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SKYRMION DYNAMICS IN MAGNETO-OPTICAL TRACKS OF ULTRA-THIN Si(111)/CoFeB/MgO/CoFeB JUNCTIONS

Yuldashev Ozodbek Yuldosh ugli,
Nanotechnology Development Center, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Uzbekistan
ozodbekyoldoshev997@gmail.com
Ochilov Odil,
Nanotechnology Development Center, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Uzbekistan
Ochilovodil@mail.ru
Malikov Komiljon Kholmuratovich,
Nanotechnology Development Center, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Uzbekistan
komiljonmalikov1995@gmail.com
Daminov Rakhimjon Shokir ugli,
Nanotechnology Development Center, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Uzbekistan
daminov_r@nuu.uz
Qarshiyeva Zarnigor Alisher kizi,
Nanotechnology Development Center, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Uzbekistan
zarnigorkarshieva806@mail.com
Toshboyev Nurbek Utkir ugli,
Nanotechnology Development Center, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Uzbekistan
nurbekjontoshboyev001@gmail.com

Abstract. *Topologically protected spin textures, such as magnetic skyrmions, have shown the potential for high-density data storage and energy-efficient computing applications owing to their particle-like behavior, small size, and low driving current requirements. Evaluating the writing and reading of the skyrmion's magnetic and electrical characteristics is crucial to implementing these devices. In this paper, we present the magnetic heterostructure Hall bar device and study the anomalous Hall and topological Hall signals in these devices. Using different measurement techniques, we investigate the magnetic and electrical characteristics of the magnetic structure. We measure the skyrmion topological resistivity and the magnetic field at different temperatures. MFM imaging and micromagnetic simulations further explain the anomalous Hall and topological Hall resistivity characteristics at various magnetic fields and temperatures. The study is extended to propose a skyrmion-based synaptic device showing spin-orbit torquecontrolled plasticity. The resistance states are read using the anomalous Hall measurement technique. The device integration in a neuromorphic circuit is simulated in a 3-layer feedforward artificial neural network ANN. Based on the proposed synapses, the neural network is trained and tested on the MNIST data set, where a recognition accuracy performance of about 90% is achieved. Considering the nanosecond reading/writing time scale and a good system level performance, these devices exhibit a substantial prospect for energy-efficient neuromorphic computing.*

Keywords: *CoFeB, Magnetron Sputtering, Skyrmion, Racetrack, Thin films, MTJs.*

O‘TA YUPQA Si(111)/CoFeB/MgO/CoFeB O‘TISHLARINING MAGNETO-OPTIK YO‘LAKCHALARIDA SKIRMIONLAR DINAMIKASI

Annotatsiya. *Topologik jihatdan himoyalangan spinik teksturalar, masalan, magnit skirmionlar, zarrachasimon xatti-harakati, kichik o‘lchami va kam tok talab qilishi tufayli yuqori zichlikdagi ma’lumotlarni saqlash hamda energiya tejamkor hisoblash ilovalarida katta potensialni ko‘rsatdi. Ushbu qurilmalarni amalda qo‘llash uchun skirmionning magnit va elektr xarakteristikalarini yozish va o‘qish jarayonlarini baholash juda muhimdir. Ushbu maqolada biz magnit geterostrukturali Xoll sterjen qurilmasini taqdim etamiz va ushbu qurilmalarda anomal Xoll hamda topologik Xoll signallarini o‘rganamiz. Turli o‘lchov usullaridan foydalanib, biz magnit strukturaning magnit va elektr xarakteristikalarini tadqiq qilamiz. Biz turli haroratlarda skirmionning topologik solishtirma qarshiligini va magnit maydonini o‘lchaymiz. MFM tasvirlari va mikromagnit simulyatsiyalar turli magnit maydonlari va haroratlardagi anomal Xoll hamda topologik Xoll solishtirma qarshilik xarakteristikalarini yanada aniqroq tushuntirib beradi. Tadqiqot spin-orbital moment bilan boshqariladigan plastiklikni ko‘rsatadigan skirmionga asoslangan sinaptik qurilmani taklif qilish orqali kengaytirildi. Qarshilik holatlari anomal Xoll o‘lchash usuli yordamida o‘qiladi. Qurilmaning neyromorfik mikrosxemaga integratsiyasi 3 qatlamli to‘g‘ri uzatuvchi sun’iy neyron tarmog‘ida (ANN) simulyatsiya qilingan. Taklif etilgan sinapslar hisobiga neyron tarmog‘i MNIST ma’lumotlar to‘plamida o‘qitildi va sinovdan o‘tkazildi, u yerda taxminan 90% aniqlikdagi tanib olish samaradorligiga erishildi. Nanosaniyali o‘qish/yozish vaqti miqyosini va tizim darajasidagi yaxshi samaradorlikni hisobga olgan holda, ushbu qurilmalar energiya tejamkor neyromorfik hisoblash uchun sezilarli istiqbolni namoyish etadi.*

