Efficiency Improvement of SnS−Based Heterojunction Solar Cell using Cu_2O Hole Transport Layer

A Thesis submitted to the Department of Electronics and Communication Engineering,
in partial fulfillment of the requirements for the degree of
Master of Science in Electronics and Communication Engineering

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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

FACULTY OF POST GRADUATE STUDIES
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This is to certify that the work entitled as "**Efficiency Improvement of SnS−Based Heterojunction Solar Cell using Cu_2O Hole Transport Layer"** by Rokaia Laizu Naima has been carried out under our supervision. To the best of our knowledge this work is an original one and was not submitted anywhere for a diploma or a degree.

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The thesis titled "**Efficiency Improvement of SnS−Based Heterojunction Solar Cell using Cu_2O Hole Transport Layer**" submitted by Rokaia Laizu Naima, Student ID. 2005108 and Session January-June' 2023, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **M.Sc. (Engineering) in ECE**.

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Dedication

DEDICATEDTO

MY PARENTS AND HONORABLE

TEACHERS

Acknowledgment

All thanks are given to the Almighty Allah, who gives me the strength, absent that I would not have attempted this research.

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Abstract

Solar energy is becoming one of the foremost important sources of green energy. This renewable energy has low prices, low pollutants, and low greenhouse gas emissions. Tin−monosulfide (SnS)−based solar cell (SC) that has been recently gaining the attention of scientists owing to their exceptional semiconducting properties. The basic objectives of this article is to propose model and enhance the performance of (Al/ITO/CeO_2/SnS/Cu_2O/Ni) photovoltaic cell and analyze the effect of Copper Oxide (Cu_2O) Hole Transport Layer (HTL) and Cerium Oxide (CeO_2) Electron Transport Layer (ETL) along with measuring the characteristics such as Open Circuit Voltage (V_{OC}), Current Density (J_{SC}), Fill Factor (FF), and Power Conversion Efficiency (PCE). Solar Cell Capacitance Simulator (SCAPS−1D) software has been used to conduct this research. The proposed structure operates effectively with a thickness (300 nm) SnS absorber layer at lower carrier concentrations (10^{15} cm^{-3}). The proposed heterostructure of (Al/ITO/CeO_2/SnS/Ni) solar cell achieved the values of PCE, V_{OC}, J_{SC} and FF are 20.34%, 0.817 V, 31.00 mA/cm^2, 80.27% respectively. In the structure of (Al/ITO/CeO_2/SnS/Cu_2O/Ni) solar cell, the value of PCE, V_{OC}, J_{SC}, and FF are obtained 27%, 0.975 V, 32.72 mA/cm^2, and 84.63%, respectively. After using Cu_2O HTL, the thickness of 30nm and doping density 10^{21} cm^{-3} that provides high efficiency 27% of the solar cell. Depending on the lower thickness and doping concentration, different layer parameters such as the CeO_2 ETL, Cu_2O HTL, and SnS absorber layer are used to improve the performance. This conception expresses that Cu_2O could be a promising HTL for reducing manufacturing costs and enhancing the efficiency of SnS-based solar cell.

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List of Abbreviation

AC	Alternating Current
Al	Aluminium
a-Si	Amorphous Silicon
APSCL	Ashuganj Power Station Company Limited
BPDB	Bangladesh Power Development Board
CPGCBL	Coal Power Generation Company Bangladesh Limited
Cu_2O	Cuprous Oxide
CeO_2	Cerium Oxide
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
CdS	Cadmium Sulfide
CuSCN	Copper(I) Thiocyanate
CZTSSe	Copper Zinc Tin Sulfide
$CH_3NH_3SnI_3$	Methylammonium Tin Tri-Iodide
Cu	Copper
$Cu(NO_3)_2$	Cupric Nitrate
CBO	Conduction Band Offset
$Cu(CH_3COO)_2$	Copper(Ii) Acetate
$CuSO_4$	Copper Sulfate
EFG	Edge Defined Film
ETL	Electron Transport Layer
ETM	Electron Transporting Material

Eg	Bang Gap
FTO	Fluorine Doped Tin Oxide
FF	Fill Factor
GW	Gigawatts
GaAlAs	Aluminium Gallium Arsenide
GaAs	Gallium Arsenide
Ga_2O_3	Gallium Oxide
HTL	Hole Transport Layer
IEA	International Energy Agency
ITO	Indium Tin Oxide
Iph	Photogenerated Current
Jsc	Current Density
LGBG	Laser-Grooved Buried-Grid
Mo	Molybdenum
NiOx	Nickel Oxide
NiO	Nickel Oxide
NWPGCL	North-West Power Generation Company Limited
RPCL	Rural Power Company Limited
EGCB	Electricity Generation Company of Bangladesh
PV	Photovoltaic
PCE	Power Conversion Efficiency
SCAPS-1D	Solar Cell Capacitance Simulator in One Dimension
SC	Solar Cell
SREDA	National Solar Energy Roadmap

SRH	Shockley Read Hall
SE	Spectroscopic Ellipsometry
SnO_2	Tin(Iv) Oxide
SnO	Tin Monoxide
TCO	Transparent Conducting Oxide
TFSC	Thin-Film Solar Cells
TiO_2	Titanium Dioxide
VBO	Valence Band Offset
Voc	Open Circuit Voltage
Wi-Fi	Wireless Fidelity
ZnS	Zinc Sulfide
ZnO	Zinc Oxide

List of symbols

α	Absorption Coefficient of Data
N_c	Densities of States in Conduction Band
N_v	Densities of States in Valence Band
m_e	Effective Mass of Electron
m_h	Effective Mass of Hole
Nt	Absorb-er Defect Density
μ	Carrier Mobility
T	Lifetime for the Electron and Hole Carriers
D	Diffusion Coefficient
L	Diffusion Length
Vth	Charge Carriers
V_a	Applied Voltage
I	Current
Io	Short Circuit Current
K	Boltzmann Constant
q	Charge of an Electron
T	Temperature
I_{ph}	photo-generated Current
G	Charge Carriers Generation Rate
Ln	Diffusion Lengths of Electrons
Lp	Diffusion Lengths of Holes
Vmp	Voltage for Maximum Power

Imp	Current for Maximum Power
Pin	Power input
Ai	Area of the interface
Qe	Electron charge
Qh	Hole charge
W	Width of the depletion zone
Imp	Current for Maximum Power
Ψ	Electrostatic Potential
Gop	Optical Generation Rate
λ	Wavelength

Chapter 1
Introduction

1.1 Introduction

Photovoltaic cells are made of semiconductors that generate energy from sunshine. Nowadays, solar cells are one of the most essential renewable resources to produce energy. It provides energy at a low cost with high efficiency. This section has covered the background of the photovoltaic cell, the objectives of our research work and the organization of the remaining chapters.

1.2 Background

The energy produced by trapping the sunlight and heat is known as solar energy. The development of renewable energy has made it possible to exploit this abundant resource in a variety of ways. It is thought of as renewable energy because it doesn't produce greenhouse gases. Solar or photovoltaic panels have a wide range of real-world uses [1]. It is utilized as an irrigation source of energy in agricultural regions and in isolated medical facilities to chill medicinal supplies.Other applications include efforts to integrate different forms of power generation into public as well as private infrastructure.Solar cells are being utilized more often as a reliable source of clean, renewable energy. It is used in a variety of fields, including aerospace, industrial, illumination in public places, smartphone charging, and domestic applications. The world's eighth most populous nation, Bangladesh is a South Asian nation. The coordinates are $88^{0}01'$ east longitude to $92^{0}41'$ east longitude and $20^{0}34'$ north latitude to $26^{0}38'$ north latitude. Across Bangladesh, the Tropic of Cancer traverses. It shares a land boundary with both India and Myanmar, while the coastline border with the Bay of Bengal.

The greatest northern latitude at which sunlight may appear overhead at midday is the tropic of cancer, which is located at 23° 26' north of the equator. At the end of June, when the northern part of the earth is most inclined toward the sun, this occurrence takes place. Bangladesh has the most renewable energy sources worldwide as a result [2]. With 1,900 kWh/m^2 annually, Bangladesh is said to get a significant quantity of solar radiation. This amounts to 4 to 6.5 kWh/m^2 every day. A draft of the National Solar Energy Road Map (SREDA) was recently released by the government. By 2041, it is intended to have 40 GW, with 40% of that coming from rooftop solar. By 2041, Bangladesh might have 50% of its current capacity made up of solar energy, according to Table 1.1 [3], if the government gives its accelerated strategy priority.In Bangladesh's rural areas, more than 25 percent of people still lack uses to electricity. For millions of individuals, diurnal functions like office, studying, and cooking become challenging or not possible after nightfall. Off-grid solar electricity, however, is quickly altering all of this. One of the most extensive indigenous solar energy programs is found in Bangladesh. People are eliminated from the need to utilize hazardous firewood and kerosene. Studying after dark can help girls become more literate. The use of less fossil fuels also reduces greenhouse gas emissions. Bangladesh, a submerged country, is starting to experience the repercussions of climate change, including rainfall and rising sea levels. Bangladesh's economy is now flourishing. The average annual growth rate is 8%, and the need for power is rapidly increasing. The nation is growing the usage of solar household systems while also establishing sizable new solar parks as part of its decarbonization efforts. There are also plans for wind farms. But coal and natural gas are also included in a larger energy mix, along with renewable energy sources.

Table 1.1. Technology wise Renewable Energy (RE) Generation Statistics MWp [3].

SL.	Source of RE	Technology	Content	Off-grid MWp	On-grid MWp	Net MWp
1.	Solar	Solar Park	9	0	261	261
		Rooftop Solar Except NEM	197	18.228	39.923	58.151
		Net Metering Rooftop	1801	0	59.361	59.361
		Solar Irrigation	2758	49.142	1.705	50.848
		Home System	6037689	263.793	0	263.793
		Minigrid	28	5.805	0	5.805
		Microgrid	0	0	0	0
		Nanogrid	2	0.001	0	0.001
		Charging Station	14	0.266	0.016	0.282
		Street Light	296861	17.065	0	17.065
		Powered Telecom BTS	1933	8.06	0	8.06
		Drinking Water System	82	0.095	0	0.095
2.	Wind	Wind Projects	3	2	0.9	2.9
3.	Hydro	Hydro Projects	1	0	230	230
4.	Biogas	Biogas to Electricity	7	0.69	0	0.69
		Biogas Plant	87536	0	0	0
5.	Biomass	Biomass to Electricity	1	0.4	0	0.4
Net energy			6428922	365.545	592.905	958.45

Approximately 2.08 percent of the current capacity that is connected to the grid is composed of green power, and hydropower, whose output has been steady since 1967, makes up 1.04 percent of that total. A significant portion of the stated 543 MW of solar electricity comes from off-grid solar, whereas grid-tied solar power plants only provide 196 MW [4].The significant number of those solar-powered domestic panels that gave Bangladesh such notoriety is now inactive due to the spread of rural electricity through the grid. Solar power dominates renewable energy in Bangladesh, with other forms of energy being comparatively little. Undoubtedly, Bangladesh is having difficulty boosting the proportion of renewable energy in its supply of energy. Bangladesh use of RE likewise does not appear to have a promising future until the authorities takes action to investigate fresh and creative approaches to using RE. Only 1% of Bangladesh, net agricultural field might be applied to create solar energy facilities with a collective capability of about 50,000 MW.The power produced by one percent land used for agriculture is mostly 82,000 GWh, which is more than the entire spending in 2020 utilizing a typical capacity factor of 4.5 hours every day for Bangladesh.

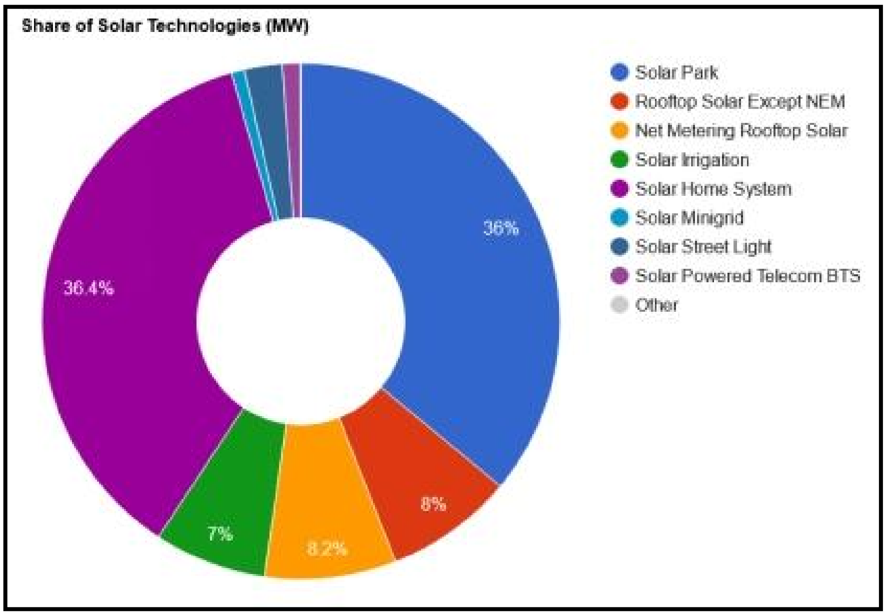


Figure 1.1. Share of solar technology in Bangladesh [3].

Solar electricity is the only dependable source of green power that can be used widely. This expectation is proven to be true despite foreign and domestic investments that have been made in grid-connected utility size solar energy plants and industrial rooftop projects [5]. The Bangladeshi government declared plans to install rooftop solar power plants on each educational facility to add additional renewable energy to the grid. In addition, the usage of electric vehicles will increase in substitution of conventional vehicles. And in 2021, the nation approved the guidelines for the registration and operation of electric vehicles, which had first been presented in 2018. According to the chairman of SREDA, Table 1.2 indicates that there are proposed 48 solar park in Bangladesh but executed 42 and 6 park are under construction.

Table 1.2: 48 Solar Park , 2386.66 MWp of Power generation. [3].

SL.	Project Name	SID	Capacity	Location	Agency
1	30MW (AC) Solar Park by Juli New Energy Co. Ltd. and Intraco CNG Ltd.	127	30 MWp	Gangachara, Rangpur	BPDB
2	Energon Technologies FZE and China Sunergy Co.Ltd (ESUN) have built a 100 MW (AC) solar park.	136	100 MWp	Mongla Upazila, Bagerhat	BPDB
3	Grid-connected solar energy power plant in Sirajganj, 6.13 MW (AC)	151	7.6 MWp	Sirajganj Sadar Upazila, Sirajgonj	NWPGCL
4	Spectra Engineers Limited and Shunfeng Investment Limited's 35 MW AC Solar Park	137	35 MWp	Shibalaya Upazila, Manikganj	BPDB

5	HETAT-DITROLIC-IFDC Solar Consortium has built a 50 MW (AC) solar park.	125	50 MWp	Gauripur, Mymensingh	BPDB
6	Grid-connected, 7.4 MWp (6.63 MW AC), Solar PV Power Plant in Kaptai	268	7.4 MWp	Kaptai Upazila, Rangamati	BPDB
7	8 MW Solar Park by Parasol Energy Ltd.	361	8 MWp	Panchagarh Sadar, Panchagarh	BPDB
8	Joules Power Limited (JPL)'s 20 MW (AC) Solar Park	128	20 MWp	Teknaf Upazila, Cox's Bazar	BPDB
9	Sharishabari, Jamalpur, 3 MW Grid-connected PV energy plant	147	3 MWp	Sarishabari Upazila, Jamalpur	BPDB
10	Building a 100 MW Solar Power Plant in the Jamalpur District's Madarganj	282	140.74 MWp	Madarganj Upazila, Jamalpur	RPCL
11	Sirajganj Solar Park, 68 MW	4249	88.75 MWp	Sirajganj Sadar Upazila, Sirajgonj	NWPGCL
12	Construction of Sonagazi's 50 MW Solar Power Plant	152	50 MWp	Sonagazi, Feni	EGCB
13	30 MW (AC) Solar Park by Jiangsu Zhongtian Technology Co Ltd. and Beximco Power Company Ltd.	132	30 MWp	Tetulia, Panchagarh	BPDB

