Giant magnetovolume effects including negative thermal expansion in thin film antiperovskite manganese nitrides

Sheena K. K. Patel[1,2] Stjepan B. Hrkac[2], Jeffrey A. Brock[1], Nelson Hua[2], Haidan Wen[3], Donald Walko[3], Oleg G. Shpyrko[2], and Eric E. Fullerton[1]

[1]*Center for Memory and Recording Research, University of California San Diego, La Jolla, California 92093, USA*
[2]*Department of Physics, University of California San Diego, La Jolla, California 92093, USA*
[3]*Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439, USA*

Presenter: Sheena K. K. Patel, Postdoctoral Scholar, CMRR
Advisor: Eric Fullerton, Director, CMRR

Antiperovskite manganese nitrides Mn_3AN (where *A* is a metal or semiconducting element) are a class of materials of interest for a wide range of physical phenomena including giant magnetoresistance, piezoelectric effects, anomalous Nernst effect, and magnetostructural effects. Studies in bulk of some of these compounds have shown giant magnetovolume effects [1, 2] including negative thermal expansion [2, 3] tied to transitions between ferrimagnetic, antiferromagnetic, and paramagnetic phases which can be tuned by composition [4]. Here, we demonstrate successful growth of thin films of Mn_3AN (001) on MgO (001) substrates which exhibit these magnetovolume effects. Films with composition $Mn_3Cu_{1-x}Ge_xN$ with x = 0.1 to 0.6 demonstrate negative thermal expansion during Néel transitions with out-of-plane thermal expansion coefficients ranging from -58±2 (10^{-6}/K) to near zero with a total out-of-plane lattice contraction of 0.3-0.8%. Films with composition $Mn_3Cu_{0.9}Ni_{0.1}N$ demonstrate a low temperature hysteretic magnetostructural phase transition with a 1.4% out-of-plane lattice expansion and a higher temperature Néel transition exhibiting negative thermal expansion with an over 0.4% out-of-plane lattice contraction. Time-resolved x-ray diffraction measurements following photoexcitation with an optical laser pulse within and through the magnetic phases conducted at the Advanced Photon Source are presented, demonstrating both positive and negative thermal expansion dynamically. Work at UCSD was supported by the U.S. Department of Energy (DOE), Office of Science, Office of Basic Energy Sciences, under Contracts No. DE-SC0018237 and DE-SC0001805. This research used resources of the Advanced Photon Source, a DOE Office of Science user facility operated for the DOE Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357.

Work at UCSD was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contracts No. DE-SC0018237 and DE-SC0001805. This research used resources of the Advanced Photon Source, a DOE Office of Science user facility operated for the DOE Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357.

References

[1] Kim, Chi, Kim, *et al.*, *Phys. Rev. B*, Vol. 68, p. 172402 (2003).
[2] Hamada and Takenaka, *J. Appl. Phys.*, vol. 111, p. 07A904 (2012).
[3] Sun, Wang, Wen, *et al.*, *Appl. Phys. Lett.*, vol. 91, p. 231913 (2007).
[4] Takenaka and Takagi. *Appl. Phys. Lett.*, Vol. 87, p. 261902 (2005).

Title: Magnetization dynamics in LSMO/NNO thin films

Abstract: Transition Metal Oxides (TMOs) are an ideal playground of correlated electron systems that host a plethora of phenomena, rich in exotic fundamental physics, and potential industrial applications due to their unique electronic structure. The transfer of the transition metal s electrons to the oxygen ion results in the density of states near the Fermi level being dominated by only the d electrons with SOC. Due to strong electron correlations in TMOs, the number of electrons per lattice site is constrained which induce local entanglement of charge, spin, and orbital degrees of freedom. This gives rise to phenomena like magnetism,quantum Hall effects, charge and spin orderings, metal-insulator transitions etc. I shall talk briefly about magnetization dynamics in the oxide ferromagnet La(0.3)Sr(0.3)MnO3 (LSMO)-NdNiO3 (NNO) heterostructure, where the metal-insulator transition, accompanied by anti-ferromagnetic transistion of NNO couples with LSMO gives rise to a conductive AFM state in the LSMO-NNO heterostructure, and its implications on the various magnetization parameters thereof.

Biswajit Sahoo
Graduate Student Researcher
Eric Fullerton Group

Resistive Switching Behavior Of Lithium Titanium Oxide During Spinel To Rock Salt Conversion For Neuromorphic Application

Bhagath Sreenarayanan[a], Biswajit Sahoo[e,f], Steven Suwito[d], Ryosuke Shimizu[a], Chi-Hsin Huang[g] Dhivya Meganathan[a], Minghao Zhang[a], Eric Fullerton[a,f,g], Zeinab Jahed[a], Bing Joe Hwang[d], Weinien Su[d], Alex Frano[e], Kenji Nomura[g], Bing Han[a*], Ying Shirley Meng[a,b,c*]

a Department of Nano Engineering, University of California San Diego, La Jolla, CA 92093, USA
b Materials Science and Engineering, University of California San Diego, La Jolla, CA 92093, USA
c Pritzker School of Molecular Engineering, University of Chicago, Chicago, IL 60637
d Graduate Institute of Applied Science and Technology, National Taiwan University of Science and Technology, Taipei, Taiwan 106
e Department of Physics, University of California San Diego, La Jolla, CA 92093, USA
f Center for Memory and Recording Research, University of California San Diego, La Jolla, CA 92093, USA
g Department of Electrical and Computer Engineering, University of California San Diego, La Jolla, CA 92093, USA

