

LIGHT EMITTING DIODE CHARACTERISTICS
(SAMPLE LAB WRITEUP)

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ABSTRACT

This lab investigates the V-I characteristic of a light-emitting diode (LED). The measured data shows that, for currents of order 10mA and above, the exponential model for the LED must be modified to include a series resistance of order 5 Ω .

EQUIPMENT

Wavetek 2015 DVM
HP3458A DVM
HP33120A Function Generator
Tektronix PS2521G Power Supply
HP54602B Oscilloscope

INTRODUCTION

The junction diode is a familiar component which is widely used for circuit applications such as rectification. When the diode is fabricated in silicon, the forward voltage drop is approximately 0.7V and the v_D - i_D characteristic relating diode voltage and current can be described by an exponential relationship:

$$i_D = I_S \exp(v_D/nV_T) \quad (1)$$

where I_S and n are scale factors, and V_T is the thermal voltage $kT/q_e \approx 25.4\text{mV}$ at room temperature.

The LED is a junction diode that emits light when forward biased. To achieve the light emitting property, it is necessary to fabricate the LED from materials other than silicon. As a result, the forward voltage drop of the LED is greater than 0.7V; usually of order 1 to 2 volts.

The purpose of this lab is to investigate the v_D - i_D characteristic of the LED, and determine how well the model of Eq. (1) applies.

Be sure the title block includes your name (and, if appropriate, your lab partner's), the ECE box number you want the writeup returned to, and the date of the report.

The abstract is a concise description of the material covered in the lab, as well as a summary of the important results. Don't just repeat the introduction from the lab handout -- be sure to include some specific result(s) from your work.

Spell out acronyms (LED) the first time they are used.

Be sure to record the equipment used, since (as we'll see later in this report) the characteristics of the instrumentation may affect the accuracy of your measurements

The introduction should provide the theoretical background for the work you will be presenting

Important equations should be set on their own line. Be sure to number every equation so you can refer to it later in the text if necessary. If there are any new symbols introduced, explain them in the text immediately following the equation.

Your introduction should concisely state the purpose of the lab, motivating the reader to understand the work to be described

CIRCUIT DESCRIPTION

Two circuits were used to measure the V-I characteristic of the LED. The first circuit, shown in Fig. 1, was used to display the V-I characteristic on an oscilloscope.

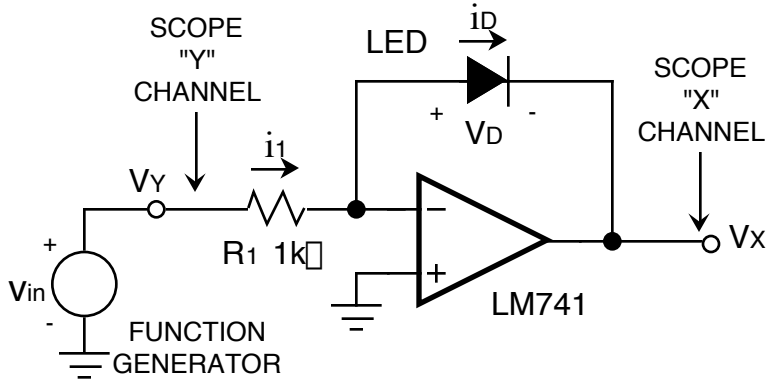


Fig. 1. Circuit for X-Y oscilloscope measurement.

The operation of this circuit can be understood by noting that the op-amp is in the inverting configuration with negative feedback; therefore the op-amp inverting input is at virtual ground. The input current is then given by $i_1 = v_Y / R_1$. Since the current into the op-amp input is (ideally) zero, the LED current $i_D = i_1$. Thus the voltage v_Y is proportional to the diode current:

$$i_D = \frac{v_Y}{R_1} \quad (2)$$

The output of the op-amp can be related to the diode voltage by using the virtual ground property:

$$v_D = -v_X \quad (3)$$

Thus, with the oscilloscope in X-Y mode, displaying v_Y on the "Y" channel gives an indication of i_D , and displaying $-v_X$ on the "X" channel (using the "invert" option on the scope to obtain the sign inversion) provides v_D . The function generator was set to provide a triangle wave for v_Y , thus sweeping the diode current over a range of values.