14	Haor Bangla-Korea Green Energy Ltd.'s 32 MW (AC) Solar Project.	126	32 MWp	Dharampasha, Sunamganj	BPDB
15	PV Power Patgram Ltd.'s 5 MW (AC) Solar Plant.	133	5 MWp	Patgram, Lalmonirhat	BPDB
16	5 MW (AC) Solar Park from Sun Solar Power Plant Ltd.	340	5 MWp	Gowainghat, Sylhet	BPDB
17	Beximco Power Co. Ltd.'s 200 MW (AC) Solar Park.	129	200 MWp	Sundarganj, Gaibandha	BPDB
18	Project-1 of the Sonagazi 100 MW Solar Power Plant	969	100 MWp	Sonagazi, Feni	EGCB
19	Project-2 of the Sonagazi 100 MW Solar Power Plant	970	100 MWp	Sonagazi, Feni	EGCB
20	50 MW Solar Power Project in Gazaria	5185	50 MWp	Gazaria Upazila, Munshiganj	RPCL
21	Project for a 50 MW Grid-Tied Solar Power Plant in Matarbari	4251	50 MWp	Maheshkhali Upazila, Cox's Bazar	CPGCBL
22	Solar Energy Plant in Sagarkandi, Sujanagar, and Pabna, 64.55 MW(AC)	4165	64.55 MWp	Sujanagar Upazila, Pabna	BPDB
23	Pabna Solar Park, 60 MW	4250	83.83 MWp	Sujanagar Upazila, Pabna	NWPGCL
24	Grid-tied solar energy plant in Rangunia, 45-55 MW(AC) on a BOO basis	4177	55 MWp	Rangunia Upazila, Chittagong	BPDB
25	Solar Power Plant with a 50	4170	50 MWp	Chuadanga-S	BPDB

	MW Grid-tied Capacity Near Chuadanga 132,33 KV Grid Substation			Upazila, Chuadanga	
26	100 MW Grid Tied Solar Project in Ashuganj	153	100 MWp	Raipura Upazila, Narsingdi, Narsingdi	APSCL
27	Joint Venture of Appolo Engineering & Construction Limited and S.M.E. Electrical Private Limited's 7 MW solar power station	4168	7 MWp	Chandpur Sadar, Chandpur	BPDB
28	50 MW solar power plant built by the consortium of SS Agro Complex Ltd. and IBV Vogt GmbH.	4167	50 MWp	Dhamrai Upazila, Dhaka	BPDB
29	Mostafa Motors Ltd. of Bangladesh and Solarland (Wuxi) Electric Science and Technology Co. Ltd. of China have formed a joint venture to build a 3.77 MW solar energy plant.	4166	3.77 MWp	Bera Upazila, Pabna	BPDB
30	Solar power plant with a 50 MW grid connection beside the 132,33 KV grid substation	4169	50 MWp	Mirsharai Upazila, Chittagong	BPDB
31	Near the Netrokona 132,33 KV Grid Substation is a 50 MW Grid-tied Solar Power Plant.	4171	50 MWp	Netrakona-S Upazilla, Netrokona	BPDB

32	Grid-tied 10 MW (AC) Solar PV Power Plant in Moulovibazar by Symbior Solar & Holland Construction	411	10 MWp	Moulvibazar Sadar, Moulvibazar	BPDB
33	Sonagazi, Feni, Solar Pv Grid Connected Power Station Construction, 109.77 MWp (82.5 MW AC)	143	109.77 MWp	Sonagazi, Feni	BPDB
34	Rahimafrooz Shunfeng Consortium's grid-connected solar power plant has a 20 MW (AC) capacity.	409	20 MWp	Debiganj, Panchagarh	BPDB
35	Scatec Solar ASA's 50 MW Solar Farm in Norway	727	50 MWp	Dimla, Nilphamari	BPDB
36	8minutenergy Singapore Holdings 2 Pte. Ltd.'s 50 MW Solar Park is in Singapore.	341	50 MWp	Panchagarh Sadar, Panchagarh	BPDB
37	Building a 90.25 MWp (68.60 MW AC) Grid Connected Solar Photovoltaic Power Plant in Gangachara, Rangpur	145	90.25 MWp	Gangachara, Rangpur	BPDB
38	Shapoorji Pallonji Infrastructure Capital Company Private Ltd.'s 100 MW Solar Project.	351	100 MWp	Pabna Sadar Upazila, Pabna	BPDB
39	Panchagarh 30 MW Solar Park	283	30 MWp	Boda, Panchagarh	RPCL

40	Grid-tied 100 MW Solar Power Station Project in Madarganj	923	100 MWp	Madarganj Upazila, Jamalpur	B-R PowerGen
41	Gridded Faridpur Solar Park	150	100 MWp	Charbhadrasan Upazila, Faridpur	NWPGCL
42	Bagerhat, Mollahat, and 100MW photovoltaic Power Plant	154	100 MWp	Mollahat Upazila, Bagerhat	RPCL

1.3 Statistical world review of Solar cell

Renewable energy from the sun is a reliable resource of power and one of the foremost important green and renewable energy sources. It is also an environmentally friendly technology. It makes a substantial contribution to identifying energy-related possibilities for sustainable development. Because of this, the sun is a particularly alluring source of energy for power generation due to the vast quantity of energy it can provide each day. Modern photovoltaic solar panels and focused sunlight applications are continually being enhanced to fulfill our demand for power [6].

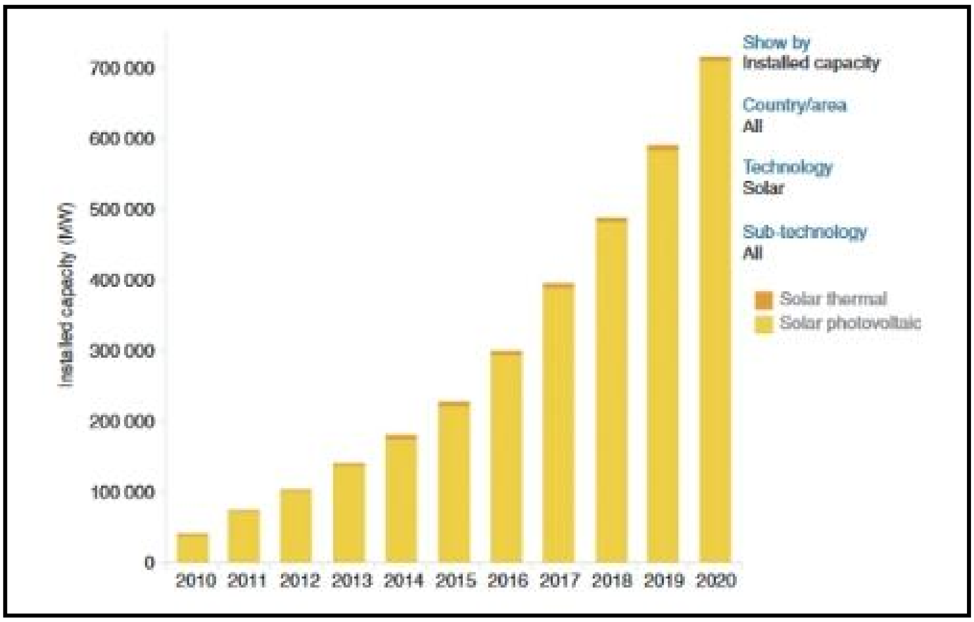


Figure 1.2: Supply of solar cells producing energy globally [6].

The environmental effect of solar technology is among the lowest of all power producing methods. PV provides power silently and without creating harmful waste or air pollution. It does not call for the transportation or combustion of liquid or gaseous fuels. PV systems may also provide availability to electricity because sunshine is a free and plentiful energy source. The expense and uncertainty associated with energy supply from politically unstable locations are eliminated by PV. The International Energy Agency (IEA) forecasts that renewable energy would increase to a 26% share by 2020, expanding by 45%, but it also predicts that without clear policy direction, yearly growth will stop after 2014.According to IEA, this would make it difficult to achieve the goals related to global climate change [7, 8].

Table 1.3: The top nations for employment creation in solar PV systems [9].

Top nations	Appeared jobs (millions)
Bangladesh	0.145
United States	0.240
India	0.205
China	2.240
Japan	0.250
Brazil	0.040
Germany	0.030
Philippines	0.020
Vietnam	0.055
Malaysia	0.050

1.4 Motivation of the Research

A renewable source of energy with little negative effects on nature, solar power encourages self-reliance on energy.It contributes to lowering overall greenhouse gas emissions. Renewable sources of energy maintain ecosystems for both present and future generations. In our research, we have used solar energy simulation that has been executed in SCAPS 1D software. The integration of solar energy improves the performance of the cell efficiency. The following research questions should be appeared:

- How can we improve the efficiency of solar cell?
- Which material we used to improve the performance of solar cell?
- How can we reduce the cost of solar cell?

1.5 Present States of the Arts and Challenges

Electricity can only be produced when sunlight is shining, which serves as one of the main issues with solar power systems. This implies electricity may be interrupted in dark and on rainy days. An additional problem is that the usage of renewable energy sources might result in the deterioration of large areas of forest or a disappearance of habitat for animals. It takes up an excessive amount of land. Some solar energy sources need the manufacturing of scarce elements. Preservation for solar power is very costly. Accelerating the development of solar-powered automobiles constitutes the challenge's main goal. Fundamentally, it is a form of opposition, and each group or vehicle that makes it to the complete zone qualifies as effective. However, it is constrained by the amount of time the sun is eliminated might lead to a resource shortage and includes toxic elements comparable to those found in semiconductors. The fact that solar energy uses several of the identical dangerous elements as technology has become its only ecological drawback. The issue of discarding dangerous materials expands increasingly difficult as solar power grows in popularity. Solar power is an appealing replacement for fossil fuels, if the problem of safe disposal is overcome, due to the lower emissions of greenhouse gases that deliver.

1.6 Objectives

According to the photovoltaic (PV) effect, solar panels transform sunshine directly into electricity. The PV effect is the transformation of photons into voltage. Linked to single-junction solar panels, hetero-junction cells are more effective in converting sunlight into energy because they can absorb various wavelengths of sunlight that enters using several layers.

This work focuses on the following aspects:

- To design and determine the effectiveness of SnS based heterostructure solar cell that provides higher efficiency.
- To evaluate the resultant curves to search out the most efficient and flexible scheme with and without Cu_2O HTL.
- To discuss the widely accessible and cheapest Cu_2O as HTL is proposed to enhance performance of hetero-structure SnS based solar cell.
- To investigate the performance of the proposed SnS based heterostructure solar cell using SCAPS 1D software.
- To compare the results of proposed and reference heterostructure solar cell performances.

1.7 Organization of chapters

This paper is composed of eight chapters. The organizations of these chapters are as follows:

- **Chapter 1:** Represents a general introduction as well as the background of solar cells. Also included in this chapter is the study of objectives.
- **Chapter 2:** Literature review and Related recent work on this problem is added in this chapter.
- **Chapter 3:** Provides an overview of Solar cell. A brief history of photovoltaic cells is presented and the advantages, disadvantages and applications of solar cells are outlined in this chapter.
- **Chapter 4:** Describes working methodology of heterostructure solar cells.
- **Chapter 5:** Displays the simulation results and discussions.
- **Chapter 6:** Shows a conclusion of the research and future scopes related to this work.

1.8 Summary

This chapter describes the major goal of this thesis. Analyzing the performance of SnS-based heterojunction solar cells.

Chapter 2

Literature review

2.1 Introduction

In this section, we will discuss the history and literature review accordingly. Already there are many studies on this solar cell efficiency. Different researchers try to achieve the high performance of PV (photovoltaic) cell. Discuss about the different solar cell efficiency.

2.2 Concept of Solar Cell

Sunlight's solar panels offer a low cost, ecologically friendly, and endless source of clean energy. All the energy required for a year may be obtained from the solar panel that reaches the earth every hour. It is simple to collect energy from direct sunshine.Solar cells may be employed as light sensors, including infrared detectors, for identifying electromagnetic radiation in the visible spectrum or to quantify the intensity of light, in addition to producing electricity[10].

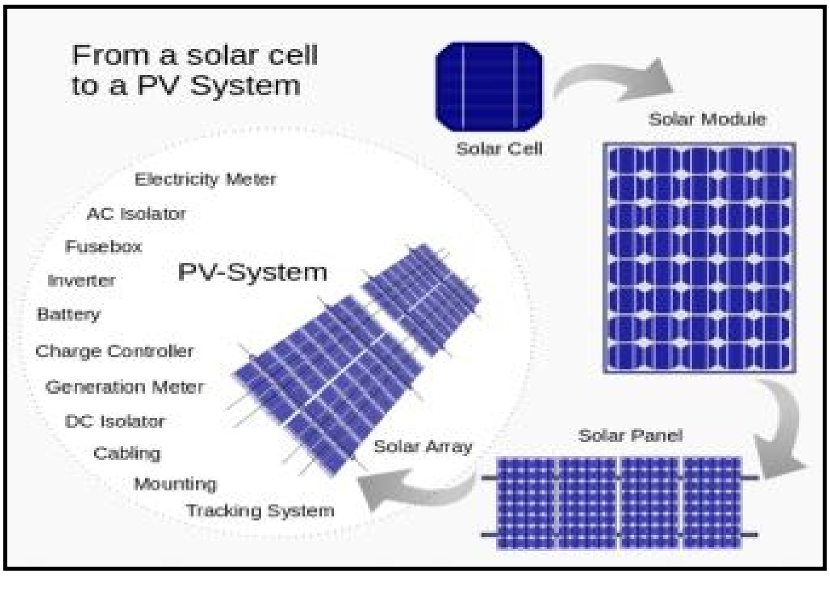


Figure 2.1: The growth of a PV system [10].

A PV cell must possess the following three characteristics in order to function:

- The process of light absorption that results in exciton-bound pairs of electron-holes, exciton-unbound electron-hole combinations, or plasmon.
- The classification of charge carriers into several categories.
- Independent carrier extraction for an external circuit.

2.3 Different kinds of PV cell

The solid-state power source known as a solar cell also known as a PV cell converts light directly into energy using the PV effect, a natural chemical and physical process. The many kinds of solar cells are shown in Table 2.1 below.

Table 2.1: Different types of solar cells [11].

Serial. No	Types of solar cell
1.	Material
2.	Panel
3.	Thin film
4.	Molecular
5.	Heterostructure
6.	Organic
7.	Semiconductor
8.	Homostructure
9.	Application types of solar cell

2.3.1 Material types of solar cell

Table 2.2: List of material types of solar cell [11].

Types solar cell	
1. Amorphous Silicon (a-Si)	2. Crystalline silicon (c-Si)
3. Biohybrid	4. Float-zone silicon
5. Cadmium telluride (CdTe)	6. Dye-sensitized solar cell (DSSC)
7. Concentrated PV cell (CVP and HCVP)	8. Gallium arsenide germanium (GaAs)
9. Copper indium gallium selenide (CIGS)	10. Hybrid solar cell
11. Organic (OPV)	12. Luminescent solar concentrator cell (LSC)
13. Perovskite	14. Micromorph (tandem-cell using a-Si/μc-Si)
15. Photoelectrochemical cell (PEC)	16. Crystalline silicon (c-Si)
17. Plasmonic	18. Thin-film solar cell (TFSC)
19. Polycrystalline (multi-Si)	20. Wafer-based solar cell crystalline
21. Quantum dot	22. Non concentrated hetrogeneos PV cell
23. Solid-state	24. Thin-film solar cell (TFSC)

2.3.2 Panel types of solar cell

Currently, there are four main types of solar cells on the marketplace [12]:

I. Monocrystalline:

They are referred to as single-crystal panel because they are created from a single plate made from original silicon that has been divided into many panes. Since they are made of silicon, their vivid black color makes them easy to identify. To make one monocrystalline cell, however, a significant amount of silicon is lost, sometimes exceeding 50%.

II. Polycrystalline:

As the term implies, they come from multiple silicon crystals, instead of merely single. Due to the little waste, it renders cells with polycrystalline structure extremely economical. Although they are made of lower-quality silicon and feature an alternate structure than monocrystalline panels.

I. Passivated Emitter and Rear Cell (PERC) panels:

- It raises the level of solar energy absorbed by reflecting sunlight back toward the cell.
- Its electron flow is inhibited, and the natural preference of electrons to combine again is decreased.
- It also makes the ability to reflect light with longer wavelengths.

II. Thin-film solar panels:

A distinctive feature of thin-film panels is their extremely fine, flexible layer structure.

Table 2.3: Efficiency and cost of different solar cells [12].

Panel type	**Efficiency (%)**	**Average Cost per Watt (Dollar $)**
(a-Si)	6-8%	0.43 – 0.50
(CdTe)	9-11%	0.50 – 0.60
(CIGS)	13-15%	0.60 – 0.70
Polycrystalline	15-17%	0.70 – 1
Monocrystalline	20% and higher	1 – 1.50
PERC	Highest (5% greater than monocrystalline)	0.32–0.65

2.3.3 Thin-Film Solar cell

The most exciting advancement in solar research is thin-film technology. The introduction of photonic crystals into absorber or transparent layers, nanoparticle at material substrates, nanotubes, and other important light-trapping techniques can all result in high conversion efficiency [13,14].

