THERMAL EVAPORATION OF COPPER DOPED TIN (II) SULFIDE ABSORBER THIN FILM FOR SOLAR CELL APPLICATION

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Untuk Yang Maha Mengetahui segala yang ada di langit dan di bumi; Dia.
Untuk wanita paling penyayang di dunia; Mama.
Untuk lelaki paling agung; Abah.
Untuk mereka yang sentiasa menyokong; Along, Angah, Alang.
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ABSTRACT

Recent reports shows that tin sulphide (SnS) is a promising material as an absorber layer in solar cell application. However, SnS had to be doped with Copper (Cu) which could help to decrease the high resistivity. SnS with various Cu weight percentage (wt%) from 5 to 20 had been deposited on glass substrate using thermal evaporation technique. The thin films were annealed in vacuum environment at 200 ^{o}C for 2 hours using tube furnace. The structural properties was characterized using X-ray diffraction, Scanning Electron Microscope, Energy Dispersive X-ray and Atomic Force Microscopy. Optical properties was determined using ultraviolet-visible spectrometer while the resistivity was measured using Four Point Probe method at standard room pressure and temperature. The thin films were matched with polycrystalline SnS having Herzbergite crystal structure and grain size estimated to be ~ 21 to 30 nm. It had almost near stoichiometry and dopant element was found in the doped thin films. The deposited thin films had good surface coverage, good crystallinity and no pinhole or cracks on the surface. The thin films had low transmission at visible light region and absorption coeeficient were above 10^5 cm^{-1}. It also revealed energy band gap around 1.52 to 2.03 eV. Doped thin film has lower band gap energy than the undoped whereas high dopant concentration caused the energy band gap to increase compared to low dopant percentage. Meanwhile, annealed thin films had lower energy band gap. The resistivity range from 0.59 to 1.80 $\times 10^3$ Ω cm. Doped thin films has less resistivity than the undoped and annealing process tends to lower the resistivity. It was observed that the properties of SnS thin films when Cu was introduced had changed and tend to improve at lower weight percentage. This demonstrated doping could modify the optical and electrical properties of SnS thin films precisely in lowering band gap energy and resistivity, thus have potential to be used as solar cell application.

ABSTRAK

Laporan terkini menunjukkan bahawa stanum sulfida (SnS) adalah bahan yang berpontensi untuk digunakan sebagai lapisan penyerap dalam aplikasi sel solar. Walaubagaimanapun, bahan SnS perlu didopkan dengan kumprum (Cu) untuk membantu mengurangkan kadar rintangan yang tinggi. SnS dengan pelbagai peratusan berat (wt%) kuprum (Cu) telah dienapkan di substrat kaca menggunakan teknik vakum penyejatan haba. Filem-filem nipis telah sepuh lindap dalam persekitaran vakum pada 200 ^{o}C selama 2 jam dengan menggunakan tiub relau. Peranan proses penyepuhlindapan ke filem-filem nipis turut dikaji. Sifat-sifat struktur dicirikan menggunakan Pembelauan X-ray, Mikroskop Pengimbasan Elektron, Tenaga Serakan X-ray dan Mikroskop Daya Atom. Ciri optik telah ditentukan dengan menggunakan Spektrometer Ultraviolet Boleh Nampak manakala kerintangan diukur menggunakan kaedah Probe Empat Titik pada tekanan bilik dan suhu standard. Filem-filem nipis dipadankan dengan SnS polihabluran mempunyai struktur kristal Herzbergite dan saiz butiran dianggarkan ~ 21 hingga 30 nm. Ia mempunyai hampir persamaan stoikiometri dan unsur dopan terdapat dalam filem nipis yang didopkan. Filem nipis yang dienap mempunyai liputan permukaan yang baik, penghabluran baik dan tiada lubang kecil atau retak di permukaan. Filem nipis tersebut mempunyai transmisi yang rendah pada kawasan cahaya boleh nampak dan pekali penyerapan lebih daripada 10^5. Ia juga mendedahkan jurang jalur tenaga sekitar 1.52-2.03 eV. Filem nipis yang didopkan mempunyai jurang jalur lebih rendah daripada filem yang tidak terdop manakala dopan yang tinggi kepekatan menyebabkan jurang jalur tenaga meningkat berbanding dopan yang rendah kepekatan. Sementara itu, filem nipis yang disepuh lindap mempunyai jurang jalur tenaga lebih rendah. Nilai kerintangan berjulat diantara 0.59-1.80 $\times 10^3\ \Omega$ cm. Saput tipis didopkan mempunyai kurang nilai rintangan daripada saput tipis yang tidak didop dan proses penyepuhlindapan cenderung untuk mengurangkan kerintangan. Dapat diperhatikan bahawa sifat-sifat saput tipis SnS telah berubah apabila Cu diperkenalkan dan cenderung untuk bertambah baik pada peratusan berat yang lebih rendah. Ini menunjukkan pendopan boleh mengubahsuai prestasi sifat optic and elektrik saput tipis SnS khususnya menurunkan jurang jalur tenaga dan rintangan, jadinya berpotensi untuk digunakan dalam aplikasi sel solar.

