CHARACTERIZATION OF Cd$_3$Se$_{1-x}$S/PbS THIN FILMS DEPOSITED BY CHEMICAL BATH DEPOSITION FOR P-N JUNCTION SOLAR CELL APPLICATION

BY

EPHANTUS NYAGA NJERU (B. Ed Sc)

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A thesis submitted in partial fulfillment of the requirements for the award of the degree of Master of Science (Electronics and Instrumentation) in the School of Pure and Applied Sciences of Kenyatta University

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DECLARATION

This work is my own original work and has not been presented for the award of a degree or any other award in any other university.

Ephantus Nyaga Njeru
Department of Physics
Kenyatta University
P.O. B OX 43844-00100
NAIROBI-KENYA

This thesis has been submitted for examination with our approval as University Supervisors

Dr. Mathew K. Munji
Department of Physics
Kenyatta University

Dr. W. K. Njoroge
Department of Physics
Kenyatta University
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<th>Definition</th>
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<tr>
<td>$A_c$</td>
<td>Surface area of a solar cell</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminium</td>
</tr>
<tr>
<td>CBD</td>
<td>Chemical Bath Deposition</td>
</tr>
<tr>
<td>CdCl$_2$</td>
<td>Cadmium chloride</td>
</tr>
<tr>
<td>CdS</td>
<td>Cadmium Sulphide</td>
</tr>
<tr>
<td>Cd$<em>x$Se$</em>{1-x}$</td>
<td>Cadmium sulphide doped with selenium</td>
</tr>
<tr>
<td>(CS(NH$_2$)$_2$)</td>
<td>Thiourea</td>
</tr>
<tr>
<td>Cu$^{2+}$</td>
<td>Copper ions</td>
</tr>
<tr>
<td>Cu$_2$S</td>
<td>Copper (I) sulphide</td>
</tr>
<tr>
<td>CuSO$_4$</td>
<td>Copper (II) sulphide</td>
</tr>
<tr>
<td>$E$</td>
<td>Input light irradiance</td>
</tr>
<tr>
<td>$E_g$</td>
<td>Band gap Energy</td>
</tr>
<tr>
<td>eV</td>
<td>Electron Volt</td>
</tr>
<tr>
<td>FF</td>
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</tr>
<tr>
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<td>Incident intensity</td>
</tr>
<tr>
<td>$I_R$</td>
<td>Reflected intensity</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared radiation</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>Short circuit current</td>
</tr>
<tr>
<td>$J_0$</td>
<td>Short circuit current density</td>
</tr>
<tr>
<td>$n$</td>
<td>Carrier concentration</td>
</tr>
<tr>
<td>Na$_2$SeSO$_3$</td>
<td>Sodium Selenosulphate</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>Ammonia</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>NIR</td>
<td>Near infrared radiation</td>
</tr>
<tr>
<td>Pb(NO$_3$)$_2$</td>
<td>Lead nitrate</td>
</tr>
<tr>
<td>Pb$^{2+}$</td>
<td>Lead ions</td>
</tr>
<tr>
<td>PbS</td>
<td>Lead sulphide</td>
</tr>
<tr>
<td>p-n</td>
<td>Semiconductor junction</td>
</tr>
<tr>
<td>S</td>
<td>Sulphur</td>
</tr>
<tr>
<td>S$^{2-}$</td>
<td>Sulphate ion</td>
</tr>
<tr>
<td>Se</td>
<td>Selenium</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet radiation</td>
</tr>
<tr>
<td>VIS</td>
<td>Visible spectrum</td>
</tr>
<tr>
<td>VIS-NI</td>
<td>Visible to near infrared</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>Open circuit voltage</td>
</tr>
<tr>
<td>Zn</td>
<td>Zinc</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Absorption coefficient</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Conversion efficiency</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Photon wavelength</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Mobility</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Resistivity</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>Sheet resistivity</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Resistance</td>
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ABSTRACT

The CdS and PbS are of great research interest due to their outstanding electronics and optical properties such as winder energy band gap phase and good antireflective properties respectively. CdS has been earlier doped by Zn and used as a window layer combined with PbS as the absorber material using the CBD method. It realised an efficiency of 0.9. It is for this reason in my research, I doped CdS with Se in the fabrication of Cd$_x$Se$_{1-x}$S/PbS P-N junction for solar cell application to see whether the efficiency could be enhanced still employing the CBD method. The chemicals used in preparation of Cd$_x$Se$_{1-x}$S were; Solutions of 0.004M Cadmium nitrate, 0.008M Ammonium nitrate, and 0.008M Thiourea. Doping of the CdS films with Se was done using varying volumes of uniform concentration of Sodium Selenosulphate (Na$_2$SeSO$_3$) solutions by volume at a constant deposition temperature of 80 ± 2°C. The PbS films were prepared from an alkaline bath using aqueous solutions of lead nitrate solution (Pb(NO$_3$)$_2$.3H$_2$O) and Thiourea (CS(NH$_2$)$_2$) which acted as a source of Pb$^{2+}$ and S$^2-$ ions, respectively. The Tri-ethanolamine solution was used as a complexing agent during the deposition process. The Cd$_x$Se$_{1-x}$S thin film deposition was done at a temperature of 80°C ± 2°C for 25 minutes while PbS deposition was done at room temperature of 27°C ± 2°C, both at normal atmospheric pressure utilizing aqueous conditions for approximately 120 minutes. In the deposition of both window and absorber layers, chemical bath deposition method (CBD) was employed. The precursor solution pH level was maintained at 9 using pH meter. Optical optimization of the thin films was done using DUV UV-VIS-NIR spectrophotometer 3700. Electrical characterization was done using four point probe connected to a Keithley2400 source meter interfaced with computer respectively for both thin films. The Cd$_{0.5}$Se$_{0.5}$S film was selected as the best candidate for cell fabrication with E$_g$ of 2.83 eV and transmittance of 89.7%, low absorbance of 1.77% and Resistivity of 1.97×10$^4$ Ω-cm in the VIS region was noted. The PbS from a 0.5M concentration was selected as the best candidate with a transmittance of 26.8%, Absorbance of 38.79% and band gap of 1.43eV. The Cd$_{0.5}$Se$_{0.5}$S/PbS fabricated cell had the following cell parameters: Open voltage (V$_{OC}$) of 0.36V Short circuit current (I$_s$) of 0.031A, Fill factor (FF) of 0.65 and cell efficiency of 1.15%. In conclusion, the Cd$_{0.5}$Se$_{0.5}$S/PbS P-N junction is appropriate for photovoltaic applications and especially in the VIS and IR region of the electromagnetic spectrum.
CHAPTER ONE

INTRODUCTION

1.1 Background of the study

There are many forms of energy but generally, energy can be categorized into renewable and non-renewable sources of energy. Solar energy is one of the renewable sources of energy. The sun is the star that dominates the solar system. The sun radiates energy at a constant rate. This solar energy radiated by the sun is deep within the sun. It is important to convert the solar energy into electrical energy which is known to be the most convenient since it is easily converted to other forms of energy easily. CdS thin films have proved to be good materials in the fabrication of devices that converts solar energy directly into electrical energy (Chapin and Pearson, 1954). It is possible to get optimal results from the above by maximizing their chemical energy inter-band transitions and other optical properties of CdS through doping processes (Abram et al., 1978). The transition of the electrons between the energy bands are of great importance as far as solar radiation harvesting is concerned in comparison with the other energy sources like fuels.

(Maczulak, 2009) reported that fuels derive their source by utilizing solar energy which is abundant, but in most cases it is wasted. Energy is the ability to do work. The energy is stored inform of fuels or radiations. Nanotechnology is the science and technology of creating nanoparticles which have dimensions in the range of nanometres. Using the
nanotechnology, it has been proven that cheap optoelectronic devices can be designed and fabricated for domestic and commercial electrical production (Piok et al., 2001). Nault (2005) found that heating from solar energy requires a P-N junction. The best alternative for oil, coal and gas as sources of energy is the solar cell. Armin (2009) reported that technology on thin film can be used to produce economically cheap optoelectronic devices that can arrest domestic electrical production. Solar energy is easily maintained and easily installable as well as being reliable. Siu and Kwok (1978) concluded that there was a need for the study of materials with good photoelectrical properties and more so the ones in the IR, VIS and UV regions of the spectrum. Good solar cells are the ones which are capable of absorbing photons from the sun and then converting that energy into electrical energy. The solar cell generally consists of two layers namely $n$-type layer and a $p$-type layer as illustrated in figure 1.1

![Figure 1.1: Diagram showing n-type and p-type thin film in a semiconductor junction.](image)

The two layers in figure 1.1 combine to form a semiconductor diode in the form of a P-N junction. The electron-hole pairs generated at the junction makes it possible for the current to flow (Kassim et al., 2010). The photon energy is mathematically equated to the product of plank’s constant and associated frequency. In case a photon possesses
energy greater than that of the band-gap of the semiconductor and gets irradiated on to the cell, it may be absorbed by the cell. The above is possible since there is a band to band transition of energy due to the electron-hole pairs created. In the fabrication of photovoltaic cells, different methods can be employed. Chemical bath deposition (CBD) method is one of the noble methods of thin film deposition because it’s cheap if used in large scale. CdS thin films can be deposited using the Chemical bath deposition method.

This is easily achieved by using cadmium salts, Thiourea and sodium selenosulphate. The optical absorption characterization results showed that as Se content in CdS film increases, band-gap, \( E_g \) decreases from 2.5eV to 1.8eV for (CdS) and (CdSe) respectively. This is attributed by the addition of Se to CdS which increases the open-circuit voltage (\( V_{OC} \)) and short-circuits current (\( I_{SC} \)) within the hetero-junction devices. In an attempt to replace the CdS with Cd\(_{x}\)Se\(_{1-x}\)S which has a higher energy gap, ternary expectation of a decrease in window absorption loss and a decrease in the lattice mismatch of CuInGaSe semiconductors (Singh and Shushan, 2008).

Copper chalcogenide thin films have been extensively studied. CBD has also been used in preparing copper thin films which have shown the possession of near ideal solar control characteristics (Kassim et al., 2010). Transmittance in the IR region, low reflectance in the VIS region so as to elude glare and high reflectance in the IR part of the electromagnetic spectrum was noted (Pathan and Lokhande, 2003). Many researchers have directed their research towards the CBD method since it has proved to
be cheap easy and convenient for large area deposition of thin films. This research is therefore intended to study a ternary material semiconductor (Cd$_x$Se$_{1-x}$S) based on Selenium doped Cadmium sulphide and also optimize it for photovoltaic application.

Khallaf et al. (2009) reported that metal chalcogenide basically (binary-2 elements) such as CdSe and CdS from group II and group VI elements forms a very interesting area as research is concerned. When they are doped with different elemental dopants like boron, indium arsenide and chlorine, they form good window material (Shadia et al., 2008). Ternary derivatives of CdS have generated a lot of research interest for applications in the field of optoelectronic devices and especially cadmium selenium sulphide (Cd$_{1-x}$Se$_x$S) which has become so popular as far as good window materials for solar cell is concerned. Deposition of CdSeS thin films has been very successful using the CBD method.

1.2 Statement of the research problem

The optimization of the CdS and thin films qualities by varying the Se dopant by volume using CBD method formed the base of the research. The above thin films are known to have high resistivity, low optical transmittance and absorbance which limit their use as optical materials for photovoltaic applications. When the above thin films are combined with PbS as the absorber material, the efficiency of the cell can be improved. They can be improved by doping them with selenium, hence there is a need to improve these poor properties and provide additional information since there is limited information on CdS
selenium doped using CBD. In this research, CdS thin films were doped using Selenium using CBD method.

1.3 Objectives

1.3.1 General objective

To deposit and characterise Cd\textsubscript{x}Se\textsubscript{1-x}S/PbS P-N junction films for solar cell application.

1.3.2 Specific objectives

i) To deposit Cd\textsubscript{x}Se\textsubscript{1-x}S thin films at a temperature of 80±2°C as the concentration of Selenium dopant is varied.

ii) To deposit PbS thin films at a temperature of 27±2°C as concentration of Pb(NO\textsubscript{3})\textsubscript{2} per volume is varied.

iii) To optically characterize the thin films prepared in (i) and (ii) above using a double beam UV-VIS NIR 3700 Shemadzu spectrophotometer.

iv) To electrically characterize the thin films prepared in (i) and (ii) above using a four point probe method.

v) To fabricate a CdxSe1-xS/PbS p-n junction for solar cell using optimal values obtained from (iii) and (iv) and characterize it using a solar cell simulator.

