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Optoelectronic Devices (OD)

Contents

A. Objectives

You will be able to understand and measure the characteristics of various Optoelectronic devices such as photoconductive cell, phototransistor, solar cell etc.

B. Introduction

Optoelectronics is the study and application of electronic devices that interact with light. In this context, *light* often includes invisible forms of radiation such as gamma rays, X-rays, ultraviolet and infrared. Optoelectronic devices are electrical-to-optical or optical-to-electrical transducers, or instruments that use such devices in their operation. Optoelectronics is based on the quantum mechanical effects of light on semiconducting materials, sometimes in the presence of electric fields. Optoelectronic devices can be classified according to the physical phenomena used in various devices as shown in Fig. 1. Combination of both electrical-to-optical/optical-to-electrical devices in a system can be found in many applications such as optocouple, fiber optical communications etc.

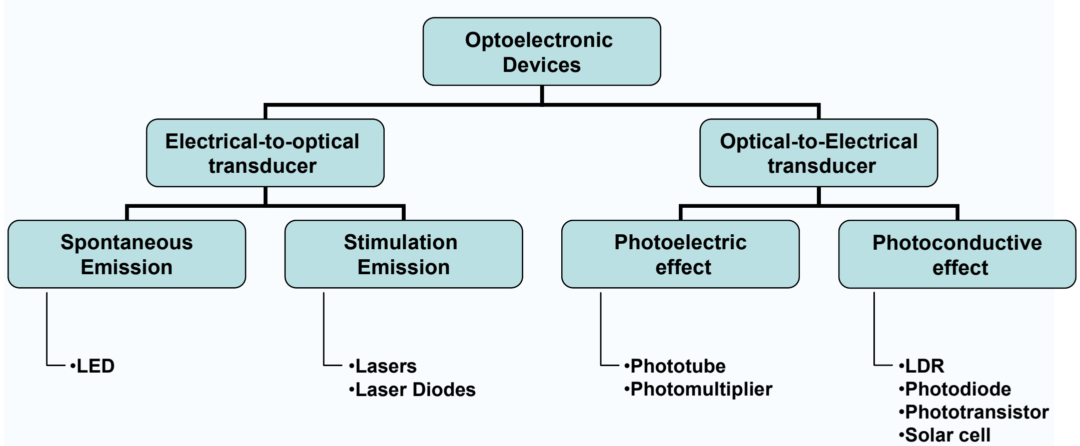

Fig. 1 Classification of optoelectronic devices with examples

1. Photoconductive Effect

The photoconductive effect is an optical and electrical phenomena, in which the electrical conductivity of a semiconductor material increases when exposure to light or an electromagnetic radiation. Consider a semiconductor material is under an optical excitation as shown in Fig. 2. If the photon energy is greater than the energy gap, E_g of the semiconductor, Incident photons become absorbed in the semiconductor, and the electron hole pairs (EHP) will be generated. Here, the relation between photon energy and wavelength, λ is

$$E = hc/\lambda = 1.24/\lambda(\text{in nm}) \tag{1}$$

where E is the electrical conductivity at thermal equilibrium
h is the Plank's constant = 6.63 x 10^{-34} J s
c is the speed of light in free space ~ 3 x 10^{8} m/s
λ and p are the electron and hole concentration at normal condition, respectively
Δn and Δp are the electron and hole concentration due to the photogeneration, respectively

Therefore, the considerable absorption will occur under the condition $E_g > E$. The band gap energies of some common semiconductor are given here, e.g. Si ~ 1.1 eV, GaAs ~ 1.43 eV, and CdS ~ 2.4 eV. The generation of EHP by the optical excitation, thus increases the conductivity of the semiconductor as follows

$$\sigma + \Delta\sigma = (n + \Delta n)q\mu_n + (p + \Delta p)q\mu_p \tag{2}$$

where σ is the electrical conductivity at thermal equilibrium
$\Delta\sigma$ is the increment of conductivity due to the optical excitation
q is the electron charge = 1.6 x 10^{-19} Coulomb
n and p are the electron and hole concentration at normal condition, respectively
Δn and Δp are the electron and hole concentration due to the photogeneration, respectively
μ_n and μ_n are the mobility of electron and hole, respectively.

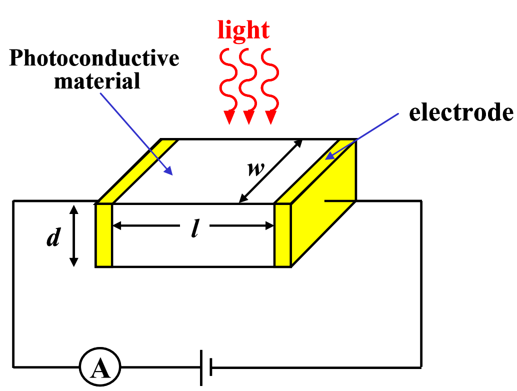

Fig. 2 A semiconductor is illuminated with light of wavelength λ.