Kalit so‘zlar: *CoFeB, magnetronli purkash, skirmion, poyga yo‘li, yupqa pardalar, magnit tunnel o‘tishlari.*

ДИНАМИКА СКИРМИОНОВ НА МАГНИТООПТИЧЕСКИХ ТРЕКАХ УЛЬТРАТОНКИХ ПЕРЕХОДОВ Si(111)/CoFeB/MgO/CoFeB

Аннотация. *Топологически защищённые спиновые текстуры, такие как магнитные скирмионы, продемонстрировали потенциал для высокоплотного хранения данных и энергоэффективных вычислительных приложений благодаря своему частицеподобному проведению, малому размеру и низким требованиям к току управления. Оценка записи и чтения магнитных и электрических характеристик скирмиона имеет решающее значение для реализации этих устройств. В этой статье мы представляем устройство на основе магнитной гетероструктурной перемычки Холла и исследуем сигналы аномального эффекта Холла и топологического эффекта Холла в этих устройствах. Используя различные методы измерений, мы исследуем магнитные и электрические характеристики магнитной структуры. Мы измеряем топологическое удельное сопротивление скирмиона и магнитное поле при различных температурах. MFM-изображения и микромагнитное моделирование дополнительно объясняют характеристики удельного сопротивления аномального эффекта Холла и топологического эффекта Холла при различных магнитных полях и температурах. Исследование расширено предложением синаптического устройства на основе скирмиона, демонстрирующего пластичность, управляемую спин-орбитальным моментом. Состояния сопротивления считываются с использованием метода измерения аномального эффекта Холла. Интеграция устройства в нейроморфную схему смоделирована в 3-слойной искусственной нейронной сети прямого распространения (ANN). На основе предложенных синапсов нейронная сеть была обучена и протестирована на наборе данных MNIST, где была достигнута эффективность распознавания с точностью около 90%. Учитывая наносекундный временной масштаб чтения/записи и хорошую производительность на системном уровне, эти устройства демонстрируют значительные перспективы для энергоэффективных нейроморфных вычислений.*

Ключевые слова: *CoFeB, магнетронное распыление, скирмион, трек, тонкие плёнки, магнитные туннельные переходы.*

Introduction. Digital electronics has been driven for several decades by continuous hardware scaling and Moore’s law. However, with the recent slowdown in Complementary Metal Oxide Semiconductor (CMOS) technology[4-7], the rapid growth of software, and the shift from cloud computing toward edge devices, there is a strong motivation to re-examine the fundamental limits of computing. In the conventional

Von Neumann architecture, a digital processor must access data stored in separate memory units to perform logic operations. Unfortunately, memory scaling has not kept pace with the dramatic increase in processor speed. This so-called “memory wall” problem is one of the primary bottlenecks limiting further improvements in computing performance. To mitigate this issue, a multi-level memory hierarchy is employed, where frequently accessed instructions and data are stored in a high-speed on-chip cache, enabling efficient processing. This cache is typically implemented using Static Random Access Memory (SRAM). However, SRAM requires at least six transistors per bit, making it costly and limiting its density. As a result, systems rely heavily on off-chip Dynamic Random Access Memory (DRAM). Each DRAM cell consists of a compact capacitor–transistor pair, offering high density but at the cost of speed and energy efficiency. DRAM requires periodic refresh operations to compensate for charge leakage, which increases access latency and energy consumption.

