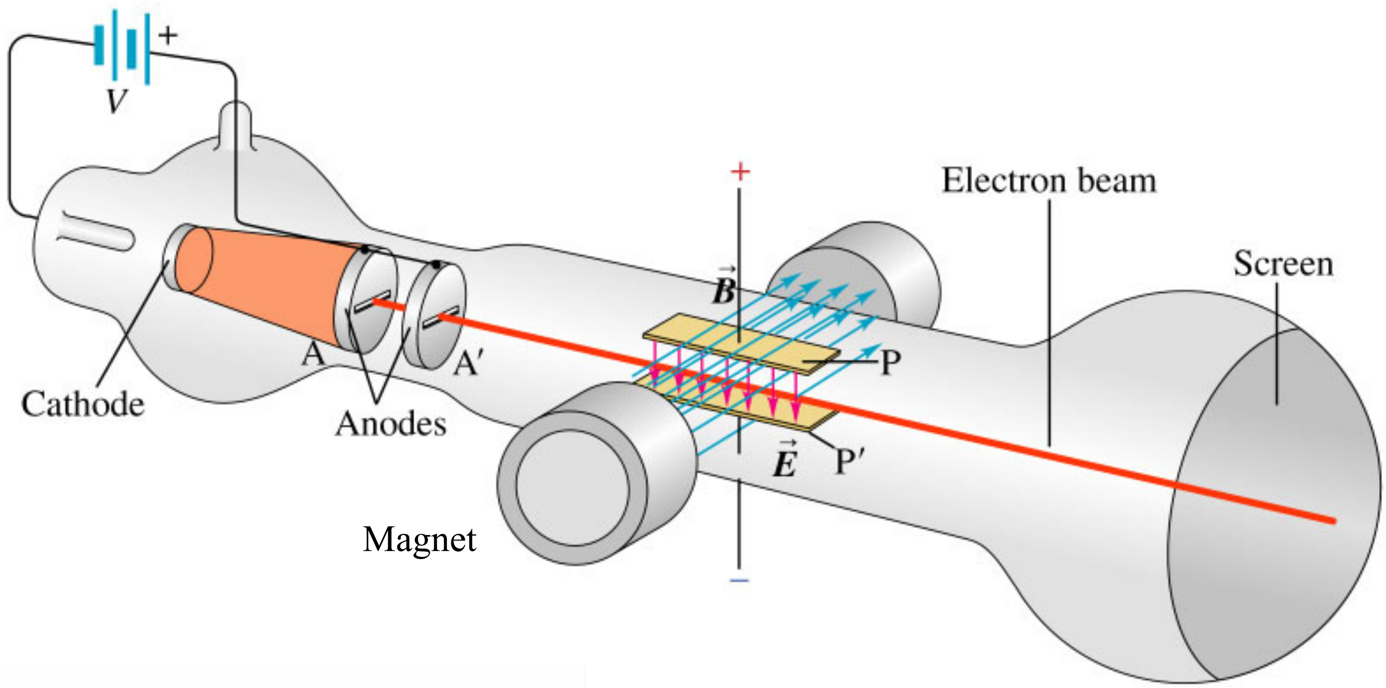
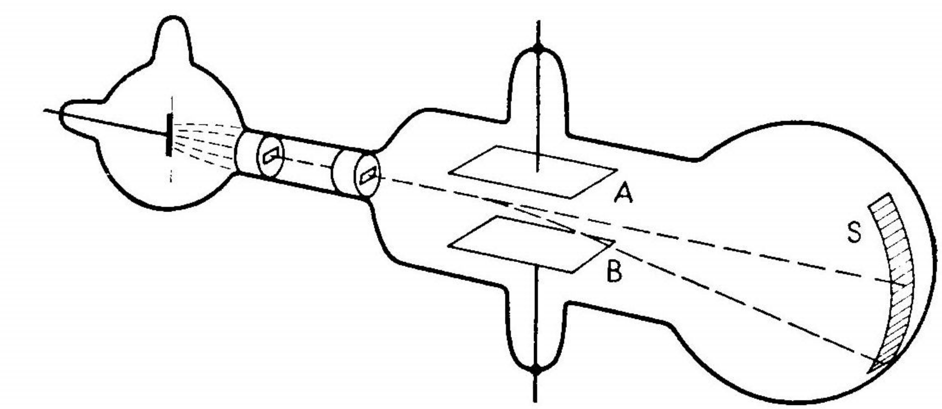
Chapter 27

