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FORMATION of SOLAR CELLS BASED ON $Ba_{0.5}Sr_{0.5}TiO_3$ (BST) FERROELECTRIC THICK FILM

Irzaman[1], H. Syafutra[1], A. Arif[1], H. Alatas[1], M.N. Hilaluddin[2], A. Kurniawan[2], J. Iskandar[2], M. Dahrul[2], A. Ismangil[2], D. Yosman[2], Aminullah[2], L.B. Prasetyo[3], A. Yusuf[4], T.M. Kadri[4]

[1]Department of Physics, FMIPA Bogor Agricultural Unversity,
Campus Darmaga Gedung Wing S Bogor, Indonesia – 16680,
[2]Graduate student of Biophysics, FMIPA Bogor Agricultural Unversity
[3]Department of Forest Resources Conservation, FAHUTAN, Bogor Agricultural Unversity, Campus Darmaga Bogor, Indonesia – 16680
[4]LAPAN Rancabungur Ciampea Bogor, Indonesia
Email : irzaman@yahoo.com

Abstract. Growth of $Ba_{0.5}Sr_{0.5}TiO_3$ (BST) 1 M thick films are conducted with variation of annealing hold time of 8 hours, 15 hours, 22 hours, and 29 hours at a constant temperature of 850 ^{0}C on p-type Si (100) substrate using sol-gel method then followed by spin coating process at 3000 rpm for 30 seconds. The BST thick film electrical conductivity is obtained to be 10^{-5} to10^{-4} S/cm indicate that the BST thick film is classified as semiconductor material. The semiconductor energy band gap value of BST thick film based on annealing hold time of 8 hours, 15 hours, 22 hours, and 29 hours are 2.58 eV, 3.15 eV, 3.2 eV and 2.62 eV, respectively. The I-V photovoltaic characterization shows that the BST thick film is potentially solar cell device, and in accordance to annealing hold time of 8 hours, 15 hours, 22 hours and 29 hours have respective solar cell energy conversion efficiencies of 0.343%, 0.399%, 0.469% and 0.374%, respectively. Optical spectroscopy shows that BST thick film solar cells with annealing hold time of 8 hours, 15 hours, and 22 hours absorb effectively light energy at wavelength of ≥ 700 nm. BST film samples with annealing hold time of 29 hours absorb effectively light energy at wavelength of ≤ 700 nm. The BST thick film refraction index is between 1.1 to 1.8 at light wavelength between ±370 to 870 nm.

Keywords: Ferroelectric material, BST, solar cells, band gap energy, solar cell efficiency
PACS: 74.62.Bf; 77.70.+a.; 77.84.Dy.

INTRODUCTION

Solar energy which is received by the earth's surface reaches 3 x 10^{24} joule per year, with the amount of 10.000 times the energy consumption throughout the world today [1]. In other words, by covering 0.1% of the earth's surface with solar cells which have 10% efficiency, it is sufficient to cover the energy needs throughout the world. Rapid development of the solar cell industry in 2004 has touched the level of 1000 MW capacity made many people more interested at this promising energy source for the future [1]. Solar cells based on amorphous silicon material from previous research have efficiency of 10.38% [2]. Solar cells module itself consists of a transparent protective glass that protects the solar cells material from the outside, and active material converting solar energy into electrical energy which is unreflective to absorb more light and reduce the reflected light, also p-type and n-type semiconductor junctions to produce electrical field [3].

Solar cells manufacturing based on amorphous silicon needs advanced technology with fairly high success rate. This solar cells manufacturing using nanoscience technology principles, which has been predicted that it will be developed in 21st century as shown at Fig. 1 [4,5]. Current available technology in Indonesian has not yet made it possible to produce solar cell devices based on amorphous silicon, so it is necessary to find alternative means of solar cells construction in crystalline form using other materials such as barium strontium titanate ($Ba_xSr_{1-x}TiO_3$) or BST[6]. The BST ferroelectric materials have the possibility to be used as solar cell material, because in general it has an energy band gap of ± 3 eV and a

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conductivity of 10^{-5} S/cm, which make BST categorized as semiconductor material [7].

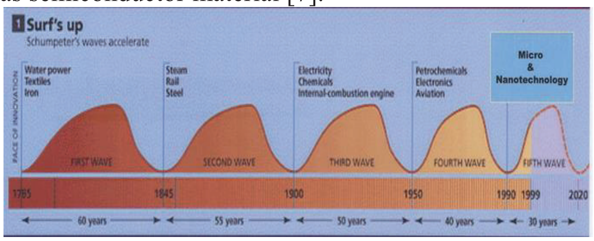


FIGURE 1. Industry development pattern in 21st century

In this study, BST film is manufactured by sol-gel method and then followed by spin coating process. Spin coating process is a micro-technology, however the output from this process is equal or similiar to output of nano technology devices. Annealing hold time is conducted with variation of 8 hours, 15 hours, 22 hours, and 29 hours at constant temperature of 850 ^{0}C. After the BST film formation is completed, it would be followed by optical characteristic testing, electrical conductivity measurement and current-voltage photovoltaic testing of the BST film.