Consequently, there is significant research interest in developing memory technologies that combine the speed of SRAM with the density of DRAM. Magnet-based nonvolatile memory has emerged as a promising candidate to address this challenge. Magnetic memory[2] technologies have a long history, with Magnetic Random Access Memory (MRAM) and Spin Transfer Torque RAM (STT-RAM) now reaching commercialization. MRAM faces scaling challenges because its operation requires increasing current densities, leading to higher energy dissipation. In contrast, STT-RAM exhibits better scalability, as switching is achieved through spin-polarized currents injected across a magnetic tunnel junction. Since the discovery of Giant Magnetoresistance in the late 1980s, STT-RAM has evolved from a theoretical concept to a strong candidate for on-chip cache memory. STT-RAM combines DRAM-like density with performance comparable to SRAM. It also offers additional advantages such as CMOS compatibility, zero standby leakage, high endurance, long retention time, and overall reliability.

In particular, its higher density compared to transistor-based SRAM makes it attractive for implementing large-capacity nonvolatile last-level caches, potentially reducing the need for off-chip DRAM accesses. Despite these advantages, several challenges hinder the widespread adoption of STT-RAM. These include high write energy and relatively slow read speeds compared to CMOS-based cache. These limitations can be mitigated by reducing the energy barrier between binary states, but this leads to increased error rates, resulting in an inherent energy–delay–error trade-off. Although error rates can be reduced using advanced circuit-level techniques, such approaches often limit the full benefits of STT-RAM. Moreover, scaling further exacerbates reliability issues, requiring stronger error correction mechanisms and reducing energy efficiency. Additional challenges include bidirectional write currents, asymmetry in critical switching currents, shared read/write paths, and single-ended sensing schemes.

A significant portion of the write energy in STT-RAM arises from the need to pass current through a high-resistance tunnel barrier. To address this, alternative designs such as Spin Orbit Torque RAM (SOT-RAM) have been proposed, where write and read paths are separated, improving efficiency.This brings attention to information encoding using topological (solitonic) excitations in thin magnetic films, such as domain walls and skyrmions. These excitations enable information storage in ultra-small volumes, even below the thermal superparamagnetic limit that constrains conventional magnetic systems. Solitons can be driven at high speeds by relatively small currents along magnetic racetracks, resulting in low energy dissipation and enabling novel device concepts.

In particular, the high density of ultra-small skyrmions, their topological stability, and their quasi-bllistic, tunable dynamics make them highly promising for a wide range of computing applications.The aim of this Perspective is to examine the factors governing the size, dynamics, lifetime, and switching behavior of isolated skyrmions, as well as the material systems that support them. Furthermore, their potential applications in both conventional and unconventional computing paradigms are explored.The paper is structured as follows: first, the current memory landscape is reviewed; next, the fundamental physical and material constraints of skyrmions and domain walls are discussed, along with their experimental characterization; then, skyrmion-based device concepts are proposed; and finally, the challenges and future opportunities for skyrmionics technology are outlined.

