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Comparative Analysis of Photoelectric Characteristics of Photosensors: A Case Study between Photoresistor, Photodiode, and Phototransistor

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Abstract
This work is focused on the comparison of optical and electrical characteristics of the most widely used photosensors in light measurement and light detection systems which include; photoresistor, photodiode and phototransistor in terms of linearity and sensitivity. Therefore, to intuitively compare their characteristics, an attempt was made by developing a light intensity measuring device which has ability to interface with the three sensors simultaneously. The device is a single system which can measure the intensity of incident light falling upon a surface, and also the current and voltage generated by each sensor when been illuminated by a light source.

The device consists of six major components: photoresistor (light dependent resistor, LDR), photodiode, phototransistor, Arduino microcontroller, Liquid crystal display (LCD) and microSD card. The heart of the device is the Arduino microcontroller which is programmed using C language to read the intensity of incident light falling upon the sensors and thereby convert the light intensity into corresponding electrical signals such as current and voltage. From the experimental data, the three sensors show good correlation between the intensity values captured by the sensors. This has proven that the sensors are good to sense beam pattern of lights. So, they can be alternatively use in any application of light measurement and light detection. More so, from the characteristic curves of sensors' current outputs to the light intensity, photodiode gives a better linearity in response to light illumination than photoresistor and phototransistor. Meanwhile, from the standard deviation analysis of the sensors' currents measured, photoresistor has a deviation of 114.10; photodiode has a deviation of 61.05 and phototransistor has a deviation of 104.59 respectively. From these values, photodiode shows good sensitivity to beam of light than photoresistor and phototransistor. So, from the satisfactory performance of this design, the device can be used in the laboratory for demonstration and research purposes especially in the area of light measurement technology.

Keywords: *Light intensity, linearity, sensitivity, photoresistor, photodiode, phototransistor, arduino-microcontroller, current, voltage.*

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I. Introduction

Photosensors have become ubiquitous in recent years due to their widespread applications in a variety of number of fields and sectors where light detection is one of the basic important factors to their operations such as medical practice, optical communication, environmental and security monitoring, analytical instrumentation, industrial control, home automation, modern agriculture, among others. However, photosensors are electro-optic devices that respond to light energy in other to change their electrical characteristics in accordance with a change in the intensity or frequency of incident light falling upon them [4]. They use the principle of photoelectric effect to convert light energy into electrical signal [1][18][19]. The electrical signal generated is either a current or voltage [3].

Basically, photosensors are designed to be sensitive to visible light or other electromagnetic radiation in a given spectral region of electromagnetic spectrum that typically lies between ultraviolet and infrared radiations [2]. Hence, they are practically meant to respond to the incident light mostly within the wavelength range around 380 to 1100 nanometres (nm). More specifically, photosensors are usually understood as light sensors or photodetectors or photoelectric sensors. There are wide varieties of photosensors, these include photoresistors, photodiodes, phototransistors, phototubes, photomultipliers, among others [15]. Based on the detection and conversion mechanism, [3] classified photosensors into one of two categories: those that are based on external photoelectric effect, in which photoelectrons are ejected from the surface of a material when struck by light such as photoemissive devices like phototube and photomultiplier; and those that based on the internal photoelectric effect, where electron-hole pairs are generated through absorption of incident photons such as photoconductive devices like photoresistor, and photovoltaic/p-n junction devices like photodiode and phototransistor. In view of the above aforementioned, [3][16][19] further categorized photosensors into the following types: photoemissive cells, photoconductive cells, and photovoltaic/p-n junction cells.

According to [4], it was revealed that these sensors have different spectral band response; hence, when choosing one, it is important to learn how the photosensor reacts in response to the power of incident light falling upon it. So, when implementing a photosensor in an application, one has to consider some very important parameters such as effective sensing distance, linearity, sensitivity, dynamic range, quantum efficiency, noise equivalent power and speed of response to describe the characteristic of such photo device [19]. These parameters are considered as the figures of merit to compare one photosensor to another and also to determine the suitability of a photosensor for a particular application in other to achieve result [3].

With this respect, several studies have been carried out by a number of researchers to investigate behaviour of different photosensors in response to light luminance.

For example, [15] worked on design and implementation of photoelectric sensor for yarn color detection. [9] worked on the analysis of the optical measurement sensitivity of the photodiode and LDR light sensors. [10] carried out a comparative study of the optical measurement sensitivity of the phototransistor and photodiode. [18] worked on a comprehensive study of comparison between different types of sensors used in the real optical operational environment that is based on optical scanning system. [12] worked on performance analysis of photoresistor and phototransistor using an automotive halogen and xenon light bulb outputs as source of illumination. But, most of these works mentioned above were based only on two of these sensors and the data are collected manually.