Theoretical Background

Ferroelectricity is a property of certain materials that possess spontaneous electric polarization (density of electric dipole moment) in the material that could be reversed by the application of an external electric field [8]. Normally, materials have two properties that are ferroelectric when under a certain phase transition temperature, called the Curie temperature and paraelectric when above this temperature. The dipole moment in this case is defined as a distance that separates the concentration of positive and negative charges in a system, i.e. a measurement of the charge system overall polarity. Several important ferroelectric materials are among others $PbTiO_3$, $Pb(Zr_xTi_{x-1})O_3$, $SrBiTaO_3$, $Pb(Mg_{1/3}Nb_{2/3})O_3$ and $Ba_xSr_{1-x}TiO_3$ [9]. At this moment, ferroelectric BST film is a very attractive technology to be developed, for example in the application of light sensors which could be produced into solar cells [10,11].

Ferroelectric BST is used in this study. Based on ICDD (International Center for Diffraction Data), the lattice constant of BST is about 3,947 Å. Barium titanate (BT) is well known to have ferroelectric properties. The Curie temperature (temperature to change from ferroelectric to paraelectric phase) of pure BT is about 130 ^{0}C. The addition of strontium to the BT to form BST will have Curie temperature of BST decreased to room temperature (25 ^{0}C) which is useful for sensors and solar cells [11,12].

Increasing in the annealing temperature leads to the grain size increasing in BST film crystal. The observed BST at annealing temperature of 700 ^{0}C has a cubic structure with lattice constant a = 3.97 Å for 30% mol of strontium [13]. Annealing temperature greatly influence the resulting film, for example atomic structure and electrical properties of the constituent film. Annealing temperature could increase hardness and tensile strength as well as decrease stress and elasticity [14,15]. Temperature variation serves to establish the orientation of BST film crystal structure that coincide with the orientation of the crystal substrate. Grain size appears more irregular at higher temperature [16]. During annealing, a rearrangement of dislocations will occur that reduce the lattice energy, while the grain boundaries do not sustain a migration. Grain growth that occurs during the primary crystallization will be stopped (growing crystals have "swallowed" all the materials that stretch). During annealing process the small grains shrink and the big ones grow larger [14].

The photovoltaic effect which is the conversion of light energy into electrical energy occur directly in the solar cell device that consist of basic components of a semiconductor material [17,18,19]. Open circuit potential (V_{oc}) is the achieved maximum potential with the presence of maximum resistance. Short circuit current (I_{sc}) is the achieved maximum current when the solar cells is short connected and there are no resistances that cross the solar cell films.

Maximum power (P_{max}) is defined as the effective area of the curve which is obtained from the relationship between the voltage and current of the solar cells. V_{max} and I_{max} that could be derived as shown in Fig. 2. The maximum power (P_{max}) is defined as the multiplication of maximum voltage (V_{max}) and maximum current (I_{max}), as shown in Equation (1) [19].

$$P_{max} = V_{max} I_{max} \tag{1}$$

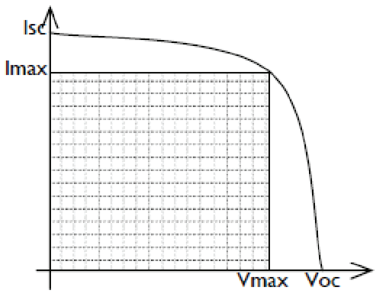


FIGURE 2. Determination of maximum current (I_{max}), maximum voltage (V_{max}) and maximum power (P_{max}) of solar cells [20].

The fill factor *(FF)* is the ratio between maximum power (P_{max}) which is derived by multiplication of V_{oc} and I_{sc}. The fill factor value is shown in Equation (2) [19].

$$FF = \frac{V_{max} I_{max}}{V_{oc} I_{sc}} \tag{2}$$

Solar cell efficiency is the ability of solar cell device to convert light energy into electrical energy in the form of electrical current and voltage. This energy conversion efficiency depends on the photon absorption properties of semiconductor materials in the solar cells[20]. Solar cell efficiency value is the ratio between generated photovoltaic electrical output and incoming light energy. Energy conversion efficiency of a solar cell is written in Equation (3):

