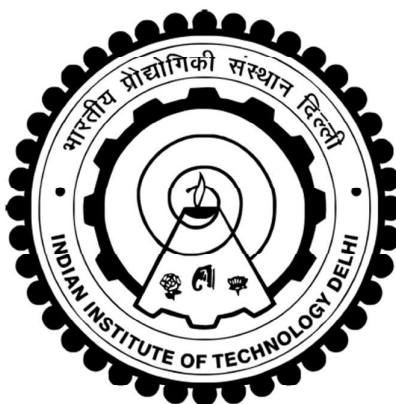


**A STUDY OF TEMPERATURE COEFFICIENT OF
RESISTANCE AND BOLOMETERIC PROPERTIES OF SOME
TRANSITION METAL DICHALCOGENIDE LAYERED
MATERIALS**

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August 2025

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BOLOMETERIC PROPERTIES OF SOME TRANSITION METAL
DICALCOGENIDE LAYERED MATERIALS**

Thesis submitted by

Shubham Saxena

in partial fulfilment of the requirements for the award of the degree of

Doctor of Philosophy



Department of Electrical Engineering

Indian Institute of Technology Delhi

August 2025

Dedicated to my caring
family

THESIS CERTIFICATE

This is to certify that the thesis titled “**A STUDY OF TEMPERATURE COEFFICIENT OF RESISTANCE AND BOLOMETERIC PROPERTIES OF SOME TRANSITION METAL DICHALCOGENIDE LAYERED MATERIALS**“, submitted by **Shubham Saxena (2018EEZ8138), Department of Electrical Engineering**, to the **Indian Institute of Technology, Delhi**, for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

Earning a doctorate has been a dream of mine which evolved slowly over the last few decades. In any field of study, a doctorate requires dedicated focused effort toward solving a research problem, involving several years of hard work. Preparation for this process starts long before one enters a graduate school. First and foremost, I would like to express my profound respect, deepest admiration and sincere thanks to both of my thesis supervisors Prof. V. Ramgopal Rao and Prof. Samaresh Das, who kept their faith in me and always enhanced my research abilities throughout the course of learning from them. Prof. Rao has devoted regular hours of discussion despite his busy schedule. The patience, breadth of knowledge, persistence, and insistence on proper scientific rigor by both of my supervisors have taught me how to conduct research work. I would like to express my sincere acknowledgment to them for introducing me to the field of two dimensional materials, synthesis and device fabrication. I got the opportunity to learn more about operating different fabrication systems like sputtering, thermal and electron beam evaporation and mask aligner and maskless lithography, reactive ion etching, vapor etcher, 3D printer etc., and would like to thank them for providing their valuable advices which are helpful in the management of research work in a Ph.D. setup. I would like to thank my research committee members Prof. Bhaskar Mitra, Prof. Madhusudan Singh, Prof. Amruta Mishra, and Prof. Rajendra Singh for their valuable periodic reviews and feedbacks. I would also like to acknowledge the staff and facility of Nanoscale Research Facility (NRF) and Central Research Facility (CRF) for providing me an opportunity of hands-on experience on various cleanroom fabrication and characterization tools including electron beam lithography. I would also like to acknowledge several colleagues in particular, Dr. Sumit Sharma, Biswajit Khan, Dr. Satish Verma, Nitish Kumar, Dr. Harmanpreet Kaur, Dr. Pawan Kumar, Dr. Aakash Kumar Jain, Dr. Amit Kumar Gupta, Dr. Veerendra Dhyani, Dr. Wasi Uddin, Mr. Prabal Dweep Khanikar, Dr. T. B. Ashagre, Dr. Sushil Kumar, Dr. Dhairya Singh Arya, Dr. Manu Garg, Mr. Mujeeb Yousuf, Mr. Suprovat Ghosh, Ms. Pinki, Mr. Khanjan Joshi, Mr. Shubham Bhatt, and Ms. Tamkeen Farooq for various technical and non-technical but fruitful and helpful discussions during the different stages of this work. I am also grateful for Prof. D. Rakshit for providing thermal camera, Prof. Anuj Dhawan and Dr Uday Dadwal for useful discussions. I am highly grateful to the Department of Electrical Engineering, CARE Department and IIT Delhi for providing me the resources to carry out my research in a timely finish of this thesis. I am also grateful for my Master's thesis adviser Prof. W. P. King and colleague Dr. Brent Nelson for teaching me the ways of conducting research activities. Last

but most importantly, I would like to thank my family members including my wife Mrs. Gunjan Raj Saxena, my mom Mrs. Raman Saxena and my dad Mr. Anil Saxena, who supported me during the ups and downs of my research work and helped me to grow up into the person that I have been fortunate to become.