*Correspondence to b3han@ucsd.edu; shirleymeng@uchicago.edu

ABSTRACT

Lithium Titanium Oxide (LTO) spinel is a widely-used electrode material in Lithium-ion batteries due to its exceptional properties, such as high lithium-ion conductivity, low voltage operation, and zero strain during lithium insertion and de-insertion. Moreover, it exhibits tunable electronic conductivity upon lithium cycling, making it a promising candidate for stable, energy-efficient resistive switching devices with applications in neuromorphic systems. To gain a deeper understanding of LTO's behavior at the mesoscopic level and its potential as a resistive switching material, we explore the impact of defects and dopants. Our research aims to elucidate the mechanisms governing LTO's performance, including stability and switching voltage, based on binding energy and defect/dopant properties. Herein, we establish a baseline using powder data to investigate the lithiation-induced switching behavior in LTO, employing a pressure setup cell. Subsequently, we extend our analysis to LTO thin films in the out-of-plane configuration, utilizing Electrochemical Impedance Spectroscopy (EIS) to monitor resistance evolution upon lithiation. Density Functional Theory (DFT) calculations are employed to examine the influence of lithiation and oxygen vacancy formation on LTO's electronic structure, including band gap and density of states, which collectively impact its resistive switching properties.We also employ Raman Spectroscopy to probe the vibrational modes of lithiated LTO thin film samples and confirm the formation of the lithiated rocksalt phase. In addition, we fabricate an Interdigitated Electrode (IDE) to evaluate the in-plane switching behavior. Finally, we present a preliminary resistive switching device utilizing LTO as the channel electrode, LiPON as the solid-state Li-ion conductor, and Li metal as the Li source, based on a transistor design. Our comprehensive characterization and computational approach aim to accelerate the development of these novel materials for use in neuromorphic device fabrication. Through this research, we seek to advance the understanding and application of LTO in emerging technologies

Si Doped ZrO_2 For Hysteresis Free High-k Dielectric

Harshil Kashyap[1], Matthias Passlack[2], Ping-Che Lee[1], Kisung Chae[3], Ajay K. Yadav[4], Jeffrey Spiegelman[5], Kyeongjae Cho[3], Asif Khan[6], Andrew C. Kummel[1]

[1.] *University of California San Diego, La Jolla, CA 92093, USA*

[2.] TSMC, San Jose, CA 95134

[3.] *University of Texas Dallas, Richardson, TX 75080, USA4*

[4.] *Applied Materials, Inc., Santa Clara, CA 95054, USA*

[5.] *Rasirc, San Diego, CA 92126, USA*

[6.] *Georgia Institute of Technology, Atlanta, GA 30332, USA*

ABSTRACT

Thin high-k dielectrics play a crucial role in achieving low leakage and high capacitance DRAM cells[1]. Various high-k materials, such as amorphous HfO_2, have shown significant improvements over SiO_2[2]. Polycrystalline or nanocrystalline HfO_2/ZrO_2 possesses nearly double the k value compared to amorphous HfO_2[3,4]. This has sparked interest in their use in future logic and memory devices. However, the presence of ferroelectric or antiferroelectric behavior in the high-k orthorhombic and tetragonal crystal phases makes them unsuitable to be used as dielectrics in a standard DRAM cell. Furthermore, the dielectric constant of crystalline HfO_2/ ZrO_2 decreases as the film thickness is reduced below 10 nm, necessitating the search for a thin high-k dielectric material[5]. In the present study, a Si-doped ZrO_2 thin film deposited by thermal atomic layer deposition (ALD) is reported that exhibits an extremely high-k value (~50) without exhibiting any hysteresis within +/-1.5V operation making it an ideal candidate for high performance DRAM. The introduction of Si doping successfully eliminates hysteresis while preserving the high-k value of the tetragonal phase of ZrO_2. These films retain a high dielectric constant even at a reduced thickness of 5nm, resulting in an equivalent oxide thickness (EOT) of 3.5A.

(1) Robertson, J. High Dielectric Constant Gate Oxides for Metal Oxide Si Transistors. *Rep. Prog. Phys.* **2006**, *69* (2), 327–396. https://doi.org/10.1088/0034-4885/69/2/R02.

(2) Tsai, W.; Ragnarsson, L.-A.; Pantisano, L.; Chen, P. J.; Onsia, B.; Schram, T.; Cartier, E.; Kerber, A.; Young, E.; Caymax, M.; De Gendt, S.; Heyns, M. Performance Comparison of Sub 1 Nm Sputtered TiN/HfO/Sub 2/ NMOS and PMOSFETs. In *IEEE International Electron Devices Meeting 2003*; IEEE: Washington, DC, USA, 2003; p 13.2.1-13.2.4. https://doi.org/10.1109/IEDM.2003.1269287.

(3) Ni, K.; Saha, A.; Chakraborty, W.; Ye, H.; Grisafe, B.; Smith, J.; Rayner, G. B.; Gupta, S.; Datta, S. Equivalent Oxide Thickness (EOT) Scaling With Hafnium Zirconium Oxide High-κ Dielectric Near Morphotropic Phase Boundary. In *2019 IEEE International Electron Devices Meeting (IEDM)*; IEEE: San Francisco, CA, USA, 2019; p 7.4.1-7.4.4. https://doi.org/10.1109/IEDM19573.2019.8993495.

