3A_The Units for Energy and Max Planck

Abstract

The color of nanosized crystals of CdSe, which is a semiconductor, moves from red towards the blue as the crystals become smaller. This is a classic example of interaction between electromagnetic radiation and atomic physics. The interaction becomes meaningful when the energy in light becomes comparable to the energy in small nanocrystals of a semiconductor.

Therefore, the discussion in this chapter centers on three aspects:

i. the energy in light waves, and
ii. the energy levels in the electronic structure in the solid state,
iii. the energy levels in nanocrystals of semiconductors.

Units

Since energy is the fundamental bridge between the three topics, let us consider its units from different perspectives. The table below lists the important physical constants that play a role in the consideration of "energy physics":

Name	Symbol	Value	Units
Avogadro's Number	N_A	6.0254×10^{23}	per g mol^{-1}
Boltzmann's Const.	k_B	1.38×10^{-23}	$J\ K^{-1}$
Gas Constant	R	8.31	$J\ K^{-1} mol^{-1}$
Permittivity Factor	ε_o	8.854×10^{-12}	$C^2 N^{-1} m^{-2}$, or $F\ m^{-1}$
Electronic Charge on an Electron	e	-1.601×10^{-19}	C
Electron Mass	m	9.107×10^{-31}	kg
Planck's Constant	h	6.624×10^{-34}	J s
Velocity of Light	c	2.998×10^{8}	$m\ s^{-1}$
Conversions			
$J \rightarrow eV$	divide by 1.602×10^{-19}	$(1\ eV = 1.602 \times 10^{-19}\ J)$	
$eV \rightarrow J$	multiply by 1.602×10^{-19}	$(1\ J = 6.24 \times 10^{18}\ eV)$	
$eV \rightarrow kJ\ mol^{-1}$	multiply by 96.53	$(1\ eV = 96.53\ kJ\ mol^{-1})$	
$kJ\ mol^{-1} \rightarrow kcal\ mol^{-1}$	divide by 4.18	$(100\ kJ\ mol^{-1} = 23.92\ kcal\ mol^{-1})$	

The fundamental unit of energy is J (Joule) which is equal to the work done when a force 1 Newton causes a displacement of 1 meter. This is the mechanical definition of energy.

In solid state physics, we are nearly always concerned with electrons, with a negative charge, and protons, with a positive charge. The force on a charge depends on the electric field, E, with has units of $V\ m^{-1}$, and is equal to

Force on a charge = eE

Consider two electrodes spaced L m apart, with a potential difference of ΔV

Therefore: $E = \frac{\Delta V}{L}$

Therefore the work done to move the charge between the two electrodes

$W = \left(e\frac{\Delta V}{L} \right) * L$ W, which is equal to $e\Delta V$ (1)

The above leads to a unit of energy which is commonly used in solid state physics: eV

1 eV = (Eq. 1), where $\Delta V = 1$ volt.

In words, it is equal to the work done to move an electron between two electrodes having a potential difference of 1 volt. The work is done on the electron (endothermic) if it is moved from the positive to the negative electrode, and work is done by the electron on the surrounding (exothermic) if the electron moves from the negative to the positive electrode.

When the charge is expressed in Coulombs and the voltage difference in volts then the product of the two has units of J.

Therefore

1 eV = (charge on one electron in Coulombs) * potential difference of 1 volt

To convert 1 eV into Joules we simply have to substitute the charge on an electron which is 1.601×10^{-19} Coulombs, or C.

Therefore: 1 eV is equal to 1.601×10^{-19} Joules.

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eV $\rightarrow$ kJ mol^{-1}	multiply by 96.53	(1 eV = 96.53 kJ mol^{-1})	
kJ mol^{-1} $\rightarrow$ kcal mol^{-1}	divide by 4.18	(100 kJ mol^{-1} = 23.92 kcal mol^{-1})	

Notes: J=Joules, cal=calorie, K=Kelvin, g=grams, C=Coulombs, F=Farads, N=Newtons, m=meters, s=seconds, k=kilo, eV=electron volts.

The physical constants spelled out in the table just above enable other relationships, for example:

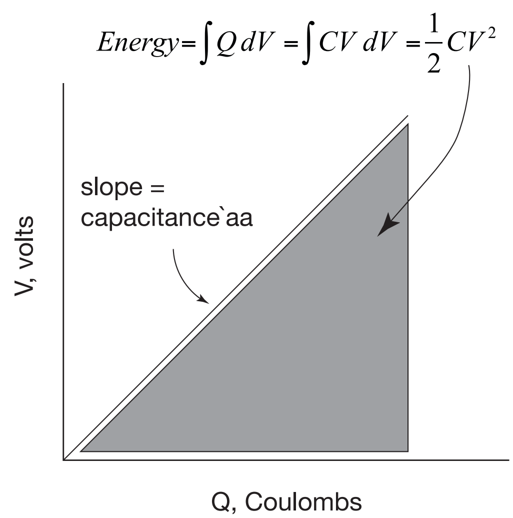
Boltzmann's Constant

$k_B T$ is the energy of thermal vibrations of atoms as a function of temperature;

Permittivity

ε_o the permittivity of vacuum when multiplied by the relative dielectric constant, ε_r, which is dimensionless relates the charge on a capacitor to the voltage difference across its "plates" to the capacitance, as given by

$C=\frac{Q}{V}$ where C is the capacitance in Farads, Q is the charge in Coulombs and V is in volts.



The electrical energy stored by the capacitor is given by the Q, V curve (like the stress strain diagram). The energy stored in the capacitor is therefore given by

$$\frac{1}{2}CV^2$$

The permittivity of vacuum is used to express the capacitance in Farads when the charge is in Coulombs and the potential difference in Volts, in the following way

$$C=\frac{A\varepsilon_o\varepsilon_r}{d}$$

where A is the surface area of the capacitor and d is the spacing between the electrodes. Note that ε_o has units of Farads/Meter, F m^{-1}.

Planck's Constant

A prism, like rain drops, can separate light into discrete wavelengths. The visible spectrum which ranges from red to blue has wavelengths of approximately 1000 nm to 400 nm. A transition towards shorter wavelengths is called the blue shift, which is the topic of this chapter.

The interaction of light and matter was spelled out by Max Planck in 1900 to explain the observation that the color of light emitted by a black body changed when heated to different temperatures, that is, there was a relationship between thermal energy and color. This relationship led to the definition of the Planck's constant, $h = 6.6252 \times 10^{-34}$ J. s, where:

$$E = h\nu = h\frac{c}{\lambda} \qquad (1)$$

Here,

- E is the energy in units of Joules or eV
- ν is the frequency, c is the velocity (m s^{-1}) and λ is the wavelength in m or nm.
- h is the Planck's constant with units of J s as is evident from Eq. (1)

The next three sections consider the three parts of this chapter: (i) the energy in light waves, (ii) the energy levels in the electronic structure in the solid state, and, (iii) the energy levels in nanocrystals of semiconductors.