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Application of barium strontium titanate (BST) as a light sensor on led lights

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ABSTRACT
Barium Strontium Titanate (BST) film has been successfully produced as a light sensor. The BST film was made by CSD method by reacting barium acetate, strontium acetate and titanium isopropoxide with mole fractions of 0.5; 0.5 and 1, respectively.The BST absorbance test showed that BST film is sensitive to visible light ranging from 475 to 750 nm. The film test showed maximum absorbance at three peak wavelengths, 475 nm, 593 nm, and 702 nm. The energy gap of the BST film was 1.9 eV which showed that the film produced was a semiconductor. The IV test showed that BST film is a photodiode. This was indicated by the shift of the curve when tested in light and dark conditions. The sensitivity test showed BST film is most sensitive to blue light, signified by the most significant change in resistance. The decrease in resistance of blue LED was 0.401KΩ/lux, while the resistance decrease of green light was 0.051KΩ/lux and red was 0.288KΩ/lux. By using optical and electrical properties, BST thin film could be used as light sensors to detect LED lights.

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Barium strontium titanate; chemical solution deposition; bbsorbance; I-V; semiconductor

1. Introduction

The development of ferroelectric materials as sensors is growing. One of the promising materials is BST [1, 2]. Irzaman explained that BST could be used for light sensor applications which could then be developed into solar cells [3–5]. BST is a ferroelectric material sensitive to changes in light intensity [6–10]. BST films also have pyroelectric properties and can be applied as temperature sensors [11].

Ferroelectric materials are a group of materials that can be polarized internally at a certain temperature range where polarization occurs as a result of an external electrical field and symmetry in the crystallographic structure inside the unit cell [12]. If the ferroelectric material is subjected to an electric field, certain atoms are displaced and

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give rise to an electric dipole moment, resulting in polarization [13]. A dipole moment per unit of volume is called dielectric polarization. There are several methods that could be used in the manufacture of BST films such as pulsed laser deposition (PLD), sol-gel process, and chemical solution deposition (CSD) methods [14–18].

A reasonably popular light source used today is the LED light. LEDs have many applications, including for lighting, displays, and even for spectroscopy. LEDs have monochromatic wavelength characteristics, making them suitable for future optical spectroscopy applications. This study aims to evaluate the sensitivity of BST film to the wavelength of LED lights.

2. Methods

2.1. Synthesis of thin film BST

Thin film BST was synthesized using the CSD method based on Equation (1). BST film was prepared by mixing barium acetate [Ba (CH3COOH) 2, 99%], strontium acetate [Sr (CH3COOH) 2, 99%] and titanium isopropoxide [Ti (C12O4H28), 99%] obtained from Sigma Aldrich. The three ingredients were dissolved with 2.5ml 2-methoxyethanol to obtain a 1 M solution [2]. The solution was mixed using a Branson 2210 ultrasonic stirrer for 90 minutes.

The prepared BST solution was grown on the substrate by a spin coating method, in which the pre-washed p-type silicon substrate was placed on a spin coater plate. Then a third of the surface of the silicon substrate was covered using seal tape so that not the entire surface of the silicon substrate was covered by BST solution. The substrate that had been placed on top of the spin coater was dripped with BST solution using a micropipette with a single penetration of 20 μl then the spin coating reactor was rotated at 3000 rpm for 30 seconds. The process was performed 3 times with 60-second pauses between each repetition [1, 3].

The next process was annealing. This process aimed to diffuse the BST solution above the silicon substrate [19]. The annealing was performed using a VulcanTM-3-130 furnace and was conducted gradually. Heating started from room temperature then the temperature was raised to the desired annealing temperature of 850 °C with a temperature rise of 100 °C/hour. And then the annealing temperature was held constant for 29 hours. The next step was furnace cooling until the room temperature was recovered. The annealing process is shown in Fig. 1.

BST that had been annealed was installed with contacts. The installation of contacts on film was conducted in order to place cables on the film. Contacts were made using aluminum by the metal oxide chemical vapor deposition (MOCVD) method [13]. Two contacts sized 2x2 mm were made on the BST film and silicon substrate sides. The next process was attaching cabling to the contacts. The cabling used silver paste as an adhesive between the cable and aluminum contacts.

