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Molybdenum as a back contact for cucl treated cds/cdte solar cells

Matheshkumar Jayabal

University of South Florida

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Molybdenum As a Back Contact for CuCl Treated CdS/CdTe Solar Cells

By

Matheshkumar Jayabal

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering Department of Electrical Engineering College of Engineering University of South Florida

Major Professor: Christos S. Ferekides, Ph.D. Don Morel, Ph.D. Yun L. Chiou, Ph.D.

Date of Approval: March 24, 2005

Keywords: Photovoltaics, Sputtering, Sublimation, Thin films, Stability

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DEDICATION

This thesis is dedicated to my family for their everlasting love and support.
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# TABLE OF CONTENTS

LIST OF TABLES  iv  

LIST OF FIGURES  v  

LIST OF SYMBOLS viii  

ABSTRACT x  

CHAPTER 1 INTRODUCTION  1  
1.1 Sources of Energy  1  
  1.1.1 Non Renewable Energy  1  
  1.1.2 Renewable Energy  1  
1.2 CdS/CdTe Solar Cells  2  

CHAPTER 2 SEMICONDUCTORS AND SOLAR CELLS  4  
2.1 Semiconductors  4  
2.2 Junctions  5  
  2.2.1 P-N Junctions  5  
  2.2.2 Metal-Semiconductor Junctions  8  
    2.2.2.1 Schottky Barriers  8  
    2.2.2.2 Ohmic Contact  11  
    2.2.2.3 Tunneling Contact  12  
2.3 Solar Cells  13  
  2.3.1 History of Solar Cells  13
CHAPTER 6  RESULTS AND DISCUSSION

6.1 Cells Contacted with doped Graphite Paste

6.2 CuCl Treated Samples
   6.2.1 Different CuCl Concentrations Used in this Thesis
   6.2.2 Molybdenum as a Back Contact for CuCl Treated Samples
      6.2.2.1 As Deposited Mo Contacted Samples
      6.2.2.2 Molybdenum Contacted Samples Annealed at 270°C
      6.2.2.3 Molybdenum Contacted Samples Annealed at 300°C
      6.2.2.4 Molybdenum Contacted Samples Annealed at 350°C
      6.2.2.5 Molybdenum Contacted Samples with Different CuCl solution
         6.2.2.5.1 Molybdenum Contacted Samples with No CuCl solution
         6.2.2.5.2 Molybdenum Contacted Samples with Different CuCl Solutions
      6.2.2.6 Molybdenum Contacted Samples with Different CdS Thickness

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

REFERENCES
LIST OF TABLES

Table 1          Properties of CdS and CdTe                                      26
Table 2          Work Functions of a Few Metals                                  28
Table 3          Performance of the Conventional Solar Cell: Doped  
                   Graphite Paste                                                      41
Table 4          Performance of the CdS/CdTe Solar Cells Without CuCl Treatment 44
Table 5          Performance of the CdS/CdTe Solar Cells With CuCl Treatment      45
Table 6          Performance of the Mo Contacted Samples Deposited  
                   at Different Temperatures                                              48
Table 7          Performance of the Mo Contacted Samples Annealed at 270°C       57
Table 8          Performance of the Mo Contacted Samples Annealed at 300°C       52
Table 9          Performance of the Mo Contacted Samples Annealed at 350°C       54
Table 10         Performance of the Mo Contacted Samples with No CuCl Treatment    57
Table 11         Performance of the Mo Contacted Samples with Solution #2 CuCl   
                   Treatment                                                            59
Table 12         Performance of the Mo Contacted Samples with Solution #3 CuCl  
                   Treatment                                                            60
Table 13         Performance of the Mo Contacted Samples with Different  
                   CdS Thickness                                                          62
LIST OF FIGURES

Figure 1       Energy Band Diagrams (a) n-type, (b) p-type                                             6
Figure 2       Band Bending at the Junction                                                              7
Figure 3       I-V Curve of the Solar Cell Under Dark Conditions                                   7
Figure 4       Energy Band Diagram of a Metal and Semiconductor Before Junction Formation              9
Figure 5       Energy Band Diagram of a Metal and Semiconductor After Junction Formation              10
Figure 6       Schottky Barrier in Forward Bias Condition                                               11
Figure 7       Schottky Barrier in Reverse Bias Condition                                                 12
Figure 8       Energy Band Diagram of a Metal-Semiconductor Contact                                      13
Figure 9       Photocurrent Generation in a Solar Cell                                                   14
Figure 10      Energy Band Diagram Of a Heterojunction                                                15
Figure 11      I-V Curve of the Solar Cell Under Dark and Illumination Conditions                    17
Figure 12      Inverted I-V Curve in the Fourth Quadrant                                                18
Figure 13      Equivalent Circuit of a Solar Cell                                                     19
Figure 14      Effect of Shunt Resistance                                                              20
Figure 15      Effect of Series Resistance                                                             21
Figure 16      Hexagonal Structure of CdS                                                             22
Figure 17      Cubic Structure of CdS                                                                 23
Figure 18      Cubic Structure of CdTe                                                                 25
| Figure 19 | Doping Profiles of Cells with Different Buffer Layers and Mo Metallization | 32 |
| Figure 20 | Variations in J-V Curves with Varying Cu Concentration | 32 |
| Figure 21 | Variations in J-V Curves with Varying Stress Time | 33 |
| Figure 22 | C-V Response with Different Amounts of Cu and Different Stress Times | 34 |
| Figure 23 | Basic CdS/CdTe Solar Cell | 35 |
| Figure 24 | CdS/CdTe Solar Cell Using HgTe:Cu And Graphite Paste | 36 |
| Figure 25 | CuCl Treated CdS/CdTe Solar Cell with Undoped Graphite as Back Contact | 36 |
| Figure 26 | CuCl Treated CdS/CdTe Solar Cell with Mo as a Back Contact | 37 |
| Figure 27 | CSS-CdS Apparatus | 38 |
| Figure 28 | Profile for the Deposition of CdS | 39 |
| Figure 29 | Set up for CuCl Treatment | 39 |
| Figure 30 | Spectral Response of the Samples with Cu-doped Graphite Contact | 42 |
| Figure 31 | Dark J-V Responses of Cu-doped Graphite Contact | 42 |
| Figure 32 | Light J-V Response of Cu-Doped Graphite Contact | 43 |
| Figure 33 | AES Depth Profile for CuCl Solution Treated Samples | 45 |
| Figure 34 | Comparison of Light J-V’s of Cu-Doped Graphite Contact, CuCl Treated and Non Treated Samples | 46 |
| Figure 35 | Performance of the Cu-Doped Graphite Paste Contact, CuCl Treated and Non Treated Samples | 46 |
| Figure 36 | Comparison of Spectral Responses of Samples with Cu Doped Graphite Contact, CuCl Treated and Non Treated Samples | 47 |
| Figure 37 | J-V Response of Mo Contacted Samples Deposited at Different Temperatures | 49 |
Figure 38  Comparison on the Performance of Mo Contacted Samples Deposited at Room Temperature and Annealed at Different Temperatures 49

Figure 39  Spectral Response of Mo Contacted Samples Deposited at Different Temperatures 50

Figure 40  J-V Response of Mo Contacted Samples Annealed at 270°C 51

Figure 41  J-V Response of Mo Contacted Samples Annealed at 300°C 52

Figure 42  Spectral Response of Mo Contacted Samples Annealed at 300°C 53

Figure 43  J-V Response of Mo Contacted Samples Annealed at 350°C 54

Figure 44  Spectral Response of Mo Contacted Samples Annealed at 350°C 55

Figure 45  Comparison on the Performance of Mo Contacted Samples Deposited at 150°C and Annealed at Different Temperatures 55

Figure 46  Comparison on the Performance of Mo Contacted Samples Deposited at 180°C and Annealed at Different Temperatures 56

Figure 47  Comparison on the Performance of Mo Contacted Samples Deposited at 200°C and Annealed at Different Temperatures 56

Figure 48  Dark J-V Response of Mo Contacted Samples with No CuCl Treatment 58

Figure 49  J-V Response of Mo Contacted Samples with CuCl Treatment 58

Figure 50  J-V Response of Mo Contacted with CuCl Treatment Samples with Different CuCl Concentrations 61

Figure 51  Spectral Response of Mo Contacted Samples with Different CuCl Concentrations 61

Figure 52  Transmission Response for the Samples Deposited for Different Durations 62

Figure 53  J-V Response of Mo Contacted Samples with Different CdS Thickness 63

Figure 54  Spectral Response of Mo Contacted Samples with Different CdS Thickness 64
LIST OF SYMBOLS

\( A_0 \)  
Ideality factor

\( \AA \)  
Angstroms

\( C \)  
Speed of light \([3 \times 10^8 \text{ m/sec}]\)

\( e^- \)  
Electron

\( E_i \)  
Intrinsic energy level (eV)

\( E_f \)  
Fermi energy level (eV)

\( E_C \)  
Energy of Conduction band (eV)

\( E_V \)  
Energy of Valence band (eV)

\( E_{Fm} \)  
Fermi energy in metal (eV)

\( E_{FS} \)  
Fermi energy in semiconductor (eV)

\( FF \)  
Fill Factor

\( h \)  
Planck’s constant \([1.053 \times 10^{-34} \text{ J sec}]\)

\( h^+ \)  
Hole

\( I \)  
Current (A)

\( I_{sc} \)  
Short-circuit current (A)

\( I_0 \)  
Open-circuit current (A)

\( I_L \)  
Current under light illumination

\( J_{sc} \)  
Short-circuit current density (A)

\( k \)  
Boltzmann constant \([1.38 \times 10^{-23} \text{ J/K}]\)

\( P_m \)  
Power density at the maximum point (W/cm\(^2\))

\( P_{in} \)  
Total solar incident power (W/cm\(^2\))

\( q \)  
Electron charge \([1.602 \times 10^{-19} \text{ C}]\)

\( R_S \)  
Series resistance (\( \Omega \))

\( R_{Sh} \)  
Parallel resistance (\( \Omega \))
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>V&lt;sub&gt;OC&lt;/sub&gt;</td>
<td>Open-circuit Voltage (V)</td>
</tr>
<tr>
<td>V&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Contact potential (V)</td>
</tr>
<tr>
<td>Φ</td>
<td>Work function (V)</td>
</tr>
<tr>
<td>Φ&lt;sub&gt;b&lt;/sub&gt;</td>
<td>Potential barrier height from the Fermi level (V)</td>
</tr>
<tr>
<td>Φ&lt;sub&gt;m&lt;/sub&gt;</td>
<td>Work function of a metal (eV)</td>
</tr>
<tr>
<td>Φ&lt;sub&gt;S&lt;/sub&gt;</td>
<td>Work function of a Semiconductor (eV)</td>
</tr>
<tr>
<td>χ</td>
<td>Electron affinity (V)</td>
</tr>
<tr>
<td>λ</td>
<td>Wavelength (nm)</td>
</tr>
<tr>
<td>ν</td>
<td>Frequency (Hz)</td>
</tr>
</tbody>
</table>
MOLYBDENUM AS A BACK CONTACT FOR CUCL TREATED CDS/CdTe SOLAR CELLS

Matheshkumar Jayabal

ABSTRACT

CdTe is one of the most promising absorbers for use in inexpensive semiconductor solar cells having achieved a high efficiency of 16.4% in small area cells [1]. One of the most important technological problems in obtaining high efficiencies is to have a good ohmic contact on the CdTe, which is characterized by a very high work function [2]. Cu is used as a dopant in CdTe at the contact to promote quantum mechanical tunneling [3]. But the oversupply of Cu causes the diffusion of Cu through CdTe to the underlying CdS layer resulting in the degradation of the cell performance. It has been reported that Cu was segregated near the CdS/CdTe junction. To avoid the Cu segregation at the junction, Cu supply should be minimized while the ohmic characteristics of p-CdTe contact are maintained [4].

