# SPIN-ORBIT-TORQUE-DRIVEN SWITCHING IN PERPENDICULAR-MAGNETIC-ANISOTROPY-BASED DEVICES FOR THE NON-VOLATILE MEMORY AND NEUROMORPHIC SYNAPSE APPLICATIONS

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# Spin-orbit-torque-driven switching in perpendicular-magnetic -anisotropy-based devices for non-volatile memory and neuromorphic synapse applications

by

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Submitted

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

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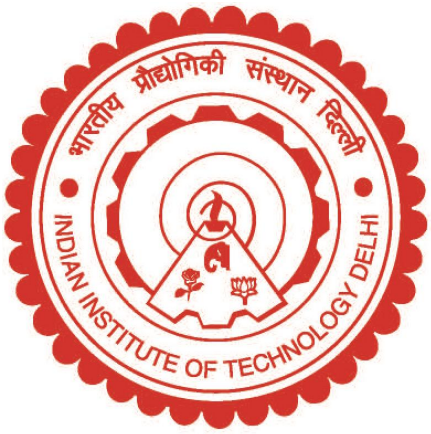


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# Certificate

This is to certify that the thesis entitled, **Spin-orbit-torque-driven switching in perpendicular-magnetic-anisotropy-based devices for non-volatile memory and neuromorphic synapse applications**, is being submitted by **Mr. Ram Singh Yadav** 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 him. He 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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*I dedicate this thesis to my parents.*

Ram Singh Yadav

# Abstract

This dissertation investigates the development and characterization of novel spintronic devices for neuromorphic computing applications. We focus on optimizing spin-orbit torque (SOT) switching and demonstrating synaptic behavior in various material systems. We explore the synaptic behavior in two types of perpendicularly magnetized materials and field-free SOT switching using a quantum material.

In the thesis, first, we optimized the PMA in ($Pt/Co/SiO_2$) and demonstrated spin-orbit torque (SOT) switching. Following this, we revealed the presence of multiple *mixed states* in $Pt/Co/SiO_2$. These *mixed states* correspond to intermediate magnetization configurations between two saturated states: all magnetic moments aligned vertically up and all moments aligned vertically down (with the ferromagnetic layer exhibiting PMA). These *mixed states* are modulated through in-plane current pulses, inducing SOT at the heavy-metal-ferromagnet interface. This allowed us to demonstrate long-term potentiation (LTP) and long-term depression (LTD) in the device, mimicking synaptic behavior. Experimentally, the synaptic bit resolution was determined to be 5 (approximately 30 distinguishable states) by measuring the stability of the *mixed states*. Additionally, the non-linearity and asymmetry in the obtained LTP and LTD are quantified experimentally and qualitatively explained through micromagnetic modeling. Micromagnetic Modelling is carried out for two scenarios: one without defects and another with edge defects. In the absence of defects, domain-wall motion causes non-linearity in the synaptic behavior, whereas edge defects restrict domain-wall motion, resulting in linear and symmetric synaptic behavior. Achieving high linearity and symmetry in the synaptic weight-update characteristic is critical for attaining high classification or regression accuracy in on-chip learning simulations.

Subsequently, we explored new heterostructures with high thermal stability and comparable switching current densities. SOT switching is experimentally demonstrated in a heavy-metal (Pt)/ferromagnetic metal (Co) gradient multilayer device, where the thickness of each Co layer remained fixed at 0.5 nm, while the Pt layer thickness increased from bottom to top (1 nm to 3 nm in increments of 0.4 nm). Using the thermally assisted SOT switching model on pulse-duration-dependent switching measurements, the thermal stability factor was determined to be 65 (across multiple devices), significantly higher than that of single-Pt-Co-layer-based devices ( 30). Notably, the switching current density remained similar for both types of devices. Additionally, the synaptic behavior of the gradient multilayer device was experimentally demonstrated, with 30 stable and distinguishable states controlled through positive current pulses (LTP) and 24 such states through negative pulses (LTD). Using non-ideality coefficients extracted from the experimentally obtained

LTP and LTD plots, the on-chip inference and learning performance of neuromorphic crossbar arrays composed of such devices are simulated.

In the final part, we explored quantum materials possessing y- and z-spin polarization due to the SHE and MSHE, respectively. The z-spin polarization is particularly useful for achieving field-free switching. Nearly 100 % field-free switching is demonstrated at a current density of $6.1 \times 10^6$ A/cm$^2$ with a pulse width of 200 $\mu$s. These results pave the way for energy-efficient SOT-MRAM and zero-field synapse devices for future neuromorphic computing systems.

Overall, the thesis advances the understanding and development of energy-efficient spintronic devices for neuromorphic computing.

# सारांश

यह शोध प्रबंध न्यूरोमॉर्फिक कंप्यूटिंग अनुप्रयोगों के लिए नवीन स्पिन्ट्रॉनिक यंत्र के विकास और विशेषताओं की जाँच करता है। हम स्पिन-ऑर्बिट टॉर्क (एसओटी) स्विचिंग को बेहतर बनाने और विभिन्न पदार्थ के सिस्टम्स में सिनेप्टिक बिहेवियर प्रदर्शित करने पर ध्यान केंद्रित करते हैं। हम दो प्रकार की परपेंडिक्युलरली मैग्नेटाइज्ड पदार्थ और एक क्वांटम पदार्थ का उपयोग करते हुए फील्ड-फ्री एसओटी स्विचिंग में सिनेप्टिक व्यव्हार का अध्ययन करते हैं।

