LAB V. LIGHT EMITTING DIODES

1. OBJECTIVE

In this lab you are to measure I-V characteristics of Infrared (IR), Red and Blue light emitting diodes (LEDs). The emission intensity as a function of the diode current will be determined as well using a photodetector. We will also see again how real diode characteristics are both similar to and different from those of the "ideal" diode.

2. OVERVIEW

The first section of the procedure involves identifying the physical structure and orientation of the LEDs based on visual observation. The two next procedural sections will use the LabView program **IV_curve.vi** to measure the I-V characteristics of test LEDs in forward and reverse bias. The final section will use the LabViEW program **LED-Output.vi** to measure the optical emission intensity of the LED as a function of the LED current. Although it is possible to collect the data for this lab very quickly, **it is essential that you understand the different regions found in the I-V characteristics of these diodes and the mechanisms by which current flows through them**.

Information essential to your understanding of this lab:

1. Understanding of the operation of biased p-n junction diodes
2. Understanding of how electrons and holes recombine to produce light.

Materials necessary for this Experiment

1. Standard testing stations
2. One each: Infrared (IR) LED, Red LED and Blue LED

3. BACKGROUND INFORMATION

3.1 CHART OF SYMBOLS

Here is a chart of symbols used in this lab. This list is not all inclusive, however, it does contain the most commonly used symbols.

Table 1. A chart of the symbols used in Lab.

Symbol	Symbol Name	Units
E	electric field	V / cm
A	junction area	cm^2
D_p	diffusivity of holes	cm^2 / sec
D_n	diffusivity of electrons	cm^2 / sec
τ_p	hole life time	sec
τ_n	electron life time	sec
τ_g	general carrier lifetime	sec
w	depletion width	cm
L_p	diffusion length of a hole	cm
L_n	diffusion length of an electron	cm
V_{bi}	built in voltage	V

3.2 CHART OF EQUATIONS

Several of the equations from the background portion of the manual are listed here.

Table 2. A chart of the equations used in this lab.

Equation	Name	Formula
1	Total diode current equation	$I = I_d + I_{nr} = I_{d'} e^{q(V-IR_s)/kT} + I_{nr'} e^{q(V-IR_s)/2kT}$
2	Peak wavelength equation	$\lambda(nm) = \frac{1240}{E_g(eV)}$

3.3 FORWARD AND REVERSE CHARACTERISITCS OF THE LEDS

You will measure the forward and reverse bias I-V characteristics of Light Emitting Diodes (LEDs) along with the relative amount of light emitted by the LEDs in this lab.

When a pn junction is forward biased, electrons and holes (carriers) diffuse across the junction from the side where their densities are large to the other side. So electrons diffuse from the n-type side to the p-type side while holes diffuse the opposite direction. When they reach the far side of the junction, they are the minority carriers and they recombine with the majority carriers. For materials with an indirect bandgap, such as silicon, nonradiative recombination predominates, resulting in heating of the lattice. (The pn junction gets hot.) For direct bandgap materials, including GaAs, AlGaAs, GaAsP, InP and GaN, the carriers can recombine by emitting a photon. This is called "radiative recombination" and it produces light when the LED is forward biased, which is called "injection luminescence".

LEDs have widespread applications today in displays (including TVs, traffic lights and signs) and as light sources for optical communications, DVD players, remote controls etc.

The total diode current is the sum of two parts: [1] a "radiative recombination" also known as a "diffusion" current (I_d) and [2] a "nonradiative recombination" current (I_{nr}). The recombination of the carriers which diffuse across the junction (I_d) results in the radiative emission. The nonradiative current (I_{nr}) results from carriers that recombine at a surface. Those carriers can recombine without giving off a photon. The surface is usually at the edges of the pn junction. The total diode current is the sum of the I_d and I_{nr}.

$$I = I_d + I_{nr} = I_{d'} \exp[q(V-IR_s)/(k_BT)] + I_{nr'} \exp[q(V-IR_s)/(2k_BT)] \qquad [1]$$

Here R_S is the device series resistance and $I_{d'}$ and $I_{nr'}$ are the saturation currents for the diffusion and nonradiative recombination currents, respectively. The light output is proportional to $I_{d'} \exp[q(V-IR_s)/(k_BT)]$. At low bias voltage the recombination current predominates and little light is emitted. With increasing bias voltage the proportion of diffusion current becomes larger and when this term dominates over the recombination current the light output is proportional to the current. At high currents the series resistance term in Eq. [1] has an important effect on the I-V characteristic, however the light versus current curve will remain linear so long as the diffusion current dominates. You will see that this is the case for our Infrared LED but not as well for our red and blue LEDs.