2.2. Characterization of BST film as a light sensor

The BST films that had been produced were characterized to evaluate their optical and electrical properties. The tests that were conducted included absorbance, IV, and sensitivity tests.

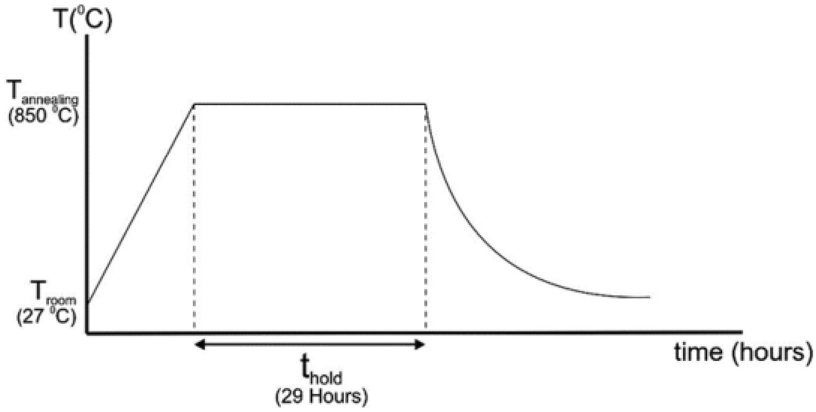

Figure 1. The annealing process.

2.2.1. Optical property test (absorbance)

The absorbance test was performed to evaluate the selectivity of the absorbed wavelength range and the gap energy of the BST. The absorbance test was performed using an Ocean Optics4000 spectrophotometer and the light source used was visible light with a testing range from 475 nm to 750 nm. The energy gap was obtained using the tauc plot method.

2.2.2. IV Test

The IV test was conducted to discover the film's current-voltage curve and its sensitivity to light. The IV test was performed with a Keithley2400 IV meter with a source voltage range of -10 V to 10 V.

2.2.3. Sensitivity test

The sensitivity test was conducted to evaluate the sensitivity of the film, which was the changes in BST film resistance when exposed to light intensity changes. The test was done with a voltage divider circuit by assembling a BST film series with a resistor. BST film was exposed to light originating from LEDs with intensities between 0 to 100 lux. The LEDs used were red, green and blue LEDs.

2.2.4. Characterization of the light source

The light source used in this study was LED lights. The test was performed using an Ocean Optics4000 spectrophotometer to determine the optimal wavelength emitted by the LED.

2.3. Electrical circuit design

The signals from the BST film were very weak. In order to render the input signals readable, they needed to be amplified using an *OpAmp* amplifier circuit. The BST film was coupled with a series of Wheatstone bridges (Fig. 2(a)) as input voltage

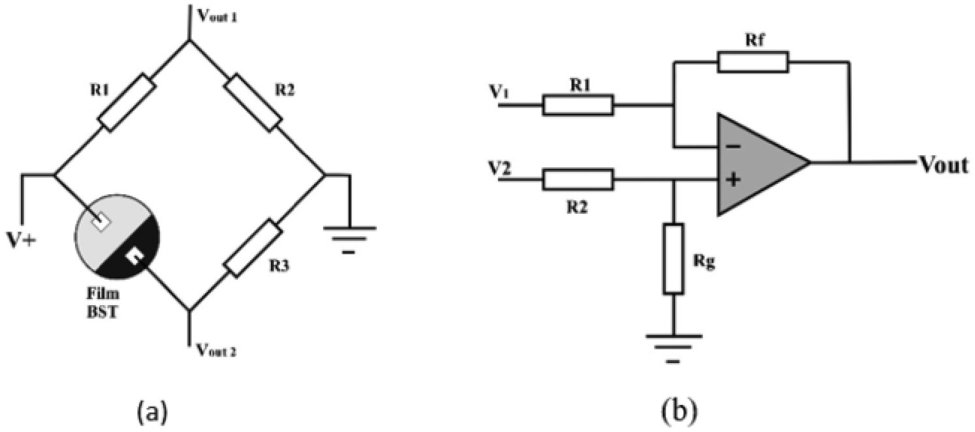

Figure 2. (a) Wheatstone bridge (b) Differential amplifier circuit.