$$\eta = \frac{\mathrm{P_{max}}}{\mathrm{P_{in}}} \text{ x } 100\% \tag{3}$$

The known optical properties of semiconductor materials could be used to determine the magnitude of the energy bandwith or energy band gap (E_g). The photon absorption process occurs when photons with greater energy than the semiconductor energy band gap are absorbed by the semiconductor material. This process usually result in emergence of electron and hole pairs, as mobile charge carriers that give electric current[21]. Optical properties could also be known from the reflectance spectrum. The film reflectance are obtained from the relationship between reflectance value (%) and light wavelength spectrum (λ) [22]. In semiconductors, the light or photon absorption coefficient (α) is a function of the light wavelength or photon energy, shown in Equation (4):

$$\alpha = \frac{4\pi\kappa_e}{\lambda} = (hv - E_g)^n \tag{4}$$

where hv is photon energy and n is constant and $\boldsymbol{\kappa}_e$ is extinction coefficient which depends on the density of the medium.

BST film energy band gap could be calculated using the *Tauc* method [23,24], i.e. the relationship between semiconductor photon absorption coefficient and photon energy incident on the semiconductor film. Assuming that n=1/2 the pulsed laser deposition (PLD) method could be used to calculate the energy band gap of $Ba_{0,5}Sr_{0,5}TiO_3$ that is grown on $LaAlO_3$ substrates. With value of n=1/2 for direct transition type [25]. Several studies that have been carried out previously indicate that the absorption coefficient is equal to $\ln[(R_{max}–R_{min})/(R–R_{min})]$ as shown in equation (5):

$$2\alpha t = \ln[(R_{\max} - R_{\min})/(R - R_{\min}) \tag{5}$$

where t is thickness of the film, while $R_{\max}$ and $R_{\min}$ are the maximum and minimum values of film reflectance, respectively and R is reflectance value that correspond to the photon energy. By plotting the $(\alpha hv)^2$ value on the y-axis and *(hv)* value on the x-axis a straight line would be obtained at a certain energy band gap range. By extrapolating this straight line when the value of $[\ln\{(R_{\max} - R_{\min})/(R - R_{\min})\}]^2 = 0$ the energy band gap range of BST film could be obtained [23,24].

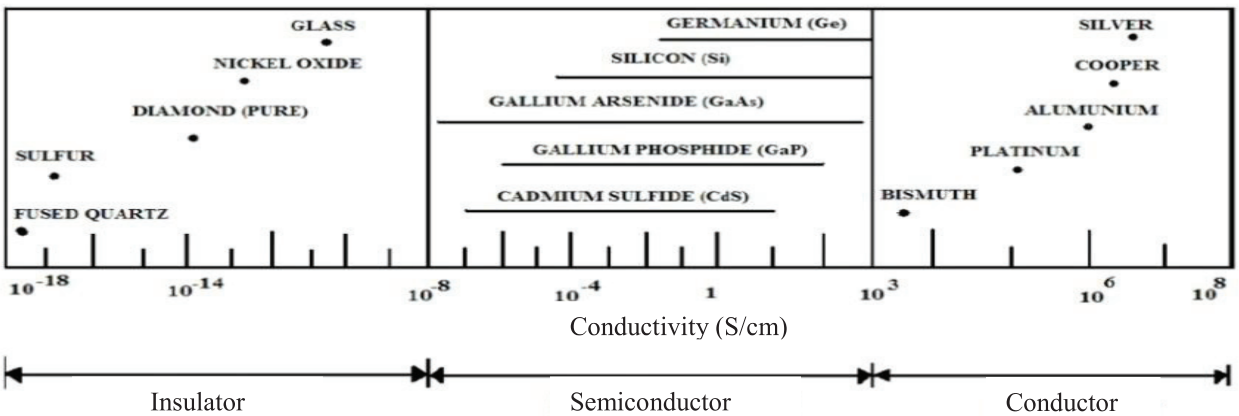


FIGURE 3. Material based on electrical conductivity [27, 29].

The relationship between reflectance and refraction index of materials is shown in Equation (6) [25,26]:

$$R = \frac{(n-1)^2}{(n+1)^2} \qquad (6)$$

Figure 3 shows electrical conductivity values of semiconductor material in the range of 10^8 to 10^3 S/cm [27, 29]. Photoconductivity is an electrical conductivity resulting from excited electrons because of energy absorbed by the electrons from photons that are incident on the electrons at the semiconductor valence band. When photons with energy greater than the semiconductor energy band gap fall on a the semiconductor surface the energy of these photons would excite electrons to transfer from the valence band to the conduction band of the semiconductor material. The electrons that are excited into the conduction band will increase the mobile charge carrier population which in turn will increase the electrical conductivity of the semiconductor material [28]. Conductivity of materials could be calculated using the Equation (7):

$$\sigma = \frac{G\ .\ l}{A} \qquad (7)$$

where *σ, l, G* and *A* are respectively the electrical conductivity of the material, the length of material, conductance, and sectional area [29].