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LIST OF SYMBOLS AND ABREVIATION

J	Joule
PV	Photovoltaic
GaAs	Gallium Arsenide
CdTe	Cadmium Telluride
$CuInSe_2$	Copper Indium Diselenide
Si	Silicon
c-Si	crystalline silicon
CIGS	Copper indium gallium selenide
TiO_2	Titanium Dioxide
SnS	Tin Sulfide
CO_2	Carbon dioxide
Cu	Copper
Sb	Antimony
eV	Electronvolt
α	Absorption Coefficient
h	Planck’s constatnt
E_g	Energy Band Gap
σ	Electrical Conductivity
ρ	Electrical Resistivity
ρ_s	Sheet Resistivity
$f(R)$	Correction Factor
t	Thickness
s	Probe spacing
wt%	Weight Percentage

at%	Atomic Percentage
XRD	X-Ray Diffraction
JCPDS	Joint Committee on Powder Diffraction Standards
XRF	X-ray Fluorescence
EDX	Energy Dispersive X-Ray Spectroscopy
SEM	Scanning Electron Microscopy
AFM	Atomic Force Microscopy
UV-Vis	Ultraviolet-Visible Spectrometer
NIR	Near Infrared Region
TFSC	Thin Film Solar Cells
PVD	Physical Vapor Deposition
CVD	Chemical Vapor Deposition
ECD	Electrochemical Deposition
TCO	Transparent Conducting Oxide
DC	Direct Current
V	Potential Difference
λ	Wavelength
θ	Diffraction Bragg Angle
Å	Angstrom = 10^{-10} m
D	Estimated grain size derived from XRD
β	FHWM of 2θ
FWHM	Full Width Half Maximum

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Energy plays a huge role in assisting mankind's way of life in industry, communication and transportation. Generally, energy can be supplied from fossil fuels (80%) such as oil (35 %), coal (23 %), and natural gas (22 %) and other energy sources (20%) such as biomass (11.5%), nuclear (6.5 %), and hydropower (2%). However, due to rapid growth of human population and modern industries, the total rate of global energy consumption has greatly increased and expected to triple by the year 2100. The demand for energy of modern society is constantly increasing. Moreover, several crisis that arise like rapid depletion of fossil fuels, global climate change and a worrying level of environmental pollution due to fossil fuel consumption have made the researchers to find a much more efficient usage of energy plus to develop an alternative, sustainable, and clean energy technologies such as solar cells, fuel cells, and biofuels to solve critical issues. For many reasons, solar energy has become an important technology that is worth paying attention (Bissels *et al*., 2014; Edenhofer *et al*., 2012).