(4) Tasneem, N.; Kashyap, H.; Chae, K.; Park, C.; Lee, P.; Lombardo, S. F.; Afroze, N.; Tian, M.; Kumarasubramanian, H.; Hur, J.; Chen, H.; Chern, W.; Yu, S.; Bandaru, P.; Ravichandran, J.; Cho, K.; Kacher, J.; Kummel, A. C.; Khan, A. I. Remote Oxygen Scavenging of the Interfacial Oxide Layer in Ferroelectric Hafnium–Zirconium Oxide-Based Metal–Oxide–Semiconductor Structures. *ACS Appl. Mater. Interfaces* **2022**, *14* (38), 43897–43906. https://doi.org/10.1021/acsami.2c11736.

(5) Jeon, S.; Das, D.; Gaddam, V. Effect of High Pressure Annealing Temperature on the Ferroelectric Properties of TiN/$Hf_{0.25}Zr_{0.75}O_2$/TiN Capacitors. In *2020 4th IEEE Electron Devices Technology & Manufacturing Conference (EDTM)*; IEEE: Penang, Malaysia, 2020; pp 1–3. https://doi.org/10.1109/EDTM47692.2020.9117887.

(6) Wang, C.-Y.; Huang, H.-C.; Chou, C.-Y.; Chen, H.-Y.; Ling, C.-H.; Lin, H.-C.; Chen, M.-J. Dielectric Constant Enhancement and Leakage Current Suppression of Metal–Insulator–Metal Capacitors by Atomic Layer Annealing and the Capping Layer Effect Prepared with a Low Thermal Budget. *ACS Appl. Electron. Mater.* **2023**, *5* (5), 2487–2494. https://doi.org/10.1021/acsaelm.2c01287.

(7) Cho, H. J.; Kim, Y. D.; Park, D. S.; Lee, E.; Park, C. H.; Jang, J. S.; Lee, K. B.; Kim, H. W.; Ki, Y. J.; Han, I. K.; Song, Y. W. New TIT Capacitor with ZrO2/Al2O3/ZrO2 Dielectrics for 60nm and below DRAMs. *Solid-State Electronics* **2007**, *51* (11–12), 1529–1533. https://doi.org/10.1016/j.sse.2007.09.030.

(8) Jeon, W. Recent Advances in the Understanding of High- *k* Dielectric Materials Deposited by Atomic Layer Deposition for Dynamic Random-Access Memory Capacitor Applications. *J. Mater. Res.* **2020**, *35* (7), 775–794. https://doi.org/10.1557/jmr.2019.335.

(9) Patil, S. R.; Barhate, V. N.; Patil, V. S.; Agrawal, K. S.; Mahajan, A. M. The Effect of Post-Deposition Annealing on the Chemical, Structural and Electrical Properties of Al/ZrO2/La2O3/ZrO2/Al High-k Nanolaminated MIM Capacitors. *J Mater Sci: Mater Electron* **2022**, *33* (14), 11227–11235. https://doi.org/10.1007/s10854-022-08097-w.

Dual-gate ambipolar oxide synaptic transistor for multistate excitatory and inhibitory responses

Presenter: ***Yong Zhang***, PhD Candidate, Department of ECE

Collaborator: ***Chi-Hsin Huang***, PhD Candidate, Department of ECE

Advisor: ***Kenji Nomura***, Associate Professor, Department of ECE

Abstract

The controllability of the synaptic behaviors, the synaptic weight update and systematic tuning of the linear conductance responses, are critical for neuromorphic computing applications. Ambipolar synaptic transistor shows the advantages of artificial synapse response type controllability, i.e., both excitatory and inhibitory synaptic behaviors, can be controlled by modulating both hole and electron transports in ambipolar devices. By using dual-gate configuration, moreover, the device shows further dynamic tunability of synaptic conductance weight update levels by the effective gate modulations to hole/electron conductance. Thus, dual-gate ambipolar synaptic transistor is expected greatly to achieve improved performance as compared with conventional single-gate device.

In this talk, we report on the development of the dual-gate ambipolar synaptic transistor using Tin monoxide, SnO channel for neuromorphic applications. Multi-state synaptic responses for both excitatory and inhibitory weight updates was successfully demonstrated in the dual-gate ambipolar SnO transistors. Based on the improvement of conductance level and the linearity of weight update in dual-gate operations, the dual-gate device showed a low-power operation within ~200 pJ per pulse, and a high accuracy pattern recognition of over 90 %, which were improved from the corresponding single-gate device. Low temperature processability and long-term stability of the device operation in ambipolar SnO transistors was also confirmed, which showed a promising flexible electronics application for neuromorphic computing.

[1] Y. Zhang, C.-H. Huang, and K. Nomura, **Dual-gated ambipolar oxide synaptic transistor for multistate excitatory and inhibitory responses**, *Applied Physics Letter* **121**, 26 (2022), 262105.

Presenter: Yuanhang Zhang
Max Di Ventra Group

Title: Collective dynamics and memory-induced long-range order in spiking oscillator arrays.

Recent work has experimentally demonstrated a new class of spiking oscillators known as "thermal neuristors," [1] which operate through thermal interactions between adjacent vanadium dioxide resistive memories. Here, we show large-scale simulations of the dynamics of both 1D and 2D arrays of thermally coupled neuristors. These simulations reveal a rich phase structure, tunable through memory strength and input voltage. Importantly, we observe a robust phase of memory-induced long-range order, which stands in stark contrast to the fragile long-range order typically observed at phase transition points. As an application, we demonstrate that a 2D array of thermal neuristors can function as a reservoir for reservoir computing, opening up new possibilities for tasks like image recognition.