The most studied III-V direct band gap semiconductors are GaAs and InP, with band gaps at 1.424 eV and 1.351 eV, respectively. The wavelength at which the material emits the most light (the brightest) has approximately the band gap energy. This peak wavelength can be found using the relation between energy and wavelength.

$$\lambda(\text{nm}) = 1240 / E_g(eV) \qquad [2]$$

The result is emission spectra having the highest intensity at 871 nm (for 1.424 *eV*) and 918 nm (for 1.351 *eV*) respectively. These wavelengths are in the near infrared region of the spectrum, and are not visible to the human eye. To be useful as an LED indicator the band gap of the semiconductor must be larger. This can be accomplished by alloying GaAs with higher energy band gap materials, such as AlAs (E_g = 2.163 *eV)* and GaP (E_g = 2.261 *eV*). This is exactly what was done for our test devices in this lab. Our Infrared LED is an AlGaAs alloy and results in a peak wavelength of ~875 nm (1.417 *eV*). Our Red LED is a GaAsP alloy with a peak wavelength of ~635 nm (1.953 *eV*). The Blue LED is made from GaN and has a peak wavelength of 428 nm (2.897 *eV*).

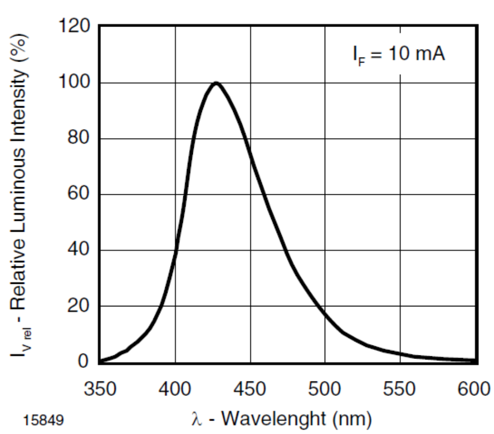
There is a large and growing market for LEDs and research is continuing to improve the efficiency of the light emission. You can read further about this in your textbook for the class. Newer III-V semiconductors are being investigated, such as $In_yGa_{1-y}N$, which have improved emission efficiencies in the visible spectrum. LEDs are now more efficient than incandescent lightbulbs as well as much more rugged, reliable and longer lived. Their response times are 100 to 1000 times faster and LEDs have now become cost effective for a variety of mass-market applications such as automotive indicator lamps, tail lights, dash lights and displays.

Figure 1 shows the emission spectra of the three LEDs we will be testing as a function of wavelength as well as the sensitivity of our detector diode. Figure 2 shows the I-V characteristics of the three LEDs. Note that the turn on increases with the increasing energy of the emission.

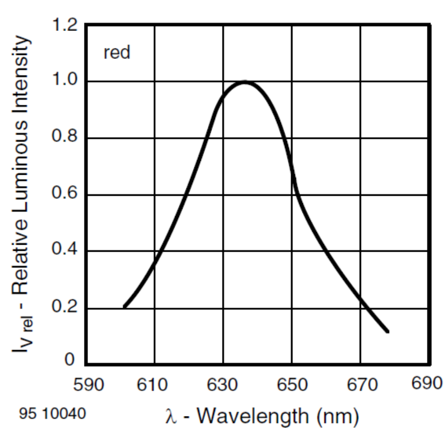
The construction of a typical LED device is shown in the cross-sectional view in Fig. 3. The LED chip is bonded to the bottom of the shallow reflector cup with conductive epoxy. This cup is on the left hand electrode in Fig. 3. A thin gold wire makes the contact between the second lead (on the right) and the top contact pad. For the indicator packages used in this laboratory experiment an epoxy or plastic dome is cast around the lead frame. The rating sheet of the LED usually specifies the forward voltage drop at 20 *mA*, the luminous intensity at the specified current, and the peak wavelength. These are all listed in Table 1.

Table 1. Specifications of LEDs.

