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Physics 214 - Laboratory 2

Photons

NAME: ______________________________

LAB PARTNER(S): ______________________________

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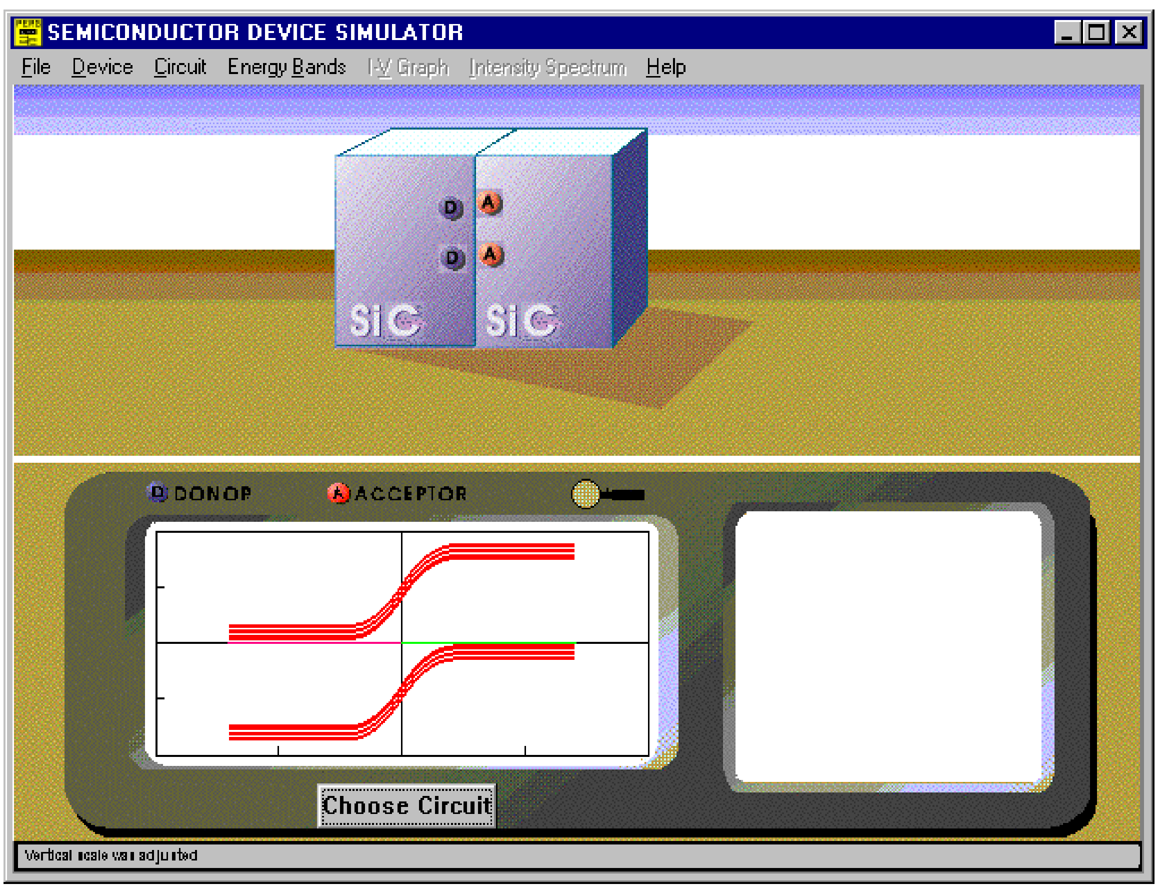
LAB SECTION: ______________________________

TA: ______________________________

DATE: ______________________________



Photons

In 1900 Max Planck first introduced the concept of energy quanta (for which he eventually won a Nobel Prize) and the now famous formula *E=hf*. Several years later, Einstein associated this quantized energy with a single indivisible 'bundle' of electromagnetic energy (which we now call a *photon**), and used this association to explain the *photoelectric effect* (for which he too eventually won a Nobel Prize). The photon is the quantum of the electromagnetic field. Photons are emitted from atoms when an electron makes a transition from a higher to a lower energy state. Each atom absorbs and emits its own characteristic energy photons. Photons are also emitted when an electron makes a transition from a higher to a lower energy state in a solid. There are important differences between atoms in isolation and atoms in bulk. Later this semester you will learn more about solids. A technologically important example of a solid that emits photons is the LED (Light Emitting Diode.) Your TV remote, your CD player, and many digital displays all use light from LEDs. Your experiment today will explore some important aspects of light using the photons from LEDs. The key idea, which you will discover and see for yourself, is that the energy of a photon is determined by its frequency (color): $E = hf = hc/\lambda$.