Cadmium telluride (CdTe)

The variation of all solar panels, CdTe has the smallest ecological footprint, water need, and energy payback period. It also shares the same inexpensive advantage as polycrystalline cells. But recycling cadmium is more expensive than recycling other materials since it is hazardous.

Amorphous silicon (a-Si)

The absence of shape in the substance is referred to as "amorphous silicon panels" (A-Si). A-Si cells often only need a small amount of silicon compared to conventional silicon cells. By sacrificing efficiency, this enables companies to maintain the lowest manufacturing costs. Because of this, a-Si panels are appropriate for low-power applications like mobile computers.

Copper indium gallium selenide (CIGS)

CIGS cells are made by depositing thin films of copper, indium, gallium, and selenium on a transparent or silicone substrate. Although not as effective as crystalline silicon panels, the integration of these components yields the best performance amongst thin-panel types.

2.4 History of solar cell

Owing to the declining accessibility of sources of clean energy, the past ten decades have become more crucial for the per-watt cost of solar power equipment. This will surely grow more inexpensive in the next years and progress as better technology as a result of both cost and usability.Photovoltaic power's main benefit above alternative traditional sources of electricity is that it can be generated using the smallest PV cell, that enables sunlight to be converted into solar energy instantly. Four generations of solar cells may be distinguished [15, 16].

1. **1G**: First-generation (1G) based on c-Si and GaAs.
2. **2G:** Second-generation (2G), often known as thin film, includes materials including CdTe, CIGS, and a-Si.
3. **3G:** Developing third generation (3G) solar cell devices such CZTSSe, DSSC, and quantum dot.
4. **4G:** Fourth generation (4G) new solar cells are sometimes referred to as "inorganic-in-organics" like hybrid perovskite.

When sun-powered mirrors were first utilized in the seventh century, solar energy had a long history. The photovoltaic (PV) activity was discovered in 1893; after several years, researchers created this technique for generating energy [17].The thin film heterostructure photovoltaic cell based on Cu_2S/CdS that likewise had 6% efficiency was published by a team at Wright Patterson Air Force Base in the US in the same year [18].

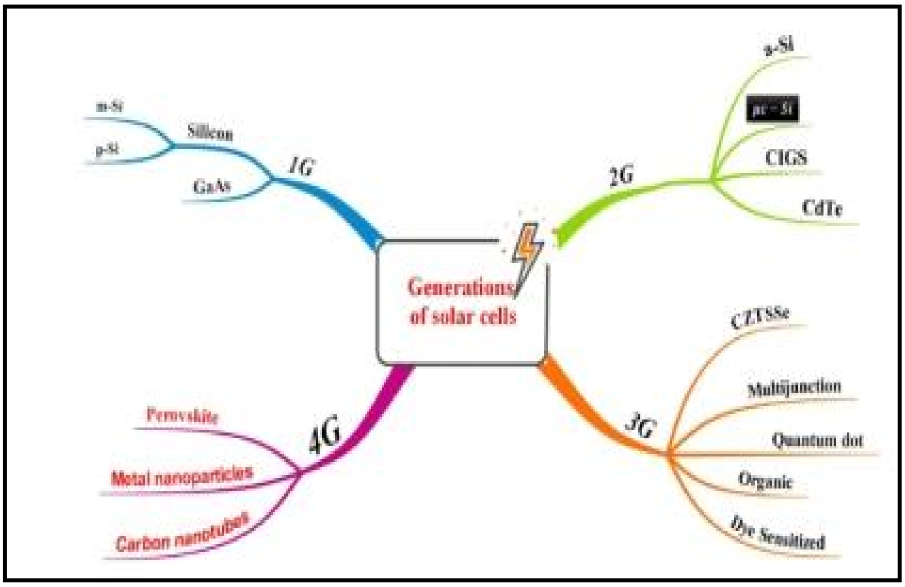


Figure 2.2: Generations of solar cells technologies [15].

A 6% GaAs PN junction solar cell was announced a year later by RCA Lab in the US. Si PV cells were already being used by the US aerospace program to power satellites at this point. To study the effects of radiation and create better radiation-tolerant systems, Li-doped Si was used as space was still the main application for photovoltaics [19]. In 1970, a team at the IoffeInstitute in the USSR, led by Nobel winner Alferov, created a heteroface GaAlAs/GaAs solar panel that addressed one of the key issues affecting GaAs devices and provided a roadmap for novel device topologies [20]. GaAs heterostructure cells with a 13% efficiency were developed as well at IBM in the USA [21]. Most of such projects were supported by a foreign assistance organization. These initiatives have shown to have relatively high rates of failure, which are mostly attributable to an absence of technological foundation, training needs, cultural differences, the payment structure's design, and other non-technical factors [22]. The PV modules have seldom failed. In many parts of the globe, where this amounts to a family's annual income, the high initial price of purchase ($100–1000) was still a significant barrier, despite the assistance from the international agencies. On the other end of the size spectrum, utilities in developed nations installed MW-size PV plants in the 1980s to assess the possibilities in two uses: as a peak-load-reduction technology, where the PV supplies extra electricity solely to meet the apex need during the afternoon or as distributed generation to decrease distribution and transmission losses [23]. To evaluate the technological and economic advantages of solar energy in utility scale applications, several American utilities investigated these uses. Other cutting-edge grid-tied PV system typologies were assessed as "demand side management" solutions, where onshore diffused solar energy is employed to lower demand as opposed to raising supply [24].

Table 2.5: Significant events in the development of the solar cell [25].

Year	Invention
1839	In liquid electrolytes, Becquerel (FR) discovered the photo galvanic effect.
1873	Smith (UK) discovered the solid Se's the conductivity of light
1877	The first discovery of the photovoltaic effect in solids is made by Adams and Day (UK) when they find photogeneration of electricity in Se tunnels.
1883	Utilizing Se film, Fritts (US) creates the first huge surface solar panel.
1888	In accordance with Heinrich Hertz's 1887 discovery of the external photoelectric effect, Russian physicist Aleksandr Stoletov created the first cell.
1905	In a seminal publication, Albert Einstein described the photoelectric impact and advanced a new quantum theory for the nature of light, for which he was awarded the Nobel Prize in Physics in 1921.
1941	P-n-junctions were found in Cu_2O and Ag_2S prototype cells by Vadim Lashkaryov.
1946	During developing the chain of innovations that would eventually lead to the transistor, Russell Ohl patented the contemporary connection semiconductor photovoltaic cell.
1948	According to Orientation to the Global Market of Semiconductors In the peer-reviewed journal Physical Review, Kurt Lehovec could be considered the first to clarify the solar energy effect.
1954	Si (Bell Lab, USA) and Cu_2S/CdS (Air Force, USA) were the first 6% effective solar panels recorded. Bell Laboratories gave a public demonstration of the first usable solar cell. Calvin Souther Fuller, Daryl Chapin, and Gerald Pearson were the creators.
1955	Si solar power cells from Hoffman Electronics (USA) are available at $1500/W.
1958	A Si standby solar panel on the NASA Vanguard spacecraft.
1959	Si solar cells from Hoffman Electronics (USA) are 10% productive.
1963	The first marketable Si modules are made by Sharp Corp. (Japan)..

1966	Employing a 1 kW array, the NASA Orbiting Astronomical Observatory was sent into orbit.
1970	Alferov, Andreev, and others created the first GaAs heterojunction photovoltaic cells in the USSR.
1972	A presentation on land-based uses was presented at the first Photovoltaic conference (IEEE).
1973	A significant year for photovoltaics: The global oil crisis prompts several countries to examine alternative energy, especially solar power, as evidenced by the Cherry Hill Conference in the USA.
1974	Tyco (USA) grows 2.5 cm wide silicon ribbon for solar power, the first substitute to silicon wafers, as part of Project Sunshine, a Japanese initiative to promote expansion of the PV sector and uses.
1975	Hovel (USA) published the first book devoted to Solar science and technology.
1980	First thin-film photovoltaic cell (USA) with a >10% efficiency.
1981	Saudi Arabia had a 350 kW Inverter assembly erected.
1982	First utility-scale PV facility of 1 MW utilizing Arco Si cells on 2-axis sensors is in California, USA.
1984	USA's Carrisa Plains had a 6 MW array developed.
1985	High-efficiency Si solar cells had a significant year: Si solar cell >25% at 200X concentration (Stanford University, USA) and >20% under ordinary sunshine (UNSW, Australia).
1986	The a-Si G4000 from Arco Solar (USA) is the first thin-film energy generator to be used commercially.
1987	The winner of the 3200 km World Solar Competition event (Australia) averaged 70 kph as 14 solar-powered vehicles crossed the finish line.
1994	(NREL, USA) GaInP/GaAs 2-terminal evaporator multistructure >30%.
1995	1000 roofs German solar home installation demonstration project was the impetus for the current supportive PV laws in Germany, Japan, and other nations.
1996	EPFL, Switzerland's photoelectrochemical dye-sensitized solid/liquid

	cell reaches 11%.
1997	The yearly generation of Photovoltaic hits 100 MW globally.
1998	A 19% efficiency Cu(InGa)Se2 thin-film photovoltaic cell (NREL, US) is equivalent to multicrystalline Si. US deployed the first concentrating array (5kW employing highly efficient GaInP/GaAs/Getriple junction cells) into orbit on Deep orbit 1.
1999	The total deployed pv capacity around the globe surpasses 1000 MW.
2000	An extensive variety of PV applications and the granting of the first Bachelor of Engineering degrees in Solar power and Renewable Engineering (UNSW, Australia) are highlighted by the Australian Olympics.
2002	The total operational solar capacity across the globe is 2000 MW. Reaching the initial 1000 MW required 25 years, but doubling it only required 3 years.

2.5 Detailed Study of Research

All over the world with fast technological spread, the utilization of energy has been increasing rapidly which estimated 30 terawatts in 2050. In recent years, due to encountering the near and future electricity requirements, solar cells are growing drastically [26]. Currently, silicon (Si)-based solar panels account for around 90% of the global supply. Si-based photovoltaic cells have several disadvantages, such as cost, reliance on the weather, need for space, worries about pollution, stiffness, as well as elevated manufacturing expenses. TFSCs are increasingly appealing in PV technology due to their low manufacturing costs, well-established fabrication processes, industrial manufacturing flexibility, and exceptionally efficient power conversion [27]. Researchers in this subject look at various criteria including earth-abundant and harmless substances to build solar cells that are more affordable and more efficient. Using natural resources, photovoltaic technologies have recently attracted considerable research interest that remarks as a more renewable and environmental alternative.

The thin film solar cells are rapidly changing and improving various applications such as satellite, streetlights, traffic, solar farms, forest areas, fans, Wi-Fi modems, and others [28]. In recent years, the solar cell is one of the major challenges for renewable energy as fabrication of lower manufacturing costs and increases conversion efficiency [29]. For this reason, SnS has gained significant attention as a new absorber in the improvement of solar cells [30]. A-Si, CdTe, and CIGS are the three most widely used thin film photovoltaic cells currently available. To achieve the performance of PV cells, several a-Si, CdTe, and CIGS-based TFSC designs have been created both practically and mathematically [31]. At 13.6%, 22.3%, and 22.1%, respectively, -Si, CdTe, and CIGS have been shown to have the highest practical efficiency [32]. Utilizing the SCAPS-1D software and the design properties of GaAsN, excellent solar cell efficiency is provided [33].

SnS has various properties like a high absorption coefficient of 10^5 cm^{-1}, a favorable band gap of 1.35 eV, and an optimum doping concentration of 10^{15}–10^{18} cm^3 [34, 35]. Furthermore, many applications of SnS-based materials are energy storage systems, photo electrochemical cells, artificial satellites, radio, and wireless transmission, etc. The promising material SnS can be adjusted by high absorption that indicates the capacity to attain terawatt energy generation [36]. Nowadays, a large amount of pragmatic SnS-based heterojunction like as TiO_2/SnS, ZnS/SnS, and ZnO/ SnS, has performed optimum cell performance [37]. The maximum efficiency of 16.26% was achieved in ZnS/SnS heterojunction PV cell that have been indicated in the works [38]. The theoretical performance of the Mo/SnS/SnO_2/Zn(O,S):N/ZnO/ITO photovoltaic cell was measured at 7.68% in the earlier work [39]. The SnS solar device with ZnS buffer layer's PCE value of 22.43% is calculated numerically [40].

Recently, it was discovered that a SnS-based TFSC composed of p-SnS/CdS/n-ZnMgO, using ZnMgO as the window layer to link with SnS and CdS layers, had an efficiency of about 23% [41]. Various inorganic HTLs, such as NiOx, CuI, CuSCN, and Cu_2O, have been successfully employed to improve PV efficiency in earlier studies on thin-film heterostructure solar panels [42–44]. To validate the accuracy of the statistically generated SnS solar cell in the current work, we first employed overall previously published SnS-based PV cell with the structure Mo/SnS/CdS/iZnO/AZO/Al [45]. The innovative heterojunction SnS TFSC arrangement with an HTL is then numerically simulated. Here, the HTLs at the rear of standard SnS solar cells made of NiOx, CuI, and Cu_2O are used to investigate a better design and enhance the cell's output characteristics. Among the suggested HTLs aimed at enhancing the outputs of SnS-based solar cells, Cu_2O is determined to be the most advantageous one for achieving the suitable band alignment at the rear contact and facilitating transport of carriers through the SnS absorbers to the rear metal interface. At present, CeO_2-based materials have obtained a significant observation in case of their environmentally applications like as catalysis, hydrogen production, and gas sensing etc [46]. However, in one of our recent works, CeO_2 ETL is an emerging element that has different characteristics such as variety of band gaps from 3.0–3.6 eV, large dielectric constant 23–26, excellent electrical and optical properties [47]. It has distinct benefits including low cost, high durability, high efficiency, flexibility, and no hazardous effect on the environment. In addition, Cu_2O is known as a p-type material which has photovoltaic characteristics with a suitable band gap of 2.17 eV. With low electron affinity of 3.2 eV, and improved hole mobility of 256 $cm^2\ V^{-1}\ s^{-1}$ expressed as a dynamic hole transport component in SnS-based heterostructure [48]. The various techniques can be arranged in Cu_2O thin film, as involving sputtering, copper oxidation and atomic layer deposition (ALD) [49, 50].

Therefore, Cu_2O has very high hole mobility, which has been applied as an HTL in various preceding experimental operations to enhance the performance of cell efficiency. According to Birant et al., the energy from the sun has the greatest potential for electricity of all natural resources, and the surface of the Earth gets enough energy in only one hour to satisfy all of humanity's energy needs for a year [51]. Photovoltaic cells may be utilized in daily life to transform sunlight directly into electricity, according to Yang et al.'s summary, which states that solar energy is unlimited, clean, and the most plentiful source of sustainable energy [52].

The element copper oxide (Cu_2O) has been suggested by Abdu et al. as a viable material for the creation of inexpensive solar cells for use on the ground. The demand for key energy sources, which are now non-renewable, is constantly rising [53]. These sources, which mostly use fossil fuels, are not only non-renewable but also significantly worsen the ongoing issue of global warming. International society is focusing on alternate energy sources due to the impending depletion and pollution issues with the aforementioned energy sources, and solar energy looks to be quite promising.

Cu_2O is a non-stoichiometic defect p-type semiconductor that Walter et al. describe, and its applications for the creation of photovoltaic cells have been acknowledged since 1920. This was before the discovery of silicon, germanium, and other potentially semiconducting materials. The photovoltaic community, however, rekindled interest in Cu_2O in the middle of the 1970s as a potential low-cost component for PV cell [54]. Early in the modern era, Cu_2O Schottky connections were thoroughly researched to be utilized as rectifying devices in radio receivers, according to Riordan, M. et al. [55]. Reviewing the work done at this time, Brattain et al. discuss the challenges posed by n-type doping [56].

Due to the accessibility of single crystal silicon and germanium, which may be doped n-type and p-type, and the introduction of the electron connection transistors in 1947 and the introduction of the metal oxide semiconductor field-effect transistor in 1960, Drobny et al. claim that interest in Cu_2O has decreased [57]. The Schottky junction PV technology was used in the Cu_2O solar cells studied at this time. The performance of Cu_2O PV devices should be enhanced by a heterostructure or metal-insulator-semiconductor arrangement, according to Rakhishani et al. By the 1980s, interest in these Cu_2O Photovoltaic cells had once again started to wane because to the low that they could attain provides a summary of the research on Cu_2O Schottky junction systems published during this time [58].