RESEARCH METHODOLOGY

BST film is grown on p-type Si (100) substrate surface with area size ±(1x0,9) cm^2 using sol-gel process. The BST solution is prepared by reacting 0,3193 grams barium acetate [$Ba(CH_3COO)_2$, 99%], 0,2572 grams strontium acetate [$Sr(CH_3COO)_2$, 99%], 0,7107 grams titanium isopropoxyde [$Ti(C_{12}O_4H_{28})$, 97,999%], and 2,5 ml 2-methoxyethanol as solvent. After the materials are mixed, the solution is shaken for ±1 hour using ultrasonic wave from Bransonic 2510 instrument with ±22 kHz frequency.

The p-type Si(100) substrate that is grown over by the BST film layer would undergo an annealing process at 850 ^{0}C with an annealing time variation of 8 hours, 15 hours, 22 hours, and 29 hours. This annealing process would be conducted with temperature increment of 1,67 ^{0}C/minute from room temperature to 850^{0}C. After the annealing process is completed, the next step is installation of aluminium 99,999% contact. This process is done by evaporation of aluminum on the p-type Si (100) substrate and BST film ($Al/Ba_{0,5}Sr_{0,5}TiO_3$/p-Si). Figure 4 shows the cross section of contact and wiring on the BST Solar Cell. After the contacts have formed, the next process is installation of the connector and fine sized copper wires on the contacts using silver paste, as shown on Fig. 5. The installation of contacts and wiring are to enable the measurement of the BST thick film characteristics by interconnecting it to related circuits and instruments to implement the process.

BST Solar Cell Characterization

Characterization of BST solar cell optical properties is done using Ocean Optic instrument to measure the relation between reflectance value (%) and wavelength spectrum (λ). From the reflectance data the energy band gap value can be calculated using Tauc method, and also the calculation of BST refraction index [23,24]. Measurement of BST solar cell using LCR meter yield the conductance value (G). The BST solar cell conductance measurements are done with different light intensity conditions, i.e. in dark condition (0 lux) and bright conditions with variable light intensities of 1000 lux, 2000 lux, 3000 lux, also 4000 lux. The conductance value (G) is used for calculating the electrical conductivity (σ) using equation (7). The circuit for current-voltage measurement is showed in Fig. 6. A light source with intensity of 55.600 lux is placed at a certain distance from the BST solar cell prototype so that the light hits the entire surface of the solar cell. Initially the potentiometer of the circuit is positioned at minimum resistance value, then gradually increased to maximum value. The readout value of each measuring gauge on the circuit is recorded at every change of resistance applied.

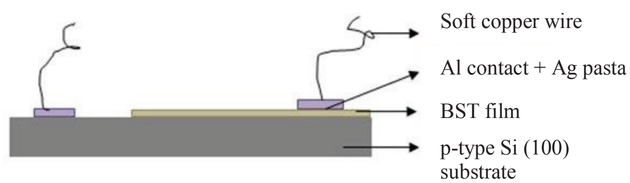


FIGURE 4. BST solar cell contact set up side view.

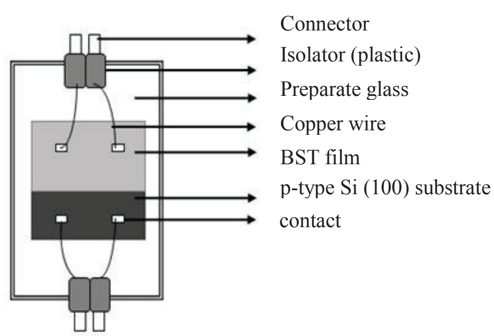


FIGURE 5. Solar cell circuit connection set up (seen from above)

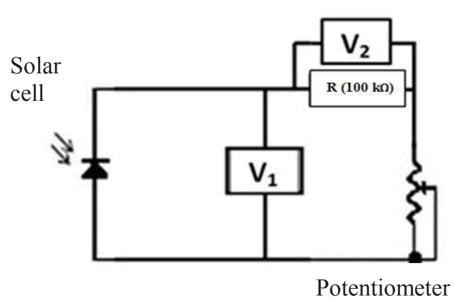


FIGURE 6. Solar cell current-voltage (I-V) measurement circuit.

RESULT AND EVALUATION

Optical Properties of BST Solar Cell

The optical properties are measured in the light wavelength region of 350 to 900 nm, The principal optical properties measured are the reflectance spectrum. It is used for determining the light absorption range of BST solar cells (minimum reflectance indicates maximum absorption). The reflectance spectrum could also be used to calculate the refraction index and the band gap range of the BST solar cells.

