

INVESTIGATING SPIN-TRANSFER AND SPIN-ORBIT TORQUES IN MAGNETIC HETEROSTRUCTURES AND ADVANCED RADIO FREQUENCY DEVICES

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**Investigating Spin-Transfer and Spin-Orbit Torques in Magnetic
Heterostructures and Advanced Radio Frequency Devices**

by

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Certificate

This is to certify that the thesis entitled, **Investigating Spin-Transfer and Spin-Orbit Torques in Magnetic Heterostructures and Advanced Radio Frequency Devices**, is being submitted by **Mrs. Pankhuri Gupta** to the Department of Physics, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**. This work is a record of bonafide research conducted by her. She has worked under my supervision and guidance and has fulfilled all the requirements for the submission of this thesis. In my opinion, the work has reached the requisite standard.

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

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Pankhui Gupta

Date:

Abstract

This thesis investigates spin-transfer torque (STT) in magnetic tunnel junctions (MTJs) and its advanced application as an RF detector. It also examines spin-orbit torques (SOT) in magnetic heterostructures featuring emerging materials with one advanced application of an ultrafast spectrum analyzer.

First, we explored the application of STT using an MTJ-based nanopillar for RF detection based on the spin torque diode effect. This chapter uses the energy-efficient method to detect RF signals in two microwave bands ($S + C$ and X bands). For a carefully chosen geometry, two modes are simultaneously excited with opposite signs of rectification voltage, enabling microwave band identification in a single device without requiring a DC bias. Additionally, the free layer (FL) and reference layer (RL) modes exhibit different field-frequency dependencies, offering another approach for RF band identification. Furthermore, we performed micromagnetic simulations, demonstrating the opposite sign of rectification voltage. The origin of this difference is attributed to the simultaneous excitation of the free and reference layers. Finally, a method to enhance bandwidth in the X band is discussed based on our simulations. Secondly, this part of the chapter explores using the spin-torque ferromagnetic resonance (STFMR) technique to measure the magnitude of the damping-like torque and the field-like torque (FLT). The bias-dependent behavior of in-plane torque (τ_{\parallel}) and out-of-plane torque (τ_{\perp}) in both parallel (P) and antiparallel (AP) configurations was investigated in the MTJ nanopillars. STFMR analysis reveals that the P and AP configurations exhibit distinct spin-torque dynamics. We observe two distinct modes in both configurations. The nonmonotonic variations of τ_{\parallel} , and τ_{\perp} for both these modes with bias voltage highlight the complex mechanisms driving bias dependence of STT in MTJs.

In the next chapter of the thesis, we focus on the determination of SOT using an insulator, EuS. We observe out-of-plane polarized spin current at room temperature by employing angle-resolved STFMR. The unconventional out-of-plane torque conductivity, $\sigma_{\text{DL}}^z = -0.13 \times 10^5 (\hbar/2e) (\Omega\text{m})^{-1}$ in the Py(=Ni₈₁Fe₁₉)/EuS bilayer is observed, which is large and comparable to the conventional in-plane damping-like torque conductivity, σ_{DL}^y . Additionally, a giant in-plane field-like torque (σ_{FL}^z) with a magnitude of 27 times larger than that of the conventional out-of-plane field-like torque (σ_{FL}^y) is also observed in the Py/EuS bilayer. The unconventional torques due to the out-of-plane polarized spin current (σ_{DL}^z and σ_{FL}^z) persist even by inserting a 10 nm-thick Cu layer between Py and EuS and vanishes by inserting a 20 nm-thick Cu layer. Our findings demonstrate that the unconventional torques in these systems originate from the interfaces through spin swapping and/or spin-orbit precession mechanisms.