<u>Equipment</u>

Desk lamp
Desk lamp with clear, straight filament bulb
Variac
Diffraction grating slide
Ruler
Mounted red, green, and blue LEDs; mounted diode
Terminal box with 1.2 kΩ series resistor and fuse
4 red and 4 black banana jack leads
Heath DC power supply or equivalent
Physics Electronic Shop (PES) Function Generator (or equivalent)
Two Fluke Model 37 Digital Multimeters
Tektronix TDS 210 Digital Sampling Oscilloscope
Banana plug oscilloscope inputs (probably already attached to oscilloscope)

The picture on the first page is from the Semiconductor Device Simulator written by the Kansas State University Physics Education Group (http://web.phys.ksu.edu/).

* Perhaps surprisingly, neither Einstein nor Planck introduced the word "photon". Instead, it was introduced by chemist Gilbert Lewis in 1926 in a letter to Nature magazine entitled "The conservation of Photons". Although his particular theory and explanation about light failed, the term 'photon' survived.

Activity 0: Identify the Equipment

This laboratory uses several pieces of electronics. Before you start doing the experiments, identify each item on the equipment list. Several items will be familiar to you from

Physics 212. Although you do not need to know the function of every knob, you should have a good idea of the function of each item.

Activity 1: Look at a Continuous Spectrum

Many of the observations that you will make in this laboratory will use a mounted, plastic diffraction grating which has 5000 lines per centimeter. The separation of adjacent lines is then (1/5000) cm. With this separation, visible light (wavelengths of 400 to 700 nm) is diffracted by angles of 10˚ to 20˚ in first order. If you hold the grating close to your eye and look straight at a light, you will see the diffracted beam on either side of the source.

Calculate the line separation – you will need it later:

What is the separation in nm between the lines of your grating? ____________ nm

The room lights must be off for Activity 1. One of the desk lamps has an unfrosted light bulb, so you can see the filament. Find the Variac. It should be off, and the knob should be set to 0. Full scale on the Variac is ~140 VAC. Plug this desk lamp into the Variac and turn the knob until you can just see some light from the filament. The Variac setting will be around 20 VAC. Look at the filament through your diffraction grating. Hold the grating with its lines parallel to the filament. To the naked eye the filament looks dull red. What does the diffracted light look like through the grating?

By increasing the filament voltage, one increases the power dissipated in the filament. Therefore, it will get hotter. If one then looks at the light through the diffraction grating, what would one expect to see? Write your prediction below:

This activity will not take long. Let everyone in the group have a chance to change the Variac setting while watching the filament.

What did you observe?

When done with this portion of the lab, turn the knob on the Variac to 0 and then also switch it off.

The room lights can be on for the next activity. Tell your instructor when you are ready.

In the following activities, you will study the minimum energy (i.e., applied voltage) required to get light emission from different "color" LED's. These activities will allow you to investigate Einstein's revolutionary (at the time) and Nobel Prize-winning proposal for the relationship between a photon's energy, E, and wavelength, λ: $E = hc/\lambda$.

<u>Activity 2: Wire-up the Circuit. Test it with a Diode.</u>

Find the aluminum terminal box at your station. The terminal box has a built-in fuse and resistor with connections soldered underneath the top panel. (The fuse is in a socket on a side panel.) With nothing else connected to the terminal box, use a multimeter as an ohmmeter to measure the resistance of the resistor (nominally 1200 Ohm):

$R_{1200\ \mathrm{Ohm}}$ = ____________Ohm

We want to monitor the current through a diode as a function of the voltage across the diode. A circuit to accomplish this is shown in the diagram on the last page at the end of this lab. The circuit is simply a diode and a resistor in series. The resistor serves two purposes: it limits the current in the circuit, and it provides an easy way to monitor that current. In order to understand the behavior of the diode, it will be necessary for you to use the precise value of its resistance (which you measured above).

