Fabrication and Characterization of Thermally Grown $MoSe_2$ Thin Film Based Broadband Photodetectors

**Thesis submitted in partial fulfillment
for the Award of Degree**

DOCTOR OF PHILOSOPHY

BY

SHIKHA SINGH

**DEPARTMENT OF ELECTRONICS ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI-221005, INDIA**

ROLL NO. 19091004 **2025**

Dedicated to my L'll Angels

Sadhvi

&

Janhvi

Dedicated to my L'll Angels

Sadhvi

&

Janhvi

CERTIFICATE

It is to certify that the thesis titled "***Fabrication and Characterization of Thermally Grown $MoSe_2$ Thin Film Based Broadband Photodetector***" being submitted by "***Shikha Singh***" to the Indian Institute of Technology (Banaras Hindu University) Varanasi, for the award of the Degree of Doctor of Philosophy (Ph.D.) in the Department of Electronics Engineering is a record of bonafide research work carried out absolutely by her under my supervision and that this work has not been submitted to any other university/institute for the award of any degree or diploma.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy, and SOTA for the award of Ph.D. Degree.

Prof. Satyabrata Jit
(Supervisor)
Department of Electronics Engineering
IIT(BHU), Varanasi 221005

(Head)
Department of Engineering IIT(BHU),
Varanasi 221005

Department of Electronics Engineering
भारतीय प्रौद्योगिकी संस्थान
Indian Institute of Technology
(बनारस हिन्दू यूनिवर्सिटी)
(Banaras Hindu University)
वाराणसी/Varanasi-22

DECLARATION BY THE CANDIDATE

I, ***Shikha Singh***, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of ***Prof. Satyabrata Jit*** from ***July 2019*** to ***June 2025*** at the ***Department of Electronics Engineering, Indian Institute of Technology (BHU), Varanasi***. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma elsewhere. I declare that I have faithfully acknowledged and accredited to the research communities wherever their works have been cited in the accomplishment of this thesis. I further declare that I have not intentionally copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports, dissertations, thesis, *etc*., or available at websites and have not included them in this thesis or cited as my own work.

Date: 01/07/2025

Place: Varanasi

Signature of the Student

Shikha Singh

CERTIFICATE BY THE SUPERVISORS

It is certified that the above statement made by the student is correct to the best of my knowledge.

Prof. Satyabrata Jit
(Supervisor)
Department of Electronics Engineering
IIT(BHU), Varanasi 221005

(Head)
Department of Electronics Engineering
IIT(BHU), Varanasi 221005

Department of Electronics Engineering
भारतीय प्रौद्योगिकी संस्थान
Indian Institute of Technology
(बनारस हिन्दू यूनिवर्सिटी)
(Banaras Hindu University)
वाराणसी/Varanasi-221005

01/07/25

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: Fabrication and Characterization of Thermally Grown $MoSe_2$ Thin Film Based Broadband Photodetector.

Name of the Student: Shikha Singh

COPYRIGHT TRANSFER

Date: 01/07/2025

Place: Varanasi

Signature of the Student

Shikha Singh

ACKNOWLEDGEMENT

I want to start by bowing my head before the Almighty for a beautiful life and blessings. First and foremost, I would like to acknowledge my deepest gratitude to Bharat Ratna, Mahamana Pt. Madan Mohan Malviya, the founder of Banaras Hindu University, for his magnificent vision and tireless efforts to provide us such a great education institute.

This thesis is a reflection of the collective effort of many people, and I feel honoured to have been supported by such amazing people. I would like to take this opportunity to express my profound gratitude to individuals who have provided me support, guidance, and assistance throughout my research journey. It was an amazing journey accompanied by encouragement, hardship, learning, bitterness, frustration and faith.

It is indeed my proud privilege to express my deep sense of gratitude and indebtedness to my research supervisor Prof. Satyabarata Jit (Professor, Department of Electronics Engineering, IIT (BHU) Varanasi), who has given me this opportunity to work under his guidance and supported me throughout my research activities. I am very thankful to him for his consistent inspiring words and critical guidance, which motivated me toward my intended conclusion. His dynamic personality, hard work, sincerity, and utmost care kept me motivated and on the right track towards my research objective. It is wholeheartedly appreciated that his immense knowledge, great suggestions and research advice proved monumental towards the success of the present study.

I want to thank the Head of the Department of Electronics Engineering, IIT (BHU), and the Central Instrument Facility (CIF) at IIT (BHU), for providing me all the necessary research facilities, and various characterization facilities required for my research work. I am extremely indebted to my research performance evaluation committee (RPEC) members, Dr. Amritanshu Pandey and Dr. Bhola Nath Pal, for their encouragement and insightful comments. Further, I would also like to thank all the faculty members for their kind cooperation and encouragement during this journey.