In practice, although the approach shown in Fig. 1 is good for obtaining a qualitative display of the V-I characteristic, the result is not sufficiently accurate for comparing performance to the model of Eq. (1). For example, at low diode currents, the bias current of the LM741 is no longer negligible, and idealizing the op-amp input current to be zero causes a significant error.

Fancy drawings are nice (and are a must for formal reports such as an MQP) - but if you can only include a sketch, that's fine too. Just be sure that circuit diagrams have component values (e.g. $1k\Omega$), reference designations for each component (e.g. R_1), part numbers for diodes and active devices (e.g. LM741). Voltage and current signals should be clearly labeled with polarity indicated (-/+ for voltages, \square for positive current).

Assume the reader has a background in electronics, but is unfamiliar with the particular topic in the lab. It is not necessary to re-derive results previously covered (for example, virtual ground); however, the operation of newly introduced circuits should be covered both qualitatively and quantitatively.

Explain how the physical measurements you make in the lab are related to the theoretical concepts you are investigating.

Be sure to discuss (somewhere in your report) any shortcomings of the techniques you are using. It may be more appropriate in the discussion section, for example, to explain deviations in measured results from expected performance.

For more accurate measurement of the V-I characteristic, the circuit of Fig. 2 was used.

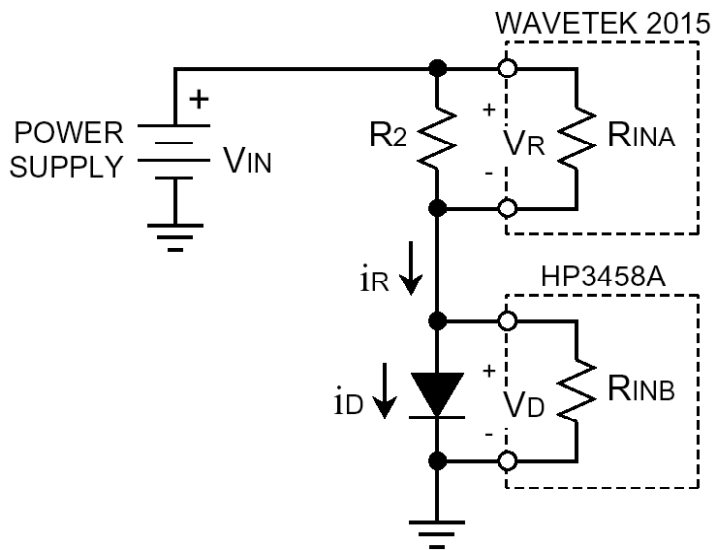


Fig. 2. Precision V-I measurement circuit.

In this circuit, the diode current was varied by changing the power supply voltage. Since the circuit is intended for precision measurements, the voltmeter input resistances R_{INA} and R_{INB} are included in the circuit. The diode voltage v_D is measured directly by the HP3458A. Circuit analysis shows that the diode current is given by

$$i_D = \frac{v_R}{R_2 \parallel R_{INA}} \parallel \frac{v_D}{R_{INB}} \quad (4)$$

To ensure an accurate determination of i_D , the voltage v_R is measured directly rather than calculated as the difference between the supply voltage and v_D .

To test the diode over a wide range of currents, different values of R_2 were used.

Here's an example of a characteristic of the instrumentation affecting the accuracy of an experiment: the input resistance of the DVM (of order $10M\Omega$) is comparable to the resistance R_2 (of order up to $1M\Omega$) in the circuit being measured.

When the derivation of an equation is relatively straightforward (in this case, just KCL, parallel resistance, Ohm's law) it's OK to leave out the details and just give the result.

MEASUREMENT RESULTS

An oscilloscope plot of the output of the circuit of Fig. 1 is shown in Fig. 3.