According to Mittiga et al., transparent semiconductors are the principal application for these transition metal oxides. The most recent advancements in copper oxide heterojunction photovoltaic cells will be the main emphasis of this review. The system with the most research has been heterojunction ZnO/Cu_2O cells [59]. While Cu_2O has a bandgap in the visible area of the sun's spectrum at around 2 eV, Olsen et al. have examined how wide bandgap ZnO serves as a window layer [60].

Even though the Cu_2O bandgap is not suitable for sunlight, Nishi et al. For devices with a ZnO window layer, astounding light to electricity efficiency of up to 4% have been recorded [61], while 5% were attained with a Ga_2O_3 layer. A V_{oc} of up to 1.2 V for a Ga_2O_3/Cu_2O heterostructure device has recently been observed, according to Lee et al. [62]. According to Brown et al., the Cu_2O bandgap is almost optimal in multi-junction simultaneous cells with three or more junctions [63]. Cu_2O is a particularly desirable absorber for semi-transparent photovoltaics, as Fortunato et al. have demonstrated. Cu_2O thin films have been employed in optoelectronic devices including thin film transistors in addition to solar cells [64].

Organic-inorganic halide of tin-based perovskite solar cells have demonstrated their potential for quickly raising their efficiency from 6.4% to 19.3% in 2014. A type of solar cell called the perovskite solar panel uses perovskite-based material as its light-absorbing layer. Methylammonium tin tri-iodide ($CH_3NH_3SnI_3$) perovskite has great characteristics including a direct bandgap (1.3eV), a high absorption coefficient, and a long diffusion length that make it extremely appealing as a photovoltaic material. Due to the fast advancement of technology, there is a rising need for energy [65].

T. Pooja et al. Here, the device is simulated using the SCAPS-1D program, and the impact of several structural characteristics on the efficiency of SnS-based solar cells has been carefully investigated for the SnS layer, CeO_2 layer, and Spiro-OMeTAD layer. It has been suggested to model and advance a special device structure for a SnS-based solar cell employing the CeO_2 electron transport layer and the Spiro-OMeTAD HTL [66].

Recent advancements in SnS-based heterojunction solar cells will be the focus of this study. Copper oxide (Cu_2O), one of the oxides, exhibits benign nature, plentiful availability, and straightforward fabrication procedure in such applications. In the SnS-based heterojunction solar cell, the p-type Cu_2O material can be used as a possible HTL. To construct highly effective and affordable thin-film PV systems, scientists will find the numerical analyses offered in this study to be helpful. We present a novel hole transport layer (HTL) for a thin-film solar cell based on tin sulfide (SnS) called cuprous oxide (Cu_2O). With the help of the one-dimensional Solar Cell Capacitance Simulator (SCAPS-1D) tool, the photovoltaic capabilities of the developed SnS solar cell are examined. Variations in the absorber layer's thickness, charge concentration, and defect density are used to evaluate the device's outputs.

In order to create an environmentally acceptable, inexpensive, and extremely effective SnS thin-film heterostructure solar cell, the less toxic Cu_2O that has been proposed can be used as a potential HTL. Using CeO_2 ETL and Cu_2O HTL with a SnS-based solar cell, we suggested a novel heterojunction (ITO/CeO_2/SnS/Cu_2O/Mo) in this study. SCAPS-1D is a practical simulation tool for achieving heterostructure cell performance efficiency.

2.6 Summary

In this chapter the literature review of different solar cells is performed. Also discuss the Cu_2O as a solar cell.

Chapter 3

Mechanism of solar cell

3.1 Introduction

This section represents an overview of SnS based heterostructure PV cell, the key concepts of solar cell that are the basis of this technique, history behind this widely used this structure, its working principle. Moreover, advantages, limitations and applications of PV cells are also discussed.

3.2 Working principle of solar cell

A photovoltaic device called a solar cell transforms solar energy into electricity. The fundamental principle behind how solar cells function is that when sunlight contacts the surface of the cell, it excites the electrons already present. As a result of their propensity to enter high-energy states, carrier production and recombination take place. This process results in a voltage and current flow across a solar cell's outer circuit. The metal electrodes may capture these electrons, and this process must be repeated repeatedly in order to generate energy from ultraviolet rays. The movement of holes as well as electrons through the metallic structure is seen in Figure. 3.1 [67]. The energy and voltage generated by only one solar cell, however, are insufficient; as a result, we often employ a collection of solar cells, also known as solar panels, to generate an adequate quantity of electricity of about 12 volts. As seen in Figure. 3.1, the photovoltaic effect governs how solar cells function. Sunlight photons strike the photovoltaic cells and are captured by semiconducting components like doped silicon. The present molecular orbital of electrons is energized. An excited electron has two options: release the energy as radiation and reenter its orbit or move around the cell unless it comes into contact with a conductor.

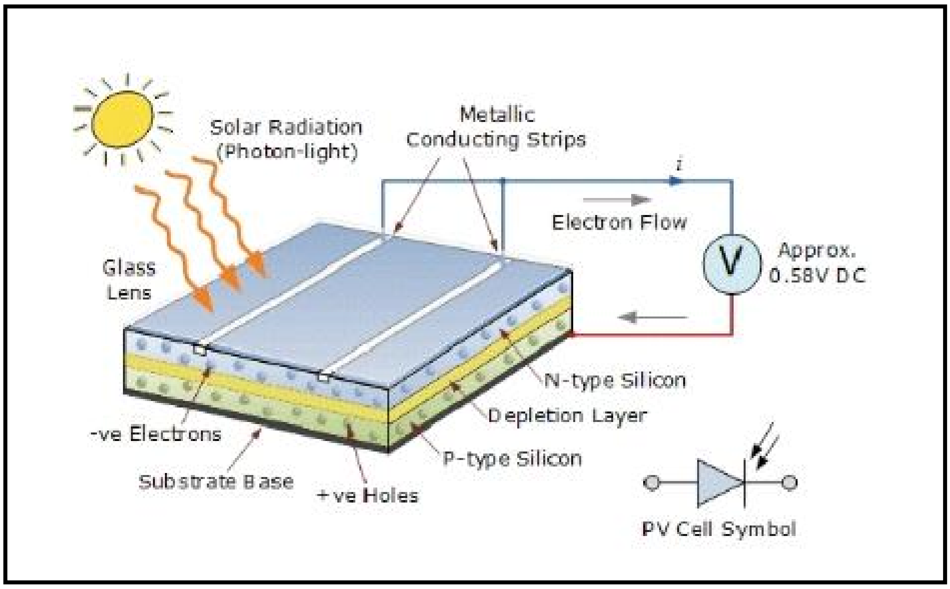


Figure 3.1: Working principle of solar cells [67].

Energy is captured when current traverses the substance in order to eliminate its electrical charge. In p-type silicon, holes, the majority charge carrier with a positive charge, are formed. Yet within the n-type silicon area, electrons make up the bulk of charge carriers. To gather the charge carriers, both the rear and front metal electrodes of the solar cell are typically linked to the solar cell. The external circuit experiences photocurrent drift when a solar cell is attached to these terminals. The photo generated or sun light-generated particles split and move in the direction of the appropriate metal contacts. The solar cell's current flow may be seen if we link it to an outside load or other power evaluation device. To let light into the substance that is active and collect the created charge carriers, the lighter side of a solar cell typically contains a transparent conducting layer.

3.3 Properties of solar cell

Photovoltaic cells generate electricity and voltage that can be used to operate a circuit that is integrated, such as a calculator, or a separate circuit. Semiconductors, which are substances with unique electronic characteristics, are required for this response [68].

3.3.1 Semiconductors of solar cell

Conductors, semiconductors, and insulators are the three types of materials that fall within the conduction classification system. These divisions result from the material's electrical characteristics, which are governed by its energy levels.This is crucial to understand that only specific distinct levels of electron energy are permitted in an atom according to the laws of quantum physics. The energy levels in bulk material are distributed into distinct energy level bands. Depending on the distance between the atoms, such energy bands are either apart from one another or overlap. Figure. 3.2. The bang gap (Eg), which occurs when the energy bands are split apart, is the space between the two bands.

The following groups make up the energy bands:

i. The largest energy band that is at least half filled is known as the valence band.

ii. The core band is made up of all the electrical bands that are below the valence band.

iii. The area of empty space above the valence band is known as the conduction band.

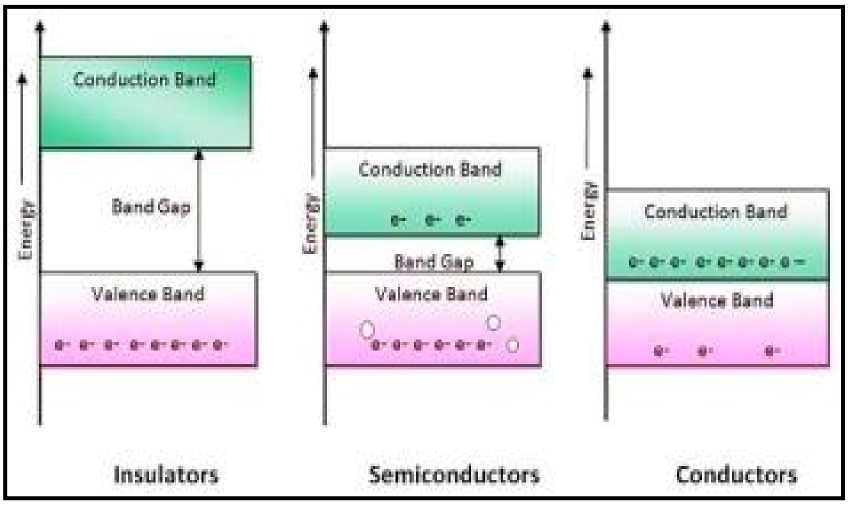


Figure 3.2: Energy band of semiconductor [68].

Intrinsic and extrinsic semiconductors are two types of semiconductors. A pure element's inherent structure can exhibit semiconducting activity, which is known as intrinsic conduction. Extrinsic conduction, on the other hand, results from the existence of impurities; in this case, the arbitrary boundary of a band gap of 2.5 eV is irrelevant [69]. Because of the electrons of the doping agent or impurity, an extrinsic semiconductor may display semiconducting behavior.

3.4 Photovoltaic effect of solar cell

Electronic components including diodes, transistors, LEDs, and solar cells may all be created by fusing p- and n-type semiconductors. The p-n junction diode is perhaps the most basic electrical device. An n-type and a p-type semiconductor are brought into contact to form this diode, which results in the formation of an area rich in holes and an area rich in electrons. Because of the recombination of electrons and holes in this area, a depletion zone will emerge at the point of contact connecting the two semiconductors.The depletion zone's size is constrained by this electric field because it prevents charge carriers from recombining in the bulk and only at the interface [70]. A p-n junction diode can have a potential applied to it by linking a strongly charged electrode to the p-type side. The carriers of charge will be drawn to the electrodes rather than the interface if their potential is inverted, which prevents recombination and, as a result, prevents current flow. The diode can be conducted effectively only in one direction. They are referred to as forward and backward biased potentials, correspondingly. Figure. 3.4 display this device's I-V characteristic. A p-n junction serves as the foundation for both diodes and solar cells. Photons will enter the substance when the gadget is lit.

- The photon passes directly through the substance.
- Photon reflection occurs.
- A photon is taken in by an atom.

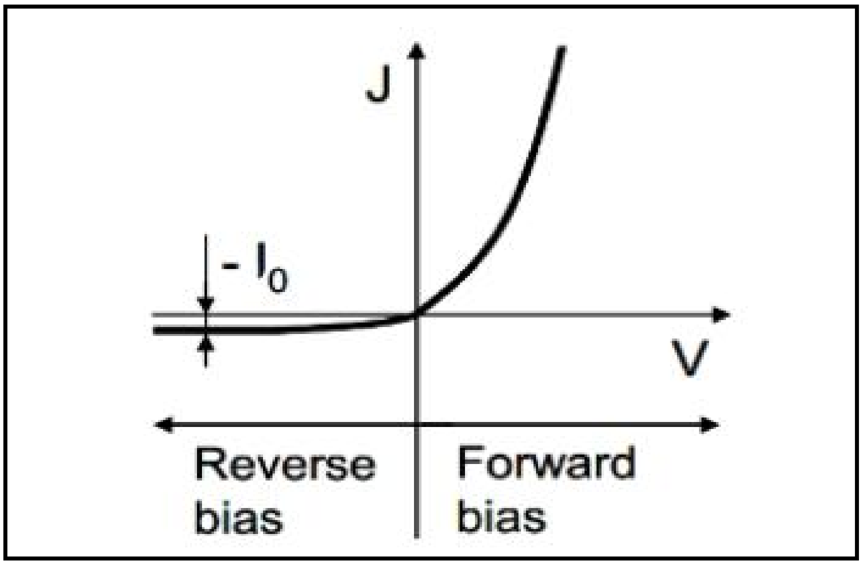
➢ 

Figure 3.4: An ideal p-n diode I-V properties [70].

In recombination of charges, a p-n junction circuit has a spontaneous electrical field at the junction of p- and n-type material [71]. Through this process, a greater amount of charge is generated on each side of the device, increasing its potential. The energy of the light source is captured through transformation to electrical power when a piece of resistance is attached to the device.

3.5 Characteristics of solar cell

Considering solar panels are truly p-n junction devices with a particular architecture, equations crucial for p-n junction description are also crucial for sun cells. The Shockley Equation 3.1, which explains how an ideal p-n diode behaves, is a key equation for semiconductors [72].

$$I(V_a)=I_0[\exp(\frac{qVa}{kT})-1] \qquad 3.1$$

Where, the amount of current (I) is expressed as an indicator of the voltage that is applied (Va) and short circuit current (Io). Additionally, T is the temperature, q is the charge of an electron, and k is the Boltzmann constant. Due to the behavior stated for a p-n diode in this equation, electricity is going to flow whenever a forward-biased voltage is used.Photogenerated current (Iph), which is produced by the movement of these charge carriers, is created. No current may flow through the device in the event of an open circuit, hence this current need to be balanced. The recombination current does this. However, photogenerated electricity will additionally pass via the external circuit if the gadget is in a short circuit. The photogenerated current must now be taken into consideration in addition to the two currents that determine the total current passing through the circuit, leading to Eq 3.2.

$$I(V_a) = I_0[\exp\left(\frac{qVa}{kT}\right)- 1]-I_{ph} \quad 3.2$$

Since the photogenerated current is zero in the absence of light, equation 3.2 simplifies to the Shockley equation; however, in the presence of illumination, the photogenerated electricity will go down the current, leading to a negative current and providing power (I-V). This behavior is readily seen in Figure. 3.5. The solar cell is propelled by photocurrent; hence increasing photocurrent will significantly boost efficiency. In Eq. 3.3, the photogenerated electricity is provided.

$$I_{ph}=qG\ (L_n + W + L_p)A_i \quad 3.3$$

Where Ln and Lp are the corresponding diffusion lengths of electrons and holes, W is the width of the depletion zone, Ai is the area of the interface, and G is the rate at which charge carriers are generated.

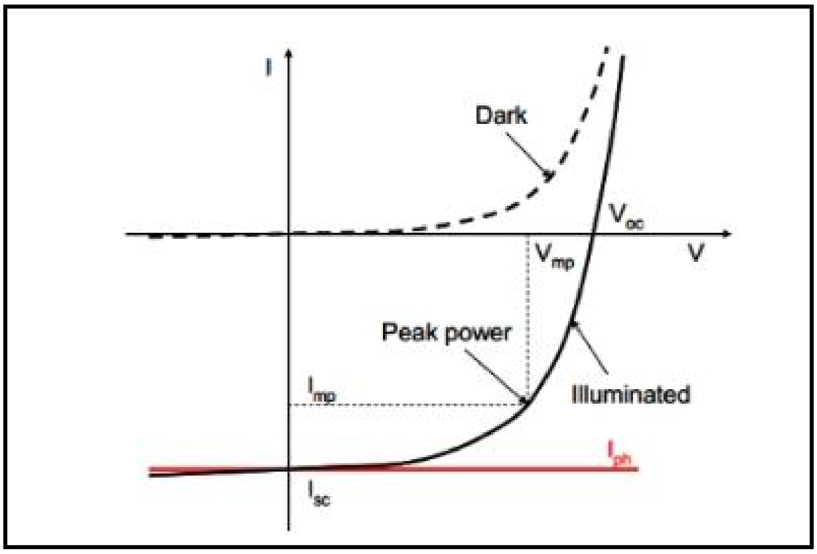


Figure 3.5: I-V properties of an ideal solar cell.