In this work, emphasis was laid on three photosensors which comprise; photoresistor, photodiode and phototransistor. These sensors are chosen for this study because they are the most widely used photosensors in many application of light. Also, they are less expensive and readily available in the market than other types of photosensors such as phototube and photomultiplier. Therefore, brief descriptions of their properties are explained below.

(i) Photoresistors

Photoresistors are special type of variable resistive elements whose resistance changes when exposed to light. Owing to this, photoresistors are also known as light-dependent resistors, LDRs [1][5][8]. The resistance of the LDRs falls from mega-ohms (MΩ) to few ohms (Ω) under bright light, that is, their resistance decrease as the level of light intensity increase and also their resistance increase as the level of light intensity decrease [17]. Compared to photodiodes and phototransistors, photoresistors are cheaper and simpler to use to detect light. They do not have a p-n junction, but are made from a thin film of semiconductor materials like cadmium sulphide (CdS), cadmium selenide (CdSe), lead sulphide (PbS), lead selenide (PbSe) [7] and gallium arsenide (GaAs) [6]. A common and popular type of photoresistor is the Mullard ORP12. Although, other types of photoresistor are available such as GL55. Thus, Figure 1 shows a typical symbol of a photoresistor and picture of the photoresistor used in the work.

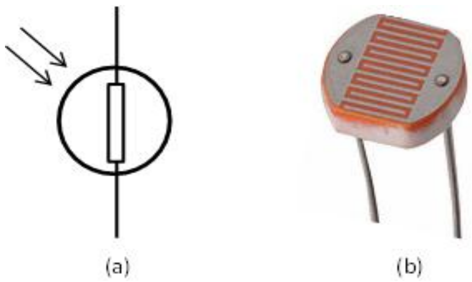

Figure 1: (a) symbol and (b) picture of Light-Dependent Resistor (LDR)

(ii) Photodiodes

A photodiode is a P-N junction device built from typical semiconductor materials, such as silicon and germanium. They are basically a two terminal device with a small transparent window on which light is allowed to hit the device and fall on the P-N junction. Photodiodes are constructed like any other convectional diodes except that when their P-N junction is exposed to light, electron-hole pairs are created at the junction and this allows the flow of current across its junction [13]. Photodiodes may be operated in two different modes: photovoltaic mode or photoconductive mode [1][13][16].

When a zero biased is applied, the photodiode is being operated in the photovoltaic mode. In this mode, photodiodes operate in a similar way to solar cells in such that when light hits the P-N junction, a voltage is produced [1]. But, when a reverse biased is applied, the photodiode is being operated in the conductive mode and in this mode, the photodiode functions as a current source as well as light detector. Figure 2 shows a typical symbol of a photodiode and picture of the diode sensor used in the work.

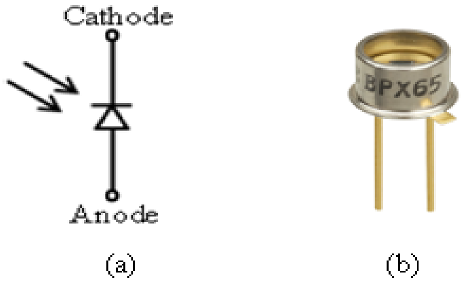

Figure 2: (a) symbol and (b) picture of Photodiode

(iii) Phototransistors

The phototransistor is also a photo-junction semiconductor device that operates in a similar way to a reverse biased photodiode. It is basically a photodiode with a current transistor amplifier as illustrated in Figure 3. So, it combines the characteristics of a transistor and a photodiode [17]. Its base terminal is not electrically connected; hence, the phototransistor can only be configured in two ways: common emitter (CE) and common collector (CC) amplifying configurations [5]. In common emitter configuration, light illumination causes the transistor output to go from high state to low state. While, in common collector configuration, light illumination causes the transistor output to go from low state to high state. Figure 3 shows a typical equivalent symbol of a phototransistor and picture of the phototransistor sensor used in the work.