Table 1. The molecular weight and mass of materials required to make 2.5 ml of 1M BST solution.

Material Name	Chemical Formula	Mole Fraction	Molecular Mass (gr/mol)	Dissolved Material Mass (gr)
Barium Acetate	$Ba(CH_3COO)_2$	0.5	255.4110	0.3193
Strontium Acetate	$Sr(CH_3COO)_2$	0.5	205.7080	0.2571
Titanium Isopropoide	$Ti(C_{12}H_{28}O_4)$	1	284.2153	0.7105

conditioning, and then it was amplified using a differential amplifier circuit (Fig. 2(b)) to amplify the input signal. The amplifier circuit used an OpAmp TL TL072CN IC.

The voltage source used was a 9 V voltage battery. The supply voltage for the microcontroller, LCD and other components of the appliance required a voltage of 5 V, requiring a power supply circuit. The power supply circuit used an LM7805 regulator IC as a voltage cutter so that the voltage became steady and constant.

3. Results and discussion

BST film has been successfully created as a light sensor. The BST film was made using a CSD method by reacting barium acetate, strontium acetate and titanium isopropoxide with mole fractions of 0.5; 0.5 and 1, respectively. The solution prepared was one molar with 2.5 ml of 2-methoxyethanol as the solvent. Using a stoichiometric calculation, the gained mass of each material was calculated. Table 1 shows the molecular weight and mass of materials required to prepare 2.5 ml of 1M BST solution.

The film that had been annealed then had cables mounted on the contacts. The function of the cables here was to facilitate the testing of the electrical properties and for blood glucose measuring instrument application. The cabling used silver paste as an adhesive between the cable and aluminum contact. The BST film model shown in Fig. 3(a,b) is the BST film that was created.

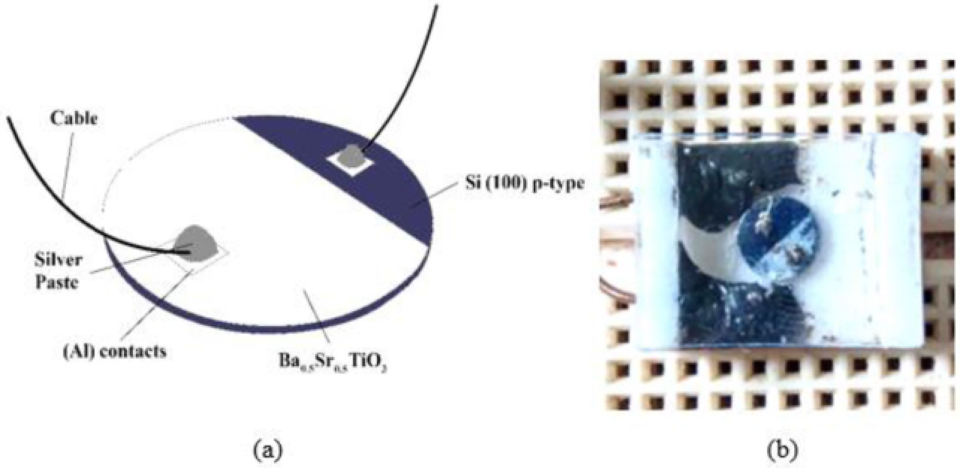

Figure 3. (a) BST film model (b) the BST film created.