2. Radiative Recombination: Spontaneous Emission

In physics, it is well known that when an atom, molecule or nucleus in an excited state drops to a lower-energy state**,** this results in the creation of a photon. In case of semiconductor, the electrons in the conduction band may make transitions to the valence band (i.e. recombine with holes in the valence band)[1]. Energy lost by an electron in making transition is given up as a photon. In a device, there are many ways by which electrical energy can be used to generate photon. For example, in LEDs an electric current causes the injection of minority carriers (electron or hole) into regions of the crystal where there are recombine with majority carriers (electron or hole), resulting in the emission of recombination radiation.

3. Examples of Optoelectronic Devices

1) Photoconductive cell or Light Detector Resistor (LDR)

Photoconductive cell is the simplest device that uses the photoconductive effect in its operation. The device structure is a resistor as shown in Fig. 2. The device conductivity, therefore is a function of the incident electromagnetic radiation. Many semiconductor materials can be used as photoconductive cells, but the commercially important ones are cdS, Ge and Si. The spectral response of CdS closely matches that of human eyes, and the cell is therefore used in applications where human vision is a factor, such as street light control or automatic iris control for cameras.

2) Photodiode

As we saw that bulk semiconductor samples can be sued as photoconductors by providing a change in conductivity proportional to an optical intensity. Junction devices can be used to improve the speed of response and sensitivity of the devices. If a *pn* junction is exposed to light of proper wavelength, the current flow across the junction will tend to increase as shown in Fig. 3. If the junction is forward-biased, the net current will be relatively insignificant. However, if the junction is reversed-biased, the change will be quite appreciable. With the electric field at the depletion region, electron generated in the p-side conduction will flow down the potential hill at the junction into the n-side and from there to the external circuit. Likewise, holes generated in the valence band of the n-side where they will add to the external circuit.

$$I = I_{\mathrm{o}}(\exp[\frac{qV}{kT}]-1) - I_{\mathrm{op}} \tag{3}$$

3) Phototransistor

The phototransistor is a bipolar junction transistor (BJT) that operates as a photodiode with a photocurrent gain. Normally, the base terminal is left floating. The photo-induced current is the transistor base current. The current gain of the transistor will thus result in a significant increase in collector current as follows

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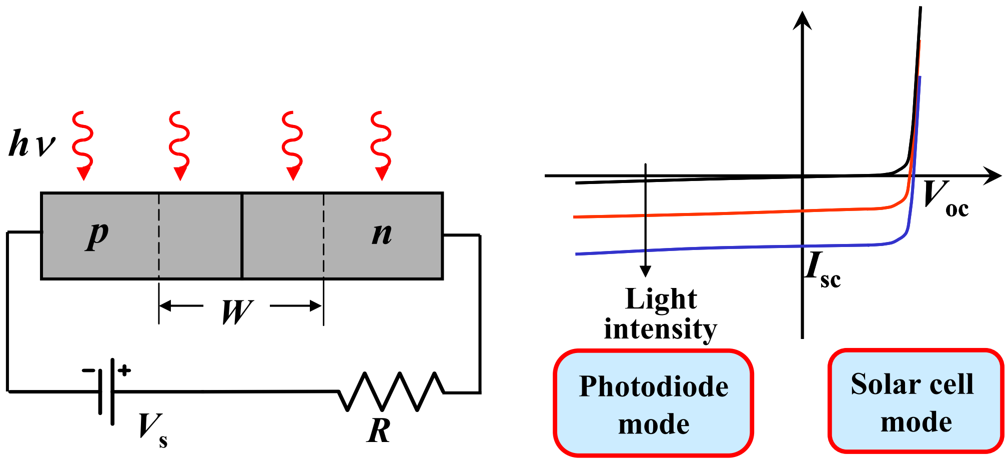
[1] There are two kinds of recombination: direct and indirection recombination, the energy given by the direct recombination as a photon of light, while the indirect recombination, the energy is generally given up as heat rather than an emitted photon.

$$I_C = (h_{fe} + 1) I_{op} \quad (4)$$

where I_C is the collector current,
h_{fe} is the forward current gain and
I_{op} is the photo-generated base current



(a) (b)

Fig. 3 (a) Device operation and (b) *I*-*V* characteristics

3) Phototransistor

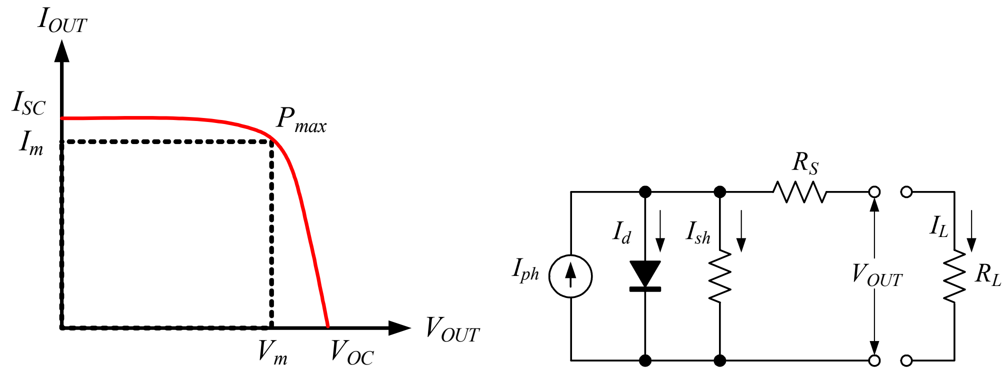
The phototransistor is a bipolar junction transistor (BJT) that operates as a photodiode with a photocurrent gain. Normally, the base terminal is left floating. The photo-induced current is the transistor base current. The current gain of the transistor will thus result in a significant increase in collector current as follows

$$I_C = (h_{fe} + 1) I_{op} \quad (5)$$

where I_C is the collector current,
h_{fe} is the forward current gain and
I_{op} is the photo-generated base current