Early Quantum Theory and Models of the Atom

Properties of the electron

J. J. Thomson's *e/m* experiment (c. 1897)





A: E and B on   B: Only B on

$$evB = eE \qquad evB = m\frac{v^2}{r}$$

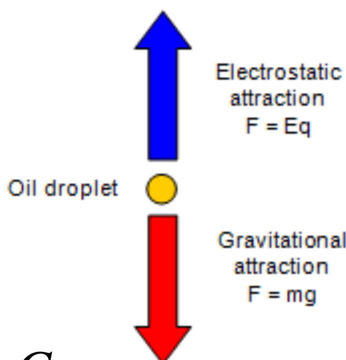
$$\therefore \frac{e}{m} = \frac{E}{B^2 r} = 1.76\times10^{11}\ \frac{C}{kg}$$

Properties of the electron

R. A. Millikan
Oil drop experiment
to determine *e* (c. 1910)

$$F_{electric} = F_{gravity} \quad \Rightarrow qE = m_{drop}g$$

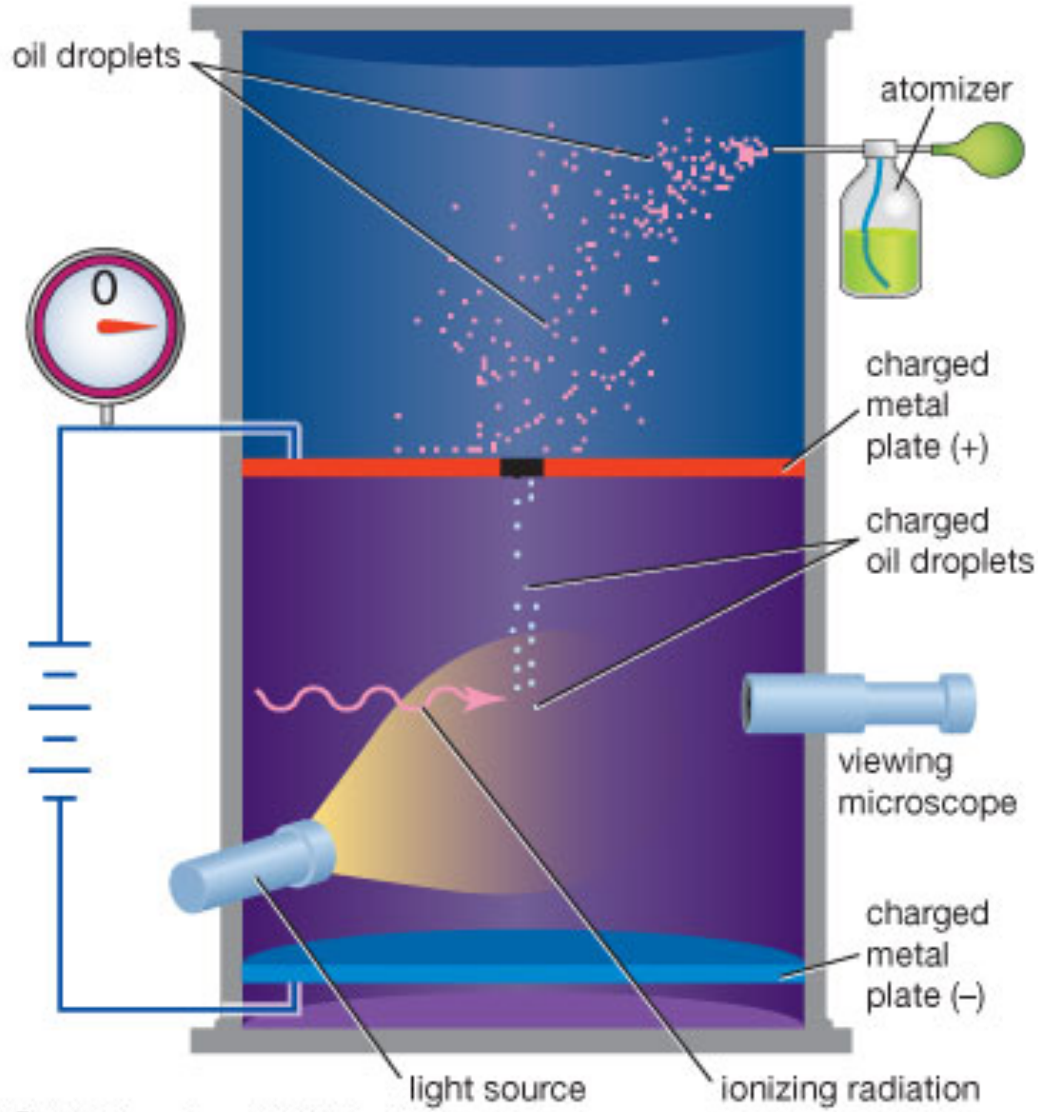
$$\therefore e = 1.6 \times 10^{-19} C$$