Solar energy is unlimited, abundant and clean of all the renewable energy resources on the earth up until now. The power from sun is tremendous energy resources. The energy intercepted by the earth is about $4x10^{24}$ J. According to U.S Energy Information Administration, the world's total energy consumption was around 5.6×10^{20} J in 2010 (Energy Information Administration (US), 2012), meaning that the solar energy delivered to the earth in about one hour is sufficient to provide the energy needs by the global population for a whole year. Photovoltaic (PV) technology is one of the best ways to harness the solar energy. A recent report from the Intergovernmental Panel on Climate Change predicts PV will account for up to 30 % of the world's electricity production by 2050, even in the moderate developments. This shows that research in solar energy and solar cell need to be persuaded so that the energy can be harvested with high efficiency (Edenhofer *et al*., 2012).

This research focusses on the absorber layer for solar cell using thin film technology. Generally, solar cells consist a light absorbing material within the cell structure which function to collect photons and release free electrons known as photovoltaic effect. The PV effect is the foundation of the conversion of electrical energy from light energy. Meanwhile, thin-film solar cells are mainly thin layers of semiconducting materials which possess photovoltaic properties deposited onto a solid backing material also known as substrate. The advantage of thin films is it prominently reduce the amount of semiconductor material required for each cell when compared to silicon wafers and therefore reduce the cost of production of PV cells (Parida *et al*., 2011).

In previous study, gallium arsenide (GaAs), cadmium telluride (CdTe), copper indium diselenide ($CuInSe_2$) and titanium dioxide (TiO_2) are materials that have been greatly used to produce thin film solar cells. Although these materials show excellent achievement, the main drawbacks are lack of abundance and non-environmental friendly (Ogah *et al*., 2009). Therefore, new promising materials are searched. Tin sulfide (SnS) has been reported as a potential material to be used as absorber layer due to its characteristics which has a direct energy band gap about 1.3 eV, around the optimum energy needed for conversion of PV solar energy. Additionally, the optical absorption coefficient is also high where most of the incident light can be absorbed by the layers thickness with only several microns (Bube, 1960). It can be deposited by a wide range of chemical and physical deposition methods. Moreover, the advantages of tin sulfide is both of these essential elements are earth abundant, and environmental risk of Sn and S are low and non-toxic (Miles *et al*. , 2009).

A research conduct by Ogah *et al*. (2009) to determine whether tin sulfide could produce a stable and efficient cells using thermal evaporation has shown that it is possible to deposit SnS layers with thickness of numerous microns and free of pinhole that is conformal to the substrate. The layers of thin film have also has been made up of columnar grains that are densely packed. The structural properties show the deposited layers are mostly SnS which has the structure of orthorhombic crystal. For the optical properties, the absorption edges shown are consistent with direct energy band gap. The energy band gap value is in the range 1.3 to 1.7 eV, where the lower values are obtained for film with thicknesses less than 1 μm and suitable for use in thin film solar cell structures.

Another study done by Miles *et al*. (2009) shows that stoichiometric SnS thin films is possible to be produced using thermal evaporation technique with adherent to the substrate, consisting of densely packed columnar grains. The thickness of thin films produced has different band gap values (1.3–1.7 eV) due to the variation in the deposition conditions but still maintaining the optimum band gap energy range for PV energy conversion (1.5 eV) and having p-type layers (Miles *et al*., 2009). However, further study need to be done on the optical and electrical properties. Besides that, the post-deposition annealing effect also need to be investigated.

In this research, we are going to prepare tin sulfide thin film as absorber layer with metallic-doping which is copper (Cu) using thermal evaporation method. Cu as metallic elements dopant has been proved to improve PV efficiency in dye sensitized solar cell (Nguyen *et al*, 2014). The performance of this layer is determined by characterizing the structural, optical and electrical properties of the copper doped SnS. This study would like to find out the possibility for copper doped tin sulfide as potential absorber layer to be used in solar cell application.

1.2 Problem Statement

The current work regarding solar cell is for the accomplishment of an absorbing layer with maximum efficiency. The material should be environmental friendly and abundant. Our aim is to find out an absorber layer for solar cell with non-toxic and abundant constituent. Besides that, the absorber layer must possess most of these properties; a high conductivity and low resistivity, small band gap energy, E_g (near 1.3 eV) to maximize absorption of solar radiation, high absorption coefficient ($\alpha > 10^4$ cm^{-1}) and low transmittance especially in the visible light spectrum (wavelength range 400 – 700 nm). Since SnS has been reported in previous study as a promising absorber material. However, SnS has drawback in electrical properties specifically resistivity which is high. This experiment want to improve the properties by introducing metallic-doping which is copper, Cu. Cu is cheap, abundance and known as good electrical conductor. By adding Cu, the thin film is expected to have lower resistivity, ρ than undoped SnS. The structural, optical and electrical properties of the thin film were characterized to find out whether it possess the requirement to be an efficient solar cell absorber layer.