4) Solar Cell

Photovoltaic cells or solar cells convert the incident solar radiation energy into electrical energy. A typical solar cell is a *pn* diode with a large surface area and very shallow junction. Incident photons are absorbed to photogenerate charge carriers that pass through an external load without an external voltage source. Without an external load, EHP photogenerated in the depletion region are separated them apart by the built-in electric field. The electrons drift and reach *n*-side, therefore they make this region negative. Similarly the holes drift and reach the *p*-side and thereby make this side positive. Consequently **an open circuit voltage** develops between the device terminals. If an external load is connected then the excess electrons in the *n*-side can travel around the external circuit, and reach the *p*-side to recombine with the excess holes here. On the extreme case, **a short circuit current** obtains when the device terminals are short together. Fig. 4(a) shows a typical current-voltage characteristic of a solar cell, as well as its equivalent circuit.



(a) (b)

Fig. 4 (a) the typical current-voltage characteristic and (b) equivalent circuit of a common solar cell.

Here I_{ph} is the photogenerated current,
I_D is the diode reverse saturation current,
I_{sh} is the current flow through shunt resistor, and
R_{sh} and R_s are the shunt and series resistance, respectively.

The power delivered to the load is Pout = IV, which is the area of the rectangle bound by I and V axes and the dashed lines shown in Fig. 4(b). Maximum power is delivered to the load when this rectangular area is maximum ImVm . Since the maximum possible current is Isc and the maximum possible voltage is Voc, IscVoc, represents the desirable goal in power deliver for a given solar cell. Here, we define the fill factor, FF, which is a figure of merit for a solar cell as

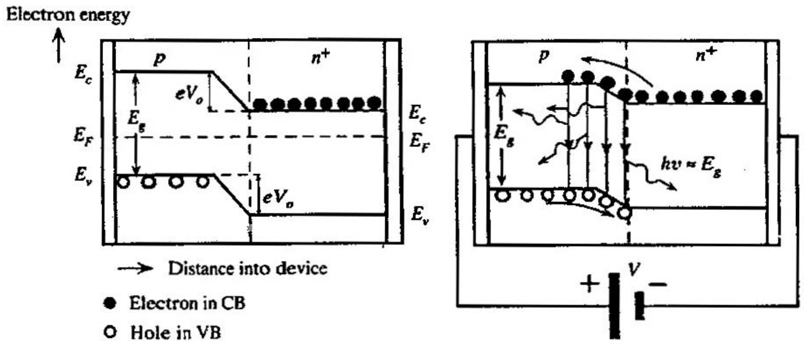
$$\mathrm{FF} = \frac{I_m V_m}{I_{sc} V_{oc}} \tag{6}$$

FF is a measure of the closeness of the solar cell I-V curve to the rectangular shape (Ideal-shape). Typically FF values are in the range of 0.7-0.85 and depend on the device material and structure. We also the efficiency of a solar cell as follows

$$\eta = \frac{I_m V_m}{W_{input}} \times 100\% = \frac{I_{sc} V_{oc}}{W_{input}} \mathrm{FF} \times 100\% \tag{7}$$

5) Light Emitting Diodes (LED)

An LED is essentially a pn junction diode typically made from a direct band gap semiconductor, for example GaAs, in which EHP recombination results in the emission of a photon. The emitted photon energy is therefore approximately equal to the band gap energy, $h\nu \approx E_g$ Fig shows the energy band diagram of an unbiased pn+ junction device in which the n-side is more heavily doped than the p-side. Fig. 5 shows the energy band diagram under biased condition, the recombination of the injected carriers (electrons and holes) around the junction and the adjacent region within the carrier diffusion length leads to photon emission.



(a) (b)

Fig. 5 The energy band diagram of an LED under (a) unbiased and (b) biased conditions.

