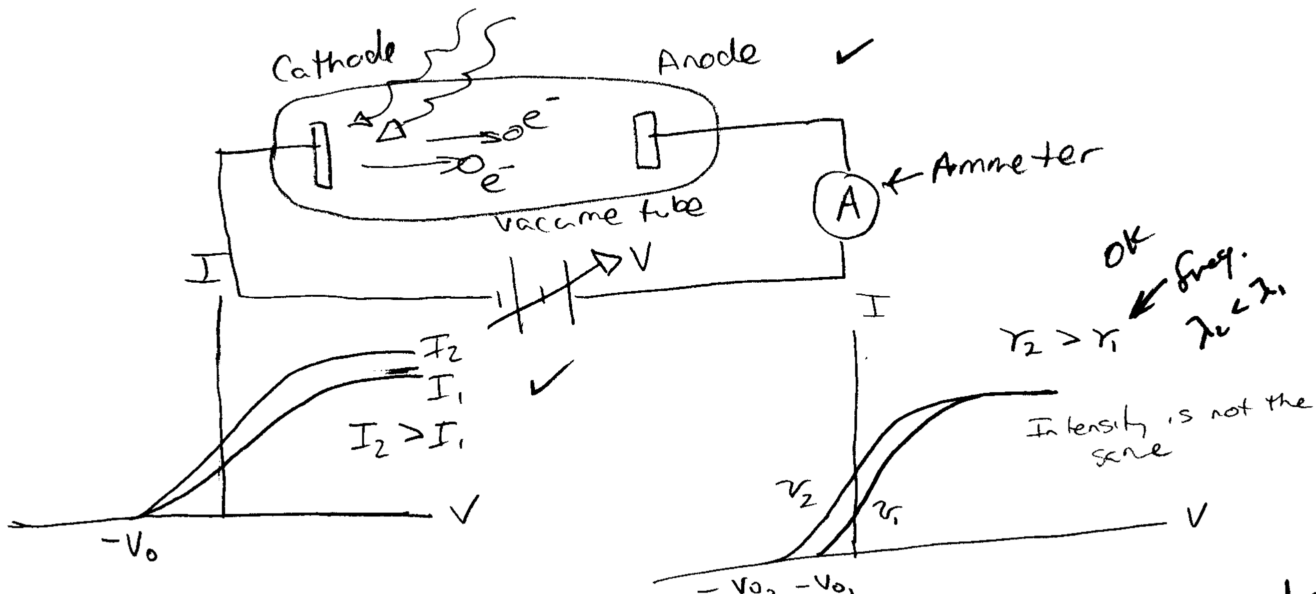
1. Photoelectric Effect

a) Sketch the apparatus used to measure the photoelectric effect and draw typical I-V curves for two different wavelengths of light and two different intensities. Indicate which is the longer wavelength and which is the greater intensity.

b) Explain what is surprising about the I-V curves from the viewpoint of classical (pre-quantum) theory. What does the experiment tell us about the nature of light?

c) What factors determine the maximum kinetic energy of the photo-emitted electrons? Sketch the dependence of the maximum kinetic energy of the photo-emitted electrons on the frequency of the light. How would the curve change if a different metal is used?

a)