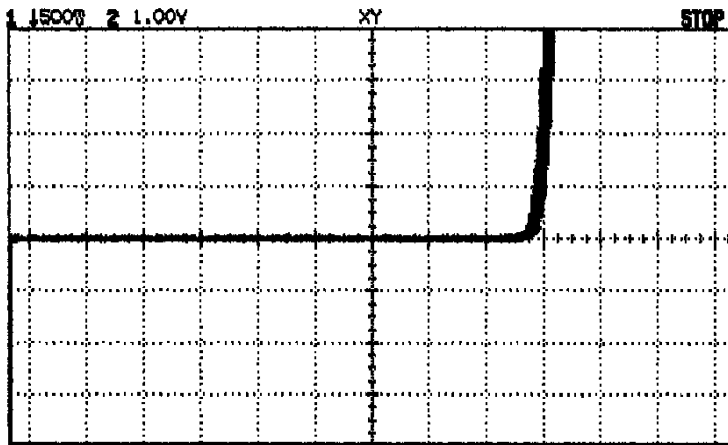


Fig. 3. Scope X-Y plot of LED V-I characteristic.
Horizontal scale: LED voltage at 0.5V/div
Vertical scale: LED current at 1mA/div

The triangle wave input was set to an amplitude of 10V peak, giving a peak current range of 10mA. With resistor $R_1=1k\Omega$, the vertical scale of 1V/div corresponds to 1mA/div for i_p . It can be seen from the plot that the forward voltage for the LED is approximately 1.5 to 1.6V at a current of order a few milliamperes. The current for negative diode voltages is zero (to within scope display accuracy), as would be expected for a reverse biased diode. The LED did not enter reverse breakdown since the input did not swing to a sufficiently negative voltage.

As can be seen from Fig. 3, the plot does not provide sufficient accuracy for a detailed comparison of the V-I characteristic to the model of Eq. (1). The measured results using the more precise circuit of Fig. 2 are given in Table 1. To cover a wide range of currents, resistors of nominal values 51Ω , $1k\Omega$, $47k\Omega$, and $1M\Omega$ were used; for each value of resistance, the input voltage was changed to vary the diode current. The resistances and voltages were varied in an approximately logarithmic fashion, to provide uniform coverage of the wide range of LED currents covered by Eq. (1). Table 1 also gives the calculated LED currents, which were determined using Eq. (4). The actual values of the resistors used for R_2 were measured using the HP3458 meter. The input resistances used for the Wavetek 2015 and HP3458A meters (from the manufacturer's specifications) were both $10M\Omega \pm 1\%$.

Use as many figures as possible: circuit diagrams, waveform sketches, graphs and tables of measured results, visual comparisons of measured vs. predicted data.

A graphic of the scope display is a great way to document waveforms, and is a must for a formal report. If you can't get a scope graphic for a lab writeup, then a careful sketch is OK.

Figure captions should be brief -- but must provide any additional information required for the reader to understand the figure; in this case, the horizontal and vertical scales of the scope plot.

In addition to what you did see in lab, also note what you didn't see, and explain it if you can. In this case, the third diode operating region (reverse breakdown) wasn't encountered, since the reverse voltage wasn't large enough.

Before going into the lab, think about the type of measurements you'll be making and what kind of effects you're investigating. Choose your data points intelligently to get maximum efficiency out of your time in the lab. In this case, logarithmic spacing of data points is a good idea. Note that the spacing doesn't have to be exact, since you're measuring and plotting both input and output -- you don't have to spend time in the lab adjusting V_{IN} for exact logarithmic spacing of data points.

Table 1. Measured results for circuit of Fig. 2

R2 [Ω] (measured)	V _{IN} [V] (nominal)	V _R [V] (measured)	v _D [V] (measured)	i _D [A] (calculated)
51.28	3	1.158	1.838	22.58E-3
51.28	3.5	1.617	1.877	31.53E-3
51.28	4	2.070	1.924	40.37E-3
51.28	4.5	2.535	1.961	49.43E-3
51.28	5	3.006	1.987	58.62E-3
1004	3	1.415	1.583	1.41E-3
1004	5	3.365	1.635	3.35E-3
1004	8	6.310	1.686	6.29E-3
1004	10	8.280	1.712	8.25E-3
46270	2	0.622	1.376	13.37E-6
46270	3	1.578	1.421	34.12E-6
46270	5	3.543	1.458	76.78E-6
46270	10	8.500	1.495	184.40E-6
46270	20	18.480	1.527	401.09E-6
983300	1.3	0.190	1.107	101.53E-9
983300	1.6	0.408	1.19	336.73E-9
983300	1.9	0.675	1.223	631.66E-9
983300	-1	-0.090	-0.907	-10.28E-9
983300	-2	-0.180	-1.818	-19.26E-9
983300	-3	-0.270	-2.72	-29.14E-9
983300	-5	-0.415	-4.583	-5.25E-9
983300	-8	-0.664	-7.335	-8.18E-9
983300	-10	-0.830	-9.169	-10.20E-9
983300	-15	-1.246	-13.75	-16.76E-9
983300	-20	-1.661	-18.34	-21.31E-9

Whenever possible, use tables to present numerical data. For each item presented, indicate the units of the measurements (for example, [Ω] or [V]). Be sure to identify values which were directly measured, values which were calculated from measurements, and nominal or noncritical values which can serve to identify data points.