Using

$$\frac{e}{m} = 1.76 \times 10^{11} \frac{C}{kg}$$

$$\therefore m = \frac{1.6 \times 10^{-19}}{1.76 \times 10^{11}} = 9.1 \times 10^{-31} kg$$



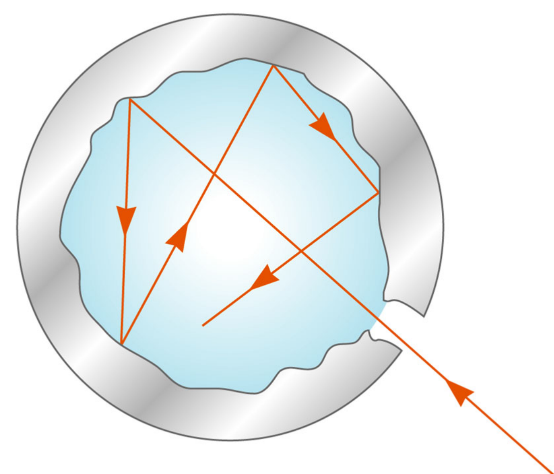
Blackbody Radiation and Planck's Hypothesis

❑ Thermal radiation

- An object at any temperature emits electromagnetic radiation called thermal radiation.
- The spectrum of the radiation depends on the temperature and properties of the object.
- From a classical point of view, thermal radiation originates from accelerated charged particles near the surface of an object.

❑ Blackbody

- Is an ideal system that absorbs all radiation incident on it and is in thermal equilibrium.
- An opening in the cavity of a body is a good approximation of a blackbody.



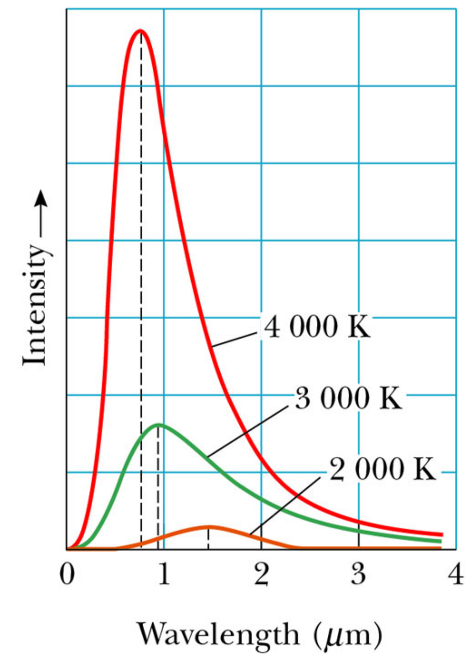
❑ Blackbody radiation

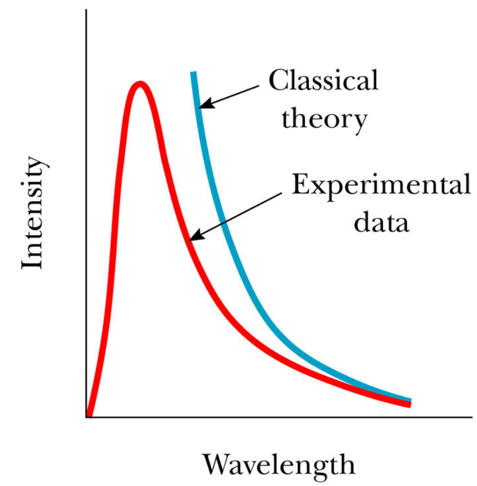
- The nature of the blackbody radiation depends only on the temperature of the body, not on the material composition of the object.
- The distribution of energy in blackbody radiation varies with wavelength and temperature.