6) Optical coupler

Optical coupler combines both electrical-to-optical and optical-to-electrical transducers into a single package. Both devices are coupling together using optical signals. Some examples of optical couplers are shown in Fig.6

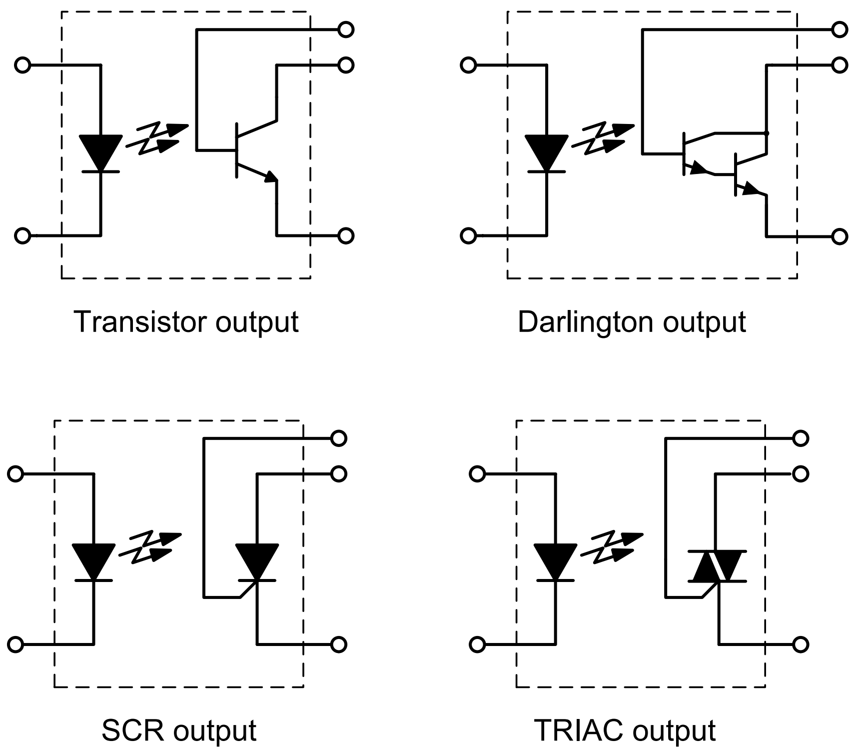


Fig. 6 Examples of Optocouplers

C. Experiments

Exp1 Photoconductive cell: The relation between device resistance and light intensity

Find the relation between resistance, R of a photoconductive cell and light intensity, P. The intensity from a given source can be adjusted by changing the distance, L between the light source and the photoconductive cell. (Assume $P \alpha \frac{1}{L^2}$).

Exp2 Phototransistor: The relation between photogenerated current and light intensity

Connect the test circuit as shown in Fig. 8, set the voltage of DC supply to 10 V. Find the relation between collector current, I_C of phototransistor and light intensity, P

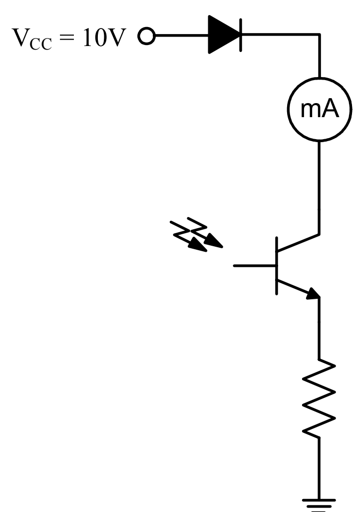


Fig. 8 Circuit diagram used to measure I_C of a phototransistor under illumination.

Exp3 Optocoupler: Device Characteristic

Use a curve tracer and oscilloscope to measure the characteristic of optocoupler. Here, the optocoupler used in the experiment, consists of an LED and phototransistor. Connect the circuit as shown in Fig. 9 (don't forget to make a short circuit between LED cathode and phototransistor emitter). Use LED anode as the base terminal of the phototransistor. Set the curve tracer to inject with the step of 2 mA into LED anode. Plot the output characteristic I_C-V_{CE} as a function of the LED current.

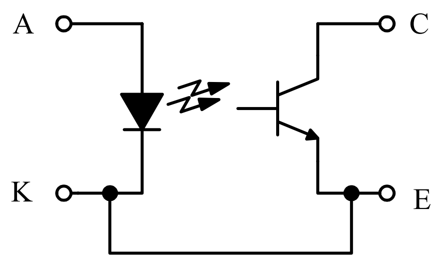


Fig. 9 The measurement of the output characteristic of an optocoupler.

<u>Exp4</u> Optocoupler: Application

Connect the test circuit as shown in Fig. 10. Set the DC supply of the phototransistor to be 10 V, adjust the DC supply of the LED circuit until the LED current equals to 6 mA (read from the ammeter). Apply square wave with amplitude 1.5 $V_{p\text{-}p}$ and frequency 1 kHz from a function generator to modulate the light intensity of LED. Use an oscilloscope to capture the waveform at the phototransistor collector compare to the square wave from the generator. Record the waveforms in AC and DC mode.