Including all your raw data, as well as the equations you used in your calculations, will allow the reader to follow (and check!) your analysis completely, from start to finish.

Feel free to use a spreadsheet or math software package to automate your calculations - but check a few of the points by hand or with a calculator, to make sure the equations in your spreadsheet are OK.

DISCUSSION

Figure 4 shows a plot of the LED current as a function of LED voltage, on a linear scale. The general shape of the plot is similar to the scope photo of Fig. 3, thus confirming the basic approach.

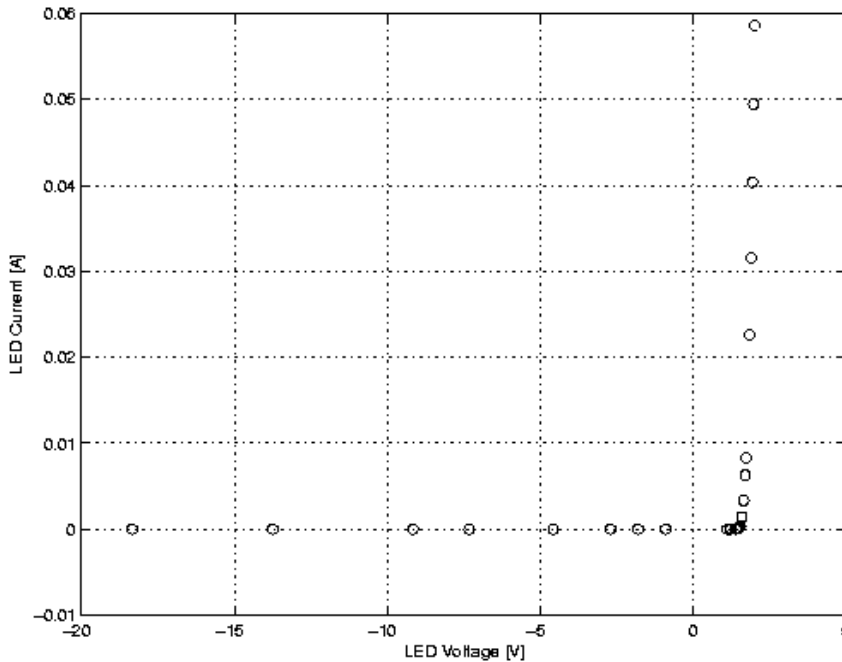


Fig. 4. Measured LED V-I characteristic.

To compare the data to the exponential characteristic of Eq. (1), it is more useful to plot the data from Table 1 on a semilog plot, as shown in Fig. 5.