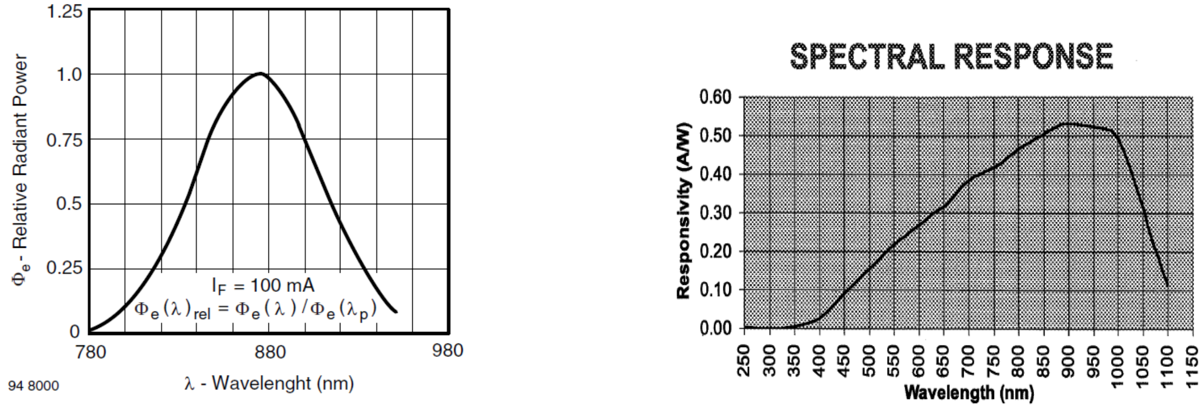
Color	V_{fwd} @ 20 mA	Light Intensity	Peak Wavelength (nm)	Composition
Infrared	1.5 *V*	20 mW/sr	875	GaAlAs
Red	2.0 *V*	10 mcd	635	GaAsP on GaP
Blue	3.9 *V*	15 mcd	428	GaN on SiC



(a)



(b)



(c) (d)

Figure 1. The spectra of the Infrared (a), Red (b) and Blue (c) LEDs. The spectral response of the photodetector (d) is also included. Note that it is most sensitive to the infrared LED and least sensitive to the blue LED.

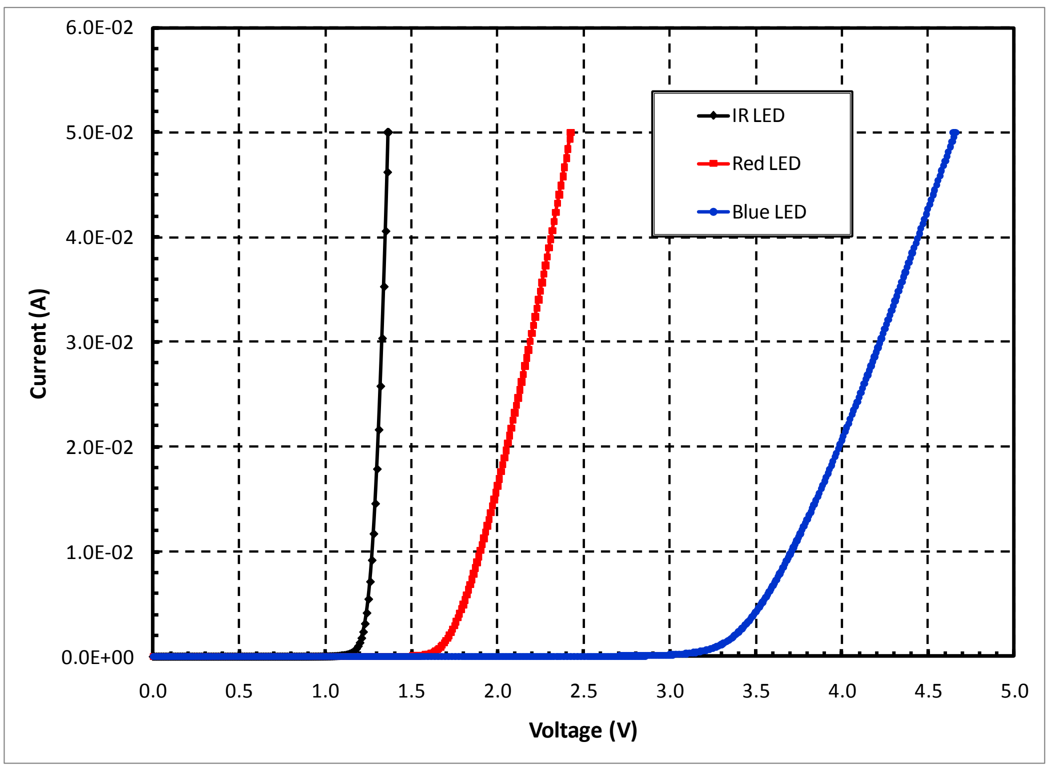


Figure 2. Typical I-V curves for the Infrared, Red and Blue LEDs.

