TRANSPORT AND ULTRAFAST TERAHERTZ EMISSION STUDIES ON EPITAXIAL Co2MnGe THIN FILMS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2025

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TRANSPORT AND ULTRAFAST TERAHERTZ EMISSION STUDIES ON EPITAXIAL Co_2MnGe THIN FILMS

by

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Department of Physics

Submitted

in the fulfilment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY

DELHI

July 2025

Dedicated

to

My Parents and Teachers

CERTIFICATE

This is to certify that the thesis entitled, **"Transport and Ultrafast Terahertz Emission Studies on Epitaxial Co_2MnGe Thin Films"**, being submitted by **Ms. Ekta Yadav** to the Department of Physics, Indian Institute of Technology Delhi, New Delhi, for the award of degree of **Doctor of Philosophy** in Physics is a record of bonafide research work carried out by her under my supervision and guidance. She has fulfilled the requirements for submission of the thesis, which to the best of my knowledge has reached the requisite standard.

The results contained in the thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my thesis advisor, Prof. Sunil Kumar, for providing me the opportunity to pursue my doctoral research under his guidance. I greatly appreciate his unwavering support and encouragement throughout my studies. His profound expertise, insightful guidance, and thoughtful approach have played a pivotal role in shaping my research skills and fostering a constructive academic mindset. His continuous inspiration has been invaluable to me during the course of my doctoral journey.

I want to thank the members of my SRC committee, Prof. Sujeet Chaudhary, Prof. B. K. Mani, and Prof. Satyananda Kar, for their fruitful discussions and constructive feedback regarding my research. I would also like to acknowledge the Department of Physics at IIT Delhi, for providing all the facilities for my research activities and travel grants. I acknowledge the Central Research Facility (CRF) and Nanoscale Research Facility (NRF) at IIT Delhi, and their scientific staff members, for their assistance with various measurements related to my research. I gratefully acknowledge the University Grant Commission (UGC), Government of India, for providing me a research fellowship.

My sincere thanks to all my labmates Dr. Madhu Bochalya, Dr. Arvind Singh, Dr. Anand Nivedan, Dr. Sandeep Kumar, Dr. Monu Kinha, Neetesh Dhakar, Satakshi Gupta, Shiwangi Puri, Prateek Nautiyal, Sandeep Jakhar, and Akanksha Yadav for their help and support during my PhD days. Thanks to my friends Nishu, Sumreti, Sushmita, Shruti, Nikita, Deepesh, Richa, Chinmay, Manoj, Arun, Arpita, Pankaj, Indraneel, Vireshwar, and Nakul, who made my stay on campus a pleasant and memorable experience. I am also grateful to my childhood friends Priyanka, Arshma, Farheen, and Rahul for their unconditional support and for the great times we shared.

I want to express my sincere respect and heartfelt gratitude to my family, whose support and understanding have always given me strength to move forward. I thank my brother Vikas for his love and support. I am filled with boundless love and appreciation for my father and mother, whose unwavering support and sacrifices have been the foundation of my journey.

Above all, I bow my head in gratitude to God, whose blessings, guidance, and grace have given me strength, perseverance, and faith throughout this journey.

Lastly, I would like to express my sincere thanks to everyone who supported me directly or indirectly during my PhD journey.

Ekta Yadav

Abstract

Ferromagnetic Co-based full Heusler alloys, known for high Curie temperature, tunable electronic properties, and half-metallicity. Recently, some of these Co-based ferromagnetic full Heusler alloys have been predicted to host Weyl fermions in their electronic band structure. The Berry curvature associated with this non-trivial topological state exhibit exotic phenomena, such as the anomalous Hall effect (AHE), Fermi arc surface states, and other Berry curvature-induced effects. Among these compounds, Co_2MnGe, which crystallizes in the $Fm\bar{3}m$ space group, exhibits half-metallicity, high spin polarization and Weyl nodes in its band structure. These properties make Co_2MnGe an excellent candidate not only for spin-based electronic devices but also for THz emitter. Optimizing its growth conditions and investigating its transport and ultrafast optical response under various external conditions are the primary focus of this thesis.

