LOW-DIMENSIONAL SILICON AND LAYERED TRANSITION METAL DICHALCOGENIDES FOR TERAHERTZ DETECTORS AND MODULATORS

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Submitted

in fulfillment of the requirements for the degree of Doctor of philosophy

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Dedicated to my
Family

CERTIFICATE

This is to certify that the thesis entitled, **"LOW-DIMENSIONAL SILICON AND LAYERED TRANSITION METAL DICHALCOGENIDES FOR TERAHERTZ DETECTORS AND MODULATORS"** being submitted by **Ms. ALKA JAKHAR** to the Indian Institute of Technology Delhi for the award of the degree of "**Doctor of Philosophy"** is a record of bonafide research work carried out by her under my guidance and supervision.

In my opinion, the thesis has reached the standard of fulfilling the requirement of all the regulations regarding the degree. The results contained in this thesis have not been submitted, in part or in full, to any other university or institute to award any degree or diploma.

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Abstract

The terahertz (THz) technology has been experienced rapid advancement in numerous potential applications in the last few years. This includes imaging, communication, material spectroscopy, security, and the bio-medical field. The THz devices and other components operating in the related frequency range are a prerequisite to harness the full potential of THz waves. The current state-of-the-art detectors such as Schottky diodes, field-effect transistors, photoconductive antennas show limited performance in terms of responsivity, bandwidth, and sensitivity. On the other side, the requirement of high modulation depth under low pumping power, broad-band frequency response, high speed, and small insertion losses is driving research to achieve effective modulation in optically controlled THz modulators. To address these aforementioned limitations, the thesis focuses on developing room temperature-operated detectors and modulators working in the THz frequency band. The THz modulators and detectors based on low-dimensional silicon (silicon nanowire) and layered transition metal dichalcogenides (TMDs) are addressed.

In the first part of the thesis, the single silicon nanowire (NW) based junctionless field-effect transistor (FET) has been demonstrated as a THz detector. The maximum responsivity is observed around 0.425 THz, with a peak value of 468 V/W. The complementary metal-oxide-semiconductor compatibility, ease of integration on chips, possibility to realize multiple pixel arrays, and scalability to higher frequencies make these devices promising for THz electronics. Further, another class of THz detector employing type-II topological Dirac semimetal Platinum telluride ($PtTe_2$) has been manifested in the 0.1-1.5 THz frequency range. The maximum responsivity of 23.6 A/W is obtained at 0.2 THz on account of the photo-galvanic effect. These detectors have promising properties, i.e., broadband response, zero-biased operation, high and linear responsivity compared to existing devices.

In the next part of this thesis, the broadband optical THz modulators based on the new class of TMDs such as Platinum diselenide ($PtSe_2$), Tantalum disulfide (TaS_2), and Molybdenum disulfide (MoS_2) have been demonstrated. The TMDs materials are grown on the silicon substrate by direct sulfurization/selenization of the different sputtered metal films. The TMDs have been incorporated in the optical-controlled semiconductor-based THz modulators to improve modulation efficiency in modulation depth (~ 80%) and speed (response time in microseconds). The high modulation depth (at low pumping power) and speed, inexpensive and straightforward fabrication process, broad frequency response (0.1-1 THz), and small insertion losses are the key attributes of these presented optical THz modulators. This work unfolds possibilities for utilizing different layered TMDs in THz imaging, wireless communication, spectroscopy, and security systems.