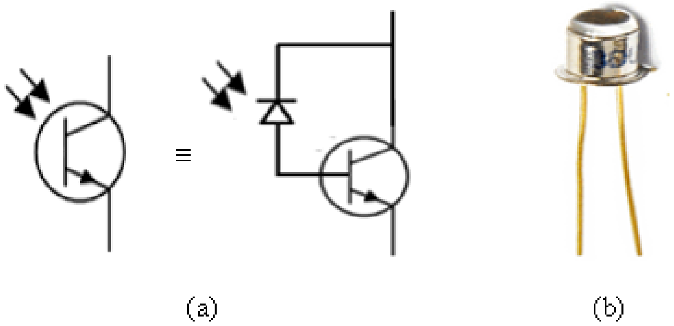

Figure 3: (a) symbol and (b) picture of Phototransistor

II. Materials and Methods

The basic block diagram of the hardware implementation of the light measuring device used to carry out this study is shown in Figure 4. The device has four major units: input unit (sensing unit), control unit, display unit and storage unit. The four units are designed independently before being coupled into one system. This is to ensure that if there is any error, they can be independently considered and corrected.

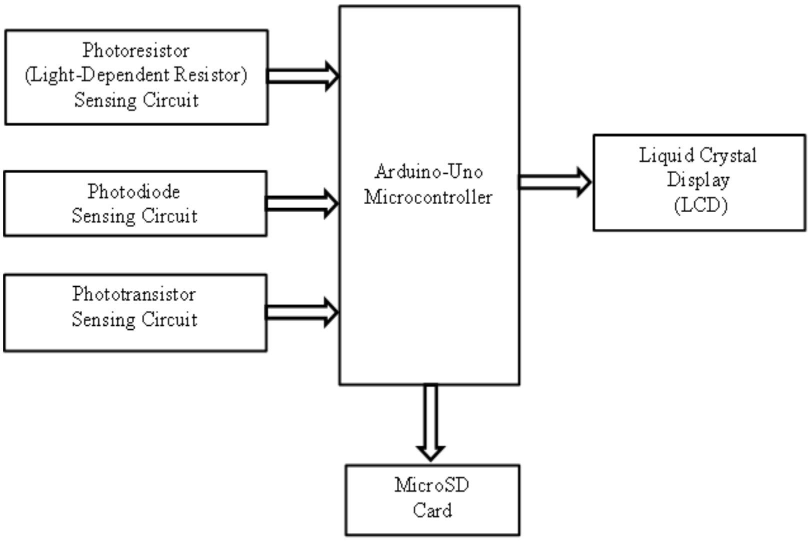

Figure 4: Block Diagram of the Light Intensity Measuring Device

(i) Input Unit

The input unit is the sensing part of the device which comprises; photoresistor (light-dependent resistor, LDR) circuit, photodiode circuit and phototransistor circuit.

Photoresistor Circuit

This section of the input unit consists of a photoresistor (light-dependent resistor, LDR ORP12) and a load resistor R1, 10 kΩ. The LDR and the resistor are connected together in series and this connection forms a potential or voltage divider network. From the circuit, one side of the LDR is connected to the reference supply voltage, +5 V and the other side is connected to the circuit ground via the load resistor, R1 as depicted in Figure 5. The choice of using this resistance value is to ensure that the widest output range does not exceed 5 V, which is the highest voltage level that powered the circuit. Also, this will enable the rate of variation in the conductivity of the LDR to be more visible. With the resulting configuration; when light strikes the LDR, the resistance of LDR changes, thus a fraction of the reference supply voltage appears at the junction between the LDR and the load resistor, R1 as an output signal. The amount of output voltage generated by the circuit is determined by the resistive value of the LDR. So, as the light intensity increases, the resistance of the LDR decreases thereby causing a high voltage at the output. While, the light intensity decreases, the resistance of the LDR increases and this results in a low voltage at the output. The generated output voltage can be determined by the voltage divider formula given in equation (1). This voltage is fed into the analogue input A0 of the microcontroller for further process into corresponding value of the intensity of incident light detected by the sensor and the conversion factor is given in equation (2).

$$V_{out} = V_{cc}\left(\frac{R1}{R_{LDR} + R1}\right) \qquad (1)$$

where V_{out} = Output voltage from the voltage divider
Vcc = Reference supply voltage to the LDR, +5 V
R1 = Resistance of the resistor reference to ground, 10 kΩ
R_{LDR} = Resistance of the photoresistor (light-dependent resistor, LDR) when illuminated