We further studied the SOT in epitaxial-FeSn/Py heterostructure, a collinear antiferromagnet with a kagome lattice. A detailed investigation of SOT is performed using the angle-resolved STFM for radio frequency current passing along different in-plane crystallographic directions. We observe a six-fold symmetric damping-like SOT directly linked to the six-fold symmetry of the epitaxial [0001]-oriented FeSn films. A substantial unconventional field-like torque originated from spin currents with out-of-plane spin polarization exhibiting unique angular dependence. This is characterized by a superposition of six-fold symmetry inherent to the FeSn crystal structure and uniaxial symmetry associated with the antiferromagnetic spin Hall effect. The unconventional field-like torque is notably enhanced when the RF current flows along the Néel vector in FeSn. These results demonstrate the existence of unconventional spin current anisotropy, which can be tuned by crystalline symmetry and Néel vector, offering a compelling pathway for advancing antiferromagnetic spintronics. Subsequently, We studied SOT in $\text{Fe}_3\text{Sn}_2/\text{Pt}$ structure using a polycrystalline, ultrathin Fe_3Sn_2 layer. In this study, we found a giant SOT in the $\text{Fe}_3\text{Sn}_2/\text{Pt}$ heterostructure, employing a polycrystalline, ultrathin Fe_3Sn_2 layer. A comprehensive analysis of SOT is conducted using angle-resolved STFM and DC-biased STFM for samples with varying Fe_3Sn_2 thicknesses of 2 nm, 3 nm, and 5 nm. Our findings reveal that the effective damping-like and field-like spin-torque efficiencies are significantly greater than those observed in conventional Pt-based systems. The variation in torque with Fe_3Sn_2 thickness is attributed to a combination of the spin Hall effect (SHE) in the Pt layer and an additional torque component originating from the bulk of Fe_3Sn_2 . The intrinsic properties of Fe_3Sn_2 are likely responsible for the giant SOT observed in this system. This discovery holds promise for developing SOT-based devices with ultra-high spin current densities and reduced power consumption.

In the final chapter, we explore the application of SOT. We demonstrate the use of spin Hall nano-oscillators (SHNOs), a device based on the SOT phenomenon, for ultra-fast microwave spectral analysis. We show mutually synchronized NC-SHNOs, with five nano-constrictions using a W (5 nm)/NiFe (3 nm)/ Al_2O_3 (4 nm) trilayer structure. This shows robust mutual synchronization, high output power (18 dB/noise), narrow linewidth (0.65 MHz), and broad frequency tunability (0.67 GHz/mA). These features enable precise and flexible spectrum analysis. Our study achieved one order of magnitude improvement in frequency resolution bandwidth (1.9 MHz) over previously reported methods using uniform-state magnetic tunnel junction STNOs. Moreover, compared to vortex-state-based STNO spectrum analyzers reported earlier, NC-SHNO-based spectrum analysis demonstrates an operating frequency one order higher. Additionally, our implementation of ultra-fast time-resolved spectrum analysis has successfully captured rapidly varying frequency components.

सारांश

यह शोधप्रबंध चुंबकीय टनल जंक्शन (MTJs) में स्पिन-ट्रांसफर टॉर्क (STT) की जाँच करता है और इसे एक उन्नत रेडियो आवृत्ति (RF) डिटेक्टर के रूप में लागू करने की संभावनाओं का अध्ययन करता है। यह उभरती हुई सामग्रियों की विशेषता वाले चुंबकीय हेटरोस्ट्रक्चर में स्पिन-ऑर्बिट टॉर्क (SOT) की जांच करता है, और इसका एक प्रमुख अनुप्रयोग एक अति तीव्र स्पेक्ट्रम एनालाइज़र के रूप में प्रस्तुत किया गया है।