सार

टेराहर्ट्ज़ (THz) तकनीक को पिछले कुछ वर्षों में कई संभावित अनुप्रयोगों में तेजी से प्रगति का अनुभव किया गया है। इसमें इमेजिंग, संचार, सामग्री स्पेक्ट्रोस्कोपी, सुरक्षा और जैव-चिकित्सा क्षेत्र शामिल हैं। THz डिवाइस और संबंधित फ़्रीक्वेंसी रेंज में काम करने वाले अन्य घटक THz तरंगों की पूरी क्षमता का दोहन करने के लिए एक पूर्वापेक्षा हैं। वर्तमान अत्याधुनिक डिटेक्टर जैसे शोट्की डायोड, फील्ड-इफेक्ट ट्रांजिस्टर, फोटोकॉन्डक्टिव एंटेना जवाबदेही, बैंडविड्थ और संवेदनशीलता के मामले में सीमित प्रदर्शन दिखाते हैं। दूसरी ओर, कम पंपिंग शक्ति, ब्रॉड-बैंड आवृत्ति प्रतिक्रिया, उच्च गति, और छोटे सम्मिलन नुकसान के तहत उच्च मॉड्यूलेशन गहराई की आवश्यकता वैकल्पिक रूप से नियंत्रित THz मॉड्यूलेटर में प्रभावी मॉड्यूलेशन प्राप्त करने के लिए अनुसंधान चला रही है। इन उपरोक्त सीमाओं को संबोधित करने के लिए, थीसिस THz फ़्रीक्वेंसी बैंड में काम कर रहे कमरे के तापमान-संचालित डिटेक्टरों और मॉड्यूलेटर को विकसित करने पर केंद्रित है। निम्न-आयामी सिलिकॉन (सिलिकॉन नैनोवायर) और स्तरित संक्रमण धातु डाइक्लोजेनाइड्स (टीएमडी) पर आधारित THz मॉड्यूलेटर और डिटेक्टरों को संबोधित किया जाता है।

थीसिस के पहले भाग में, सिंगल सिलिकॉन नैनोवायर (NW) आधारित जंक्शनलेस फील्ड-इफेक्ट ट्रांजिस्टर (FET) को THz डिटेक्टर के रूप में प्रदर्शित किया गया है। अधिकतम प्रतिक्रियाशीलता 0.425 THz के आसपास देखी जाती है, जिसका शिखर मान 468 V/W है। पूरक धातु-ऑक्साइड-अर्धचालक संगतता, चिप्स पर एकीकरण में आसानी, कई पिक्सेल सरणियों को महसूस करने की संभावना, और उच्च आवृत्तियों के लिए मापनीयता इन उपकरणों को THz इलेक्ट्रॉनिक्स के लिए आशाजनक बनाती है। इसके अलावा, टाइप-II टोपोलॉजिकल डायराक सेमीमेटल प्लेटिनम टेल्यूराइड (PtTe2) को नियोजित करने वाले THz डिटेक्टर का एक अन्य वर्ग 0.1-1.5 THz फ़्रीक्वेंसी रेंज में प्रकट हुआ है। 23.6 A/W की अधिकतम प्रतिक्रियाशीलता 0.2 THz पर फोटो-गैल्वेनिक प्रभाव के कारण प्राप्त की जाती है। इन डिटेक्टरों में मौजूदा उपकरणों की तुलना में आशाजनक गुण हैं, यानी ब्रॉडबैंड प्रतिक्रिया, शून्य-पक्षपाती संचालन, उच्च और रैखिक प्रतिक्रिया।

इस थीसिस के अगले भाग में, प्लेटिनम डिसेलेनाइड (PtSe2), टैंटलम डाइसल्फ़ाइड (TaS2), और मोलिब्डेनम डाइसल्फ़ाइड (MoS2) जैसे TMD के नए वर्ग पर आधारित ब्रॉडबैंड ऑप्टिकल THz मॉड्यूलेटर का प्रदर्शन किया गया है। TMDs सामग्री को विभिन्न स्पटर वाली धातु फिल्मों के प्रत्यक्ष सल्फराइजेशन/सेलेनाइजेशन द्वारा सिलिकॉन सब्सट्रेट पर उगाया जाता है। मॉड्यूलेशन गहराई (~ 80%) और गति (माइक्रोसेकंड में प्रतिक्रिया समय) में मॉड्यूलेशन दक्षता में सुधार के लिए टीएमडी को ऑप्टिकल-नियंत्रित सेमीकंडक्टर-आधारित THz मॉड्यूलेटर में शामिल किया गया है। उच्च मॉडुलन गहराई (कम पंपिंग शक्ति पर) और गति, सस्ती और सीधी निर्माण प्रक्रिया, व्यापक आवृत्ति प्रतिक्रिया (0.1-1 THz), और छोटे सम्मिलन नुकसान इन प्रस्तुत ऑप्टिकल THz मॉड्यूलेटर की प्रमुख विशेषताएं हैं। यह कार्य THz इमेजिंग, वायरलेस संचार, स्पेक्ट्रोस्कोपी और सुरक्षा प्रणालियों में विभिन्न स्तरित TMD के उपयोग की संभावनाओं को प्रकट करता है।