$$\text{Photoresistor (LDR) reading} = \text{AnalogRead (A0)} \qquad (2)$$

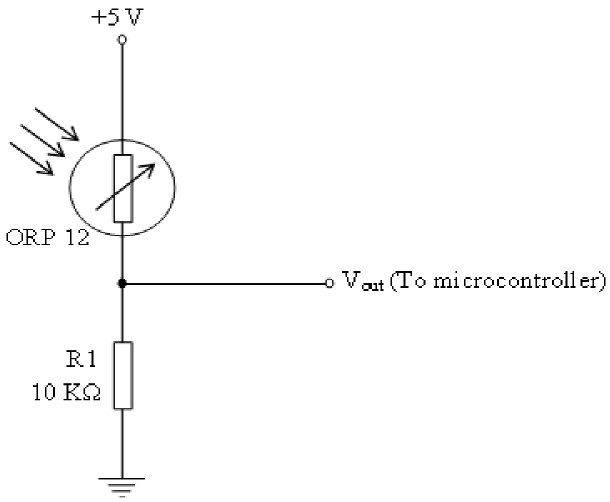

Figure 5: Photoresistor (Light-Dependent Resistor, LDR) Sensing Circuit

Photodiode Circuit

The photodiode sensor used in this unit is BPX 65, a silicon PIN photodiode from OSRAM opto semiconductor. The photodiode is used in a photoconductive mode by connecting it in reverse biased configuration as illustrated in Figure 6. So, when light hits the photodiode, a current which is proportional to the intensity of light falling upon the sensor is created across the diode's junction. This generated current is very small and for it to be measured to give the reading of the intensity of incident light; a transimpedance amplifier, that is, a current to voltage converter was employed to convert the current to voltage signal and also to amplify the obtained voltage signal to a range that can be used by other devices or be read by the microcontrollers. The amplifier was built around LT1013CN8, a low-noise operational amplifier (op-amp). The amplifier was configured in an inverting mode with a feedback resistor R_f, 8 MΩ connected in parallel with capacitor, C_f, 2pF as indicated in Figure 6. The capacitor, C_f, in the circuit is used to stabilize the amplifier against any oscillation. The amplifier operates in such that the current created across the diode's junction flows through the feedback resistor, R_f and the value of the current multiplied by the resistance, R_f creates an output voltage at the op-amp's output. The gain of the amplifier is set by the feedback resistor, R_f and since the amplifier is in inverting mode, the feedback resistor has a value of $-R_f$. With this circuit; as the light intensity increases, the output voltage generated become more positive. This generated voltage can be determined by the expression given in equation (3). This output voltage is fed into the analogue input A1 of the microcontroller for further process into corresponding value of the intensity of light detected by the sensor and the conversion factor is given in equation (4).

$$V_{out} = I_{ph} \times R_f \qquad (3)$$

where V_{out} = Output voltage generated by the photodiode when illuminated
I_{ph} = Photocurrent generated by the photodiode when illuminated
R_f = Feedback resistance

$$\text{Photodiode reading} = \text{AnalogRead (A1)} \qquad (4)$$

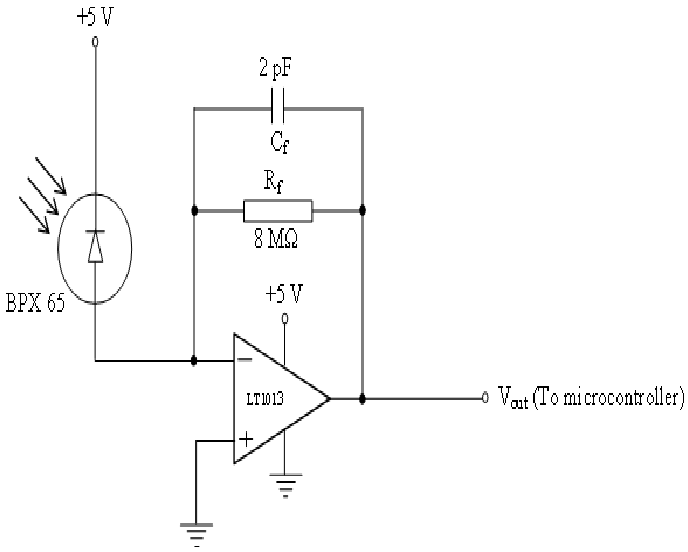

Figure 6: Photodiode Sensing Circuit

Phototransistor Circuit

The phototransistor sensor used in this section of the study is 3DU5C, an NPN phototransistor type. The phototransistor is connected in series with a load resistor R3, 200 kΩ as shown in Figure 7. The collector of the phototransistor is connected to the reference voltage supply, +5 V and the emitter is connected to the circuit ground via the load resistor, R3. With this circuit; when light strikes the phototransistor, current which is proportional to the intensity of light falling upon the sensor is set up at the base. This generated base current is internally amplified by the transistor's internal gain to give collector current. Thus, these currents combined together and flow into the emitter which in turns creates a voltage drop across the load resistor, R3. This voltage drop is the output voltage signal generated by the circuit and this is taken from the emitter connection of the phototransistor as depicted in Figure 7. This circuit configuration is a common collector or emitter follower amplifier arrangement which generates an output that moves from a low voltage state to a high voltage state when light is detected. The generated output voltage is fed into the analogue input A2 of the microcontroller for further process into corresponding light level detected by the sensor and the conversion factor is given in equation (5).

