Simple DC Circuits and I-V Curves

Goals:

1. Learn how to perform manual and automated data acquisition with SMUs (Source-Meter Units).
2. Examine terminal characteristics of diodes and resistors.
3. Examine voltage and current dividers with the SMUs.
4. Obtain model parameters from a Silicon solar cell in the dark and under light.
5. Design and test a color-balanced LED light source.

Preparation:

1. Carefully review this document.
2. Be sure to understand the analysis of the circuits to be built.
3. Complete Prelab1.
4. Examine the lab bench. Its appearance is shown in the photo below (see Fig. 1)
5. Be able to apply results of diode/solar cell analysis to measured data.
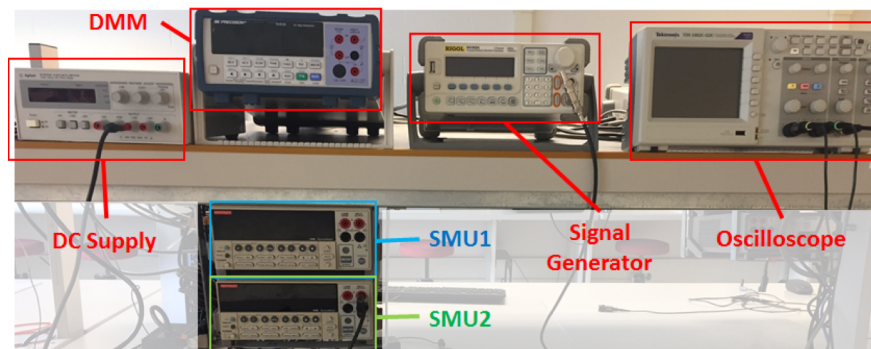6. Bring a memory stick with you to lab so you can save and transfer files.

Fig. 1: ECE 2100 Lab Bench.

There are two SMUs per bench, connected to the computer by GPIB (General Purpose Interface Bus): the upper instrument is at address 5 and the lower at address 7. There is an oscilloscope for examining voltage waveforms and a signal generator for voltage waveform generation. Finally, a triple output dc power supply and Digital Multi-Meter (DMM) round out each bench. You may need to log into the bench's computer using the following login:

Ph237-xx\ph237 where xx is the 2-digit number of the computer (printed on the front of the computer), password: ECE_2100. Hopefully this login is not required.

Experiments:

1.1 Voltage Divider - Automated SMU Test

(a) **Get Parts:** Obtain a protoboard, a 1 kΩ and a 9.1 kΩ from the TAs. Measure the value of each resistor with the DMM. Record these values for your lab report. For reference the DMM is shown in Fig. 2 along with the identification of key features such as Function Select Keys and lead connections.
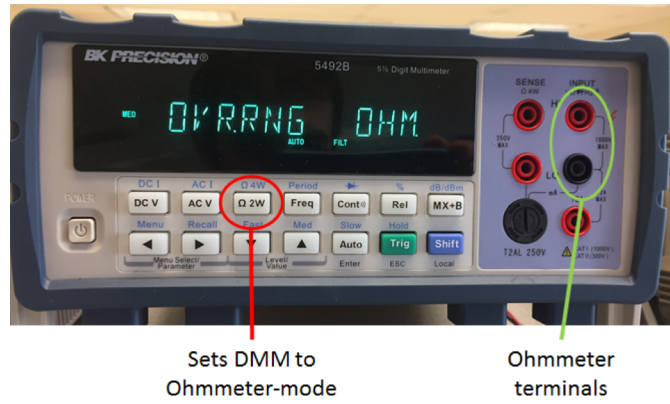
Fig. 2: Photograph of the DMM.

