Electrical Photoconductivity of Ta$_2$O$_5$ Doped Based on Ba$_{0.5}$Sr$_{0.5}$TiO$_3$ Thin Film

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Abstract. Ba$_{0.5}$Sr$_{0.5}$TiO$_3$ (BST) thin films were deposited on Si (100) p-type substrates using a chemical solution deposition (CSD) method and doped with 0%, 2.5%, 5%, 7.5%, 10% tantalum pentaoxide (Ta$_2$O$_5$). Chemical Solution Deposition Method (CSD) used the spin coating techniques with a rotational speed of 3000 rpm for 30 seconds. BST thin films annealed at a temperature 850 °C, then characterized by, LCR meter for electrical conductivity characterization. The result shows that electrical conductivity and dielectric constant value of BST and Ta$_2$O$_5$ doped based on BST (BSTT) thin films are in the range semiconductor materials. The electrical conductivity values obtained increased when the higher intensity light is used whereas resistance value could decrease if the light intensity is increased. Dielectric values obtained in the range from 7.29 to 16.11. The addition of tantalum pentaoxide dopant will increases electrical conductivity value of BST thin films. Electrical conductivity data show that BST thin films have shown the characteristic of the photoconductivity.

1. Introduction

Ferroelectric materials have been widely studied and developed in the last few years by scientists. Barium strontium titanate (BST) thin film is the one of ferroelectric materials that intensively developed. Barium Strontium titanate (BST) thin film is widely used for the applications in microelectronic devices such as non volatile memory device, dynamic random access memory (DRAM), sensor devices [1], temperature sensor [2], light sensor [3], ferro-electrics solar cells [4], electrical conductor [5], semiconductor devices [6], microwave devices [7] owing to their high dielectric constant, relatively low dielectric loss tangent, large electric field tunability, long lifetime, and good temperature stability.

In particular, photoconductive is one of the most important characteristics for sensor applications such as light sensor [3]. This characteristics including dielectric and conductance properties of BST thin films are affected by many factors, such as the Ba/Sr ratio, the growth temperature, the crystallographic orientation, the grain size, the defect chemistry, the oxygen vacancies, the stress/strain state, and the dopants [8]. To optimize the dielectric and conductivity properties of BST thin films, BST have been doped with Mn[9], gold[10], MgO[11], ZrO$_2$[12], Niobium[13] and Fe$_2$O$_3$[3].

BST thin films have been deposited by various technique such as metal organic chemical vapor deposition, pulsed laser deposition, magnetron sputtering, radio frequency sputtering and sol gel processing[14]. The role of annealing process influenced on microstructure of BST thin film crystal.
The higher annealing temperature, the higher grain size of BST thin film crystal. The reaction of BST construction can be seen by the following equation:

$$0.5\text{Ba(CH}_3\text{COO)}_2 + 0.5\text{Sr(CH}_3\text{COO)}_2 + \text{Ti(C}_2\text{H}_5\text{O}_4\text{)} + 22\text{O}_2 \rightarrow \text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3 + 17\text{H}_2\text{O} + 16\text{CO}_2$$

In this study, BST thin films have been deposited by chemical solution deposition (CSD) method on p-type Si (100) substrate, and then was directly spin coated at 3000 rpm at 30 s for three times. The purpose of the work was to study the effects of doping Ta$_2$O$_5$ on dielectric properties and conductivity value of BST thin films.

2. Research and Method

2.1. Materials preparation

Materials that used in this study are barium acetate [Ba(CH$_3$COO)$_2$, 99%], strontium acetate [Sr(CH$_3$COO)$_2$, 99%], titanium isopropoxide [Ti(C$_2$H$_5$O$_4$)$_2$, 99.999%], tantalum pentaoxide [Ta$_2$O$_5$]. As solvent, 2- methoxymethanol [H$_2$COCH$_3$CH$_2$OH, 99%], tantalum pentaoxide, p-type Si (100) substrates, corning glass substrate, aquabides, HF (fluoride acid), slide glass, and aluminum foil. First, The p-type Si (100) substrates were cleaned by ultrasonic stirring in acetone (2 minutes) and ethanol (2 minutes). Thin film Ba$_{0.5}$Sr$_{0.5}$TiO$_3$ that was overgrown on top of p-type silicon substrate and corning glass substrate, aquabides, HF (fluoride acid), slide glass, and aluminum foil. Subsequently, thin film were annealed at 850°C for 15 hours and then heater is adjusted to a constant annealing temperature for 15 hours. Furthermore, the furnace cooling until back to room temperature for 12 hours. Then we used aluminium as contacts on BST thin film.