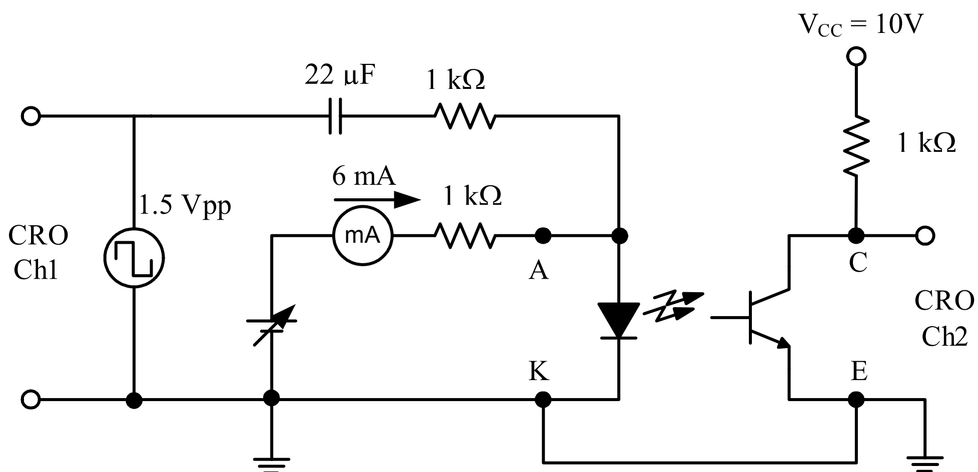


Fig. 10 Circuit diagram for signal transmission using an optocoupler.

<u>Exp5</u> Solar Cell: I-V characteristic

1) use a multimeter to the device resistance under dark condition, change the terminal connections. From the results, determine the terminals of n-side and p-side?

2) Connect the circuit in Fig. 11, apply the solar cell with a constant light source. Vary the value the adjustable resistor to find I_{sc}, V_{oc} and other data with the digital voltmeter and ammeter.

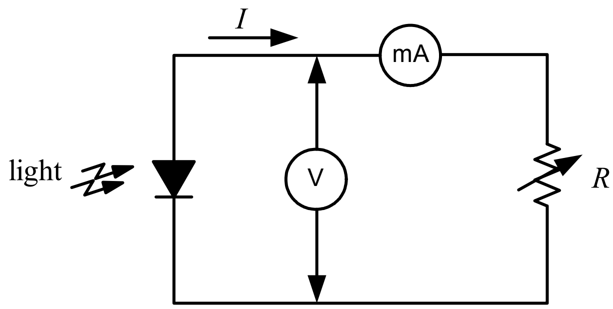


Fig. 11 Circuit diagram for measuring *I*-*V* characteristic of a solar cell.

Curve Tracer Manual

Curve tracer can be used to display a semiconductor characteristic on a CRO display. This home-brewed curve trace is designed to use with the following devices:

- Diode
- BJT: NPN and PNP
- JFET: P and N-channel
- MOSFET: P and N-channel with both depletion and enhancement mode

General Specifications

-Collector/Drain Sweep Voltage	
Sweep frequency:	Ramp signal with 100-500 Hz
Sweep voltage:	±15 V continuously adjustable
Maximum output current:	40 mA (limited by the short circuit current of LM324)
-Step Generator (Base current or Gate voltage)	
No. of Steps	7 lines for base current 8 lines for gate voltage
Current per step	10, 20, 50 μA; 0.1, 2 mA
Volt per step	0.1, 0.2 and 0.5 V
-Power supply	220 V 50 Hz
-Device current	Calculated from the voltage across the 100-Ω series resistor (inside the box)

Controls and Connections

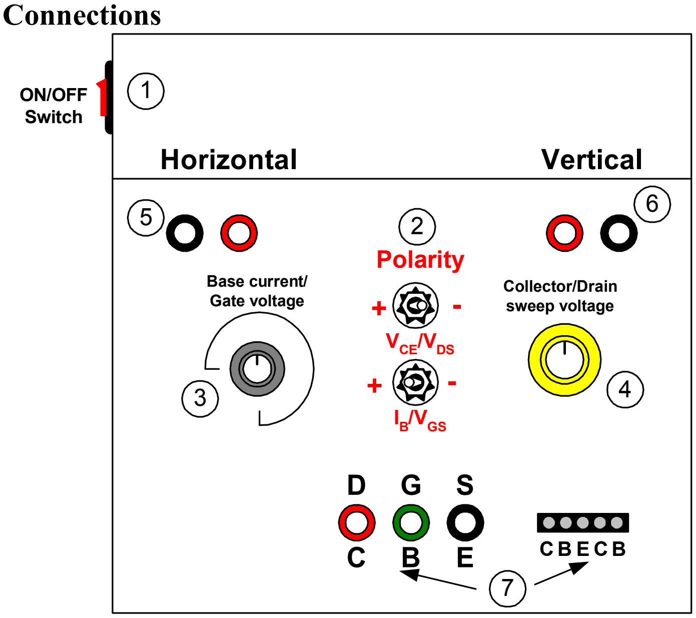


Fig. 1 The layout of controls and connectors on the curve trace

1) ON/OFF switch Turn on the AC power

2) Polarity switches - V_{CE}/V_{DS} - I_B/V_{GS}	Select the mode of operations (see table 1)
3) Base current/	Sets the step of base current or gate voltage Gate voltage switch
4) Collector/Drain	Adjusts the amplitude of the sweep voltage across Sweep voltage control device under test
5) Horizontal jacks	Connections to horizontal CRO input
6) Vertical jacks	Connections to vertical CRO input
7) Device connection jacks	Connections to the device under test