In this thesis, the main objective is to understand the role of Cu at the CdS/CdTe interface. Here the Cu is added at the CdS/CdTe interface and is avoided at the back contact. It is been reported that metals like Mo does not diffuse into the cell. In this thesis, Mo is deposited as the back contact metal. The deposition conditions are varied to find the optimum device performance. The Cu concentration is also varied to study the role of Cu at the interface and the cells are compared with the conventional solar cells where Cu is used at the back contact.
Almost everything that we require to fulfill our needs in this modern society requires the use of the earth's resources - that is land, water and energy. Excessive use of these resources causes an increase in the demand of the resources and also causes environmental problems around the world.

1.1 Sources of Energy

1.1.1 Non Renewable Energy

Energy is classified as non-renewable energy and renewable energy. Nonrenewable energy is that conventional energy which is produced by burning fossil fuels such as coal and will be exhausted in the near future. Burning fossil fuels produces chemical pollution from nitrous oxides and acid rain from sulphur dioxide. Burning fuels also produce greenhouse gases including vast amounts of carbon dioxide that causes global warming. Nuclear energy is another type of non renewable energy. Nuclear energy is the energy released when atoms are either split or joined together. A mineral called uranium is needed for this process. At each stage of the process various types of radioactive waste are produced. This waste is poisonous and can cause harm to people and the environment coming into contact with it.

1.1.2 Renewable Energy

Renewable energy is that energy that is derived from resources that are regenerative. Types of renewable energy resources include moving water (hydro, tidal, and wave power), thermal gradients in ocean water, biomass, geothermal energy, solar energy and wind energy. Solar energy is light and heat energy from the sun. Solar cells convert sunlight into electrical energy. Thermal collectors convert sunlight into heat
energy. Solar technologies are used in watches, calculators, water pumps, space satellites, for heating water and supplying clean electricity to the power grid. There is enough solar radiation striking the surface of the earth to provide all of our energy needs. Photovoltaic energy is the conversion of sunlight into electricity through a photovoltaic (PV) cell, commonly called a solar cell. Sunlight is composed of photons or particles of energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a photovoltaic cell, they may be reflected, pass right through, or be absorbed. Only the absorbed photons provide energy to generate electricity. When enough energy is absorbed by a semiconductor, electrons are excited and dislodged from the material's atoms.

PV cells can be made of many different semiconductor materials. Silicon is one of the materials used in the earliest successful PV devices and at present, it is the most widely used PV material. Though high purity silicon single crystalline is necessary for high efficiency solar cells the processing technology for these cells is sophisticated and the production cost is high due to the requirement of a bulk material. Thin film photovoltaic modules are produced by depositing thin layers of semiconductor materials on various substrates. Thin films can be produced with various low cost processing techniques.

1.2 CdS/CdTe Solar Cells

CdTe is an attractive material for solar energy conversion. It has a direct bandgap of 1.5eV, which is in the range for optimal conversion of sunlight into electricity, and also has a very high absorption coefficient for light, which means that a very thin film is needed for converting sunlight into electricity in places where a few microns of silicon is required. CdTe can be deposited in thin film form on a number of inexpensive substrates, and can be doped both p-type and n-type.

Development of a stable and low ohmic resistance electrical contact on CdTe is essential for high efficiency and long term stability of CdTe/CdS solar cells. CdTe semiconductor has a high electron affinity; therefore most metals form a non ohmic
contact which reduces the solar cell performance. The use of Cu at the back contact improves the contact to thin film CdTe solar cells. Copper diffuses into the CdTe producing a heavily doped p- layer. However a back contact containing Cu is generally unstable because Cu diffuses into the CdTe and the performance of the cell tends to degrade [8]. The purpose of this thesis is to study the effect of Cu on the solar cell. The other goal is to minimize or eliminate Cu from the device or the back contact. For this purpose the cells were treated with CuCl solution and various back contacts such as Mo and undoped graphite have been used.
CHAPTER 2
SEMICONDUCTORS AND SOLAR CELLS

2.1 Semiconductors

Semiconductor is a material whose electrical conductivity is intermediate between that of a metal and an insulator and its conductivity increases with temperature and in the presence of impurities. Semiconductors, depending on their properties can be classified into a number of ways; some of them are listed below

• Based on their purity semiconductors can be classified into
  i. Intrinsic semiconductor: A pure semiconductor that has no impurities to change the electronic properties of the material.
  ii. Extrinsic Semiconductor: A semiconductor material intentionally doped with impurity atoms to change the electronic properties of the material.

Depending upon the type of impurity added, semiconductors can be classified into

  i. n-type: Semiconductors with excess electrons are called n-type
  ii. p-type: Semiconductors with excess holes are called positive or p-type

• Based on their structure they are classified into

  i. Single Crystalline: Semiconductors in which the atoms are arranged in an repeated and orderly manner over the entire area of the material.
  ii. PolyCrystalline: Semiconductors in which the atoms are arranged in subsections and are disoriented relative to the other subsections.
  iii. Amorphous: Semiconductors in which there is no recognizable order in the arrangement of the materials within the material.
2.2 Junctions

Junctions are crucial to many semiconductor applications such as diodes, lasers, rectifiers and solar cells. When p-type and n-type materials are placed in contact with each other, the junction behaves very differently than either type of material individually. Homojunctions are formed when a single material is altered so that one side is p-type, dominated by holes, and the other side is n-type, dominated by electrons. A heterojunction is formed by contacting two different semiconductors. There are a number of ways in which junctions can be classified and some of them are discussed in the following sections.

2.2.1 P-N Junctions

A p-n junction consists of a p-type semiconductor and a n-type semiconductor joined together thereby forming a junction. Such diodes show a pronounced rectifying behavior.

The p-n junction can be used as a rectifier, as an isolation structure and as a voltage-dependent capacitor. In addition, they can be used as solar cells, photodiodes, light emitting diodes and even laser diodes. They are also an essential part of Metal-Oxide-Silicon Field-Effects-Transistors (MOSFET’s) and Bipolar Junction Transistors (BJT).

p-n junctions can be classified into

i. Step junctions: A p-n junction that has a sharp junction with a p-type material on one side and a n-type material on the other side is called a step p-n junction

ii. Graded junctions: A graded junction is a p-n junction that has a graded impurity profile across the junction.

Figure 1 shows the energy band diagram of a p-type and n-type material before they are brought into contact. \( E_c \) represents the lowest possible energy state in the conduction band. Electrons in the conduction band are free to move about the crystal, thus the name conduction band. \( E_v \) represents the highest energy state in the valence band. Since electrons have a tendency to fill the lowest available energy states, the valence band is always nearly completely filled with electrons and holes. The Fermi energy \( (E_F) \) is the maximum energy occupied by an electron at zero Kelvin.
When n-type and p-type materials are joined together an interaction takes place between the two types of material at the junction as a result of the excess holes in one material and the excess electrons in the other. To reach thermal equilibrium, electrons and holes which are close to the metallurgical junction diffuse across the junction into the \( p \)-type and \( n \)-type region respectively where hardly any electrons and holes are present. This process leaves the ionized donors and acceptors behind, creating a region around the junction, which is depleted of mobile carriers. We call this region the depletion region. The charge due to the ionized donors and acceptors causes an electric field, which in turn causes a drift of carriers in the opposite direction. The diffusion of carriers continues until the drift current balances the diffusion current, thereby reaching thermal equilibrium as indicated by a constant Fermi energy.

![Energy Band Diagrams](image)

**Figure 1 Energy Band Diagrams** (a) n-type, (b) p-type

The built-in potential \( V_o \) in a semiconductor equals the potential across the depletion region in thermal equilibrium. Figure 2 shows the band bending of the junction when the two semiconductors are brought together.
The performance of a photovoltaic solar cell is determined by the amount of power the cell is able to produce from the incident light. The current-voltage curve (I-V curve) is one of the important plots that determine the power output. A current/voltage curve expresses the possible combinations of current and voltage output of a photovoltaic device. The I-V curve of a solar cell in dark is shown in Figure 3.
The current under dark conditions is given by the expression

\[ I = I_0 \left[ e^{(qV/A_0kT)} - 1 \right] \]

Where \( I_0 \) is the reverse saturation current or the dark current and \( A_0 \) is the diode quality factor.

2.2.2 Metal-Semiconductor Junctions

Metal-to-semiconductor contacts are of great importance since they are present in every semiconductor device. In many cases it is required to deposit metal on semiconductors to form a contact. The contact can behave either as a Schottky barrier or as an ohmic contact depending on the characteristics of the interface. These two cases will be discussed in the following sections.

2.2.2.1 Schottky Barriers

The barrier between the metal and the semiconductor can be explained with an energy band diagram. Let us consider the case of an ideal metal and n-type semiconductor energy diagrams separately. The individual band diagrams are shown in figure 4. The work function of a material is the energy required to remove an electron from the Fermi energy level to vacuum. The work function varies with the type of metal used and for most metals the work function is about 5eV. For example, the work function of gold (Au) is 5eV.