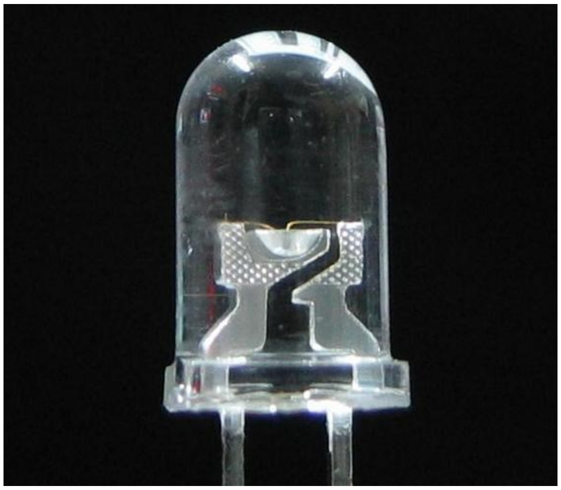


Figure 3. Construction of an indicator type of LED. Picture from http://smspower.org

3.4 MEASUREMENT OF LED LIGHT OUTPUT USING A PHOTODIODE

Photo detectors can take various forms, but the one we will use in this lab is simply a reverse biased diode. Light shining on a diode produces electron-hole pairs. When the diode is reverse biased, the electron-hole pairs generated in the junction region are swept out by the electric field there and produce current. As a result, the current flowing through the reverse biased diode is directly proportional to the amount of light shining on it. We will use a reverse biazsed "pin" diode to detect the light coming from our LEDs. ("pin" in "pin diode" stands for "p-type – intrinsic – n-type" and indicates that the width of the junction region has been made larger by having an intrinsic region placed between the n and p-type regions.) A photo of a typical pin diode in a plastic package is shown in Fig. 4.

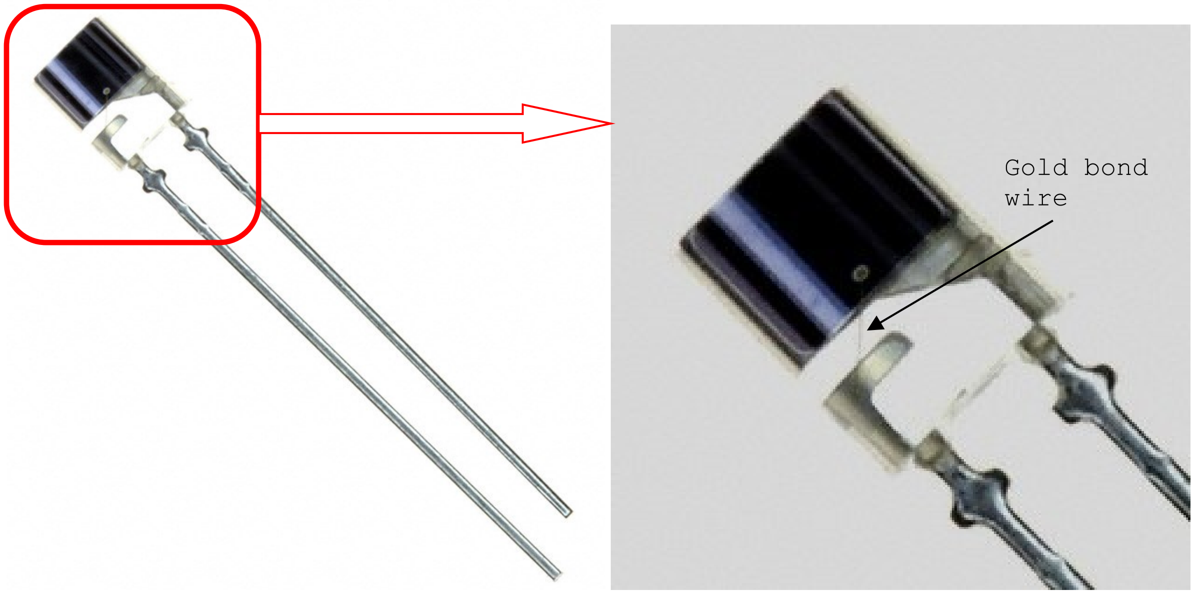


Figure 4. Construction of a typical pin photodiode. The photodiode is placed on the right hand lead and a thin gold wire connects to it's top. Picture from http://parts.digikey.com