1.3 Objectives of Study

The objectives of this project are as follows:

i. To fabricate copper doped tin sulfide thin film at different weight percentage (wt%) from 5% to 20% using thermal evaporation technique

ii. To determine the effect of annealing process on the sample surface

iii. To characterize the optical and electrical properties of doped tin sulfide thin film

1.4 Scope of Study

The sample is made of tin sulfide powder with purity of 99.9% and copper powder with purity of 99.9%. It is to be prepared using thermal evaporation method with different copper-doping weight percentage which are 5%, 10%, 15% and 20% respectively. All the samples are annealed at 200^{o}C for two hours under vacuum environment which could help to optimize the crystallinity and surface morphology of the thin film. Constant temperature is chosen as the tin sulphide could be oxidized at more than 200^{o}C. The structural properties is characterized using X-ray Diffraction (XRD), Energy Dispersive X-ray Spectroscopy (EDX), Scanning Electron Microscopy (SEM), and Atomic Force Microscopy (AFM). The optical properties such as absorbance and transmittance is analysed using ultraviolet-visible (UV-Vis) spectrometer in the wavelength range (200-1800nm) with an incident light perpendicular to the surface plane of the films. The electrical properties is evaluated using Four Point Probe technique to determine the electrical resistivity.

1.5 Significance of the study

The findings of the research could be useful to improve the efficiency of solar cell nowadays. The suitable material composition could be identified. Besides that, the optimized conditions to grow the thin film will be determined. When all of this optimum parameters are understood, a solar cell with best characteristics such as low band gap energy and low resistivity could be produced using the same technique. Therefore, this research can be a reference for industrial field especially in photovoltaic field. Thus, this study could save cost and time in preparing the sample. As consequence, this may reduce the price of solar cell in the market. Other than that, this research may establish a standard value for the characterization.

1.6 Thesis Outline

This thesis is divided into five chapters. Chapter 1 presents the background study of the research and the problem statement that gives motivation to conduct the experiment. Objectives of this study are also shown in this chapter. Chapter 2 discussed the previous work that have been done by others and also explain the analysis that is used. Chapter 3 describes the methodology used to prepare the samples and the working of analytical instruments for the experiments. Chapter 4 presents the experimental results that is obtained from the analysis and further discussed with previous work. Lastly, chapter 5 summarize the findings and conclude the experiments. Some outlook that can be done for future work is also mentioned to further improve the experiments.

REFERENCES

Ali, N., Hussain, A., Wan Shamsuri, W. N., Shaari, A., & Ahmed, R. (2016). Antimony sulphide, an absorber layer for solar cell application. *Applied Physics A*, *122*(1), 1–7.

Ali, N., Hussain, S. T., Khan, Y., Ahmad, N., Iqbal, M. A., & Abbas, S. M. (2013). Effect of air annealing on the band gap and optical properties of SnSb2S4 thin films for solar cell application. *Materials Letters*, *100*, 148–151.

Ali, N., Iqbal, M. A., Hussain, S. T., Waris, M., & Munair, S. A. (2012). Optoelectronic properties of cadmium sulfide thin films deposited by thermal evaporation technique. *In Key Engineering Materials*, 510, 177-185).

Alonzo-Medina, G. M., González-González, A, Sacedón, J. L., & Oliva, A. I. (2013). Understanding the thermal annealing process on metallic thin films. *IOP Conference Series: Materials Science and Engineering*, *45*, 12013.

Asim, N., Sopian, K., Ahmadi, S., Saeedfar, K., Alghoul, M. A., Saadatian, O., & Zaidi, S. H. (2012). A review on the role of materials science in solar cells. *Renewable and Sustainable Energy Reviews*, *16*(8), 5834–5847.