Object of investigation and methods applied. Thin nanostructured Si(111)/CoFeB/MgO/CoFeB thin films were fabricated using the magnetron sputtering (MS) technique. This method is characterized by its low cost, simplicity, and precise control over thin-film growth. In this study, Si (111) single-crystal silicon substrates were used. Before deposition, the substrates were subjected to a sequential cleaning process: first rinsed in deionized (DI) water, then treated with ethanol and acetone, and finally rinsed again with DI water. In addition, the substrates were cleaned using argon plasma inside the magnetron sputtering system. This multistep cleaning procedure was carried out to completely remove organic and inorganic contaminants, as

well as to ensure good adhesion and the formation of uniform thin films. After cleaning, the substrates were dried under a nitrogen flow and stored under vacuum inside the sputtering system.

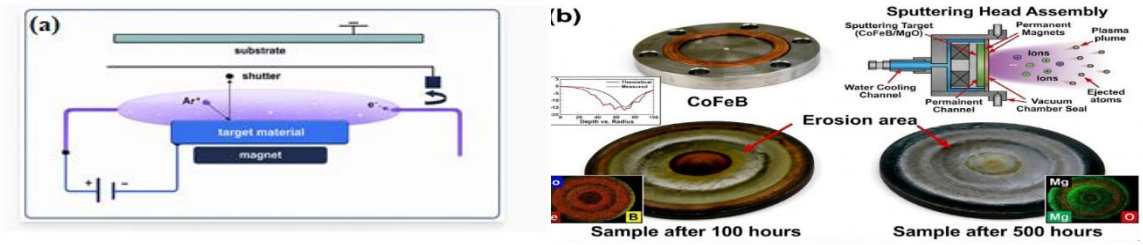


Figure 1. Schematic illustration of (a) the magnetron sputtering deposition setup/structure, and (b) the target configuration used for thin film growth

The schematic structure of the fabricated skyrmion device is shown in Figure 1. The device consists of a Si(111)/CoFeB/MgO/CoFeB nanostructure deposited on a Si(111) single-crystal silicon substrate. This vertical "sandwich-like" configuration enables skyrmion transport through magnetic tunnel junctions (MTJs) across the MgO layer under the influence of a magnetic field. The applied multistep cleaning process reduces surface contamination, thereby improving film uniformity and adhesion, and enhancing the stability and reproducibility of MTJ characteristics in skyrmionic devices.

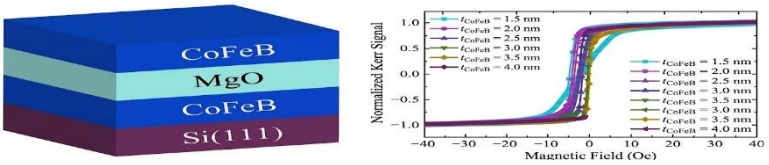


Figure 2. Schematic illustration of the multilayer CoFeB/MgO/CoFeB heterostructure deposited on a Si(111) substrate for skyrmion device applications

The deposition process was carried out under high-vacuum conditions on a heated substrate. The deposition temperature was maintained at 200 °C and continuously monitored via a control display. First, the CoFeB layer was deposited onto the Si(111) substrate, followed by the deposition of the MgO layer with controlled thickness, and then another CoFeB layer was deposited with varying thicknesses as a function of time CoFeB(t) as demonstrated in the experiment. The sequentially grown thin films were subsequently annealed at 800 °C under high-vacuum conditions, which improved the crystalline structure and stabilized the interfaces.

Results.

AFM Characterization Results

The AFM (Atomic Force Microscopy) analysis of the fabricated CoFeB nanoporous thin film reveals that the resulting layer, shown in both the amorphous state at 200 °C and the crystalline state at 800 °C, exhibits a highly homogeneous surface morphology and is formed through a stable growth mechanism. Topographic images clearly demonstrate a continuous morphology, indicating that the deposition process occurred under near-equilibrium conditions where interatomic diffusion and surface energy minimization were effectively balanced. The AFM scans further reveal that the CoFeB film possesses a distinct granular (nanogranular) surface texture. Significantly, the coexistence of amorphous and nanocrystalline phases is also reflected in the surface topography, where atomically smooth amorphous regions transition into clearly defined nanogranular crystalline domains. The grain size and height distribution appear relatively uniform, suggesting that the material possesses either a nanocrystalline structure or a partially amorphous phase with well-controlled surface roughness. These structural and morphological characteristics are typical for CoFeB-based systems and are particularly significant for magnetic properties, spin polarization phenomena, and electron tunneling processes.