$6\frac{1}{2}$

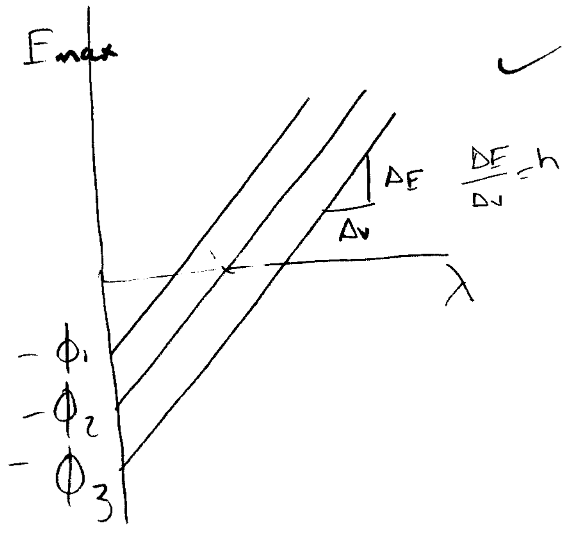
b) $I = \frac{1}{2} c \varepsilon_0 E$

Classically we would expect The energy of Light to go up as The indensity increases because $I = \frac{1}{2} c \varepsilon_0 E$, but what we find is as the intensity Goes up The # of atoms keeps increasing but not the energy. What we find is The energy increases because of increased ν because of $E = h\nu$ (constant). This means Light is a particle and ~~a wave~~

it does.

actually the experiment shows light is particle-like.

c) The maximum kinetic energy is effected by The frequency of the light and the work function of the metal x



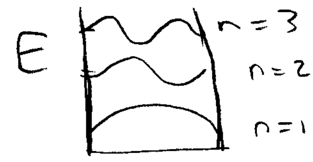
The Line would Go either up or down depending on the metal used

$-\phi$ = work function of metal

2. Quantum Mechanics

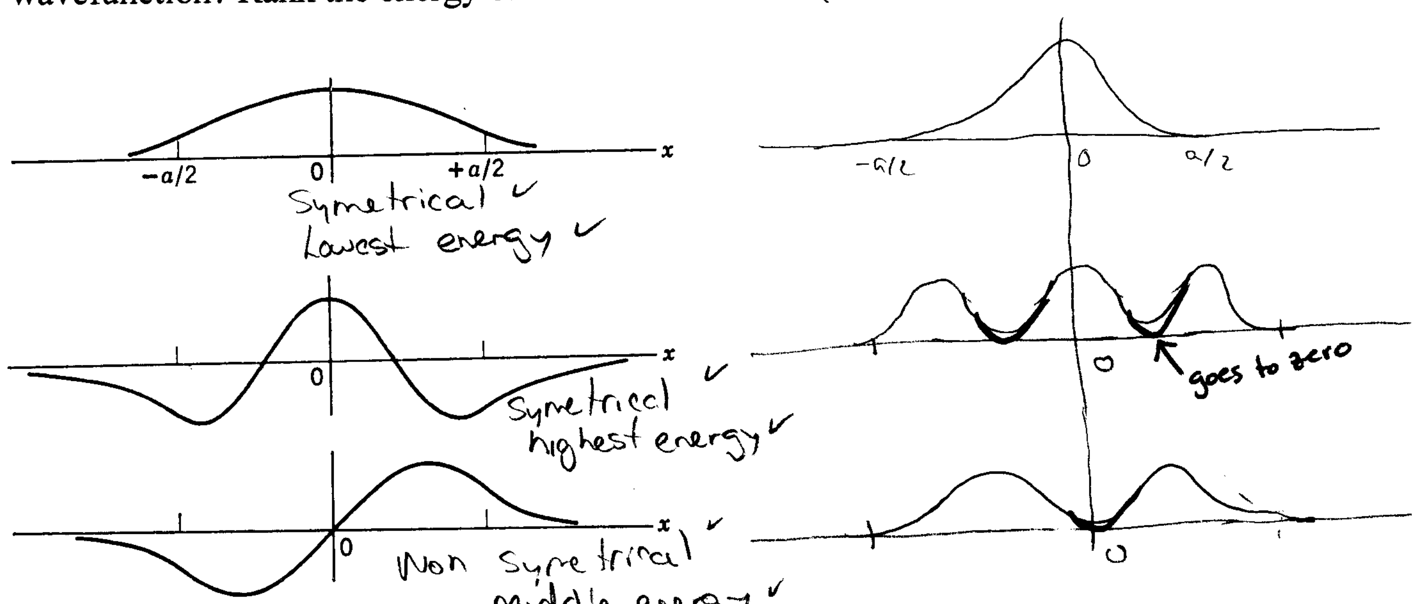
a) In the quantum mechanical solution of an electron in the infinite square-well potential and the Coulomb potential, we found that the electron's energy is quantized. Explain what is meant by a quantized energy.