The energy difference between the vacuum and the conduction band end is called as the electron affinity energy \( (q\chi) \) of the semiconductor. For silicon the electron affinity is 4.05eV. Therefore the work function for a semiconductor is the energy difference between the vacuum and the Fermi energy level.

\[ \Phi_s = \chi + (E_C - E_{FS}) \text{ eV} \]
For Silicon, doped with an n-type dopant the Fermi level is about 0.2 eV below its conduction band minimum. Hence, its separation from vacuum is 4.25 eV which is about 0.75 eV above the Fermi level of Au. When we bring the two materials into intimate contact the difference in the average electron energy can be expected to transfer electrons from the semiconductor to the metal until the average electron energies are equal at equilibrium as shown in Figure 4. Figure 4 shows the band diagram when the metal and semiconductor junction is formed. In order to align the Fermi levels the electrostatic potential of the n-type semiconductor is raised with respect to the metal.

The situation is similar to that of a p-n junction. A depletion region is formed near the junction. The positive charge due to uncompensated donor ions in the semiconductor is balanced by excess electron in the metal. The difference in the work function of the two materials causes the bands to bend and gives rise to a contact potential $V_0$. The band bending stops electrons transferring from the semiconductor to the metal contact and so the resistance will be high across the junction. This metal contact is called as a Schottky contact or a Schottky diode. The effect of biasing on the band bending and current flow is discussed in the next section.
Figure 5  Band Diagram of a Metal and Semiconductor after Junction Formation

A voltage is applied from the metal to the semiconductor in the same manner as a p-n junction. When a negative voltage is applied on the n-type semiconductor and a positive voltage to the metal which is a forward bias condition, the Fermi energy of the metal is lowered with respect to the Fermi level of the semiconductor. The balance between diffusion and drift is disturbed and more electrons will diffuse towards the metal than the number drifting into the semiconductor. This leads to a positive current through the junction at a voltage comparable to the built-in potential. Figure 6 and Figure 7 shows the forward and reverse bias effect on the band diagram respectively.
When the junction is reverse biased, the Fermi energy of the metal is raised with respect to the Fermi level of the semiconductor thereby increasing the potential across the semiconductor. The depletion width increases and so does the electric field at the interface. The barrier restricts electron flow from the semiconductor to the metal. Therefore in reverse bias the junction has a rectifying behavior.

### 2.2.2.2 Ohmic Contact

Metal to Semiconductor ohmic contacts is very important to solid state devices. A perfect ohmic contact would have no voltage drop across the junction of the semiconductor and the metal. The Schottky barrier is zero for an ohmic contact. Here the carriers flow freely in either direction of the junction since there is minimal resistance. For a n-type semiconductor an ohmic contact means that the work function of the metal must be closer or smaller than the electron affinity of the semiconductor. For a p-type semiconductor the work function of the metal is either higher or equal to the electron affinity of the semiconductor.
2.2.2.3 Tunneling Contact

One of the approaches to obtain a near ohmic contact is to dope the semiconductor heavily near the contact. Such contacts do have a positive barrier at the metal-semiconductor interface, but also have a high enough doping in the semiconductor that there is only a thin barrier separating the metal from the semiconductor. If the width of the depletion region at the metal-semiconductor interface is very thin, on the order of 3 nm or less, carriers can readily tunnel across such barrier. This process of current transport where the carriers do not overcome the potential barrier but instead tunnel through the interface is called tunneling and such a diode is called tunneling diode. Figure 8 shows the band diagram of a tunneling contact. The same technique is used in back contacts of CdS/CdTe solar cells.
2.3 Solar Cells

A solar cell is a device that uses the photoelectric effect to generate electricity from light, thus generating solar power. Solar cells are used to power many kinds of equipments, including satellites, calculators and remote radiotelephones.

2.3.1 History of Solar Cells

The development of the solar cell stems from the work of the French experimental physicist Antoine-César Becquerel back in the 19th century. In 1839, Becquerel discovered the photovoltaic effect while experimenting with an electrolytic cell containing two metal electrodes. He found that certain metals and solutions would produce small amounts of electric current when exposed to light.

In 1877, Charles Fritts constructed the first true solar cells by using junctions formed by coating the semiconductor selenium with an ultra thin, nearly transparent layer.
of gold. Fritts's devices were very inefficient, transforming less than 1 percent of the absorbed light into electrical energy, but they were a start.

By the 1930s both the selenium cell and the copper oxide cell were being employed in light-sensitive devices such as photometers, for use in photography. These early solar cells however, still had energy conversion efficiencies of less than 1 percent.

Solar cell efficiency finally saw substantial progress with the development of the first silicon cell by Russell Ohl in 1941. In 1954, three other American researchers, G.L. Pearson, Daryl Chapin, and Calvin Fuller, demonstrated a further-refined silicon solar cell capable of 6% energy conversion efficiency. Today silicon cells, as well as those made of gallium arsenide, with efficiencies of more than 20% have been fabricated. CdTe solar cells fabricated in laboratories approach 16-percent efficiency.

2.3.2 Solar Cell Operation

The solar cells are photovoltaic devices that convert sunlight directly into electricity. The solar cell consists of a junction that is formed by bringing a p-type and n-type semiconductor together. The two materials can either be of the same or different materials.

![Figure 9 Photocurrent Generation in a Solar Cell](image-url)
When light strikes the cell, a certain portion of the light is absorbed within the semiconductor material. This means that the photon energy of the absorbed light is transferred to the semiconductor.

The energy incident on the semiconductors in terms of wavelength is given by

\[ E = \frac{C}{\nu} \]

Where \( \nu \) is the frequency in hertz and \( C \) is the velocity of light. The incident light knocks electrons loose, allowing them to flow freely leading to diffusion of the carriers. A electric field develops and separates electrons and holes. The flow of electrons and holes are shown in Figure 9. This flow of electrons and holes produce a current, and by placing metal contacts on the top and bottom of the PV cell, we can draw that current off to use externally.

### 2.4 Heterojunctions

When two crystals of semiconductors with different energy gaps are combined, a heterojunction is formed. The energy band diagram at thermal equillibrium is shown in Figure 10.

![Figure 10 Energy Band Diagram Of a Heterojunction][24]
Light, with energy less than $E_{g1}$ but greater than $E_{g2}$ passes through the first semiconductor. The first semiconductor acts as a window, the second semiconductor, the absorber. Carriers generated in the depletion region and within a diffusion length of the junction are collected and contribute to the photocurrent. In heterojunctions, the use of two chemically different materials introduces certain problems not encountered in homojunctions such as chemical compatibility and stability, reproducibility of the physical and chemical interface and the lattice compatibility at the metallurgical junction. Despite the problems mentioned above, the use of heterojunctions has a few attractive features.

Firstly, the heterojunctions allow the use of semiconductors that can only be doped either p-type or n-type and have attractive properties like better match to the solar spectrum, direct band gap or better-cost considerations. Secondly, heterojunctions of the window absorber form can be used to form structures that shield carriers from the top surface or back surface recombination sinks. Thirdly, the heterojunction solar cell is capable of producing more open circuit voltage than a homojunction even though the built-in voltage is the same in both the structures.

### 2.5 Parameters of a Solar Cell

Several parameters characterize the performance of a solar cell and in this section we will review some of the parameters that characterize the solar cell.

The product of the voltage and current in the fourth quadrant of the I-V curve signifies the amount of output power that is delivered by the solar cell. Figure 11 shows the inverted I-V curve in the fourth quadrant.

The total current is given by the expression

\[ I = I_0 \left[ e^{(qV/A_0 KT)} - 1 \right] - I_L \]

Where $I_0$ is the reverse saturation current or the dark current and $A_0$ is the diode quality factor and $I_L$ is the current generated by the cell under illumination.
Figure 11 I-V Curve of the Solar Cell Under Dark and Illumination Conditions

The short-circuit current ($I_{sc}$) is the current produced when the positive and negative terminals of the cell are short-circuited and the voltage between the terminals is zero and a zero load resistance.

The open-circuit voltage ($V_{oc}$) is the voltage across the positive and negative terminals under open-circuit conditions, and the current is zero and it corresponds to a load resistance of infinity. $V_{oc}$ is given by the equation

$$V_{oc} = A_o (KT/q)(I_{sc}/I_o + 1)$$
The cell is operated over a wide range of voltages and currents. By varying the load resistance from zero which is the short circuit condition to infinity which is the open circuit condition, the highest efficiency can be determined. On the I-V curve, the maximum-power is given as the product of the maximum voltage and the maximum current which is indicated in Figure 12.

Another parameter of interest is the Fill factor and is given by the equation

$$FF = \frac{V_m * I_m}{V_{oc} * I_{sc}}$$

The conversion efficiency of a solar cell is the percentage of the light energy that is converted from the incident light on a PV device into electrical energy and it is given by the equation

$$Efficiency \; \eta = \frac{P_m}{P_{in}} = \frac{FF * V_{oc} * I_{sc}}{P_{in}}$$

Where $P_m$ is the maximum power and $P_{in}$ is the power incident on the solar cell.
2.5.1 Series and Shunt Resistance

An equivalent circuit of a solar cell is given in Figure 13 with the shunt and series resistances. Ideally the series resistance is to be zero and the shunt resistance infinity but there is always a finite value for both the series and the shunt resistance. Taking into account the series and the shunt resistances the total current from the device is given by the equation

\[ I = I_o \left\{ \exp\left(\frac{V - IR_s}{A_o kT}\right) - 1 \right\} - I_L + \frac{V - IR_s}{R_{sh}} \]

![Figure 13 Equivalent Circuit of a Solar Cell](image)

2.5.2 Effect of Series and Shunt Resistance

The series resistance includes the resistances due to the bulk materials of the n-type and p-type semiconductors, the bulk resistance of the contact material, the contact resistance between the metallic contacts in the back and front to the semiconductor materials. The series resistance can be estimated from the I-V curves. The reciprocal of the slope of the I-V curve in the forward bias gives the series resistance. This is shown in Figure 14.
$R_s$ has no effect on the $V_{oc}$ and very little effect on the $I_{sc}$. However the fill factor (FF) is affected by $R_s$ leading to a reduction in conversion efficiency. The shunt resistance can also be found out from the I-V curves. The reciprocal of the slope of the I-V curve in reverse bias gives the shunt resistance and this is shown in Figure 15.

Shunt resistance is lowered due to leakage paths near the junction. These leakage paths are light sensitive and lead to light induced shunting. The presence of pinholes in the film lowers the shunt resistance. When the shunt resistance is reduced it affects the fill factor. It also increases the $I_0$ which causes a decrease in the $V_{oc}$ and hence the efficiency.

![Figure 14 Effect of Series Resistance](image-url)
Figure 15 Effect of Shunt Resistance
CHAPTER 3
MATERIALS

Thin film CdS /CdTe photovoltaic cells are being developed as a low-cost alternative to conventional silicon solar cells. In this chapter the properties of Cadmium Sulphide and Cadmium Telluride are discussed briefly.