If the charge carrier propagation distance is greater, additional electrons flow into the depletion zone and are separated since this is the average distance a charge carrier may travel before recombination takes place. The current during a short circuit (Isc), which corresponds to measure for the current flowing at no voltage thus, the intersection with the I-axis, is one of the most crucial factors for characterizing the efficiency of photovoltaic cells. The highest possible voltage and power are Vmp and Imp. A significant ratio that may be derived from these values is the FF. The greater value for FF produces a more squared-like shape, which causes the Vmp and Imp to approach the Isc and Voc and raise the highest possible power supply.

$$FF = \frac{I_{mp}V_{mp}}{i_{mp}V_{mp}} \qquad 3.4$$

The most significant ratio is the conversion efficiency, which is represented by Eq. 3.5.The energy in the light source is known as the incident power, and in solar cell research, a standard of 1000 W/m^2 of the AM1.5 spectrum is utilized.

$$\eta = \frac{p_m}{p_{in}} = \frac{I_{sc}V_{oc}FF}{P_{in}} \qquad 3.5$$

3.6 Advantages of Solar cell

Solar cells used in photovoltaic cells may capture solar energy and generate electricity for homes and businesses. While modern solar cells provide many benefits for individuals and companies alike, there are a few drawbacks as well. The benefits and drawbacks of solar cells are shown below [73].

Renewable Energy

Solar energy is an alternative source of energy, making the usage of solar cells the most evident benefit. Renewable sources of energy include the sun, wind, and waves; in this case, the sun is the source of energy.Solar energy is unique in that it will always be available. Although it may appear unimportant, solar energy may serve as a reliable source of electricity generation indefinitely.

Cost-effective

The ability to reduce your electric bill significantly since you don't have to pay for the energy you produce is another advantage of employing solar cells. Depending on how many panels you use, you may save anywhere from £160 to £430 on your annual power cost. Additionally, you have the chance to profit from your solar system. Additionally, you can get several solar panel incentives, and there will be additional long-term financial advantages. In terms of maintenance expenses, solar cells can surpass all other energy sources.

Environment pollution

Using photovoltaic cells, there is nearly no pollution, which is a huge benefit. Comparatively speaking to traditional energy sources, this is a little portion.
Furthermore, worries about dying photovoltaic cells have considerably diminished because of advancements in cell recycling.

Innovative Energy

Green energy is a major subject these days, and photovoltaic is one of the best ways to combat global warming. Among other forms of renewable energy, this is additionally one of the industrial sectors with the most cutting-edge technology. It has already created a cutting-edge field of study that is constantly being developed and researched. Government investment in this sector has reached record levels, creating innumerable employment at all levels, from researchers to scientists to PV installers. The employment prospects that the solar cell sector may offer if the investments continue are therefore another benefit.

Long Term Energy

Solar power plants frequently have a lengthy lifespan and exceptional sturdiness. Additionally, PV panels sometimes come with a warranty of at least 20 years, making them a dependable source of power for your roof.

Figure 3.6: Advantages of solar cells.

Selling Energy

It is frequently simpler to sell your house for a better price if it contains solar panels. If you wish to invest in solar cells, there are several subsidies and incentives available in the UK.

Infinite Energy

The ability to harness solar energy is a novel market that is always being researched and developed since solar energy is a source of power that will never run out.

3.7 Disadvantages of Solar Cells

Solar cell use might have several disadvantages. Here are a few of the most significant drawbacks of solar energy that you should take into account before adopting solar [73].

High Cost

An introductory solar system purchase has a hefty price tag. Though solar technology is continually evolving, it is realistic to predict that costs will decrease in coming years.

Depends on the weather

The energy system may noticeably be impacted by a few days of overcast or wet weather.

Expensive Energy Storage

Solar energy must be utilized immediately unless it is stored in huge batteries. Most of the time, it makes more sense to solely utilize solar power through the day and draw power from the grid at night.

Utilizes Much of Space

There is a lot of room needed for solar PV panels, but some rooftops may not be big enough to accommodate the number of solar panels you want to have.

Figure 3.7: Disadvantages of solar cells.

3.8 Applications of Solar Cell

Biogas Solar cells are lightweight, strong, and need little upkeep. It was originally used in a communication satellite after being discovered in 1950. Several solar cells use for various needs [74]:

Transportation Using Solar Cells

In autos, renewable energy from the sun is employed. Photovoltaic cells produce this solar energy. The motor or storage battery receives this electricity for power.

Calculators that use solar cells

Solar energy cells are used in solar-powered calculators. These calculators use solar power to operate. Calculators run on power provided by the sun's light. Solar calculators perform admirably in daylight.

Solar Farms

Power from these massive systems is fed into local or regional networks utilizing fixed or solar-tracking panels.

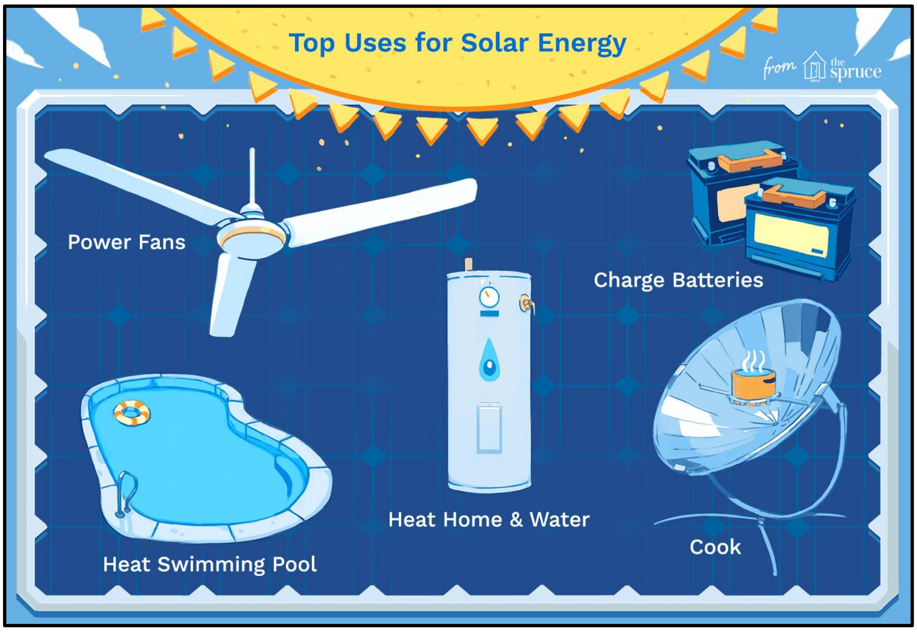


Figure 3.8: Applications of solar cell.

Outlying Areas

It is not always possible, cheap, or even practicable to connect transmission lines to locations where light is needed.

Independent Power

Photovoltaic may power standalone appliances, tools, and meters in urban or rural settings. Garage meters, transitory road signs, alarm mobile devices, wireless transmitters, irrigation water motors, stream-flow indicators, distant security posts, highway lights, and other devices can all be powered by PV.

Space Power

For many years, the primary energy source for spacecraft which circle the planet has been sunlight. Orbital and space exploration is going to depend on high-efficiency photovoltaic technology. For initiatives including the International Space Station (ISS) and ground exploration of the Sun and Mars, it has supplied energy.

Building-Related Demands

Photovoltaic material can be integrated into the framework of a structure such as windows, roofing slates, or covering that have multiple purposes. PV material can also be covered with umbrellas and parking structures to offer obscuring as well as power.

Military Applications

When flexibility or durability are critical, thin-film pv that is adaptable and inexpensive can be employed. Military can carry portable PV power gadgets during combat or at remote locations.

3.9 Summary

In addition to producing biomass, wind, hydro power, and wave energy, solar energy represents a huge source of immediately useful energy. In this chapter we discussed the basic of solar cell, application and limitation is also included.

Chapter 4
Working methodology

4.1 Introduction

In this chapter we have discussed the working methodology on the modeling of the proposed SnS based solar cell. We also discussed the material properties of solar cells. The software simulation and model will be discussed in this chapter. The action panel and flowchart are also discussed here.

4.2 Material and Method

The proposed model of SnS−based heterojunction (Al/ITO/CeO_2/SnS/Cu_2O/Ni) solar cell structure has been depicted in Figure. 4. 1. In this heterojunction, the front contact is ITO, the windows layer (ETL) as CeO_2, the absorber layer as SnS, HTL as Cu_2O, and back contact as Nickel (Ni) were used respectively. The diagram energy in Figure. 4. 2, shows that the SnS layer is less than the conduction band offset (CBO) in CeO_2 ETL layer. Then, the electron could effectively be conducted from SnS via CeO_2 to ITO whereas holes could blockade CeO_2 caused by extremely large valance band offset (VBO) within them. From the figure, it is viewed that the VBO within the valence band of Cu_2O and SnS absorber layer is very small due to the HTL being superior to the SnS layer. Besides, conduction band offset (CBO) within the SnS and Cu_2O layer are considerably extensive due to blocking the flow of electrons. Consequently, Cu_2O HTL builds a compatible contact with SnS to conduct holes via Cu_2O to the back electrode, where it interrupts the electron movement to contact the back electrode. As a back electrode of Nickel (110) and front electrodes of (Al) Aluminum (111) have been both employed in metal work function of 5.63 eV and 4.26

eV respectively. Using previous scientific theories and experimental publications, the values of ITO, CeO_2, SnS, and Cu_2O were recorded in Table 4.1 [75-79]. The interfacing parameters for the analysis of SCs are found in Table 4.2. The research of heterostructure solar cell used absorption coefficient data of SnS, Cu_2O, and CeO_2 layerwhich has been applied for SCAPS-1D simulation and we get better efficiency.

4.2.1 Properties of Material

The simulation components of proposed SnS-based heterojunction solar cells are ITO, CeO_2, SnS, and Cu_2O recorded in Table 4.1. From literature, the research of absorption coefficient data of SnS, Cu_2O, and CeO_2 was applied for this simulation which is highly efficient for heterostructure solar cells.

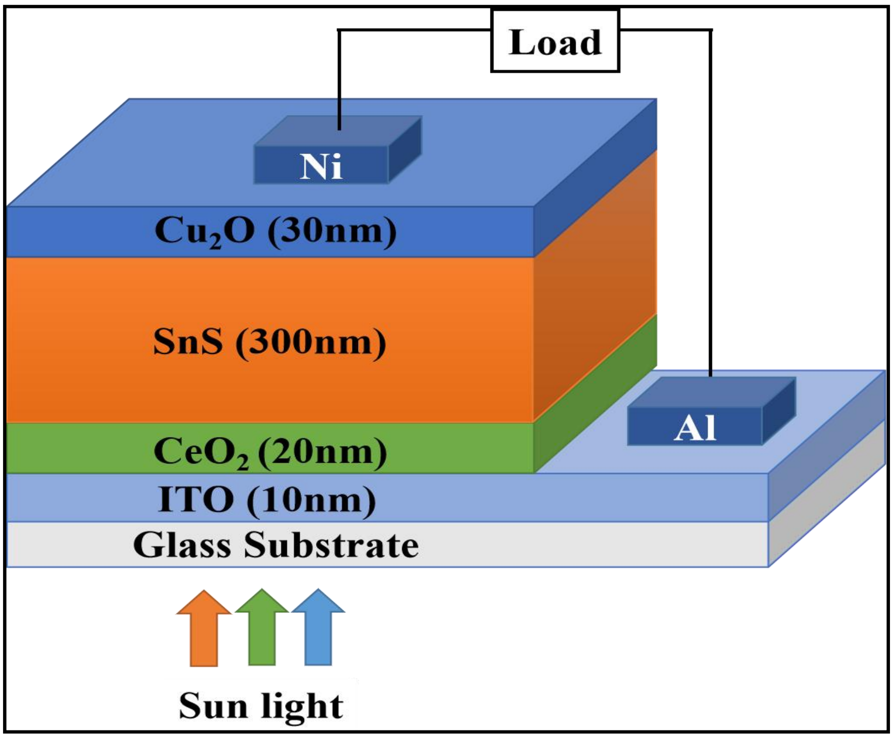


Figure 4.1: The proposed schematic model of heterostructure solar cell.

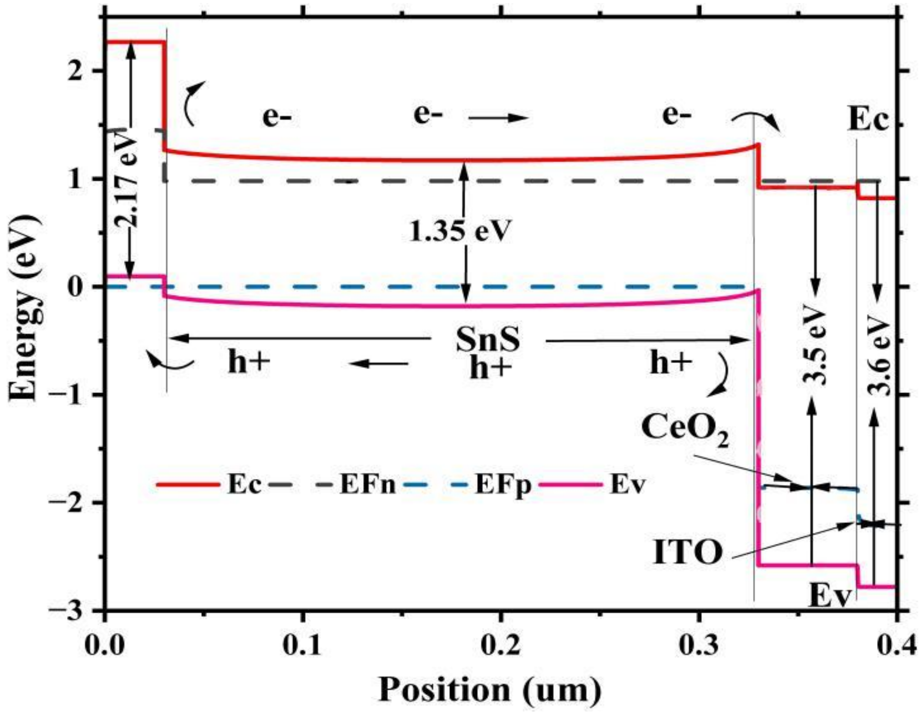


Figure 4.2: Energy level structure of proposed heterostructure solar cell.

4.3 Numerical Analysis of SCAPS 1D

Solar energy systems might be simulated using standard computational program that can solve the fundamental semiconductor models [80]. Numerous mathematical simulators, including AMPS , wxAMPS, SILVACO ATLAS, COMSOL and SCAPS, have been utilized to investigate the characteristics of TFSCs [81]. According to Burgelman et al. in their research comparing between SCAPS and other simulators, SCAPS has benefits over these modeling applications, including the capacity to reproduce a maximum of seven distinct stages tandem cells that are simple to use, and intuitive under control. The computations were conducted utilizing the most recent version 3.3.0.7 of SCAPS-1D, a numerical modeling tool for one-dimensional solar cells.

Table 4.1: Simulation parameters of heterostructure solar cell.

Types of Parameters (unit)	Values			
	ITO	CeO_2	SnS	Cu_2O
Thickness (nm)	10	20	300	30
Eg (eV)	3.6	3.5	1.35	2.17
The affinity of electron (eV)	4.5	4.6	4.2	3.20
Dielectric constant, €	8.9	9	13	7.11
CB (cm^{-3})	2.2×10^{18}	1×10^{20}	1.1×10^{18}	1.8×10^{18}
VB (cm^{-3})	1.8×10^{19}	2×10^{21}	4.76×10^{18}	2.4×10^{19}
µe (cm^2/Vs)	10	100	140	2
µh (cm^2/Vs)	10	25	4.3	25
ND (cm^{-3})	10^{21}	10^{21}	0	0
NA (cm^{-3})	0	0	10^{15}	1×10^{21}
Defect type (cm^{-3})	0	10^{14}	10^{14}	10^{14}
Recombination (cm^3s^{-1})	0	2.3×10^{-9}	2.3×10^{-9}	2.3×10^{-9}

Table 4.2: For simulation interfacing parameters of heterostructure solar cell.