I humbly thank all CRME lab staff, Department of Electronics Engineering, especially Mr. Sanjeev Srivastava, Mr. Lal Bahadur, Mr. V. K. Singh, and Mr.Shyam Narayan, where I have completed my major research work, for providing me kind cooperation and support for fabrication experiments. I am grateful to all the Lab technical staff, Departmental library staff, non-teaching staff, and MTS for their kind support throughout my research period.

I would also like to acknowledge the administration of IIT BHU, Shreenivas Deshpande Library, Gymkhana, Health Centre, Sir Sunder Lal Hospital, Malviya Bhawan, Proctor Office, GRTA office and Canteen for helping me in various forms during my stay in campus.

I would like to express my sincerest regards and love for my parents Shree Rajendra Bahadur Singh and Smt. Reena Singh, for their constant support, love and blessings throughout my life. I will always be in debt, no matter what I do, and I will always be your reflection. My most profound appreciation goes to my siblings Mr. Manvendra Singh and Mr. Mrityunjay Singh for their encouragement, support and love throughout my life.

I would also like to express my profound gratitude to my dear friend Dr. *(late)* Avinash Paliwal who has been a foundation pillar of my research journey. His encouragement, guidance and kind supportive approach provided me strength and confidence to step into in the field of research.

I would like to express my sincere gratitude towards my husband Mr. Shivram Singh for his support, patience and understanding during my research journey. Also, I am thankful to my in-laws Mr. Pushparaj Singh and Mrs. Gayatri Singh for their kind support and blessings.

I am grateful to all my seniors, Dr. Chandan Kumar, Dr. Amit Kumar, Dr. Deepak Kumar Jarwal, Dr. Kamalaksha Baral, Dr. Ashwini Kumar Mishra, Dr. Rishibrind Kumar Upadhyay, Dr. Deepchandra Upadhyay, Dr. Ashish Kumar Singh, and Dr. Vijaya Kumar Devarakonda, for their support and valuable suggestions.

I would like to express my special thanks to my seniors Dr. Abhinav Pratap Singh and Dr. Jogendra Singh Rana for their constant support and suggestions in analysing all the technical stuff. I would also like to thank Dr. Prashant Kumar, Dr. Varun Kumar Singh and Dr. Ankit Verma for providing a healthy environment to carryout my research work and open to discussions ranging. I am also thankful to Mr. Harshit Shrivastava and Mrs. Richa Baranwal for their encouragement and friendly suggestions.

Above all, I thank Bhagwan Shree Kashi Vishwanath for giving me the strength, knowledge, ability, and opportunity to undertake this research study and to complete it satisfactorily. Without their blessings, this achievement would not have been possible.

At last, I would like to thank everyone, whose name may not be here, but who helped me directly or indirectly in making this thesis work success.

(Shikha Singh)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Details
APD	Avalanche Photodiode
AFM	Atomic Force microscopy
ALD	Atomic Layer Deposition
CQD	Colloidal Quantum Dot
CVD	Chemical Vapor Deposition
DI	De-ionized
EQE	External Quantum Efficiency
2 D	Two-dimentional
FETs	Field-Effect Transistors
FWHM	Full-width-at-half-maximum
ITO	Indium doped Tin Oxide
LPE	Liquid Phase Exfoliation
NIR	Near Infrared
NRs	Nanorods
NDIR	Non-Dispersive Infrared Spectroscopy
MoS2	Molybdenum disulphite
MoSe2	Molybdenum diselenide
MSM	Metal-Semiconductor-Metal
MOCVD	Metal Organic Chemical Vapor Deposition
MBE	Molecular Beam Epitaxy
OLED	Organic Light Emitting Diode
OCT	Optical Coherence Tomography
SAED	Selected Area Electron Diffraction
SMU	Source and Measuring Unit
TMDs	Transition Metal Dichalcogenides
TEM	Transmission electron microscopy
TFT	Thin Film Transistor
WS2	Tungstun disulphide
WSe2	Tunstun diselenide
WDM	Wavelength Division Multiplexing
UV-Vis	Ultraviolet-Visible
VLC	Visible Light Communication
VTD	Vacuum Thermal Deposition
XRD	X-ray Diffraction
XPS	X-ray Photoelectron Spectroscopy
ZnO	Zinc Oxide

LIST OF SYMBOLS

Symbol	Abbreviation
A_{eff}	Effective area of the device
Al	Aluminium
Ag	Silver
E_g	Energy Bandgap
E_{ph}	Photon Energy
E_C	Bottom of the Conduction Band
E_V	Bottom of the Valence Band
α	Absorption Coefficient
β	Band tailing parameter
h	Plancks constant
v	Frequency
c	Velocity of light
e	Electron charge
f_{3-dB}	3-db bandwidth
I_{dark}	Current Under Dark Condition
I_{light}	Current Under Illumination Condition
I_{ph}	Photocurrent
J_d	Dark current density
E_F	Fermi Energy Level
P_{opt}	Incident Optical Power
t_r	Rise time
t_f	Fall time
R	Responsivity
D^*	Specific Detectivity
λ	Wavelength
ϕ_M	Metal work function
ϕ_S	Semiconductor work function

PREFACE

The interest in Transition Metal Dichalcogenides (TMDs) has increased rapidly in past couple of years for optoelectronic applications. Soon after the advent of graphene, the first 2D material Research and Development (R&D) community motivated researchers to explore other alternative 2D materials due to their scalability and thickness dependent optical and electrical properties. Their indirect semiconducting nature in bulk changes as direct semiconductor when layered down to monolayer and this ensues due its weak van-der-Waals interactions between layers.