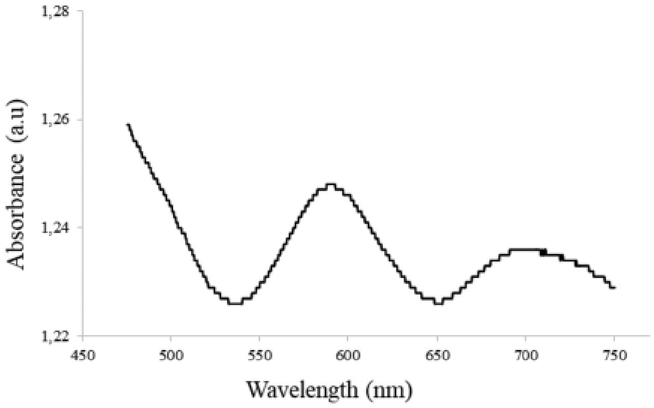

Figure 4. The BST film absorbance.

3.1. Characterization of the BST film and light sources

3.1.1. Optical property test (absorbance)

The BST film absorbance test (Fig. 4) showed that BST film is sensitive to visible light, ranging from 475 to 750 nm. The film test showed that the maximum film absorbance was at three peak wavelengths: 475 nm, 593 nm, and 702 nm.

The data obtained from these measurements were then processed to obtain the BST film energy gap. The energy gap is the amount of energy between the valence band and the conduction band. Absorption in the film occurs because of the excitation of electrons from the filled or valence state to an empty state (conduction). The absorbance coefficient value is a function of the wavelength and energy function of the photon written in the form of Equation (1):

$$\alpha h\nu = A(h\nu - E_G)^m \quad (1)$$

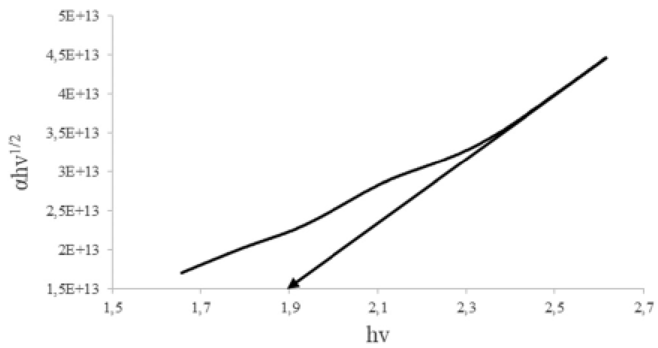

Figure 5. The BST film band gap energy.

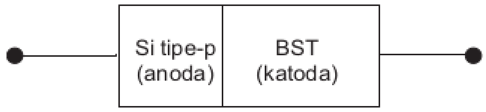

Figure 6. The p-n connection in photodiode.

Where A is a constant, hv is the energy of the photon, the value m can be ½ for the direct transition and 2 for the indirect transition and E_G is the optical band gap.

The energy gap is obtained by using the tauc plot method, which is plotting the relationship between $(\alpha hv)^{1/n}$ to hv. Extrapolation was conducted on the curve which had the highest gradient and intersected the *hv* axis; the value that intersected the *hv* axis is the gap energy (Irzaman *et al.*, 2013). Figure 5 shows the relationship of $(\alpha hv)^{0.5}$ as the *Hb* function [20]. The E_G value was obtained by extrapolation on the hv axis resulting in the BST film gap gain of 1.9 eV, which indicated that the film produced was a semiconductor.

3.1.2. I-V test

The IV test was performed to evaluate the current-voltage relationship in BST film. The BST film created was a link between two semiconductors, the p-type and n-type semiconductors. The silicon substrate used was a p-type semiconductor, while the BST solution grown on the substrate was an n-type semiconductor. This connection was made during crystal growth, during the annealing process to be exact. Schematically, the p-n diode connection is shown in Fig. 6. The p-type and n-type connections are known as a p-n junction.

Figure 7 is the result of the IV test. The test was done in the range of −10 V (reverse bias) to 10 V (forward bias). The IV curve pattern shows that the BST film produced was a diode because the curve closely resembled diode curve characteristics. This shows that the basic principle of the p-n connection in the sample worked. To evaluate the film's sensitivity to light, the film was tested in two conditions, dark (± 2 lux) and bright (± 452 lux) conditions. The test revealed that the BST film was sensitive to light, making the film a photodiode. This was indicated by a shift in the curve when tested in light and dark conditions. From the graph it can be seen that the flow in the dark conditions was less than that in bright conditions; this happened because the film resistance was greater in dark conditions, while in bright conditions it was smaller. This was because when the film received energy in the form of light, the electrons were released from the