2.2. Film Characterization

BST and BSTT thin films characterization were electrical conductivity and dielectric constant. The capacitance was measured at 100 kHz with a precision LCRmeter model Agilent 4284. The dielectric constant and capacitance value can be calculated by the following Equation (1):

$$C = \varepsilon \frac{\varepsilon_0 A}{d}$$

where:

- $C$ = Capacitance
- $\varepsilon$ = Dielectric constant
\[ \epsilon_0 = \text{Free space dielectric constant} \ (8.85 \times 10^{-12} \ C^2 \ m^{-2} \ N^{-1}) \]
\[ d = \text{Thickness (m) of the BST film.} \]
\[ A = \text{Capacitor area (m^2)} \]

Another method to calculate the dielectric constant of BST film is using an oscilloscope and low pass filter circuit (Figure 1). This following equation (2) is a correlation between electrical conductivity and resistance, then conductivity can be calculated.

\[ \sigma = \frac{L}{RA} \quad (2) \]

where:
\[ \sigma = \text{electrical conductivity of thin film (S/m)} \]
\[ R = \text{resistance of BST (Ohm)} \]
\[ A = \text{contact area (m^2)} \]
\[ L = \text{contact spacing (m)} \]

3. Results and Discussion

3.1. Dielectric Constant BST Thin Films

One of the benefits of BST thin film can be used as a capacitor. The characteristics of the capacitor arise due to the depletion layer on the p-n connection. In this layer, there are a negative and positive charges. This layer of depletion arises because electrons and holes diffuse into areas of low concentration. The hole in p-type is higher concentration than the hole in n-type. They diffuse from the p-type to the n-type. The same process occurs in electrons. But this process does not happen continuously. If the hole leaves the p-type area and disappears into the n-type region because recommendation process, an acceptor will be ionized into negative form in the p-type region then form a negative area. The same thing happens to the electrons that leaving the positive charge area on the n-type region, it generates an electric field that starts from positive charge space, ending in a negative charge space. This electric field inhibits the hole to diffuse from the p-type region to the n-type, and inhibit the electron to diffuse from the n-type to the p-type[16].

The characterization of dielectric constant BST thin film was performed by arranging an electrical circuit shown in Figure 1. Figure 2 shows the output of the oscilloscope. The image shows the curvature of the box signal due to the process of storing the charge on the ferroelectric material. Therefore, thin film BST with Ta$_2$O$_5$ doping can be used as a capacitor.
Figure 2. Oscilloscope signal of BST a) without doping b) doping content of Ta$_2$O$_5$ 2.5% c) doping content of Ta$_2$O$_5$ 5% d) doping content of Ta$_2$O$_5$ 7.5% e) doping content of Ta$_2$O$_5$ 10%.

Dielectric properties symbolize the density of electrostatic flux in a material when electrical potential is applied. Table 1 shows that the dielectric constant increases with increasing Ta$_2$O$_5$ dopant’s concentration. The addition of doping will cause the value of the dielectric constant increased. The addition of Ta$_2$O$_5$ doping levels grown on BST thin film, will increase the number of doping donors. Then it will increase the number of negative charge carriers concentration and internal electric field. This process caused the depletion region grow larger. Then the dielectric molecule will increase as well. Finally Ta$_2$O$_5$ doped thin film have better dielectric properties than undoped thin films. Figure 3 shows the correlation of Ta$_2$O$_5$ doping variation to the dielectric constant.