This means that the energy increases proportiardly to the state it is in, in intervals of n\ ? X

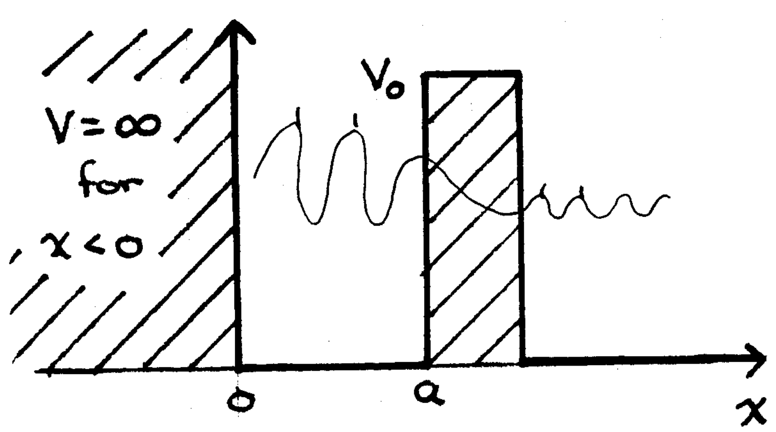


b) A solution of Schrödinger's equation yielded the following wavefunctions. Sketch the probability density for the electron for each wavefunction. What is the symmetry of each wavefunction? Rank the energy of each wavefunction (lowest, middle, highest).

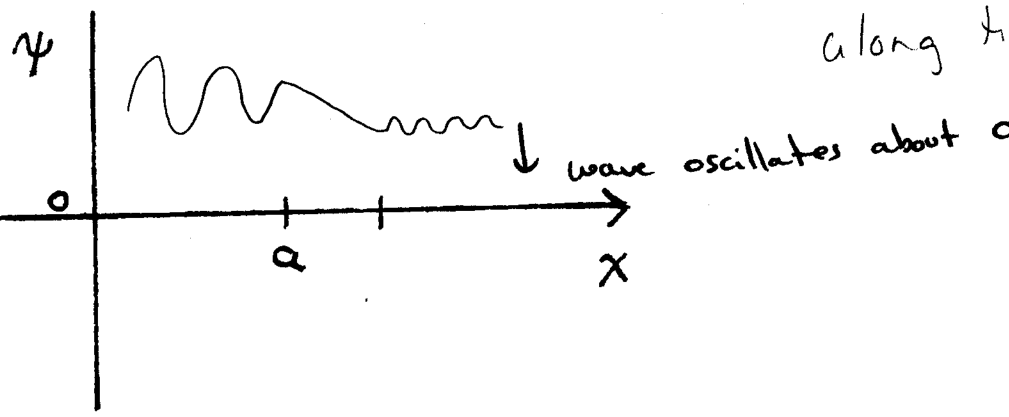
1



c) Consider the potential illustrated below. An electron with $E < V_0$ is inserted into the potential well between $x = 0$ and $x = a$. Sketch a possible wavefunction for the electron a short time later. What happens to the electron after a long time? (Hint: think about the square well and quantum tunneling through a potential barrier.)



The wave length gets smaller along time Later X



3. Coulomb Potential and Atoms

a) What quantum numbers label the wavefunction of an electron in an atom? What are the allowed values that each of the quantum numbers may have?

b) How does the energy of the electron in a hydrogenic atom depend on the principle quantum number n? How does the energy depend on the atomic number Z?

c) Phosphorus has the electronic configuration $[Ne]3s^23p^3$. Sprint the electronic configuration for the valence electrons using a box for each orbital wavefunction and an arrow (up or down) for each electron.

