

**INVESTIGATIONS OF THE MAGNETIC
ANISOTROPY, EXCHANGE BIAS AND
FERROMAGNETIC RESONANCE IN Co, Ni₈₁Fe₁₉
AND Co/Ir₂₂Mn₇₈ THIN FILMS**

EKTA



**DEPARTMENT OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2023**

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by

EKTA

DEPARTMENT OF PHYSICS

Submitted

in the fulfilment of the requirement of the degree of the Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2023

Dedicated
To
My Parents and Teachers

CERTIFICATE

This is to certify that the thesis entitled "**INVESTIGATIONS OF THE MAGNETIC ANISOTROPY, EXCHANGE BIAS AND FERROMAGNETIC RESONANCE IN Co, Ni₈₁Fe₁₉ AND Co/Ir₂₂Mn₇₈ THIN FILMS,**" being submitted by **Ms. EKTA** to the Indian Institute of Technology Delhi, New Delhi, for the award of the degree of **Doctor of Philosophy** in Physics is a record of bonafide research work carried out by her. She has worked under my supervision and guidance and has fulfilled the requirements for the submission of this thesis, which, in my opinion, has reached the requisite standard.

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

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ABSTRACT

Spintronics devices are now being designed and manufactured under two broad categories. The first one involves the development of novel materials with increased spin polarisation and improved magnetic properties to perfect the existing giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR)-based technologies. To accomplish this, an important physical phenomenon of "exchange bias" is utilised in the magnetic tunnel junctions (MTJs) in which an antiferromagnetic (AF) layer is placed in contact with one of two ferromagnetic (FM) layers, because of which the magnetization of this FM layer does not respond to external fields. Thus, exchange bias involves the fixing of magnetization of one of the two FM layers (*i.e.*, pinning of spins of FM) by exchange coupling at the interface of the AF/FM layer, which is the motivation for this thesis work. The second kind of endeavour is dedicated to how to improve or modify the design of devices so that spin filters work better on transportation from one layer to another layer in a device.

Spintronics has advanced the field of magnetoresistance random access memories (MRAMs) by developing Spin Transfer Torque (STT)-based MRAMs, or STT-MRAMs, which manipulate and switch the magnetic moments using electric current. The read/write speed of spintronic devices is approaching the GHz range of frequencies because of fast growth, and the magnetization dynamics of thin magnetic films is becoming a significant part of device performance. As a result, the design of future generation spintronic devices is based on magnetization dynamics. Ferromagnetic resonance (FMR) is a critical approach for realising the STT mechanism and magnetization dynamics in ferromagnetic/nonmagnetic (FM/NM) heterostructures. In the present thesis work, we have studied the different types of magnetic anisotropy specifically exchange bias phenomena in Cobalt (Co) thin films.

Firstly, the thickness dependent (10-60 nm), static and dynamical magnetic properties of Co thin films are investigated. For all the samples, uniaxial magnetic anisotropy is found to be dominant over cubic anisotropy. This study confirms the unique role of deposition geometry on the magnetic anisotropy and damping in Co thin films. After investigating this, we have done the detailed study of interface behaviour of IrMn/Co system through exchange bias phenomenon. A high value of exchange bias is obtained at room temperature, without applying any magnetic field during growth. This type of behavior of exchange bias field (H_E) with thickness of cobalt layer (t_{Co}) can be linked to the structural quality of Co-layers and the interface between Co and IrMn layers. The H_{EB} is found to increase by a huge margin of 215% dynamically (measured through FMR) and 313% statically (measured through MOKE) with the reduction in Co thickness from 20 nm to 6 nm. In particular, we have also studied the spin-pumping phenomena in IrMn/Co due to the influence of strong spin-orbit coupling in IrMn through FMR measurements. The higher value of effective damping constant (α_{eff}) in IrMn(10nm)/Co(t_{Co} =10nm)/Si as compared with intrinsic damping constant α_{Co} of reference sample Al(2.5nm)/Co(10nm) is attributed to occurrence of spin pumping phenomena IrMn(10nm)/Co(t_{Co})/Si system.

In addition to this, the study covers influence of growth rate on structural, magnetic and transport properties of NiFe thin films grown at different sputtering power. The NiFe films are found to be of polycrystalline nature with *fcc*-structure with quite smooth with interface roughness <1 nm. Energy Dispersive X-ray spectroscopy (EDX) mapping of the samples conclusively suggest the continuous and uniform growth of the films. Magnetization dynamics properties of single layer NiFe thin films are very sensitive to the growth rate. For all the samples, the values of effective magnetization (M_{eff}) are found to lie below 0.9T, which are smaller than the bulk

saturation magnetization value ($\sim 1.00\text{T}$) of NiFe. At lower temperatures, the dominant scattering mechanism is the electron-magnon (e-m) scattering while that for the high temperature regime is the electron phonon (e-p) scattering.