Ayouchi, R., Leinen, D., Martín, F., Gabas, M., Dalchiele, E., & Ramos-Barrado, J. R. (2003). Preparation and characterization of transparent ZnO thin films obtained by spray pyrolysis. *Thin Solid Films*, *426*(1–2), 68–77.

Bissels, G. M. M. W., Schermer, J. J., Asselbergs, M. A. H., Haverkamp, E. J., Mulder, P., Bauhuis, G. J., & Vlieg, E. (2014). Solar Energy Materials & Solar Cells Theoretical review of series resistance determination methods for solar cells. *Solar Energy Materials and Solar Cells*, *130*, 605–614.

Bube, R. H. (1960). Photoconductivity. *Wiley Encyclopedia of Electrical and Electronics Engineering*.

Chan, J., & Friedberg, P. (2002). Four-point probe manual. *EECS 143 Microfabrication Technology*, 1–3.

Cheng, L. L., Liu, M. H., Wang, M. X., Wang, S. C., Wang, G. D., Zhou, Q. Y., & Chen, Z. Q. (2012). Preparation of SnS films using solid sources deposited by the PECVD method with controllable film characters. *Journal of Alloys and Compounds*, *545*, 122–129.

Cheng, S., & Conibeer, G. (2011). Physical properties of very thin SnS films deposited by thermal evaporation. *Thin Solid Films*, *520*(2), 837–841.

Chopra, K. L., Paulson, P. D., & Dutta, V. (2004). Thin-film solar cells: an overview. *Progress in Photovoltaics: Research and Applications*, *12*(2-3), 69-92.

Devika, M., Koteeswara Reddy, N., Sreekantha Reddy, D., Ahsanulhaq, Q., Ramesh, K., Gopal, E. S. R., Hahn, Y. B. (2008). Synthesis and Characterization of Nanocrystalline SnS Films Grown by Thermal Evaporation Technique. *Journal of The Electrochemical Society*, *155*(2), H130.

Devika, M., Reddy, N. K., & Gunasekhar, K. R. (2011). Structural, electrical, and optical properties of as-grown and heat treated ultra-thin SnS films. *Thin Solid Films*, *520*(1), 628–632.

Devika, M., Reddy, N. K., Ramesh, K., Gunasekhar, K. R., Gopal, E. S. R., & Reddy, K. T. R. (2006a). Influence of annealing on physical properties of evaporated SnS films. *Semiconductor Science and Technology*, *21*(8), 1125.

Devika, M., Reddy, N. K., Ramesh, K., Gunasekhar, K. R., Gopal, E. S. R., & Reddy, K. T. R. (2006b). Low resistive micrometer-thick SnS: Ag films for optoelectronic applications. *Journal of the Electrochemical Society*, *153*(8), G727–G733.

Devika, M., Reddy, N. K., Reddy, D. S., Reddy, S. V., Ramesh, K., Gopal, E. S. R., Hahn, Y. B. (2007). Optimization of the distance between source and substrate for device-grade SnS films grown by the thermal evaporation technique. *Journal of Physics: Condensed Matter*, *19*(30), 306003.

Djessas, K., & Masse, G. (2000). SnS thin films grown by close-spaced vapor transport. *Journal of Materials Science Letters*, *19*, 2135–2137.

Earnshaw, A., & Greenwood, N. (1997). Chemistry of the Elements. Second Edition. Butterworth-Heinemann.

Edenhofer, O., & Madruga, R. P. (Eds.). (2012). *Special Report on Renewable Energy Sources and Climate Change Mitigation: Summmary for Policymakers: a Report of Working Group III of the IPCC and Technical Summary*. Intergovernmental Panel on climate change.

Elshabini, A., Elshabini-Riad, A. A., & Barlow, F. D. (1998). *Thin film technology handbook.* McGraw-Hill Professional.

Energy Information Administration (US) (Ed.). (2012). *Annual Energy Outlook 2012: With Projections to 2035*. Government Printing Office.