4. PREPARATION

1. Read through Sections 8.1 and 8.2 of Streetman and Banerjee. We will use a pin detector in lab and several LEDs (Infrared, Red and Blue)
2. Design a method for determining whether the substrate of the LED chip is *p* or *n* type.
3. Obtain the values of the forward voltage for the diode *I-V* characteristics shown in Fig. 2. Compare this with the values of the peak emission wavelengths shown in Table 1. (Use Eq. 2 to get energies.)
4. Estimate the series resistance from the I-V curves shown in Fig. 2.

5. PROCEDURE

In this experiment you will study the characteristics of three indicator LEDs that emit in the infrared, red and blue parts of the spectrum. Check that the longer lead wire of the LED is the positive terminal. The detector used in this experiment has a square 0.3 x 0.3 cm^2 geometry. The longer lead denotes the anode (or positive lead) for forward bias. Hence, when used as a detector in the reverse biased mode, this terminal must be negatively biased to 10 *V*. Use a current compliance value of 5 mA.

1. Measure the forward *I-V* characteristics of the three LEDs using the "**IV_curve.vi**" program.

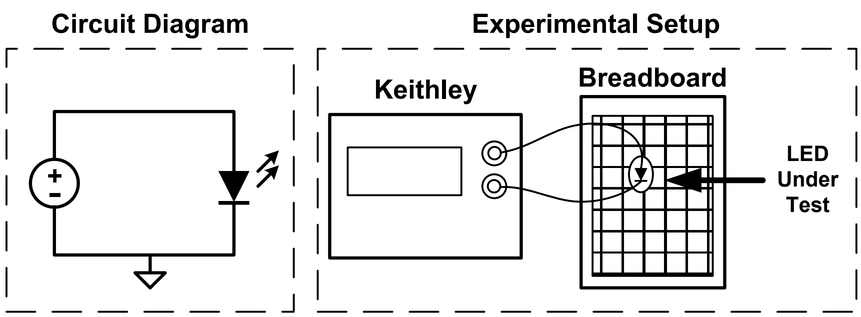


Figure out the best settings to use. Be sure to limit the current to a maximum value of less than 200 mA (Infrared), 30 mA (Red) and 20 mA (Blue). You may need to adjust the values to obtain an optimum set of curves. Save the *I-V* measurements for each of the diodes.

A. Display the data on a linear *I*-linear *V* plot and obtain the usual diode *I-V* curve.
B. To look at the exponential dependence of the current on voltage, switch to the **log *I*- linear *V* scale**. This curve should be linear at low currents and saturate at high currents due to the effect of the series resistance. As indicated in Eq. [1] there are two recombination currents, differing only in the prefactor of the *kT* term in the exponent. Thus Eq. 1 can be rewritten in terms of an effective diode current

$$I = I_o \exp[q(V-IR_s)/(nk_BT)] \qquad [3]$$

where *n* has a value between 1 and 2, depending on whether the diffusion current or the nonradiative current dominates. The value of *n* is most easily obtained from a semilog plot of *I* vs. *V*, selecting a linear region of the curve. Calculate the values of *n* along the forward bias curves for all three diodes using the equation