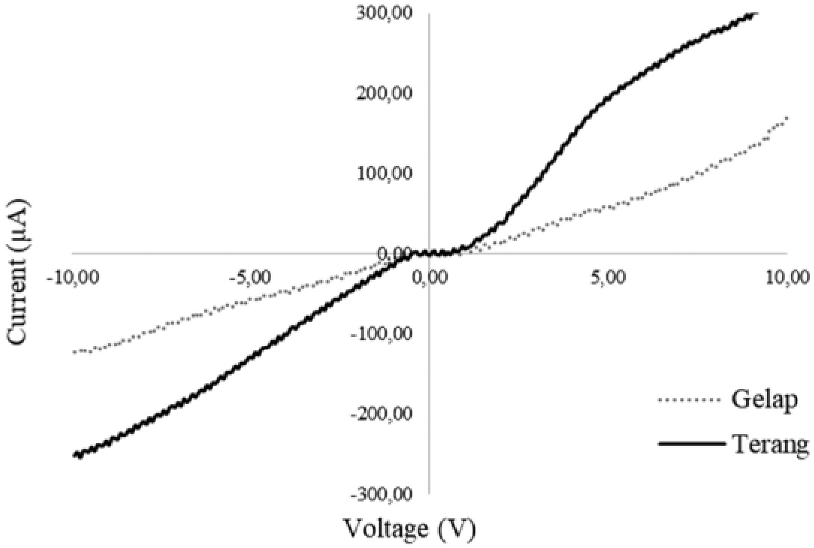

Figure 7. I-V of BST film in light and dark conditions.

valence band to the conduction band, thus increasing the charge carrier and increasing the electrical conductivity [11].

The result of the IV test showed that the breakdown voltage or the minimum voltage to flow the current from the BST film was -0.3 V, while the Knee Voltage or voltage at the moment the current started to rise when forward biased was found to be 0.6 V.

3.1.3. Sensitivity test

The film sensitivity test was performed to evaluate the change in film resistance when there was a change in light intensity. The testing was done by series assembling of the BST film with a resistor (voltage divider circuit) (Fig. 8). The amount of BST film resistance could be calculated using Equation (2) where the value of R used was 100 KΩ and the source voltage was 5 V. By measuring the V_{out} value, the BST film resistance could be obtained.

$$V_{out} = \frac{R}{R + R_{BST}} V_{supply} \tag{2}$$

During testing, the BST film was exposed to light coming from the LED. The LEDs used were red, green and blue with variations in intensity increasing from zero to 100 lux. The sensitivity test (Fig. 9) showed that the electrical resistance of the film decreased as the light intensity increased. From the graph it can be seen that the curve has a high linearity with a large correlation coefficient (R^2): 0.9129 for the red LED, 0.9862 for the green LED, and 0.9899 for the blue LED, demonstrating that the film possessed good characteristics to be used as a light sensor. From the graph, it can be seen that the BST film was most sensitive to blue light with the most significant change in resistance. The decrease in resistance of the blue LED was 0.401KΩ/lux, while the green light was 0.051KΩ/lux and the red light 0.288KΩ/lux.

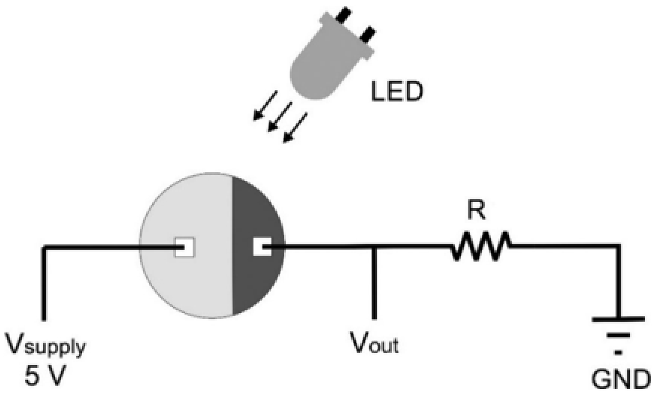

Figure 8. Voltage divider circuit.

