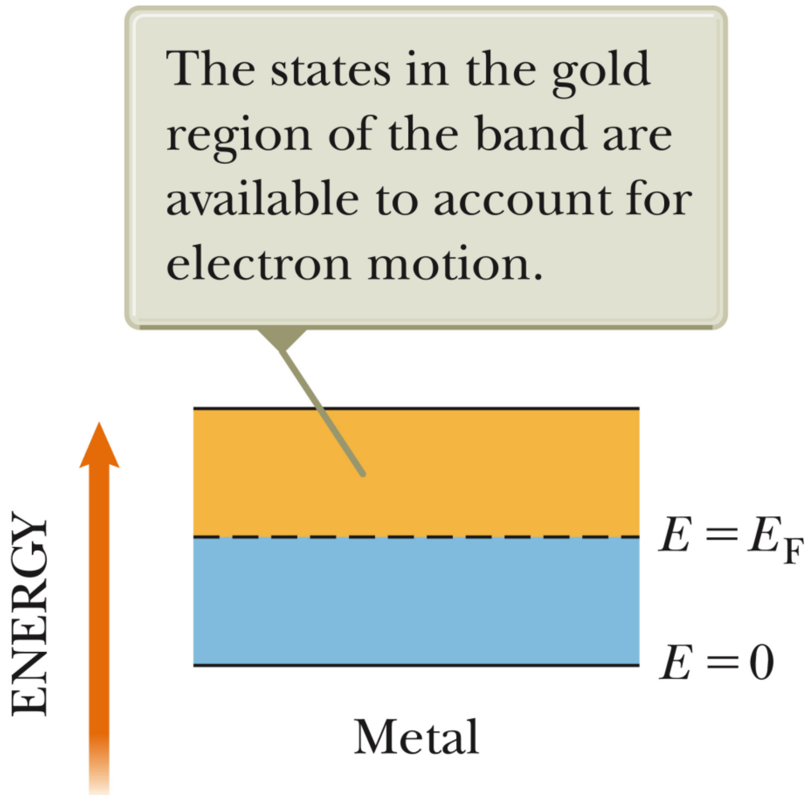
highest filled state for
metal

highest filled state for
insulator

Insulator



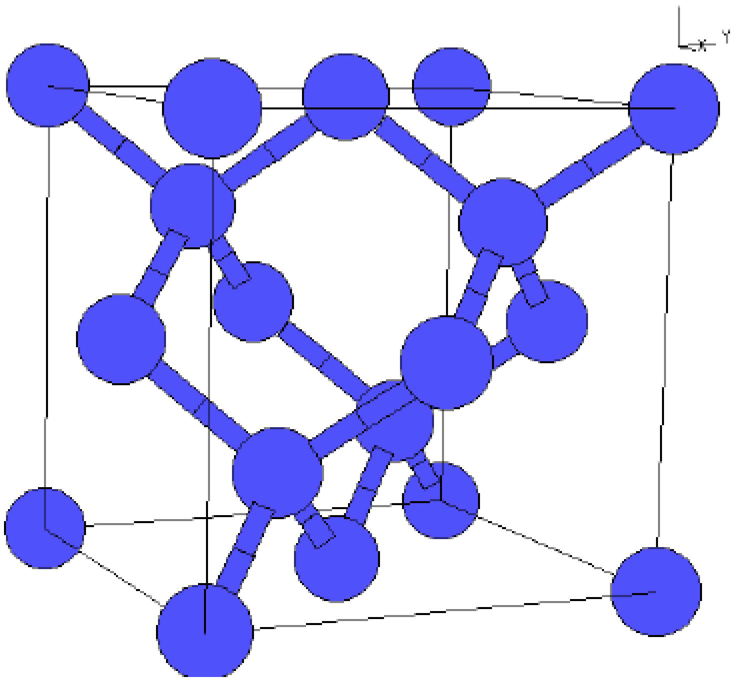
Metal

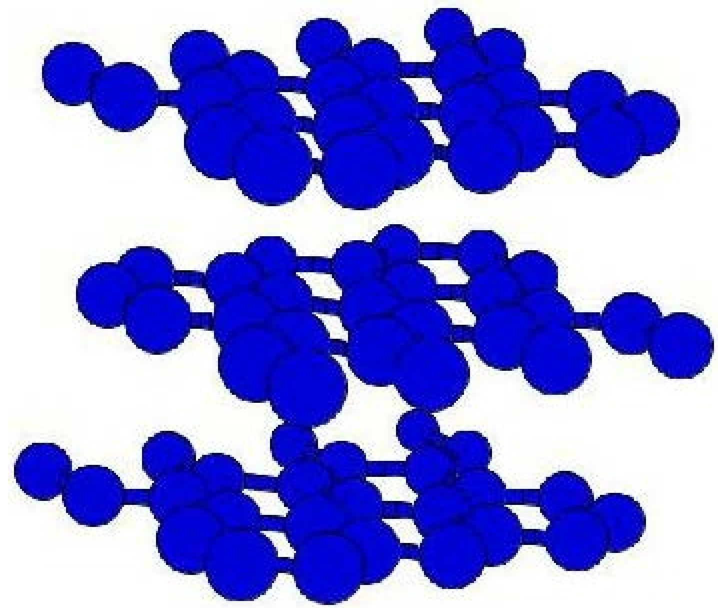