Find the DC power supply, the multimeters, and the oscilloscope. The diode banana plug marked with the diode symbol —▶|— must be inserted in a pair of banana jacks on the terminal box. Before connecting the DC supply, be certain that it is off and that its voltage knob is turned fully counter-clockwise (off). Connect the red jack of the DC supply to the terminal box where indicated, and the black jack of the DC supply to the COM jack of one of the multimeters. This multimeter will be used as an ammeter. Connect its mA/μA jack to the terminal box as shown, and set the meter to DC mA. This ammeter will indicate the current passing through the circuit elements. The current should be kept below 30 mA. This is the maximum current allowed in the circuit. The LEDs (light emitting diodes) can be damaged by a high current. Connect the other multimeter as shown. It will be used as a voltmeter to monitor the voltage of the DC power supply.

What is the maximum current that you should never exceed to avoid damaging the circuit? ____________________

You will use two channels of the oscilloscope in XY mode. In this mode the oscilloscope screen is like a Cartesian coordinate system and two voltages are displayed as horizontal and vertical coordinates. Channel 1 will be X, or horizontal. Channel 2 will be Y, or vertical. Activate the oscilloscope by pressing RUN. Set VOLTS/DIV for both channels to 1.00 V. Press CH 1 MENU and verify the following settings: Coupling DC, BW Limit Off, Volts/Div Coarse, Probe 1X, Invert: On. Verify the same settings for CH 2 MENU, but with INVERT set to Off. Press the DISPLAY button and verify/enter the settings: Type = Dots, Persist = Off, Format = XY.

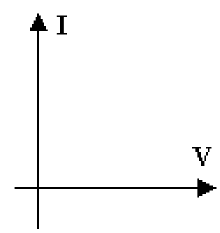
With no inputs connected you should see only a single dot in the center of the screen. Adjust the VERTICAL POSITION of CH 1 and CH 2 to put the dot in the center of the screen. (The HORIZONTAL POSITION knob of the oscilloscope is disabled in XY mode. Channel 1 controls the horizontal in XY mode.)

Now make connections to the oscilloscope. The banana jacks on the connectors attached to the scope are color-coded. The black jack is ground. The red jack is signal. Use a red banana plug cable to connect the signal side (red) of Channel 2 to the side of the resistor shown in the wiring diagram. Use a black cable to connect the ground side (black) of Channel 2 to the other side of the resistor. Next connect the signal side (red) of Channel 1 to the side of the diode shown in the wiring diagram. You do <u>not</u> have to make a connection to the ground side of Channel 1, because the two channels have a common ground at the oscilloscope.

Channel 1 is now set to read the voltage across the diode; channel 2 is set to read the voltage across the 1200-Ohm resistor. The voltage across the resistor is proportional to the current in the circuit. (You may notice that the little dot has become a diagonal slash, due to pickup in the circuit. This will not affect the results below.)

Why is the voltage across the resistor proportional to the current in the circuit? ____

With two channels you can display the current passing through the diode and the voltage across the diode at the same time. You are investigating the characteristic curve, or I-V curve of the diode.



Turn on the DC power supply and slowly increase the voltage while watching the oscilloscope. If your circuit is connected correctly, you should see the current (the vertical signal) increase rapidly above a voltage (the horizontal signal) of ~0.7 V. If you do not see this response, ask for help.

Now you will estimate the "resistance" of the diode below and above threshold. We often define the resistance as V/I. But this only makes sense for a *linear* circuit element like a resistor. More generally, we can define it as $\Delta V/\Delta I$.

Record the current through the circuit for the following approximate voltages from the power supply (also record the actual voltage, using the second multimeter). All values should be positive.