$$\text{Phototransistor reading} = \text{AnalogRead}(A2) \qquad (5)$$

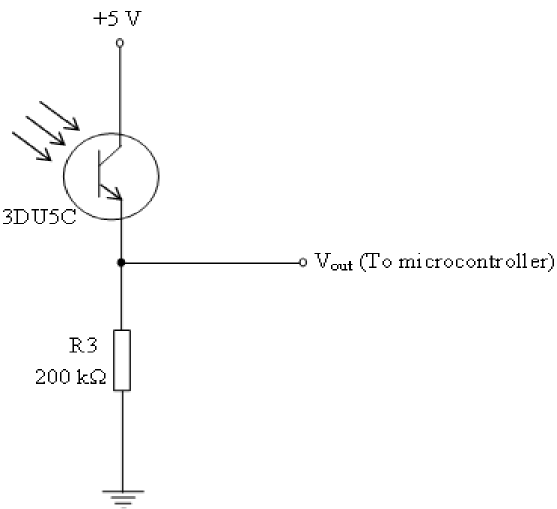

Figure 7: Phototransistor Sensing Circuit

(ii) Control Circuit

This section of the device is the unit which process the voltage signals generated by the photosensors into the corresponding incident light intensity values. This was accomplished using an Arduino Uno microcontroller board, a device that can be programmed for various purposes. The microcontroller is a small sized device on a single IC containing processor core, memory and programmable Input-Output peripheral. Figure 8 shows the picture of the microcontroller board. The board consists of Atmega 328P, a processor that is designed for the use of embedded applications, in contrast with microprocessor which are used for personal computers and other general purpose applications. Atmega328 is a low power; high performance CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. Atmega328 provides 32 KB of in-system self-programmable memory with read and write capability and 1KB EPROM [11].

Figure 8: Arduino Uno Microcontroller Board.

(iii) Display Unit

The display unit of the device is achieved using 16 characters x 2 lines Hitachi's HD44780 liquid crystal display (LCD) module. The display is a 16 pin which works with maximum power supply of 5 V and the data can be sent in either 4 bit, 2 operations or 8-bit, 1 operation so that it can be interfaced to an 8-bit Microcontroller [14]. Here, the LCD was configured using 4 bit, 2 operation system. The LCD is used to display the values of the light intensity level, voltage and current measured by the photoresistor, photodiode and phototransistor when been illuminated.

Figure 9: 16 x 2 Liquid crystal display (LCD).

(iv) Storage and Power unit

This unit of the device is achieved using microSD card shield module and TFT secure data (SD) card. The microSD card shield communicates with microcontroller through SPI communication protocol to automatically record the measurements taken by the photosensors over time for further analysis. The entire system was powered using a 12 V lithium battery via the input pin V_{in} on the microcontroller board, while the other units of the device such as the photoresistor, photodiode, phototransistor, microSD card and the LCD were powered with 5 V obtained from the voltage output pin on the microcontroller board. The schematic circuit diagram of the device is depicted in Figure 10, while the internal circuitry of the complete assembly of the device and the housing chamber of the sensors are shown in Figure 11.