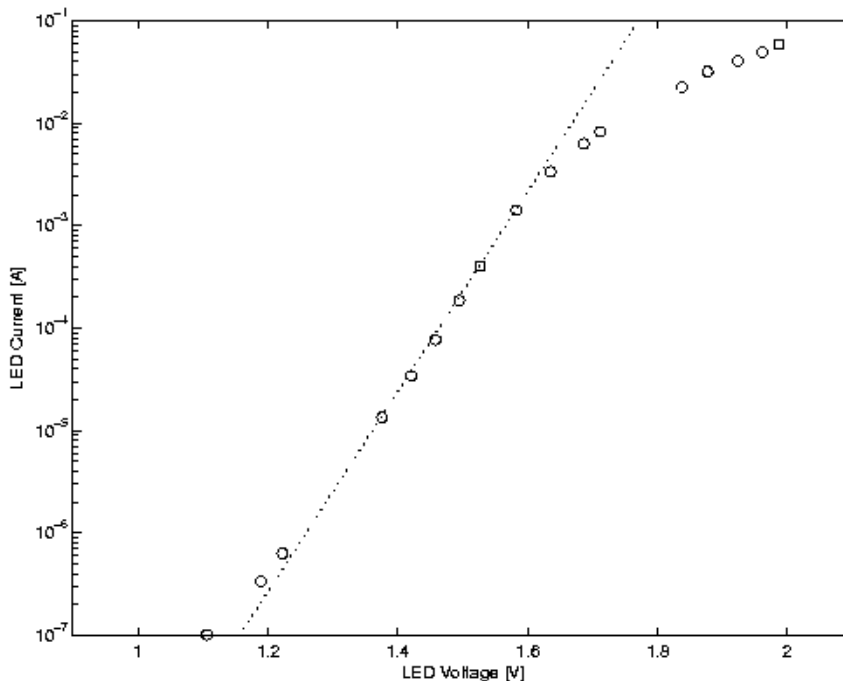


Fig. 5. Measured LED V-I characteristic, comparison to exponential model prediction.

This section discusses the measurements in light of the theory presented in the introduction. The discussion is essential to conveying the meaning of the information you've gathered in the lab.

Again, a picture is worth a thousand words - use lots of figures to illustrate the significance of your data. These figures were prepared using MATLAB; the code is available on the course web page.

Be sure the axes of your plot are clearly identified, indicating the quantity being plotted and its units.

In addition to just presenting the data in a figure, be sure to interpret it as well. In this case, for example, an examination of the linear axis plot shows that a semilog plot is better for looking an exponential characteristic.

When plotting measured points to be compared with theoretically expected performance (the dashed line, in this case) it's a good practice to plot the measurements as points (rather than connecting them with a line, as is done by default in some graphing software). This makes it easier to identify which data points follow the theory, and which ones deviate.

As can be seen from the figure, the measured data follow the theoretical prediction of Eq. (1) quite well for moderate currents, over a range of 100nA to 1mA. The dashed line in Fig. 5 represents the prediction of Eq. (1) with parameters $I_s=4.97E-19$ and $n=1.75$. These were obtained with a "least squares" fit to the measured data points over that region.

For higher currents, it can be seen from Fig. 5 that the measured data deviates significantly from the prediction of Eq. (1). The reason is that a real LED has a series resistance R_s , which contributes a voltage drop $i_D R_s$ that is not accounted for in the prediction of Eq. (1). This additional drop is not significant at low currents, but at high currents causes the deviation seen in Fig. 5.

The simple theory of Eq. (1) can be modified by adding the voltage drop $i_D R_s$ in series with the voltage predicted by Eq. (1), giving:

$$v_D = nV_T \ln \left[\frac{i_D}{I_s} \right] + i_D R_s \tag{5}$$

Fig. 6 shows the measured data plotted relative to the prediction of Eq. (5) (solid line) with $R_s=4.65\Omega$, which was obtained with a least squares fit. Parameters I_s and n were unchanged. It can be seen that the modified theory predicts the actual performance well at both low and high currents.