$V_{ps,0}$ = 0 volts:	Actual $V_{ps,0}$ = ________volts	I_0 = __________mA
$V_{ps,0.5}$ = 0.5 volts:	Actual $V_{ps,0.5}$ = ________volts	$I_{0.5}$ = __________mA
$V_{ps,4}$ = 4 volts:	Actual $V_{ps,4}$ = ________volts	I_4 = __________mA
$V_{ps,5}$ = 5 volts:	Actual $V_{ps,5}$ = ________volts	I_5 = __________mA

Now calculate the circuit resistance.

Below threshold:	Above threshold:
$R_{total} = (V_{ps,0.5} - V_{ps,0})/(I_{0.5} - I_0)$	$R_{total} = (V_{ps,5} - V_{ps,4})/(I_5 - I_4)$
=__________________	= __________________

Finally, calculate the effective "resistance" of the diode, by subtracting off the actual resistance of the 1200-Ohm resistor, which you measured above: "R_{diode}" = $R_{total} - R_{1200\ Ohm}$

$R_{diode,\ below\ threshold}$ = ______________ $R_{diode,\ above\ threshold}$ = ______________

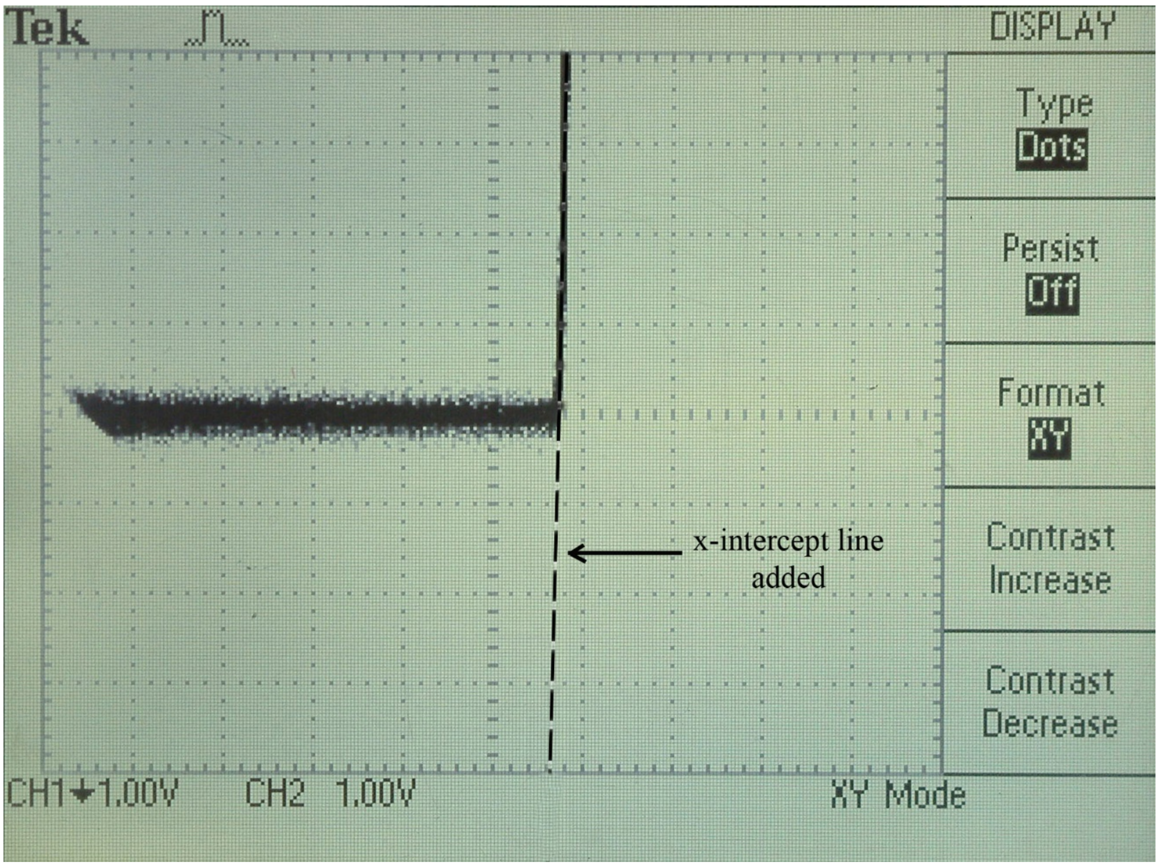
(The resistance above threshold might be very small. It is conceivable that you could calculate a negative number due to uncertainties in the measurements. Don't worry about this – we are mainly interested in your understanding the order of magnitude of the effect.)