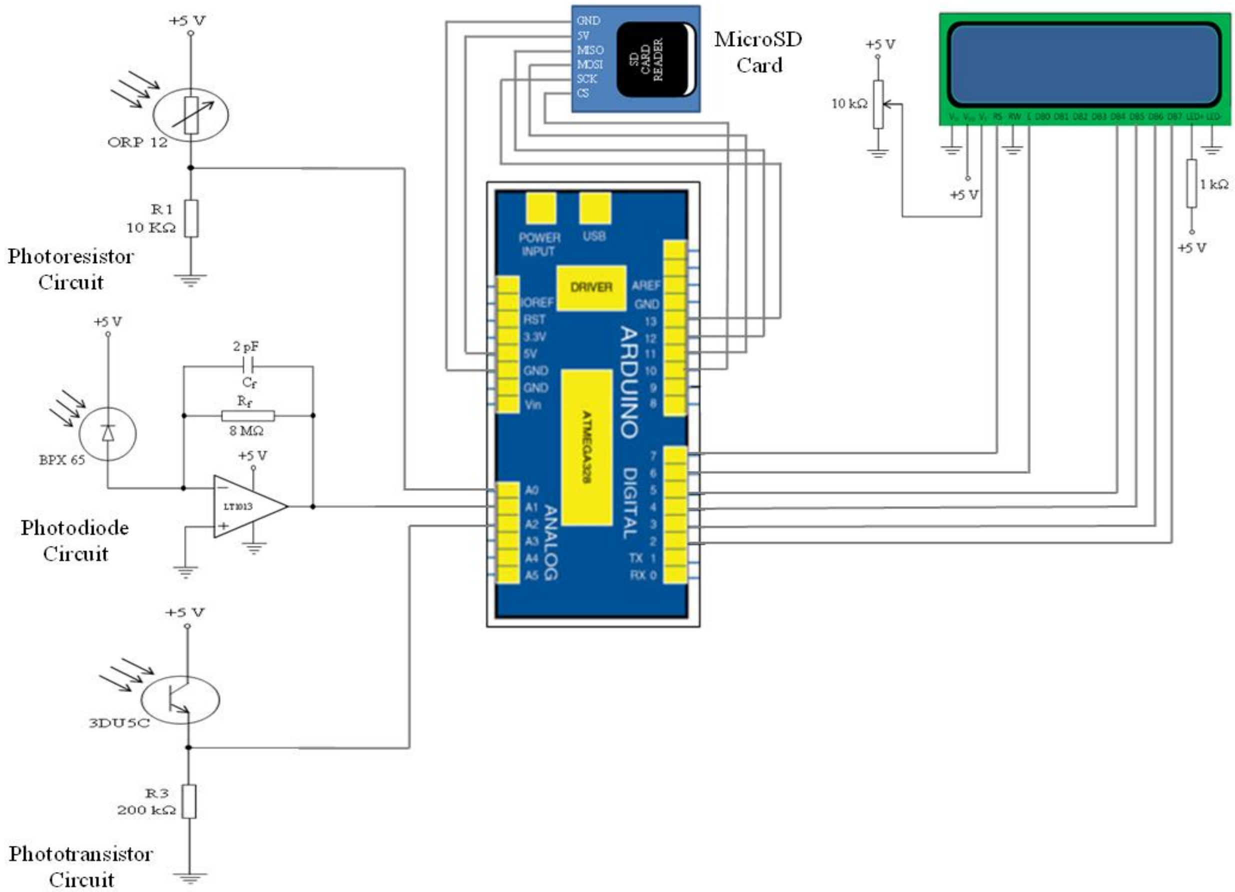

Figure 10: Schematic Circuit Diagram of the Developed Light Measuring Device.

(a) (b)

Figure 11: (a) The Internal Circuitry of the Developed Light Measuring device and (b) Sensors' Chamber.

III. Experimental Setup

The experimental setup of this study was carried out in an indoor environment under a dark condition at room temperature. This is done to shield against any light traces from other source. In the setup, the light source is provided by using a filament lamp with power rate of 150 Watt. The lamp is bright enough to give a wide spectrum of visible wavelengths, and the spectrum of the light has sufficient optical power at the wavelengths of interest. So, it can be used as a light source for many optical measurements. The lamp was set at a fixed distance from the sensors and it is used to illuminate the sensors at the same time. A light dimmer was employed to adjust the lighting level of the lamp and at every lighting level, the intensity of incident light captured by the individual sensor as well as the voltages and currents generated by the sensors are measured by the microcontroller and recorded automatically into the microSD card for further analysis. The results of the measurement are presented in Table 1. Consequently, these values are used to determine the sensitivity of the sensors. The typical experimental setup of the study is shown in Figure 12.

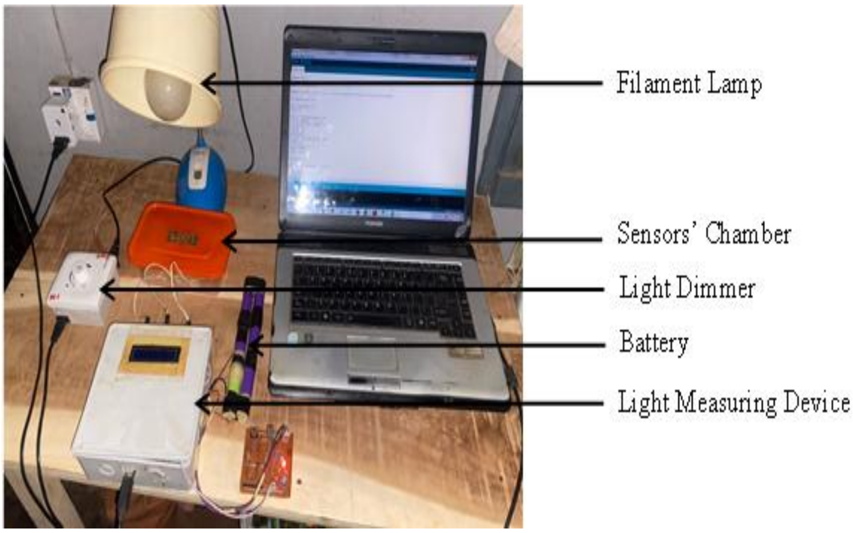

Figure 12: The Experimental Setup for measuring the Optical and Electrical Parameters of Photoresistor, Photodiode and Phototransistor