3.1 Cadmium Sulphide

Thin films of CdS have been used as a junction partner in CdTe, CuInSe\textsubscript{2}, InP and CuInGaSe solar cells for many years and it is the most widely used window material for thin film CdTe solar cells due to its large bandgap and high transparency.

Cadmium sulphide, like other II-VI semiconductors has a crystal structure and can take two forms namely zinc blende (cubic and wurtzite (hexagonal) structure [5]. The two structures are shown in Figure 16 and Figure 17. In the hexagonal structure each Cd atom is surrounded by four nearest S atoms. In the cubic structure each S atom is surrounded by four Cd atoms.

![Figure 16 Hexagonal Structure of CdS](image)
CdS is a direct band gap II-VI compound semiconductor with bandgap energy of 2.42 eV at room temperature. The conductivity of CdS, as in the case of any II-VI semiconductor is influenced by the number of S vacancies. The native defects may be point defects or dislocations. Point defects may be vacancies or interstitial atoms. The Sulphur vacancies become ionized donors and contribute to the n-type conductivity [10].

As deposited CdS is reported to have a high resistivity in the order of $10^6$ ohm-cm [20]. It has been found out that the resistivity of the CdS can be reduced by annealing the CdS film in H$_2$ ambient. The decrease in resistivity is believed to be caused due to the depletion of S by the formation of H$_2$S and the consequent increase in the donor density. Some of the other effects of hydrogen annealing that have been reported are

- A decrease in the amount of oxygen adsorbed at the grain boundaries [20].
- Adsorption of hydrogen within the grain boundary passivates broken bonds [20].
- Recrystallization to increase grain size or anneal out dislocations [20].
All these effects decrease intergrain boundary and increase conductivity.

O₂ and Cl play an important role in the II-VI compounds. Oxygen is present during the deposition of CdTe and during post deposition heat treatment. Chlorine is present during a post deposition heat treatment. Oxygen has the following effects on CdTe solar cells [11, 12]

i. Formation of oxides like CdO which leads to the formation of a solid solution between the chalcolenide and the oxide. This may produce a shift in the band gap and energy level of defects [20].

ii. Being an isoelectronic impurity in II-VI compounds, oxygen acts as a trap depending upon the ionicity of the compound. [13].

iii. Oxygen adsorbed at the surface can act as an electron trap or as an acceptor and can change the conductivity of the films. This effect is important because the surface area is larger due to the grain boundaries [14].

The optical properties of CdS make it a good choice as a window layer for thin film solar cells. It absorbs light below a wavelength of about 510nm.

There are several techniques for the deposition of CdS like Chemical Bath Deposition (CBD), Close Spaced Sublimation (CSS), Screen printing, Vacuum evaporation, Spray pyrolysis, MOCVD and sputtering [6]. Although the CBD process has given the best results with 16% conversion efficiency, large scale production is questionable due to problems encountered with the cadmium wastes. Recent results with cells made by CSS technique have been equally effective with added advantage of being more pure.

3.2 Cadmium Telluride

Cadmium telluride is another prominent polycrystalline thin-film material. CdTe is an II-VI semiconductor and comes in the zinc blende structure as shown in the Figure 18.
Cadmium tellurium

Figure 18 Cubic Structure of CdTe

With a nearly ideal bandgap of 1.44 eV at room temperature CdTe is a direct bandgap material. CdTe also has a very high absorptivity. It has a lattice parameter of 6.48 Å [15]. CdTe can be doped n-type or p-type. CdTe is characterized by a number of native defects which act as donors or acceptors. There are a number of ways in which CdTe can be deposited like Close Spaced Sublimation (CSS), chemical spraying, Chemical Vapor Deposition (CVD), Electro deposition and galvanic deposition. Some of the properties of CdS and CdTe are listed in Table 1 [16].
Table 1 Properties of CdS and CdTe

<table>
<thead>
<tr>
<th></th>
<th>CdS</th>
<th>CdTe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap (eV)</td>
<td>2.42</td>
<td>1.44</td>
</tr>
<tr>
<td>Electron Affinity</td>
<td>4.5</td>
<td>4.2</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>9.7</td>
<td>7.2</td>
</tr>
<tr>
<td>Mobility (Electrons) at room Temp (cm /Vs)</td>
<td>340</td>
<td>1200</td>
</tr>
<tr>
<td>Mobility (Holes) at room Temp(cm /Vs)</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>2.33</td>
<td>2.5</td>
</tr>
<tr>
<td>Lattice Parameters (Å)</td>
<td>5.832</td>
<td>6.447</td>
</tr>
</tbody>
</table>
CHAPTER 4
LITERATURE REVIEW-CDTE BACK CONTACT TECHNOLOGY

Among the II-VI compounds, CdTe is one of the most promising absorbers for use in inexpensive semiconductor solar cells. One of the major problems in CdTe solar cells is the poor contact stability. This chapter discusses contact issues for CdTe solar cells and some approaches to address these issues. The role of Cu and its effect on the back contact is also reviewed.

4.1 The Contact Problem

The formation of an effective back contact depends on two key material properties. They are

1. The electron affinity of the material 
2. The doping level of the material

CdTe has a high electron affinity of 4.5 eV and the distance between the conduction band and the Fermi level in the case of p-CdTe is estimated to be 1.38-1.48 eV. So the total work function of CdTe is 5.9 eV[5]. Therefore a high work function metal is required to form a good ohmic contact with the p-CdTe. Table 2 shows some work functions of the most commonly used metals for contacts. Not many metals presents such a high value of work function [16]. When the workfunction of the contact material is not higher than the workfuntion of the surface to which it is contacted a Schottky barrier is formed. The Schottky barrier acts as a diode reverse biased to the CdS/CdTe junction diode and increases the contact resistance and reduces the solar cell performance.
Another problem in achieving ohmic contact is the high resistivity of CdTe. The charge density of the CdTe is controlled to a large extent by its native defects. Native defects act as donors and acceptors with Cd and Te vacancies acting as acceptors and donors respectively. These defects can also form complexes with the dopants making the carrier concentration control very difficult. In a polycrystalline material, excessive series resistance arises from potential barriers both at the grain boundaries and at the p-type ohmic contact[5]. This is because the oppositely charged grain boundary states effectively compensate the dopant. For large grain boundary regions, the effective mobility is strongly reduced by the grain boundary barriers.

### 4.2 Approaches to Back Contact

There are several ways to make ohmic or pseudo-ohmic contacts to a CdTe. The following section briefly discusses two of the most typical ways.

1. Use of a compound with a higher work function than p-CdTe.
2. Heavily doping the semiconductor adjacent to the contact to permit quantum mechanical tunneling through the surface barrier.

As mentioned earlier, since no metal has a work function as high as that of a p-CdTe, a variation of the first method is used. This involves a layer of semiconductor at the contact that will form a pseudo-ohmic contact to the metal [17].

In the second method a pseudo ohmic contact is formed by doping the CdTe adjacent to the contact highly p-type to promote tunneling. Chemical etching of CdTe with Nitric-Phosphoric solution or Bromine-Methanol solution widens grain

---

**Table 2 Work Functions of Few Metals[5]**

<table>
<thead>
<tr>
<th>Metal</th>
<th>Work function (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>4.26</td>
</tr>
<tr>
<td>Al</td>
<td>4.28</td>
</tr>
<tr>
<td>Au</td>
<td>5.10</td>
</tr>
<tr>
<td>Co</td>
<td>5.00</td>
</tr>
<tr>
<td>Cu</td>
<td>4.65</td>
</tr>
<tr>
<td>Ni</td>
<td>5.15</td>
</tr>
<tr>
<td>Pd</td>
<td>5.12</td>
</tr>
<tr>
<td>Mo</td>
<td>4.60</td>
</tr>
</tbody>
</table>
boundaries and leaves a metastable tellurium rich p+ CdTe surface which reduces the Schottky barrier [17].

4.3 Role of Copper

After etching the p-CdTe to form a Te rich layer a metal contact is deposited. Most of the metal contact use Cu in them. Copper at the back contact can form a distinct Cu$_{2-x}$ Te layer or it can locally increase the effective doping level in the CdTe at the back contact through interdiffusion [21]. The former lowers the back contact barrier while the latter narrows the barrier. In either case, the current through the back contact should be less limited when Cu is added. Conversely the removal of Cu from the back contact region progressively limits the current flow through the back diode [18]. The problem with Cu in the back contact is that it tends to diffuse away from the contact under thermal and electrical fields towards the CdS/CdTe junction. This diffusion can cause a shunting effect and thereby degrade the cell performance. It has been found that after the contact for the samples have been deposited with Cu, there is some accumulation of Cu in the CdS layer of the cell [25]. The Cu concentration increases in the CdS when compared to the CdTe layer.

4.3.1 The Various Types of Contacts Based on Cu

4.3.1.1 Au:Cu Contact

Gold (Au) is one of the contacts that have been under constant study since it has a high work function. Gold can be used alone or it can be deposited as a final metal layer after various surface treatments. Gold can be deposited on the sample by chempelating in a Au ion solution. It has been found that the cadmium diffuse out of the CdTe with the diffusion of gold into these vacancies that provides the required extrinsic p-type doping.

Another possibility is the formation of a thin layer of AuTe$_x$ which either forms the actual contact or helps to lower the barrier height. Gold can also be deposited by vapor deposition with Cu on a previously prepared surface of CdTe. In this method the CdTe layer is etched with Bromine /methanol solution which creates Cd vacancies [5]. Copper and Au can be sequentially deposited by PVD techniques
followed by annealing. Cu acts as a substitutional acceptor for Cd thereby increasing the doping concentration near the surface of p-type CdTe.

4.3.1.2 ZnTe: Cu Contacts

ZnTe is another material that is used widely in CdS/CdTe solar cells. ZnTe has a valence band offset with CdTe and when it is doped with Cu it forms a good ohmic contact to the solar cell. ZnTe is a p-type semiconductor with a direct band gap of 2.2 eV. ZnTe has a very low valence band discontinuity of -0.14 eV[20] with CdTe and so it provides no hindrance to the flow of holes towards the contact. Copper is added to dope the ZnTe highly p-type. The amount of copper added plays an important role since both higher and lower concentrations of Cu causes a reduction in the electrical properties of solar cells. Copper proves to be detrimental to device performance by forming interstitials or defect complexes that act as recombination centers and so the devices become unstable.

4.3.1.3 HgTe:Cu and Doped Graphite Paste Contact

Mercury telluride has a very high work function of 5.9 eV and is ideally suited as a back contact for the CdS/CdTe solar cell. It also has a nearly matching lattice parameter to the CdTe (-.3% mismatch) with which it forms a solid solution over the whole composition range. HgTe has been used as a contact to p-type CdTe of 10-15 Ω resistivity. The deposition of p-HgTe on p-CdTe may be carried out by the direct combination of the elemental vapors in a gas-flow system and by the close-spaced sublimation (CSS) technique. The process parameters in the direct combination technique are more readily controlled than those in the CSS technique.