### Table 1. Capacitance and dielectric constant of thin film

| Doping Ta$_2$O$_5$ percent | Dielectric Constant | Capacitance Value |
|----------------------------|---------------------|-------------------|
| 0%                         | 7.287               | 0.246 nF          |
| 2.50%                      | 9.76                | 0.208 nF          |
| 5%                         | 11.73               | 0.27 nF           |
| 7.50%                      | 12.25               | 0.28 nF           |
| 10%                        | 16.11               | 0.29 nF           |

Figure 3. The correlation of Ta$_2$O$_5$ doping variation to the dielectric constant.
3.2. Electrical Conductivity Analysis of Thin Film

The electrical conductivity is capability of material to conduct an electric current. Natural and artificial materials occur in nature can be classified as conductors, semiconductors, and insulators. The measurement of the electrical conductivity of thin film was done by measuring its conductance value using LCR meter. Based on conductance data, resistance value will be obtained using Equation 2, then the value of electrical conductivity can be calculated. Light sensitivity was conducted to determine whether the resulting thin film is a type of photoconductivity. Measurement of thin film conductance was done in the dark conditions and bright conditions with variations in light intensity of 250 lux, 500 lux, 750 lux and 1000 lux.

The electrical conductivity of the semiconductor could change when the material was given the light source. The doping increases the conductivity values with applied radiation, where the values are greater for higher light intensity as shown in Figure 3. The reason behind the increasing conductivity was due to the excitation of the electrons in the valence band to the conduction band. The electrons in the conduction band move freely under the influence of the electric field. Therefore, the more excited electrons to the conduction band due to irradiation will cause the electrical current increase, as well as with increasing electrical conductivity.

The effect of Ta$_2$O$_5$ doping content variation and the intensity of light on the conductivity of thin films can be seen in Table 2. Table 2 shows that maximum conductivity occurs at light intensity of 1000 lux and 10% doping level. The increasing of light intensity that fell off on thin films will increases the electrical current of thin films, ultimately raising the electrical conductivity of thin films. Generally, the addition of Ta$_2$O$_5$ doping improves the conductivity of thin films. Increasing value of electrical conductivity due to the addition of doping tantalum penta oxide. Doping process of pentavalent atoms produces many electrons in the conduction band because each pentavalent atom supports one conduction band electron. Increasing value of Ta$_2$O$_5$ doping is shown to provide significant effect on increasing the conductivity of BST as can be seen at Figure 4 and Table 2.

The electrical photoconductivity are the energy such as a light source that falling on the photoconductive cell (BST thin film) will cause a change in cell resistance, then the electrical voltage will change. From the conductivity characteristics, it can be seen that the film had an electrical photoconductivity characteristics. It can be seen from Figure 4, there are shifting in the value of conductance when the thin films was given a different doping. Based on the electrical properties obtained, Ta$_2$O$_5$ doped BST thin film is potential for sensor applications.

![Figure 4. The relation between electrical conductivity to light intensity](image-url)
4. Conclusion

BST thin films were successfully deposited on Silicon (100) p-type substrates using a chemical solution deposition (CSD) method and doped with 0%, 2.5%, 5%, 7.5%, 10% tantalum pentaoxide \((\text{Ta}_2\text{O}_5)\). The dielectric constant and conductivity value of BST thin films increase with increasing \(\text{Ta}_2\text{O}_5\). The highest conductivity value was occured at BST thin film that given a light intensity of 1000 lux and doping content of \(\text{Ta}_2\text{O}_5\) 10%. The conductivity values increase with increasing light intensity and show photoconductivity characteristic of thin film. Based on the electrical properties obtained, BST with \(\text{Ta}_2\text{O}_5\) doping is potential for sensor applications.

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**Table 2. Electrical conductance BST thin Film**

| Light Intensity (Lux) | Conductivity (\(10^5\) S/m) |
|-----------------------|-------------------------------|
|                       | No doped | 2.5% | 5% | 7.5% | 10% \(\text{Ta}_2\text{O}_5\) |
| 0                     | 4.04     | 5.91 | 7.17 | 8.7 | 11.05 |
| 250                   | 6.8      | 11.3 | 14.68 | 24.5 | 39.2 |
| 500                   | 11.6     | 39.49 | 40.27 | 64.69 | 77.3 |
| 750                   | 29.85    | 47.63 | 48.48 | 71.85 | 87.13 |
| 1000                  | 31.3     | 54.3 | 62.64 | 80.81 | 118.61 |
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