Turn down the DC supply and interchange its output leads. Turn back on the DC supply and set the voltage across the diode to the voltage you just recorded. (The sign will change because you switched the leads.)

You should see no current passing through the circuit. A diode passes current or conducts in only one direction, and then only if the voltage is above the turn-on threshold.

Activity 3: Display the Complete I-V Curve for the Diode

You can display the complete I-V curve by continuously varying the input voltage. Use the function generator to sweep the voltage. Turn off and disconnect the DC supply. Take the multimeters out of the circuit. They are no longer needed. Note that the function generator cannot deliver as high a current as the DC supply, so you don't need to worry about damaging the diode. Connect the input leads to the function generator. A sine wave of a few hundred Hz will give good results. Turn on the function generator and increase its amplitude until the I-V curve takes up most of the oscilloscope screen. You should see the diode turn on at about 0.7 V. Ask for help if you do not see the entire I-V curve (similar to the I-V curve for a diode shown in the picture below).



Note that the polarity of the voltage across the 1200-Ohm resistor, with the Channel 1 (X, or Horizontal) input to the oscilloscope inverted, should give the above result – current through the LED increases with increasing forward-bias voltage across the LED. If your oscilloscope is such that it does not have the inverting option on the scope's Channel 1/Channel 2 input menu, then your I-V display will be inverted relative to that shown above. The important result here is that a diode allows current to flow only in one direction.

The picture above shows how you can estimate the turn-on voltage. Imagine you can draw a straight line on the part of the I-V curve at which the current is increasing. You can call the turn-on voltage the intercept of your imaginary straight line and the horizontal axis.

Activity 4: Display the Complete I-V Curve for the Red LEDs

Substitute the red LED for the diode. The red LED is mounted on the red plug (good "human-factors" engineering). The I-V curve will be similar to the I-V curve of the diode (the D in LED does stand for "diode"), but the turn-on voltage will be different.

What is the turn-on voltage for the red LED? ___________________________ V

The voltage across the diode indicates the energy given to charge carriers (electrons and holes, but more about that later in the course.) If the diode turns on at *X* volts, then the charge carriers are getting *X* electron-volts of energy. The charge carriers can give up this energy by emitting a photon. How does the energy the charge carriers get at the turn-on voltage compare to the energy of a red photon?

Activity 5: Display the Complete I-V Curve for the Blue LEDs

Red LEDs were first introduced commercially by GE in 1962, following the work of Holonyak and Bevacqua. (Holonyak left GE soon afterwards for the University of Illinois.) Blue LEDs are ~ 10 years old, and now even ultra-violet (UV) LEDs exist. Want a challenge? Develop the X-Ray LED!!! Blue photons have a higher energy than red photons. Will the turn-on voltage of a blue LED be higher or lower than the turn-on voltage of a red LED?

I predict that the turn-on voltage of a blue LED will be _______________ than the turn-on voltage of a red LED.

Substitute the blue LED for the red LED. The blue LED is mounted on the blue plug. The I-V will be similar to the I-V curve of the red LED.

What is the turn-on voltage for the blue LED? ___________________________ V Is the turn-on voltage for the blue LED higher than for the red LED? ______

Activity 6: Display the Complete I-V Curve for the Green LEDs

I predict that the turn-on voltage of a green LED will be _______________ than the turn-on voltage of a red LED, and _________________than for a blue LED.

Substitute the green LED for the blue LED. The green LED is mounted on the green plug. The I-V will be similar to the I-V curve of the red LED.