Example: 2 materials made of pure carbon:

graphite (semi-metal)

diamond (insulator)





E_g=5.5 eV

E_g=0.0 eV

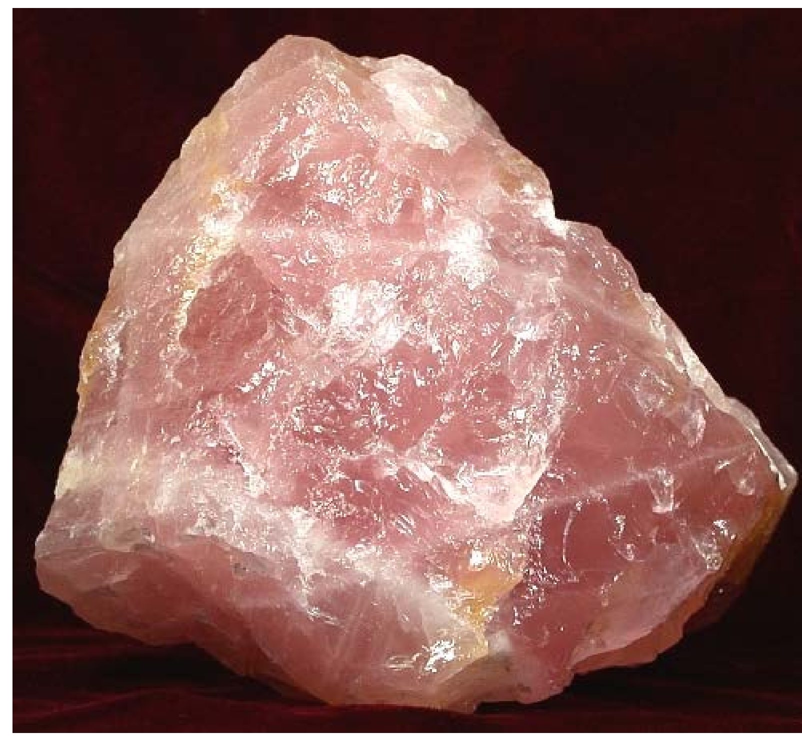
Which photo is diamond?