  - The total amount of energy (area under the curve) it emits increase with the temperature.
  - The peak of the distribution shifts to shorter wavelengths. This shift obeys **Wien's displacement law:**

$$\lambda_{\max} T = 2.898 \times 10^{-3}\ \mathrm{m \cdot K}$$

- The classical theory of thermal radiation at the end of 19th century failed to explain the distribution of energy of the blackbody radiation.





❑ Planck's hypothesis

- To solve the discrepancy between the classical physics prediction and the observation of the blackbody radiation spectrum, in 1900 Planck developed a formula for the spectrum that explains the observed spectrum behavior.
- Planck's hypothesis:
  - Blackbody radiation is produced by submicroscopic charged oscillation (resonators).
  - The resonators are allowed to have only certain discrete energies given by:

$$E_n = nhf$$

n **= quantum number (positive integer)**

f **= frequency of vibration of the resonators**

h **= Planck's constant =** $\mathbf{6.626 \times 10^{-34}}$ **J s**

- Energy is quantized.
- each discrete energy value represents a different quantum state, where the quantum number *n* specifies the quantum state.

Example. a) Find the temperature of the Sun's surface assuming that it emits blackbody radiation and the wavelength of the peak in its intensity distribution is at 500 nm (in the yellow region).b) Find the temperature of the star Betelgeuse (in the Orion constellation) which is classified as a Red Giant (near the end of its life cycle) with peak wavelength 890 nm.

$$\lambda_{\max} T = 2.898 \times 10^{-3} \ \mathrm{m \cdot K}$$

a) Sun: $$T = \frac{2.898 \times 10^{-3}}{\lambda_{\max}} = \frac{2.898 \times 10^{-3}}{500 \times 10^{-9}} = 5800 \ K$$

b) Betelgeuse: $$T = \frac{2.898 \times 10^{-3}}{890 \times 10^{-9}} = 3260 \ K$$ Much cooler than the Sun

Example: **Black body radiation emitted from an incandescent light bulb filament.** A light bulb is connected to a variable voltage source which is set on low, medium, and high voltage, giving colors of the filament of faint red, bright orange, and white. If the temperatures associated with these settings are 1000° K, 3000° K, and 6000° K, respectively, find the peak wavelength of the light emitted at each of these settings assuming black body emissions.

$$\lambda_{\max} T = 2.898 \times 10^{-3} \text{ m} \cdot \text{K}$$

$$\lambda_{\max} = \frac{2.898 \times 10^{-3}}{T_{red}} = \frac{2.898 \times 10^{-3}}{1000}$$

$$= 2.90 \times 10^{-6} m = 2900\ nm$$

RED

$$\lambda_{\max} = \frac{2.898 \times 10^{-3}}{T_{orange}} = \frac{2.898 \times 10^{-3}}{3000}$$