What is the turn-on voltage for the green LED? _______________________ V
Is the turn-on voltage for the green LED higher than for the red LED? _____
Is the turn-on voltage for the green LED higher than for the blue LED? _____

Activity 7: Measure the Wavelength of the Light from the LEDs

This activity is more easily done with the room lights off. Using your diffraction grating, look at the light from the blue LED. The LED emits most of its light out of the top of the epoxy dome. You should stand up and look straight down at the LED.

The next question is not facetious.

What color(s) is(are) the light from the blue LED? _________________________

You can make a reasonably accurate measurement of the wavelength of the light from the LED using just the diffraction grating and a ruler. Looking down on the LED, hold the grating close to your eye and a distance L = 30 cm away from the LED. Use the ruler to set the distance between the grating and the LED. Then place the ruler horizontal and at the same level as the LED. With a little adjustment of the ruler you should see the two diffraction spots, one on either side of the LED, on the scale of the ruler. (You may actually see four spots, two on either side of the LED, from the first and second order diffraction.) Measure distance y between the diode and the first order diffraction spot. You are not trying for high precision, but you should be able to read the distance to an accuracy of ~ 0.5 cm. You may find it easier to measure the distance between the left and right diffraction spots and then divide by two to get y. Since you will see a band of colors, try to measure the wavelength at the approximate center of the band.

The measured distance, y, is _____________________________ cm.

Now you should be able to compute the wavelength of the light. Recall two equations about diffraction gratings:

$$y/L = \tan\theta \qquad d\sin\theta = n\lambda .$$

Here is some space to do your computation:

The wavelength of the “blue” light is ____________________ nm. The measured wavelength should agree (to within ~10%) with your value from the Prelab. Does it?

Repeat the above measurements for the red LED. Again, the question below is not facetious.

What color(s) is (are) the light from the red LED?__________________________

Make the same measurement of the distance between the two spots of the diffracted beams.

The measured distance, y, is ______________________________ cm.

Do the same calculation of the wavelength of the light:

The wavelength of the red light is ____________________ nm. The measured wavelength should agree (to within ~10%) with your value from the Prelab. Does it? ___________

Finally, repeat the above procedure for the green LED, and perform the same calculation for the wavelength of the light of the green LED.

The wavelength of the green light is ____________________nm

Activity 8: The Grand Finale

The measured turn-on voltage, V, multiplied by the electric charge, e, is approximately equal to the energy given to an electron in the LED just before it emits a photon. To account for all the energy, we would have to understand the details of a p-n junction in the LED. Nevertheless, the energy of the photon emitted from the LED is approximately equal to eV with V equal to the turn-on voltage. [Certainly the photon's energy can be no greater than the energy of the electron that emitted it, though it could be less – before emitting the photon, the electron could lose some energy interacting with the material of the junction.] You measured λ and V with classical tools – using a diffraction grating, obtaining $\lambda_{measured}$, and a voltmeter (or oscilloscope), obtaining $V_{measured}$. Actually you have just observed something very non-classical:

As the energy of each electron, E_e (in eV), increases in passing through the p-n junction of the LED, the wavelength, λ ______________________________.

Now, let's see how well you can verify the energy-wavelength relation for the photon,

$$E_\gamma = hf = hc/\lambda = 1240\ eV \cdot nm/\lambda$$

using the data that you have obtained. Complete the following table:

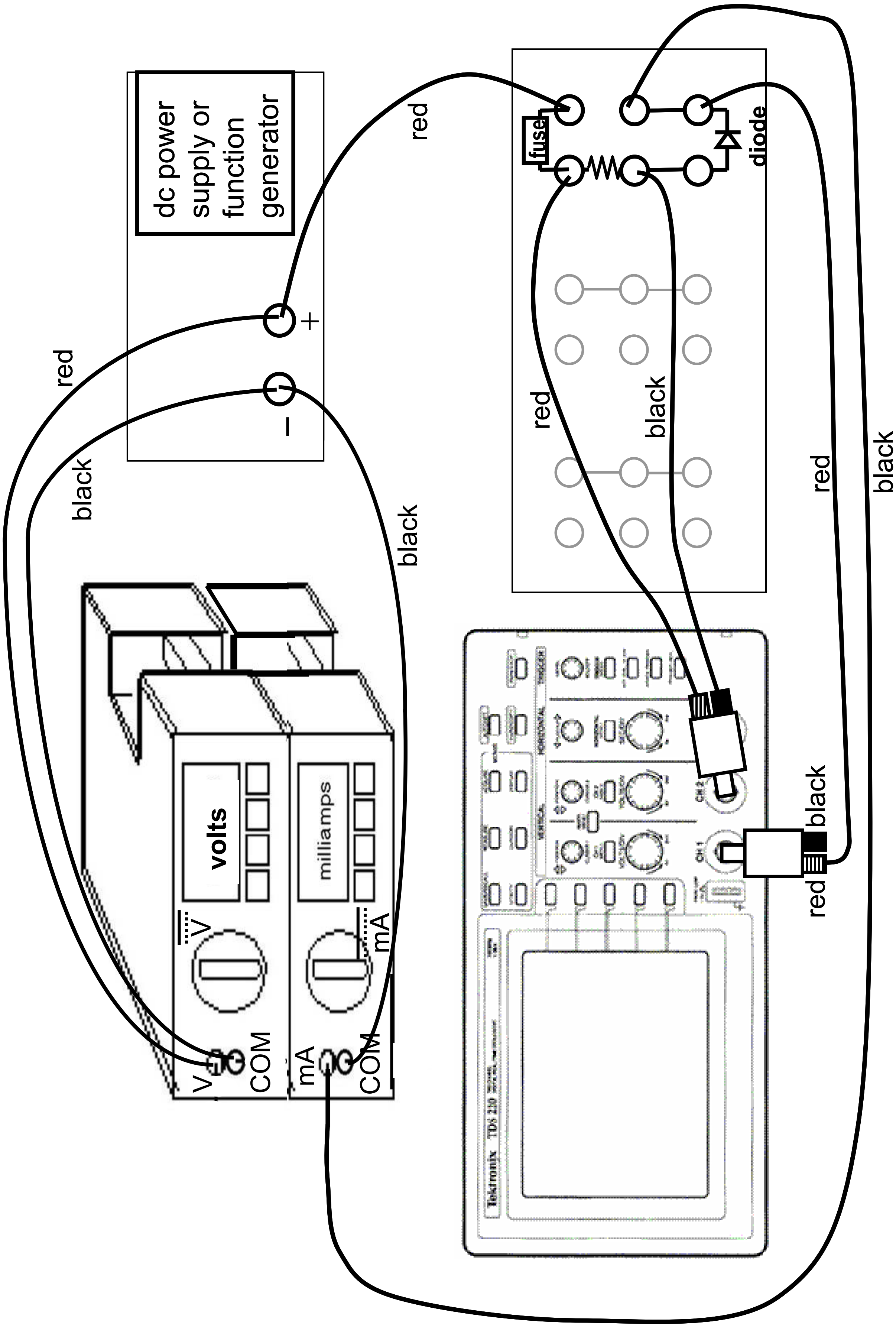
	$\lambda_{measured}$ (in nm)	$E_\gamma = hc/\lambda_{measured}$ (in eV)	$E_e = eV_{measured}$ (in eV)	$100(E_\gamma - E_e)/E_e$ % difference
Red LED				
Green LED				
Blue LED				

(Due to the intricacies of the electron-to-photon energy conversion in an LED, your agreement may only be semi-quantitative. Don't worry – a host of other experiments have verified the photon energy-frequency and energy-wavelength relations to extreme precision.)

The main idea you should remember from this lab is that **energy** is fundamentally linked to **frequency** according to Planck's formula **E=hf**. Remember also that the wavelength **λ** and the frequency **f** are related according to the formula **λf=c**, where **c** is the speed of electromagnetic waves in vacuum.

Clean-up Check List:

Switch off power to all of the instruments. Disconnect all of the leads and put the leads in the bin. Put the diode and LEDs in one place. Leave the ruler, the diffraction grating, and the other equipment ready for the next group.


dc power
supply or
function
generator
+
–
red
black
red
black
fuse
diode
red
black
red
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volts
V
COM
milliamps
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COM
red
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Tektronix
TDS 210
CH 1
CH 2