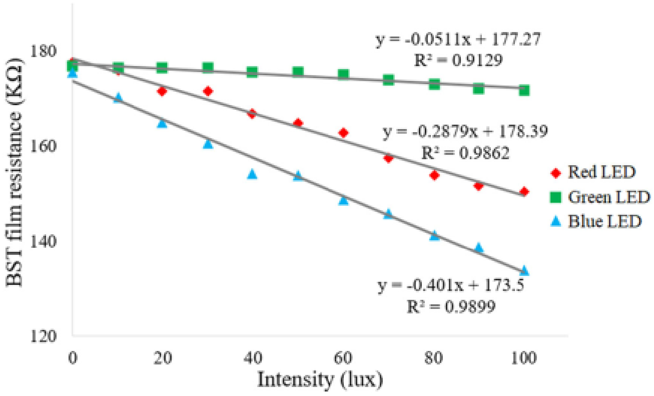

Figure 9. BST film sensitivity.

3.2. Electrical circuit

3.2.1. Signal amplifier circuit design

Signals from the BST film were very weak; therefore, they needed to be amplified with an OpAmp amplifier circuit. The BST film was coupled with a series of Wheatstone bridges for signal conditioning and then amplified using a differential amplifier circuit (Fig. 10). The differential amplifier circuit was a circuit comparing two inputs, V1 and V2. This amplifier circuit was built with an OpAmp TL072CN IC.

The gain in the differential amplifier circuit can be calculated using Equations 3 and 4 with the values of R4, R5, Rg and Rf of 100 KΩ, 100 KΩ, 1 MΩ and 1 MΩ, respectively. From the calculation, the theoretical gain in the opamp circuit was found to be 10 times. Figure 11 is the test result of the amplifier circuit. The amplifier circuit was tested by inputting a voltage and measuring the output voltage. Data showed that the output voltage approached the theoretical voltage value. Actual output voltages are always smaller than the source voltages. The amplifier circuit design used a source voltage of 5 V. The maximum output voltage was in the range of 3.42 V; this was due to the limited ability of the IC in amplifying.

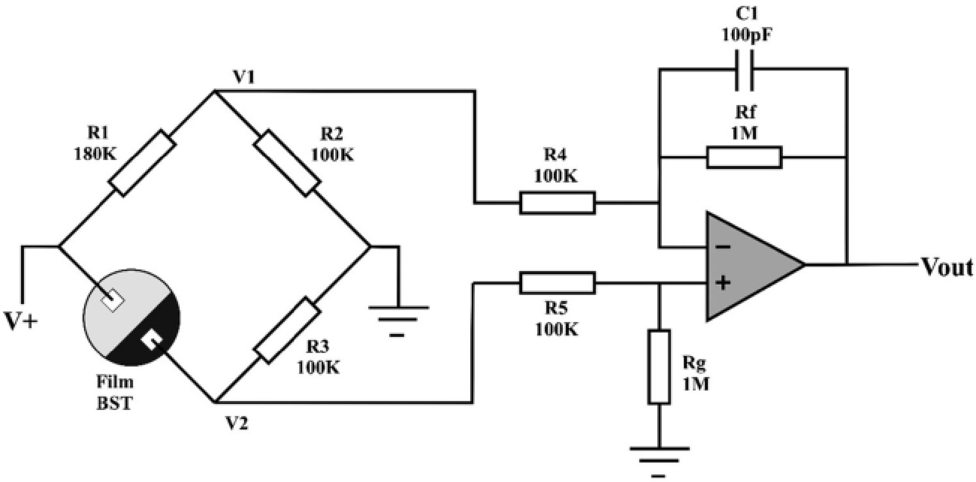

Figure 10. The BST film amplifier circuit.