1.4 Rationale of the study

The CdS thin films have proved to form good window materials due to their transmittance and electrical ranges (Abu-safe et al., 2004). The PbS has also proved to be a good absorber material as far as solar cells are concerned. Through doping the CdS
thin film with Selenium, we can obtain solar cells with varying efficiencies which in turn can be used for different applications. The ternary alloys of semi-conductors offer cheaper alternatives as far as solar cells are concerned. Ternary alloys are also known to have a well-defined band structure which varies continuously with the compounds composition. The Cd$_x$Se$_{1-x}$S and PbS forms a part of these ternary alloys. There is little information on CdS doped with Selenium semiconductors, hence the choice of researching on these ternary semiconductors for photovoltaic applications. The optical properties of Cd$_x$Se$_{1-x}$S and PbS are appropriate for solar cell applications as window and absorber materials respectively. There is a need to optimise these two materials for solar cell applications. In the event of optimising these films, this thesis also investigated the effect of doping CdS with Selenium on the optical and electrical properties and finally fabricated a Cd$_x$Se$_{1-x}$S/PbS solar cell using the optimised thin films conditions.

1.5 Structure of thesis

This research report has six chapters. The first chapter is the introduction of the background of the research was done and related to the research itself. Highlights on how the thin films in the fabrication of p-n junction for solar cell is done. Selection of good materials for use in the solar cell fabrication is clearly and scientifically analysed. Justification for the above choice of the materials is given. General and specific research objectives are given in point form and finally the thesis structure is clearly highlighted.
Chapter two gives the related work done by other researchers on areas related to my research. Emphasis of the reported literature on the electrical and optical properties of doped CdS with various dopants is paramount in this research work. A brief analysis of the results of band gap, resistivity and other characterization properties obtained by different deposition methods and conditions are mentioned. Great concentration is accorded the Selenium doped CdS thin films deposited by CBD method. A brief conclusion on both electrical and optical properties of PbS at room temperature when deposited by CBD method. The chapter ends up with a description of some reported literature which has similar work as that of the fabricated CdS/PbS solar cells as well as identifying the research gaps.

Chapter three gives the theoretical background considerations in the entire research. The theory on the semiconductor thin film’s analysis and performance is well highlighted. The methods and materials to be used in this research are well presented in chapter four. Chapter five gives results and discussions using tabulated and graphical format. Useful optical constants and cell parameters for solar cell are also given. Chapter six is the last chapter which concentrates on recording conclusions and recommendations on the whole project work. References citation and the appendices are presented thereafter respectively.
CHAPTER TWO

LITERATURE REVIEW

In this chapter, a review of some related work on deposition of CdS and PbS thin films is done. Cadmium sulphide and lead sulphide thin films are semiconductor compounds of the type II-IV which form an interesting area as far as many practical purposes are concerned and specifically for photovoltaic cells applications among others. The above two materials are suitable for photovoltaic cells. Most of the group II-VI thin films compounds includes compounds formed from elements of group II and VI of the periodic table. Through studies, the above group of materials have revealed much more about their general nature, features of their chemical stability and their energy gaps at room temperature (Ohring, 1990).

2.1 Cadmium Sulphide (CdS) thin films

CdS, CdSe and CdTe belong to group II-VI which forms most of chalcogenide semiconductors. This group of semiconductors is of great interest since they do have high photoconductivity in the visible region of the electromagnetic spectrum. Among the above materials, CdS is the most appealing as far as photoconductivity is concerned, hence it is mostly applicable in solid state devices (Abu-safe et al., 2004). Mosiori (2015) reported CdS being considered as a good window material for CIGS and CdTe solar cells. Thus CdS used in thin film deposition is on increase. The study of the same CdS should also increase to match the application demand. There is much concentration from researchers on optimizing the CdS and PbS thin films properties.
Some researchers have focused on enhancing the optical properties of the thin films (Amanullah et al., 2005). Al-yashi (2007) suggested that the electrical properties of doped CdS thin films can achieve higher efficiency. Dzhafarov et al. (2006) likewise noted that doped CdS thin films could produce high efficiency in photovoltaic solar cells. The improvement of the pure cadmium sulphide (CdS) has been tried so as to come up with large grain CdS films after deposition on low cost precursors. Ohring (199) found that the type of precursor solutions used played a very crucial role in the initial stages of growth of the CdS thin films. Investigations on CdS thin films are very encouraging due its many milestones attained by earlier researchers.

Different deposition methods and techniques have been used to obtain photovoltaic cell quality thin layers although this will be thoroughly discussed later in chapter three. It is of inevitable effort to note the bottlenecks of all the deposition methods so as to avoid the methods when carrying out researches. Ramaiah et al. (2000) noted some difficulties in obtaining stoichiometric Cadmium sulphide thin films could also be obtained by the evaporation method although the spray deposition method could only work at higher temperatures.

### 2.1.1 CdS thin film’s electrical properties

The electrical properties of pure Cadmium sulphide (CdS) thin film are mostly dependent on the deposition conditions. Mahmoud et al. (2000) realised that evaporation method prepared thin films for photovoltaic cell applications usually have a resistivity between
to $1.0 \times 10^3 \Omega$-cm. Shadia et al. (2010) noted that CdS thin films are usually n-type in nature and its conductivity is facilitated by stoichiometry deviation, hence influences the films to have cadmium excess or sulfur vacancies. The resistivity decreases as the thin film increases in thickness. In the thermal evaporation technique, the ratio of Cd: S = 1:5 thin films showed the lowest resistivity of $10^{-3} \ \Omega$-cm from CdS: In [1:5] samples. On the contrary, doped thin films resistivity is relatively insensitive to the substrate’s temperature. This is when compared with the pure cadmium sulphide thin films. When CdS is doped with Indium, films shows an increase in their carrier concentration by almost orders of magnitude up to a concentration of 2% by weight and thereafter the size of carrier concentration stagnates (Shadia et al., 2010).

Chlorine has been used as a dopant of CdS thin films. Tsai et al. (1996) through their research noted that pure Cadmium sulphide when doped with Chlorine gas presented low photoconductivity at room temperatures. Also Chlorine doped CdS showed a decrease in their hall mobility as the temperature increased. The thin films prepared by evaporation technique where CdCl$_2$ mixed with CdS powders showed increased resistivity and carrier concentration. Abu-safe et al. (2004) did a research and noted that for the pure Chlorine low-doped thin films; there is a rapid increment on mobility. (i.e below 0.05% CdCl$_2$). CdS doped with Chlorine gas is invariably n-type with resistivity having a range of about $10^8 \ \Omega$-cm. Tsai et al. (1996) noted an exponential increase in carrier concentration on the thin films with respect to the precursor temperature. Bacakshi and Cerik (2006) found that the as-deposited thin films using the sputtering method recorded a resistivity of up to $10^8 \ \Omega$-cm. This is similar with (Herrero et al., 2000) findings on their research where the
chemically bath prepared CdS thin films after annealing at 200°C in vacuum and in Argon showed a resistivity decreasing from $10^5 \, \Omega$-cm to about $10 \, \Omega$-cm. Another similar resistivity results were reported but for thinner than 0.5μm films by Uda et al. (1990).

Shalabaeva et al. (2017) reported that Cd$_x$Se$_{1-x}$S thin films deposition was successful on a quartz substrate by thermal evaporation of the bulk material in vacuum by laser evaporation deposition. Altosaar et al. (2004) noted that the most widely researched photovoltaic cells are cadmium sulphide (CdS) cells. The efficiencies of these CdS cells are limited by some factors. Through a series of researches, CdS films have been adopted for use as window materials for photovoltaic devices like solar cells, sensors, lasers etc. and they can be deposited using several methods.

Cruz et al. (2006) deposited CdS thin films by CBD onto the SnO$_2$ covered glass substrates and found that transmittance reduced greatly in the visible spectrum. Al-ayashi (2007) reported that when incident photon streams are directed onto semiconductor material, electrons are released and if the energy of photons is sufficient then current flows. Sandeep (2008) used electrochemical deposition method to prepare CdS films from a solution of cadmium chloride (CdCl$_2$), sulphur, and dimethyl sulfoxide and the films showed a work function of 4.7eV. Ezema et al. (2006) doped CdS with selenium by CBD method using sodium selenosulphate (Na$_2$SeSO$_3$) as the source of selenium and reported a resistivity of as low as $1.7 \times 10^{-2} \, \Omega$ cm and a carrier density as
high as $1.91 \times 10^{19}$ cm$^{-3}$. The band gap of CdS:Se films slightly decreased as the concentration ratio of Selenium to Cadmium in the preparation solution increased.

A photovoltaic cell requires a good absorber layer. The quality of this layer determines its cell efficiency and performance. CBD method has been used to deposited $n$-type and $p$-type ternary semiconductors that have direct band gaps for use in fabricating photovoltaic cells. The bottleneck of trying to replace ternary semiconductors with silicon based semiconductors has attracted many researchers. The main aim of this research is to optimize Cd$_x$Se$_{1-x}$S thin films for photovoltaic use, as well as fabricating a photovoltaic cell using locally available materials by an easy, cheap and simple method (CBD).

### 2.1.2 CdS thin film’s optical properties

The main determinants of pure CdS thin films optical properties are microstructure and the deposition conditions. High transmittance and good near-IR reflectance are well known properties of CdS thin films. Amanullah et al. (2005) found that evaporated CdS thin films are specularly reflecting. The lumpiness of the film surface increases with thickness causing large diffuse scattering in the film. The optical constants refractive index $n$ and extinction coefficient $k$ determined from evaporated thin films over the wavelength range 0.25μm to 2.0μm by measurement of normal incident, reflectance and transmittance and taking to account of the surface texture. The analysis of the above resulted in a direct transition ranging from 2.42 eV to 2.82 eV. A combined direct and in-direct transition of
beyond 2eV is also evident. Both the refractive index \(n\) and extinction coefficient \(k\) values appeared as if they were directly dependent on the substrate temperature of deposition. The refractive index \(n\) approached a value close to that of the single crystal material.

Mahmoud et al. (2000) reported the refractive index of CdS having increased linearly with that of film thickness, however the extinction coefficient \(k\) rapidly decreased inversely with the increase in wavelength in the range of 400-600nm. This is attributed to the increase in optical density. Vigil-Galan et al. (2005) reported that sputtered pure Cadmium sulphide (CdS) thin films showed sharp optical trend of cut-off near 0.52μm with respect to the \(E_g\) of pure Cadmium Sulphide. This is similar to that obtained through spray deposition method although the fundamental absorption edge is not affected by the microstructure.

Rami et al. (1990) reported on chemically bath prepared CdS thin films from different sources of Cadmium for example Chloride and Acetate. The above present or allow a high transmittance of between 70-80\%, one can deduce that very thin pure Cadmium sulphide (CdS) are capable of allowing a transmission of close to or below 500 nm wavelength. This should be a correspondence to CdS energy gap. This was true until when a stronger absorption was realised at around 300 nm and this was an attribute of the glass substrate presence. The average transmittance in wavelength range of 400- 800 nm depends solely on the CdS thin film thickness due to the absorption in the films (Herrero et al., 2000).
2.2 PbS thin films

Lead sulphide (PbS) is a crucial semiconductor with a direct narrow band gap of about 0.4 eV at 300K. It is considered to have an excitation Bohr radius of about 18 nanometers. These two characteristics make the PbS thin films suited for use as infrared detection and solar cell application. The above two properties are very much correlated with the nature of the substrates used and the growth conditions. Seghaier *et al.* (2006) reported on PbS thin films having been prepared using the chemical bath deposition. Both transmittance and reflectance of less than 40% was recorded within 300-1800 nm wavelength range. This is attributed to the film’s surface diffuse reflections while their dark electrical resistance was in the range of $10^{10}$-$10^{11}\Omega cm^{-1}$.

PbS thin films are generally p-type because of their high absorbance and the two properties earlier mentioned. Amusan *et al.* (2007) found that PbS films absorption depicted a non-linear type of relationship with respect to deposition time. Misle (2009) did a research on CBD method and noted that it attracted many researchers since it does not call for sophisticated instruments and its cheapness. He also reported that CBD was easy and convenient to carry out. For large scale deposition, CBD was the best choice since it yielded good quality thin films. It is suggested that the Lead sulphide (PbS) thin films when optimized can make quite good absorber material for both visible and infrared light in the electromagnetic spectrum. In this scientific report, the optical and electrical characteristics of pure Cadmium sulphide films as deposited employing the CBD technique. The precursor solution concentration will be varied from 0.3M up to 0.7M.
2.3 CdS/PbS Solar Cell

Pure cadmium sulphide (CdS) and Lead sulphide PbS semiconductor materials are widely used as far as CBD method of deposition is concerned. Between 1969 and 1970’s solar cells of CdS/PbS were reported with an open circuit voltage ($V_{oc}$) of up to 450 mV and a short circuit current ($I_{sc}$) of less than 1mA/cm$^2$. Harumi et al. (1995) made a report on CdS/PbS/Ag using the CBD method. The cell fabricated realised an open circuit voltage ($V_{oc}$) of more than 500 mV, Short circuit current ($I_{sc}$) of above 3 mA/cm$^2$. These values were obtained under a 1.0 kW/m$^2$ illumination.