सबसे पहले, हमने STT के अनुप्रयोग को MTJ-आधारित नैनोपिलर के माध्यम से रेडियो आवृत्ति डिटेक्शन में स्पिन टॉर्क डायोड प्रभाव के आधार पर अध्ययन किया। यह अध्याय दो माइक्रोवेव बैंड्स (S+C और X बैंड्स) में रेडियो आवृत्ति सिग्नलों का पता लगाने के लिए ऊर्जा-कुशल विधि का उपयोग करता है। विशेष रूप से चुनी गई ज्योमेट्री के लिए, दो मोड्स एक साथ उत्तेजित होते हैं, जिनकी रेक्टिफिकेशन वोल्टेज की संकेत दिशा विपरीत होती है, जिससे DC बायस की आवश्यकता के बिना एक ही डिवाइस में माइक्रोवेव बैंड की पहचान संभव होती है। इसके अतिरिक्त, फ्री लेयर (FL) और रेफरेंस लेयर (RL) मोड्स में भिन्न चुंबकीयक्षेत्र-आवृत्ति निर्भरता देखी जाती है, जो रेडियो आवृत्ति बैंड पहचान का एक और तरीका प्रदान करती है। साथ ही, हमने माइक्रोमैग्नेटिक सिमुलेशंस किए, जो रेक्टिफिकेशन वोल्टेज के विपरीत संकेत को दर्शाते हैं। इस अंतर का मूल कारण FL और RL की एक साथ उत्तेजना को माना गया है। अंततः, हमारी सिमुलेशंस के आधार पर X बैंड में बैंडविड्थ को बेहतर बनाने की एक विधि पर चर्चा की गई है। दूसरे भाग में, इस अध्याय में स्पिन-टॉर्क फेरोमैग्नेटिक रेजोनेंस (STFMR) तकनीक का उपयोग करके डैम्पिंग-लाइक टॉर्क (DLT) और फील्ड-लाइक टॉर्क (FLT) की परिमाण को मापा गया है। MTJ नैनोपिलर्स में समानांतर (P) और असमानांतर (AP) विन्यासों में इन-प्लेन टॉर्क (τ_{\parallel}) और आउट-ऑफ-प्लेन टॉर्क (τ_{\perp}) के बायस-निर्भर व्यवहार की जांच की गई। STFMR विश्लेषण से ज्ञात होता है कि P और AP विन्यासों में विशिष्ट स्पिन टॉर्क गतिकी देखी जाती है। दोनों में दो अलग-अलग मोड्स प्रकट होते हैं। इन मोड्स में τ_{\parallel} और τ_{\perp} की गैर-रेखीय बायस वोल्टेज पर निर्भरता STT की जटिल प्रकृति को दर्शाती है।

थीसिस के अगले अध्याय में, SOT के निर्धारण पर ध्यान केंद्रित किया गया है, जिसमें एक विसंवाहक EuS का उपयोग किया गया है। हम कोण-समाधान STFMR तकनीक के माध्यम से कमरे के तापमान पर आउट-ऑफ-प्लेन पोलराइज़्ड स्पिन करंट का निरीक्षण करते हैं। Py (=Ni₈₁Fe₁₉)/EuS दोहरी परत में एक अपारंपरिक आउट-ऑफ-प्लेन टॉर्क चालकता $\sigma_{DL}^z = -0.13 \times 10^5$ ($\hbar/2e$)($\Omega \cdot m$)⁻¹ प्राप्त हुई, जो पारंपरिक इन-प्लेन डैम्पिंग-लाइक टॉर्क चालकता σ_{DL}^y के तुलनीय है। साथ ही, एक विशाल इन-प्लेन FLT (σ_{FL}^x), जिसकी मात्रा पारंपरिक आउट-ऑफ-प्लेन FLT (σ_{FL}^y) से 27 गुना अधिक है, भी Py/EuS दोहरी परत में देखी गई। ये अपारंपरिक टॉर्क्स Cu की 10 nm मोटी परत Py और EuS के बीच जोड़ने पर भी बनी रहती हैं लेकिन 20 nm परत जोड़ने

पर समाप्त हो जाती हैं। हमारे निष्कर्ष दर्शाते हैं कि ये टॉक्स इंटरफेस-आधारित स्पिन स्वैपिंग और/या स्पिन-ऑर्बिट प्रीसेशन से उत्पन्न होते हैं।