IV. Results and Discussions

The data in Table 1 clearly shows the results of optical and electrical parameters of the photoresistor, photodiode and phototransistor when illuminated by a light source. From the Table, the result shows good correlation and satisfactory correspondence among the sensors' readings on the values of light intensity measured. Hence, the sensors can be alternatively used in any application of light measurement and light detection. The graphs shown in Figures 13, 14 and 15 indicate the characteristic curves of sensors' current outputs to light intensity for the sensors. From the graphs, it was observed that with each of these devices, the current outputs increased as the light intensity increased but it was seen that photoresistor's current output is not linear with varying illumination; this indicates that photoresistors are non-linear devices. While photodiode's and phototransistor's current outputs show better linearity than that of photoresistor, but photodiode's current output has more linearity and uniformity in response to varying illumination than that of phototransistor. Hence, this shows that photodiodes are good photo devices that respond linearly to the light intensity falling upon their surfaces. Meanwhile, the sensors' sensitivity was taken from each sensor's current standard deviation value. The reason for using the standard deviation values directly is that absorption of photons in photoresistor did not cause flow of current as it is in photodiode and phototransistor, rather it results to variation of its resistance. Thus, if the design was calibrated with any value other than the standard deviation value; there is a chance of getting error. So, from these findings, it was seen that photoresistor, photodiode and phototransistor have standard deviation values of 114.10, 61.05 and 104.59 respectively. From this result, photodiode has the least deviation value and indicates that it is more sensitive to light illumination and has better performance than photoresistor and phototransistor.

Table 1: Results of Optical and Electrical Parameters of Photoresistor, Photodiode and Phototransistor in response to Light Illumination

Photoresistor (Light Dependent Resistor, LDR)			**Photodiode**			**Phototransistor**		
Intensity of Illumination (lux)	**Voltage Output (V)**	**Current Output (μA)**	**Intensity of Illumination (lux)**	**Voltage Output (V)**	**Current Output (μA)**	**Intensity of Illumination (lux)**	**Voltage Output (V)**	**Current Output (μA)**
0	0	0	0	0	0	0	0	0.51
4	0.02	2.38	6	0.04	3.11	8	0.05	3.91

9	0.04	6.87	8	0.07	4.21	10	0.11	8.88
24	0.25	14.55	26	0.21	13.2	29	0.19	18.1
43	0.37	24.85	41	0.33	22	45	0.22	27.8
55	0.41	36.14	52	0.63	26	56	0.48	39
58	0.48	41.08	57	0.68	29.2	60	0.57	43.2
73	0.56	52.82	73	0.76	38.8	75	0.63	56
108	0.77	65.66	105	0.97	52	107	0.71	77
125	1.03	80.49	123	1.05	60.1	126	0.86	89.2
138	1.49	93.2	135	1.11	67	131	1.07	94
158	1.55	113	155	1.24	76	159	1.39	117
174	1.82	129.1	172	1.38	84	178	1.7	134.4
210	2.08	155.4	202	1.47	99	205	2.12	161
226	2.24	172.2	228	1.63	111	224	2.15	182
237	2.61	187	236	1.71	116	238	2.26	198.5
251	2.89	211.8	244	1.82	119	248	2.31	217
268	3.07	241.6	262	1.96	128	267	2.53	229
270	3.15	248.5	277	2.08	139	273	2.71	238
285	3.21	263.3	282	2.17	143	290	3.28	247.6
310	3.32	288.2	304	2.25	157	308	3.51	265.7
315	3.56	301.25	317	2.37	165	320	3.58	278
341	3.65	318.44	333	2.46	173	337	3.63	295
346	3.71	328	351	2.57	184	348	3.74	305
370	3.88	345	362	2.69	197	364	3.82	311

