Control of magnetic skyrmion: Theoretical design of skyrmion device

W. Koshibae, Y. Kaneko, J. Iwasaki, M. Kawasaki, Y. Tokura and N. Nagaosa
(RIKEN Center for Emergent Matter Science (CEMS), Wako, Saitama 351-0198, Japan)

The key to develop the magnetic memory devices is nothing more than the control technique of the magnetic texture by external fields. The recent studies reveal that skyrmion,[1)] the nano-sized magnetic texture, is driven by a much smaller electric current density than that for the magnetic domain wall motion, and hence, the potential application of the skyrmion has attracted much attention. To utilize the skyrmion for device applications, the control technique for creation (write), annihilation (erase) and motion (transport) must be established. We theoretically study the creation, annihilation and current-driven motion of skyrmion in the chiral and dipolar magnets in two dimensions, by numerically solving Landau-Lifshitz-Gilbert equation. By the numerical study, we explore the optimal condition to control the skyrmion in the ferromagnetic background.[2)]

Figure 1 shows the schematic figure of the magnetic skyrmion in the thin-film system. In Fig.1 (a), the vortex like structure is in the ferromagnetic background and the magnetic moments wind perpendicular to the radial direction of the circular magnetic texture. This is the Bloch skyrmion and is often observed in the chiral magnets. In Fig.1 (b), on the other hand, the winding plane includes the radial direction. This is the Néel skyrmion and is often found in the artificially composed super-lattice magnet. The Bloch and the Néel skyrmions are in the same topological class: The topology of the skyrmion is characterized by the skyrmion number which is defined by the wrapping number of a sphere by the magnetic moments. The skyrmion number of the perfect ferromagnetic state is zero but it is −1 for the skyrmion in the ferromagnetic background. Because of the difference in topology, the skyrmion cannot be reached from the perfect ferromagnetic state within the continuous deformation of the magnetic texture. As a result, the skyrmion carries a (meta-) stability and is protected by a potential barrier. To overcome this barrier, a large energy enough to destroy the magnetic ordering is needed. However, the spatial discontinuity gives a favorable environment to change the topology of magnetic texture and the stability is reduced. For example, the skyrmion is created rather easily at the edge of a magnet in comparison to the deep inside of the system. Also the local heating provides the hot spot where the skyrmions are nucleated.

The topology of the skyrmion is of crucial importance for the current driven motion: Because of the vorticity of the swirling magnetic texture, a Magnus effect occurs along with the motion of the skyrmion. By utilizing this effect, the large spin-transfer-torque effect appears and moving velocity of the skyrmion is enhanced compared to the domain wall motion.

We show the numerical results of the real-time dynamics of the magnetic textures induced by external stimuli and discuss the creation, annihilation and current-driven motion of skyrmion(s) for the theoretical design of the skyrmion memory devices.

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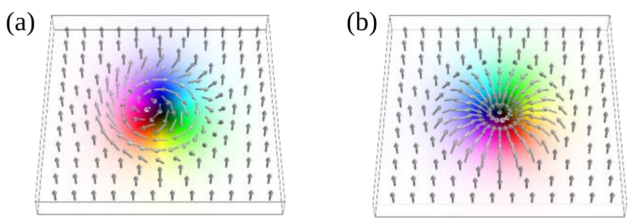

Fig. 1 Shematic figure of the magnetic skyrmion.
(a) Bloch skyrmion. (b) Néel skyrmion. (see text)

Elucidation and application of current-induced domain wall motion

Teruo Ono
(Institute for Chemical Research, Kyoto University, Japan)

Current-induced magentic domain wall motion has been attracted much attention both from scientific and technological points of view[1]. When a magnetic DW is driven by electric current via adiabatic spin torque, theory predicts a finite threshold current even for a perfect wire without any extrinsic pinning[2]. We have shown that this intrinsic pinning determines the threshold current, and thus that the adiabatic spin torque dominates the DW motion resulting in DW motion along electron flow direction, in a perpendicularly magnetized Co/Ni system sandwiched by a symmetric capping and seed layers[3-7]. On the other hand, current-induced DW motion against electron flow direction has been observed in ultrathin magnetic films in which the structural inversion symmetry (SIA) was broken[8, 9]. Recently, this DW motion against electron flow direction has been explained by the combination of a chiral DW stabilized by Dzyaloshinskii–Moriya interaction (DMI) and spin Hall torque[10-12]. Effect of DMI on the field-induced DW motion is also discussed[13].