$$n = (q/k_BT)[\ (V_2 - V_1) / (\ln(I_2/I_1))\ ] \qquad [4]$$

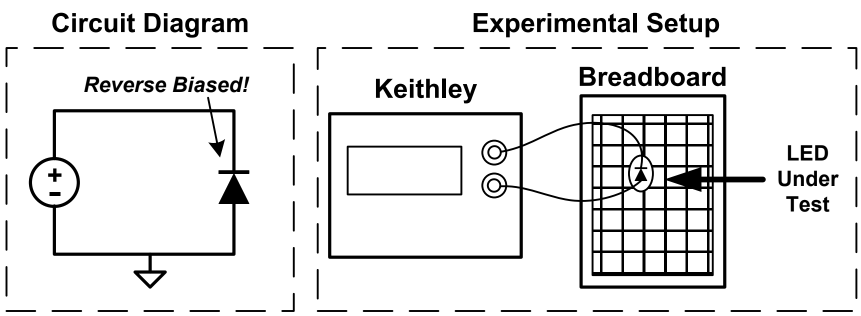
C. A simple expression for the series resistance is obtained from Eq. 3 by taking the derivative with respect to I of both sides. Rearranging the equation yields

$$R_s = (dV/dI) - (k_B T/(qI)) \quad [5]$$

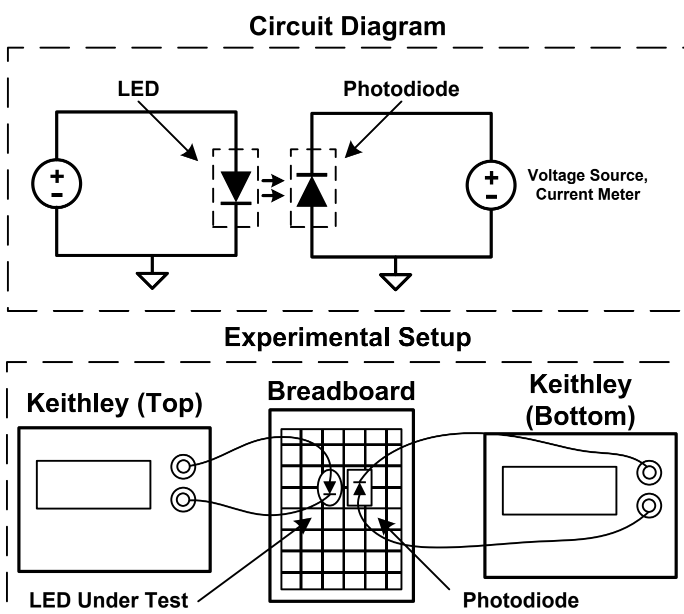
and for large diode currents the first term on the right hand side dominates the expression. Thus on a linear I - linear V plot the differential slope of the I-V curve gives the value of the series resistance. **For your report <u>you will determine the *n* values</u> of the diode equation at different currents from the semilog plot of *I vs. V*. From the linear plot of the *I vs. V* dependence <u>you will determine the series resistance</u>.**

D. Draw the side view of the LED geometries by looking through the plastic domes after you are done. Determine the semiconductor type of the substrate by examining this geometry (Hint: the long leg of the LED is positive).

2. Measure the reverse bias I-V characteristics of the three LEDs up to 10 V reverse bias.



3. Measure the current dependence of the light output using the "**LED-Output.vi**" program. Step the LED current to the maximum values (200 mA (Infrared), 30 mA (Red) and 20 mA (Blue)) in 40 equal steps. That way you will have 41 datapoints for your graphs. Use compliance values of 3V for Red LED, 5V for Blue LED and 1.5 V for IR LED.



Does the LED light output increase linearly with current? What differences are there between the three different devices? What similarities?

6. LAB REPORT

- Write a summary of this experiment.
- Diode Design and Fabrication
    - Show the diagrams you drew of the side view of the LED geometries you obtained by looking through the plastic domes.
    - Show the semiconductor type of the substrate you obtained for each LED and describe how you came to this conclusion.
- Forward and Reverse I-V Characteristics.
    - Attach 2 plots of the LEDs' Forward bias characteristics. One will be linear current vs. linear voltage. The other plot will be a semilog plot (Log current vs linear voltage.) <u>Plot all three LEDs together</u> so that you have a total of 2 plots.
    - Attach a plot of the **ideality factor (*n*)** for all three LEDs. Are there deviations from n=1 or 2?
    - Attach a plot of the **series resistance**. Are there significant differences between the three LEDs?
    - Attach a plot of the Reverse bias I-V characteristic. Are there any significant differences between the three LEDs?
- Current Dependence of the Light Output
    - Attach a plot of the light output as measured by the photodiode current as a function of current of the LEDs.
    - Calculate the slope of the curves. Is the dependence linear over the complete current range? Explain the origin of the current dependence of the diodes.