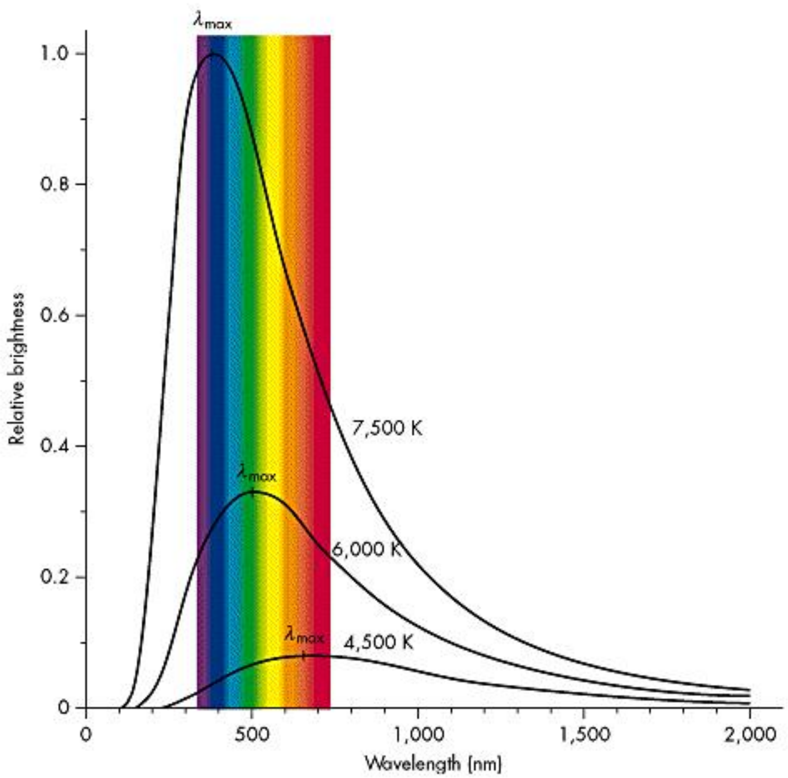
$$= 9.70 \times 10^{-7} m = 970\ nm$$

ORANGE

$$\lambda_{\max} = \frac{2.898 \times 10^{-3}}{T_{white}} = \frac{2.898 \times 10^{-3}}{6000}$$

$$= 4.80 \times 10^{-7} m = 480\ nm$$

WHITE

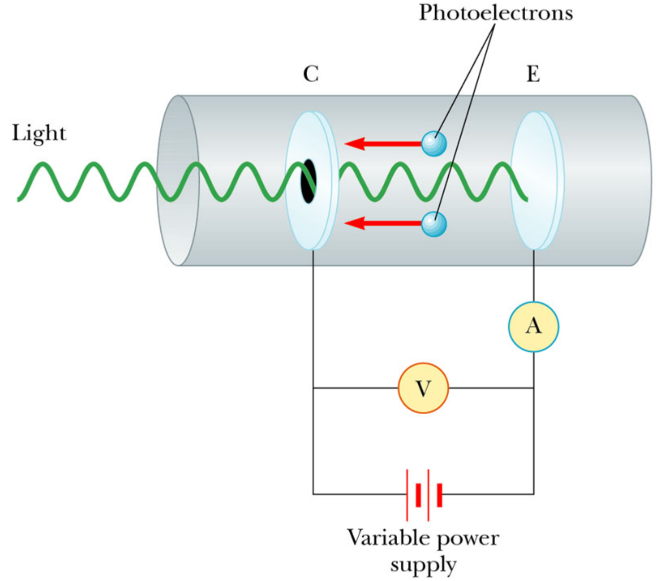


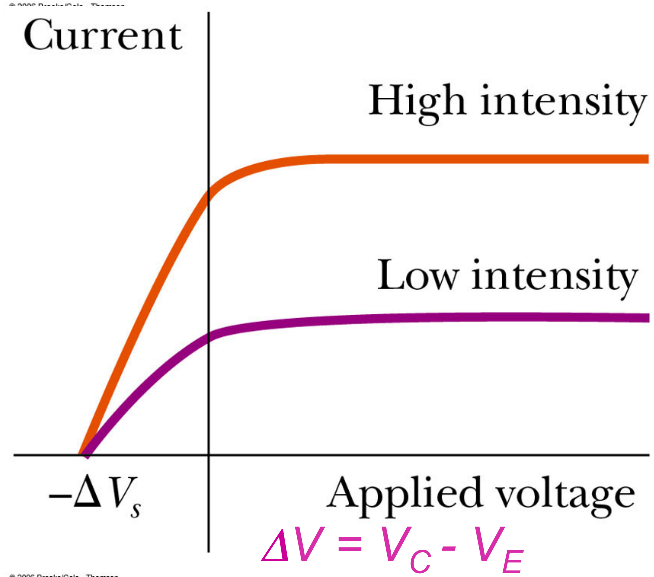
Photoelectric Effect and Particle Theory of Light

❑ Photoelectric effect

- Light incident on certain metallic surfaces causes the emission of electrons from the surfaces.
- This phenomenon is called photoelectric effect and the emitted electrons are called photoelectrons.

- For an electron to reach Plate C when $\Delta V < 0$, its kinetic energy must be at least $e\Delta V$.
- When ΔV is equal to or more negative than $-\Delta V_s$, the stopping potential, no electrons reach C and the current is zero.
- The maximum kinetic energy of the photo-electrons is : $KE_{max} = e\Delta V_s$
- The stopping potential is independent of the radiation intensity.