Parameters (unit)	Values	
	Cu_2O/SnS	CeO_2/SnS
Type of Defect Density	Neutral	Neutral
Qe (cm^2)	1×10^{-19}	1×10^{-19}
Qh (cm^2)	1×10^{-19}	1×10^{-19}
Er (eV)	0.06	0.06
The defect label (cm^{-3})	1×10^{10}	1×10^{10}
Working temperature (K)	273−500	

The model for simulation was created using the SCAPS-1D program to examine the effects of the various factors on the efficiency of the photovoltaic cell. Although CZTS, CIGS, CdTe, and kesterite thin-film solar panels were extensively studied using SCAPS, the computational setting of SCAPS may be expanded to examine the efficiency of solar cells[82]. The SCAPS platform included both the most recent results and some additional data with in-depth analysis [83]:

$$\frac{\partial^2\psi}{\partial x^2} + \frac{q}{\epsilon}\left[p(x) - n(x) + N_D - N_A + p_p - p_n\right] = 0 \qquad 4.1$$

$$\frac{1}{q}\frac{dJ_p}{dx} = G_{op}(x) - R_{(x)} \qquad 4.2$$

$$\frac{1}{q}\frac{dJ_p}{dx} = -G_{op}(x) + R_{(x)} \qquad 4.3$$

Where, ε is the dielectric constant, q is electron charge, N_D and N_A are donor and acceptor density, Ψ is electrostatic potential, p, n, are hole and electron concentration, ρp, ρn, are hole and electron distribution, Jp, Jn are current densities of hole and electron respectively. In the next equation, R is referred to as total absorption from direct and indirect sources, while Gop is known as the optical generation rate. Each of the parameters is a function of x, the location. The equilibrium band graph, transport carrier characteristics, and recombination profile may all be represented in 1D using SCAPS. By using the SCAPS-1D program to optimize the various solar cell design parameters, this simulation research was carried out. First, the thickness of the ETL, absorber, and HTL layers were tuned. The influence of other factors, such as photonic recombination, acceptor density, defect density, and series-shunt resistances, was regarded as zero at 300K to optimize the ETL, absorber, and HTL layer thickness.

4.4 Simulation factors of the proposed structure

The physical and chemical phenomena known as the photovoltaic effect is used by solar cells as part of its functioning mechanism to produce energy from sunlight. When absorbed photons have enough excitation energy, electrons and holes can flow in various directions depending on whether they are within the conduction band or the valence band [84]. Light or dark lighting determines the basic condition. The J_{SC}, V_{OC}, FF, and PCE are photovoltaic characteristics used to characterize the performance of a solar device.

The simulation of SCAPS 1D software is firstly running the action panel. Then the problem is set to the software. This time we add different layers and include input parameters. After including input parameter, the environment of the program is set such as light, voltage and efficiency. Then running the simulation program and display the results. Finally, we extract data and get output.The Diagram below outlines the steps for using SCAPS and its action panel to perform a simulation.

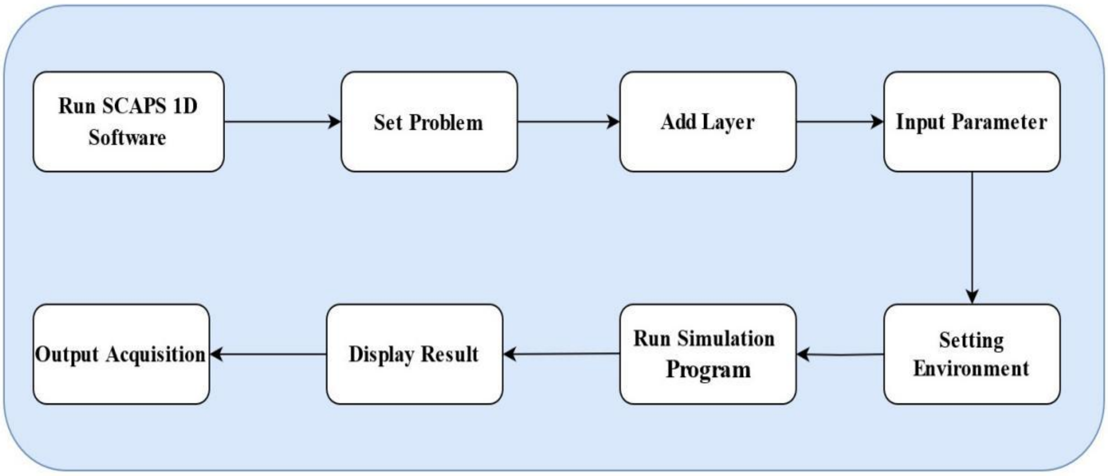


Figure 4.3: Simulation diagram of SCAPS-1D software.

Figure 4.4: Action panel of SCAPS 1D software.

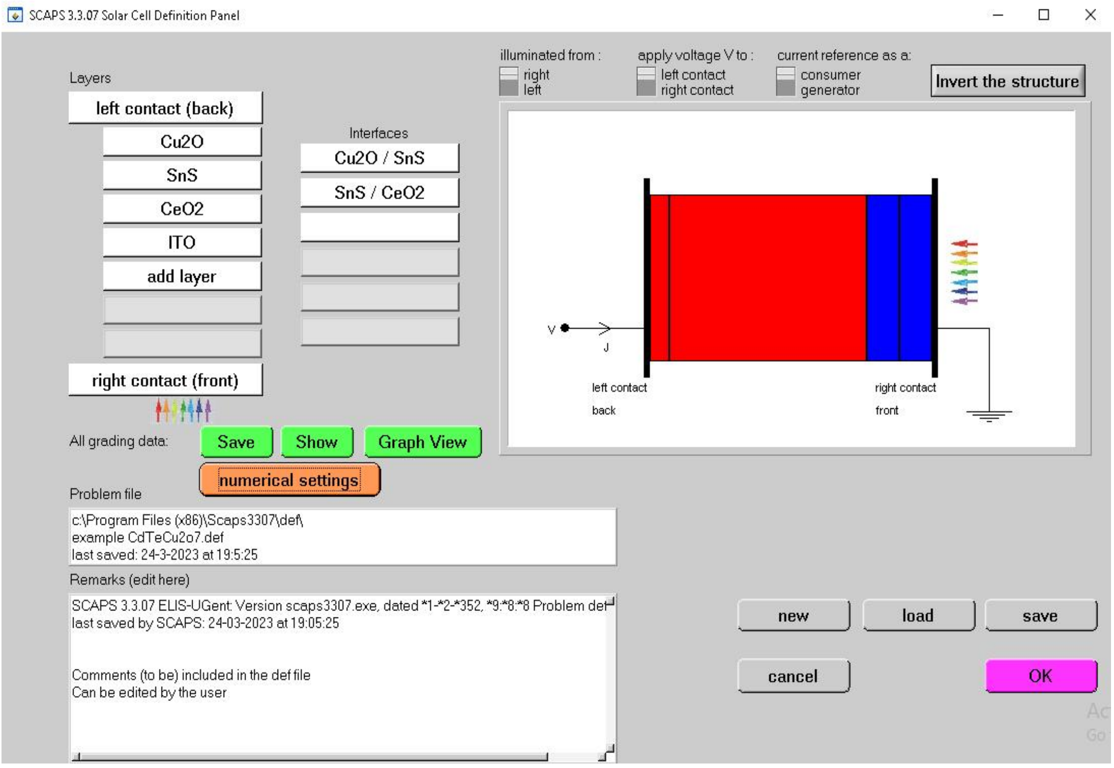


Figure 4.5: Solar cell definition panel adding different layer.

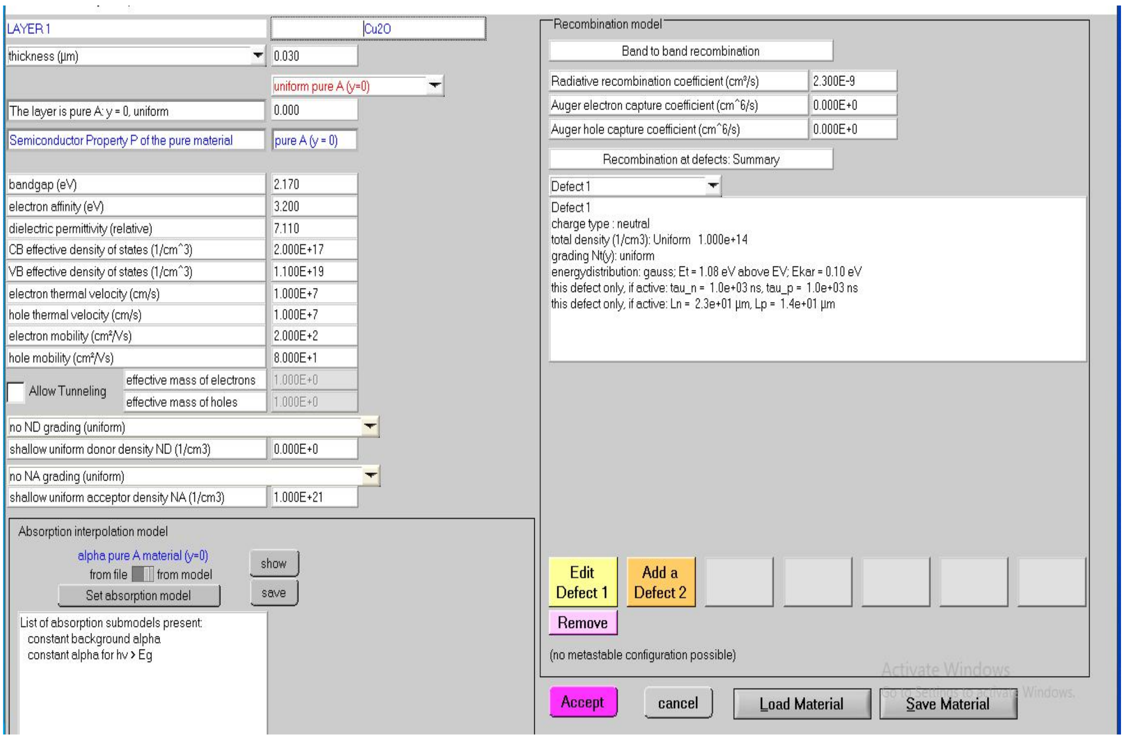


Figure 4.6: Add different layer input parameter.

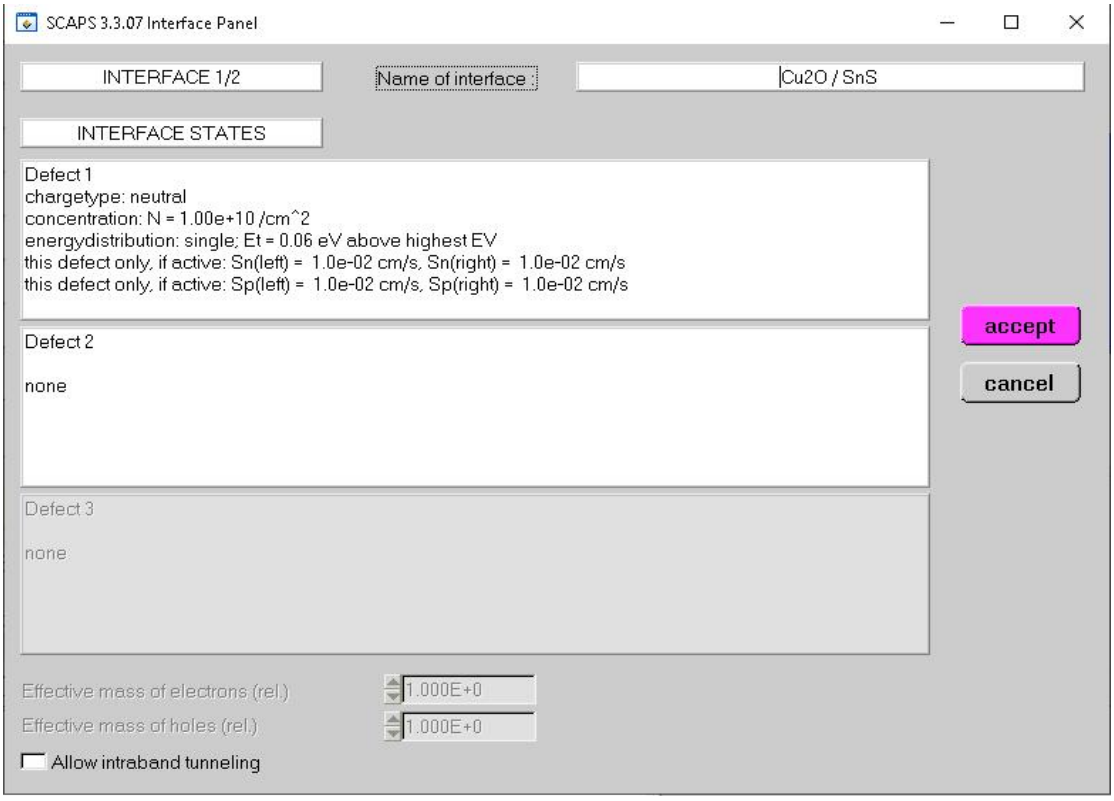


Figure 4.7: Add interfacing layer parameter.

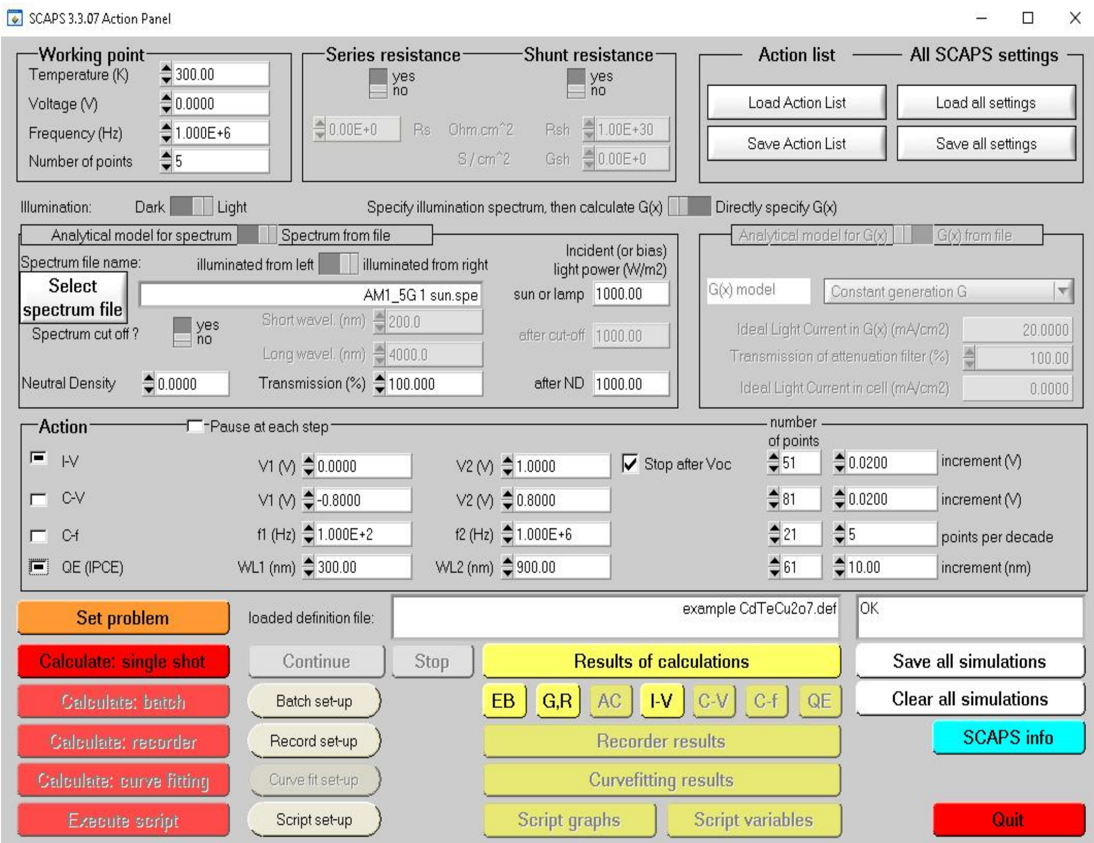


Figure 4.8: Setting the environment of action panel.