All the new technologies for production of photovoltaic cells are geared towards the utilization of very thin film geometry. This is aimed at economizing the materials used so as to maximum energy conversion from the incident photo radiations. Investigation about the rate of performance of CdSeS/PbS solar cell structures by sequentially depositing them one at time using the chemical bath deposition method for both Cd$_x$Se$_{1-x}$S and PbS layers will be done.

2.4 Related studies

Photovoltaic cell contacts are generally metallic for good conductivity. Good conductors of electricity can enhance the cell efficiency, so it is wise to select good contacts. When the circuit is closed, direct current tends to flow. Generation of electricity was first done by a French scientist, A.E. Becquerel in 1839. By 1946 this cell efficiency had improved to only 1%. Various thin-film technologies being developed target reducing the mass of
light absorbing material required in creating these cells hence in turn reduce processing costs.

Chapin and Pearson (1954) recorded that by 1883 a working photovoltaic cell had been built but in addition they used a semiconductor of selenium with an extremely thin layer of gold as contacts. Siu and Kwok (1978) did a research on the photovoltaic effect of CdS/Cu₃S thin-film solar cells deposited by chemical sprayed CdS films using a dipping method. The CdS photovoltaic response, film thickness, grain-size, structure, spectral responses and I-V character was much affected by the preparation method.

The thermal evaporation method technique was employed in bulk material in vacuum and a successful deposition on glass substrate reported. (El-Nahass et al., 1992). A band gap $E_g$ of 0.4 to 0.5 eV was realised using Vegard’s relation. Cruz et al. (2006) deposited CdS thin films by CBD onto the SnO₂ covered glass substrates and found that transmittance reduced greatly in the visible spectrum. Sandeep (2008) used electrochemical deposition method to prepare CdS films from a solution of cadmium chloride (CdCl₂), sulphur, and dimethyl sulfoxide and the films showed a work function of 4.7eV. Ezema et al. (2006) doped CdS with selenium by CBD using sodium selenosulphate (Na₂SeSO₃) as the source of selenium and reported resistivity of $1.7 \times 10^{-2}$ Ω cm and carrier density of $1.91 \times 10^{19}$ cm$^{-3}$. The energy band gap of CdS:Se thin films slightly decreased as the concentration ratio of Selenium to Cadmium in the preparation solution increased. The study is investigating the performance of Cd₃Se¹⁻S
and PbS thin films and finally fabricate a photovoltaic cell using the optimized values obtained throughout the investigation using the CBD method.
CHAPTER THREE

THEORITICAL CONSIDERATIONS

3.1 Semiconductor thin films

Semiconductor materials are the ones which exhibit a number of useful but also unique properties related to their electronic structure. Semiconductors can be fabricated to be in bulk, wafer or in thin films. A semiconductor material is said to be in thin film form only when it is built up as a thin layer on a substrate by a controlled condensation of the individual atomic, molecular, or ionic species (Amanullah et al., 2005). Thin films are also regarded as two dimensional materials fabricated by process of condensation of atoms, molecules or ions. This is what makes them have unique properties significantly different from their corresponding bulk materials. These unique properties are as a result of the changes that occur in their physical dimensions, geometry and microstructure. Thick films are prepared either by a different application of solution dispersion or by paste of the material on a substrate and then letting them to dry irrespective of their thickness (Khallaf et al., 2009).

In thin films there are deviations from the properties of the corresponding bulk materials that arise because of their small thickness, large surface-to-volume ratio and their unique physical structure which is a direct consequence of the growth process (Amanullah et al., 2005). Most of the new thin technologies coming up are based on the use of materials with very thin film geometry because they tend to lower costs and also lower material
consumption (Shadia et al., 2008). It is currently known that a relatively small group of elements and compounds have important electrical property called ‘semi-conduction’. This is a property where they are neither good electrical conductors nor good electrical insulators but instead their ability to conduct electricity is intermediate and that is why these materials are called semiconductors.

3.2 Solar energy

Solar energy is the type of energy which originates from the sun and reaches the earth surface in form of an electromagnetic wave. A solar cell is a device that is capable of converting light energy into electrical energy through photoelectric effect. This cell is a semiconductor p-n junction that exhibit unique and useful properties related to their electronic structure. Solar energy is abundant, non-pollutant and renewable in nature.

3.3 Solar cell

When a photon is incident on the cell, it gets absorbed by an electron in the valence band and therefore gets excited and moves to the conduction band. The above concept creates a hole in the valence band. The electron and holes generated act as free charge carriers and heavily contribute to the photo-generated current. Unless there is an electric field created, the electrons and holes are free to move randomly and are capable of recombining (Nelson, 2003).
3.3.1 The thin film p-n junction solar cell

Solar cells are basically made from thin film p-n semiconductor diode. They convert sunlight directly into electricity by exploiting a physical process called photovoltaic effect (Markvat, 1998). It only generates direct current from solar radiation. Solar energy is composed of photons with energy corresponding to different wavelengths in the electromagnetic spectrum (IR-VIS-UV). As photons fall on a solar cell, they are reflected, transmitted or absorbed. Only absorbed photons are the ones which generate electricity. Photons with energy ($h\nu$) greater than band gap of the semiconductor are absorbed by electrons in the valence band thereby exciting them to higher states. These excited electrons cross the band gap to the n-side leaving behind an empty space called a hole, hence creation of electron-hole (E-H) pairs near the junction. These E-H pairs in turn generate a photocurrent. The E-H pairs are separated by internal junction electric field (built-in potential). Holes drift to the p-side while electrons drift towards the n-side. This creates potential across the junction as in figures 3.1 and 3.2 (Wielder, 1982; Stone, 1993; Shar et al., 1999; Yilmaz, 2004).

**Figure 3.1:** Diagram of P-N heterojunction solar cell (Markvat, 1998).
Figure 3.2: (a) P-N heterojunction solar cell at thermal equilibrium in dark. (b) P-N junction solar cell under illumination, open circuit conditions, where: 1 and 2 refers to N-type and P-type semiconductor in the PN junction respectively, \( E_g \) is band gap, \( E_F \) is fermi level, CB is conduction band, VB is valence band and \( V_{oc} \) is open circuit voltage (Tsubomura and Kobayashi, 1993).

The E-H pairs increase minority charge carrier concentration. The potential energy barrier decreases allowing the current to flow and open circuit voltage (\( V_{oc} \)) is generated across the junction (Tsubomura and Kobayashi, 1993; Stone, 1993). \( V_{oc} \) is limited by the band gap energy (\( E_g \)) of the absorber material. Maximum \( V_{oc} \) is calculated using the following relation (Kemell, 2003):

\[
\text{Max } V_{oc} = \frac{E_g}{e}
\]  
(3.1)
Where $V_{oc}$ is open circuit voltage, $e$ is electron charge and $E_g$ is the energy band gap.

### 3.3.2 Thin film solar cells

A thin-film solar cell is a second generation solar cell that is made by depositing on or more layers on a substrate. Thin film is a layer of a material which can range from fractions of nanometer to several micrometers in thickness. A photovoltaic cell is a cell which is capable of generating an electrical power by converting solar radiation in to direct electricity using semiconductors that exhibit photovoltaic effect (Markvart, 1998). New researches on the thin film are still on due to the need of the environment friendly source of energy. It’s a global necessity to see every country going green in terms of energy sources.

### 3.3.3 Solar cell parameters

Figure 3.3 shows a one-diode equivalent circuit diagram of an ideal solar cell, which includes a current generator representing photo-extinction (Markvart, 1998).

![Figure 3.3: The Ideal diode model for a solar cells (Markvart, 1998).](image)
The current flowing through the circuit in the presence of light is given by the following equation, (Kemell, 2003);

\[ I = I_0 \left[ \exp \left( \frac{qV}{AkT} \right) - 1 \right] - I_L, \]  

(3.2)

where,

- \( I_0 \); is the saturation current,

- \( A \); is ideality factor, and

- \( I_L \); is the light generated current.

All the parameters in equation 3.2 are all important as far as solar cells are concerned. We need to look at each of the parameters, quantifying the performance of a solar cell individually.

### 3.3.3.1 Short circuit current (\( I_{sc} \))

Short circuit current (\( I_{sc} \)) is the current through the solar cell when the voltage across the solar cell is zero. (i.e when the solar cell is short circuited.) Alternatively short circuit current can also be defined as the current on the solar cell when no bias is applied to the cell. \( I_{sc} \) can be obtained when \( V=0 \) in equation 3.2 yielding equation 3.3 (Kemell, 2003);

\[ I_{sc} = -I_L \]  

(3.3)
3.3.3.2 Open circuit voltage (\(V_{oc}\))

The open-circuit voltage (\(V_{oc}\)) is defined as the maximum voltage available from a solar cell. \(V_{oc}\) can be realised when the current in a solar cell is Zero. The open-circuit voltage corresponds to the magnitude of forward bias on the solar cell junction with the light-generated current. \(V_{oc}\) is developed when terminals are open (i.e infinite load resistance) \(V_{oc}\) is given by equation 3.4, (Kemell, 2003);

\[
V_{oc} = A \left[ \frac{kT}{q} \right] ln \frac{I}{I_0} + 1
\]  

(3.4)

3.3.3.3 Dark and light I-V characteristic of solar cell

The surface of the earth is illuminated by the sun during the day. The expectation of radiant heat is definitely during these illumination hours. It may sound odd to measure the performance of the solar cell during the night or in darkness. This trend of cell performance in dark is not very important however the dark I-V measurements can be used to examine the diode properties (Markvart, 1998). Under illumination, small fluctuations in the light intensity add considerable amounts of noise to the system making it difficult to produce (Markvart, 1998). An illustration of I-V curves for a solar cell under both illumination and in the dark is shown by figure 3.4 below.
The I-V curve of a PV cell in light mode is shown in figure 3.4.

**Figure 3.4:** Dark and light I-V characteristic of solar cell (Markvart, 1998).

**Figure 3.5:** Diagram showing current-voltage (I-V) curve of a PV cell in light mode
3.3.3.4 Fill Factor (FF)

Fill factor (FF) is defined as the ratio of the actual maximum obtainable power to the product of the open circuit voltage and short-circuit current. From Figure 3.5 $P_{\text{max}}$ is maximum power that is obtained where $V_{\text{max}}$ and $I_{\text{max}}$ are voltage and current points at $P_{\text{max}}$, $P_{\text{max}}$ is area of the rectangle with sides $V_{\text{max}}$ and $I_{\text{max}}$;

$$P_{\text{max}} = I_{\text{max}} V_{\text{max}}$$  \hspace{1cm} (3.5)

The definition of FF is the ratio of maximum power to the product of $V_{\text{oc}}$ and $I_{\text{sc}}$;

$$\text{FF} = \frac{V_{\text{max}} I_{\text{max}}}{V_{\text{oc}} I_{\text{sc}}}$$  \hspace{1cm} (3.6)

FF is an index which gives the quality of a solar cell in terms of performance.

3.3.3.5 Efficiency (\(\eta\))

The efficiency of a solar cell is defined as the ratio of $P_{\text{out}}$, to that of electrically generated power or to the input power on the cell. This parameter is a capability on how a solar cell converts solar energy to electrical energy;

$$\eta = \frac{V_{\text{oc}} I_{\text{sc}} \text{FF}}{P_{\text{in}}}$$  \hspace{1cm} (3.7)

$P_{\text{in}}$ is a product of area of the solar cell and the irradiance and hence it can be expressed as below;

with, $$P_{\text{in}} = E_{\text{in}} \times A$$  \hspace{1cm} (3.8)

where, $E_{\text{in}} = \text{Irradiance}$
A = Area of the cell

3.3.3.6 Series and shunt resistances

Solar cells are known to undergo parasitic losses. This is due to the interconnection and intrinsic resistance of the semiconductor. These losses in the solar cell can be assumed as series and shunt resistance with respect to the ideal solar cell. Figure 3.6 shows the schematic representation of series and shunt resistance in a solar cell.