❑ Photoelectric effect (cont'd)

Observations	Predictions by wave theory
No electrons are emitted if the incident light frequency falls below a cutoff freq. f_c.	Wave theory predicts that this effect should occur at any frequency, provided the intensity is enough.
The max. kinetic energy of the photoelectrons is independent of light intensity.	Light of higher intensity carries more energy into the metal per unit time and eject photoelectrons with higher energies.
The max. kinetic energy of the photoelectrons increases with light frequency.	No relation between photoelectron energy and incident light frequency is predicted.
Electrons are emitted from the surface almost instantaneously even at low intensities (10^{-9} s) .	It is expected that the photoelectrons need some time to absorb the incident radiation before they acquire enough kinetic energy to escape.

❑ Einstein's particle theory of light

- Einstein successfully resolve the mystery in 1905 by extending Planck's idea of quantization to electromagnetic waves.
- Einstein's theory:
  - A localized packet of light energy (photon) would be emitted when a quantized oscillator made a jump from an energy state $E_n = nhf$ to the next lower state $E_{n-1} = (n-1)hf$.
  - From conservation of energy, the photon's energy is:

$$E = hf$$

  - A well localized photon can give all its energy hf to a single electron in the metal.
  - An electron in the metal is bound by electromagnetic force and it needs to gain a certain energy (work function W_0) to be liberated:

$$KE_{max} = hf - W_0$$

TABLE 27.1

Work Functions of Selected Metals Metal	W_0 ϕ (eV)
Na	2.46
Al	4.08
Cu	4.70
Zn	4.31
Ag	4.73
Pt	6.35
Pb	4.14

❑ Einstein's particle theory of light

- Predictions of Einstein's theory:

Cutoff frequency

Photoelectrons are created by absorption of a single photon that has enough energy to overcome the work function.

Independence of KE_{max} of light intensity

KE_{max} depends on only the frequency of light and the work function.

Linear dependence of KE_{max} on light frequency

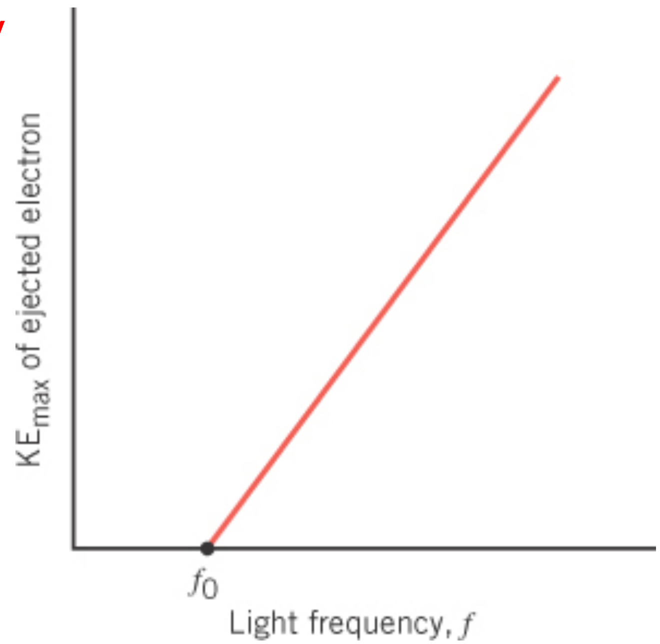
$KE_{max} = hf - W_0$ explains it.

Instantaneous production of photoelectrons

The light energy is concentrated in packets.
If the light has enough energy (frequency),
no time is need to knock-off a photoelectron.

$$KE_{max} = hf_0 - W_0 = 0$$

$$\boxed{f_0 = \frac{W_0}{h}}$$



Example: The Photoelectric Effect for a Silver Surface

The work function for a silver surface is 4.73 eV. Find the minimum frequency that light must have to eject electrons from the surface.

$$hf_o = \underbrace{\mathrm{KE}_{\max}}_{=0\,\mathrm{J}} + W_o$$

$$f_o = \frac{W_o}{h} = \frac{(4.73\ \mathrm{eV})(1.60\times10^{-19}\ \mathrm{J/eV})}{6.626\times10^{-34}\ \mathrm{J\cdot s}} = 1.14\times10^{15}\ \mathrm{Hz}$$

Example. Photoelectric effect on lead.

