

# Estimation of band gap of different semiconductor materials through diode I/V characterization

## A Brief Introduction to *pn* Junction Diodes

A *pn* junction is obtained when a p-doped semiconductor is brought into metallurgical contact with a n-doped semiconductor. Figure 1 shows an energy diagram for a *pn* junction at zero bias. At the interface there is a depletion region sandwiched between two neutral regions- 'p' and 'n' respectively. The electron carrier concentration in the neutral n-region is given by the shallow dopant concentration  $N_D$ . Similarly, the hole carrier concentration in the neutral p-region is given by the acceptor concentration  $N_A$ .

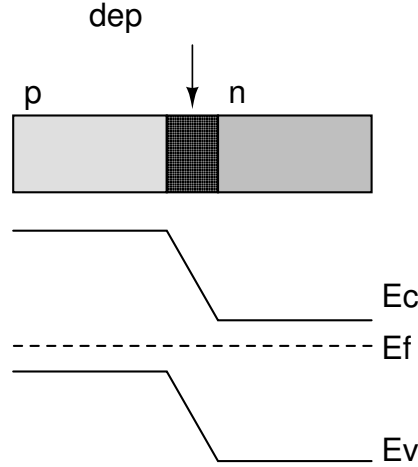


Figure 1: Energy band diagram of unbiased *pn* junction

Focusing on the n-side, application of a forward bias results in hole injection through the depletion region into the neutral n-region. The conductivity of the n-region is increased by minority carrier injection (holes are minority carriers in n-region and vice versa in the p-region). (As an aside, this is what makes semiconductors special- by application of voltage, the conductivity of the material can be changed and can be changed by modulating the majority or minority carrier density depending on the device architecture.) A similar argument is valid for holes.

Again focusing on the n-side, on application of forward bias, the hole concentration on the n-side increases exponentially with applied voltage in an ideal diode. This enables the electrons to recombine with holes. If the recombination is radiative, then it is accompanied by light emission. We see from this argument that the energy of the light emitted should be equal to the band gap. So materials with different band gaps will emit light of different frequency and hence different colour. This is the principle of working of LEDs.

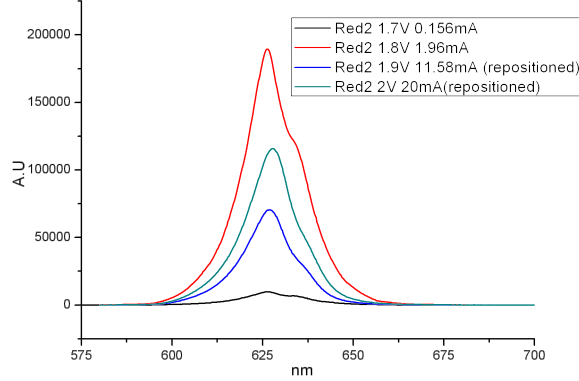
In this experiment, we need a method to distinguish between the diodes on basis of their band gaps and also determine the numerical values of the same. This can be achieved as follows:

1. By choosing different coloured LEDs, choice of diodes with materials of different band gap is easily made.
2. The peak emission wavelength of the LED is a measure of the band gap i.e.

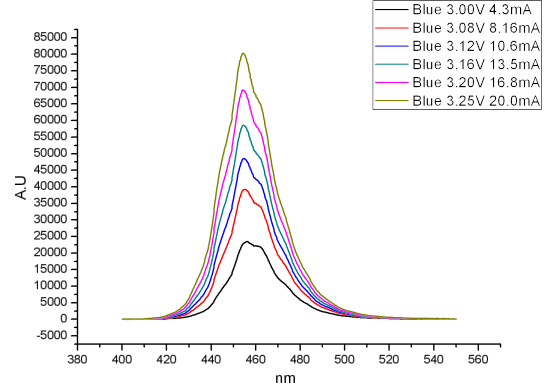
$$E_g = \frac{1240}{\lambda} \quad (1)$$

where  $E_g$  is the band gap in electron Volts (eV) and  $\lambda$  is the emission wavelength in nanometers (nm).