[1] Qiu, E., Zhang, Y. H., Di Ventra, M., & Schuller, I. K. (2023). Reconfigurable cascaded thermal neuristors for neuromorphic computing. Advanced Materials, 2306818.
Work supported by DOE under Grant No. DESC0020892.

Presenter: Brian Li
Dr. Frank Talke Group

Title: 3D Printed Gyroid Elastomer and Silicone Composite for Simulating Human Soft Tissue

This research presents the design, fabrication, and testing of an anisotropic composite consisting of a 3D-printed gyroid elastomer scaffold and a soft silicone matrix to simulate human tissue. Our study aims to demonstrate that these composites can be produced with directionally dependent mechanical properties similar to human tissue. In our prior study, a composite of a thermoplastic elastomer and silicone was shown to be effective at producing stress-stiffening behavior by tuning the material stiffness of the thermoplastic elastomer and the silicone. In this presentation, we create composites with complex anisotropic stress-strain responses by modifying the 3D periodic scaffold structure of the thermoplastic elastomer known as the gyroid. The anisotropic structure is achieved through parameter modification of the gyroid equation. The periodicity of the gyroid cells is reduced in one of the coordinate directions, causing uneven scaffolding reinforcement. Three types of composite tensile coupons were manufactured:

1. coupons with distortion parallel to the axis of tension
2. coupons with distortion perpendicular to the axis of tension
3. coupons with distortion diagonal to the axis of tension

Uniaxial tensile load tests were conducted, and the deformation results were obtained using contact-free 2D digital image correlation. The results show that 3D structured composites can represent the complex anisotropic stress response seen in human soft tissue.

Optical Tracking in Computer-Navigated Surgery using ArUco Markers

Ananya Rajan

PI: Dr. Frank E. Talke

Abstract

Computer-assisted surgical navigation has become a popular solution in difficult operations where a high amount of precision is required. Current state-of-the-art methods of surgical navigation involve tracking reflective 3D marker spheres using IR stereoscopic cameras. However, the cost of implementing such systems may not be affordable for smaller healthcare systems. We aim to develop an inexpensive augmented reality surgical navigation system that is capable of overlaying an MRI image of the patient by using an AR headset to speed up surgical procedures while also improving their accuracy. We propose that fully optical navigation has the potential to be a viable alternative to reflective marker navigation. We use fiducial ArUco markers to facilitate the tracking of real-time position, with the objective of precise MRI overlay. Using two inexpensive cameras, we design and calibrate a stereoscopic camera to record the 3D position of an ArUco marker moving in the X and Y directions. A positioning platform was developed to assess the position predicted from the stereoscopic camera to the real-life position of the marker. Additionally, we explore the possibility of using different color spaces and physical marker colors to improve the detection percentage and accuracy of markers. We identified that black-and-white ArUco markers using the Red, Green, and Blue (RGB) color space gave the highest detection percentage. Next, with the aim of surgical instrument tracking and trajectory planning, it is crucial to track ArUco markers as they move in all 6 degrees of freedom to mimic the motion of instrument handling during surgery. We are performing related tracking experiments using 3D ArUco dice of various shapes and sizes. These are moved around with the help of a robotic arm to understand how accurately our stereoscopic camera can identify 3D markers that are small enough to prevent weighing down of surgical instruments. For future work, we plan to improve our tracking accuracy by improving camera quality and tracking algorithms. We will utilize deep learning to perform 3D reconstruction of patient-specific anatomies for MRI overlay, and also expand into trajectory prediction of surgical instruments.

Presenter: Songyuan Lu
Frank Talke Group

Title: Use of Augmented Reality in Computer-navigated Surgery

The integration of Augmented Reality (AR) technology in medical applications offers a groundbreaking approach to enhancing surgical precision and patient outcomes. Our project is focusing on the use of AR in computer-navigated surgery, particularly for the treatment of chronic back pain.

In the initial stages of development, we are utilizing the Meta Quest 3, an advanced MR headset, to build an AR navigation system. This system is being developed using Unity, a powerful 3D engine, well-suited for creating complex and detailed virtual environments. Our goal is to integrate real-time 3D visualization with patient-specific anatomical data from MRI scans. This integration is expected to significantly enhance the accuracy of surgical instrument navigation. Alongside this, we are employing test models, such as cubes and body shape prototypes, to refine the system's functionality in a simulated environment.

Presenter: Abdoulaye Ndao

Title: Symmetry and topology in photonic nanostructures

Abstract: The quest for smaller, lighter, and more efficient optical components usually comes at the price of reduced functionalities. In this talk, I will provide an overview of how topological approaches to control light-matter interaction enable novel photonic devices with unique features and enhanced performance. I will discuss our recent breakthrough in demonstrating the first topological light source that unidirectionally outcouples to a waveguide from magnetic biased photonic crystal cavities of arbitrary shape. I will also discuss singularities of non -Hermitian systems and their application in biology and healthcare by detecting attomolar concentrations of anti-immunoglobulin G. In the last part of the talk, I will present a premier achromatic broadband metalens that is strategically engineered to span an octave bandwidth with high efficiency. Such devices will be suitable for free space and integrated optics and pave the way towards more complex and versatile systems with applications in high-capacity classical and quantum communications, as well as sensing.