Characterization of Absorption Spectrum

Figure 7 shows the light reflectance value of BST solar cells related to the wavelength spectrum, that indicate the annealing process affect the BST solar cells light absorption properties. BST solar cells with annealing hold time of 8 hours is more effective to absorb light in the wavelength range $\lambda \geq 650$ nm (near infrared). BST samples with annealing hold time of 15 hours have highest light absorption at $\lambda \leq 450$ nm (near UV), and $\lambda \geq 700$ nm (near infrared). BST samples with annealing hold time of 22 hours have highest light absorption at $\lambda \geq 750$ nm (near infrared). While BST samples with annealing hold time of 29 hours have highest light absorption at $\lambda \leq 450$ nm (near UV).

The annealing process at constant temperature of 850 ^{o}C with different annealing hold time variations affect the property of light absorption of BST solar cells. It is possible that the light absorption spectrum disparity is due to the growth of crystal grain that are effecting film densification resulting in film thickness shrinking [14,30]. The annealing process affect the grain size of films, making it dense, orderly and homogen [16]. The homogenity and density of crystal grains in BST film is improved with adequate annealing hold time, and thus making its properties more consistent.

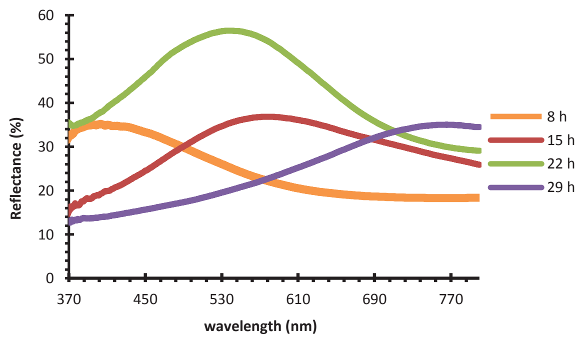


FIGURE 7. Reflectance spectrum of BST solar cells.

Refraction Index

The BST film reflectance spectrum could be transformed into refraction index spectrum using Equation (6). Figure 8 shows the refraction index spectrum in the measured light wavelengths of BST films with different annealing hold times. The refraction index is proportional to the reflectance.

Refraction index properties are based on annealing hold times. For BST film with annealing hold time of 8 hours the lowest refraction index is 1.2 for the lowest reflectance value and the highest refraction index is about 1.4 for the highest reflectance value. For BST film with annealing hold time of 15 hours the refraction index is between 1,15 to 1,42. For BST film with annealing hold time of 22 hours the refraction index is between 1,35 to 1,79. For BST film with annealing hold time of 29 hours the refraction index is between 1,1 to 1,4. These refraction index values agree with earlier research results that show the value of refraction index for $Ba_xSr_{1-x}TiO_3$ of about 1,4 to 1,9 [25,26,31].

Calculation of Energy Band Gap

The reflectance values of BST film could be used to calculate the semiconductor energy band gap, given that within the measured light wavelength range of lowest reflection value (or highest absorption) the photon energy absorption by electrons is at highest to cross the energy band gap [23,24]. From the reflectance spectrum in Fig. 7 the value of energy band gaps are obtained with the variation of annealing hold time of each BST solar cell samples using Tauc method [23,24].

From the graph in Fig. 9 it could be seen that the energy band gap values for BST solar cells annealing hold time of 8 hours, 15 hours, 22 hours and 29 hours are 2.6 eV, 3.15 eV, 3.22 eV and 2.62 eV, respectively.

These values are in accordance to high photon energy in the short wavelength (about 2 to 3 eV). This result is not too different from earlier study of $Ba_{0,5}Sr_{0,5}TiO_3$ energy band gap impurified by Ti, Mg, and Al that show the band gap have a value of about 3 eV [31].

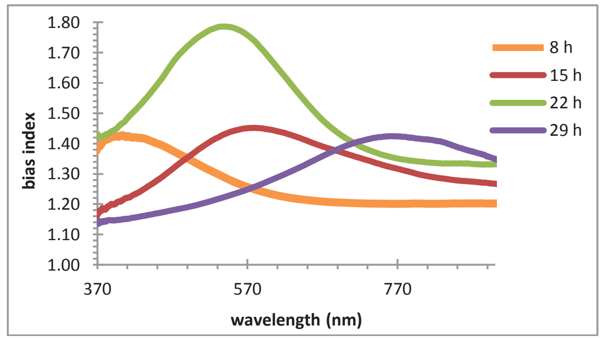


FIGURE 8. Relation of BST solar cells refraction index versus light wavelength (nm)