The research work in the thesis is categorized into two sections, focusing on the structural, magnetotransport, and ultrafast Terahertz (THz) emission studies of Co_2MnGe. The first section focuses on the growth and fundamental characterization of Co_2MnGe thin films, which were deposited on MgO substrates using the pulsed laser deposition (PLD) technique. Structural characterization reveals that the films are epitaxial with B2 ordering, while transport measurements confirm their metallic behaviour. Further investigation using AHE measurements indicates that intrinsic mechanisms dominate over extrinsic contributions, implying a nonzero Berry curvature, which is a characteristic signature of Weyl semimetals. These findings suggest that Co_2MnGe is a candidate Weyl material, motivating further exploration of its topological and spintronic properties.

The second section focuses on ultrafast processes in Co_2MnGe thin films using THz time-domain spectroscopy, a powerful technique for probing topological states and spintronic phenomena. This section is driven by three key objectives. First, it is demonstrated that Co_2MnGe thin films emit THz radiation upon femtosecond laser excitation, with emission efficiency and topological properties being highly sensitive to growth temperature. To further understand the behaviour of the films, temperature, wavelength, and polarization-dependent THz emission measurements were performed on an optimized film, providing insights into the influence of external parameters. Finally, we analysed the ultrafast photocurrent response in the surface as well as the bulk of Co_2MnGe thin film and investigated underlying linear and nonlinear mechanisms governing these responses at both room and low temperature (15K). The overall study presented in this thesis advances our fundamental understanding of Co_2MnGe ferromagnetic full Heusler alloy through rigorous analysis of its growth, structural characterization, and by investigating their topological characteristics via magnetotransport and ultrafast THz emission studies.

सार

फेरोमैग्नेटिक Co-आधारित पूर्ण हेस्लर मिश्रधातु, उच्च क्यूरी तापमान, ट्यूनेबल इलेक्ट्रॉनिक गुणों और अर्ध-धात्विकता के लिए जाने जाते हैं। हाल ही में, इनमें से कुछ Co-आधारित फेरोमैग्नेटिक पूर्ण हेस्लर मिश्रधातुओं में उनके इलेक्ट्रॉनिक बैंड संरचना में वेइल फर्मियन की मेजबानी करने की भविष्यवाणी की गई है। इस गैर-तुच्छ टोपोलॉजिकल स्थिति से जुड़ी बेरी वक्रता असामान्य घटनाओं को प्रदर्शित करती है, जैसे कि असामान्य हॉल प्रभाव (AHE), फर्मी आर्क सतह की स्थिति और अन्य बेरी वक्रता-प्रेरित प्रभाव। इन यौगिकों में, Co_2MnGe, जो $Fm\bar{3}m$ स्पेस ग्रुप में क्रिस्टलीकृत होता है, अपनी बैंड संरचना में अर्ध-धात्विकता, उच्च स्पिन ध्रुवीकरण और वेइल नोड्स प्रदर्शित करता है। ये गुण Co_2MnGe को न केवल स्पिन-आधारित इलेक्ट्रॉनिक उपकरणों के लिए बल्कि THz एमिटर के लिए भी एक उत्कृष्ट उम्मीदवार बनाते हैं। इसकी वृद्धि की स्थितियों को अनुकूलित करना और विभिन्न बाहरी स्थितियों के तहत इसके परिवहन और अल्ट्राफास्ट ऑप्टिकल प्रतिक्रिया की जांच करना इस थीसिस का प्राथमिक फोकस है।

थीसिस में शोध कार्य को दो खंडों में वर्गीकृत किया गया है, जो Co_2MnGe के संरचनात्मक, मैग्नेटोट्रांसपोर्ट और अल्ट्राफास्ट टेराहर्ट्ज़ (THz) उत्सर्जन अध्ययनों पर केंद्रित है। पहला खंड Co_2MnGe पतली फिल्मों की वृद्धि और मौलिक लक्षण वर्णन पर केंद्रित है, जिन्हें पल्स्ड लेजर डिपोजिशन (PLD) तकनीक का उपयोग करके MgO सब्सट्रेट पर जमा किया गया था। संरचनात्मक लक्षण वर्णन से पता चलता है कि फिल्में B2 ऑर्डरिंग के साथ एपिटैक्सियल हैं, जबकि परिवहन माप उनके धात्विक व्यवहार की पुष्टि करते हैं। AHE माप का उपयोग करके आगे की जांच से संकेत मिलता है कि आंतरिक तंत्र बाहरी योगदानों पर हावी है, जिसका अर्थ है एक गैर-शून्य बेरी वक्रता, जो वेइल सेमीमेटल्स का एक विशिष्ट हस्ताक्षर है। ये निष्कर्ष बताते हैं कि Co_2MnGe एक संभावित वेइल सामग्री है, जो इसके टोपोलॉजिकल और स्पिनट्रॉनिक गुणों की आगे की खोज को प्रेरित करती है।