(b) **Build Voltage Divider with SMUs**: Build the voltage divider circuit shown below in Fig. 3. The resistor leads are inserted into the protoboard as shown (in blue and violet). Each line of 5 sockets are shorted together, forming a node that allows you to make interconnections quickly. The SMU leads have alligator clips which directly attach to the resistor leads. Get help from a TA if needed. R_2 is the 9.1 kΩ resistor.
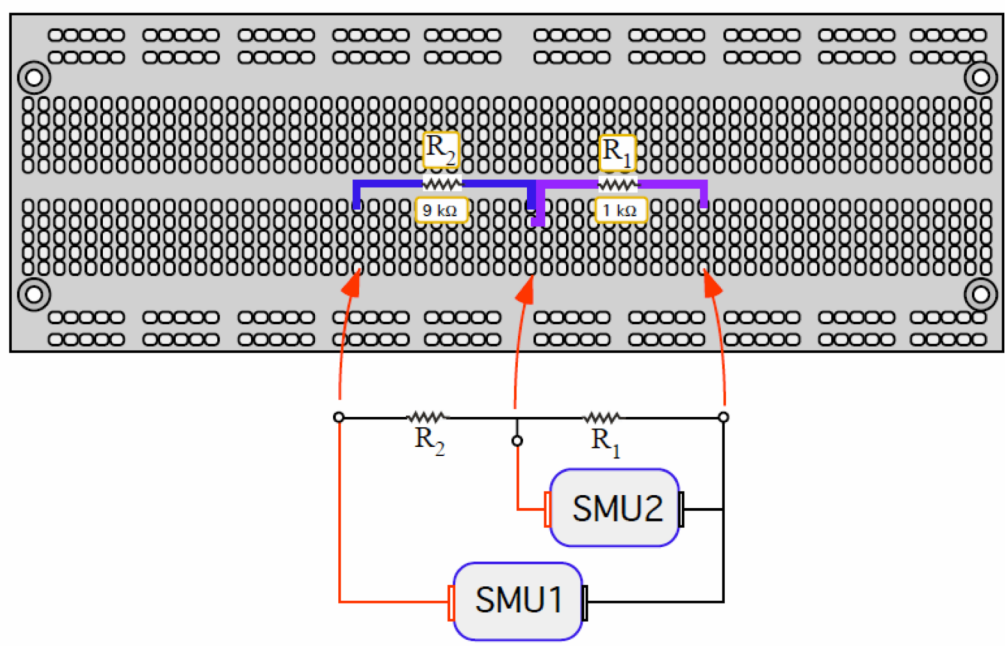

Fig. 3: Voltage Divider circuit with SMU connections

(c) **What is an SMU?**: The SMU is a Source-Meter Unit. The SMU combines a programmable source (can be either current or voltage) with a meter (also either voltage or current). The SMU can be manually operated, but its utility lies in the ease in which a computer can control it and collect data. You will use a computer to run the SMU in this lab. But before you begin, here are a few definitions.

If you use the SMU as a voltage source, it will ask you for the "current compliance." An ideal voltage source can deliver as much current as needed to maintain the voltage, but unlimited current could be dangerous. The compliance range is the maximum amount of current you will let the source provide. If the load tries to draw more current than the

compliance range, the voltage will drop. Think about what you are doing when setting compliance. For example if you are driving a 1 kΩ load with 10 Volts, obviously you will need 10 mA, so setting a compliance of 20 mA would provide enough margin for variance and still keep equipment safe.

Similarly, if you use the SMU as a current source, the compliance range determines the absolute maximum voltage it will allow before stopping.

When you open the software controller for the SMU, you will see that it can be configured as a voltage sweep, a current sweep, a voltmeter, an ammeter, and various other schemes. In this lab we will use it to sweep voltages and record both voltage and currents, but first we will set it up for a manual measurement. The control buttons shown in Fig. 4 allow you to manually set the parameters for a measurement.
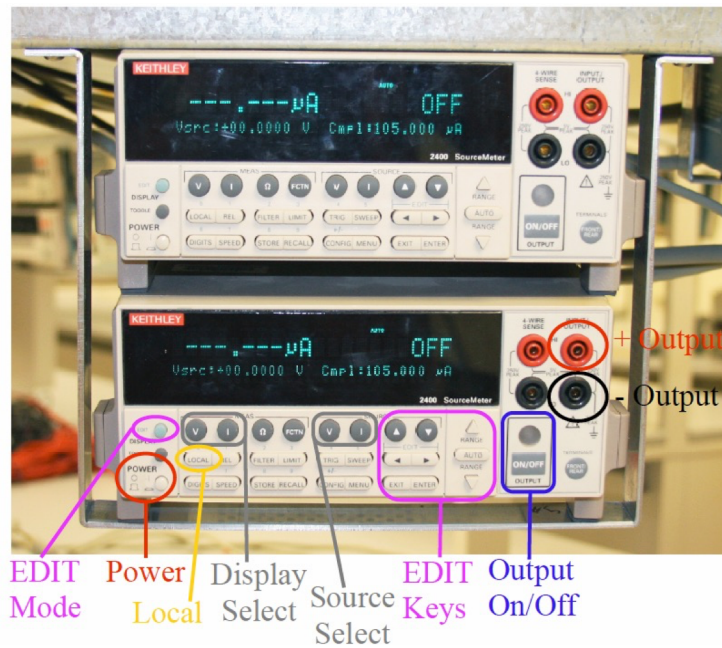