Practical Shaping Codes for TLC Flash Memories

Presenter: ***Simeng Zheng***, Graduate Student, ECE

Collaborators: ***Andrew Tan***, Graduate Student, ECE; ***Carolina Fernandez Moreno***, ENLACE Student Researcher; ***Ismael González Valenzuela***, ENLACE Student Researcher

Advisor: ***Paul H. Siegel,*** Professor, CMRR

Shaping codes are designed to encode information for use on communication and storage channels with a cost constraint by matching a target symbol distribution. Liu et al. [1] analyzed the optimal shaping codes for structured sources and provided a coding scheme for optimal shaping. In flash devices, cells gradually wear out with repeated programming and erasing (P/E) operations, and the damage caused by P/E cycling is dependent on the program level. It has been demonstrated in [1] that optimal shaping codes designed for English and Chinese novels can enhance lifetime and store more information for MLC flash devices (2 bits per cell).

In this project, we aim to formulate optimal shaping codes for TLC flash memories (3 bits per cell) and implement the codes on our Flash Characterization Platform. The experimental steps are described as follows: the wear costs of 8 programmed levels are found empirically; the optimal shaping scheme is then designed according to theorems in [1] and the level distributions optimally match the minimum average wear costs; the coding scheme is realized by the concatenation of compression and Varn code; we write the shaping codewords and original context into several flash blocks. Experimental results show 10X lifecycle improvement when we employ the optimal shaping codes on the sources of Spanish novel.

We combine this shaping code scheme with the code-aware generative channel modeling [2] to facilitate our research on generalized shaping codes. The code-aware channel models leverage knowledge transferred from a pre-trained model using pseudo-random data and has been verified on constrained channels with realistic outputs and only 10% training samples compared to pseudo-random datasets.

[1]. Y. Liu, P. Huang, A. W. Bergman, and P. H. Siegel, "Rate-constrained shaping codes for structured sources," *IEEE Trans. Inf. Theory*, vol. 66, no. 8, pp. 5261-5281, Aug. 2020.

[2]. S. Zheng, P. H. Siegel, "Code-aware storage channel modeling via machine learning," in *IEEE Inf. Theory Workshop (ITW)*, pp. 196-202, 2022.

Double Density Evolution Construction for Polar Codes with Local Global Decoding

Presenter: ***Ziyuan Zhu***, Graduate Student, ECE

Researcher: ***Ziyuan Zhu***, Graduate Student, ECE

Advisor: ***Paul H. Siegel,*** Professor, CMRR

In this study, we present a novel construction method for the outer code for augmented polar codes [1] and local-global polar codes [2]. Leveraging the concept of density evolution construction [3] for polar codes, we enhance the outer polar code design by substituting the channel input with the outcome of density evolution on the inner polar code. Our findings demonstrate a notable improvement in the performance of global decoding for the augmented codes and local-global codes. Presently, empirical results are limited to the Binary Erasure Channel (BEC).

[1] A. Elkelesh, M. Ebada, S. Cammerer and S. t. Brink, "Flexible Length Polar Codes through Graph Based Augmentation," SCC 2017; 11th International ITG Conference on Systems, Communications and Coding, 2017, pp. 1-6.

[2] Z. Zhu, W. Wu and P. H. Siegel, "Polar Codes with Local-Global Decoding," 2022 56th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2022, pp. 392-396, doi: 10.1109/IEEECONF56349.2022.10051996.

[3] R. Mori and T. Tanaka, "Performance of Polar Codes with the Construction using Density Evolution," in IEEE Communications Letters, vol. 13, no. 7, pp. 519-521, July 2009, doi: 10.1109/LCOMM.2009.090428.

Tapping the Potential of Spiral Storage on Persistent Memory

Presenter: ***Wenyu Peng***, Graduate Student, ECE

Researcher: ***Wenyu Peng***, Graduate Student, ECE

Advisor: ***Paul H. Siegel,*** Professor, CMRR

Collaborators: ***Tao Xie***, Professor, SDSU

The advent of byte-addressable persistent memory (PM) has led to a resurgence of interest in adapting existing dynamic hashing schemes to PM. Compared with its two well-known peers (extendible hashing and linear hashing) [1], spiral storage [2] has received little attention due to some limitations. In this research, however, we show that spiral storage has a huge potential for PM. This is mainly because it performs a hash table expansion through address remapping, and thus, incurs fewer rehashing operations.

To tap the potential of spiral storage for PM, several lightweight implementation-level techniques including a lookup table, a log-free expansion mechanism, and a fast recovery method are proposed. The three dynamic hashing schemes are then evaluated on a multicore server equipped with Intel Optane DC Persistent Memory Modules (DCPMM) [3]. Our experimental results demonstrate that, compared to its two peers, spiral storage can achieve better performance under realistic workloads where reads and writes are mixed. Besides, it can recover faster after a system crash.

[1] Enbody R J, Du H C. Dynamic hashing schemes[J]. ACM Computing Surveys (CSUR), 1988, 20(2): 850-113.

[2] Mullin J K. Spiral storage: Efficient dynamic hashing with constant performance[J]. The Computer Journal, 1985, 28(3): 330-334.

[3] Micro. 2015, 3D-X-Point Technology. https:// investors.micron.com/ news-releases/ news-release-details/ micron-updates-data-center-portfolio-strategy-address-growing (2021).