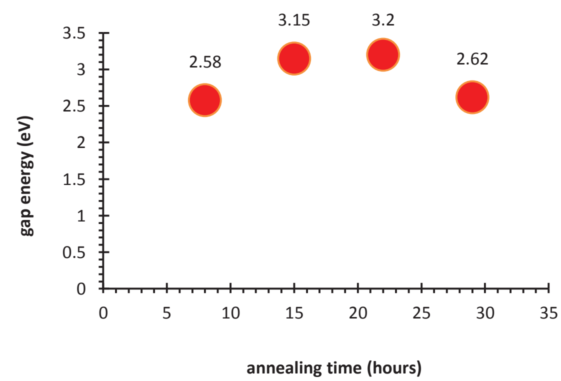


FIGURE 9. BST solar cells band gap with variation of annealing hold time

Shown in Fig. 9 for BST film sample with annealing hold time of 8 hours the energy band gap between the valence band and the conduction band is narrower than BST film sample with annealing hold time of 15 hours, 22 hours, and 29 hours. In comparison to annealing hold time of 15 hours, the annealing hold time of 22 hours have extended the energy band gap. The discrepancy of energy band gap widths are probably due to the annealing process that make the crystal expand. The annealing hold time of 8 hours, 15 hours and 22 hours are still within the crystal formation stage, and the crystal structure have not yet reached perfected stage [32]. On BST sample with annealing hold time of 29 hours, the energy band gap width narrows indicating the possibility of crystal formation almost reaching its perfect stage due to more adequate growth of crystal grains [14].

Electrical Conductivity of BST Solar Cells

The measurement of conductance (G) is done in dark conditions (0 lux), and bright conditions with variations in light intensity of 1000 lux, 2000 lux, 3000 lux and 4000 lux. The electrical conductivity of each BST solar cell film sample with annealing hold time variation is calculated using Equation (7).

Figure 10 shows the conductivity value of each BST film with different annealing hold times versus incident light intensity on the film surface.The conductivity increase with more light intensity on the BST film surface. The greater light intensity incident on the BST film surface will provide greater photon energy absorption to excite more electrons from the valence band to the conduction band in semiconductor material.

The measured results show that the BST films have an electrical conductivity value of 10^{-5} to 10^{-4} S/cm, and that it could be classified as ~~a~~ semiconductor material. The electrical conductivity properties to define BST film as semiconductor material refer to previous studies [7,9,10,13]. With annealing hold time of 8 hours, 15 hours and 22 hours for BST film the measured electric conductivity quantity is found to be in opposite relation to the energy band gap quantity. The wider energy band gap result in lower conductivity of BST film semiconductor samples. The wider energy band gap may be as result of annealing hold time to be shorter than the required crystal formation time, and the crystal growth have not yet reached perfected crystal structure stage. For BST film samples with annealing hold time of 29 hours the possibility of crystal grain growth is closer to perfected crystal structure formation, and the energy band gap is narrower resulting in more semiconductor material conductivity than the samples with annealing hold time of 15 hours and 22 hours [14-16].

I-V Characteristics of BST Solar Cells

Current-voltage characterization are carried out on BST solar cell films with variable annealing hold time using the circuit in Fig. 6. The light source used provide an intensity upon the BST solar cell film surface at 8.34 mW/cm^2. The sectional area of the photovoltaic cells irradiated is ±(0.75 x 0.9) cm^2. The current-voltage characterization results of the BST solar cell films are in agreement with the characterization results of general solar cells as a whole. Figure 11 shows the maximum power of BST solar cell films based on differences in annealing hold time and Fig. 12 shows four parameters i.e V_{oc}, I_{sc}, fill factor, and eficiency based on differences in annealing hold time.

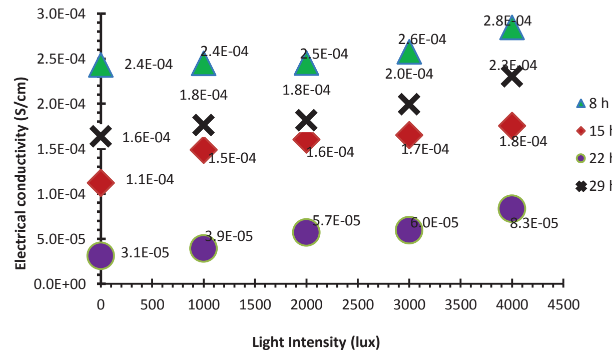
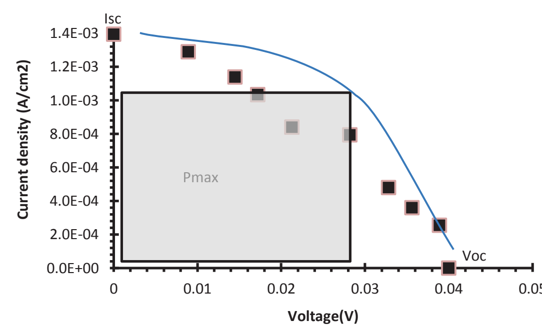
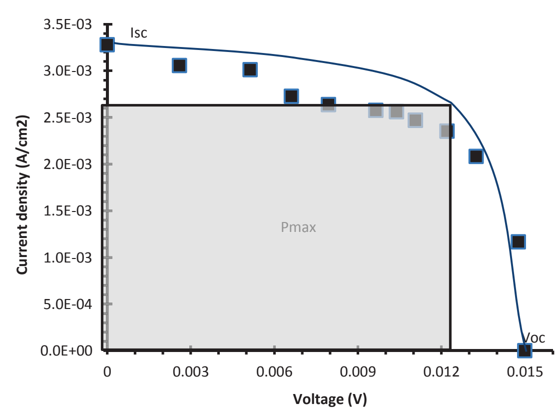