Fig. 4: Detailed view of Keithley 2400 SMUs.

(d) **Turn on the 2 SMUs:** Turn on the 2 SMUs using the power button (not the output ON/OFF)

(e) **Perform a Manual measurement of current from SMU1 (I_1) and across SMU 2 (V_2):** On SMU 1, push the "V" button under source, and then push the "edit" button. This should cause the left most digit (a zero) to blink. Use the left-right arrows under source to set the blinking digit to be just left of the decimal, and then use the up-down arrows to set it to "1". Push the edit button again so that one of the digits next to "cmpl" is blinking. We want a current compliance of more than 105 µA (the default) so push up arrow marked "range" which increase the maximum compliance by 10x, then push the "source" up arrow, to set the compliance to about 1 mA. The screen should look like Fig. 5. Now, on SMU 2, push the "I" button under source and the "V" button under measure. Since all we want to do is measure voltage, we don't need to change anything else. Now push the "OUTPUT ON/OFF" button on each. A red or blue light should turn on (the color depends on the SMU). SMU1 should now be displaying how much current it is sourcing through your series resistors, and SMU2 should be showing you how much voltage is

across R_1. Do the numbers make sense? If so, record them for your lab report. If not, ask one of the TAs for help. Push the "OUTPUT ON/OFF" buttons again so the outputs and lights are off.
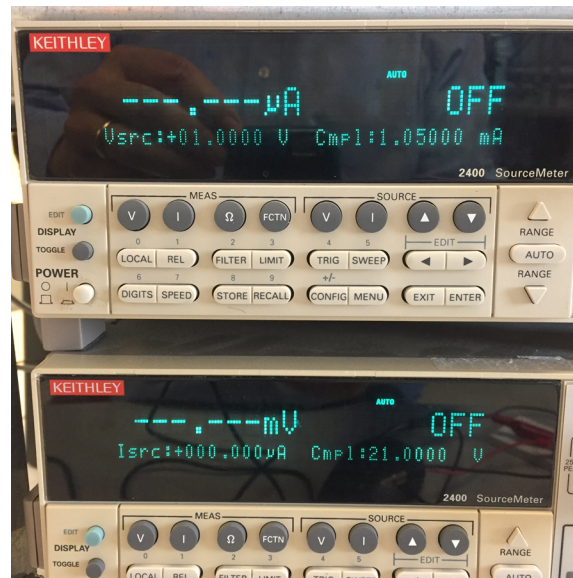

Fig. 5: Expected SMU readout

(f) **Run Software**: Run the Keithley program for controlling the SMUs by clicking the "LabTracer" icon in the upper right corner of the computer's desktop (or, if that fails, go to Start→All Programs→Keithley Instruments→Labtracer 2.0) wait for a window to appear as shown below in Figure 6. If the symbol in the center of the window shows a circuit element *other* than a resistor, simply click the symbol to bring up a pop-up menu of possible elements, then click on the resistor in the menu.
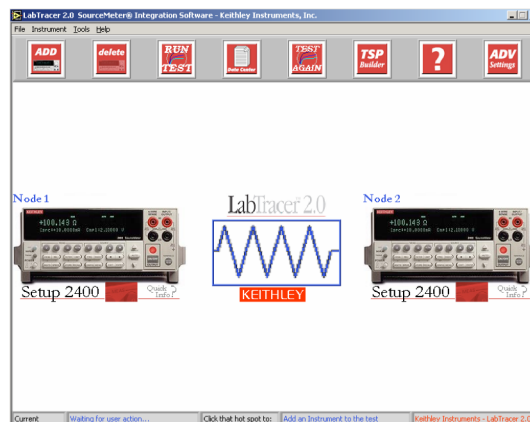

Fig. 6: LabTracer main window with the voltage divider test running.