The p-HgTe/p-CdTe contact resistance is found to be very similar to the Au/p-CdTe contact resistance. High efficiency solar cells have been produced by using a mixture of HgTe: Cu and graphite paste. It is believed that an interlayer of Cu₂Te and Hg₁₋ₓCdₓTe which is highly p-doped is formed, which helps in the tunneling of carriers across the contact [21]. After the CdTe deposition the samples are etched with bromine/methanol solution to make it more p-type. The contact paste
is then applied followed by air drying. The samples are then annealed in helium ambient at 270°C for 25 minutes.

4.3.1.4 Cu/Mo, Sb₂Te₃/Mo, Sb/Mo Back Contacts

It has been found that rf-sputtered Sb₂Te₃ is a suitable buffer material for high efficiency solar cells. A buffer layer of Sb, Sb₂Te₃ or Cu is deposited by PVD techniques and then the back contact is completed by metallization by vacuum evaporation or sputtering of Mo layer. Cells with Mo metallization and buffer layer of Sb, Sb₂Te₃ do not degrade. They even show some improvement after the initial illumination. This increase in efficiency can be explained by two effects. One, it could be the saturation of recombination centers in the bulk CdTe and the trap states in the interface region and secondly it could form an optimum compound at the interface [22].

The carrier concentration at the back contact is responsible for the barrier height and hence the roll over in the I-V characteristics. The carrier concentration at the back contact of cells with Sb₂Te₃/Mo is the highest and corresponds to a lower barrier height. Although the Carrier concentration near the back contact of the Cu/Mo cells is lower than that of the Sb₂Te₃/Mo cells, a barrier height of .22 eV is low enough to create a quasi-ohmic contact. Cells with Sb/Mo back contact have the lowest Carrier concentration and the highest barrier height with 0.6 eV.

The SIMS depth profiling on the different contacts showed that there was interdiffusion from the surface to the bulk and then towards the junction in the case of Cu back contacts. An accumulation of Cu in the front contact is also observed. There was no indication for Mo or Sb₂Te₃ to diffuse from the back contact towards the junction. Figure 19 shows the doping profiles of cells with different buffer layer and Mo metallization.
4.4 Effect of Copper Diffusion on Electrical Properties of Solar CdS/CdTe Cell

Figure 20 and Figure 21 show the J-V characteristics when the amount of Cu in the back contact is varied. When no Cu is used the fill factor is significantly reduced and the back barrier limits the current above Voc [18]. There are progressive improvements up to a standard amount, but additional Cu makes little difference.
Copper is well known to be a fast diffuser. Copper moves along the grain boundaries and sometimes diffuses away from the contact, leaving it more resistive, and the movement towards the primary diode junction decreases the effectiveness. When a cell with a standard amount of Cu is stressed at elevated temperature there is a current limitation and a roll over. This reduces the fill factors of the devices significantly.

The Capacitance-Voltage response of CdS/CdTe solar cells also varies with the amount of Cu used in the back contact. Figure 22 shows the C-V response. Without Cu, the capacitance of the cell is found to be independent of voltage and has a value corresponding to the depletion of the CdTe layer. As Cu is added, the region near the back of the contact was no longer depleted suggesting that Cu interdiffusion increased the carrier density in the region. When the cells are subjected to elevated temperature stress, the cells with smaller amount of Cu show that most of the CdTe is fully depleted since much of the Cu has moved away from the back contact region.

![Figure 21 Variations in J-V Curves with Varying Stress Time](image)
4.5 Motivation

Although a number of contact technologies have been suggested, the problem of obtaining a stable, low resistance contact still remains as the main concern. Copper plays a very crucial role in all the contact technologies. Copper is used primarily to form low barrier contacts to p-type CdTe absorbers. It is found out that, though the initial performance of the cells with Cu in the back contact is high, the cells tend to degrade. This degradation is attributed to the diffusion of Cu to the junction leading to shunting paths through the grain boundaries. Therefore the cells are unstable and the efficiency of the cells drops rapidly.

The motivation of this thesis comes from the need of better understanding of the role of Cu at the interface and the back contact. In this thesis, Cu is eliminated from the back contact and Cu is introduced directly in the CdS/CdTe interface. This is done by treating the cells in a CuCl solution. Since Mo does not diffuse towards the interface, Mo is deposited at the back contact instead of the Cu doped graphite contact and the performances of the cells are studied.
CHAPTER 5

DEVICE STRUCTURE AND PROCESSING OF CDS/CDTE SOLAR CELLS

In this chapter the device structure of a CdS/CdTe heterojunction solar cell, a CuCl treated solar cell, and a solar cell with molybdenum as a back contact are presented along with their processing techniques and procedures.

5.1 Device Structure

The cells used for this thesis were fabricated on high purity 7059 borosilicate glass with a very high transmission and an electrical conductivity close to that of metals.

![Figure 23 Basic CdS/CdTe Solar Cell](image)

The basic cell structure that is used at the University of South Florida is shown in Figure 23. The front contact is a 1µm thick layer of tin oxide deposited by MOCVD technique. CdS layer of thickness 0.8µm is deposited over the tin oxide layer. The CdS can be deposited either by CBD technique or CSS technique. The samples used in this thesis are all deposited by CSS technique. The sample is then dipped in a solution of DI water and CuCl. Samples processed this way will be referred to as “CuCl-treated” samples.
CdTe with a thickness of 5-6µm is deposited by CSS technique on top of the CuCl treated samples. Samples are then treated with CdCl2 and then a back contact layer is deposited on the sample. Different back contact materials are used with different techniques at the university. Silver is deposited on the contacts for greater durability.

Figure 24 shows schematic diagram of a CdS/CdTe solar cell that uses a Cu doped graphite paste contact. The paste is made by mixing HgTe:Cu and a graphite paste which is called EB003 made by a company called Acheson colloids.

**Figure 24 CdS/CdTe Solar Cell Using HgTe:Cu And Graphite Paste**
Samples with these type of contacts have shown that the performance of these samples have been degrading and is attributed to diffusion of Cu towards the junction. Figure 25 shows a schematic diagram of a CuCl treated sample that uses graphite paste as the back contact.

**Figure 25 CuCl Treated CdS/CdTe Solar Cell with Undoped Graphite as Back Contact**
In these types of cells the contacts are the EB003 graphite paste that has no Cu mixture in them. Figure 26 shows a schematic diagram of a CdS/CdTe solar cell that has Mo as its back contact. Such samples are treated with CuCl solution after CdS deposition.

![Schematic diagram of a CdS/CdTe solar cell with Mo as a Back Contact](image)

**Figure 26 CuCl Treated CdS/CdTe Solar Cell with Mo as a Back Contact**

The stepwise fabrication procedure for the solar cells with CuCl treatment and Mo back contact is discussed in the rest of the chapter.

### 5.2 Deposition of Tin Oxide (SnO₂)

The Transparent Conducting Oxide (TCO) forms the front contact for the solar cell. Tin Oxide doped with fluorine is the most often used TCO. Tin oxide is deposited as the first layer of a CdS/CdTe solar cell. SnO₂ is deposited on the 7059 borosilicate glass by MOCVD technique.

The source for tin is a metal organic precursor called Tetramethylin (TMT). The Fluorine source is halocarbon Trifluorobromomethane(CBrF3). High purity (99.99%) oxygen and helium are used as ambients. The deposition of SnO₂ is a two layer process where the first layer is doped SnO₂ and the second layer is a undoped layer. A high resistive layer between the SnO₂ and CdS has shown better performance and enhances
the stability. The final thickness of SnO$_2$ is about 0.8 –1 µm and the SnO$_2$ has a sheet resistance of about 7-12 Ω/□.

5.3 Cadmium Sulphide

Cadmium Sulphide (CdS) is deposited onto the tin oxide layer, by the Close Spaced Sublimation (CSS) technique. The deposition process is controlled by varying the pressure inside the chamber, the substrate and the source temperature, the spacing between the source and substrate and the type of ambient gases used. The temperatures of the substrate and source are controlled by temperature controllers which are connected to thermocouples. The temperature controllers that were used for the experiments were a K- type thermocouple and the model number was Omega CN4400. Lamps are used to heat up the source and the substrate graphite plates. The lamps that were used for these experiments were halogen lamps and the model number was OSRAM NAED 54559 with a operating power up to 2000W. The chamber is purged with necessary gases like O$_2$ and He using the inlet and outlet ports. The schematic of the chamber setup is shown in Figure 27.

![Figure 27 CSS-CdS Apparatus](image)

**Figure 27 CSS-CdS Apparatus**

Reactors tubes were of quartz glass and had a inner diameter of 57mm and outer diameter of 60mm and the length was 1 foot. Dimensions of the graphite plates were 45mm length and breadth and the thickness was 5mm. Spacers are placed between the source and substrate and the thickness of the spacers was 3mm. The source and substrate temperatures and the deposition time profile are shown in Figure 28 [23].
The substrate temperature was maintained at 550 °C and the source temperature at 650 °C.

5.4 CuCl Treatment

After the CSS CdS deposition onto the SnO₂ layer, the samples are treated with CuCl solutions in order to introduce various quantities of Cu. The setup for the CuCl treatment is showed in Figure 29. The solutions are heated to a temperature of 90 °C with continuous and then the samples are dipped into the solution for various times.

5.5 Cadmium Telluride

After the CuCl treatment, CdTe is deposited on the CdS layer using the CSS process. The set up for the CdTe is the same as that of CdS (Figure 27). At first the CuCl
treated CdS is annealed in H₂ ambient at 390°C for 10 minutes. The chamber is then purged with He and O₂ gases. Deposition of CdTe is done in a pure He and O₂ ambient. The thickness of the deposited CdTe layer is about 5-7 µm. The deposition is done at a source temperature of 650-680°C and the substrate temperature around 550-580°C. The CSS process is based on the reversible dissociation of CdTe at high temperatures.

$$2\text{CdTe} \quad \leftrightarrow \quad 2\text{Cd} + \text{Te}_2$$

Following the CdTe deposition the structures are CdCl₂ treated. The samples are then etched using a bromine methanol solution.

### 5.6 Back Contact

The different types of contacts used for the samples in this thesis are listed below.

1. Molybdenum for CuCl treated CdS samples.
2. Undoped graphite paste for CuCl treated CdS samples.
3. Cu doped graphite paste for samples with no CuCl treatment for fabricating the baseline device for comparison purposes.