a) Quantum numbers

$n = \{1, 2, 3, 4 \ldots\}$ ✓

$\ell = \{0, 1, 2, 3, \ldots n-1\}$ ✓

$m_\ell = \{-\ell \ldots 0 \ldots +\ell\}$ ✓

$m_s = \pm 1/2$ ✓

7½

b) $E \propto Z$

E varies Directly with Z ✗

important

$E \propto \frac{-1}{n^2}$

E varies with the Inverse of n^2

$E \propto \frac{-Z^2}{n^2}$

c) Phosphorus

[Ne] [↑↓] 3s [↑][↑][↑] 3p ✓

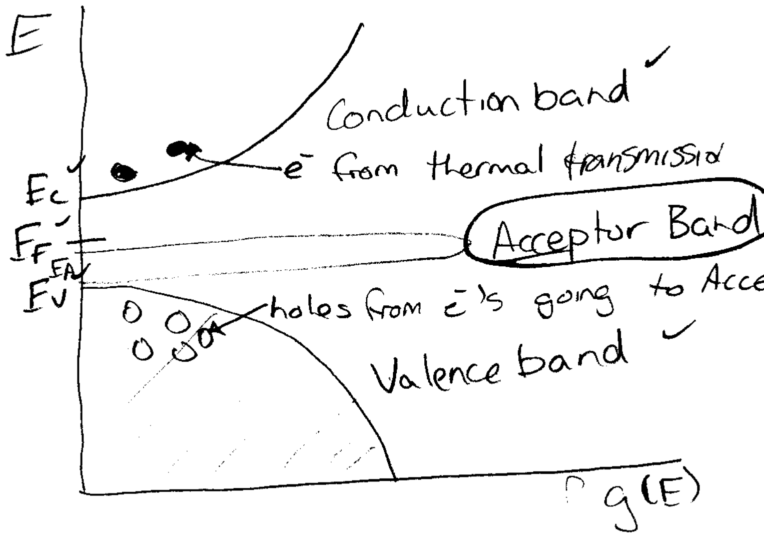
4. Band Theory of Solids

a) Sketch the density of states diagram for a semiconductor like silicon. Label the diagram with the important energies and indicate which states are occupied by electrons.

b) In terms of a band diagram, what distinguishes a metal from a semiconductor?

c) Explain why a metal is a much better conductor than a semiconductor.

a)

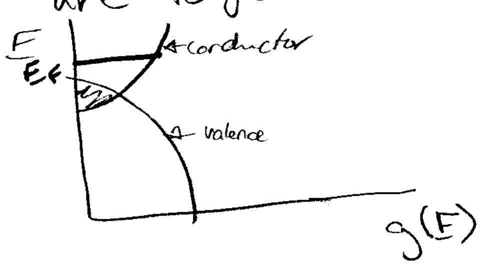


$E_g = E_c - E_v$

we haven't done doping yet

6

b) In the band diagram for a metal there is no E_g the conduction band and ~~..~~ valence band are together



metals have a partially filled band ie E_f is within a band.

c) metal is much better of a conductor because metal has lots of free electrons at E_f, where semiconductors have fewer. Also the E_g does not have to be overcome

need to say something about all the e^-'s in the valence band.

1. Semiconductors

A semiconductor is characterized by the following parameters: bandgap $E_g = 1.7\,\text{eV}$, electron effective mass $m_e^* = 0.25 m_e$, hole effective mass $m_h^* = 0.5 m_e$, electron mobility $\mu_e = 500 \frac{\text{cm}^2}{\text{Vs}}$, and hole mobility $\mu_h = 200 \frac{\text{cm}^2}{\text{Vs}}$. Calculate the following for $T = 300\,\text{K}$:

a) The effective density of states for the conduction and valence bands, N_C and N_V.

b) The intrinsic concentration of electrons in the conduction band, n_i.

c) The conductivity of the semiconductor, σ.

