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.

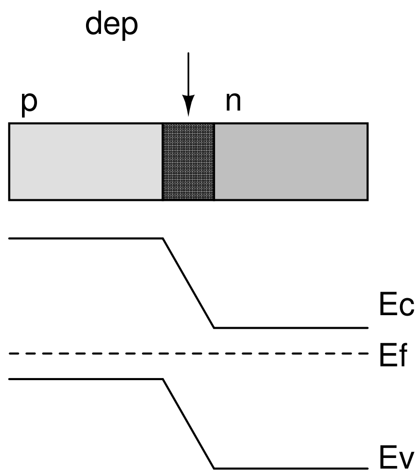


Figure 1: Energy band diagram of unbiased *pn* junction

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.

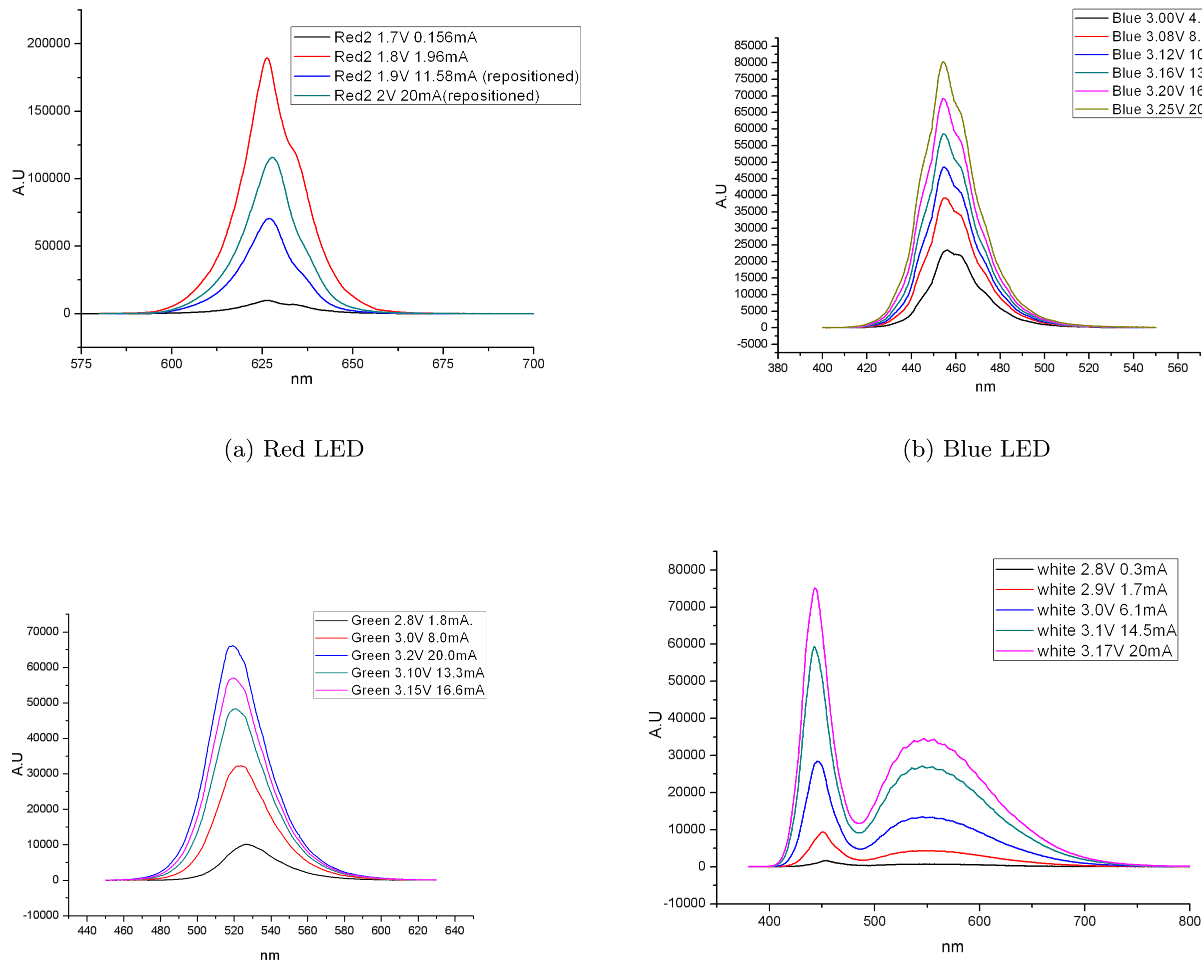
In this experiment, we need a method to distinguish between the diodes on basis of their band gaps and also determine the numerical values of the same. This can be achieved as follows:

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.

$$E_g = \frac{1240}{\lambda} \tag{1}$$

where E_g is the band gap in electron Volts (eV) and λ 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:

$$I_D = I_{00} e^{-\frac{E_g}{kT}} \left(e^{\frac{qV_D}{\eta kT}} - 1 \right) \tag{2}$$

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 $I_S = I_{00} e^{-\frac{E_g}{kT}}$. Assuming $qV_D \gg \eta kT$, equation (2) can be rewritten in logarithmic form as:

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

For an ideal diode, η=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_0A 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 mA $\leq I_D \leq$ 1 mA.

Answering the Questions:

1. **Why does the intensity of light increase with current?**
   - When the current through the LED increases, more minority carriers (holes and electrons) are injected into the diode. This leads to more recombination events, which increases the intensity of light emission.
2. **Why does the white LED show two wavelengths?**
   - White LEDs usually emit a combination of different wavelengths to create white light. This is often achieved by using a **blue or UV LED** coated with a **phosphor layer**. The blue or UV light excites the phosphor, causing it to emit light at a longer wavelength, typically in the yellow or red spectrum. The combination of these two wavelengths (blue and yellow) gives the appearance of white light.

Formula/Concept	Formula	Description
Diode Current Equation	$I_D = I_S\left(e^{\frac{qV_D}{\eta kT}} - 1\right)$	Shockley equation for current in a forward-biased diode
Reverse Saturation Current	$I_S = AT^2e^{-\frac{E_g}{kT}}$	Reverse saturation current depends on band gap E_g, constant A, and temperature T
Thermal Voltage	$V_T = \frac{kT}{q}$	The voltage corresponding to thermal energy at a given temperature (approx. 25.9 mV at room temperature)
Built-in Potential	$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_AN_D}{n_i^2}\right)$	Built-in potential for a pn junction, dependent on doping concentrations and intrinsic carrier density
Depletion Width	$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{N_A+N_D}{N_AN_D}\right)V_{bi}}$	Width of the depletion region in a pn junction
Depletion Capacitance	$C_{dep} = \frac{\epsilon_s}{W}$	Capacitance of the depletion region
Charge Density in Depletion Region	$Q_D = qN_AW_p = qN_DW_n$	Charge density in depletion region (p-side and n-side)
Minority Carrier Diffusion Length	$L = \sqrt{D\tau}$	Distance a minority carrier travels before recombining
Junction Capacitance (Reverse Bias)	$C_j = \frac{C_0}{\sqrt{1+\frac{V_R}{V_{bi}}}}$	Junction capacitance as a function of reverse bias voltage
Intrinsic Carrier Concentration	$n_i = AT^{3/2}e^{-\frac{E_g}{2kT}}$	Intrinsic carrier concentration depending on the material's band gap and temperature
LED Band Gap-Wavelength Relation	$E_g = \frac{1240}{\lambda}$	Band gap E_g related to emission wavelength λ for LEDs
Forward Bias Approximation	$I_D \approx I_Se^{\frac{qV_D}{\eta kT}}$	For large forward bias, diode current simplifies to this exponential form
Breakdown Voltage (Zener Diodes)	(Experimentally Determined)	The breakdown voltage is specific to Zener diodes and depends on doping and material properties