Ettema, A., De Groot, R. A., Haas, C., & Turner, T. S. (1992). Electronic structure of SnS deduced from photoelectron spectra and band-structure calculations. *Physical Review B*, *46*(12), 7363.

Ghosh, B., Das, M., Banerjee, P., & Das, S. (2008). Fabrication and optical properties of SnS thin films by SILAR method. *Applied Surface Science*, *254*(20), 6436–6440.

Ghosh, B., Das, M., Banerjee, P., & Das, S. (2009). Characteristics of metal/p-SnS Schottky barrier with and without post-deposition annealing. *Solid State Sciences*, *11*(2), 461–466.

Gómez-Pozos, H., Maldonado, A., & Olvera, M. de la L. (2007). Effect of the [Al/Zn] ratio in the starting solution and deposition temperature on the physical properties of sprayed ZnO:Al thin films. *Materials Letters*, *61*(7), 1460–1464.

Guneri, E., Gode, F., Ulutas, C., Kirmizigul, F., Altindemir, G., & Gumus, C. (2010). Properties of P-Type SnS Thin Films Prepared By Chemical Bath Deposition. Chalcogenide Letters, 7(12), 685–694.

Habibi, M. H., & Talebian, N. (2005). The effect of annealing on structural, optical and electrical properties of nanostructured tin doped indium oxide thin films. *Vacuum*, *52*(1), 53–59.

Hartman, K., Johnson, J. L., Bertoni, M. I., Recht, D., Aziz, M. J., Scarpulla, M. A., & Buonassisi, T. (2011). SnS thin-films by RF sputtering at room temperature. *Thin Solid Films*, *519*(21), 7421–7424.

Hegde, S. S., Kunjomana, G., Prashantha, M., Kumar, C., & Ramesh, K. (2013). Photovoltaic structures using thermally evaporated SnS and CdS thin films. *Thin Solid Films*, *545*, 543–547.

Hermann, A. M. (1998). Polycrystalline thin-film solar cells — A review. *Solar Energy Materials and Solar Cells 55*, 75–81.

Ikeda, M., Itoh, K., & Sato, H. (1968). Electrical and Optical Properties of CdS-MnS Single Crystals. *Journal of the Physical Society of Japan*, *25*(2), 455–460. JOUR.

Jain, P., & Arun, P. (2013). Influence of grain size on the band-gap of annealed SnS thin films. *Thin Solid Films, 548,* 241–246.

Jun-Ho, C., Ashok, K., Kissinger, N. S., Ra, Y. H., Sim, J. K., Kim, J. S., & Lee, C. R. (2011). Effect of thermal annealing on the structure, morphology, and electrical properties of Mo bottom electrodes for solar cell applications. *Journal of the Korean Physical Society*, *59*(3), 2280-2285.

Kaelble, E. F. (1967). Handbook of X-rays: for diffraction, emission, absorption, and microscopy. McGraw-Hill.

Khairy, M., & Zakaria, W. (2014). Effect of metal-doping of TiO2 nanoparticles on their photocatalytic activities toward removal of organic dyes. *Egyptian Journal of Petroleum*, *23*(4), 419–426.

Kuo, S., Chen, W., Lai, F., Cheng, C., Kuo, H., Wang, S., & Hsieh, W. (2006). Effects of doping concentration and annealing temperature on properties of highly-oriented Al-doped ZnO films. *Journal of Crystal Growth*, *287*, 78–84.

Leach, M., Reddy, K. T. R., Reddy, M. V., Tan, J. K., Jang, D. Y., & Miles, R. W. (2012). Tin sulfide thin films synthesised using a two steps process. *Energy Procedia*, *15*(2011), 371–378.

Manoj, P. K., Joseph, B., Vaidyan, V. K., & Amma, D. S. D. (2007). Preparation and characterization of indium-doped tin oxide thin films. *Ceramics International*, *33*(2), 273–278.

Manohari, A. G., Dhanapandian, S., Manoharan, C., Kumar, K. S., & Mahalingam, T. (2014). Effect of doping concentration on the properties of bismuth doped tin sulfide thin films prepared by spray pyrolysis. *Materials Science in Semiconductor Processing*, *17*, 138-142.