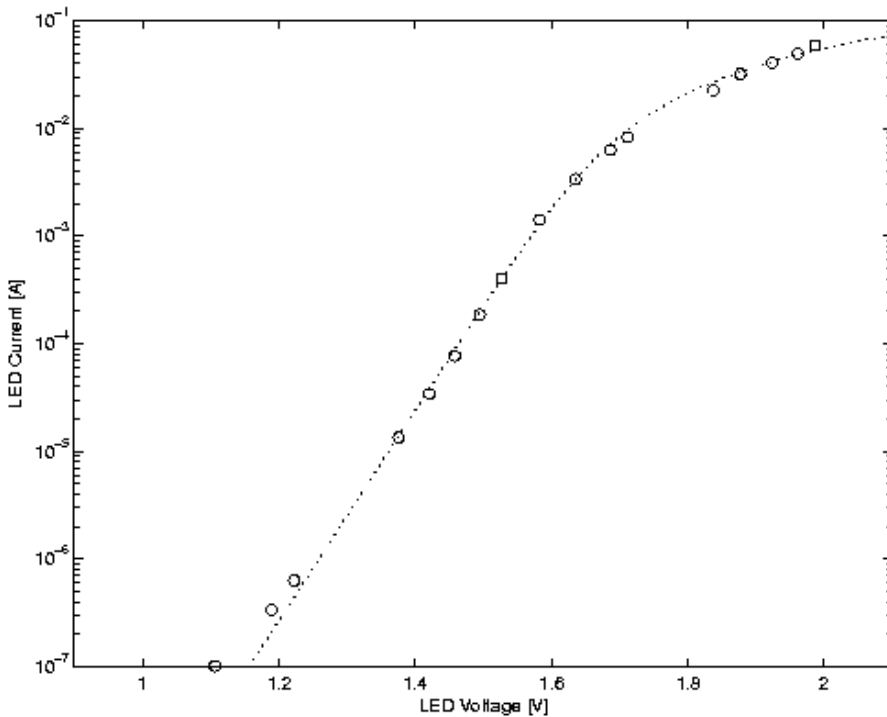


Fig. 6. Measured LED V-I characteristic, comparison to exponential with series resistance.

*There's no shame in measurements that aren't perfectly aligned with theory. **Never ever** "fudge" your data to make it agree with theory - in circuit analysis, the theory often uses approximations to simplify design. An honest look at your measurements will let you know how much error is involved in the approximations. If you can explain the deviation and modify the theory to account for it, that's great. But even if you can't, at least alert the reader to the limitations of the theory.*

It's bad enough that falsifying or leaving out data points is dishonest -- but it also prevents you from finding effects which are genuinely new. In this case, leaving out the data points for currents above 1mA would have prevented us from seeing the effect of R_s .

Your comparisons of measurement to theoretical prediction should be as clear as possible - that's why plotting them on the same graph is essential. Similarly, if the prelab for this lab had involved (for example) simulation on SPICE, this would be a good place to plot the measured data vs. a SPICE simulation result.

CONCLUSION

The V-I characteristic of a light-emitting diode (LED) was measured using two circuits, one providing an approximate visual indication on an oscilloscope and the other providing more precise measurements. Both sets of measured data showed general conformance to the typical diode operating regions of forward and reverse bias. Reverse breakdown was not investigated.

Measured data from the precision circuit showed good agreement with the exponential model of forward bias at currents of order 1mA and below, with performance characterized by parameters $I_s=4.97E-19A$ and $n=1.75$. At currents above 1mA, the measurements showed significant deviations from the simple theory. The exponential model was modified to include a series resistance of 4.65Ω , which yielded a model that showed good agreement over a current range of 100nA to 50mA.

With these parameters extracted from measured data, performance can be predicted over a wide range of operating conditions. Including the effect of R_s is especially important, since in illumination applications the LED is usually biased at a current of order 10mA, where the effect of R_s was significant. The parameters were extracted for a single LED - it might be of interest to determine the variability of these parameter values, for example over temperature or between different types of LEDs.

No need to be long-winded here -- just summarize the main results, perhaps adding a few words regarding the results that may be of interest to significant applications.

If appropriate, this is a good place to mention future work that would follow logically from the results observed in the lab.

GENERAL LAB REPORT COMMENTS

The lab report should be a concise report of the important results in the lab. It should be a complete record of your work in the lab: theoretical background, calculations and anticipated performance, empirical verification, and discussion of the results. While the report does not need to be as detailed as the lab notebook, it should "stand alone" - that is, it should be sufficiently self-contained so that it can be read and understood without reference to the lab handout.

The format used here is straightforward: introduction, circuit description, measurement results, discussion, conclusions. This format isn't mandatory; feel free to modify it for a particular lab if the presentation is clearer. For example, if a lab deals with two separate circuit techniques, a better presentation may result from a two-part writeup, with each part following the basic format. It's up to you: think about the material you are presenting, and decide what is the most effective way to present it.

The length of the writeup should be anywhere from 5 to 10 pages, including figures and tables. There is no extra credit for lengthy reports, which rather than being impressive actually are far more likely to go unread and unappreciated.

As far as the level of technical discussion in the report: assume the reader has a background in electronics, but is unfamiliar with the particular topic in the lab. It is not necessary to re-derive results previously covered (for example, the gain of a simple op-amp circuit); however, the operation of newly introduced circuits should be covered both qualitatively and quantitatively.

As in the lab notebook, use as many figures as possible: circuit diagrams, waveform sketches, graphs and tables of measured results, visual comparisons of measured vs. predicted data.