In Cu doped graphite contacts, a graphite paste prepared by mixing HgTe:Cu is applied on the etched samples and allowed to air dry for a few hours to remove the solvents from the paste. After drying the samples are annealed at 270°C for 25 minutes. These samples are not treated with CuCl solution. For the CuCl treated samples undoped graphite contact is used. No intentional Cu is used for these samples. The samples is allowed to dry for a few hours to remove the solvents and then annealed at 270°C for 25 minutes.

For Mo contacted samples, the Mo is deposited on the bromine methanol etched samples by sputtering. The pressure during the sputtering process is 5mTorr.

* CuCl –treated samples implies that the CdS is dipped in CuCl solution.

The thickness of the Mo back contact was 6000Å. The samples are annealed at various temperatures from 270-350°C. Following the annealing the cell is scraped to expose the SnO₂ surface. Indium is soldered to the SnO₂ layer to form a front metal contact. This completes the fabrication of the CdS/CdTe solar cells.
CHAPTER 6

RESULTS AND DISCUSSION

This chapter discusses the results obtained during this work. The objective was to study the effect of adding Cu to CdS and eliminating Cu at the back contact. Mo is used instead of graphite.

6.1 Cells Contacted with Doped Graphite Paste

The performance of a baseline sample with doped graphite paste is shown in Table 3. These samples are the conventional cells with the previously optimized conditions.

Table 3 Performance of the Conventional Solar Cell: Doped Graphite Paste

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-13-A2-1-a</td>
<td>830</td>
<td>70.80</td>
<td>21.61</td>
<td>12.69</td>
</tr>
<tr>
<td>2-13-A2-1-b</td>
<td>830</td>
<td>70.90</td>
<td>20.55</td>
<td>12.09</td>
</tr>
<tr>
<td>2-13-A2-1-c</td>
<td>830</td>
<td>70.80</td>
<td>22.01</td>
<td>12.90</td>
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<tr>
<td>2-13-A2-1-d</td>
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<td>71.10</td>
<td>21.50</td>
<td>12.35</td>
</tr>
<tr>
<td>2-13-B2-1-a</td>
<td>830</td>
<td>70.5</td>
<td>21.55</td>
<td>12.61</td>
</tr>
<tr>
<td>2-13-B2-1-b</td>
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<td>71.40</td>
<td>21.10</td>
<td>12.35</td>
</tr>
<tr>
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<td>69.60</td>
<td>21.70</td>
<td>12.38</td>
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<tr>
<td>2-13-B2-1-d</td>
<td>820</td>
<td>69.90</td>
<td>20.60</td>
<td>11.80</td>
</tr>
</tbody>
</table>

The Spectral response for the cells of table 3 is shown in Figure 30.
Figure 30 Spectral Response of the Samples with Cu Doped Graphite Contact

Figure 30 shows that the Q.E in the mid range is 90% on the average. The transmission in the blue region is 20% indicating that the CdS layer is thick. All the four samples show consistency in the spectral response.

Figure 31 Dark J-V Response of Cu Doped Graphite Contact

The dark and light J-V curves for the samples in table 3 is shown in Figure 31 and Figure 32 respectively.
In Figure 32 the shunt resistance is same for all the samples and the series resistance 1Ω-cm\(^2\) approx. The series resistance of the third sample is 1.3 Ω -cm\(^2\). The light J-V response shows that the response is similar for all the samples and the series resistance is approximately 3.2 Ω -cm\(^2\) - 3.5 Ω -cm\(^2\) for all the samples and the shunt resistance is 750 Ω -cm\(^2\). These samples will serve as a reference for the CuCl treated devices.

![Light J-V Response of Cu Doped Graphite Contact](image)

**Figure 32 Light J-V Response of Cu Doped Graphite Contact**

### 6.2 CuCl Treated Samples

The CdS films in these types of solar cells are treated with a CuCl solution with different concentrations. The different concentrations that are used in this thesis are given in the next section. All the cells presented are fabricated are kept constant with the exception of the back contact. Cuprous Chloride treated samples are typically contacted either with undoped graphite paste or sputtered Mo.

#### 6.2.1 Different CuCl Concentrations Used in this Thesis

Different CuCl concentrations used in this thesis are listed below.

- **Sol#1** is \(6 \times 10^{-8}\) M.
- **Sol#2** is \(3 \times 10^{-8}\) M
- **Sol#3** is \(2 \times 10^{-7}\) M.
Table 4 Performance of the CdS/CdTe Solar Cells Without CuCl Treatment

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-15-B8-a</td>
<td>790</td>
<td>35.10</td>
<td>20.86</td>
<td>5.78</td>
</tr>
<tr>
<td>8-15-B8-b</td>
<td>810</td>
<td>36.10</td>
<td>20.69</td>
<td>6.05</td>
</tr>
<tr>
<td>8-15-B8-c</td>
<td>810</td>
<td>39.20</td>
<td>20.90</td>
<td>6.36</td>
</tr>
<tr>
<td>8-15-B8-d</td>
<td>810</td>
<td>40.50</td>
<td>22.49</td>
<td>7.37</td>
</tr>
<tr>
<td>8-15-A8-a</td>
<td>770</td>
<td>21.50</td>
<td>21.37</td>
<td>3.54</td>
</tr>
<tr>
<td>8-15-A8-c</td>
<td>800</td>
<td>31.00</td>
<td>21.32</td>
<td>7.38</td>
</tr>
<tr>
<td>8-15-A8-d</td>
<td>790</td>
<td>31.70</td>
<td>20.30</td>
<td>5.08</td>
</tr>
</tbody>
</table>

Table 4 lists the performance data for cells fabricated without CuCl treatment and contacted with undoped graphite paste. It can be seen that all these cells exhibit very low fill factors. Table 5 lists similar data. In this case the samples are contacted with graphite. However these cells have received the CuCl treatment. Comparing the result in the two tables, it is clear that the CuCl treated cells tend to improve in FF (21.5%-40.5% to 61%-65%) and \( V_{oc} \) (790-810mV to 820-830mV).
Table 5 Performance of the CdS/CdTe Solar Cells with CuCl Treatment

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-15-1B8-a</td>
<td>830</td>
<td>64.30</td>
<td>20.68</td>
<td>11.04</td>
</tr>
<tr>
<td>8-15-1B8-b</td>
<td>830</td>
<td>63.30</td>
<td>21.84</td>
<td>11.47</td>
</tr>
<tr>
<td>8-15-1B8-c</td>
<td>830</td>
<td>63.70</td>
<td>19.30</td>
<td>10.20</td>
</tr>
<tr>
<td>8-15-1B8-d</td>
<td>830</td>
<td>64.80</td>
<td>20.60</td>
<td>11.08</td>
</tr>
<tr>
<td>8-15-1A8-a</td>
<td>820</td>
<td>61.30</td>
<td>22.79</td>
<td>11.46</td>
</tr>
<tr>
<td>8-15-1A8-b</td>
<td>820</td>
<td>62.30</td>
<td>22.90</td>
<td>11.69</td>
</tr>
<tr>
<td>8-15-1A8-c</td>
<td>820</td>
<td>61.00</td>
<td>20.13</td>
<td>10.06</td>
</tr>
<tr>
<td>8-15-1A8-d</td>
<td>820</td>
<td>61.20</td>
<td>21.20</td>
<td>10.63</td>
</tr>
</tbody>
</table>

Based on the AES depth profile showed in Figure 33 of CuCl treated samples, CuCl treated samples cleanly shows that Cu is introduced in the CdS.

![Figure 33 AES Depth Profile for CuCl Solution Treated Samples](image-url)
Figure 34 shows the light J-V response indicating that the low FF for non treated cells is due to a poor back contact. The above device results suggest that this Cu affects the $V_{oc}$ which can be expected since the $V_{oc}$ depends on the internal surface properties. It also appears to affect the back contact which suggests that the Cu affects the CdTe doping.

Figure 34 Comparison of Light J-V’s of Cu Doped Graphite Contact, CuCl Treated and Non Treated Samples

Figure 35 summarizes the typical performance for

1. Copper doped graphite contacts
2. CuCl treated CdS with undoped graphite contacts
3. Graphite contacted samples with no CuCl treatment

Figure 35 Performance of the Cu Doped Graphite Contact, CuCl Treated and Non Treated Samples
It can be seen that though the variations in $V_{oc}$ for the three contacts is less, the FF’s vary from 40% in the samples with no Cu treatment to 65% in CuCl treated samples and the samples with Cu doped graphite contacts have the highest FF of 71%.

Figure 36 shows that Spectral response of the same samples clearly indicating that the current generation is very similar in all though the CdS layer is very thick in all the samples.

Figure 36 Comparison of Spectral Responses of Samples With Cu Doped Graphite Contact, CuCl Treated and Non Treated Samples

6.2.2 Molybdenum as a Back Contact for CuCl Treated Samples

In the previous section the CuCl treated samples used undoped graphite paste as the back contact. Molybdenum is tried instead of graphite and the performance of the solar cells is studied. Molybdenum is RF sputtered with a 5mTorr Argon pressure. The thickness of the Mo contact is 6000Å. The Mo is deposited at various temperatures ranging from room temperature to 200°C.
6.2.2.1 As Deposited Mo Contacted Samples

In order to study the effect of the as deposited Mo contact, the samples are measured without post contact annealing. Table 6 shows the performance of the samples deposited at various temperatures ranging room temperature to 200°C.

Based on these results it can be seen that the CuCl treated cells contacted with Mo deposited at 180°C and 200°C had better performance in terms of $V_{oc}$ and there was not much of a variation in terms of FF and currents. The J-V response in Figure 37 shows that there is roll over in the fourth quadrant in all the samples.

### Table 6 Performance of the Mo Contacted Samples Deposited at Different Temperatures

<table>
<thead>
<tr>
<th>Deposition Temperature [°C]</th>
<th>Sample no</th>
<th>$V_{oc}$ [mV]</th>
<th>FF [%]</th>
<th>$J_{sc}$ [mA/cm²]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
<td>4-22-2A-d</td>
<td>780</td>
<td>49.20</td>
<td>20.30</td>
<td>7.94</td>
</tr>
<tr>
<td></td>
<td>5-3-B3-b</td>
<td>790</td>
<td>50.40</td>
<td>19.84</td>
<td>7.90</td>
</tr>
<tr>
<td>150</td>
<td>5-20-A12-c</td>
<td>740</td>
<td>52.70</td>
<td>19.20</td>
<td>7.49</td>
</tr>
<tr>
<td></td>
<td>5-20-1A12-b</td>
<td>720</td>
<td>55.00</td>
<td>20.75</td>
<td>8.22</td>
</tr>
<tr>
<td>180</td>
<td>5-3-1A1-a</td>
<td>750</td>
<td>50.20</td>
<td>20.10</td>
<td>7.56</td>
</tr>
<tr>
<td></td>
<td>5-3-A2-d</td>
<td>820</td>
<td>55.00</td>
<td>19.70</td>
<td>8.89</td>
</tr>
<tr>
<td>200</td>
<td>5-3-1B3-d</td>
<td>800</td>
<td>54.90</td>
<td>20.42</td>
<td>8.97</td>
</tr>
<tr>
<td></td>
<td>5-3-A1-d</td>
<td>790</td>
<td>54.20</td>
<td>21.17</td>
<td>9.06</td>
</tr>
</tbody>
</table>
Figure 37 J-V Response of Mo Contacted Samples Deposited at Different Temperatures
The roll over for these samples indicates a poor back contact. Figure 38 summarizes the performance of the CuCl treated samples with Mo back contact and it is seen that the performance is essentially identical.