हमने एपिटैक्सियल-FeSn/Py हेटरोस्ट्रक्चर में SOT का भी गहन अध्ययन किया, जो कि एक समरेखीय एंटीफेरोमैग्नेट है और कागोमे लैटिस संरचना दर्शाता है। विभिन्न इन-प्लेन क्रिस्टल दिशाओं से गुजरने वाली रेडियो आवृत्ति धारा के लिए कोण-समाधान STFMR तकनीक द्वारा SOT का विश्लेषण किया गया। एपिटैक्सियल [0001]-ओरिएंटेड FeSn फिल्मों की छह-गुना समरूपता से मेल खाता हुआ एक छह-गुना समरूप डैम्पिंग-लाइक SOT देखा गया। साथ ही, एक उल्लेखनीय आउट-ऑफ-प्लेन स्पिन पोलराइजेशन वाले स्पिन करंट से उत्पन्न अपारंपरिक FLT देखा गया, जो क्रिस्टल और एंटीफेरोमैग्नेटिक स्पिन हॉल प्रभाव के कारण मिली-जुली समरूपता दर्शाता है। जब रेडियो आवृत्ति धारा FeSn में Néel वेक्टर के साथ प्रवाहित होता है, तो यह FLT और अधिक प्रबल हो जाता है। ये निष्कर्ष स्पिन करंट अनिसोट्रॉपी की उपस्थिति को दर्शाते हैं, जिसे क्रिस्टलीय समरूपता और Néel वेक्टर द्वारा नियंत्रित किया जा सकता है। इसके बाद हमने बहुक्रिस्टलीय, अति पतली Fe₃Sn₂ परत का उपयोग करके Fe₃Sn₂/Pt संरचना में SOT का अध्ययन किया। इस अध्ययन में, हमने Fe₃Sn₂/Pt हेटरोस्ट्रक्चर में उच्च SOT पाया। कोण-समाधान STFMR तकनीक द्वारा, विभिन्न मोटाई (2 nm, 3 nm, 5 nm) वाले नमूनों के लिए विस्तृत विश्लेषण किया गया। निष्कर्षों से पता चला कि डैम्पिंग-लाइक और फील्ड-लाइक टॉर्क की दक्षताएँ पारंपरिक Pt-आधारित प्रणालियों की तुलना में काफी अधिक हैं। टॉर्क में यह अंतर Fe₃Sn₂ की मोटाई के साथ Pt लेयर में स्पिन हॉल प्रभाव और Fe₃Sn₂ के बल्क से उत्पन्न होने वाले अतिरिक्त टॉर्क घटक के संयोजन के कारण होता है। Fe₃Sn₂ की अंतर्निहित विशेषताएँ इस विशाल SOT के लिए उत्तरदायी मानी जाती हैं, जो उच्च स्पिन करंट डेंसिटी और कम पावर खपत वाले उपकरणों के लिए आशाजनक है।

अंतिम अध्याय में, हम SOT के अनुप्रयोग का पता लगाते हैं। हम अति तीव्र माइक्रोवेव स्पेक्ट्रल विश्लेषण के लिए SOT परिघटना पर आधारित एक उपकरण, स्पिन हॉल नैनो-ऑसिलेटर (SHNO) के उपयोग को प्रदर्शित करते हैं। हम W(5 nm)/NiFe(3 nm)/Al₂O₃(4 nm) त्रिपरत संरचना का उपयोग करके पाँच नैनो-संकुचनों के साथ पारस्परिक रूप से सिंक्रनाइज़्ड NC-SHNO दिखाते हैं। यह मजबूत पारस्परिक सिंक्रनाइज़ेशन, उच्च आउटपुट पावर (18 dB/noise), संकीर्ण लाइनविड्थ (0.65 MHz), और व्यापक आवृत्ति ट्यूनेबिलिटी (0.67 GHz/mA) दिखाता है। इससे स्पेक्ट्रम विश्लेषण अधिक सटीक और लचीला बनता है। इस अध्ययन में पूर्ववर्ती MTJ-STNO विधियों की तुलना में आवृत्ति रेज़ोल्यूशन बैंडविड्थ में दस गुना सुधार (1.9 MHz) हासिल किया गया। इसके अतिरिक्त, NC-SHNO आधारित स्पेक्ट्रम विश्लेषण ने वॉर्टेक्स-स्टेट STNO एनालाइज़र्स की तुलना में एक ऑर्डर उच्च ऑपरेटिंग आवृत्ति प्राप्त की। इसके अतिरिक्त, हमारे अति तीव्र समय-समाधान स्पेक्ट्रम विश्लेषण के कार्यान्वयन ने तेजी से बदलते आवृत्ति घटकों को सफलतापूर्वक पकड़ लिया है।

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