Table 1 Polarity settings for various semiconductor devices

Device		Polarity	
		I_B/V_{GS}	V_{CE}/V_{DS}
BJT	**NPN**	+	+
	PNP	-	-
JFET	**N-channel**	-	+
	P-channel	+	-
Enhancement MOSFET	**N-channel**	+	+
	P-channel	-	-
Depletion MOSFET	**N-channel**	-	+
	P-channel	+	-

Testing Procedures

1. While the curve tracer is off, connect the curve tracer to a CRO (Horizontal to CH1 and Vertical to CH2), set the CRO to X-Y mode.
2. Set the Polarity switches according to the type of the device (see Table 1 for reference)
3. Connect the device to the curve tracer
4. Adjust the Collector/Drain sweep voltage control to the fully minimum position (turning counter clockwise), switch on the curve tracer
5. Set the Base current/ Gate voltage switch (for BJT set the bias in μA or mA range and for JFET or MOSFET set the bias in V range) For instance, at 10 μA setting, the curve trace will inject the base current I_B into BJT with 10 μA step, starting from 0, 10, 20, 30, 40, 50 and 60 μA, 7 lines in total. If we set the control at 0.1 V, this equipment will apply V_{GS} to the Gate with 0.1 V step, starting from 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 and 0.7 V, 8 lines in total
6. Adjust Collector/Drain Sweep voltage control to the desired value (turning clockwise position)
7. Adjust the X-scale and Y-scale of CRO to obtain the best viewing on the CRO screen
8. Record your results.
9. Turn Collector/Drain Sweep voltage control to the minimum position, switch off the curve tracer, disconnect the device. Repeat the procedures from step 2 for the new testing.

Note the device current can be calculated from the voltage on the Y-axis by dividing with the resistance value of 100-Ω. This 100-Ω resistor is connected in series with the device under test.

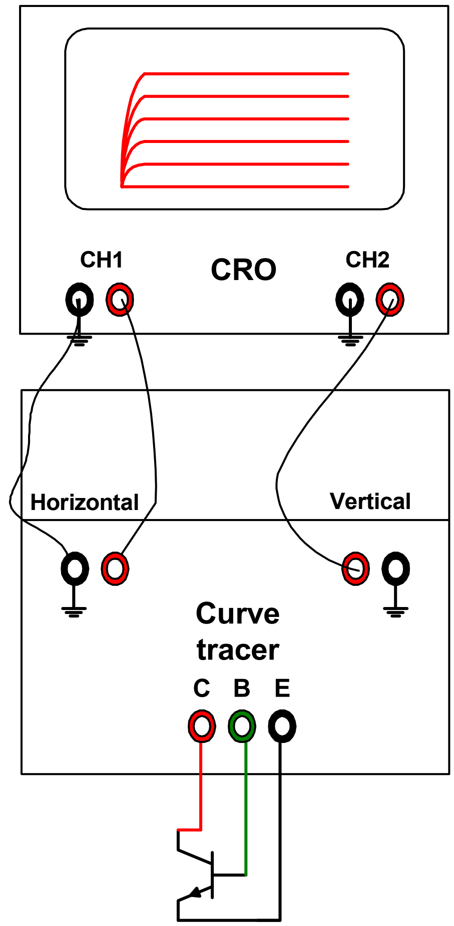


Fig. 2 Connecting between CRO and curve trace for device characterization.

Student Name: ______________________________________ID: ________________
Date: ______________Group: _____________Instructor signature:_______________

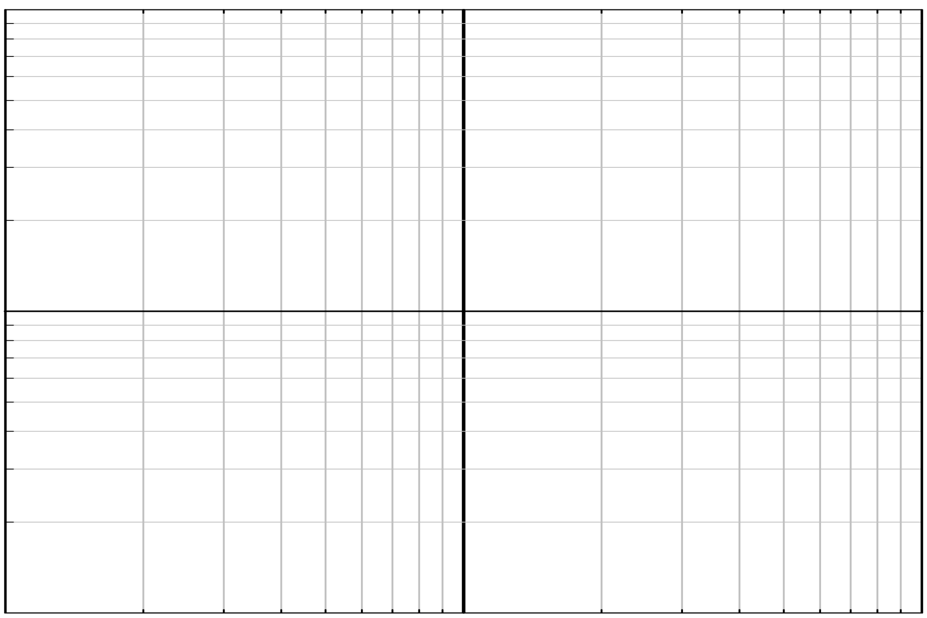
Experimental Report

Optoelectronic Device (OD)