Heat Dissipation Enables Computational Power Through Spiking Oscillators

Erbin Qiu, Yuan-Hang Zhang, Massimiliano Di Ventra, and Ivan K. Schuller

Heat dissipation, a widespread phenomenon in our world, especially within semiconductor chips, sets significant constraints on shrinking the size of these chips. In our study, we exploit the heat dissipation concept among spiking oscillators for computational purposes. These oscillators, termed neuristors, demonstrate various reconfigurable electrical behaviors akin to biological neurons. These include phenomena such as the all-or-nothing law, type-II neuronal rate coding law, spike-in and DC out effect, spike-in and spike-out effect, and stochastic leaky integrate-and-firing law, all achieved solely through heat interaction. Information transmission between the successive neural layers occurs via heat, eliminating the need for traditional CMOS circuits. Notably, we achieve both inhibitory and excitatory functionalities within a single oxide device, enhancing its adaptability. This groundbreaking approach simplifies the implementation of reconfigurable cascading neural layers, showing promise for scalable and energy-efficient thermal neural networks. This advancement holds significant potential for driving progress in brain-inspired computing.

Acknowledgements

E.Q. and I.K.S. were supported by the Air Force Office of Scientific Research under award number FA9550-22-1-0135. Y.-H.Z. and M.D. were supported by the Department of Energy under Grant No. DE-SC0020892.

Presenter: Nareg Ghazikhanian
Professor Ivan Schuller Group

Title: "Filament localization and tuning of resistive switching characteristics in VO_x via selective ion irradiation

Various materials exhibit resistive switching, a useful feature which lends well to the development of novel bioinspired electronic devices, notably artificial neurons and synapses for neuromorphic computing. In a number of material systems, this effect occurs through the percolation of conducting filaments across an otherwise insulating matrix. Often, the location and switching parameters of the resistive switching are impacted by inherent material defects, which poses a serious challenge for scalability of neuromorphic circuits. By selectively engineering defects using a focused ion beam, we report a novel method of locally tuning a material's electronic properties (i.e. conductivity and metal-insulator transition temperature) and by extension, controlling the location and geometry of the conducting filament. In addition to confining the conducting filament to the irradiated region, we observe a greater than 3 orders of magnitude reduction in resistive switching power. Our work demonstrates that local ion irradiation is an efficient tool for fine-tuning material properties related to resistive switching. This offers promising avenues for new energy-efficient biomimetic circuitry.

This work was supported by the Air Force Office of Scientific Research under Award No. FA9550-22-1-0135. Device fabrication and irradiation were carried out at the NANO3 cleanroom facility at UC San Diego.

Presenter: Yun Chen
Kesong Yang Group

Title: First principle investigation of chiral helimagnetism in $CrNb_3S_6$ and $CrTa_3S_6$

Abstract: Chiral helimagnets are considered a superior candidate for future magnetic memories, due to their unique helical magnetic structure. In past experimental studies, it has been discovered that $CrNb_2S_6$ and $CrTa_2S_6$ are chiral magnets exhibiting such chiral helimagnetism. In our work, we endeavored to investigate the unique topological magnetic properties of $CrNb_2S_6$ and $CrTa_2S_6$ by utilizing first-principles calculations based on Density Functional Theory (DFT).

Impact of elastically responsive interfacial Dzyaloshinskii-Moriya interaction on the phonon-driven breathing mode of the skyrmion.

Presenter: ***Egor Savostin***, Ph.D. student, Material Science and Engineering Department

Advisor: ***Prof. Vitaliy Lomakin***, Professor, Electrical and Computer Engineering Department

Abstract: This work explores the behavior of the skyrmion breathing mode (BM) when exposed to elastic waves and pulses in a MgO/CoFe/Pt trilayer deposited on a piezoelectric substrate. Typically, changes in magnetization are associated with deformations caused by magnetoelastic interactions. However, this study considers how strains affect the interfacial Dzyaloshinskii-Moriya interaction (DMI). We use Levy-Fert theory to describe the dependence of DMI vector on the strain field. Then, considering only inverse magnetostriction, we introduce a system of differential equations for elastically driven dynamics of a skyrmion in terms of radius and chirality angle. We show that DMI response to the elastic perturbations increases the BM's nonlinearity. We also investigate how the skyrmion's BM interacts with the changes in the DMI due to elastic waves and pulses using complete magnetoelastic simulations that describe both direct and inverse magnetostriction effects.

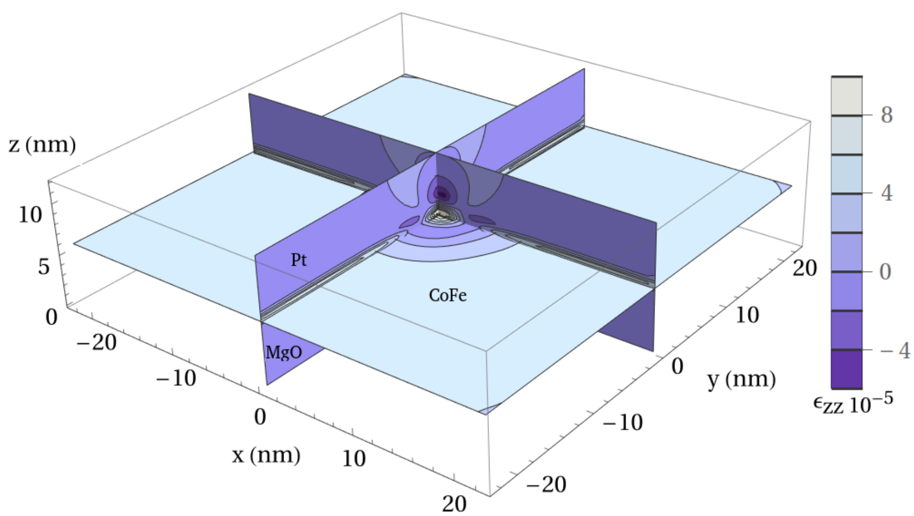

Figure 1.
Distrubution of initial magnetostriction εzz strains generated by a skyrmion in MgO(6 nm)/CoFe(0.7 nm)/Pt(6 nm) trilayer.