A. left B. right

Some energy band gaps:

C (diamond)	5.5 eV
SiO_2 (quartz)	8.9
NaCl (rock salt)	8.5

Two images of quartz:



Semi-conductor materials; E_g < 5 eV or so

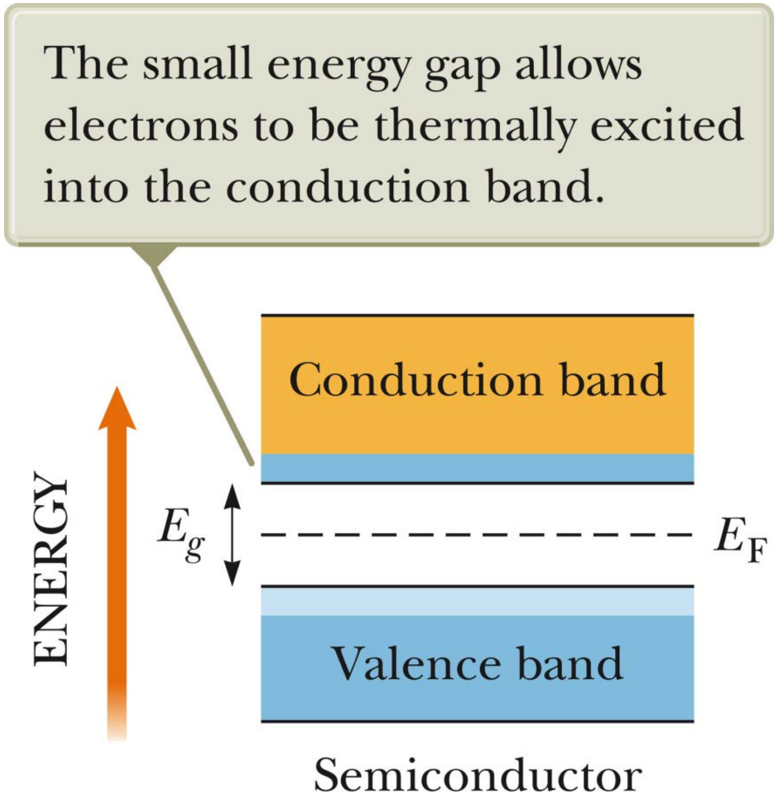


TABLE 43.3

Energy-Gap Values for Some Semiconductors

	E_g (eV)	
Crystal	**0 K**	**300 K**
Si	1.17	1.14
Ge	0.74	0.67
InP	1.42	1.34
GaP	2.32	2.26
GaAs	1.52	1.42
CdS	2.58	2.42
CdTe	1.61	1.56
ZnO	3.44	3.2
ZnS	3.91	3.6

Electron conductivity in metals and semiconductors:

$$\sigma = \frac{ne^2\tau}{m^*} = ne^2\tau \frac{1}{\hbar^2}\frac{\partial^2 \varepsilon(k)}{\partial k^2}$$