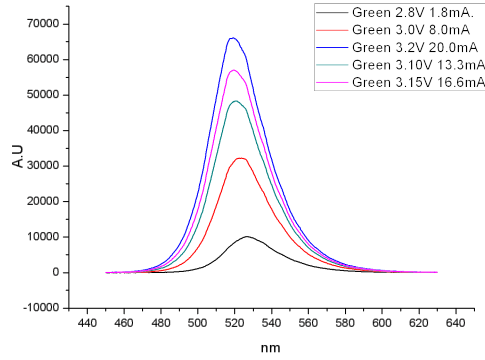
We should emphasize that this scenario is true for ideal diodes- which are only grown in text books! Figure 2 shows the spectra of different coloured LEDs driven at different current levels. As expected, the intensity of light emission increases with current as minority carrier injection increases. Notice that the white LED shows two wavelengths. Why?



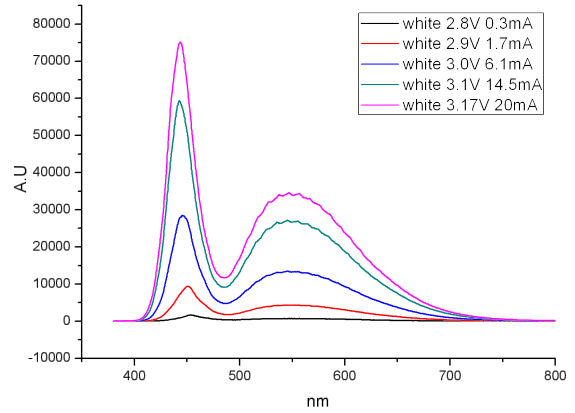
(a) Red LED



(b) Blue LED



(c) Green LED



(d) White LED

Figure 2: Emission Intensity v/s Wavelength of various LEDs for different currents

## I-V Characteristics of an Ideal Diode

The I-V characteristics of a diode in forward bias is given by the equation:

$$I_D = I_0 e^{-\frac{E_g}{kT}} \left( e^{\frac{qV_D}{\eta kT}} - 1 \right) \quad (2)$$

Where  $V_D$  and  $I_D$  indicate voltage across the diode and current through the diode respectively. The saturation current  $I_S$  is given as  $I_S = I_0 e^{-\frac{E_g}{kT}}$ . Assuming  $qV_D \gg \eta kT$ , equation (2) can be rewritten in

logarithmic form as:

$$\ln \left( \frac{I_D}{I_{00}} \right) + \frac{E_g}{kT} = \frac{qV_D}{\eta kT} \quad (3)$$

For an ideal diode,  $\eta=1$ . Thus, for constant  $I_D/I_{00}$ ,  $V_D$  is proportional to  $E_g$ . If  $I_{00}$  does not vary very much from material to material, then for a constant  $I_D$ ,  $V_D$  will increase as the band gap increases. Hence one way to test equation (3) is to determine  $V_D$  for a constant value of  $I_D$  for LEDs of different colours and plot  $V_D$  v/s  $E_g$  of the LED obtained from its emission spectrum and look at the correlation. This precisely, is the experiment.

### **What would be a smart way to choose the value of $I_D$ for the experiment?**

Equation 2 is valid for ideal diodes, which are grown in text books. Real diodes use technology for both materials growth and processing. We list below some reasons for the non-ideality of real diodes.

- (a) In an ideal diode, the applied voltage is assumed to drop entirely across the depletion region. In a real diode, the neutral region has a finite resistance. There is hence a non-zero voltage drop across the neutral region which can only be inferred and not measured. Clearly this is important for “large” currents.
- (b) At low currents in forward bias, there is a departure from ideal behavior. This arises due to defects in the material which gives rise to “recombination” currents rather than diffusion current- which requires a modification of (2).
- (c) What is important is the current density  $J_0$ . Different diodes used here may have different areas ( $A$ ) and hence the actual current i.e.  $J_0 A$  may vary.

Thus, it is important not to choose a very low current (reason (b)) or a very high current (reason (a)). A possible choice could be  $0.5 \text{ mA} \leq I_D \leq 1 \text{ mA}$ .