In the past couple of years, 2D materials based photo-detectors have been intensively investigated. The huge light absorption and ultrathin thickness make them potential candidate for broadband, highly sensitive, and flexible photodetection. As compared to Graphene, TMDs have larger bandgap including MoS_2 and $MoSe_2$, hence, can have significantly longer carrier lifetimes, which make them strong contenders for realizing highly sensitive photodetectors. Though $MoSe_2$ is comparively less explored material than MoS_2 in the TMDs family but have several advantages over latter such as higher electrical conductivity and light absorption capacity, higher carrier mobility, superior photodetection responsivity, fast response times.

The present thesis consists of work carried out for fabrication and characterization of thermally grown $MoSe_2$ thin film based broadband photodetectors. This thesis is divided into five chapters which are briefly outlined below.

Chapter 1 covers basic introduction to photodetectors, their classification based on structures and spectal response, their key parameters, selection of material for photodetection. It also provides basic introduction to Transition Metal Dichalcogenides (TMDs), their optoelectronic properties and different methods for synthesis and fabrication of TMDs along with the brief description of the instruments used for device fabrication and characterization. At the end of the chapter, a brief literature review is carried out to define the scope of the present thesis work.

In **Chapter 2,** an Ag/$MoSe_2$ thin film/Ag structure based metal-semiconductor-metal (MSM) broadband photodetector fabricated on SiO_2 coated Si substrate is reported. The nano-powder synthesized by the hydrothermal route was used for fabricating $MoSe_2$ thin film by thermal evaporation technique. The interdigitated Ag Schottky contacts were fabricated on the $MoSe_2$ film by thermal evaporation method to obtain the desired structure. The fabricated device showed the maximum responsivity, specific detectivity and external quantum efficiency (EQE) of ~50 mA/W, ~4.5×10^{11} Jones and ~ 16% respectively at 415 nm under the applied bias voltage of 1.5 V. The fabricated device also showed fast time response with rise (fall) time as 17.76 ms (18.38 ms) at room temperature.

Chapter 3 presents fabrication and characterization of an n-$MoSe_2$/p-Si heterojunction based broadband photodetector by depositing an n-$MoSe_2$ thin film on a ⟨100⟩ p-Silicon substrate (2–5 Ω-cm resistivity) by a thermal evaporation method. The facile hydrothermal route was adopted to synthesize $MoSe_2$ powder. The photoresponse of the fabricated device was measured at room temperature using monochromatic light of 300–1100 nm wavelengths. The maximum responsivity, specific detectivity, and external quantum efficiency (EQE) of the fabricated device were obtained as 316.25 mA/W, 1.54×10^{11} Jones, and ~45%, respectively, at 890 nm with the applied reverse bias voltage of 2 V. The rise time and fall time of the device was 396 and 224 ms, respectively.

Chapter 4, explores an ITO/n-ZnO CQDs/n-$MoSe_2$/ Ag structure based high performance ultraviolet-visible (UV-Vis) broadband photodetector where the n-n heterojunction between ZnO colloidal quantum dots (CQDs) and $MoSe_2$ thin film fabricated on an Indium tin oxide (ITO) coated glass substrate forms the active region of the device. The ZnO CQDs synthesized by hot-injection method was spin-coated on the substrate while $MoSe_2$ nanopowder synthesized by hydrothermal method was deposited on the ZnO CQDs layer by thermal evaporation method to obtain the ZnO CQDs/$MoSe_2$ heterojunction. The heterojunction showed a broad absorption spectrum covering the UV-Vis region. Under applied bias voltage of 2 V, the proposed photodetector showed the maximum responsivity (R) of ~282 A/W, specific detectivity (D) of $\sim 9\times10^{12}$ Jones and external quantum efficiency (EQE) of ~90000% at 380 nm in the UV region whereas R ~16.15 A/W, D ~ 5.37×10^{11} Jones, EQE ~3660% were measured at 550 nm in the visible region. The transient response analysis of the device measured at room temperature showed a rise time (fall time) as 7.25 sec (2.25 sec) at 380 nm and 1.2 sec (2.2 sec) at 550 nm.

In **Chapter 5**, the thesis concludes with the significant contribution and summary of the results achieved in this research work. This chapter also contains the future scope of the thesis work present in this thesis.