Thus, the work done for this thesis links the relation between the growth and spin dynamic properties of various FM and FM/NM heterostructures. Additionally, it provides a fundamental understanding about the interfacial effects like exchange bias phenomenon and spin-pumping that occur in AF/FM interfaces. This work will be very important for the optimization of the materials used in actual implementation of spintronics memory.

सार

स्पिंट्रोनिक्स उपकरणों को अब दो व्यापक श्रेणियों के तहत डिजाइन और निर्मित किया जा रहा है। पहले वाले में मौजूदा जायंट मैग्नेटोरेसिस्टेंस (GMR) और टनल मैग्नेटोरेसिस्टेंस (TMR)-आधारित तकनीकों को सही करने के लिए बड़े हुए स्पिन ध्रुवीकरण और बेहतर चुंबकीय गुणों के साथ नॉवेल सामग्री का विकास शामिल है। इसे पूरा करने के लिए, "एक्सचेंज बायस" की एक महत्वपूर्ण भौतिक घटना का उपयोग मैग्नेटिक टनल जंक्शन (MTJ) में किया जाता है जिसमें एक एंटीफेरोमैग्नेटिक (AF) परत को दो फेरोमैग्नेटिक (FM) परतों में से एक के संपर्क में रखा जाता है, जिसके परिणामस्वरूप इस AF का चुंबकीयकरण होता है। परत बाहरी क्षेत्रों पर प्रतिक्रिया नहीं करती है। इस प्रकार, एक्सचेंज बायस में AF/FM परत के इंटरफेस पर एक्सचेंज बायस कपलिंग द्वारा दो FM परतों (यानी, AF के स्पिन की पिनिंग) में से एक के चुंबकीयकरण को एक और अलाइन करना शामिल है, जो इस थीसिस कार्य के लिए प्रेरणा है। दूसरे प्रकार का प्रयास उपकरणों के डिजाइन को सुधारने या संशोधित करने के लिए समर्पित है ताकि स्पिन फिल्टर डिवाइस में एक परत से दूसरी परत तक परिवहन पर बेहतर काम कर सकें।

स्पिंट्रोनिक्स ने स्पिन ट्रांसफर टॉर्क (STT) आधारित एमआरएम (MRAM), या एसटीटी-एमआरएम (STT-MRAM) विकसित करके मैग्नेटोरेसिस्टेंस रैंडम एक्सेस

मेमोरी (MRAM) के क्षेत्र को उन्नत किया है, जो विद्युत प्रवाह का उपयोग करके चुंबकीय क्षण में हेर-फेर और स्विच करता है। तेजी से विकास के परिणामस्वरूप स्पिट्रॉनिक उपकरणों की रीड / राइट की गति आवृत्तियों की गीगाहर्ट्ज रेंज तक पहुंच रही है, और पतली चुंबकीय फिल्मों की चुंबकीयकरण गतिशीलता डिवाइस के प्रदर्शन का एक महत्वपूर्ण हिस्सा बन रही है। नतीजतन, भविष्य की पीढ़ी के स्पिट्रॉनिक उपकरणों का डिजाइन चुंबकीयकरण गतिशीलता पर आधारित है। फेरोमैग्नेटिक रेजोनेंस (FMR), फेरोमैग्नेटिक/नॉनमैग्नेटिक (FM/NM) हेट्रोस्ट्रक्चर में एसटीटी मैकेनिज्म और मैग्नेटाइजेशन डायनामिक्स को साकार करने के लिए एक महत्वपूर्ण दृष्टिकोण है। वर्तमान थीसिस कार्य में, हमने विभिन्न प्रकार के चुंबकीय अनिसोट्रॉपी का अध्ययन किया है, विशेष रूप से कोबाल्ट (Co) पतली फिल्मों में एक्सचेंज बायस का आदान-प्रदान किया है। सबसे पहले, मोटाई पर निर्भर (10-60 nm), सह पतली फिल्मों के स्थिर और गतिशील चुंबकीय गुणों की जांच की जाती है। सभी नमूनों के लिए, क्यूबिक अनिसोट्रॉपी पर यूनिसेक्सियल मैग्नेटिक अनिसोट्रॉपी प्रमुख पाया गया है। यह अध्ययन पतली फिल्मों में चुंबकीय अनिसोट्रॉपी और डैम्पिंग पर जमाव ज्यामिति की अनूठी भूमिका की पुष्टि करता है। इसकी जांच करने के बाद, हमने एक्सचेंज बायस घटना के माध्यम से IrMn/Co सिस्टम के इंटरफेस व्यवहार का विस्तृत अध्ययन किया है। विकास के दौरान किसी भी चुंबकीय क्षेत्र को लागू किए