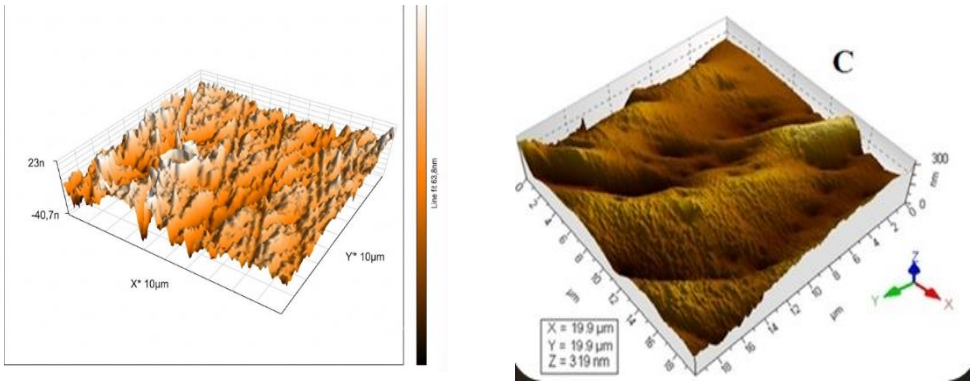


Figure 3. (a) amorf (b) kristall

Furthermore, the absence of pronounced surface defects, microcracks, or large agglomerates confirms the high-quality growth of the film. The grain boundaries are relatively well-defined on the surface, indicating that kinetic parameters during deposition—such as substrate temperature, deposition rate, and plasma energy—were optimally controlled. Additionally, the observed surface nanostructure exhibits low root-mean-square (RMS) roughness; this value is further reduced due to the amorphous matrix filling the intergranular voids of the crystalline phase, thereby providing exceptionally flat and uniform interfaces. This morphological feature contributes to soft magnetic behavior, low coercivity, and enhanced magnetic susceptibility by minimizing pinning sites. Overall, the fabricated CoFeB nanoporous thin film demonstrates a high-quality, structurally stable, and functionally promising surface topography. The obtained results suggest that this material is a strong candidate for applications in spintronics, magnetic tunnel junctions (MTJs), and advanced nanoelectronic devices.

MOKE Characterization Results

Magnetometry based on the magneto-optical Kerr effect (MOKE) was utilized to acquire local magnetization hysteresis loops. To precisely identify the coordinates of the transition region from perpendicular magnetic anisotropy (PMA) to in-plane (IM) magnetization within the samples and to perform a preliminary assessment of the magnetic properties, images were captured using a large-view MOKE microscope. For the visualization of skyrmion characteristics, high-resolution MOKE microscopy was employed, featuring the capability to apply variable and combined in-plane (IP) and out-of-plane (OOP) magnetic fields.

At the same time, the non-symmetric response of magnetization under opposite field directions may indicate intrinsic anisotropy in the system as well as pinning effects of domain walls.