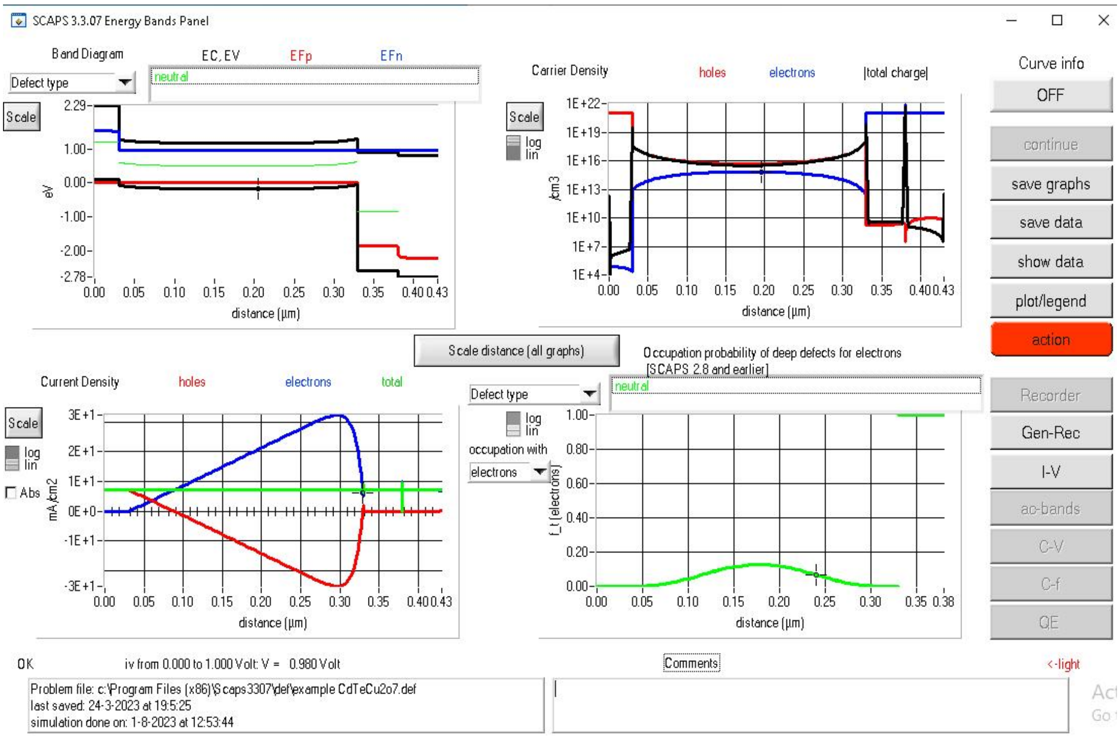


Figure 4.9: Energy band diagram of solar panel.

4.5 Surface Recombination of solar cell

The short-circuit current and open-circuit voltage can both be significantly impacted by surface recombination.By putting a passivating layer on the topmost surface, one may often lower the high surface rate of recombination by lowering the amount of dangling silicon bonds there [85].

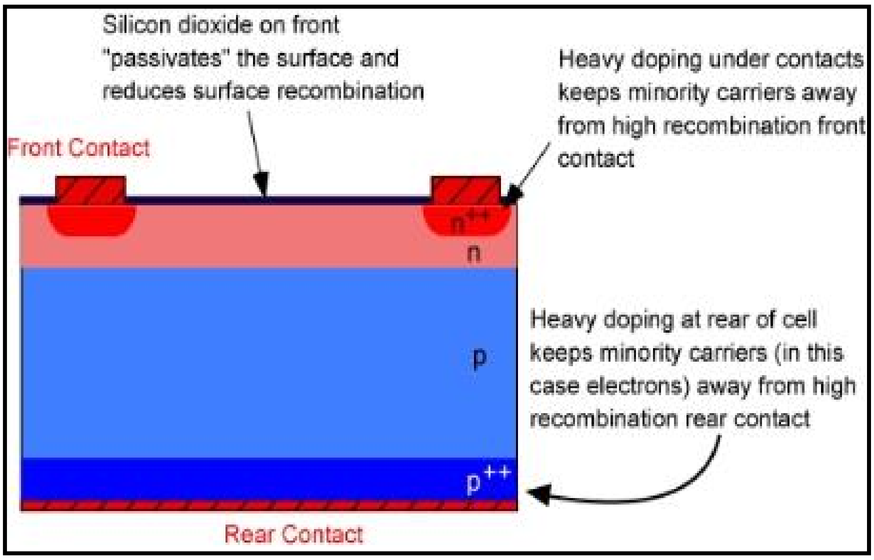


Figure 4.10: Methods for minimizing the effects of surface recombination.

Because the interface has a low level of defects, the bulk of the electronics industry uses a thermally generated silicon dioxide layer to passivate its outer layer. Dielectric layers like silicon nitride are frequently employed in industrial photovoltaic cells. Although solar panels made of silicon typically include an insulating passivating layer, silicon dioxide cannot be used to passivate any area with an ohmic metal contact. Instead, by increasing the doping under the top contacts, the impact of surface recombination can be reduced.

5.6 Summary

The purpose in this chapter is to observe the working methodology on the modeling of the proposed heterostructure solar cell. And shows the block diagram and simulation work of solar cell.

Chapter 5

Results and Discussions

5.1 Introduction

The result and performances of the proposed model of SnS based solar cell will be discussed in this chapter. The simulation efficiency of SnS based solar cell are also shown here.

5.2 Results Analysis

The SCAPS-1 software setup panel should have this part, which analyzes the efficiency of the settings for each layer, before simulations may begin. For accurate numerical findings, absorption is a crucial parameter. To prevent the empirical determined by the simulator was computed using Equation 5.1 from the values of absorption parameter k and the wavelength λ.

$$\alpha = 4\pi k/\lambda \qquad 5.1$$

Perhaps the most important physical properties that affect the transit of photogenerated carriers, carrier recombination through the heterojunction, fermi level splitting, and the efficiency of photovoltaic cells is band alignment. While the other material properties of the various layers were held constant, we first evaluated the effects of the compositional change of the absorber layer on the efficiency of the photovoltaic cell. The comparison of SnS−based SCs is shown in Table 5.1.

Table 5.1: Optimized data have been evaluated against previous studies.

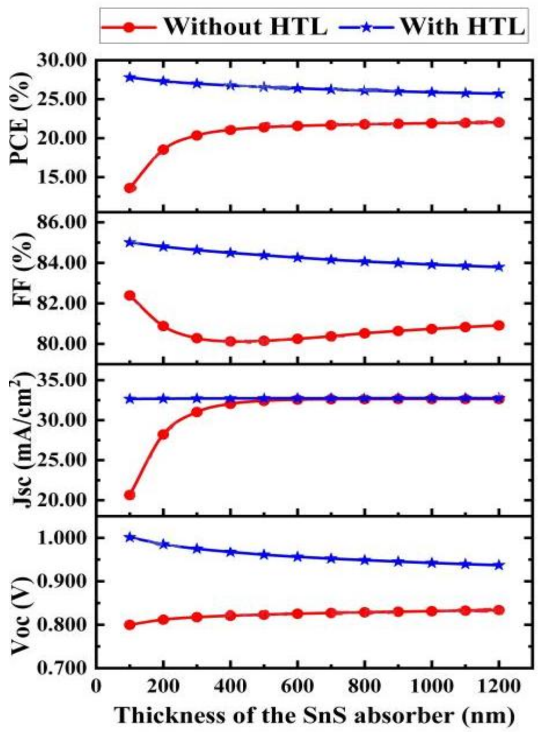
Structure	Values					
	SnS thickness (nm)	J_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	PCE (%)	Ref
ITO/CeO_2/SnS/Spiro-OMeTAD/Mo	1400	33.74	0.887	85.61	25.65	[66]
ITO/CeO_2/SnS/NiO/Mo	1400	32.67	0.890	86.19	25.1	[86]
ZnO/CdS/SnS/NiO	1000	34.20	0.904	86.97	26.92	[87]
SnS/CZTSSe	2000	33.52	0.83	85.6	23.92	[88]
ITO/SnO_2/SnS/NiO/Mo	1450	32.5	0.961	85.4	27.6	[89]
TiO_2/n-SnS/SnS/Ag/SnS/p-SnS/ITO	300	15.1	0.50	0.64	4.83	[90]
FTO/TiO_2/SnS/P_3HT/Ag	300	7.35	0.85	0.45	2.81	[91]
Si/SiO_2/Mo/SnS/Zn(O,S):N/ZnO/ITO/Ag	300	20.645	0.344	0.56	3.88	[92]
Al/ITO/CeO_2/SnS/Ni	**300**	**31.00**	**0.817**	**80.27**	**20.34**	**Proposed work**
Al/ITO/CeO_2/SnS/Cu_2O/Ni	**300**	**32.72**	**0.975**	**84.63**	**27**	**Proposed work**

The comparison of different SnS based heterostructure solar cells using various thicknesses to determine the performance analysis. We proposed a novel SnS-based heterostructure (Al/ITO/CeO_2/SnS/Cu_2O/Ni) solar cell that enhance high efficiency of 27%. The Cu_2O HTL layer, SnS absorber layer, and CeO_2 ETL layer have been selected to optimum thicknesses of 30nm, 300nm, and 50 nm, respectively.

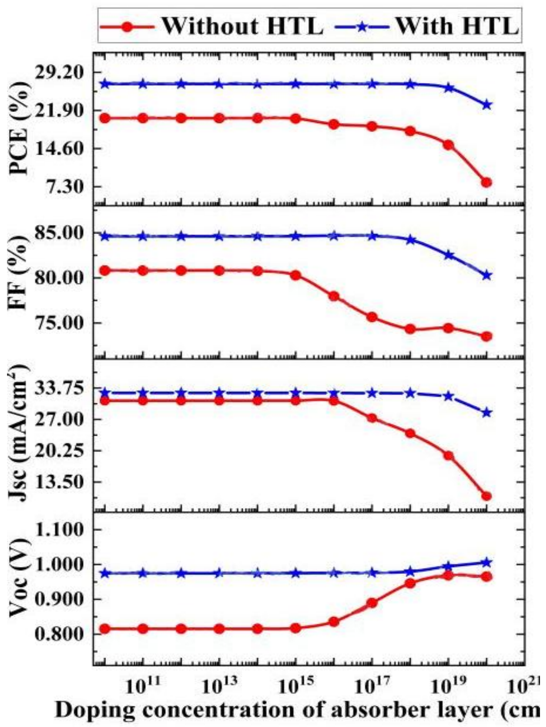
Depending on the lower thickness of absorber layer 300 nm and lower doping concentration $10^{15}cm^{-3}$,are used to improve the efficiency and reducing manufacturing costs of solar cell. Therefore, the SnS-based heterostructure solar cell achieved high efficiency of with and without Cu_2O HTL layer.

5.3 Effects of Different Thickness, Carrier Density and Defect of SnS Layer

In the structure of (Al/ITO/CeO_2/SnS/Cu_2O/Ni) SC, the SnS as an absorber layer of thickness, doping concentration and defects are the key conducting parameters. These influence both the acquisition and production of photo-generators. In proportion to the depth of the SnS layer, carrier production and rates of regeneration rise. The characteristics of the remaining layers were retained held constant to investigate the effects of SnS layer thickness and doping density on solar efficiency metrics of our proposed cells. To gain significant cell performance of the SnS layer is necessary to optimize defects, charge density and thickness. Analyzing the cell efficiency, the thickness of SnS layer from 100nm to 1200 nm and carrier density from 10^{10} to 10^{21} cm^{-3} are depicted in Figure 5.1 (a) and Figure 5.1 (b). When the thickness rises from 100nm to 1200nm, the Voc is decreased. In SnS layer the thickness of 300nm and doping concentration 10^{15} cm^{-3}, we get optimized value of Voc is 0.975 V, Jsc is 32.72 m/cm^2, FF is 84.63% and PCE is 27% using Cu_2O HTL. The impact of defect varied from 10^{10} to 10^{21} cm^{-3}, with and without HTL layer are shown in Figure 5.1 (c). When the defect varies from 10^{10} to 10^{21} cm^{-3}, the Voc, Jsc ,FF and PCE decreases. In 10^{14} cm^{-3} the defect gets better efficiency of 27% SnS absorber layer with Cu_2O HTL. Without Cu_2O HTL, the Voc, Jsc, FF and PCE are obtained 0.817 V, 31.00 mA/cm^2, 80.27%, 20.34% respectively. When the defect is > 10^{14} cm^{-3}, the Voc, Jsc, FF and PCE rapidly decrease.



a)



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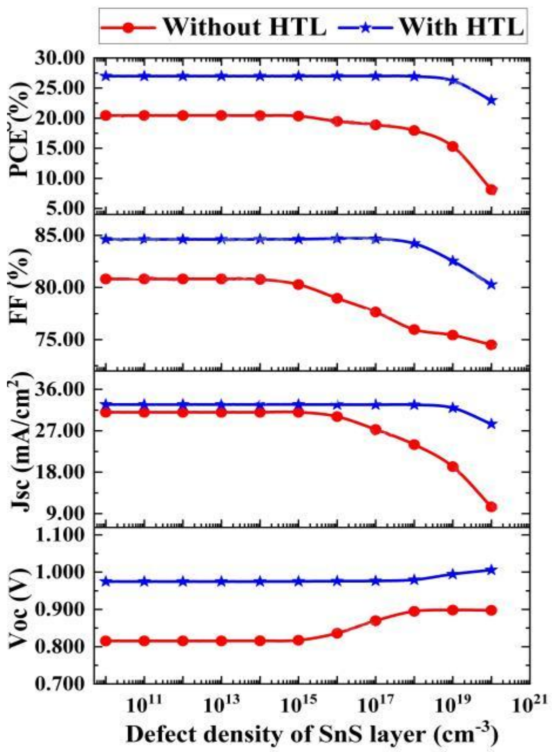


c)

Figure. 5.1: Different cell performance properties due to changes in the a) Thickness b) Doping concentration c) Defect density of the SnS layer.

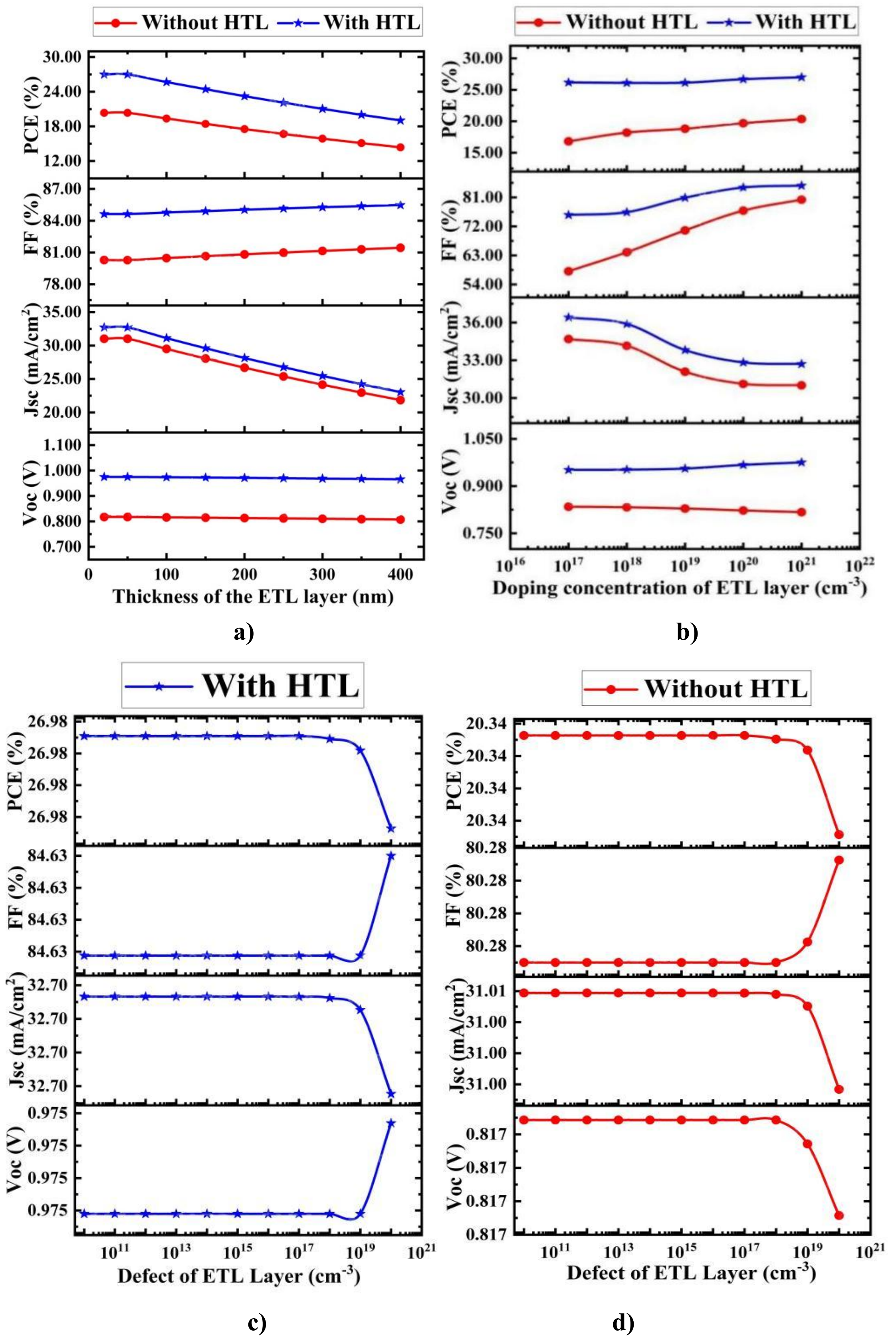
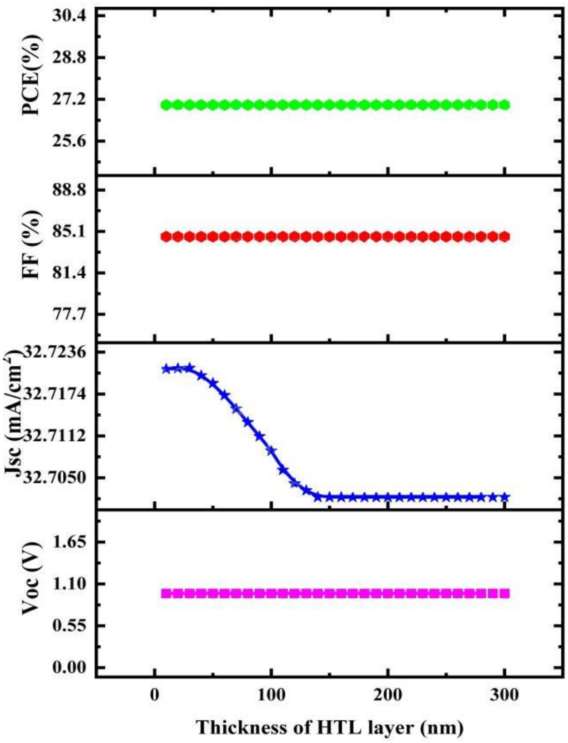
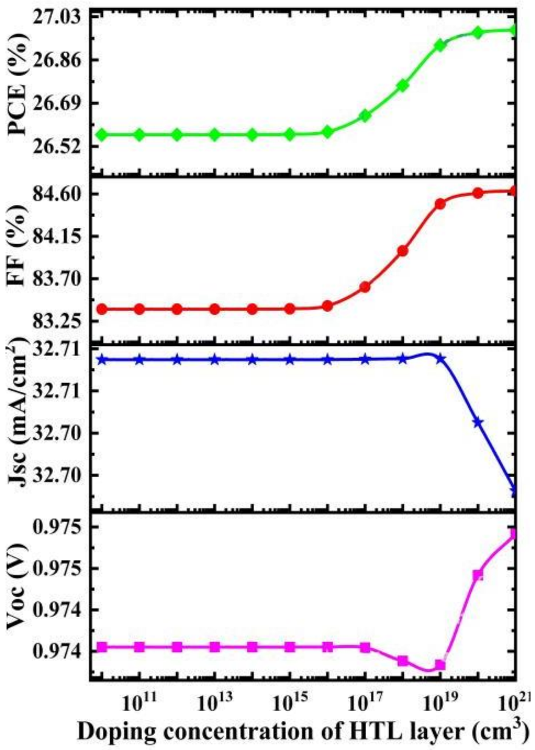