FIGURE 10. The electrical conductivity related to variation of annealing hold time for BST solar cells and different light intensity.



(a)



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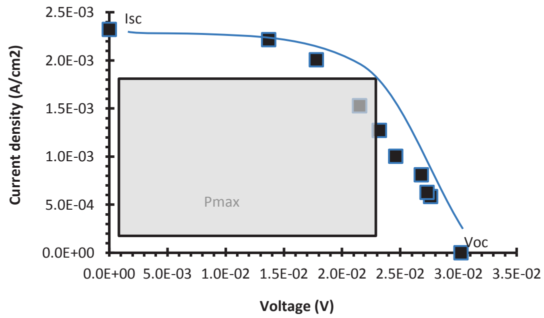

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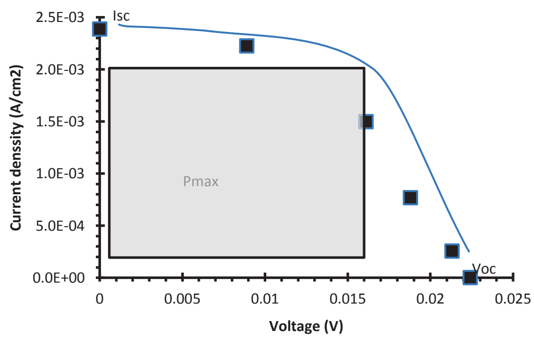
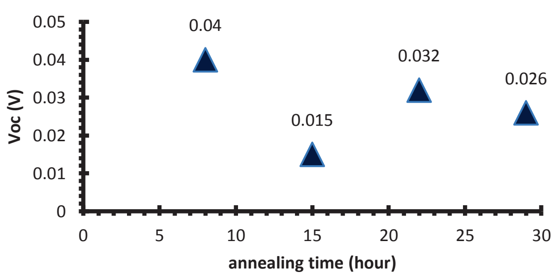
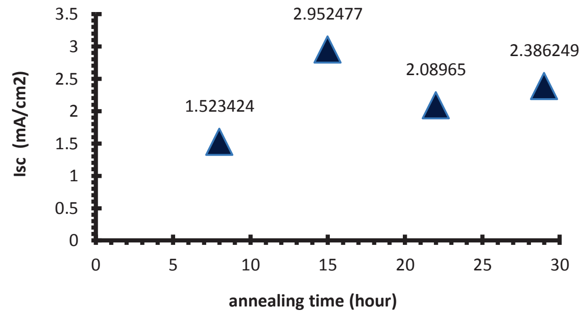


(d)

FIGURE 11. Relationship of (a) 8 hour, (b) 15 hour, (c) 22 hour, (d) 29 hour annealing hold time of BST solar cells and output power.



(a)



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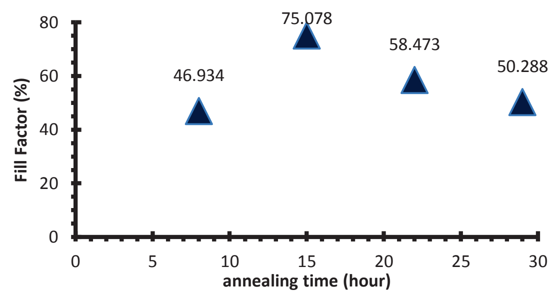

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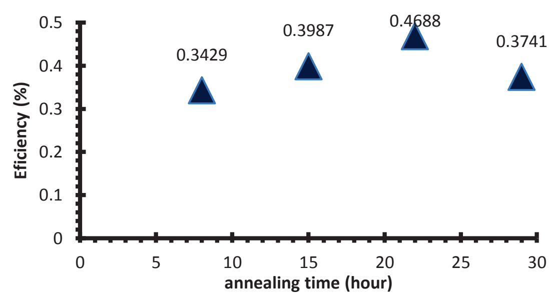

(d)

FIGURE 12. Relationship of BST solar cell parameters and the annealing hold time of (a) 8 hours, (b) 15 hours, (c) 22 hours and (d) 29 hours