(g) **Examine SMU Setup**: Click on the SMU icon, and select the model 2400. Click on "Setup 2400." A series of tabs can be selected to view or alter measurement parameters. The appearance of the window with the Source tab selected is shown in Figure 7. Select the **Source** tab.
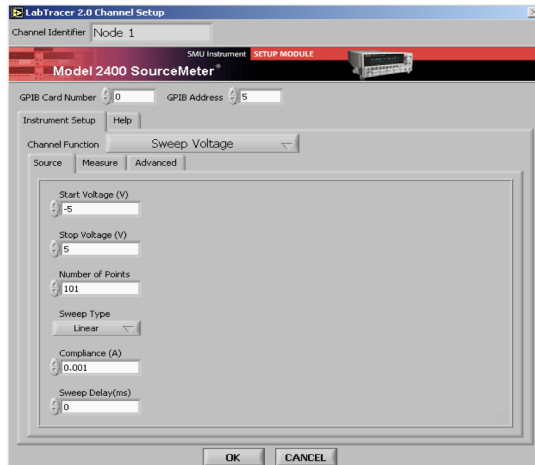
4

Fig. 7: LabTracer Setup window for SMU 1 with Source tab selected.

Important thing to do: Confirm that the GPIB address is set to 5 on SMU 1 (the one pictured on the left side of the screen) **and to 7 on SMU 2** (the one pictured on the right side of the screen)**. When a measurement doesn't work, it is usually because the GPIB address was not set.

Select the **channel function** (*Sweep Voltage* for SMU 1, *Voltmeter* for SMU 2) for each SMU. On SMU1, under **Source** set the **Start voltage to -5 V**, the **Stop voltage to 5 V**, and the **Number of data points to 101**. The **current compliance** is also set to 1 mA as shown. Note that we are sweeping the DC bias voltage from a negative value to a positive value. Record all parameters set in this window for your lab report!

Now select the **Measure** tab and the window will appear as shown below in Figure 8. In this window, we select what is to be measured (both current and voltage). The integration time also appears in this window and is set to an intermediate value of 0.1. The Filter option is not in use for this lab. When OK is hit, the Main window is displayed again. Record all parameters set in this window for your lab report.
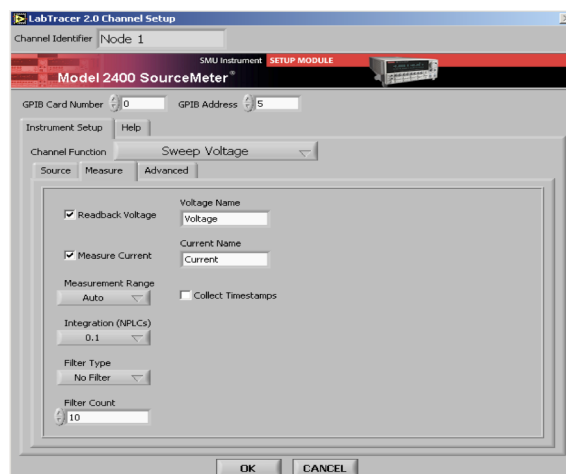

Fig. 8: LabTracer Setup window for SMU 1 with Measurement tab selected.

(h) **Set SMU 2 to be a Voltmeter:** Set SMU 2 to be a voltmeter in the channel function. On SMU 2 set the compliance voltage to 5 V under the Source tab. Heads up: sometimes the

channel number switches to something other than 7 after selecting the voltmeter function, so confirm the channel is still 7.