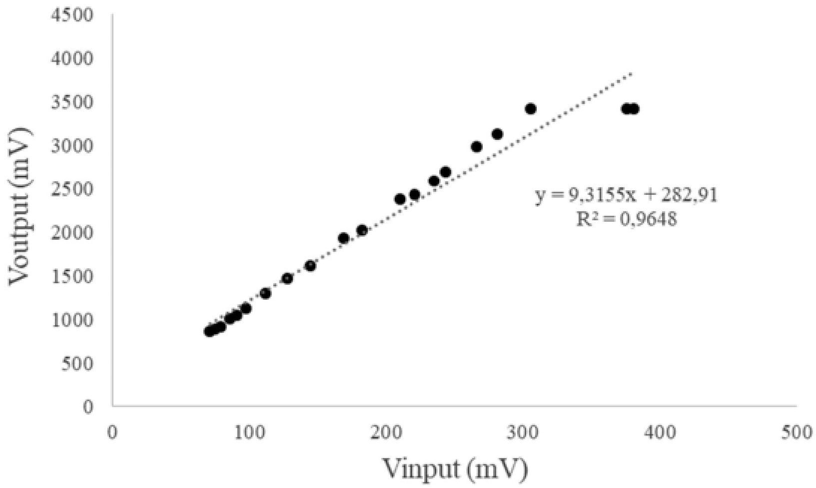

Figure 11. Results of the BST film amplifier circuit testing.

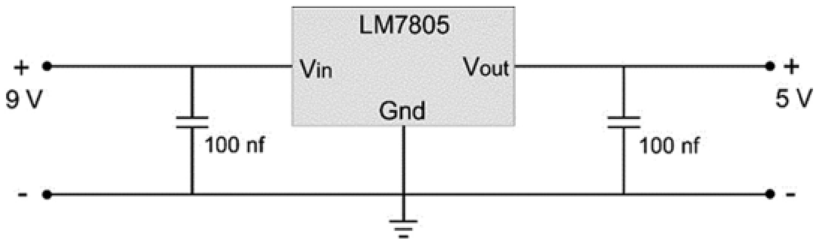

Figure 12. Power supply circuit.

$$V_{out} = -V_1\left(\frac{R_f}{R_4}\right) + V_2\left(\frac{R_g}{R_5 + R_g}\right)\left(\frac{R_f + R_4}{R_4}\right) \quad (3)$$

Table 2. Power supply circuit test results.

Input Voltage (V)	Output Voltage (V)
0.78	0
1.31	0
2.69	0
4.50	1.52
5.36	4.39
5.76	4.71
6.86	4.96
7.97	4.97
9.24	5.00
12.53	5.00

If R4 = R5 and Rf = Rg, Equation 4 can be simplified into:

$$V_{out} = \frac{R_f}{R_4}(V_2 - V_1) \quad (4)$$

The value of the gain of the opamp (gain):

$$\begin{aligned} Gain &= \frac{V_{out}}{V_{in}} \\ &= \frac{V_{out}}{V_2 - V_1} \\ &= \frac{R_f}{R_4} \\ &= \frac{1\ M}{100\ K} \\ &= 10\ times \end{aligned}$$

3.2.2. Construction of the power supply circuit

The power supply circuit served to supply voltage to the microcontroller, LCD, amplifier circuit and BST light sensor. The circuit was built with an LM7805 regulator IC and two capacitors. Figure 12 shows the power supply circuit that was constructed. The LM7805 IC served to cut and stabilize the input voltage to a constant voltage of 5 V while the capacitor served to stabilize the input voltage and output. Table 2 is the result of the power supply circuit testing. Testing was done by providing input voltage from 0 to 12.53 V and measuring the output voltage. Input voltages above 6.86 V had a constant output voltage of 5 V while those below were no longer constant. This was because the LM7805 IC has a minimum input voltage, which in this case the minimum IC voltage was 6.86 V. The voltage source in the equipment designed was a 9 V battery.

4. Conclusion

By utilizing optical and electrical properties, BST thin films can be used as light sensors to detect LED lights. BST films are most sensitive to blue light with the most significant change in resistance. The decrease in resistance of blue LED was 0.401KΩ/lux while the resistance decrease in green light was 0.051KΩ/lux and red 0.288KΩ/lux.

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