ABSTRACT

Two-dimensional (2D) materials have layered structure with unique properties. One of the properties of interest is the temperature coefficient of resistance (TCR) which should be large for fast thermal sensors. The TCR is the calculation of the relative change in resistance per degree of temperature change. Taking a step further, tunable TCR is a concept that involves the control of TCR by the gate voltage. In this thesis, this concept is tested on transition metal dichalcogenide (TMD) which are composed of a transition metal (M) and two chalcogen (X) atoms (MX_2). Here M can be Molybdenum, Platinum, or Tungsten etc. and X can be Sulphur, Selenium or Tellurium etc. In this thesis, we have shown that in a field effect transistor device, three TMD 2D semiconductor materials WSe_2 , MoS_2 , and $MoSe_2$ have a TCR, which can be controlled by varying the applied gate voltage. Also, all the above mentioned TMDs have TCR which are several times higher than metallic thin films based thermal sensors.

This first three technical chapters (chapter 3-5) of this dissertation are focused on showing the higher TCR value and TCR tunability of different TMD materials and understanding the mechanism using an experimental analysis. For characterization, atomic force microscope (AFM) is used to measure flake height and Raman spectroscopy and electron probe microanalyzer is used to characterize different TMD flakes. It is shown that WSe_2 TCR could be controlled to 300% of its value within 10V of applied gate voltage and is found to have the highest value of $-8.7\%K^{-1}$ at just above the threshold voltage. Also, the magnitude of p- WSe_2 TCR is 19 times that of metallic thin films. We show that in the case of n- MoS_2 , the TCR can be varied to 60% of its value within 40 V. Also the in terms of maximum magnitude the TCR is found to be $-1.52\%K^{-1}$ at $5V\ V_g - V_t$. (adjusted threshold voltage). Also, the magnitude of n- MoS_2 TCR is 3 times that of metallic thin films. Similarly for $MoSe_2$, the TCR can be tuned to about 200% of its value for 15 nm thick flake within a gate voltage change of 7 V, with the highest recorded value being $-2.75\%K^{-1}$ which is also 5.5 times the typical metallic thin films based devices. Also, the average relative uncertainty in TCR is observed to be 3.8% for the 65 nm devices and 4.6% for the 15 nm $MoSe_2$ devices, respectively. Thus, specific high or low values of TCR can be tuned using the gate voltage for the studied three different TMD materials. This has applications in higher sensitivity bolometers, thermal sensors, and accelerometers.

The fourth technical chapter (chapter # 6) of this dissertation is focused on a flexible nanomechanical bolometer fabricated using MoS₂ and polydimethyl siloxane (PDMS), which is used to measure radiation intensity via mechanical transduction and band gap transition. The fabricated devices are used to estimate the gauge factor (GF) and absorption coefficient of the material from the valley and peak data of current-time curves. The peaks observed in the current time graph can be attributed to photocarrier generation mechanism. Valleys obtained in the current time graphs are related to the GF of the sensing matrix. The GF of 100 and absorption coefficient of $2 \times 10^6 \text{ cm}^{-1}$ is obtained for the MoS₂ on PDMS device. Also, specific detectivity of $4.95 \times 10^{11} \text{ cm Hz}^{1/2} \text{ W}^{-1}$ and responsivity of -219 V/W is obtained. The work presented here is highly encouraging for the utilization of MoS₂ & PDMS in bolometers, thermal sensors and photodetectors.