Figure 3.6: Schematic illustration of a 1-diode equivalent solar cell circuit model
3.3.3.7 Series Resistance

Solar cell series resistance is due to metal-semiconductor contact resistance, resistance in metal contacts, and resistance in semiconductor substrate. These three types of resistances are ohmic. $R_S$ is the resistance the carriers encounter. Low conductivity of the window layer, absorber layer and recombination of carriers into the bulk materials contribute to the $R_S$. The series resistance reduces the maximum obtainable output power and hence softens the I-V characteristics of a solar cell in the fourth quadrant. This eventually degrades fill factor (FF) of the cell. It has been observed that the fill factor of a solar cell decreases by 2.5% for each 0.1 increase in resistance (Meena et al., 2002).

![Diagram showing the effect of series Resistance on the I-V curve of a solar cell](image)

**Figure 3.7:** Diagram showing the effect of series Resistance on the I-V curve of a solar cell
3.3.3.8 Shunt Resistance

Shunt resistance is due to leakage currents, pinholes and voids. Shunt resistance degrades the fill factor and \( V_{oc} \). The resistance of the diode is mostly more than the \( R_{sh} \), which enables current path through the shunt resistance thereby affecting the \( V_{oc} \). Variation in I-V characteristics with \( R_{sh} \) shown in figure 3.7

![Diagram showing the effect of Shunt Resistance on the I-V curve of a solar cell](image)

**Figure 3.8:** Diagram showing the effect of Shunt Resistance on the I-V curve of a solar cell

3.3.3.8 Diode factor

Diode factor is a parameter that gives the ‘perfectness’ of the p-n junction. The diode factor is sometimes referred to as “squareness”. The diode factor is dependent on the mechanism of junction transport. For example if \( A=1 \), where \( A \) is the ideality factor. The \( A \) is clearly seen when we match the I-V diode curves. The transport is dominated by diffusion; if recombination is primary transport mechanism then the value of \( A \) is closer to 2. Transport
processes and material dictate the quality of factor. For optimal results in solar cells, the diode factor is close to unity. Defects and impurities increase the value of $A$. $A$ is determined by the slope of the $\ln (I)$ against $V$ curves.

3.5 Thin film deposition methods

There are many methods of thin film deposition. We have around five methods of thin film deposition namely: Physical Vapour deposition (PVD), Chemical Vapour deposition (CVD), Chemical bath deposition (CBD), Spin coating, Plating and Oxidation.

3.6 Chemical bath deposition method

We have three techniques which are classified as CBD methods. These are solution growth process method or Chemical bath deposition method, screen printing and spray pyrolysis method. CBD is method used to deposit thin chemical films and nanomaterials. This method is best for large-area batch processing or continuous deposition.
CHAPTER FOUR

MATERIALS AND METHODS

This chapter commences by giving an outline of the procedures used to prepare the glass substrates before the deposition process starts. This is followed by the deposition procedures in details. Thirdly there is highlight on how the characterization of the thin films is carried out. The fabrication process of the solar cell then follows stating the instruments used to characterize the cell. Lastly the concepts and procedures on solar cell characterization are presented.

4.1 Materials for thin film deposition

Analytical grade chemicals were purchased from chemical shops and used deposit thin films. To realize the deposition of Cd$_x$Se$_{1-x}$S thin films, chemicals used were; Ammonium nitrate (NH$_4$NO$_3$), Cadmium nitrate (Cd(NO$_3$)$_2$), 29.4% Ammonia and double distilled de-ionized water. In the deposition of lead Sulphide (PbS) thin films, the following chemicals were used; Thiourea (CS(NH$_2$)$_2$), Tri-ethanolamine(C$_4$H$_6$O$_6$), Lead nitrate solution(Pb(NO$_3$)$_2$) and sodium hydroxide solutions.

4.1.1 Glass substrate cleaning

A substrate is defined as a surface of a solid onto which a thin film can be deposited through the adsorption process. Choice of the surface as far as texture and nature are concerned is very crucial since they do dictate the properties of the deposited thin films. The ordinary
glass microscope slides (Pyrex) were substrate choice for this research work. The chemical composition of the above microscope slides were rated as follows; 0.4% K₂O, 2.2% Al₂O₃, 3.8% Na₂O, 12.9% B₂O₃ and 80.5% SiO₂ (Valensuela et al., 2003). Cleaning of glass substrate procedure was as follows: First the glass substrates were soaked in liquid detergents and left for around 30 minutes under sonication. This was followed by rinsing the glass substrates in distilled water. They were then immersed in distilled water and put in sonication for another 30 minutes. Then the glass slides were removed and rinsed again in double distilled water and then left to dry in a desiccator. Once the glass substrates were dried in the desiccator, then they were ready for the deposition process.

4.2 Chemical bath deposition (CBD) method

CBD method is purely based on the concept of controlled precipitation from precursor solution containing a compound on a suitable substrate. The substrate is inserted in an aqueous solution containing the precursors; a metal ion, chalcogenide source, the added acid or base and a complexing agent is necessary so as to get rid of the unwanted compounds which may be formed in the deposition process. A complexing agent is utilized in deposition of thin films e.g. NH₃, tri-ethanolamine, disodium ethyle diaminetetra acetate etc.

A typical chemical bath solution is comprised of three parts: at least one salt of metal M⁺ⁿ, a source of chalcogenide X⁻ᵐ (where X = oxygen, sulphur, selenium, etc.), and a complexing agent in aqueous solution. The metal salts are chosen from moderate to high solubility salts and the desired end product. The chalcogenide source is chosen based on
the desired end product and also on the rate at which $X^{-m}$ is generated. The formation of pure Cadmium sulphide (CdS) thin film, the Cd ion can be obtained from the following Cadmium salts; (Cd(NO$_3$)$_2$), CdAc, CdCl$_2$, and CdSO$_4$. On the other hand, the Sulphur ion used in the formation of CdS can originate from Thiourea (NH$_2$CSNH$_2$). Thiourea is an organic sulphur containing reducing agent. Other organic Sulphur containing reducing agents includes Thioacetamidamide (NH$_2$CSH$_3$). Ammonia (NH$_4$OH) is another good reducing agent though it doesn’t have its own Sulphur ion.

There are two models as far as CBD growth in the production of CdS thin films is concerned. The first model is Ion-by-ion which entails the growth of the CdS by Cd$^{+2}$ and S$^{-2}$ ions. The resultant deposited film in this first case is fairly thin. The second model is Cluster-by-cluster where the growth of the thin film is realized by the adsorption process where the colloidal CdS particles precipitate in the precursor solution. Khallaf et al. (2009) found that use of cluster-by-cluster technique yielded Powderly and thick films. Amanullah et al. (2005) noted that the deposition of CdS occurred when [Cd$^{+2}$] and [S$^{-2}$] ionic product exceeded the CdS solubility product [K]. The release Cd$^{+2}$ ions of are known to be gradual from the dissociation of a Cadmium complex part. Decomposition of Thiourea in alkaline solution yields S$^{+2}$ ions. The chemical formation mechanism of CdS is given by equations 4.1 to 4.7 (Amanullah et al., 2005);

a) Break down of Ammonium hydroxide in aqueous solution forming an alkaline solution and a complex agent as shown by equation 4.1;

$$\text{NH}_3 + \text{H}_2\text{O} \rightarrow \text{NH}_4^+ + \text{OH}^- \quad (4.1)$$
b) On the other hand, complex compounds are formed by Cadmium salts in the ammonium hydroxide solution as shown by equations 4.2 to 4.4;

\[
\begin{align*}
4(\text{NH}_3) + \text{Cd(NO}_3)_2 & \rightarrow \text{Cd(NH}_3)4[\text{NO}_3]_2 \quad (4.2) \\
\text{Cd(NH}_3)_4^{+2} & \rightarrow 4\text{NH}_3 \cdot \text{Cd}^{2+} \quad (4.3) \\
\text{Cd(OH)}_2 & \rightarrow 2(\text{OH})^- + \text{Cd}^{2+} \\
2(\text{NH}_3) + \text{Cd(OH)}_2 & \rightarrow \text{Cd(NH}_3)_2^{2+} + 2(\text{OH})^- \quad (4.4)
\end{align*}
\]

c) Thiourea being the sulphide ion source, simultaneously releases the following ions in alkaline media as shown by equation 4.5 and 4.6;

\[
\begin{align*}
(\text{NH}_2)_2\text{CS} + 3\text{OH}^- & \rightarrow 2\text{NH}_3 + \text{CO}_3^{2-} + \text{SH}^- \quad (4.5) \\
\text{SH}^- + \text{OH}^- & \rightarrow \text{S}^- + \text{H}_2\text{O} \quad (4.6)
\end{align*}
\]

d) Finally a chemical reaction of Cadmium and Sulphide ions takes place to form CdS as per the equation 4.7;

\[
\begin{align*}
\text{Cd}^{+2} + \text{S}^{-2} & \rightarrow \text{CdS} \quad (4.7)
\end{align*}
\]

From equation 4.1 to 4.7, one can see that there is a correlation between the ammonia concentration and the Cd$^{+2}$ concentrations in the solution. Formation of Cadmium hydroxide [Cd(OH)$_2$] and tetra-ammine-cadmium [Cd(NH$_3$)$_2$$^{+2}$] complex ions is key in the formation of hydroxide ions [OH] is paramount in this productive reaction. The doped CdS thin films show some contributions from the dopant atoms which makes the research a bit more interesting to the researchers. The above gives lee way to vary the optical properties of the CdS thin films through doping process.
It is easy to deposit PbS thin films using the ion-to-ion technique even at room temperatures. The simple procedure for the above process can be represented as follows; lead ions present are complexed by Tri-ethanolamine in the solution to obtain a Lead complex ion (Popa et al., 2006);

\[
Pb(NO_3)_2.3H_2O + TEA \rightarrow [Pb(TEA)]^{2+} + 2(NO_3^-) + 3H_2O \quad (4.8)
\]

The complex ion \([Pb(TEA)]^{2+}\) formed breaks down to gradually release Lead ions as given by equation 4.9;

\[
[Pb(TEA)]^{2+} \rightarrow Pb^{2+} + TEA \quad (4.9)
\]

Simultaneously, Hydroxyl ion breaks from Thiourea the as follows;

\[
[(H_2N_2CS)] + OH^- \rightarrow CH_2N^2 + HS^- + H_2O
\]

\[
HS^- + OH^- \rightarrow H_2O + S^{2-} \quad (4.10)
\]

The two ions \(Pb^{2+}\) and \(S^{2-}\) chemically react to form a Lead sulphide (PbS) precipitate. The formed lead Sulphide precipitate gets deposited into a thin film. This is through the ion-to-ion mechanism as shown by equation 4.11;

\[
Pb^{2+} + S^{2-} \rightarrow PbS \quad (4.11)
\]

4.3 Experimental procedure

4.3.1 Deposition Cd_xSe_{1-x} S thin films

All the chemicals used to prepare the precursor solution for this project were of the analytical grade chemicals. The required masses for the analytical grade chemicals were
weighed accurately using a chemical balance so as to prepare the following solutions; pure Ammonium nitrate, Thiourea, Sodium Selenosulphate and Cadmium nitrate. Accurately weighed amounts of chemicals were used to constitute solutions of 0.004M Cadmium nitrate, 0.008M Ammonium nitrate, and 0.008M Thiourea in de-ionized water, stirred till all the particles dissolved and 20ml of each solution was to be used and hence put into a separate beaker. Topping up the volume to 100ml using de-ionized water was done. The water bath was heated to about 80±2°C while stirring. Using a burette, drop-wise addition of NH₄OH (29.4%) was done to the mixture so as to fix a pH of 9. The precursor solution was heated until a temperature of 80°C. The substrate was then inserted vertically into the precursor solution. The deposition time was of 25 minutes. The temperature of the precursor solution was maintained at 80°C ±2°C throughout the deposition process.

Doping of the CdₓSe₁₋ₓS films was done by varying volumes of uniform concentration of Sodium selenosulphate (Na₂SeSO₃) solutions by using the value of x by the formula \( x = \frac{B}{C+B} \), where B is the number of varying moles of Sodium selenosulphate solution and C being the number of moles of Cadmium nitrate. The value of x calculated using the above equation ranged from 0.05 to 0.95 (i.e. 0.05, 0.25, 0.5 and 0.75). After the deposited films dried up, the characterization of the films was done as-deposited. Figure 4.1 shows the chemical bath deposition set-up which was used.
Figure 4.1: Diagram of the Chemical Bath Deposition set-up.

Table 4.1: Deposition parameters varied to get the desired value of x.