Fast approach for Solving Periodic Micromagnetic problems with Finite Element Method

*Fangzhou Ai, Prof. Vitaliy Lomakin**
Department of electrical and computer engineering, University of California, San Diego
Center for memory and recording research, U University of California, San Diego

Abstract: Periodic structures frequently arise in micromagnetic modeling, posing unique challenges in achieving accurate solutions. In finite element method, calculating the potential first then obtaining the field from curl of that is a common routine. For electromagnetic problems, the scalar periodic green's function (PGF) is a well-established method [1], which assumes phase shift and wavenumbers for the free space wave propagation. In micromagnetic problems, we are more likely to encounter static problems where no phase shift and wave propagation present, which leads to a diverged PGF even in 1D case. To overcome this limitation, we present a fast and effective technique for estimating the potential by computing the near field and far field separately. In handling the near field, it can be evaluated rapidly as a standard task [2]. Specifically, we employ the Non-Uniform Fast Fourier Transform (NUFFT) in our in-house micro-magnetic solver Fastmag [3] with minor updates to accommodate the contributions from multiple near-zone images. For the far field, our method proves that despite the divergence of the PGF, in a neutral system where the total magnetic charges sum to zero, the potential remains convergent. By isolating the near field, we achieve a smoother distribution of the far field, allowing for the computation of the far field potential on a sparser grid then interpolating to desired locations, which is very efficient. To control the error, we can adjust the density of the sparse grid, the number of subtracted near-zone cells, and the interpolation order, Fig. 1 illustrates how error is related to different configurations. Our method can handle 1D, 2D, and 3D periodicity, such as an infinite long wire, or an infinite large film etc. It can also extend to any problems involving neutral units beyond micromagnetism.

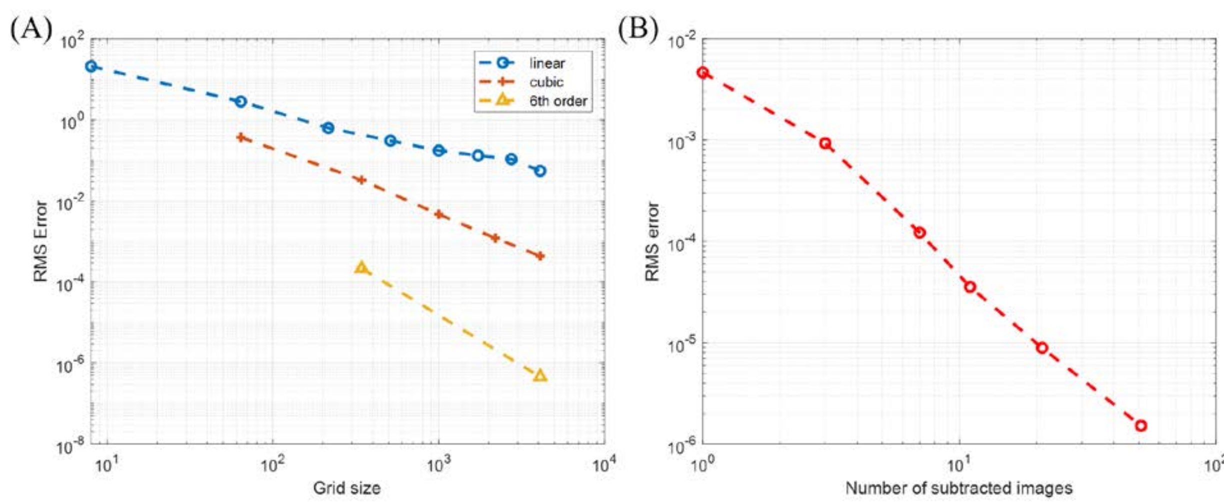

Fig. 1, Illustration of the error between interpolated far field and theoretical value with 1D periodicity. (A) Error comparison for 1st, 3rd, and 6th order interpolation with varying sparse grid sizes, considering the subtraction of only 0th and 1st unit cells. (B) Error analysis of cubic interpolation with 1000 sparse grid points and different numbers of subtracted near-zone unit cells.

References

[1] S. Li, D. A. Van Orden, and V. Lomakin, *IEEE Trans Antennas Propag*, vol. 58, no. 12, pp. 4005–4014 (2010)

[2] N. Engheta, W. D. Murphy, V. Rokhlin et al, IEEE Transactions on Antennas and Propagation, vol. 40, no. 6, pp. 634-641 (1992)

[3] B. Livshitz, A. Boag, H. N. Bertram et al, *Journal of Applied Physics*, vol. 105, pp. 7–541 (2009)

Abstract for CMRR review

Student: Jiawei Duan

Professor: Vitaliy Lomakin

Magnetization dynamics is described by the Landau–Lifshitz–Gilbert (LLG) equation, which states that the dynamics of the magnetization is related to the torque related to various physical interactions, including a component due to the magnetic field. As the operating frequency and device size increase, the magnetostatic approximation for the magnetic field is no longer valid, and electrodynamic effects, such as eddy currents, must be accounted for. The dynamic magnetic field must be obtained via Maswell's equations. Several methods have been introduced to solve Maxwell's equations for eddy current problems, including solving the phi-A-phi/phi-T-phi formulation derived from Maxwell equation using finite element method (FEM), and by evaluating an integral equation with proper boundary conditions [-]. One of the downsides of using typical FEM is the need in a large airbox region to properly account for the decaying magnetic field outside the conducting domain. Such an airbox increases the numerical problem size, thus reducing the performance and increasing the memory requirements, and also may introduce numerical errors.