Figure. 5.2: Different cell performance properties due to changes in the a) Thickness b) Doping concentration c) with and d) without defect of the CeO_2 ETL.



a)



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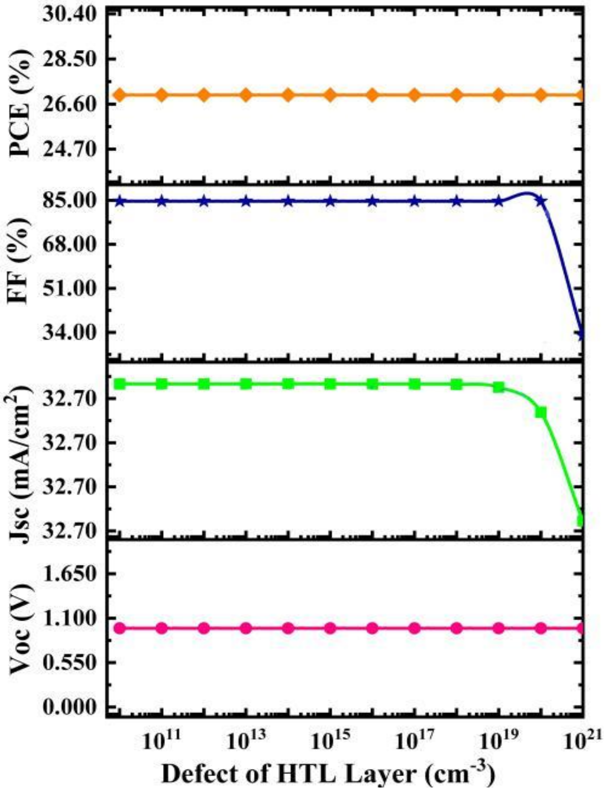


c)

Figure. 5.3: Different cell performance properties due to changes in the a) Thickness b) Doping concentration c) Defect of the Cu_2O HTL.

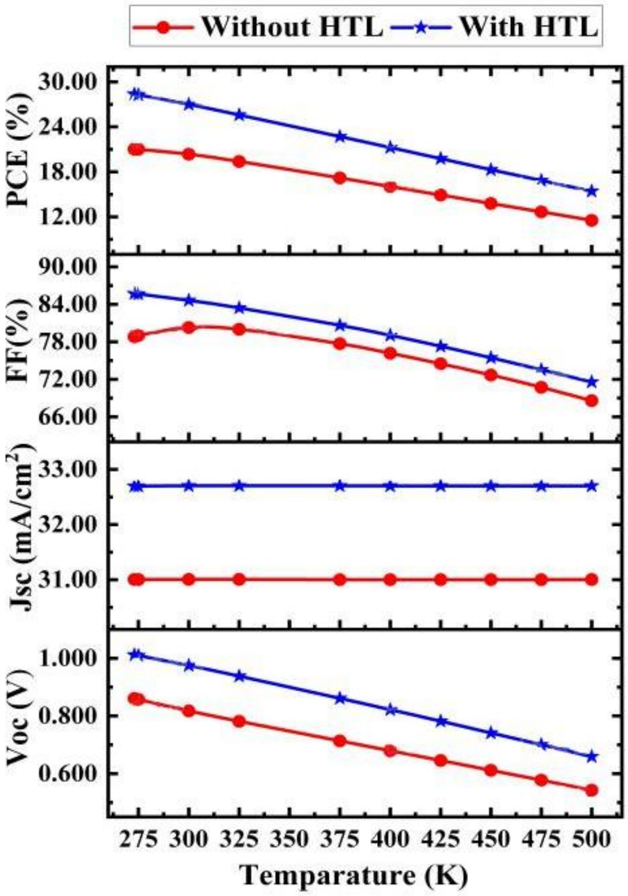
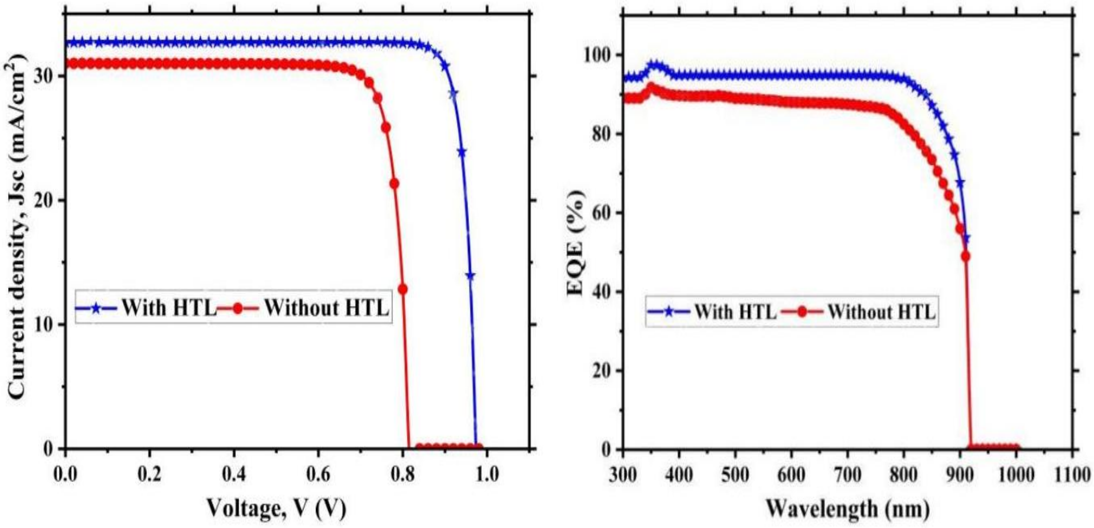


Figure. 5.4. Working temperature of SnS based solar cell with and without Cu_2O HTL layer.



a) **b)**

Figure. 5.5. a) J−V curve and b) QE characteristics of SnS based solar cell with andwithout Cu_2O HTL.

5.4 Effect of Thickness, Carrier Density and Defect of CeO_2 ETL

When the thickness of the buffer layer varies, the photovoltaic characteristics of the SnS-based heterojunction solar cell with and without HTL are altered. It varies in thickness from 20 to 400 nm. As shown in Figure 5.2 (a), all the other Solar metrics are somewhat decreased when the thickness of the CeO_2 is raised, whether the BSF design has been present or not. Figure 5.2 (b) shows the evaluation of the effect of CeO_2 ETL carrier density on solar characteristics. According to our research, most Solar metrics start to improve at a doping density of 10^{21} cm-^{3} for designs with ETL. As shown in Figure 5.2 (c), 5.2 (d), the defect of CeO_2 has increased from 10^{12} to 10^{18} cm^3 while the defect density kept constant at 10^{14} cm^{-3}.

5.5 Effect of Thickness, Carrier Density and Defect of Cu_2O HTL

For researching the effect on system functionality, the thickness of Cu_2O layer changed from 10 to 300 nm and carrier concentration of 10^{10} to 10^{21} cm^{-3} illustrated in Figure 5.3 (a) and Figure 5.3 (b). The doping density of Cu_2O has been examined with respect to thickness of 30 nm at 10^{21} cm^{-3} acceptor carrier density. For Cu_2O HTL layer, the optimum thickness 30nm calculated the value of Voc, Jsc, FF and PCE are found 0.975 V, 32.702 mA/cm^2, 84.63%, 27% at doping density 10^{21} cm^{-3}, and defect at 10^{14} cm^{-3}. When the carrier concentration are increases from 10^{10} to 10^{21} cm^{-3} the Voc, Jsc, FF and PCE are increases. In Figure 5.3 (c), the defect density also influences the efficiency of Cu_2O HTL layer which is greater than 10^{14} cm^{-3}.

5.6 Impact of Temperature on the Proposed Solar Cell

The heterostructure (Al/ITO/CeO_2/SnS/Cu_2O/Ni) solar cell operating temperature with and without Cu_2O HTL has been controlled to ensure stability are found in the following Figure 5.4 The length of the energy gap decreases when the temperature of a solar cell increases, which causes a slight rise in J_{SC}. As a response, the V_{OC} of the solar cells would be decreased. At higher temperatures, the solar cells FF and PCE decrease because of a decrease of V_{OC} and a negligible increase in J_{SC}.

5.7 Performance of the Proposed Structure

The efficient SnS-based solar cells computed Current Voltage (JV) and Quantum Efficiency (EQE) curves with and without HTL are depicted in Figure 5.5 (a) and 5.5 (b). The hetero-structure Al/ITO/CeO_2/SnS/Cu_2O/Ni solar cell values obtained for the value of V_{OC}, J_{SC} are 0.975 V, 32.72 mA/cm^2. Without Cu_2O HTL layer the heterojunction (Al/ITO/CeO_2/SnS/Ni) solar cell calculated the results of Voc is 0.817 V, J_{SC} is 31.00 mA/cm^2. The designed solar cell reduces photo−carrier regeneration and improves the edge of absorption at longer wavelength ranges, which enhances the solar cells efficiency. Hence, the insertion of the Cu_2O HTL in the heterostructure importantly enhances voltage as well as current. Therefore, the use of Cu_2O HTL layer provides better power convergence efficiency of SC.

5.8 Summary

To improve the efficiency of a Cu_2O HTL-based SnS-based heterostructure solar panel, this is then followed by more discussions. And the results are also simulated in this chapter.

Chapter 6

Conclusion

The heterostructure solar cell provides high efficiency with low cost. In this simulation analysis, SCAPS-1D was used to compare the performance characteristics of our proposed SnS-based (Al/ITO/CeO_2/SnS/Cu_2O/Ni) SC, with and without an Cu_2O HTL layer. As an electron transport layer material, CeO_2 with the optimal thickness has been utilized rather than the traditional and hazardous cadmium sulfide (CdS). The Cu_2O HTL layer, SnS absorber layer, and CeO_2 ETL layer have been selected to optimum thicknesses of 30nm, 300nm, and 20 nm, correspondingly. The proposed (Al/ITO/CeO_2/SnS/Cu_2O/Ni) SnS-based heterojunction SC with Cu_2O HTL layer has been calculated the value of PCE, V_{OC}, J_{SC}, and FF were 27%, 0.975 V, 32.72 mA/cm^2, 84.63% respectively. The lower thickness of 30nm and doping density of 10^{21} cm^{-3} of Cu_2O HTL layer provides lower fabrication expenses and better efficiency. The efficiency of solar energy is more useful to generate power for practical applications such as industries, traffic lights, remote communication and other public infrastructure. This study offers direction for the cost−effective development of a more efficient SnS-based solar cell. SnS is a potential thin-film solar-cell semiconductor made up of plentiful reliable components with the right optical characteristics for photovoltaic use. Currently developed multifunctional high-efficiency solar cells have conversion efficiencies that are noticeably greater than single-junction photovoltaic cells. Because unopened SnS normally shows p-type electrical conduction, heterojunction arrangements containing p-type SnS as well as n-type semiconductors have been used in SnS solar cells.

In heterostructure photovoltaic panels with a straight p-i-n structure, we have included Cu_2O as a hole-transport material. As a result of Cu_2O inclusion in a direct-structured heterostructure photovoltaic cell, these characteristics demonstrated that the increased efficiency in (Al/ITO/CeO_2/SnS/Cu_2O/Ni) cells was caused by lower series resistance, high shunt resistance, and poor ideality factor. By reviewing the existing situation and upcoming work on the creation of exceptionally efficient multi-junction SnS solar cells, we bring the essay to a close. It is essential that the band gap can be tuned if SnS is to be used in heterojunction photovoltaic cells. The energy range of 0.9-1.6 eV can be controlled for the band gap fluctuation of the solid state of SnS with compounds that are associated. Making a solid solution containing SnS with various chalcogenides may also allow for band gap management. To increase the conversion of heterojunction devices, future research should look at the carrier type regulation of the perovskite, multijunction, homojunctions and tandem solar cell.

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APPENDIX DETAILS

Software

There are two programs utilized in this thesis work. These are SCAPS-1D 3307 simulation 2018 and OriginPro 2023 package.

SCAPS-1D 3307 simulation

SCAPS is a 1-dimensional simulation program that uses the Poisson's equation, continuity equations for the electron and hole, and spectrum response Quantum Efficiency to determine energy bands, current-voltage characteristics, and quantum efficiency. The device is modeled using SCAPS, which is utilized to examine solar information such short circuit current density (J_{SC}), open-circuit voltage (V_{OC}), fill factor (FF), and power conversion efficiency (PCE).

Design Procedure

The design procedure of SCAPS-1D 3307 simulation 2018 has been given below:

At the beginning opening the SCAPS 1D software

↓

Open action panel (Setting standard parameter)

↓

Set problem

↓

Add layer

↓

(I) Parameter input

↓

Layer 1 - Cu_2O HTL (30 nm)

↓

Layer 2 - SnS absorber layer (300 nm)

↓

Layer 3 - Ce_2O ETL (20 nm)

↓

Layer 4 - ITO (10 nm)

↓

(II) Add interface layer

↓

Cu_2O/SnS Layer

↓

SnS/CeO_2 Layer

↓

Setting light mode on

↓

Select I-V/Q-E

↓

Calculating single shot

↓

Energy band panel

↓

Show Data

↓

Data extraction

Software 2

Origin® and OriginPro® 2023 have been released, according to OriginLab, a well-known producer of analysis of data and graphical tools. The most recent edition of OriginLab's acclaimed software program includes more than 100 new features and enhancements in addition to several brand-new Applications that expand Origin's graphing and analytical features.

Working Procedure

At the beginning, opening the OroginPro software (version 2023)

↓

Setting the environment to add a new column

↓

Data Input

↓

Select data to plotting

↓

Multi-panel plot

↓

Stack graph

↓

Setting and scaling graph

↓

Export graph