<table>
<thead>
<tr>
<th>Batch no.</th>
<th>Value of (x)</th>
<th>Formula.</th>
<th>Vol. of Cadmium nitrate soln. (cm$^3$)</th>
<th>Vol. of Sodium selenosulphate (cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.0</td>
<td>CdS</td>
<td>20.0</td>
<td>0.0</td>
</tr>
<tr>
<td>B</td>
<td>0.75</td>
<td>Cd$<em>{0.25}$Se$</em>{0.75}$S</td>
<td>20.0</td>
<td>5.0</td>
</tr>
<tr>
<td>C</td>
<td>0.5</td>
<td>Cd$<em>{0.5}$Se$</em>{0.5}$S</td>
<td>20.0</td>
<td>10.0</td>
</tr>
<tr>
<td>D</td>
<td>0.25</td>
<td>Cd$<em>{0.25}$Se$</em>{0.75}$S</td>
<td>20.0</td>
<td>15.0</td>
</tr>
<tr>
<td>E</td>
<td>0.05</td>
<td>Cd$<em>{0.05}$Se$</em>{0.95}$S</td>
<td>20.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

The following formula given by equation 4.13 below was used to calculate the various concentrations of the precursor solutions used in the entire thin films deposition process;

$$ Molarity = \frac{\text{No.of moles x volume used}}{1000} $$  \hspace{1cm} (4.13)
Concentration was given by;

\[ Concentration = \frac{\text{mass used}}{RMM \times 1000} \text{ in moles per litre.} \quad (4.14) \]

4.3.2 Deposition PbS thin films

Analytical grade chemicals were purchased and their masses weighed accurately using a chemical balance so as to prepare the following solutions; solution of 1M Sodium hydroxide, 1M Thiourea and 1M Tri-ethanolamine. Variation range of Lead nitrate solution concentration was from 0.3M to 0.7M with an interval of 0.1M each. The precursor solutions were mixed in a 100ml beaker as follows; 5ml of Lead nitrate solution followed by 5ml of 2M sodium hydroxide and the mixture stirred. When the mixture turns milky, 6ml of 1M Thiourea was added followed immediately by 1M Tri-ethanolamine (2M) and the mixture was thoroughly stirred.

The dried glass substrates from a desiccator were vertically inserted and the mixture maintained for two hours at room temperature. The concentration of Lead nitrate solution was varied as per table 4.2.
Table 4.2: The parameters used in deposition of PbS thin film

<table>
<thead>
<tr>
<th>Pb$^{2+}$ Conc. (mol)</th>
<th>Vol. of lead nitrate soln Pb$^{2+}$ (cm$^3$)</th>
<th>Vol. 1M NaOH soln (cm$^3$)</th>
<th>Vol. of 1M TU (cm$^3$)</th>
<th>Vol. of TEA (cm$^3$)</th>
<th>Time (Min)</th>
<th>Temp. ±2°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>120</td>
<td>27</td>
</tr>
<tr>
<td>0.4</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>120</td>
<td>27</td>
</tr>
<tr>
<td>0.5</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>120</td>
<td>27</td>
</tr>
<tr>
<td>0.6</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>120</td>
<td>27</td>
</tr>
<tr>
<td>0.7</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>120</td>
<td>27</td>
</tr>
</tbody>
</table>

4.4 Characterization of deposited thin films

The thin films characterization was carried out in two forms, namely electrical and optical characterization. The electrical characterization was looked in to then followed by the optical characterization.

4.4.1 Electrical characterization.

In the electrical characterization of the thin films, the sheet resistivity and conductance was measured. The resistivity is the inverse of conductance as given by equation 4.16 on page 41.
4.4.1.1 Sheet resistivity

The sheet resistance \( R_{sh} \) is a measure of opposition of electric charges offered in a two dimensional film of uniform thickness. This resistance is used in describing semiconductor materials’ surface resistance. The SI unit for this sheet resistance is Ohm/sq. The instrument used to determine the sheet resistivity was the four point probe machine. In addition, the film must be symmetrical as shown in the figure 4.2 so as to minimize errors.

**Figure 4.2:** Diagram showing how to measure the sheet resistivity

Measurements are taken by sourcing the current through points 1 and 2 and potential difference is measured across points 3 and 4 as shown in figure 4.2. The values for current and voltage were then used to obtain resistivity of the film. Considering a thin film layer of thickness \( t \ll s \) (probe spacing), Current rings instead of spheres were obtained. The thin film’s sheet resistivity \( \rho \) was determined using four point probe method (Agumba, 2010). The four point probes were connected with a 2400 Keithley source meter. This method is per Van der Pauw set up (Pathinettam et al., 2000). A geometry square mapping of Cd\(_x\)Se\(_{1-x}\).
S and PbS thin films was adopted in measurement of resistivity as shown in the figure 4.2. Measurements were made through four contact probes at each corner of the thin film labeled 1, 2, 3 and 4 in an anticlockwise manner using Keithley 2400 source meter. X₁ and X₂ refers to the probe spacing on the thin film. The measurements taken were V₁₂ and I₃₄, V₃₄ and I₁₂, V₂₃ and I₁₄, V₁₄ and I₂₃ from which sheet resistance (ρ) was determined using equation 4.15 below:

\[
\rho = \frac{E}{J}
\]  (4.15)

where E is the the electric field magnitude (in volts per meter, V/m), J is the current density (in amperes per square metre, A/m²). Electric sheet resistivity (ρ) can also be defined as “how strong a material opposes the flow of electric charges”. The SI unit of sheet resistivity is [Ωm]. Electric conductivity (σ) or specific conductance is just the reciprocal quantity of resistance. Conductance is a measure of the ability to conduct an electric current. The conductivity is given by equation 4.16;

\[
\sigma = \frac{1}{\rho}
\]  (4.16)

The conductance is measured in Siemens per meter (S.m⁻¹) as its SI unit. where E is the the electric field magnitude (in volts per meter, V/m), J is the current density (in amperes per square metre, A/m²) and ρ is the static resistivity (in ohm-meter, Ω-m). Resistivity in both conductors and resistors can be expressed as in equation 4.17;

\[
\rho = R \left( \frac{A}{l} \right)
\]  (4.17)

where l is the length of the material (in meters m), R is the electrical resistance of the uniform specimen (in ohms, Ω), and A is the cross-sectional area (in square meters).
4.4.2 Optical properties measurement

In optical characterization of the thin films, the following constants were investigated: energy transmittance (T), refractive index (n), band gap ($E_g$), absorbance coefficient ($\alpha$), extinction coefficient ($k$) and reflectance (R). These constants are hereby looked into one by one.

4.4.2.1 Energy band gap ($E_g$)

The energy and gap ($E_g$) is the quantity of energy attained by an electron as it moves from the valence band to the conduction band. Scout program was used to determine the thin film’s band gap ($E_g$). The magnitude of Energy band gap ($E_g$) is the difference between the valence band (V-B) and the conduction band (C-B) of a certain material. This band gap energy is given in electron-volts (eV). The same $E_g$ can be determined by use of graphical method. The graph of $(\alpha h\nu)^2$ against the photon energy ($h\nu$) was drawn, and the value where the curve cuts the x-intercepts through extrapolation gives the $E_g$ (Al-ayashi, 2007). Figure 4.3 shows a sample of 0.5M PbS thin film band gap ($E_g$) obtained through the extrapolation method.
The absorption coefficient ($\alpha$) was determined from the relation in equation 4.18;

$$\alpha = 2.303 \left( \frac{A}{d} \right)$$  \hspace{1cm} (4.18)

where, $d$ is the thickness of the film and $\alpha$ is the absorbance coefficient value at a given wavelength ($\lambda$) and $A$ is the cross-sectional area in square metres. The two thin films Cd$_x$Se$_{1-x}$S and PbS are known to have direct band gaps and for direct transitions, the absorption coefficient ($\alpha$) is given by the following equation 4.19 (Ugwu and Onah, 2007);

$$\alpha = \left( \frac{h \nu - E_g}{h \nu} \right)^{1/2}$$  \hspace{1cm} (4.19)

The thin film’s band gap ($E_g$) can be obtained graphically through extrapolating the linear portions of the plots of ($\alpha h \nu$)$^2$ Vs ($h \nu$). That is when $\alpha$ is equated to zero.
4.4.2.2 Refractive index (n)

The refractive index ($n$) is a ratio which gives the information about the extent of bending of the radiation path as it transverses from one medium to another. The ratio ($n$) forms a very integral part as far as the opto-electronic devices and photovoltaic applications are concerned and hence there is a need to simulate it. The Scouts software has some preconfigured relations and constants governs the semiconductor materials as far as refractive index ($n$) and energy band gap ($E_g$) are concerned. Ravindra et al. (2006) came up with a relation 4.20 which could relate the refractive index to the band gap;

$$n = 4.08 - 0.62E_g$$

(4.20)

(Reddy et al. (2006) modified relation 4.20 to get relation in equation 4.21 which could overcome the short comings encountered by the relation in equation (4.20);

$$n = 3.59 - Log_e(E_g)$$

(4.21)

4.4.2.3 Absorbance coefficient ($\alpha$)

The absorption coefficient ($\alpha$) was also simulated using the same Scout software. The software is preconfigured with constants which could give the desired results as far as semiconductors are concerned. It is such a crucial parameter since it shows the correlation between the absorption coefficient ($\alpha$) and the photon energy ($hv$) such that for direct allowed transition, the relation reduces to Tauc’s equation 4.22;

$$\alpha = (hv - E_g)^{1/2}$$

(4.22)
Intensity in the thin films can be given by equation 4.23 from the fundamental relations of photon transmission and absorbance (Abdullah, 2007);

\[ I = I_0 e^{-\alpha t} \]  

(4.23)

where \( A = \log \frac{I_0}{I} \), \( \alpha = \frac{(2.303A)}{t} \) and \( t \) is the thickness of the film.

### 4.4.2.4 Extinction coefficient (k)

The Scout software was used to simulation the extinction coefficient (k). The obtained (k) was compared to the one realised in equation 4.24 (Abdullah, 2007). The extinction coefficient can be related with absorption coefficient as in equation 4.24;

\[ \alpha = \frac{4\pi k}{\lambda} \]  

(4.24)

The equation 4.24 an reorganized to get the extinction coefficient as in equation 4.25 (Keszler, 2007);

\[ k = \frac{\alpha \lambda}{4\pi} \]  

(4.25)

where \( \lambda \) is the wavelength of the photon and \( \alpha \) is the absorption coefficient.

### 4.4.2.5 Transmittance (T)

The transmittance is known to be the fraction of the incident electromagnetic power that is transmitted through a sample. Both the reflectance (R) and transmittance (T) of \( \text{Cd}_x\text{Se}_{1-x} \) and \( \text{PbS} \) films were measured using the UV-VIS NIR spectrophotometer 3700 DUV
whose schematic illustration is shown on figure 4.4 below. The graphs of transmittance and reflectance against the corresponding wavelengths were plotted. Scout software was then used to simulate the transmittance data since it is already configured with some optical constants of the solid state properties of thin films.

When photons of a certain wavelength and intensity $I_o \text{ (photon/cm}^2\text{)}$ is incident on a film, the photons carrying energy which is greater than the $(E_g)$ of the film, causes the electrons to undergo excitation and then absorbed and those with energies less than the band gap do not cause any excitation of the electrons and hence they are transmitted without any absorption. The transmittance therefore compares the intensities of incident ($I_o$) and transmitted ($I_t$) photons and is given by equation 4.26:

$$\text{Transmittance (T)} = \frac{I_t}{I_o}$$  \hspace{1cm} (4.26)

The schematic representation of light transmission in the spectrophotometer is shown below by figure 4.4.

**Figure 4.4:** Schematic diagram of a double beam spectrophotometer (http\:www.lab-training.com content.)
4.5 Solar cell fabrication

Both optical and electrical properties are important to consider when optimizing the performance of the fabricated cell. The individual thin films of both Cd$_x$Se$_{1-x}$S and PbS prior to fabricating the solar cell, are characterized to get the optimal values for use during cell fabrication. The window layer should have wide band gap, highest transmittance and lowest absorbance among other optical properties. On the contrary the absorber material should exhibit the following properties: very narrow band gap, low transmittance and high absorbance. The above two thin films should have lowest sheet resistivity. After the above considerations, then the optimized conditions were used in photovoltaic fabrications. An Aluminium drop paste was deposited on the Cd$_{0.5}$Se$_{0.5}$S to form the contact. Care was taken to ensure a small contact point as possible. An Aluminium paste was then finally used to make the back contact. The figure 4.5 below shows the resulting schematic representation of Al/PbS/ Cd$_{0.5}$Se$_{0.5}$S /Al/glass photovoltaic solar cell.