दूसरा खंड THz टाइम-डोमेन स्पेक्ट्रोस्कोपी का उपयोग करके Co_2MnGe पतली फिल्मों में अल्ट्राफास्ट प्रक्रियाओं पर केंद्रित है, जो टोपोलॉजिकल अवस्थाओं और स्पिनट्रॉनिक घटनाओं की जांच के लिए एक शक्तिशाली तकनीक है। यह खंड तीन प्रमुख उद्देश्यों से प्रेरित है। सबसे

पहले, यह प्रदर्शित किया गया है कि Co_2MnGe पतली फिल्में फेमटोसेकंड लेजर उत्तेजना पर THz विकिरण उत्सर्जित करती हैं, जिसमें उत्सर्जन दक्षता और टोपोलॉजिकल गुण वृद्धि तापमान के प्रति अत्यधिक संवेदनशील होते हैं। फिल्मों के व्यवहार को और अधिक समझने के लिए, तापमान, तरंग दैर्ध्य और ध्रुवीकरण पर निर्भर THz उत्सर्जन माप एक अनुकूलित फिल्म पर किए गए, जो बाहरी मापदंडों के प्रभाव के बारे में जानकारी प्रदान करते हैं। अंत में, हमने सतह के साथ-साथ Co_2MnGe पतली फिल्म के थोक में अल्ट्राफास्ट फोटोकरंट प्रतिक्रिया का विश्लेषण किया और कमरे और कम तापमान (15K) दोनों पर इन प्रतिक्रियाओं को नियंत्रित करने वाले अंतर्निहित रैखिक और गैर-रैखिक तंत्रों की जांच की। इस थीसिस में प्रस्तुत समग्र अध्ययन Co_2MnGe फेरोमैग्नेटिक पूर्ण ह्यूस्लर मिश्रधातु के विकास, संरचनात्मक लक्षण वर्णन के कठोर विश्लेषण, तथा मैग्नेटोट्रांसपोर्ट और अल्ट्राफास्ट THz उत्सर्जन अध्ययनों के माध्यम से उनकी टोपोलॉजिकल विशेषताओं की जांच के माध्यम से हमारी मौलिक समझ को आगे बढ़ाता है।

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LIST OF ABBREVIATION

ARPES	Angle-resolved photoemission spectroscopy
BS	Beam splitter
CPGE	Circular photogalvanic effect
EOS	Electrooptic sampling
WP	Wollaston prism
FFT	Fast Fourier transform
FWHM	Full width at half maximum
HHG	High harmonic generation
DOS	Density of states
IAC	Intensity autocorrelation
LCP	Left circular polarization
RCP	Right circular polarization
LP	Linear polarization
LPGE	Linear photogalvanic effect
MR	Magnetoresistance
OPA	Optical parametric amplification
OR	Optical rectification
HWP	Half wave plate
QWP	Quarter wave plate
PC	Pockels cell
PCS	Photoconductive sampling
SHG	Second-harmonic generation
PM	Parabolic mirror
PPMS	Physical property measurement system
MPMS	Magnetic property measurement system
PSAC	Phase-sensitive autocorrelation

AFM	Atomic force microscopy
XRR	X-ray reflection
THz	Terahertz
PLD	Pulsed laser deposition
ISHE	Inverse spin Hall effect
OHE	Ordinary Hall effect
SOC	Spin orbit coupling
AHE	Anomalous Hall effect
XRD	X-ray diffraction
WSM	Weyl semimetal
STE	Spintronic THz emitter