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

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Thesis submitted by

Shubham Saxena

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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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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 MoS_2 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 $2x10^6$ cm^{-1} is obtained for the MoS_2 on PDMS device. Also, specific detectivity of 4.95 $x10^{11}$ cm $Hz^{1/2}$ W^{-1} and responsivity of -219 V/W is obtained. The work presented here is highly encouraging for the utilization of MoS_2 & 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 मटीरियल WSe_2, MoS_2 और $MoSe_2$ 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 WSe_2 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-WSe_2 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 $MoSe_2$ 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 MoS_2 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 2x106 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 ($1.6\text{x}10^{-19}$ 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,

ħ 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

Pl total light intensity

P_0 light intensity at the surface

R Channel electrical resistance

π gauge factor

Δ change in associated quantity