![Diagram of a fabricated solar cell](image)

**Figure 4.5**: Diagram of a fabricated solar cell.
4.6 Solar cell characterization

The testing of the fabricated Cd$_x$Se$_{1-x}$S/PbS cell for in-door solar cell was carried out using the solar cell simulator. The photovoltaic cell properties such as $(I_{SC})$ and $(V_{OC})$ were determined. This was done using the solar cell simulator. The data obtained from the solar cell simulator was manipulated to generate the fill factor $(FF)$ and cell efficiency $(\eta)$. The I-V results were tabulated so as see their relations. This was possible through the variation of the control resistance and the corresponding values of voltage and current recorded. It is from these results the I-V plots were done to get the properties of interest like fill factor $(FF)$ and efficiency $(\eta)$. By use of the solar cell simulator, calculation of the fill factor $(FF)$ and efficiency $(\eta)$ of the solar cell was done. Fill factor being the ratio of the obtainable power at the maximum power point $(P_m)$ over the product of the $(V_{OC})$ and $(I_{SC})$ (Uda $et$ $al.$, 1990). This is seen to reduce to the fill factor being the ratio of the maximum power at the maximum power point $P_m$ to the product of the $V_{OC}$ and $I_{SC}$. The equation for fill factor is given by equation 4.27;

$$FF = \frac{V_{max}I_{max}}{V_{oc}I_{sc}}$$  \hspace{1cm} (4.27)

Replacing the denominator $(V_{OC} \times I_{SC})$ with the power of the input light irradiance yielded the cell efficiency $\eta$. The efficiency $(\eta)$ was then determined using the quotient of maximum power obtained to that of input power. The input power $(P_{in})$ is a product of light irradiance $E$ (in W/m$^2$) and the surface area $A_c$ of the solar cell normally. The efficiency was obtained from equation 4.28 (Pethe, 2003);
\[ \eta = \frac{V_{\text{max}}I_{\text{max}}}{P_{\text{in}}} = \frac{V_{\text{o.c}}I_{\text{sc}}FF}{P_{\text{in}}} \] (4.28)

It is worth noting that the P_{\text{in}} is also a product of the irradiance (E_i) and the cell area (A_c) under illumination. The efficiency (\eta) is always expressed as a percentage so as to get the percentage cell efficiency (\%\eta).
CHAPTER FIVE

RESULTS AND DISCUSSIONS

In this chapter, presentation of the experimental results or findings obtained is done. Discussions of the findings of the research are also done. The results are presented in form of tables and graphs. First the optical characterization results of both Cd$_x$Se$_{1-x}$S and PbS thin films is given then followed by their electrical characterization. The results are discussed and compared with the available literature review. The choice of the optimized thin films after characterization was done and reasons given for the choice. Finally the chapter highlights the fabrication of the solar cell as well as giving the fabrication method. Solar cell parameters like fill factor (FF) and efficiency ($\eta$) for the fabricated cell are given.

5.1 Thin film’s Optical results

5.1.1 Optical results of Cd$_x$Se$_{1-x}$S thin films

Figure 5.1 below illustrates the variation between the transmittance with wavelength of Se doped CdS (Cd$_x$Se$_{1-x}$S) thin films. Wavelength selected was from 200 to 2000nm. From the graphical observation, all Cd$_x$Se$_{1-x}$S thin films exhibited a higher transmittance in comparison with non-doped CdS (i.e above 79% in the visible region wavelength range). Cd$_{0.5}$Se$_{0.5}$S had the highest transmittance in the same visible region. The increase in transmittance as the Selenium concentration per volume increase is attributed to the formation of the CdSeS phases/nanocrystals (Mosiori, 2013). The doping of CdS thin films with Se makes the films more transparent. These results agree with the ones presented by
Kasim et al. (2008) since they got 80% and above transmittance over 300-1200nm wavelength range. A transmittance of over 90% in the 300-1200 nm wavelength range was reported by Kumar and Sankaranayanan (2009).

![Figure 5.1: Transmittance Vs wavelength of Se doped CdS](image)

Figure 5.2 is a graph that shows the relationship between the reflectance and wavelength of the Cd$_x$Se$_{1-x}$S thin films. The reflectance range was from 8-15% as shown in figure 5.2. The non-doped CdS thin films recorded the highest reflectance of about 15% than all the other Se doped CdS thin films. The Cd$_{0.5}$Se$_{0.5}$S thin film presented a reflectance of 8.6% which was the lowest compared to the other samples in the range of 380 nm to 780 nm. From the results, it is evident that there is reflectance reduction due to the Se increase in CdS thin films. This was attributed by the formation of CdSeS phases/nanocrystals. As the doping CdS with Selenium makes the films more transparent. The above results were in
agreement with the trend given by Kasim et al. (2008) that they recorded a 45\% reflectance and below in the 300nm to 900nm wavelength range.

![Graph showing reflectance vs wavelength for CdS and various CdSeS thin films.](image)

**Figure 5.2:** Reflectance Vs wavelength of Se doped CdS

Figure 5.3 shows the absorbance of the Cd$_x$Se$_{1-x}$S thin films varies with wavelength. It is evident that all the thin films of Cd$_x$Se$_{1-x}$S are poor absorbers since the absorption range is below 6\% in all the thin films in the visible spectrum. The doping of the CdS with Se makes the thin films more transparent hence reducing its absorbance. This is attributed to the formation of CdSeS phases. Selenium can be a good dopant to CdS since it directly varies the absorbance of the doped CdS thin films. Kumar and Sankaranayanan (2009) reported similar observations within 300nm to 1200nm wavelength range.
Figure 5.3: Reflectance Vs wavelength of Se doped CdS

5.1.1.2 Simulated transmission curves for Cd$_x$Se$_{1-x}$S thin films.

The optical data (transmittance and reflectance) was simulated in Scout software. The software uses various optical models to generate its own numerical values through simulations which are then compared with the experimental data. The simulated numerical values are used to obtain the optical constants such as band gap, refractive index and extinction coefficient. Three models were used in the simulations namely, Drude model, Harmonic oscillator and O’Leary-Johnson-Lim (OJL) inter-band transition model. The software generated graphs for transmittance, reflectance and absorbance. Figure 5.4 shows an example of how Cd$_{0.5}$Se$_{0.5}$S thin film simulated data fitted using Scout software hence reproducing similar and reliable optical constants of the thin films. The Scouts software is preconfigured with these optical constants which are produced when the experimental data
fits to the simulation ones. The Absorption (α), dielectric (Ɛ), refractive index (n), extinction (k), and band gap $E_g$ are the constants obtained from the simulated data. Their discussion follows then.

**Figure 5.4:** Cd$_{0.5}$Se$_{0.5}$S thin film’s transmission simulated and experimental curves

### 5.1.1.3 Band gap ($E_g$)

The band gap ($E_g$) for all the samples was obtained after simulation was done using the Scout software. The procedures of getting the bad gap ($E_g$) are well explained in process 4.4.2.1. Table 5.1 below is an illustration of the comparison between the band gaps obtained using the Scouts software simulations and the ones obtained using the method of extrapolation. Variation of the $E_g$ versus the Se concentration in the precursor is shown by figure 5.5
**Table 5.1**: Variation of $E_g$ with Cd$_x$Se$_{1-x}$S

<table>
<thead>
<tr>
<th>Formula</th>
<th>Value of $x$</th>
<th>Extrapolated $E_g$ ±0.05[eV]</th>
<th>Simulated $E_g$ ±0.05[eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS</td>
<td>1.0</td>
<td>2.41</td>
<td>2.46</td>
</tr>
<tr>
<td>Cd$<em>{0.95}$Se$</em>{0.05}$</td>
<td>0.95</td>
<td>2.63</td>
<td>2.65</td>
</tr>
<tr>
<td>Cd$<em>{0.75}$Se$</em>{0.25}$</td>
<td>0.75</td>
<td>2.77</td>
<td>2.76</td>
</tr>
<tr>
<td>Cd$<em>{0.5}$Se$</em>{0.5}$</td>
<td>0.5</td>
<td>2.79</td>
<td>2.78</td>
</tr>
<tr>
<td>Cd$<em>{0.25}$Se$</em>{0.75}$</td>
<td>0.25</td>
<td>2.73</td>
<td>2.72</td>
</tr>
</tbody>
</table>

---

**Figure 5.5**: $E_g$ versus Cd$_x$Se$_{1-x}$S on both simulated and extrapolated data

All the Cd$_x$Se$_{1-x}$S thin films had higher band gaps than non-doped CdS thin films as shown on both figure 5.5 and table 5.1. Cd$_{0.5}$Se$_{0.5}$S recorded highest band gap of 2.79 eV from the
extrapolated results. The increase in transmittance as the Se concentration increase can be attributed to the formation of the CdSeS phases. As the CdSeS phases increases, the transparency also increases. The Optimized doped CdS was at the value of $x = 0.5$ which is close to the report given by Kasim et al. (2008) where the Optimized value of $x$ was 0.58 although the dopant Zinc.

5.1.1.4 Refractive index ($n$)

This is the ratio of the sine of incident angle to the sine of refracted angle when a light wave transverses through matter. The constant ($n$) shows how much the light wave bends as it transverses through the sample material. Refractive indices for all samples based on the simulated and extrapolated values are given against their $E_g$. The range of the wavelength was from 380nm to 780nm. The Vegard’s refractive indices were given by relation 5.4 on page 57 and the obtained $n$ results as shown in table 5.2.

Table 5.2: Variation of refractive index of $\text{Cd}_x\text{Se}_{1-x}\text{S}$ with concentration of $x$.

<table>
<thead>
<tr>
<th>Formula</th>
<th>Value of (1-x)</th>
<th>$n \pm 0.005$</th>
<th>Vegard’s calc. $\pm 0.005$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS</td>
<td>0.0</td>
<td>2.58</td>
<td>2.55</td>
</tr>
<tr>
<td>$\text{Cd}<em>{0.95}\text{Se}</em>{0.05}\text{S}$</td>
<td>0.05</td>
<td>2.45</td>
<td>2.44</td>
</tr>
<tr>
<td>$\text{Cd}<em>{0.75}\text{Se}</em>{0.25}\text{S}$</td>
<td>0.25</td>
<td>2.36</td>
<td>2.36</td>
</tr>
<tr>
<td>$\text{Cd}<em>{0.5}\text{Se}</em>{0.5}\text{S}$</td>
<td>0.5</td>
<td>2.35</td>
<td>2.62</td>
</tr>
<tr>
<td>$\text{Cd}<em>{0.25}\text{Se}</em>{0.75}\text{S}$</td>
<td>0.75</td>
<td>2.38</td>
<td>2.39</td>
</tr>
</tbody>
</table>
The information on the local fields within the thin films and the electronics can be traced on material’s refractive index (n). The thin film’s colour is dictated by its refractive index (n). Relation 5.3 can be used to calculate the refractive index (n) (Ravindra et al., 2006);

\[
 n = \frac{1 + R^{\frac{1}{2}}}{1 - R^{\frac{1}{2}}} \tag{5.3}
\]

R is the reflectance and n is the refractive index of the thin film. The energy band gap (E\text{\textsubscript{g}}) and refractive index (n) are related linearly as given by equation 5.4 (Ravindra et al., 2006);

\[
 n = 4.08 - 0.62E_g \tag{5.4}
\]

From figure 5.5 on page 55, the refractive index (n) obtained from experimental data presented a similar trend compared to the results obtained through simulation. The refractive index (n) showed an inverse relation with respect to Se concentration in the bath. This exhibited property of high transmittance was good for a window layer. From Figure 5.6 (a) and (b), it is noted the refractive index varies inversely with the Se concentration. Also from figure 5.6 (a) and (b), the refractive indices of thin films varies inversely with the Selenium dopant in the precursor. The above is attributed by the decrease of the electric and dielectric fields inside the films hence reducing the normal dispersion of radiations as they transverse through the sample.
Figure 5.6: (a) CdxSe1-xS thin film’s refractive index Vs wavelength

Figure 5.6: (b) CdxSe1-xS thin film’s refractive index vs photon energy
5.1.1.5 Dielectric constant (\( \varepsilon \))

Dielectric constant (\( \varepsilon \)) is the ratio of the permittivity of a material to the permittivity of free space (\( \varepsilon_0 \)). It is an expression of the extent to which a material concentrates electric flux and is the electrical equivalence of relative magnetic permittivity. These constants were simulated by the Scouts software and the constants generated. Figure 5.7 (a) shows the variation of the real dielectric constant (\( \varepsilon_1 \)) of \( \text{Cd}_x\text{Se}_{1-x}\text{S} \) thin film with respect to wavelength. The real dielectric gradually reduces with increase in wavelength since the increase in wavelength translates to a wave carrying less power and energy. The pure CdS thin film showed the highest dielectric constant while \( \text{Cd}_{0.95}\text{Se}_{0.05}\text{S} \) thin film recorded the lowest.