Mathews, N. R., Colín García, C., & Torres, I. Z. (2013). Effect of annealing on structural, optical and electrical properties of pulse electrodeposited tin sulfide films. *Materials Science in Semiconductor Processing*, *16*(1), 29–37.

Miles, R. W., Ogah, O. E., Zoppi, G., & Forbes, I. (2009). Thermally evaporated thin films of SnS for application in solar cell devices. *Thin Solid Films*, *517*(17), 4702–4705.

Muiva, C. M., Sathiaraj, T. S., & Maabong, K. (2011). Effect of doping concentration on the properties of bismuth doped tin sulfide thin films prepared by spray pyrolysis. *Ceramics International*, *37*(2), 555–560.

Nair, M. T. S., & Nair, P. K. (1991). Simplified chemical deposition technique for good quality SnS thin films. *Semiconductor science and technology*, *6*(2), 132.

Noguchi, H., Setiyadi, A., Tanamura, H., Nagatomo, T., & Omoto, O. (1994). Characterization of vacuum-evaporated tin sulfide film for solar cell materials. *Solar Energy Materials and Solar Cells*, *35*(C), 325–331.

Nwofe, P. a., Reddy, K. T. R., Tan, J. K., Forbes, I., & Miles, R. W. (2012). Thickness Dependent Optical Properties of Thermally Evaporated SnS Thin Films. *Physics Procedia*, *25*, 150–157.

Ogah, O. E., Reddy, K. R., Zoppi, G., Forbes, I., & Miles, R. W. (2011). Annealing studies and electrical properties of SnS-based solar cells. *Thin Solid Films*, *519*(21), 7425–7428.

Ogah, O. E., Zoppi, G., Forbes, I., & Miles, R. W. (2009). Thin films of tin sulfide for use in thin film solar cell devices. *Thin Solid Films*, *517*(7), 2485–2488.

Ozta, M. (2008). Influence of Grain Size on Electrical and Optical Properties of InP Films. *Chinese Physics Letters*, *25*(11), 4090–4092.

Parida, B., Iniyan, S., & Goic, R. (2011). A review of solar photovoltaic technologies. *Renewable and Sustainable Energy Reviews*, *15*(3), 1625–1636.

Pecharsky, V., Zavalij, P., Votano, J. R., Parham, M., & Hall, L. H. (2008). *Fundamentals of Powder Diffraction and Structural Characterization of Materials, Second Edition*. New York, USA: Springer US.

Ramakrishna Reddy, K. T., Koteswara Reddy, N., & Miles, R. W. (2006). Photovoltaic properties of SnS based solar cells. *Solar Energy Materials and Solar Cells*, *90*, 3041–3046.

Ramzan, M., Ahmed, E., Niaz, N. A., Rana, A. M., Bhatti, A. S., Khalid, N. R., & Nadeem, M. Y. (2015). AFM applications to study the morphology of HfO2 multilayer thin films. *Superlattices and Microstructures*, *82*, 399–405.

Reddy, N. K., & Reddy, K. T. R. (2005). SnS films for photovoltaic applications: Physical investigations on sprayed SnxSy films. *Physica B: Condensed Matter*, *368*(1–4), 25–31.

Saeed, A., Ali, N., & Syed, W. A. A. (2013). Photovoltaic Effect In The Metal Based Sulfosalt Thin Film Deposited By Physical Vapor Deposition Technique. *Chalcogenide Letters*, *10*(4), 143–150.

Santhosh Kumar, K., Gowri Manohari, A., Lou, C., Mahalingam, T., & Dhanapandian, S. (2016). Influence of Cu dopant on the optical and electrical properties of spray deposited tin sulfide thin films. *Vacuum*, *128*, 226–229.

Schneikart, A, Schimper, H.-J., Klein, A, & Jaegermann, W. (2013). Efficiency limitations of thermally evaporated thin-film SnS solar cells. *Journal of Physics D: Applied Physics*, *46*(30), 305109.