(i) **Initiate Measurement and generate an I-V curve**: Click on the RUN TEST button and the measurement begins. The SMUs will be automatically configured, and you can watch the current and voltage values as they scan. When completed the Data Center window appears as shown in Figure 9. **However, there will be nothing plotted on your graph. Select the "Define Graph" button** and set your x and y axes to be Voltage_1 and Current_1. If the curve is linear then record the voltage and current values at each voltage extreme (± 5V) and calculate the slope of the line. **Note:** The raw data is viewed by clicking the DATA SHEET tab. Invert the slope you calculated for this I-V curve; what does this quantity represent? **Second Note**: if the SMUs didn't run, check your channel numbers in the set-up, then make sure all the GPIB cables are connected.
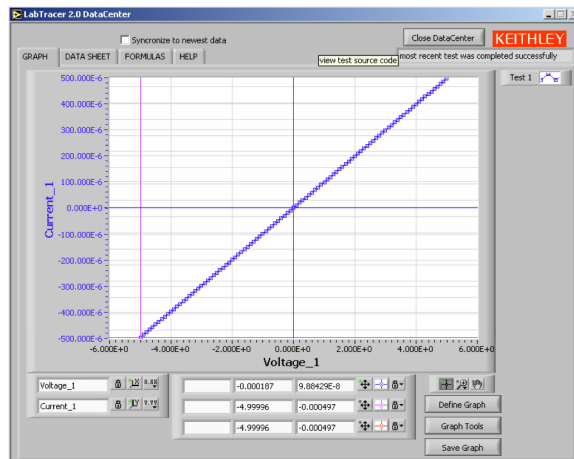

Fig. 9: LabTracer DataCenter Graph window, plotting Current_1 vs Voltage_1.

(j) **Plot combined resistance across voltage:** Under the FORMULAS tab, define a voltage division factor *Res* = Voltage_1/Current_1 and click CREATE to store this formula. If you highlight Res and hit the EDIT tab you can view the formula. Re-run the test from the main menu. Go back to the graph (hit the GRAPH tab) and then strike the Define Graph key (lower right hand corner). Select the *Res* vs. Voltage_1 and display this graph. Expand the vertical axis such that small variations in the estimated resistance are clearly visible. This is done by editing the lower and upper number labels on the y axis of the plot. Are there any weird results on the plot that you can ignore? Why?

With a satisfactory plot **save both the window image** (Ctrl-Alt-PrintScreen, then Ctrl-V to paste the image elsewhere, or save the graph directly into a JPEG file. Whatever works for you is fine) **and the raw data** which can be saved under the DATA SHEET tab. Clicking the Save Data tab (lower right hand corner) will create a data file (.txt) which you will store on your thumb drive. This image or re-plotted data will be used in the lab analysis questions to follow.

It is strongly recommended that you save things directly to your jump-drive, as, if the computer crashes, *it will erase all your files on its hard drive!*

(k) **Plot the voltage division factor vs. the source voltage**. Under the FORMULAS tab, define a voltage division factor f_{div}= Voltage_2/Voltage_1. Again zoom in so the average value and small variations are clearly visible.

1.2 Current Divider – Automated SMU Test

(a) **Build the Current Divider with SMUs**: Build the current divider circuit shown in Figure 10 with the same parts as the voltage divider. Get help from a TA if needed. Explain why SMU2 is connected with the polarity that is shown. Recall, R_2 is the 9.1 kΩ resistor.

(b) **Modify each SMU's Set Up**: Program SMU1 to SWEEP CURRENT from -50 µA to +50 µA in 101 steps (which you can type as 50e-6). A 10 volt compliance on SMU1 should be adequate. Why? Select an integration time of 0.1. On SMU2, you can select a current meter (Ammeter on the Channel Function List). Select a reasonable compliance limit of say 100 µA.