$m_e^* = .25 m_e$

$m_h^* = .5 m_e$

$\mu_e = 500 \frac{cm^2}{Vs}$

$\mu_h = 200 \frac{cm^2}{Vc}$

$E_g = 1.7 eV$

$T = 300K$

a) $N_c = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}$

$= 2\left(\frac{2\times\pi(.25\times 9.1\times10^{-31} kg)(1.38\times10^{-23} JK^{-1})(300k)}{(6.63\times10^{-34} Js)^2}\right)^{3/2}$

$N_c = 3.124\times10^{24} m^{-3} = \boxed{3.124\times10^{+18} cm^{-3}}$ ✓

$N_V = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}$

$= 2\left(\frac{2\pi(.5\times 9.1\times10^{-31})(1.38\times10^{-23} JK^{-1})(300k)}{(6.63\times10^{-34} Js)^2}\right)^{3/2}$

$N_v = 4.418\times10^{24} m^{-3} = \boxed{4.418\times10^{18} cm^{-3}}$

forgot the factor of 2
$8.8\times10^{18} cm^{-3}$

9

b) $n_i = (n_c n_v)^{1/2} \exp\left(-\frac{E_g}{2kT}\right)$

$= (3.124\times10^{18}\times4.418\times10^{18})^{1/2} \exp\left(\frac{-1.7eV}{2(300k)(8.62\times10^{-5} eV K^{-1})}\right)$

3.715×10^{18}

$= 19724.9\ cm^{-3}$

$n_i = \boxed{19725 cm^{-3}}$ ok given the above N_v.

$\sigma = e n \mu_e + e p \mu_h = e n_i(\mu_e + \mu_h)$

$= 19724.9\times(500 cm^2/Vs + 200 cm^3/Vc)e$

$= \boxed{2.21\times10^{-12}\ /\Omega cm}$ ok given the above n_i

$\gamma =$

$R_{ph} = \frac{I}{h\nu} = \frac{\Delta N_{ph}}{A \Delta t}$

2. Photo-electric Effect

a) A multi-alkali metal is used as the photocathode material in a photo-emissive electron tube. The longest wavelength radiation that gives photo-emitted electrons is 325 nm. If ultra-violet radiation of wavelength 275 nm is incident on to this photocathode, what is the maximum kinetic energy (in eV) of the photo-emitted electrons? What is the work function of the metal? What voltage applied to the collecting electrode would extinguish the photocurrent?

b) The 275 nm light has an intensity of 10 mW/cm^2. The photocathode is a disk with a 1 cm radius. The emitted electrons are collected by applying a positive bias of 100 V to the anode. What is the photocurrent assuming that the quantum efficiency of the photocathode is 0.2. What happens to the photocurrent if the anode voltage is doubled to 200 V?

Note: Quantum efficiency is the ratio of emitted electrons to absorbed photons.

a) $\lambda_{max} = 325\,nm$ $\quad$ UV = 275 nm $\quad$ max KE

$$\Phi = \frac{hc}{e\lambda} = \frac{(6.626\times10^{-34} J\cdot s)(3\times10^{8} m/s)}{(1.6\times10^{-19} J/eV)(325\times10^{-9} m)}$$

3.82269

$$= \boxed{3.823\,eV} \checkmark$$

$$KE = \frac{hc}{e\lambda} - \Phi$$

$$= \frac{(6.626\times10^{-34} J\cdot s)(3\times10^{8} m/s)}{(1.6\times10^{-19} J/eV)(275\times10^{-9} m)} - 3.823$$

9

$$\approx 4.5177\,eV - 3.82269\,eV$$

$$= .695\,eV \checkmark$$

$$V = \frac{KE_m}{e} = \frac{.695\,eV}{(1.6\times10^{-19} J/eV)} = 4.34\times10^{18}\,V \times$$

? great, I'll just get my 10^{18} volt power supply.

b) 275 nm Light $\quad$ $I = 10\,mW/cm^2$ $\quad$ 1 cm radius

photo current $\quad$ + 100 V to anode

$A = \pi r^2$

$A = (2)\pi r^2$

$= 2\pi(.01m)^2$

$= 6.28\times10^{-4} m^2$

$$J = \frac{e I \lambda}{hc} = \frac{(1.6\times10^{-19} C)(10\times10^{-3}\times10^{4} J/s\,m^2)(275\times10^{-9})}{(6.626\times10^{-34} Js)(3\times10^{8} m/s)}$$

$$J = 22.135\,Am^{-2}$$

$$I = 22.135\,Am^{-2} \cdot 6.28\times10^{-4} m^2 \times .2$$

Photo current → $\boxed{I = .00278\,A}$ × silly error.