Schroder, D. K. (2006). *Semiconductor material and device characterization*. (D. K. Schroder, Ed.) (Third Edition). John Wiley & Sons.

Seo, Y., & Jhe, W. (2007). Atomic force microscopy and spectroscopy. *Reports on Progress in Physics*, *71*(1), 16101.

Serway, R. A., & John W. Jewett, J. (2013). *Physics for Scientists and Engineers with Modern Physics*. Ninth Edition. Boston, USA. Cengage Learning.

Shanthi, E., Dutta, V., Banerjee, A., & Chopra, K. L. (1980). Electrical and optical properties of undoped and antimony-doped tin oxide films. *Journal of Applied Physics*, *51*(12), 6243–6251.

Sharma, M. K. (2013). Study Of Modification in the efficiency of solar cell. *Journal of Global Research in Computer Science*, *4*(4), 112-118.

Shuai, Z., & Cheng, S. (2011). Thermally evaporated SnS : Cu thin films for Solar, *Proceedings of the 2011 6th IEEE International Conference on Nano/Micro*

Engineered and Molecular Systerns (61076063), 889–892.

Sinsermsuksakul, P., Chakraborty, R., Kim, S. B., Heald, S. M., Buonassisi, T., & Gordon, R. G. (2012). Antimony-doped tin (II) sulfide thin films. *Chemistry of Materials*, *24*(23), 4556-4562.

Skoog, D. A., Holler, F. J., & Crouch, S. R. (2007). *Instrumental analysis*. Cengage Learning India.

Smits, F. M. (1958). Measurements of Sheet Resistivity with the Four-Point Probe. *Bell Syst Tech J*.

Stuart, R. V. (1983). *Vacuum technology, thin films, and sputtering: an introduction* (2nd edition.). University of Michigan: Academic Press.

Svitasheva, S. N., & Gilinsky, A. M. (2013). Influence of doping level on shift of the absorption edge of gallium nitride films (Burstein-Moss effect). *Applied Surface Science*, *281*, 109–112.

Thangaraju, B., & Kaliannan, P. (2000). Spray pyrolytic deposition and characterization of SnS and SnS2 thin films. *Journal of Physics D: Applied Physics*, *33*(9), 1054.

Tripathi, B., Singh, F., Avasthi, D. K., Bhati, A. K., Das, D., & Vijay, Y. K. (2008). Structural, optical, electrical and positron annihilation studies of CdS:Fe system. *Journal of Alloys and Compounds*, *454*(1–2), 97–101.

Vatansever, D., Siores, E., & Shah, T. (2012). Alternative Resources for Renewable Energy: Piezoelectric and Photovoltaic Smart Structures. In *Global Warming - Impacts and Future Perspective*, Prof. Dr. Bharat Raj Singh (Ed.), InTech.

Vorontsov, A. V, Savinov, E. N., & Zhensheng, J. (1999). Influence of the form of photodeposited platinum on titania upon its photocatalytic activity in CO and acetone oxidation. *Journal of Photochemistry and Photobiology A: Chemistry*, *125*(1–3), 113–117.

Vossen, J. L., Chaudhari, P., & Raether, H. (1977). Physics of thin films. *New York: Academic*..

Wasa, K., Kitabatake, M., & Adachi, H. (2004). *THIN FILM MATERIALS TECHNOLOGY: Sputtering of Compound Materials*.

World Energy Council. (2013). World Energy Resources, 468.

York, N. (2002). *HANDBOOK OF THIN-FILM DEPOSITION PROCESSES AND TECHNIQUES*. (K. Seshan, Ed.). Noyes Publications.

Yue, G. H., Wang, W., Wang, L. S., Wang, X., Yan, P. X., Chen, Y., & Peng, D. L. (2009). The effect of anneal temperature on physical properties of SnS films. *Journal of Alloys and Compounds*, *474*(1–2), 445–449.

Zhang, S., Cheng, S. Y., Jia, H. J., & Zhou, H. F. (2011). Preparation and Characterization of Aluminium-Doped SnS Thin Films. *Advanced Materials Research*, *418–420*, 712–716.