**Figure 5.7:** (a) \( \text{Cd}_x\text{Se}_{1-x}\text{S} \) thin film’s real dielectric constant Vs wavelength
Figure 5.7: (b) CdSe\textsubscript{1-x} thin film’s real dielectric constant Vs photon energy

Figure 5.7 (b) shows the real dielectric constant ($\varepsilon_1$) of the Cd\textsubscript{x}Se\textsubscript{1-x}S varies with the photon energy. The value of the real dielectric constant ($\varepsilon_1$) increased gradually with the increase of the photon energy. The undoped CdS posted the highest real dielectric constant of above 0.55 at 4.25eV. The lowest real dielectric constant ($\varepsilon_1$) was showed by Cd\textsubscript{0.95}Se\textsubscript{0.05}S of 0.35 at 4.25eV. CdS thin film as shown from figures 5.7 (a) and figures 5.7 (b). The dielectric constant ($\varepsilon$) related almost inversely with the wavelength. From above, a conclusion can be made that low dielectric constant is a better choice as far as solar cells are concerned.
Figure 5.8: (a) CdxSe1-xS thin film’s imaginary dielectric constant ($\varepsilon_i$) Vs wavelength

Figure 5.8: (b) CdxSe1-xS thin film’s imaginary dielectric constant ($\varepsilon_r$) Vs photon energy
The Scout software simulated how the imaginary dielectric ($\varepsilon_i$) constants related with the wavelength as shown by Figure 5.8 (a). The variation of imaginary dielectric ($\varepsilon_i$) with the photon energy is given in figure 5.8 (b) as simulated by the Scout program. From figures 5.8 (a) and figures 5.8 (b), the imaginary dielectric constant ($\varepsilon_i$) has high values at shorter wavelengths. The Se concentration shows an inverse variation with the dielectric constant.

5.1.1.6 Absorption and extinction coefficients ($\alpha$ and $k$)

The absorption coefficient ($\alpha$) of a material with respect to a given wavelength determines the spatial region in which most of the light is absorbed. This constant $\alpha$ can also be seen as the property of a material which defines the amount of light absorbed by it. The inverse of the absorption coefficient, $\alpha^{-1}$ is the average distance travelled by a photon before it gets absorbed. Absorption is the exact reverse of radiative recombination. Figure 5.9 (a) is an illustration of how the absorbance spectra of Cd$_x$Se$_{1-x}$S thin films varied with given wavelengths. The thin films showed very low absorbance coefficients ($\alpha$) beyond the 1000nm wavelength.

Extinction coefficient ($k$) is important since it gives a measure of the diminishing rate of the transmitted photon inform of absorption and scattering process in the thin film. Equation 5.5 given by (Keszler, 2007) was used to calculate the extinction coefficient ($k$);

$$k = \frac{\alpha \lambda}{4\pi} \quad (5.5)$$

Figure 5.9 (b) shows the extinction coefficients ($k$) of the samples with respect to the photon wavelength. The extinction coefficients are generally seen to gradually reduce from or
above the 1000nm wavelength. The increase in Se dopant in the thin films led to gradual decrease in the extinction coefficient. The above yielded to a very small extinction coefficient and this is indeed a good property of a window material. The thickness of the thin films deposited was at an average of 112nm which is a very small thickness.

![Graph](image-url)

**Figure 5.9:** (a) Absorbance coefficient Vs wavelength graph for CdxSe1-xS

![Graph](image-url)

**Figure 5.9:** (b) Extinction coefficients Vs wavelength graph for CdxSe1-xS
5.1.2 Lead sulphide (PbS) thin film’s Optical properties.

5.1.2.1 Absorbance, Transmittance and Reflectance

Figure 5.11 shows how the PbS transmittance spectra varied with given wavelength. The wavelength ranged from 300-2000nm. Generally the transmittance of PbS is registered below 50% in the visible and near infra-red region of the electromagnetic spectra. The low transmittance shown above is an indication of a material suited for an absorber material in solar cell applications. The concentration of precursor solution affected the PbS films thickness and transmittance. The thickness of the thin films also affected the transmittance inversely. The 0.5M solution yielded the PbS with the lowest transmittance of below 30% within the wavelength range of 600-200nm.

![Transmittance Vs Wavelength Graph](image)

**Figure 5.10:** Transmittance Vs wavelength graph for PbS thin films of various concentration.
Figure 5.11 shows reflectance against the wavelength from 300-2000nm. A reflectance of below 55% was obtained. A reflectance blue shift edge of 300nm was observed. The 0.5M solution deposited PbS film with the lowest reflectance of about 36% within the wavelength range of 800nm to 2000nm.

![Figure 5.11: Reflectance Vs wavelength graph for PbS thin films of various concentration](image)

Absorption results were generated by using relation (5.6) in excel program:

\[
A = 100 - (T + R)
\]

(5.6)

Where \(A\) is the absorbance, \(T\) is the transmittance and \(R\) the reflectance of the light intensity through the thin film under investigation using the spectrophotometer. From 0.2M solution, the increase of concentration gave rise to the absorbance up to 0.5M. The absorption results
showed a trend of decreasing absorbance with the solution concentration increase from 0.5M as the turning point. The 0.5M solution was then chosen as the best for solar fabrication.

![Figure 5.12: Absorbance Vs wavelength graph for PbS thin films of various concentrations](image)

The absorbance Vs wavelength plots in figure 5.12 above shows a general correlation between the absorbance and concentration of the precursor solution. The absorbance of the thin films increased with the increase in concentration up to 0.5M then started to show a slight decrease with concentration increase. This was attributed to the fact that thicker films have bigger crystallites resulting in more inter-granular space and hence the optical density of the film reduces.
5.1.2.2 Simulated and experimental transmission curves for PbS thin films

The Scout program is software customized to generate important dielectric constants on semiconductor thin film materials. The software is pre-configured with these constants based on the type of the material using some scientific models. Models used were Drude model for carriers and Harmonic oscillator model for carriers. Figure 5.13 shows a graph of the 0.5M PbS thin film’s experimental and simulated data of the transmission against the wavelength. The wavelength range used was 300-2000nm. As seen in the figure 5.13, the experimental results were simulated and gave a good fit and hence the constants extracted from the Scout’s software are reliable. The constants generated for were; extinction coefficient \((k)\), band gap \((E_g)\), absorption coefficient \((\alpha)\) and dielectric constant \((\mathcal{E})\).

**Figure 5.13:** Experimental and simulated transmission fit graph of 0.5M PbS film
5.1.2.3 Band gap ($E_g$)

PbS thin film band gaps were obtained using the Scout’s software simulation and the extrapolation methods. In the extrapolation method, a plot of $(a\nu v)^2$ against energy ($\nu v$) was done for all the films. The linear part of the plot was extrapolated so as get the intercept which corresponds to the band gap $E_g$. The results obtained are given in Table 5.4 and graphically represented on a graph in figure 5.14 respectively. The band gap ($E_g$) for the optimal PbS was 1.44 eV which is within the range reported by Popa et al. (2006) i.e a range of 0.41 – 2.7 eV. The above value is a proof that indeed PbS is a good absorber material. The Scout program method for $E_g$ extraction process was as follows; after the simulation, through the main window the OJL(EO) was selected from the fit parameters window, then the value before it was divided by a constant 8085 to get the $E_g$ for the sample. The band gap obtained using the second method slightly differed from the one obtained using the first one as shown in table 5.3. Although the two methods gave band gaps with slight differences, a similar trend was seen to be maintained.

Table 5.3: Band gaps from simulation and extrapolation method

<table>
<thead>
<tr>
<th>Concentration of Pb(NO$_3$)$_2$</th>
<th>$E_g$ (eV) from extrapolation</th>
<th>$E_g$(eV) from SCOUT</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2M</td>
<td>1.7405</td>
<td>1.75</td>
<td>±0.08703</td>
</tr>
<tr>
<td>0.3M</td>
<td>1.6866</td>
<td>1.702</td>
<td>±0.08433</td>
</tr>
<tr>
<td>0.4M</td>
<td>1.4630</td>
<td>1.52</td>
<td>±0.07315</td>
</tr>
<tr>
<td>0.5M</td>
<td>1.4314</td>
<td>1.44</td>
<td>±0.07157</td>
</tr>
<tr>
<td>0.6M</td>
<td>1.4336</td>
<td>1.46</td>
<td>±0.07168</td>
</tr>
<tr>
<td>0.7M</td>
<td>1.4526</td>
<td>1.51</td>
<td>±0.07263</td>
</tr>
</tbody>
</table>
5.2 Thin film’s electrical properties

5.2.1 Cd$_x$Se$_{1-x}$S thin film’s electrical properties

The sheet resistivity ($R_{SH}$) of the Cd$_x$Se$_{1-x}$S thin films was determined using the instrument known as the four point probe. The four point probe machine was interfaced with Keithley 2400 source metre via a relay. The probe spacing was measured using a Vanier caliper then recorded as ‘x’ to be used in sheet resistance as per diagram 4.2. Figure 5.15 shows the results of both resistivity and conductivity varying with the concentration of Se dopant. From the results in table 5.4, it is evident that the sheet resistivity had inverse variation with Se ion concentration. This inverse relation ranged from $2.32 \times 10^4$ to $1.81 \times 10^4 \, \Omega$-
cm. The minimum value of $1.81 \times 10^4 \, \Omega\cdot\text{cm}$ was obtained from Cd0.5Se0.5S thin film and translated to a conductivity of $5.52 \times 10^{-5} \, \Omega^{-1}\text{cm}^{-1}$. An increase in Se ion concentration resulted in an increase in resistivity. The presence of Se in CdS causes the film to have some SeS and CdSeS nano-crystals. The SeS crystals are amorphous in nature and this causes more phonon dispersion in the film since they act as scattering centres which in turn increases resistivity of the thin film. Although the film resistivity increases, it can be used for photovoltaic applications with adjustments on resistivity either by adding dopants that may reduce resistivity or introducing low resistivity grids. Considering the above keenly, the value of $x$ chosen was 0.5.

Table 5.4: Cd$_x$Se$_{1-x}$S thin film’s recorded resistivity and conductivity

<table>
<thead>
<tr>
<th>Formulae for Cd$_{1-x}$Se$_x$S</th>
<th>Value of $x$</th>
<th>Resistivity ($\rho$) $\times 10^4$ $[\Omega\cdot\text{cm}]$</th>
<th>Conductivity ($\sigma$) $\times 10^{-5}$ $[\Omega^{-1}\text{cm}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS</td>
<td>1.0</td>
<td>2.32</td>
<td>4.31</td>
</tr>
<tr>
<td>Cd$<em>{0.95}$Se$</em>{0.05}$S</td>
<td>0.95</td>
<td>2.13</td>
<td>4.69</td>
</tr>
<tr>
<td>Cd$<em>{0.75}$Se$</em>{0.25}$S</td>
<td>0.75</td>
<td>1.97</td>
<td>5.08</td>
</tr>
<tr>
<td>Cd$<em>{0.50}$Se$</em>{0.50}$S</td>
<td>0.5</td>
<td>1.81</td>
<td>5.52</td>
</tr>
<tr>
<td>Cd$<em>{0.25}$Se$</em>{0.75}$S</td>
<td>0.25</td>
<td>2.26</td>
<td>4.42</td>
</tr>
</tbody>
</table>

From both figure 5.7 (a) and (b), the real dielectric constants obtained from doped CdS films was less compared from pure CdS films. The dielectric constant ($\varepsilon_r$) reduced as the wavelength increased. The imaginary dielectric constant ($\varepsilon_i$) presented higher values at shorter wavelength or higher photons. As the Se concentration increased, the dielectric constant generally reduced. Usually a low dielectric constant is a preference in photovoltaic materials since a thin film of low dielectric constant does not store electric which can
interfere with the transport carriers. The above ensures that there is less optical recombination losses experienced in the cell.