The duration of annealing hold time could effect the crystal structure, crystal morphology regularity compilers, and thickness of BST film [16]. This have further effect on the formation of energy band gap distance on the semiconductor material due to crystal makeup influence on the disposition of electron and hole diffusion between n-type region and p-type region. Photon energy larger than the energy band gap is required to excite the electrons over the energy band gap, i.e. from the semiconductor valence band to conduction band to form mobile charge carriers that give out electric current in the semiconductor material. Effective longer annealing hold time provided to the crystal growth to complete toward more regular and perfect crystal structure formation will result to more favorable semiconductor energy band gap to augment electron transfer to conduction band by absorption of photon energy. This will make the semiconductor material to better produce electric current. If shorter annealing hold time is applied to crystal growth that result in imperfect crystal formation, then the insufficient semiconductor energy band gap could restrict the electrons to absorb optimal photon energy. At longer annealing hold time the small crystal grains will shrink and be taken up by the larger crystal grains. This grain growth occurs when the primary crystallization process have ceased [14]. The crystal structure is denser and the energy band gap become narrower, In order for photons to be absorbed as much as possible by valence electrons, then the absorber must have larger band gap, then it is possible to absorb light with variation of photon energy levels [35].

TABLE 1. BST Solar cells parameters related to annealing hold time.

I-V Parameters	Annealing Time (hours)			
	8	15	22	29
V_{oc} (V)	0.04	0.015	0.032	0.026
Current density - I_{sc} (mA/cm^2)	1.52342	2.95247	2.08965	2.38624
V_{max} (V)	0.026	0.0125	0.023	0.016
Current density - I_{max} (mA/cm^2)	1.1	2.66	1.7	1.95
Power density - P_{max} (μW)	28.6	33.25	39.1	31.2
Power density - P_{input} (mW)	8.34	8.34	8.34	8.34
Fill Factor (%)	46.934	75.078	58.473	50.288
Eficiency (%)	2,68x10^{-5}	3,51 x10^{-5}	4,53 x10^{-5}	3,22 x10^{-5}

The result of I-V measurement on Table 1 shows the value of fill factor which is calculated based on Equation (2). The BST solar cell efficiency is calculated based on Equation (3). The largest efficiency of solar cells is owned by the largest band gap. It's because the solar cells with wide band gap, require more absorbed photons energy to excite electron from valence band to conduct band [35, 36]. When solar cells become more optimal to absorb light energy, then more energy is converted from light into electric current [20, 23-26].

Theoretically, solar cells with ferroelectric based material have light energy absorption efficiency range between 2.5% to 10% [11]. Ferroelectric materials that have been tested theoretically are used as solar cell materials such as triglycine sulphate (TGS) [Curie temperature, C ≈ 10^3 K], lithium tantalate ($LiTaO_3$) [C ≈ 10^5 K], sodium nitrite ($NaNO_2$) [C ≈ 103 K] [11]. The BST Curie temperature (C ≈ 300 K) [11,12], is much lower than the Curie temperatures of those other materials. This is probably the cause that the BST solar cell efficiency is lower than those obtained from previous study on ferroelectric material.

CONCLUSION

The annealing hold times of BST films are considered to be relatively too short, i.e. for 8 hours, 15 hours, and 22 hours. The crystallization process does occur in the film, but it still have not yet formed as a perfect crystalline structure. A longer annealing time (29 hours) is required for the crystallization process to complete towards its more perfected form. The optical properties of light absorption spectrum show BST solar cell films with annealing hold time of 8 hours, 15 hours, and 22 hours to absorb effectively the light wavelength region $\lambda \geq 700$ nm. For BST solar cell film samples with annealing hold time of 29 hours will effectively absorb light at the wavelength region $\lambda \leq 700$ nm. Refractive index of BST films are obtained in the range of 1,1 to1,8 for wavelength range ±370 to 870 nm. The semiconductor energy band gap value is obtained from the measured reflectance values using Tauc method that are based on BST film annealing hold time of 8 hours, 15 hours, 22 hours, and 29 hours, and based on these annealing hold times the energy band gaps are to be 2.58 eV, 3.15 eV, 3.2 eV and 2.62 eV, respectively.

The electrical conductivity value (σ) is obtained from calculation using conductance (G) indicate that BST solar cell films are classified as semiconductor material with electric conductivity in the order of 10^{-5} to 10^{-4} S/cm. The electrical conductivity will increase with more light intensity incident on the film surface. The I-V characterization show that BST film has the potential to be a solar cell device. The light energy conversion efficiency based on BST film annealing hold time of 8 hours, 15 hours, 22 hours, and 29 hours are respectively 0.343%, 0.399%, 0.469% and 0.374%. The fill factor of BST films with annealing hold time of 8 hours, 15 hours, 22 hours, and 29 hours are 46.9%, 39.9%, 58.5% and 50.23%, respectively.

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