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List of Abbreviations and Symbols

Abbreviations

AFM	Atomic Force Microscopy
AlGaN	Aluminum Gallium Nitride
BOX	Buried Oxide
CDW	Charge Density Wave
CMOS	Complementary Metal Oxide Semiconductor
CVD	Chemical Vapor Deposition
EBL	Electron Beam Lithography
EDS	Energy Dispersive X-ray Spectroscopy
FDTD	Finite Difference Time Domain
FET	Field Effect Transistor
GaAs	Gallium Arsenide
GaN	Gallium Nitride
HEMT	High-Electron Mobility Transistor
HSQ	Hydrogen Silsesquioxane
MD	Modulation Depth
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NEP	Noise Equivalent Power
NW	Nanowire
PCA	Photoconductive Antenna
PMMA	Polymethyl methacrylate
RIE	Reactive Ion Etching
SBD	Schottky Barrier Diode
SEM	Scanning Electron Microscopy
SNR	Signal to Noise Ratio
Si	Silicon

SOI	Silicon On Insulator
THz	Terahertz
TMDs	Transition Metal Dichalcogenides
XPS	X-ray Photoelectron Spectra
2D	Two Dimensional

Symbols

λ	Wavelength
eV	Electron Volt
f_c	Cut-off frequency
R_s	Series Resistance
C_p	Parasitic Capacitance
P_{in}	Incident Terahertz Power
A_{THz}	Terahertz Beam Area
A_{eff}	Effective Area of the Device
D	Directivity
R	Responsivity
S_I	Noise Current Spectral Density
S_V	Noise Voltage Spectral Density
D	Detectivity
W	Watt
V	Voltage
A	Ampere
Hz	Hertz
τ	Carrier Recombination Time
ω	Terahertz Angular Frequency
ω_p	Plasma Frequency
e	Electron Charge

$\boldsymbol{m}$	Electron Mass
$\boldsymbol{n}$	Electron Density
$\boldsymbol{T_0}$	Transmission without Laser Power
$\boldsymbol{T_P}$	Transmission with Laser Power
$\boldsymbol{Tx_{offset}}$	DC Voltage
$\boldsymbol{Tx_{Amplitude}}$	AC Voltage
$\boldsymbol{f_{clock}}$	Clock Rate
$\boldsymbol{j}$	Current Density
$\boldsymbol{E}$	Electric Field
$\boldsymbol{\varepsilon_0}$	Dielectric Constant
$\boldsymbol{V_g}$	Gate Voltage
$\boldsymbol{V_T}$	Threshold Voltage
$\boldsymbol{C}$	Channel Capacitance
$\boldsymbol{s}$	Plasma Velocity
$\boldsymbol{K}$	Wave Vector
$\boldsymbol{v}$	Electron Velocity
$\Delta\boldsymbol{U}$	Terahertz Induced DC Voltage
$\boldsymbol{L}$	Channel Length
$\boldsymbol{\sigma}$	Conductivity
$\boldsymbol{\chi}$	Photogalvanic Coefficient
T	Photon-drag Constant
$\boldsymbol{k}$	Carrier Momentum
$\boldsymbol{E_f}$	Fermi Energy
$\boldsymbol{v_f}$	Fermi Velocity
$\boldsymbol{\beta}$	Scattering Constant
$\boldsymbol{\lambda^\omega}$	Wrapping Constant
$^\circ\boldsymbol{C}$	Degree Celsius
$\boldsymbol{\tau_r}$	Rise Time
$\boldsymbol{\tau_f}$	Fall Time
$\boldsymbol{c}$	Speed of Light
$\boldsymbol{E_{THz}}$	Terahertz Electric Field Amplitude

$\Delta\emptyset$	Phase Difference between Terahertz and Laser Signal
$\boldsymbol{h}$	Planck Constant
$\boldsymbol{\mu}$	Carrier Mobility
$\boldsymbol{n_{sub}}$	Substrate Refractive Index