![Graph showing Resistivity and Conductivity against concentration in terms of X in the bath]

**Figure 5.15:** Cd$_x$Se$_{1-x}$S resistivity against concentration in terms of $x$

### 5.2.2 PbS thin film’s electrical properties

The electrical sheet resistance of PbS thin film samples was measured using the four point probe method. Figure 4.2 shows the layout used while determining the sheet resistance. After the sheet resistance was measured, the sheet electrical conductance was calculated using relation 4.16 on page 41. From figure 5.20, it is observed that the resistivity at a concentration of 0.3M PbS was $1.239 \times 10^4 \, \Omega \cdot \text{cm}$ and then decreased to $8.38 \times 10^3 \, \Omega \cdot \text{cm}$ at a concentration of 0.5M PbS. An increase in molarity beyond 0.5M resulted in increased resistivity. The resistivity ranges from $1.928 \times 10^4 \, \Omega \cdot \text{cm}$ to $8.38 \times 10^3 \, \Omega \cdot \text{cm}$ which translates to a conductivity range of $5.18 \times 10^{-4} \, \text{S} \cdot \text{cm}^{-1}$ to $1.12 \times 10^{-4} \, \text{S} \cdot \text{cm}^{-1}$. Close values
were obtained by Eshafie and Ekpunobi, (2004) who had reported a resistivity range of $10^3$ \( \Omega \text{-cm} \) by using spray pyrolysis method and Mulik et al. (2004) with an electrical conductivity range of $10^{-3}$ S-cm\(^{-1}\) to $10^{-4}$ S-cm\(^{-1}\). The different resistivity values at different concentrations indicates that the nature and degree of amorphousness of the films depend on concentration.

**Table 5.5:** PbS thin film’s resistivity and conductivity

<table>
<thead>
<tr>
<th>Concentration of Pb(NO(_3))(_2)</th>
<th>Resistivity ((\rho)) (\pm 0.005 \times 10^3) [(\Omega\text{-cm})]</th>
<th>Conductivity ((\sigma)) (\pm 0.0005 \times 10^{-5}) [(\Omega\text{-cm})^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2M</td>
<td>19.28</td>
<td>5.187</td>
</tr>
<tr>
<td>0.3M</td>
<td>12.39</td>
<td>8.071</td>
</tr>
<tr>
<td>0.4M</td>
<td>10.76</td>
<td>9.294</td>
</tr>
<tr>
<td><strong>0.5M</strong></td>
<td><strong>8.38</strong></td>
<td><strong>11.933</strong></td>
</tr>
<tr>
<td>0.6M</td>
<td>8.43</td>
<td>11.862</td>
</tr>
<tr>
<td>0.7M</td>
<td>9.37</td>
<td>10.672</td>
</tr>
</tbody>
</table>
Figure 5.16: PbS thin films resistivity Vs concentration plot

The concentration of 0.5M PbS thin films was chosen as the optimum concentration since it had the lowest resistivity of $8.38 \times 10^3 \ \Omega\text{-cm}$. The above optimum thin film of PbS was used during the Cd$_x$Se$_{1-x}$S/PbS solar cell fabrication.

5.3 Cd$_x$Se$_{1-x}$S/PbS solar cell’s optical properties

After considerations of all the optimal conditions, Cd$_{0.5}$Se$_{0.5}$S thin film was chosen as the best window layer as far as solar cell is concerned. The above was arrived after considering the following: largest optical band gap of 2.83 eV, highest transmittance of 89.7%, lowest absorption of 1.77% in the visible region of the spectra and fairly low sheet resistivity and dielectric constants. The optimum absorber layer chosen was 0.5M PbS due to its lowest transmittance of 26.8% in the visible region of the spectra and fairly high absorbance of 38.79% in the visible region of the spectra as well as dielectric constants. Aluminium paste was used to make the back and front ohmic contacts. The values of current with respect to
its corresponding voltages were recorded for different data points as shown in table 5.6. The power values were obtained by getting the product of current and voltage as shown in table 5.7. The I-V values were used to plot the graph shown in figure 5.17. The above processes were done using the solar cell simulator. Table 5.7 shows the experimental results obtained using the solar simulator. From the results it is seen that the maximum power point is at 0.00693W, given by the product of 0.27V and 25.65mA as shown in both table 5.6 and figure 5.17. The solar cell fill factor (FF) was obtained by use of equation 4.27 on page 48. The solar cell efficiency was obtained by application of relation 4.28 on page 49. In equation 4.28, the efficiency (\( \eta \)) is given by the ratio of the maximum power at the power maximum point to that of the power of the irradiance (\( P_{in} \)). It is worth noting that the \( P_{in} \) is also a product of the irradiance (\( E_i \)) and the cell area (\( A_c \)) under illumination. The solar cell area was 6.0 cm\(^2\) while the solar cell simulator lamp had the irradiance of one sun (1000W/m\(^2\)). Dividing the \( P_{max} \) of 0.00693W with the product of 1000W/m\(^2\) and \( A_c \) of 0.0006m\(^2\) yielded to an efficiency of 1.155 when expressed as a percentage as shown in table 5.7.
Table 5.6: Measured current and voltage from Cd$_{x}$Se$_{1-x}$/S/PbS solar cell using solar cell simulator

<table>
<thead>
<tr>
<th>Voltage [V]</th>
<th>Current [A]</th>
<th>Power(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.02945</td>
<td>0</td>
</tr>
<tr>
<td>0.05</td>
<td>0.02945</td>
<td>0.00147</td>
</tr>
<tr>
<td>0.1</td>
<td>0.02945</td>
<td>0.00295</td>
</tr>
<tr>
<td>0.15</td>
<td>0.02945</td>
<td>0.00442</td>
</tr>
<tr>
<td>0.2</td>
<td>0.0285</td>
<td>0.0057</td>
</tr>
<tr>
<td>0.23</td>
<td>0.0281</td>
<td>0.00646</td>
</tr>
<tr>
<td>0.25</td>
<td>0.0272</td>
<td>0.0068</td>
</tr>
<tr>
<td>0.26</td>
<td>0.0266</td>
<td>0.00692</td>
</tr>
<tr>
<td>0.27</td>
<td>0.02565</td>
<td>0.00693</td>
</tr>
<tr>
<td>0.29</td>
<td>0.0237</td>
<td>0.00687</td>
</tr>
<tr>
<td>0.31</td>
<td>0.02185</td>
<td>0.00677</td>
</tr>
<tr>
<td>0.33</td>
<td>0.019</td>
<td>0.00627</td>
</tr>
<tr>
<td>0.35</td>
<td>0.01425</td>
<td>0.00499</td>
</tr>
<tr>
<td>0.36</td>
<td>0.0095</td>
<td>0.00342</td>
</tr>
<tr>
<td>0.36</td>
<td>9.50E-04</td>
<td>3.42E-04</td>
</tr>
</tbody>
</table>

Table 5.7: Recorded Cd$_{x}$Se$_{1-x}$/S/PbS solar cell parameters

<table>
<thead>
<tr>
<th>Cell parameters</th>
<th>Parameter value/ Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{SC}$</td>
<td>0.02945</td>
</tr>
<tr>
<td>$V_{OC}$</td>
<td>0.360</td>
</tr>
<tr>
<td>$V_{Max}$</td>
<td>0.27</td>
</tr>
<tr>
<td>$I_{Max}$</td>
<td>0.02565</td>
</tr>
<tr>
<td>$P_{Max}$</td>
<td>0.006926</td>
</tr>
<tr>
<td>FF</td>
<td>0.6532</td>
</tr>
<tr>
<td>$\eta$</td>
<td>1.16%</td>
</tr>
</tbody>
</table>
Figure 5.17: Graph of current and Power Vs Voltage for Cd$_x$Se$_{1-x}$S/PbS cell on two vertical axes.

The fabricated Cd$_x$Se$_{1-x}$S/PbS solar cell recorded an open voltage of $V_{OC} = 0.36$V, $I_{SC} = 0.02945$A, a fill factor of $FF = 0.6532$ and a cell efficiency of $\eta = 1.16$% as shown in Table 5.7. It can be observed that the fabricated cell produced slightly a higher current than that reported by Harumi et al. (1995) with a $V_{OC}$ of $0.45$V and $I_{SC}$ of $0.001mA/cm^2$. Fill factor is a measure of quality of the cell and therefore a large fill factor of 1 or very close to 1 is desirable and it corresponds to the I-V sweep that is more square-like. The typical fill factors ranges from 0.50 to 0.82 (50% - 82%). Considering the square like nature of the I-V curve and fill factor of my cell being 0.6532 and an efficiency of 1.16%, a conclusion is
made that the fabricated Cd$_x$Se$_{1-x}$S/PbS cell formed is suitable for p-n junction for solar cell applications with some modifications.
CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The outcome of both Cd$_x$Se$_{1-x}$S and PbS thin films deposition was a success. The deposition of the thin films was done on ordinary glass substrate. The method of deposition of the thin films was chemical bath deposition (CBD). The doping effects on the window layer with the Se dopant was investigated. (i.e pure Cadmium Sulphide was doped with different quantities of Selenium per volume in the precursor solution). The concentration of Se was varied using different volumes of Sodium Selenosulphate into the other precursor solutions. On the absorber layer, lead nitrate solution concentrations were varied from 0.3M to 0.7M at 0.1M intervals. Cd$_x$Se$_{1-x}$S thin films exhibited high transmittance in the VIS and IR regions of the optical spectrum (up to 89.7%). The Cd$_x$Se$_{1-x}$S thin film band gap ($E_g$) obtained ranged from 2.41eV to 2.83eV. The Cd$_{0.5}$Se$_{0.5}$S had the highest transmittance and highest band gap of 89.7% and 2.83eV respectively.

Refractive index and dielectric constants decreased with increase in Se concentration which is an indication of increasing transparency. The resistivity of the Cd$_x$Se$_{1-x}$S thin films decreased with the increase in Se concentration and it ranged from $1.87 \times 10^4 \ \Omega$-cm to $2.26 \times 10^4 \ \Omega$-cm. The above was attributed by the incorporation of the Se into the molecular interspacing structure in CdS crystals. PbS thin films exhibited good qualities for absorber material since they recorded a transmittance of less than 42% and a band gap of less than
1.8eV. High extinction and absorption coefficients were obtained in PbS thin films. PbS thin film’s resistivity ranged between $8.38 \times 10^3 \, \Omega\text{-cm}$ to $1.92 \times 10^4 \, \Omega\text{-cm}$. Cd$_{0.5}$Se$_{0.5}$S thin film was selected as the best window material for solar cell fabrication. This was arrived at by the fact that the Cd$_{0.5}$Se$_{0.5}$S film exhibited highest transmittance, largest band gap, lowest extinction and absorption coefficients as well as relatively low resistance. The 0.5M PbS thin film qualified as the best absorber material due to its opposite levels of the window material properties. The fabricated Cd$_x$Se$_{1-x}$S/PbS solar cell recorded the following cell parameters; $I_{SC} = 0.02945\, \text{A}$, open circuit voltage $V_{OC} = 0.36$, Fill factor $FF = 0.6532$ and efficiency $\eta = 1.16\%$. From these solar cell parameters, it is concluded that the Cd$_{0.5}$Se$_{0.5}$S/PbS when fabricated is capable of forming a p-n junction well suited for photovoltaic applications.

**6.2 Recommendations**

After a keen consideration of the following obtained cell parameters of the fabricated Cd$_{0.5}$Se$_{0.5}$S/PbS cell; $V_{OC} = 0.36\, \text{V}$, $I_{SC} = 0.02945\, \text{A}$, $FF = 0.6532$ and $\eta = 1.15\%$, the following recommendations were made.

1) The fabricated Cd$_{0.5}$Se$_{0.5}$S/PbS solar cell can be adopted for the supply of low power consuming gadgets like light sensors or radiation sensors with some improvements for commercial purposes.

2) Study can be carried out to investigate how the annealing may affect the Cd$_{0.5}$Se$_{0.5}$S/PbS cell parameters and if yes, to what extent.
3) The Aluminium front and back contacts can be replaced by Silver ones, to check whether the efficiency of the fabricated Cd$_{0.5}$Se$_{0.5}$/PbS cell can be enhanced.

4) Other methods of thin film deposition can be explored to compare their results with the CBD technique ones.
REFERENCES


Mosiori, C. O., Njoroge, W. N. and Okumu, J. (2013). Electrical and optical characterization of Cd$_{x}$Zn$_{1-x}$S/PbS thin films for photovoltaic applications. *Thesis. Department of Physics, Kenyatta University*.


APPENDICES

APPENDIX I: UV-VIS-NIR Spectrophotometer 3700 DUV (Shimadzu)
APPENDIX II: Four point probes connected to Keithley 2400 source meter for measurement of sheet resistance
APPENDIX III: Solar simulator