(c) **Perform the Measurement and Record the Data**. Strike the RUN TEST button and the measurement begins. Disregard the error message stating that function f_{div} is no longer defined, it appears because we are no longer recording Voltage_2. When completed the Data Center window appears on the desktop again. Make plots of Current_2 vs. Current_1 and Voltage_1 vs Current_1. Once again, estimate slope and equivalent resistance. Record the image of this plot and save the raw data as they will be needed for analysis later. Alter the definition of the division factor (f_{div}) to reflect current division, and repeat the measurement. Produce an optimized plot of f_{div} and Res vs Current_1 and save the image and raw data.
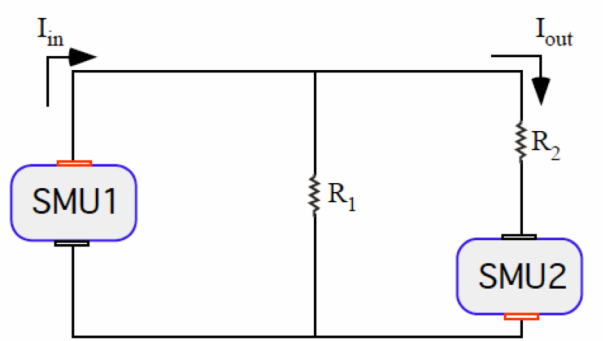

Fig. 10: Current Divider circuit with SMU connections.

2 Device Characterization

In this experiment we are going to produce terminal or current-voltage characteristics (also called I-V measurements) of several two-terminal devices. It should be obvious by now that only one SMU is required to accomplish this. Note: When you take ECE3150 your will use two SMUs to perform I-V testing on three-terminal devices called transistors. Now if you review Figure 6, the main window you will find a delete button at the top, which, once clicked, will remove the second SMU (the lower unit) from the program's control. You can turn off the power to SMU 2.

2.1 Photovoltaic (solar panel) Terminal characteristics

In this experiment we are going to obtain the terminal characteristics of a solar panel. Obtain one from the TAs. Solar cells are essentially just specialized diodes. The panels we will look at consist of 4 silicon cells in series.

(a) **Connect SMU1 and PV**. Connect the red lead of the PV to the positive SMU lead, the negative SMU lead to the black lead (use alligator clip leads).

(b) **Setup SMU1**: Modify the SMU1 parameters to accomplish the following: 151 data points, -2 to +4 volts linear voltage sweep, integration time (NPLC) set to 1, and a current compliance of 100 mA.

(c) **Perform I-V measurement of the PV in the dark**: Place one of the tubs (from the TAs) over your solar panel. Initiate the measurement and view the data center window. Create a diode current vs voltage plot. Estimate the diodes turn-on voltage from this plot. How does it compare with that of a single silicon diode (~ 0.7 volts)? Save your results for later analysis.

(d) **Perform I-V measurement of the PV in bright light**: Obtain one of the lamp adapters from the TAs, plug it in to SMU 2 and manually set the SMU to source 300 mA of current (ensure the voltage compliance is at least 20 V) and place your solar panel beneath the lamp (see Figure 11). Initiate the measurement on SMU1 as in part 2.1c, and view the data center window. How did your I-V curve change? Save your results for later analysis.
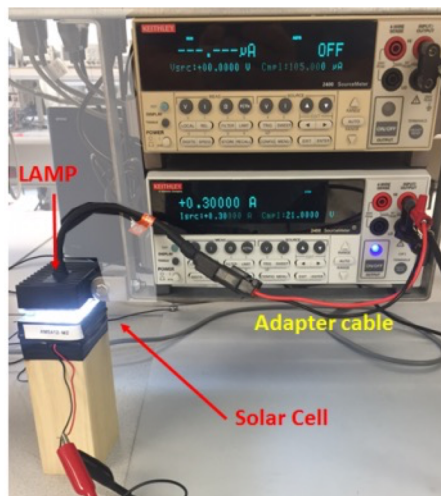

Fig. 11: Solar cell under lamp.

2.2 Light-Emitting Diode Terminal Characteristics

In this experiment we are going to obtain the terminal characteristics of three Light Emitting Diodes (LEDs). Obtain one of the three-color LEDs from the TAs (this is actually 3 LEDs, with their anodes shorted together). As diodes do not have linear or symmetric I-V characteristics, polarity of the connection matters. We have already connected the three LEDs in a protoboard, with the black wire for the anode (negative terminal) and the red, green, and blue wires to the cathodes of LEDs of those colors.