$$n \equiv \#\ \text{carriers/volume}$$

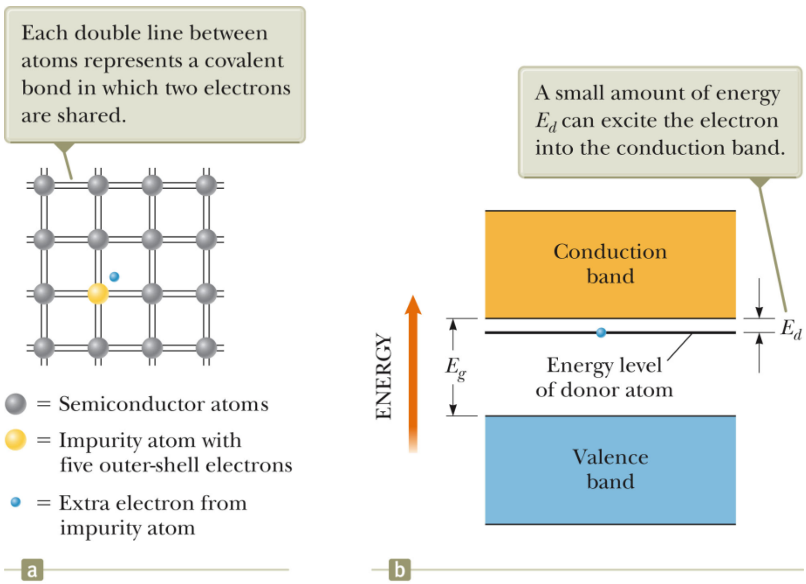
$$\tau \equiv \text{scattering time}$$

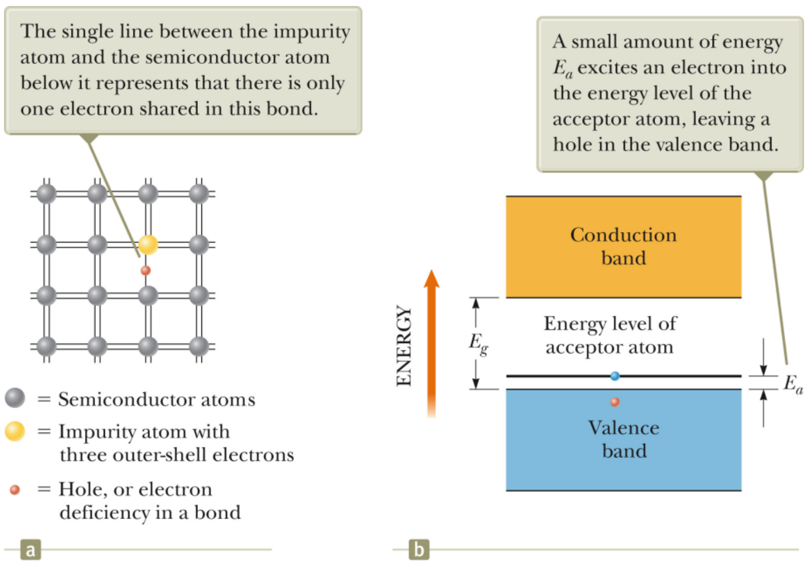
$$\frac{1}{m^*} \equiv \frac{1}{\hbar^2}\frac{\partial^2 \varepsilon(k)}{\partial k^2} \quad \text{"effective mass"}$$

In a perfect semiconductor at T=0K n=0. To control conduction, impurities are introduced.