शोध प्रबंध के पहले भाग में, हमने ($Pt/Co/SiO_2$) में पीएमए को ऑप्टिमाइज़ किया और एसओटी स्विचिंग प्रदर्शित की। इसके बाद, हमने $Pt/Co/SiO_2$ में कई मिश्रित अवस्था की उपस्थिति दर्शाई, जो दो सैचुरेटेड अवस्था (सभी मैग्नेटिक मोमेंट्स ऊर्ध्व दिशा में ऊपर और सभी नीचे) के बीच इंटरमीडिएट मैग्नेटाइजेशन कॉन्फ़िगरेशन्स को दर्शाती हैं। ये मिक्स्ड अवस्था, इन-प्लेन करंट पल्सेस द्वारा मॉड्युलेट की जाती हैं, जो हेवी-मेटल–फेरोमैग्नेट इंटरफेस पर एसओटी प्रेरित करती हैं। इससे हमें लॉन्ग-टर्म पोटेंशिएशन (LTP) और लॉन्ग-टर्म डिप्रेशन (LTD) को प्रदर्शित करने में सफलता मिली, जो सिनेप्टिक व्यव्हार का अनुकरण करते हैं। प्रयोगात्मक रूप से, मिश्रित अवस्था की स्थिरता को मापकर सिनैप्टिक बिट रिज़ॉल्यूशन 5 (लगभग 30 अलग–अलग अवस्थाएँ) निर्धारित किया गया। प्राप्त LTP और LTD में गैर-रैखिकता और असममिति को मापा गया और माइक्रोमैग्नेटिक मॉडलिंग द्वारा गुणात्मक रूप से समझाया गया। माइक्रोमैग्नेटिक मॉडलिंग दो परिदृश्यों के लिए की गई – एक बिना डिफेक्ट्स के और दूसरा एज डिफेक्ट्स के साथ। बिना डिफेक्ट्स की स्थिति में, डोमेन-वॉल मोशन सिनेप्टिक बिहेवियर में गैर-रैखिकता उत्पन्न करता है, जबकि एज डिफेक्ट्स, डोमेन-वॉल मोशन को सीमित करते हैं, जिससे सिनेप्टिक बिहेवियर अधिक रैखिक और सममित बनता है। सिनेप्टिक वेट-अपडेट कैरेक्टरिस्टिक में उच्च रैखिकता और सममिति प्राप्त करना, ऑन-चिप लर्निंग सिमुलेशन्स में उच्च क्लासिफिकेशन या रिग्रेशन एक्यूरेसी के लिए महत्वपूर्ण है।

इसके बाद, हमने नई हेटरोस्ट्रक्चर्स का अध्ययन किया जिनमें उच्च तापीय स्थिरता और तुलनीय स्विचिंग धारा घनत्व थीं। एसओटी स्विचिंग को एक हेवी-मेटल (Pt)/फेरोमैग्नेटिक मेटल (Co) ग्रेडिएंट बहुपरत यंत्र में प्रदर्शित किया गया, जहाँ प्रत्येक Co लेयर की मोटाई 0.5 nm निश्चित रखी गई, जबकि Pt परत की मोटाई नीचे से ऊपर की ओर क्रमशः 1 nm से 3 nm तक (0.4 nm के अंतराल में) बढ़ाई गई। थर्मली असिस्टेड एसओटी स्विचिंग मॉडल का उपयोग करते हुए, पल्स-ड्यूरेशन-डिपेंडेंट स्विचिंग मेज़रमेंट्स से थर्मल स्टेबिलिटी फैक्टर 65 (कई यंत्र में)

निर्धारित किया गया, जो कि एकल Pt-Co लेयर आधारित यंत्र (30) की तुलना में काफी अधिक था। विशेष रूप से, दोनों प्रकार के यंत्र के लिए स्विचिंग धारा घनत्व लगभग समान रही। इसके अतिरिक्त, ग्रेडिएंट मल्टीलेयर यंत्र में सिनेप्टिक व्यव्हार को भी प्रदर्शित किया गया, जिसमें पॉजिटिव करंट पल्सेस (LTP) द्वारा 30 स्थिर व अलग-अलग अवस्थाएँ तथा नेगेटिव पल्सेस (LTD) द्वारा 24 अवस्थाएँ नियंत्रित की गईं। प्रयोगात्मक रूप से प्राप्त LTP और LTD प्लॉट्स से निकाले गए नॉन-आइडियलिटी कोएफिशिएंट्स का उपयोग करके, ऐसे यंत्र से बने न्यूरोमॉर्फिक क्रॉसबार एरेज़ के ऑन-चिप इन्फरेंस और लर्निंग परफॉर्मेंस का अनुकरण किया गया

अंतिम भाग में, हमने ऐसे क्वांटम पदार्थ का अध्ययन किया जो SHE और MSHE के कारण y- और z-स्पिन पोलराइजेशन दर्शाते हैं। z-स्पिन पोलराइजेशन, विशेष रूप से फील्ड-फ्री स्विचिंग प्राप्त करने में उपयोगी है। लगभग 100% फील्ड-फ्री स्विचिंग को $6.1 \times 10^6 A/cm^2$ की धारा घनत्व और 200 $\mu s$ की पल्स विड्थ पर प्रदर्शित किया गया। ये परिणाम भविष्य के न्यूरोमॉर्फिक कंप्यूटिंग सिस्टम्स के लिए ऊर्जा-कुशल एसओटी-एमआरएएम और ज़ीरो-फील्ड सिनेप्स यंत्र का मार्ग प्रशस्त करते हैं।

कुल मिलाकर, यह शोध-प्रबन्ध न्यूरोमॉर्फिक कंप्यूटिंग के लिए ऊर्जा-कुशल स्पिन्ट्रॉनिक यंत्र की समझ और विकास को आगे बढ़ाती है।

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