(a) **Connect SMU1 and red LED**. Connect the red lead of the LED to the positive SMU lead, the negative SMU lead to the black LED lead - use alligator clip leads.

(b) **Setup SMU1**. Modify the SMU1 parameters to accomplish the following: 151 data points, -2 to +4 volts linear voltage sweep, integration time (NPLC) set to 1, and a **current compliance of 20 mA**.

(c) **Perform I-V measurement of the LED**: Initiate the measurement and view the data center window. A diode current versus voltage plot should appear. Estimate the diode's turn on voltage from this plot. How does it compare with that of a silicon diode (~ 0.7

volts)? Make note of the bias conditions which result in light emission. **Also note at what voltage the LED consumed 10 mA**. **Save your data**.

(d) **Examine the logarithmic current versus voltage plot**. If you examine the raw data, you should notice that the LED current is increasing over many orders of magnitude as the diode enters its forward bias regime (+ voltages in our sweep). Accordingly it is often useful to plot these characteristics on a logarithmic current scale. You will be asked to do this in the analysis. This graph can also be produced using this software. We must first define an absolute value of diode current - you can't take the log of a negative number (why is there a negative region? Think about the previous section's results). This is done in the formula screen as before. Before you rerun your test, delete the f_{div} formula from earlier, as once it errors, your new formula will not be calculated. Once you have a variable for the absolute value of current, repeat the measurement and plot the absolute value of diode current versus diode voltage on the graph. Now if you look in the lower left hand corner of the graph screen, your plotted variables are listed. To make a logarithmic plot of the absolute value of current, strike the Y.YY key, click the Mapping Mode tab and select logarithmic (see Figure 9). A log I vs. V curve should appear. In the section of the curve where the LED is on, there should be a linear portion of the characteristic (as in forward bias the current increases exponentially with voltage). At some large forward bias we can see a sub-linear log I vs. V curve as the diodes series resistance starts to become dominant.

(e) **Repeat these measurements (steps c and d) for the Green and Blue LEDs**. In each case *save your data* (under a different file name) and record the Voltage required to achieve the following currents: **4 mA for Blue**, **2.5 mA for Green** (these values have been empirically observed to provide approximate color balance).
Keep this LED, as you will need it for section 3.

3. Design a color-balanced light-source

LEDs are seeing increased use in lighting and displays, but they generally produce monochrome light. One way to generate "white" light from LEDs is to fake it with 3 LEDs, one red, one green, one blue, whose combined output looks white to the human eye. The goal here is to do this using your 3-color LED.

(a) **Try the simplest approach:** Short the three diodes' cathodes together, and use the SMU to sweep the voltage (same settings as in part 2.2, but change the compliance to 30mA). Save the I-V curve. Qualitatively, what color did the LED appear to be? Did this work? (And if it did, would there be a part b?)

(b) **Design a resistor network to balance the currents:** Based on your measurements from part 2, and applying the same approach as in Prelab problem 3, choose 3 resistors, such that when they are attached as shown in Figure 12, and supplied with 4 V, each LED receives the following currents: Red: 10 mA, Green: 2.5 mA, Blue: 4 mA. Obtain these resistors, and build the circuit. Note that you will not be able to find the precise resistor values you calculate: choose the closest value you can find. Confirm the values of R_R, R_G and R_B with the DMM, and note them down for your report.

(c) **Manually program the SMU as a 4 V source:** Confirm that the LED looks approximately white, write down the current consumed, and confirm it is about what you expect. You may need to restart the SMU to put it back in manual mode.