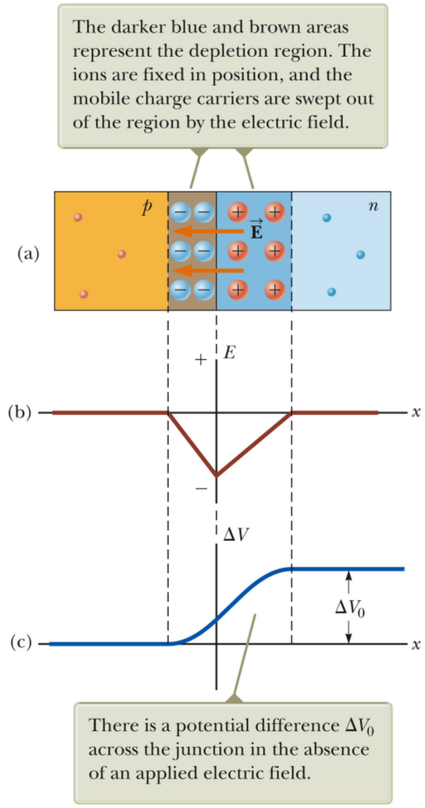
Electron doping

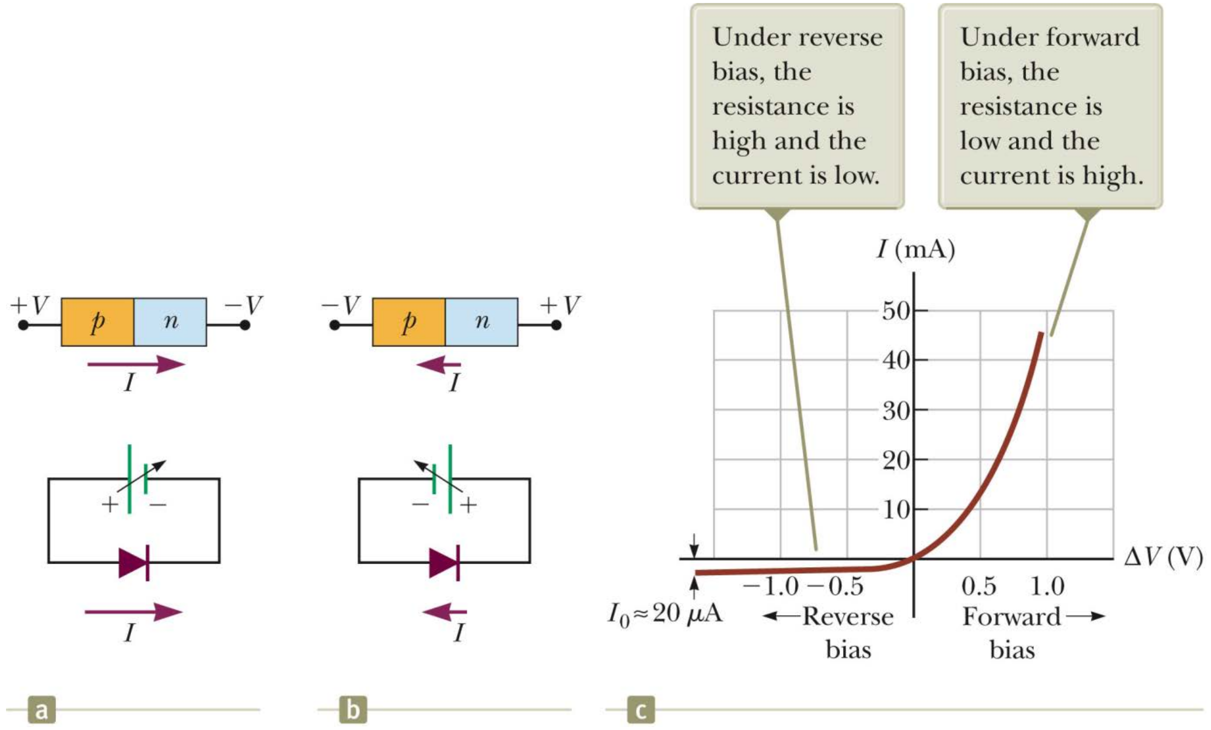
"Hole" doping



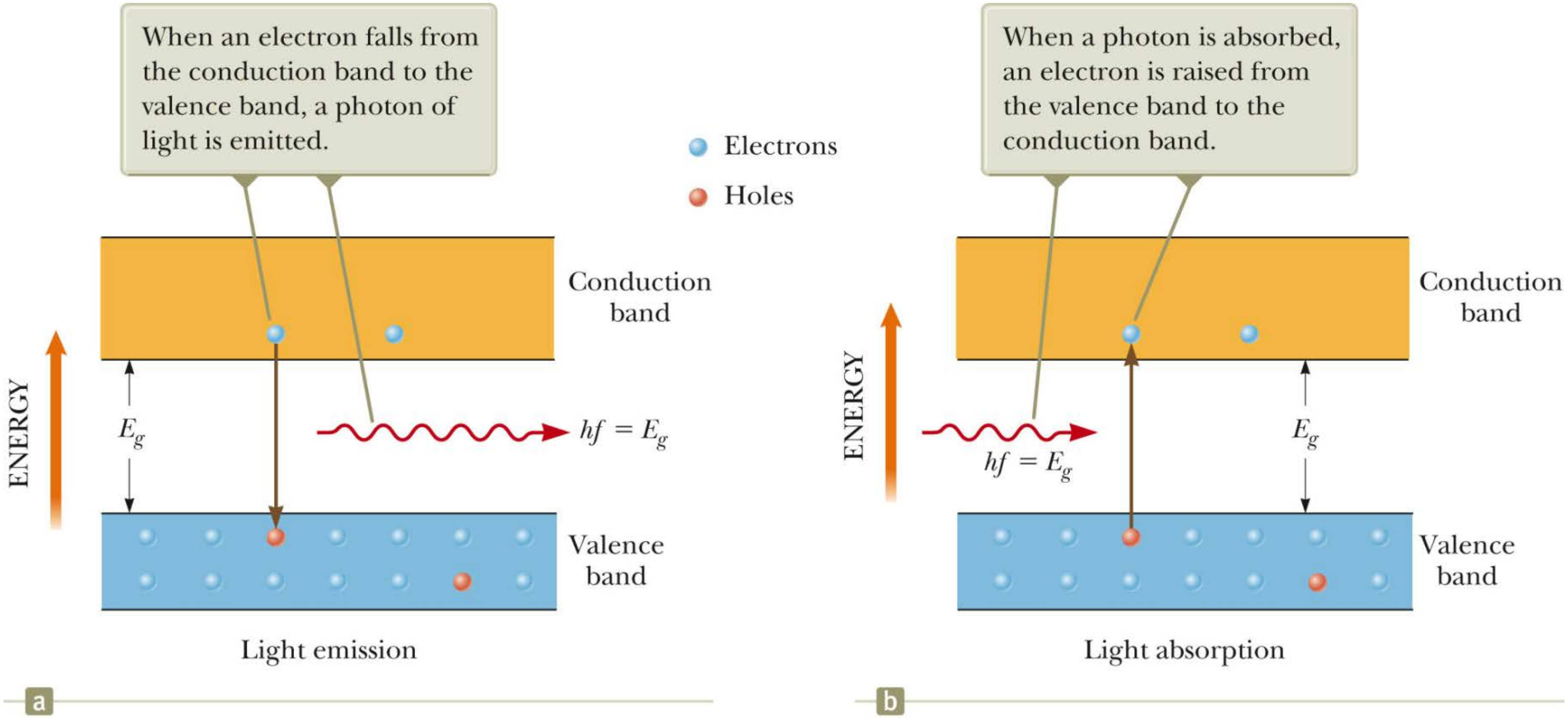


Semiconductor devices; combining electron doped and hole doped materials to control the flow of mobile charriers





Photovoltaic devices



Laser technology:

- System with ground and excited state at desired λ (E_{ex}-E_g=hc/λ).
- Standing EM wave
- Mechanism for "population inversion"

The Helium–Neon Gas Laser

Figure 41-21 shows a type of laser commonly found in student laboratories. It was developed in 1961 by Ali Javan and his coworkers. The glass discharge tube is filled with a 20:80 mixture of helium and neon gases, neon being the medium in which laser action occurs.

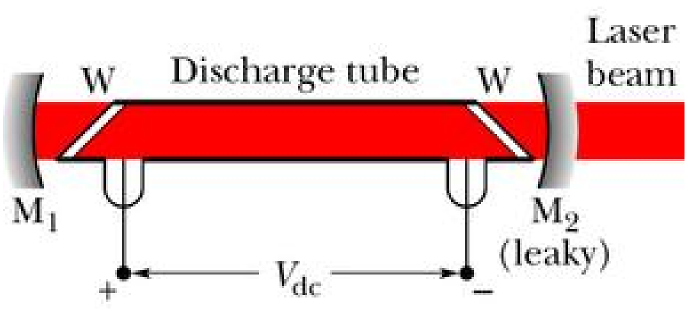


Fig. 41-21 The elements of a helium–neon gas laser. An applied potential V_{dc} sends electrons through a discharge tube containing a mixture of helium gas and neon gas. Electrons collide with helium atoms, which then collide with neon atoms, which emit light along the length of the tube. The light passes through transparent windows W and reflects back and forth through the tube from mirrors M_1 and M_2 to cause more neon atom emissions. Some of the light leaks through mirror M_2 to form the laser beam.

Figure 41-22 shows simplified energy-level diagrams for the two atoms. An electric current passed through the helium–neon gas mixture serves—through collisions between helium atoms an electrons of the current—to raise many helium atoms to state E_3, which is metastable.