सार

द्वि-आयामी (2D) सामग्रियों में अद्वितीय गुणों के साथ परतदार संरचना होती है। दिलचस्प गुणों में से एक प्रतिरोध का तापमान गुणांक (TCR) है जो तेज़ थर्मल सेंसर के लिए बड़ा होना चाहिए। TCR तापमान परिवर्तन के प्रति डिग्री प्रतिरोध में सापेक्ष परिवर्तन की गणना है। एक कदम आगे बढ़ते हुए, ट्यूनेबल TCR एक अवधारणा है जिसमें गेट वोल्टेज द्वारा TCR का नियंत्रण शामिल है। इस थीसिस में, इस अवधारणा का परीक्षण संक्रमण धातु डाइचेलकोजेनाइड (TMD) पर किया गया है जो एक संक्रमण धातु (M) और दो चाकोजेन (X) परमाणुओं (MX₂) से बना है। यहाँ M मोलिब्डेनम, प्लैटिनम या टंगस्टन आदि हो सकता है और X सल्फर, सेलेनियम या टेल्यूरियम आदि हो सकता है। इस थीसिस में, हमने दिखाया है कि एक फील्ड इफ़ेक्ट ट्रांजिस्टर डिवाइस में, तीन TMD 2D सेमीकंडक्टर मटेरियल WSe₂, MoS₂ और MoSe₂ में एक TCR है, जिसे लागू गेट वोल्टेज को बदलकर नियंत्रित किया जा सकता है। साथ ही, ऊपर वर्णित सभी टीएमडी में टीसीआर है जो धातु की पतली फिल्म आधारित थर्मल सेंसर की तुलना में कई गुना अधिक है। इस शोध प्रबंध के पहले तीन तकनीकी अध्याय विभिन्न टीएमडी सामग्रियों के उच्च टीसीआर मूल्य और टीसीआर ट्यूनेबिलिटी को दिखाने और गुणात्मक विश्लेषणात्मक मॉडल का उपयोग करके तंत्र को समझने पर केंद्रित हैं। लक्षण वर्णन के लिए, एएफएम का उपयोग फ्लेक की ऊंचाई को मापने के लिए किया जाता है और विभिन्न टीएमडी फ्लेक्स को चिह्नित करने के लिए रमन स्पेक्ट्रोस्कोपी और इलेक्ट्रॉन जांच माइक्रोएनालाइजर का उपयोग किया जाता है। यह दिखाया गया है कि WSe₂ TCR को लागू गेट वोल्टेज के 10V के भीतर इसके मूल्य के 300% तक नियंत्रित किया जा सकता है और थ्रेसहोल्ड वोल्टेज से ठीक ऊपर -8.7% K⁻¹ का उच्चतम मूल्य पाया जाता है। साथ ही, p-WSe₂ TCR का परिमाण धातु की पतली फिल्मों से 19 गुना है इसके अलावा, n-MoS₂ TCR का परिमाण धातु की पतली फिल्मों से 3 गुना है। इसी तरह MoSe₂ के लिए, TCR को 7 V के गेट वोल्टेज परिवर्तन के भीतर 15 एनएम मोटी परत के लिए इसके मूल्य के लगभग 200% तक ट्यून किया जा सकता है, जिसमें उच्चतम दर्ज मूल्य -2.75% K⁻¹ है जो कि सामान्य धातु की पतली फिल्मों पर आधारित उपकरणों से 5.5 गुना अधिक है। TCR डेटा के आधार पर एक गतिशीलता मॉडल भी प्रस्तावित किया गया है। इसका उपयोग इष्टतम TCR बोलोमीटर, थर्मिस्टर और थर्मल सेंसर डिजाइन करने के लिए किया जा सकता है। इस प्रकार, तीन अलग-अलग TMD सामग्रियों के लिए गेट वोल्टेज का उपयोग करके TCR के विशिष्ट उच्च मूल्यों को ट्यून किया जा सकता है। इसके उच्च संवेदनशीलता वाले बोलोमीटर, थर्मल सेंसर और एक्सेलेरोमीटर में अनुप्रयोग हैं। इस शोध प्रबंध का चौथा तकनीकी अध्याय MoS₂ और पॉलीडिमिथाइल सिलोक्सेन (PDMS) का उपयोग करके निर्मित एक लचीले नैनोमैकेनिकल बोलोमीटर

पर केंद्रित है, जिसका उपयोग मैकेनिकल ट्रांसडक्शन और बैंड गैप संक्रमण के माध्यम से विकिरण की तीव्रता को मापने के लिए किया जाता है। निर्मित उपकरणों का उपयोग वर्तमान समय वक्रों के घाटी और शिखर डेटा से सामग्री के गेज कारक (GF) और अवशोषण गुणांक का अनुमान लगाने के लिए किया जाता है। वर्तमान समय ग्राफ में देखे गए शिखरों को फोटोकैरियर जनरेशन मैकेनिज्म के लिए जिम्मेदार ठहराया जा सकता है। वर्तमान समय ग्राफ में प्राप्त घाटियाँ सेंसिंग मैट्रिक्स के GF से संबंधित हैं। PDMS डिवाइस पर MoS_2 के लिए 100 का GF और $2 \times 10^6 \text{ cm}^{-1}$ का अवशोषण गुणांक प्राप्त किया जाता है। यहाँ प्रस्तुत कार्य बोलोमीटर, थर्मल सेंसर और फोटोडिटेक्टर में MoS_2 और PDMS के उपयोग के लिए अत्यधिक उत्साहजनक है।

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ABBREVIATIONS

AFM Atomic force microscope

CVD Chemical vapor deposition

PVD Physical vapor deposition

CARE Center for applied research in electronics

FET Field effect transistor

IITD Indian Institute of Technology, Delhi

VDW Van der Waals

PDMS Polydimethyl siloxane

SEM Scanning electron microscope

TMDC/TMD Transition metal dichalcogenide

EPMA Electron probe microanalyzer

RTD Resistance Thermal Detectors

TCR Temperature coefficient of resistance

NTCR Negative temperature coefficient of resistance

CI Charge Impurity

NOTATION

r Radius, m

α Temperature coefficient of resistance

μ mobility

ϵ_0 permittivity of vacuum

ϵ_r relative permittivity

n number of carriers

C_{ox} oxide capacitance of the silicon dioxide dielectric layer

e the electronic charge (1.6×10^{-19} C),

V_g the gate voltage

V_t the threshold voltage

ζ change in threshold voltage w.r.t. V_g

t Silicon dioxide layer thickness

R_T Channel electrical resistance at temperature T

R_0 Channel electrical resistance at reference temperature 300K

T Temperature

γ is absorption coefficient,

$\hbar$ is the reduced Plank's constant,

ω is the frequency of the radiation,

Q_e average number of electron-hole pairs produced from one photon

G_e number of generated pairs of electron & holes

P_l total light intensity

P_0 light intensity at the surface

R Channel electrical resistance

π gauge factor

Δ change in associated quantity