(d) **Set up the SMU for another sweep**: Sweeping from -1 V to 5 V, in 301 steps, with compliance set to 40 mA. Save the I-V curve. Qualitatively, how did the brightness and color change as voltage was swept?
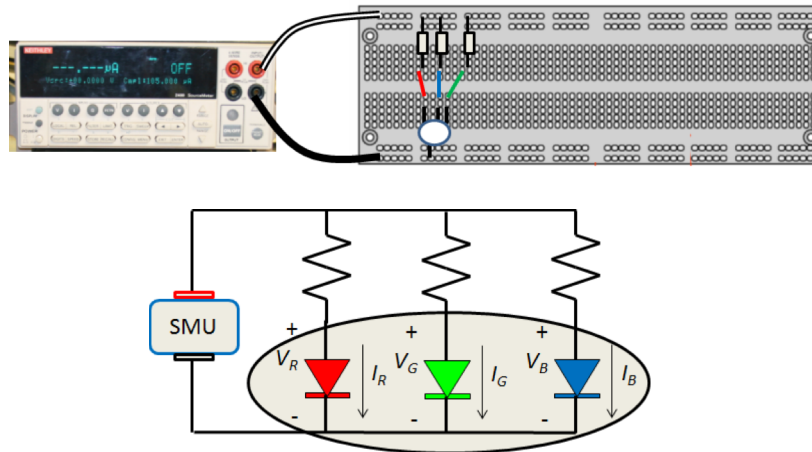

Fig. 12: Physical arrangement and circuit for color-balanced LED.

Wind down:

Dismantle circuit (but not the LED and its colored leads!) and place your protoboard and the devices you tested in the bins that the TAs have provided. Carefully arrange the instruments' leads so they look nice. Transfer all generated files for access on the computers outside this lab on your flash drive. Do not leave any of your files on the desktop or on any local drives, as they will be permanently deleted when the machines periodically self-restart.

Analysis:

1. Plot the I-V curve and computed resistance for the series resistance circuit from the SMU data, and explain any deviations from the expected shape of the curves.

2. In the SMU data collected on the voltage divider, compare the resistance value obtained from the inverse slope of the I-V curve with that predicted by using the nominal values of R_1 and R_2 (1 kΩ and 9.1 kΩ), and the measured values of each resistor (from lab part 1.1(a)). For each prediction, indicate the percent difference from the measured value.

3. Plot Voltage_2 vs Voltage_1, and the voltage division factor versus the applied source voltage on a blown up vertical scale, and explain any deviations from the expected shape of the curves.

4. In the SMU data collected on the voltage divider, compare the measured voltage ratio with that predicted by using the nominal values and the measured values of each resistor (from lab part 1.1(a)). For each prediction, indicate the percent difference from the measured value.

5. Describe why the SMU polarities are given as shown in Figure 10 for the current divider.

6. Plot the parallel resistance for the current divider versus source current on a blown up vertical scale such that deviations from the predicted value can be seen. Describe why there is a discrepancy. Compare with what would be predicted from the nominal and measured resistor values.

7. Plot the current division factor for the current divider versus source current on a blown up vertical scale such that deviations from the predicted value can be seen. Describe why there is a discrepancy. Compare with what would be predicted from the nominal and measured resistor values.

8. Plot the I-V curve of the solar cell in the dark and under light. Describe, qualitatively, how the I-V curve shifts, and how it changes shape. Construct a model assuming relatively ideal diodes, but with series resistance; that is, try to extract I_o and R_s as described in Prelab problem 4, and the parallel photo-induced current.

9. Under light, estimate the maximum output power available, and the "fill factor" of the solar cell.

10. What portion of the bias sweep of the LED (lab part 2.2.c) was accompanied by light emission for each LED?

11. Make an I-V plot on a linear scale for each LED and illustrate the determination of the turn on voltage of the diode.

12. Use the real diode equation (the one with parameters η and I_0) and find values for the ideality factor (η) and the reverse saturation current (I_0) which best fit your measured data on the LED (in the dark). Add a series resistance term to fit data at high drive voltages. Prepare a log current versus forward bias voltage plot which compares your measured data to the fitted real diode equation plus series resistance model. Show measured data as symbols and the model as a continuous line.

13. Plot the I-V curve of the combined LEDs (without resistors): explain your results in terms of your measured result from the individual diodes.

14. Explain your choice of resistors for balancing the currents, based on you previous results.

15. Plot the I-V curve of your combined, balanced circuit. Confirm appropriate current consumption at 4 V, and label different regions of operation, describing the color and brightness in each region. Explain the shape of the I-V curve in terms of the turn-on voltage of each LED, and its associated resistor.