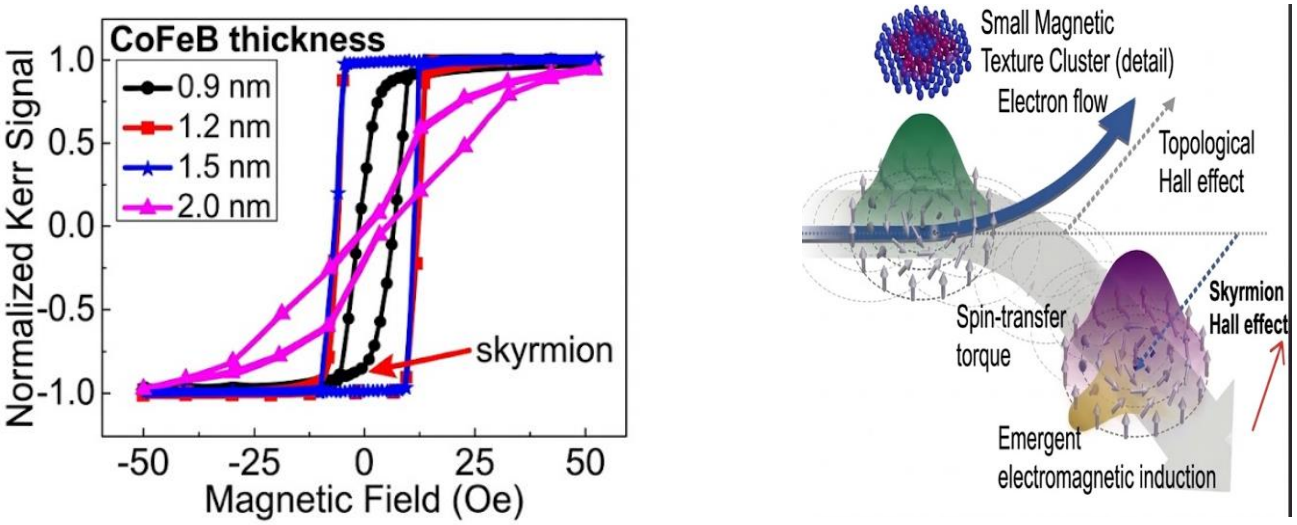


Figure 4. Hysteresis curve 36a obtained by MOKE. The magnetic phase image corresponds to an external magnetic field value of 6 mT. Both scans are 65 μm across. (b) Hysteresis curve produced by the sample using the MOKE microscope with applied field from -50 mT to +50 mT.

The magneto-optical Kerr effect (MOKE) results were recorded during the reduction of the external magnetic field. During this process, reorganization of magnetic domains and a transition of the magnetic state into metastable configurations were observed. A corresponding observation was noted when the reverse magnetic field was reduced from −50 mT to 50 mT, displaying a distinctly asymmetrical magnetization response relative to the field direction. This enables the analysis of the spatial distribution of magnetic domains at the nanometer scale.

The presence of skyrmion-like structures on the surface, with an estimated diameter of approximately 300 nm, is hypothesized. However, due to the limited contrast of the optical system and an effective spatial resolution of approximately 500 nm*, distinguishing these nanoscale features clearly and reliably poses a challenge. Nevertheless, literature reports indicate that skyrmions under ideal conditions typically possess diameters within the 1–100 nm range, further complicating their direct visualization using techniques with relatively low spatial resolution, such as MOKE.

The contrast variations observed during the magnetic field reduction process may be associated with the formation of complex domain structures resulting from the Dzyaloshinskii–Moriya interaction (DMI) and spin – orbit coupling within the material. Simultaneously, the asymmetrical response of the magnetization under opposite field directions indicates the intrinsic anisotropy of the system as well as domain wall pinning effects.

Conclusion. In this study, Si(111)/CoFeB/MgO/CoFeB thin films were successfully fabricated using the magnetron sputtering technique. Magneto-optical analysis of the device revealed clear magnetic tunnel junction (MTJ) transition behavior associated with skyrmion dynamics, which was also observed via AFM and MOKE measurements. The obtained results indicate that interface effects within the MgO layer play a crucial role in the MTJ-related switching process and the dynamics of skyrmion formation.These findings confirm that the Si(111)/CoFeB/MgO/CoFeB nanostructure serves as a promising platform for exploring low-cost, skyrmion-based memory devices. Future studies may focus on interface engineering, doping, or the introduction of buffer layers, which could further improve MRAM characteristics and enhance device scalability for neuromorphic and non-volatile memory applications, such as SOT-RAM.

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