Figure 38 Comparison on the Performance of Mo Contacted Samples Deposited at Room Temperature and Annealed at Different Temperatures
Figure 39 shows the spectral response of the samples deposited at different temperatures. It can be seen that all the samples exhibit collection losses as indicated by the decrease in QE at long wavelengths and this could be due to the formation of a Schottky diode at the back contact. There are greater collection problems in the as-deposited samples and the 180°C deposited samples.
6.2.2.2 Molybdenum Contacted Samples Annealed at 270°C

Following the measurements listed in Table 6, the same cells were annealed at 270°C for 25 minutes and their I-V characteristics were remeasured. Table 7 shows the Voc performance of these devices. There is no consistent variation in the $V_{oc}$ of the samples before and after heat treatment at 270°C. The FF’s also show only a small increase after annealing which is insignificant. This indicates that the heat treatment at 270°C does not affect the samples.

Comparing the J-V curves from Figure 40, it is found that the roll over increased for the samples deposited at room temperature and 200°C when compared to that of 180°C and 150°C which is inconsistent.
Table 7 Performance of the Mo Contacted samples annealed at 270°C

<table>
<thead>
<tr>
<th>Deposition Temperature [°C]</th>
<th>Sample no</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
<td>4-22-2A-1-d</td>
<td>760</td>
<td>57.20</td>
<td>21.50</td>
<td>9.34</td>
</tr>
<tr>
<td></td>
<td>5-3-B3-1-c</td>
<td>800</td>
<td>57.70</td>
<td>20.14</td>
<td>9.29</td>
</tr>
<tr>
<td>150</td>
<td>5-20-A12-c</td>
<td>730</td>
<td>58.00</td>
<td>20.00</td>
<td>8.46</td>
</tr>
<tr>
<td>180</td>
<td>5-3-A2-1-a</td>
<td>800</td>
<td>55.70</td>
<td>21.12</td>
<td>9.41</td>
</tr>
<tr>
<td>200</td>
<td>5-3-1B3-1-b</td>
<td>800</td>
<td>57.50</td>
<td>20.45</td>
<td>9.40</td>
</tr>
<tr>
<td></td>
<td>5-3-A1-1-a</td>
<td>780</td>
<td>53.70</td>
<td>19.56</td>
<td>8.19</td>
</tr>
</tbody>
</table>

The shunt resistance for the 180°C is 650Ω-cm² whereas the shunt resistance for the other cells is around 800Ω-cm². The series resistance for the cells deposited at 180°C and 150°C is approximately 25 Ω-cm² of the cells deposited at room temperature and 200°C is 90 Ω-cm².

Figure 40 J-V Response of Mo Contacted Samples Annealed at 270°C
6.2.2.3 Molybdenum Contacted Samples annealed at 300°C

Samples deposited at various temperatures are annealed at a higher temperature of 300°C and their J-V performance of the samples is studied.

Table 8 Performance of the Mo Contacted Samples Annealed at 300°C

<table>
<thead>
<tr>
<th>Deposition Temperature [°C]</th>
<th>Sample no</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
<td>4-22-2A-2-a</td>
<td>770</td>
<td>55.30</td>
<td>17.60</td>
<td>7.51</td>
</tr>
<tr>
<td></td>
<td>5-3-B3-2-d</td>
<td>810</td>
<td>55.80</td>
<td>19.99</td>
<td>9.03</td>
</tr>
<tr>
<td>150</td>
<td>5-20-1A12-b</td>
<td>780</td>
<td>62.00</td>
<td>20.75</td>
<td>10.03</td>
</tr>
<tr>
<td>180</td>
<td>5-3-A2-2-a</td>
<td>820</td>
<td>59.60</td>
<td>20.98</td>
<td>10.25</td>
</tr>
<tr>
<td>200</td>
<td>5-3-1B3-2-a</td>
<td>820</td>
<td>58.30</td>
<td>20.82</td>
<td>9.95</td>
</tr>
<tr>
<td></td>
<td>5-3-A1-2-b</td>
<td>800</td>
<td>54.10</td>
<td>21.69</td>
<td>9.38</td>
</tr>
</tbody>
</table>

Comparing Table 8 and Table 9, it is seen that for all the samples annealed at 300°C, there is an increase of 20mV when compared to the samples annealed at 270°C. The fill factors show some inconsistency when comparing the samples annealed at 270°C and 300°C. There is no considerable change in the currents.

Figure 41 J-V Response of Mo Contacted Samples Annealed at 300°C
Figure 6.12 shows that the roll over is greater for samples deposited at room temperature and 200°C when compared to the 150°C and 180°C deposited samples which indicates that the samples do not show a regular trend when annealed at 300°C. The shunt resistance for the samples deposited at 150°C, 180°C and room temperature was 740Ω-cm², 720Ω-cm² and 720Ω-cm² respectively and that of the samples deposited at 200°C is 640Ω-cm². The series resistances for the samples deposited at 200°C, room temperature, 150°C and 180°C are 13 Ω-cm², 14 Ω-cm², 11 Ω-cm² and 10 Ω-cm² respectively.

![Graph showing spectral response of Mo contacted samples annealed at 300°C](image)

**Figure 42 Spectral Response of Mo Contacted Samples Annealed at 300°C**

Figure 42 indicates that the Q.E for the 180°C and 200°C deposited samples annealed at 300°C is around 90% in the mid region and is around 85% for samples deposited at room temperature and 150°C. This shows that the samples annealed at temperatures greater than 180°C had better current collection.

6.2.2.4 Molybdenum Samples annealed at 350°C

The Mo back contacted samples deposited at different temperatures are annealed at 350°C and its J-V performance is studied.
Table 9 Performance of the Mo Contacted Samples Annealed at 350°C

<table>
<thead>
<tr>
<th>Deposition Temperature [°C]</th>
<th>Sample no</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>6-10-B9-a</td>
<td>700</td>
<td>47.30</td>
<td>20.53</td>
<td>6.79</td>
</tr>
<tr>
<td>180</td>
<td>6-10-B8-a</td>
<td>760</td>
<td>72.70</td>
<td>21.95</td>
<td>11.32</td>
</tr>
<tr>
<td>200</td>
<td>6-10-A9-d</td>
<td>740</td>
<td>63.00</td>
<td>21.68</td>
<td>10.38</td>
</tr>
</tbody>
</table>

Table 9 shows that, when the annealing temperature is raised above 300°C the performance of the samples deposited at various temperatures tends to decrease. The Voc reduces by 80-100mV. It is noticed that the Fill factors increase significantly for the samples deposited at 180°C (14% increase) and 200°C (5% increase).

Figure 43 J-V Response of Mo Contacted Samples Annealed at 350°C

The J-V response in figure 43 indicates that there is roll over in all of these samples but is more predominant in the samples deposited at 200°C. The shunting resistance for the 150°C, 180°C and 200°C is 1300 Ω-cm², 1800 Ω-cm² and 1600 Ω-cm² respectively. The series resistances for the samples deposited at 200°C, room 150°C and 180°C are 160Ω-cm², 13Ω-cm² and 9Ω-cm² respectively.
Figure 44 Spectral Response of Mo Contacted Samples Annealed at 350°C

The spectral response in the figure 6.15 indicates that though the collection in the red region is above 90% for samples deposited at 180°C, it can be seen that there is some collection problems in the mid region. This is observed in all the samples. This could be attributed to the high annealing temperature damaging the bulk region.

Figure 45 Comparison on the Performance of Mo Contacted Samples Deposited at 150 °C and Annealed at Different Temperatures
Figure 45, Figure 46, Figure 47 summarizes the performance of the cells deposited at various temperatures ranging from room temperature to 200°C and annealed at different temperatures ranging from 270°C to 350°C.

<table>
<thead>
<tr>
<th>Room temp</th>
<th>270°C</th>
<th>300°C</th>
<th>350°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc(mV)</td>
<td>820</td>
<td>800</td>
<td>820</td>
</tr>
<tr>
<td>Fill Factor(%)</td>
<td>55</td>
<td>55.7</td>
<td>59.6</td>
</tr>
</tbody>
</table>

**Figure 46 Comparison on the Performance of Mo Contacted Samples Deposited at 180 °C and Annealed at Different Temperatures**

<table>
<thead>
<tr>
<th>Room temp deposition</th>
<th>270°C annealing</th>
<th>300°C annealing</th>
<th>350°C annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc(mV)</td>
<td>800</td>
<td>820</td>
<td>820</td>
</tr>
<tr>
<td>Fill Factor(%)</td>
<td>54.9</td>
<td>57.5</td>
<td>58.3</td>
</tr>
</tbody>
</table>

**Figure 47 Comparison on the Performance of Mo Contacted Samples Deposited at 200 °C and Annealed at Different Temperatures**
The graphs indicate that all the samples annealed at 350°C had a low $V_{oc}$ when compared to the other annealing temperatures. It is noted that though the performance of the cells annealed at 270°C and 300°C are almost equal, the 300°C has a 20mV increase and a 4% increase in FF. All the samples mentioned hereafter are deposited at 180°C and annealed at 300°C since these samples give the best performance.

6.2.2.5 Molybdenum Contacted Samples with Different CuCl Solution

6.2.2.5.1 Mo Contacted Samples with No CuCl Solution

Fixing the deposition temperature at 180°C and the annealing temperature at 300°C, the CuCl concentration was varied to vary the amount of Cu in the cells and the performance of the cells is noted.