<u>Exp1</u> Photoconductive cell: The relation between device resistance and light intensity

L (cm)	100	90	80	70	60	50	40	30	20	10
R (Ω)										

Plot the photoconductive resistance *R* as a function of the light intensity $1/L^2$ using log-log scale

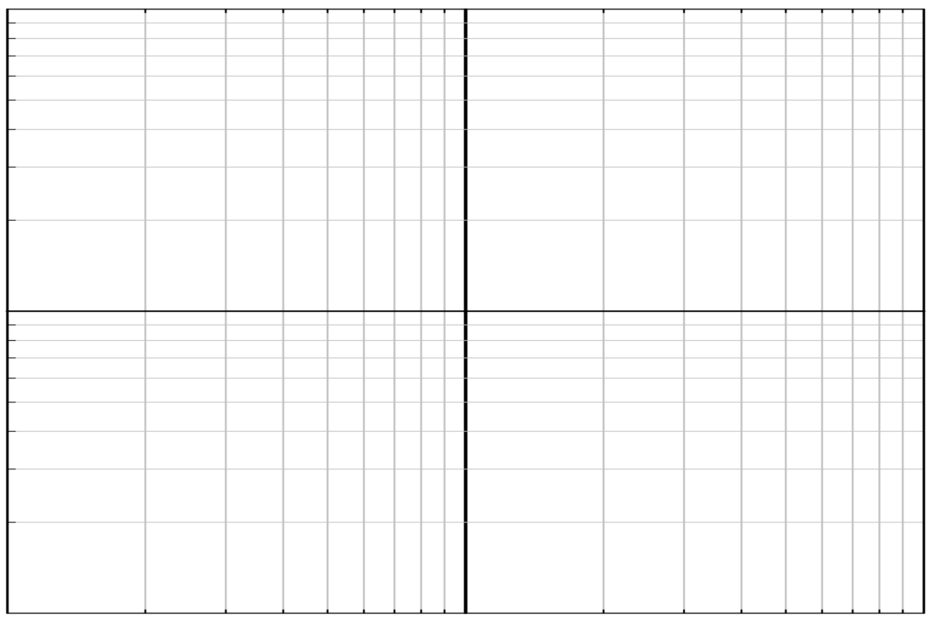


<u>Discussion</u>

<u>Exp2</u> Phototransistor: The relation between photogenerated current and light intensity

L (cm)	100	90	80	70	60	50	40	30	20	10
I (mA)										

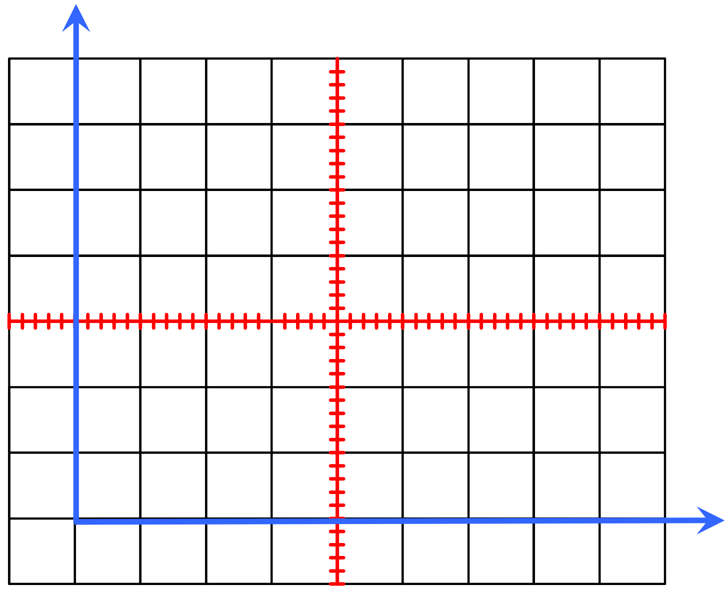
Plot the collector current, I_C as a function of the light intensity, $1/L^2$ using log-log scale



<u>Discussion</u>

<u>Exp3</u> Optocoupler: Device Characteristic

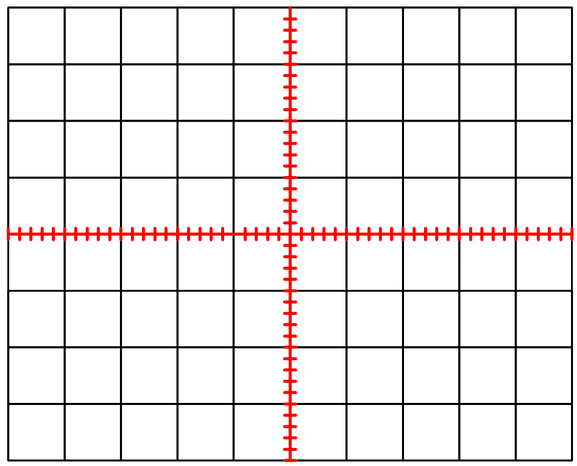
CH1: VOLT/DIV switch = V/div
CH2: VOLT/DIV switch = V/div
I_{LED} step