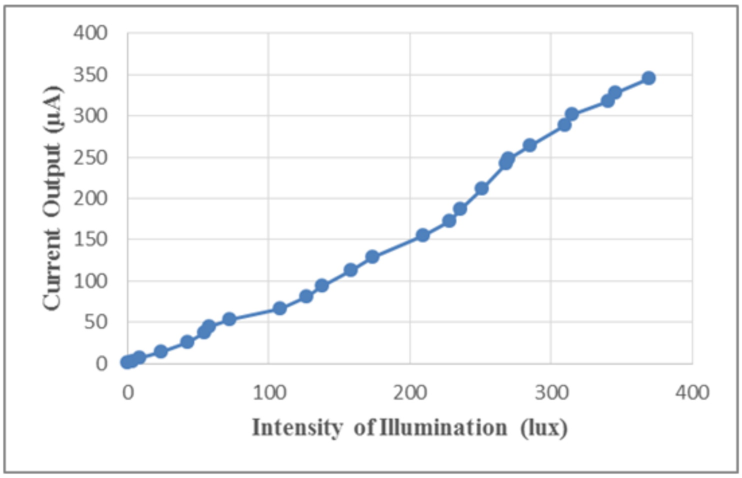

Figure 13: Characteristic Curve of Photoresistor's Current Output to Light Intensity

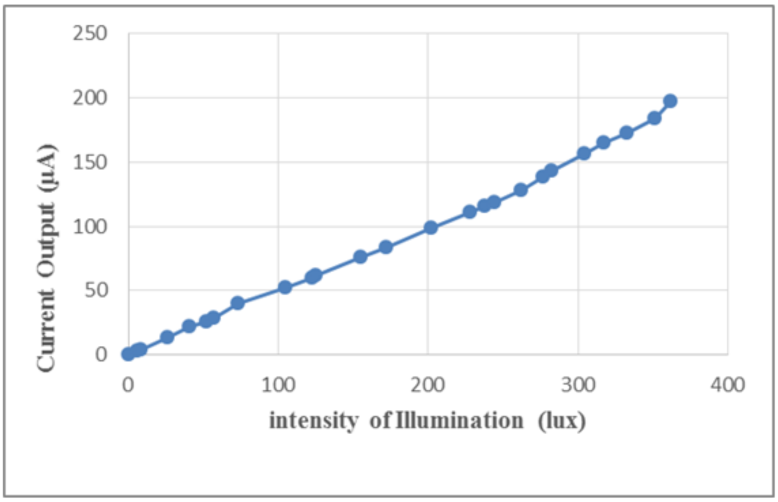

Figure 14: Characteristic Curve of Photodiode's Current Output to Light Intensity

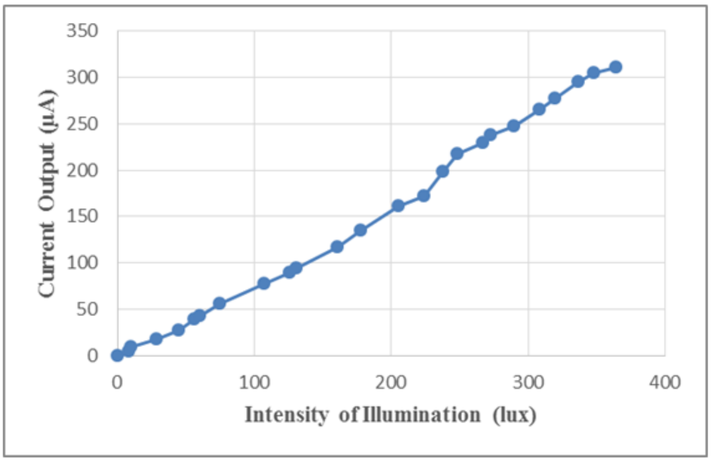

Figure 15: Characteristic Curve of Phototransistor's Current Output to Light Intensity.

V. Conclusion

In this work, a method has been presented to develop a microcontroller based light measuring device which can interface with multiple light sensors simultaneously to measure the intensity of incident light falling upon a surface as well as the voltage and current generated by such illumination.

From the results given in Table 1 by these three sensors, it is clear that the sensors are good to sense the beam pattern of lights. This conclusion is decided only because of strong correlation in between the values of light intensity measured by the sensors. Also, the results demonstrated in Figures 13 to 15 had proven that photodiode respond linearly to beam of light falling upon its surface than photoresistor and phototransistor. The device is relatively cheaper and it can be proposed as a better replacement for the high cost lux meter and quantum meter available in the market as the developed device was made and assembled from inexpensive materials that are locally sourced for. Therefore, the device can be used in the laboratory for demonstration and research purposes as well as in control industries. The device is cost-effective, portable and more feasible to use because of its simple design.

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