What is the maximum kinetic energy of photoelectrons emitted from the surface of lead, W_0=4.14 eV, if light of frequency 2.8 x 10^{15} Hz is incident on the surface?

$$KE_{\max} = hf - W_0$$

$$= \left(6.63\times10^{-34}\right)\left(2.8\times10^{15}\right) - (4.14)\left(1.60\times10^{-19}\right)$$

$$= 1.19\times10^{-18}\,J = 7.46\; eV$$

Example. a) Find the energy of a photon with wavelength 210 nm.
b) When light with this wavelength falls on a metal, the photoelectric circuit is brought to zero at a stopping voltage of 1.64 V. Find the work function of the metal.

$$a)\ E = hf = h\frac{c}{\lambda} = \left(6.63\times10^{-34}\right)\frac{\left(3.00\times10^{8}\right)}{\left(210\times10^{-9}\right)} = 9.47\times10^{-19}\,J$$

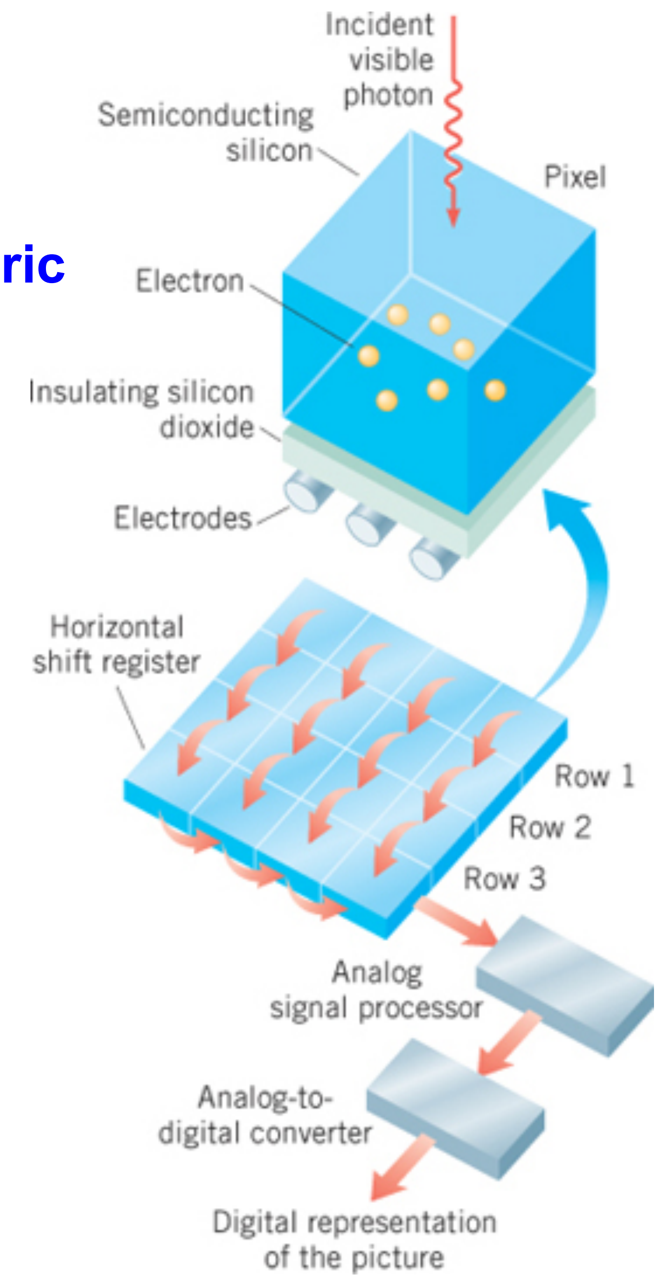
$$= 5.92\ eV$$

$$b)\ KE_{\max} = e\Delta V_s = \left(1.60\times10^{-19}\right)\left(1.64\right) = 2.62\times10^{-19}\,J$$

$$= 1.64\ eV$$

$$KE_{\max} = hf - W_0 \quad \Rightarrow W_0 = hf - KE_{\max} = 5.92 - 1.64 = 4.28\ eV$$

The Charge-Coupled Device (CCD) used in digital cameras to capture pictures is based on the photoelectric effect.



A safety feature in garage door openers is based on the photoelectric effect.