Here, we present a two-step approach, which allows truncating the computational domain to an arbitrary small airbox or not have an airbox at all. In the first step of this approach, we calculate the magnetic field assuming corresponding magnetic scalar potential to be zero on the outer boundary of the computational domain. In the second step, we correct this solution by calculating the static field generated by the effective surface magnetic charges on the outer boundary obtained based on the domain truncation in the first step. We implement the approach in a FEM code, which uses a modification of the phi-T formulation [-] with edge elements for the vector potential and nodal elements for the scalar potential. The electromagnetic solver is coupled with the FastMag micromagnetic solver [-] to allow modeling combined magnetization-eddy current dynamics in complex magnetic materials and devices.

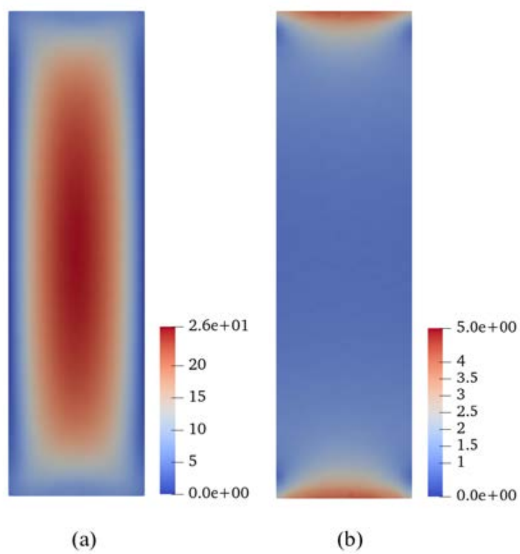

Fig. 1. (a) Total magnetic field induced by eddy current after the correction in the second step. (b) Correction magnetic field induced by effective surface magnetic charges in the second step.

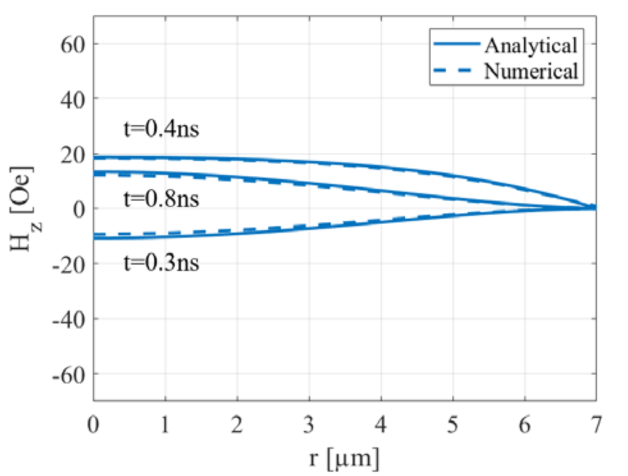

Fig. 2. Axial component Hz of the magnetic field induced by eddy current at the first step, at 0.3ns, 0.4ns and 0.8ns respectively, compared to analytical solutions.

Generalized Drift Diffusion Model for Micromagnetics: Unifying Interface and Bulk Spin Transfer Torques, Spin Hall effect, and Anomalous Hall Effect

Presenter(s): ***Xueyang Wang***, Graduate Student, ECE

Researcher(s): ***Xueyang Wang***, Graduate Student, ECE

Advisor(s): ***Vitaliy Lomakin***, Professor, ECE

Micromagnetic modeling of spin polarized current effects is important for a set of applications. Drift diffusion like models, such as Valet-Fert and drift diffusion models, have an appeal due to their ability to describe complex spin behaviors. The Valet-Fert model describes interfacial spin transfer torque via magnetoelectronic circuit theory with parameters that can be obtained experimentally. However, the model assumes the spin is aligned with the ferromagnetic layer. Drift diffusion model allows handling torques in cases of continuously varying magnetization, such as domain wall motion. However, it assumes that the spin accumulation is continuous at ferromagnetic – nonmagnetic interface, and it does not describe the interface torques. Additionally, its parameters are not directly linked to experimental results.

Here, we show that the Valet-Fert and drift diffusion models can be unified, which allows using the Valet-Fert related experimental material parameters in the drift diffusion model as well as include interfacial and bulk torques in ferromagnetic layers via two more parameters describing the absorption of traverse spin accumulation. We also include spin accumulation generated by the spin hall effect and anomalous hall effect for non-magnetic and ferromagnetic layers. The unified model was implemented as a finite element solver and coupled with the FastMag micromagnetic solver. Fig. 1 shows the solution verification for a 5-layer structure. Numerical study of spin torque and spin Hall effects in various structures will be shown.

Figure 1: Comparison between analytical and FEM solution of the unified model. Inset in (a) shows the considered 5-layer structure with three magnetic layers separated by two non-magnetic layers. (a) Charge potential vs. z and (b) spin potential for the numerical and analytical solutions showing good agreement.