Table 10 Performance of the Mo Contacted Samples with No CuCl Treatment

<table>
<thead>
<tr>
<th>Sample no</th>
<th>$V_{oc}$ [mV]</th>
<th>FF [%]</th>
<th>$J_{sc}$ [mA/cm$^2$]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-17-1B-a</td>
<td>700</td>
<td>57.10</td>
<td>19.77</td>
<td>7.90</td>
</tr>
<tr>
<td>6-17-1B-c</td>
<td>730</td>
<td>62.20</td>
<td>19.20</td>
<td>8.70</td>
</tr>
</tbody>
</table>

Table 10 indicates that the samples with Mo back contact and no Cu treatment has a decrease of 70 to 100mV in $V_{oc}$ but the FF remained the same indicating that Cu is present in the CdTe region as a dopant and makes it more p-type. The currents remain the same for samples with and without Cu treatment. These samples serve as a baseline for comparison of samples with various Cu concentrations.
Figure 48 Dark J-V Response of Mo Contacted Samples with No CuCl Treatment

Figure 48 and figure 49 indicates that the cell has a high series resistance indicating a bad back contact formation. The roll over can be seen in these samples.

Figure 49 J-V Response of Mo Contacted Samples with CuCl Treatment

6.2.2.5.2 Molybdenum Contacted Samples with Different CuCl Solutions

Keeping the samples with no Cu treatment and Mo back contacts as a baseline, the moly contacted samples were treated with various concentrations of CuCl treatment with concentrations ranging from $3 \times 10^{-8}$ (Sol#2) to $2 \times 10^{-7}$ M(Sol#3).
Table 11 Performance of the Mo Contacted Samples with Solution #2 CuCl Treatment

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5-7B-b</td>
<td>740</td>
<td>70.50</td>
<td>21.70</td>
<td>11.32</td>
</tr>
<tr>
<td>7-5-7B-d</td>
<td>730</td>
<td>71.00</td>
<td>21.20</td>
<td>10.98</td>
</tr>
<tr>
<td>7-5-7A-c</td>
<td>770</td>
<td>72.60</td>
<td>21.32</td>
<td>11.91</td>
</tr>
<tr>
<td>7-5-7A-d</td>
<td>810</td>
<td>69.20</td>
<td>21.95</td>
<td>12.30</td>
</tr>
<tr>
<td>8-2-A2-a</td>
<td>690</td>
<td>73.50</td>
<td>20.90</td>
<td>10.59</td>
</tr>
<tr>
<td>8-2-A2-b</td>
<td>690</td>
<td>73.00</td>
<td>21.00</td>
<td>10.57</td>
</tr>
<tr>
<td>8-2-B2-a</td>
<td>700</td>
<td>72.50</td>
<td>21.32</td>
<td>10.81</td>
</tr>
<tr>
<td>8-2-B2-b</td>
<td>680</td>
<td>71.4</td>
<td>20.57</td>
<td>9.98</td>
</tr>
</tbody>
</table>

Tables 11 and Table 12 show the performance of cells treated with solution #2 and solution #3 respectively. It is noted that though a cell treated with solution #2 has the highest $V_{oc}$ of 810 mV, the average $V_{oc}$ is 730 mV with the lowest $V_{oc}$ being 680 mV. The highest $V_{oc}$ for samples treated with solution #3 is 800 mV with the average $V_{oc}$ being 780 mV. The fill factors is similar for the all the samples. This indicates that the reduction in the $V_{oc}$ is due to the effect of the Cu doping, with the CuCl solution having greater Cu in it has greater $V_{oc}$. The current for these two types of Cu treated samples showed inconsistency.
Table 12 Performance of the Mo Contacted Samples with Solution #3 CuCl Treatment

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5-1-7B-c</td>
<td>760</td>
<td>70.70</td>
<td>21.92</td>
<td>11.77</td>
</tr>
<tr>
<td>7-5-1-7B-d</td>
<td>780</td>
<td>68.30</td>
<td>21.70</td>
<td>11.56</td>
</tr>
<tr>
<td>7-5-1-7A-a</td>
<td>770</td>
<td>64.20</td>
<td>22.10</td>
<td>10.92</td>
</tr>
<tr>
<td>7-5-1-7A-c</td>
<td>760</td>
<td>68.70</td>
<td>22.43</td>
<td>11.71</td>
</tr>
<tr>
<td>8-2-1A2-c</td>
<td>780</td>
<td>73.10</td>
<td>19.14</td>
<td>10.91</td>
</tr>
<tr>
<td>8-2-1A2-d</td>
<td>790</td>
<td>72.20</td>
<td>19.32</td>
<td>11.01</td>
</tr>
<tr>
<td>8-2-1B2-a</td>
<td>790</td>
<td>72.40</td>
<td>19.10</td>
<td>10.92</td>
</tr>
<tr>
<td>8-2-1B2-b</td>
<td>800</td>
<td>70.90</td>
<td>19.13</td>
<td>10.85</td>
</tr>
</tbody>
</table>

The J-V response in Figure 50 indicates that there is roll over in all of these samples but is more predominant in the samples treated with solution#2 indicating that Cu doping is more in the case of the solution#3 treated samples. The shunting resistance for the samples treated with solution#2 CuCl solution is 1400 Ω-cm² and for the samples treated in solution#3 is 1700 Ω-cm² respectively and their series resistances are 34Ω-cm² and 13Ω-cm² respectively.
Figure 50 J-V Response of Mo Contacted Samples with Different CuCl Concentrations

The spectral response shown in figure 51 indicates that the average Q.E in the mid region for the samples treated with both the CuCl solutions is approximately 90%. Though there is some collection problems in both the type of samples, it is more predominant in samples treated with solution#2 CuCl solution.

Figure 51 Spectral Response of Mo Contacted Samples with Different CuCl Concentrations

6.2.2.6 Molybdenum Contacted Samples with Different CdS Thickness

Since the solution #3 CuCl solution gave consistent results and samples treated with greater CuCl concentrations gave poor results, the samples that are produced henceforth is treated with solution #3. Having the CuCl concentration fixed, the CdS thickness is varied and its effect on the samples is studied to find if the thickness of the CdS affects the performance of
the cells. The CdS was deposited for a thickness of 800Å, 1000Å, 1200Å and 1400Å. The transmission for each CdS sample is shown in Figure 52.

### Table 13 Performance of the Mo Contacted Samples with Different CdS Thickness

<table>
<thead>
<tr>
<th>CdS Thickness</th>
<th>Sample no</th>
<th>Voc [mV]</th>
<th>FF [%]</th>
<th>Jsc [mA/cm²]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>800Å</td>
<td>8-2-A9-a</td>
<td>0.800</td>
<td>67.80</td>
<td>23.00</td>
<td>12.70</td>
</tr>
<tr>
<td>1000Å</td>
<td>8-2-1A9-c</td>
<td>0.800</td>
<td>63.90</td>
<td>23.00</td>
<td>11.75</td>
</tr>
<tr>
<td>1200Å</td>
<td>8-2-B9-b</td>
<td>0.810</td>
<td>68.20</td>
<td>23.00</td>
<td>12.87</td>
</tr>
<tr>
<td>1400Å</td>
<td>8-2-1B9-a</td>
<td>0.820</td>
<td>67.80</td>
<td>22.40</td>
<td>12.45</td>
</tr>
</tbody>
</table>

Table 13 indicates that the variation in the thickness of the CdS does not affect the performance. It is seen that the difference in the Voc is insignificant and the variation in the fill factors for the sample is inconsistent. The current is same for all the samples indicating that the thickness does not affect the back contact. The samples presented in Table 13 are the best cells that have been produced with Mo as the back contact and Cu being introduced at the CdS.

![Figure 52 Transmission Response for the CdS Samples Deposited for Different Durations](image)

**Figure 52 Transmission Response for the CdS Samples Deposited for Different Durations**
The J-V response in Figure 53 indicates that the samples with greater CdS thickness show greater roll over in forward bias. The shunting resistance for the samples deposited for is 1200 $\Omega$-cm$^2$ and for the other samples it is 1600 $\Omega$-cm$^2$ respectively and the series resistance for the 4mins CdS deposition is 8$\Omega$-cm$^2$ and for the other samples it is approximately 160$\Omega$-cm$^2$.

Figure 53 J-V Response of Mo Contacted Samples with Different CdS Thickness

Figure 54 indicates that the maximum Q.E in the blue region is for the 4mins CdS deposited sample since it has the thinnest CdS layer. The Q.E in the mid region is the same for all the samples and is approximately 90%. These samples had the highest currents when compared to all the samples with a current increase of 2mA/cm$^2$. 
Figure 54 Spectral Response of Mo Contacted Samples with Different CdS Thickness
Sputter deposited molybdenum is the main area of concentration in this thesis. The CdS films are deposited by CSS process and the samples are treated with CuCl solution to prevent excessive Cu at the back contact. The samples with different back contacts are compared. Molybdenum is deposited as the back contact and its performance is studied. Initially Mo is deposited with 6000Å thickness at different temperatures to find the optimal deposition conditions. Then the annealing temperatures are varied to find the optimal annealing temperature. When the deposition conditions are determined the CuCl concentrations are varied and the best concentration was determined.

The parameter that is affected most is the fill factor. When the CuCl concentration is varied the fill factors increase, the open circuit voltage varies in certain experiments. Increase in the fill factors could be due to the reason that more Cu reaches the back contact thereby decreasing the series resistance. Though high fill factors are obtained, the roll over in the forward bias for almost all the samples for higher bias voltages is seen.

As a preliminary step high efficiencies are obtained with the Mo samples. The performance is nearly equal to the solar cells that are made with Cu doped graphite contacts. A conversion efficiency of 12.87% was achieved when sputter deposited molybdenum is used as a back contact and a conversion efficiency of 12.90% was obtained for cells contacted with copper doped graphite. The $V_{oc}$ varied from 820mV to 830 mV for samples contacted with copper doped graphite and the fill factors were around 71%. The CuCl treated samples had a $V_{oc}$ and FF of 830mVand 64% respectively.
The sputter deposited molybdenum back contacted samples showed improvement in performance after the samples were annealed after deposition. The FF increased from 54% to 59% when the samples were annealed at 300°C. The FF’s increased further to 71% when the CuCl solution concentration was optimized. The $V_{oc}$ remained constant for all these samples.

In terms of future work, the deposition conditions can be varied. It is stated that the pressure in the sputtering chamber and the sputtering power affects the properties of the Mo deposition. These parameters can be varied and its performance can be studied. The CuCl concentrations can also be varied to a greater extent. The CdTe thickness can also affect the performance of the back contact. The stability of the CuCl treated sample is an issue that needs greater investigation. The stability of the CuCl treated samples with doped graphite paste has shown some positive signs in terms of degradation. Similar stability investigations can be done on the Mo back contact samples.

In conclusion, a set of optimized deposition conditions is presented for the Mo back contacts to the CSS deposited CdS/CdTe solar cells.
REFERENCES