If voltage is doubled The current stays the same because the intensity of Light is not increasing ✓

3. Lasers

a) One could, in principle, make a laser out of a gas of atomic hydrogen. What two levels could be used for the amplifying transition? Why did you choose these levels? What wavelength of light would be produced?

b) If the lifetime of an electron in the excited state of the amplifying transition is 100 μs, what is the intrinsic linewidth of the light from the laser.

$E_n (eV) = -13.6/n^2$ e^- must be excited from E_1 to a quantized level $(-13.6/n^2)$ eV

$\Delta E = (-13.6/n_2^2 - (-13.6/n^2))$ eV

λ must be between 400nm and 780nm

$\lambda = \frac{hc}{\Delta E}$ $\frac{(6.626\times10^{-34} J/s)(3\times10^8 m/s)}{\approx 590nm}$

$\Delta E = 3.369\times10^{-19} \div 1.6\times10^{-19}$ J
≈ 2.106 eV

from 4-2

$\Delta E = \frac{-13.6}{4^2} + \frac{13.6}{3^2} = .66$

$\Delta E_{42} = \frac{-13.6}{4^2} + \frac{13.6}{2^2} = -2.55$ eV

$\Delta E_{3-2} = \frac{-13.6}{3^2} + \frac{13.6}{2^2} = 1.89$ eV ← This level is the closest to needed wavelength for visible spectrum

$\Delta E_{3-1} = \frac{-13.6}{9} - 13.6 = +12$ eV

$\Delta E_{2-1} = \frac{-13.6}{4} - 13.6 - 10.2$ eV

need to find a metastable level to achieve population inversion.

? not a given condition

Transition from 3-2

O

$\Delta E_{3-2} = 1.89$ eV

$\lambda = \frac{hc}{1.89eV} \Rightarrow \frac{(6.626\times10^{-34} J/s)(3\times10^8 m/s)}{(1.6\times10^{-19} J)(1.89 eV)}$

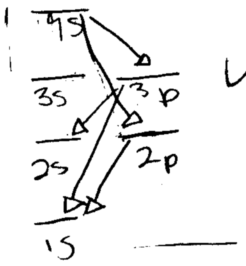
= 656nm

b)

4. Atoms

a) An excited hydrogen atom has its electron in the 4s state. Indicate with an energy level diagram all possible transitions that can occur while the electron returns to the ground state. Calculate all wavelengths of light that will be emitted during these transitions.

b) The first ionization energy of chlorine is 12.97 eV; the electron comes from the 3p subshell. What is the effective nuclear charge (Z) acting on this electron?



✓

$\frac{1}{\lambda} = R_\infty (Z^2)\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$

for 4-3 $\frac{1}{\lambda} = (1.0974 \times 10^7 m)(1)\left(\frac{1}{3^2} - \frac{1}{4^2}\right)$

$\lambda = 187.4 nm$ 1.88 μm

for 4-2 $\frac{1}{\lambda} = (1.0974 \times 10^7)(1)\left(\frac{1}{2^2} - \frac{1}{4^2}\right)$

$\lambda = 485 nm$ ✓

9½

for 3-2 $\frac{1}{\lambda} = (1.0974 \times 10^7)\left(\frac{1}{2^2} - \frac{1}{3^2}\right)$

$= 656 nm$ ✓

for 3-1 $\frac{1}{\lambda} = (1.0974 \times 10^7)\left(1 - \frac{1}{9}\right)$

$= 102 nm$ ✓

for 2-1 $= \frac{1}{\lambda} = (1.0974 \times 10^7)\left(1 - \frac{1}{4}\right)$

$= 121 nm$ ✓

b) $E = \frac{Z_{eff}^2 (13.6 eV)}{n^2}$

$\frac{(12.97 eV)(n^2)}{13.6 eV} = Z_{eff}^2$

$\frac{(12.97)9}{13.6 eV}$

$Z_{eff} = 2.93$ ✓