बिना कमरे के तापमान पर एक्सचेंज बायस का एक उच्च मूल्य प्राप्त होता है। कोबाल्ट परत (t_{Co}) की मोटाई के साथ एक्सचेंज बायस क्षेत्र (H_E) के इस प्रकार के व्यवहार को सह-परतों की संरचनात्मक गुणवत्ता और Co और IrMn परतों के बीच के इंटरफ़ेस से जोड़ा जा सकता है। एक्सचेंज बायस क्षेत्र 20nm से 6 nm तक मोटाई में कमी के साथ गतिशील रूप से 215% (FMR के माध्यम से मापा गया) और 313% स्थिर रूप से (MOKE के माध्यम से मापा गया) के बड़े अंतर से बढ़ा हुआ पाया गया है। विशेष रूप से, हमने FMR मापन के माध्यम से IrMn में मजबूत स्पिन-ऑर्बिट कपलिंग के प्रभाव के कारण IrMn/Co में स्पिन-पंपिंग घटना का भी अध्ययन किया है। IrMn(10nm)/Co(t_{Co} =10nm)/Si में प्रभावी डैम्पिंग स्थिरांक (α_{eff}) का उच्च मूल्य संदर्भ नमूना Al(2.5nm)/Co(10nm) के आंतरिक डंपिंग स्थिरांक α_{Co} की तुलना, के लिए IrMn(10nm)/Co(t_{Co})/Si में स्पिन पम्पिंग घटना प्रणाली का होना जिम्मेदार है।

इसके अलावा, अध्ययन में अलग-अलग स्पटरिंग पावर पर विकसित NiFe पतली फिल्मों के संरचनात्मक, चुंबकीय और परिवहन गुणों पर विकास दर के प्रभाव को शामिल किया गया है। NiFe फिल्में *fcc*-संरचना के साथ पॉलीक्रिस्टलाइन प्रकृति की पाई जाती हैं, इंटरफ़ेस खुरदरापन <1 nm के साथ काफी चिकनी होती हैं। एनर्जी डिस्पर्सिव एक्स-रे स्पेक्ट्रोस्कोपी (EDX) नमूनों की मैपिंग फिल्मों के निरंतर और

समान विकास का निर्णायक रूप से सुझाव देती है। एकल परत NiFe पतली फिल्मों के चुंबकत्व गतिकी गुण विकास दर के प्रति बहुत संवेदनशील होते हैं। सभी नमूनों के लिए, प्रभावी चुंबकीयकरण (M_{eff}) के मान 0.9T से नीचे पाए जाते हैं, जो NiFe के संतृप्ति चुंबकीयकरण मूल्य ($\sim 1.00\text{T}$) से छोटे होते हैं। कम तापमान पर, प्रमुख प्रकीर्णन तंत्र इलेक्ट्रॉन-मैग्नेटॉन (e-m) स्कैटरिंग है, जबकि उच्च तापमान शासन के लिए इलेक्ट्रॉन फोनन (e-p) स्कैटरिंग है।

इस प्रकार, इस थीसिस के लिए किया गया कार्य विभिन्न FM और FM/NM हेटरोस्ट्रक्चर के विकास और स्पिन गतिशील गुणों के बीच संबंध को जोड़ता है। इसके अतिरिक्त, यह AF/FM इंटरफेस में होने वाले एक्सचेंज बायस घटना और स्पिन-पंपिंग जैसे इंटरफेसियल प्रभावों के बारे में मौलिक समझ प्रदान करता है। स्पिंट्रॉनिक्स मेमोरी के वास्तविक कार्यान्वयन में उपयोग की जाने वाली सामग्रियों के अनुकूलन के लिए यह कार्य बहुत महत्वपूर्ण होगा।

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LIST OF ABBREVIATIONS

ABBREVIATIONS	DEFINITION
MRAM	Magnetic random-access memory
STT	Spin transfer torque
SOT	Spin orbit torque
MTJ	Magnetic tunnel junction
GMR	Giant magneto resistive effect
TMR	Tunnel magnetoresistance
FM	Ferromagnetic
NM	Non-magnetic
AF	Antiferromagnetic
FMR	Ferromagnetic resonance
MOKE	Magnetic optic kerr effect
UMA	Uniaxial magnetic anisotropy
MCA	Magneto-crystalline anisotropy
PMA	Perpendicular magnetic anisotropy