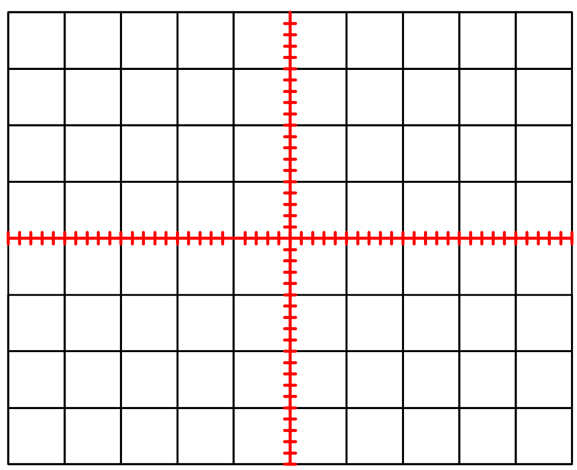
<u>Discussion</u>

<u>Exp4</u> Optocoupler: Application

Case I: AC mode
CH1: VOLT/DIV switch = V/div
CH2: VOLT/DIV switch = V/div
TIME/DIV switch= /div



Case II: DC mode
CH1: VOLT/DIV switch = V/div
CH2: VOLT/DIV switch = V/div
TIME/DIV switch= /div



<u>Discussion</u>

<u>Exp5</u> Solar Cell: *I-V* characteristic

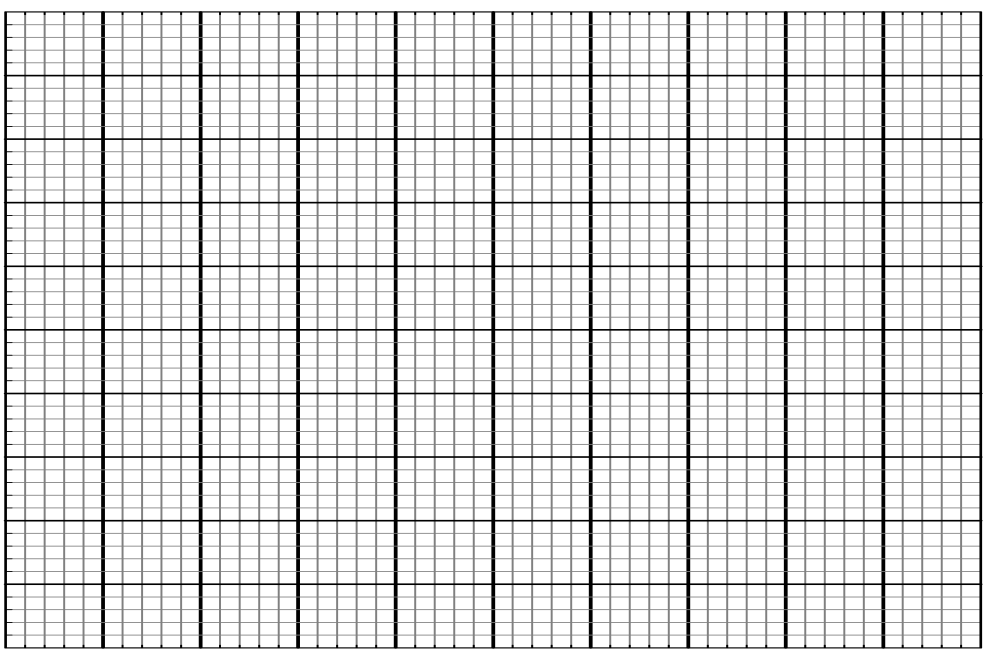
Rectify characteristic

I) Red terminal: positive Black terminal: negative	$R =$
II) Black terminal: positive Red terminal: negative	$R =$

I-V characteristic

R (Ω)	0	2	4	6	8	10	20	40	60	80	100
I (mA)	(I_{sc})										
V (Volt)											

R (Ω)	200	400	600	800	1000	2000	4000	6000	8000	10000	∞
I (mA)											
V (Volt)											(V_{oc})



Discussion

Questions

1) Compare advantages and disadvantages of the photoconductive cell to those of other photodetectors in terms of sensitivity, speed of response etc.
2) What parameters determine the optical wavelength emitted from an LED?
3) Is the rectifying property of a typical diode identical to that of a solar cell? Explain why?
4) If we change the material of solar cell, the value of V_{oc} will be changed or not? Give reason?
5) Design a DC power supply with the output voltage of 5 V and current of 20 mA, using the solar cell in the experiment. Calculate the number of cells and describe or sketch the connection configuration of cells? (series, parallel or compound)?