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Dzyaloshinskii-Moriya interaction at metallic bilayer interfaces

K. Nakamura[1], A-M. Pradipto[1,2], T. Akiyama[1], and T. Ito[1]
[1] Department of Physics Engineering, Mie University, Tus 514-8507, Japan
[2] Institute for Chemical Research, Kyoto University, Uji 611-0011, Japan

In ferromagnetic and heavy metal interfaces, the Dzyaloshinskii-Moriya interaction (DMI), which arises from an asymmetric interface stacking and the strong SOC, plays a key role that may give rise to particular magnetic textures. More specifically, the DMI is essential to stabilize the domain walls in a Néel configuration with a given chirality. Recent measurements and theory for the interfacial DMI have opened new possibilities to obtain understanding on the origin of the DMI and its relation with the details of the electronic and atomic structures of materials.

Here, we present the systematic investigation on the interfacial DMI between 3d transition-metals (TM=Co, Fe) thin films and heavy-metals (X=Ta, W, Re, Os, Ir, P) from first principles.[1)] Calculations were performed within the generalized gradient approximation using the full-potential linearized augmented plane-wave method in a slab geometry, where the spin-spiral structures of a wave vector, q, without the spin-orbit coupling (SOC) were first treated in the generalized Bloch theorem and then the SOC was introduced by the second variational method, in which large unit cells (supercells) with lattice constants corresponding to wavelengths of commensurate spin-spiral structures were employed. The 2400 special k-points (in the chemical BZ) were used to reduce the numerical errors. The DMI parameters were estimated from the total energy with respect to the spin-spiral wavevectors.

The results predict that the DMI parameters depend significantly on the species of both the 3d and heavy metals; typical examples are shown in Fig.1, where the DMI parameter in the Co/Pt has a positive value while that in the Co/Ir has a negative one. We confirmed that for both interfaces, when the Co thickness increases the DMI parameters roughly converge to constant values although the absolute values decrease, and thus the signs of the DMI parameters do not alter with the increase of layer thickness. The results of the Co/Pt agree with experiments and suggest that the DMI originates mainly at the interfaces. We have further checked the interfacial structural dependence by comparing the obtained DMI parameters for both fcc and hcp stackings at the TM/X interfaces, and find that the DMI parameters depend on the stacking structures but the sign does not change. Our results further show that the DMI parameters are related to the orbital magnetic moments of the heavy metal elements. In the talk, we will present/discuss systematically the details of the DMI at the 3d and heavy-metal interfaces.

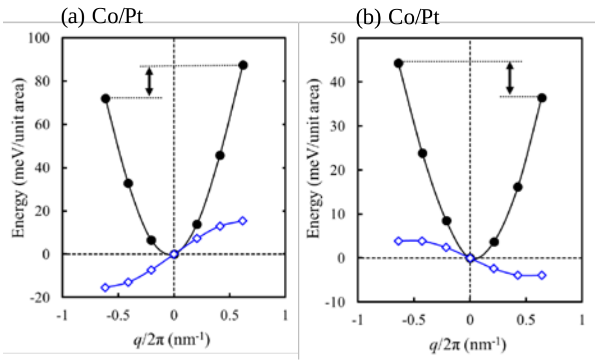

Fig.1. Formation energies of spin-spiral structures, E_{spiral}, as a function of wave number, q, for (a) Co/Pt and (b) Co/Ir interfaces. Open diamonds indicate the difference in the E_{spiral} between q states, where the gradient corresponds to the DMI parameter.

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Co/Ni-nanowire based magnetic shift registers

T. Kondo, T. Shimada, M. Quinsat, M. Kado, Y. Ootera, N. Umetsu, S. Hashimoto, S. Nakamura
(Corporate R&D Center, Toshiba Corporation)

World-wide expansion of ICT infrastructures has demanded the rapid development of the markets for information storage devices. Especially, the CAGR of 40% is expected in next 5-years for the solid-solid data-storage devices which are used in various applications from smart-phones to servers in data-centers. To cover such a huge demand in the next decade however, it is needed to create novel technologies which can realize the nonvolatile memory chip having much larger bit-area-density than that of the state-of-art NAND-flash memory with the fabrication cost as same as that of the current technology.

We are interested in magnetic shift register (MSR), so called "race-track memory",[1] as one of the candidates for the Tera-bit class nonvolatile memory fitting to the data-storage. We believe that the concept of the MSR, in which the magnetic nanowires acts as shift-register without gating elements and wires to identify spatial positions of stored data, has unique and great advantage for the purpose. The simple structure of MSR as a memory cell storing multi-bits will allow us to fabricate the memory chip with ultra-high bit-densities through the processes with acceptable costs.

From this point of view, we have been carrying out researches related to MSR which are from studies of current-induced domain wall motion (CIDWM) in nanowires to the examination of chemical vapor deposition of magnetic thin-layers as the magnetic device fabrication technique.[2-5] In this presentation we are going to show our recent experimental results on Co/Ni-nanowire based MSR's.

The MSR's shown in this presentation were fabricated from Co/Ni-multilayer-based stack structures prepared by using a magnetron sputtering system. We have been focusing the studies using the MSR's on DW-position control and multi-bit read out operations. The position control of DW's has realized by utilizing periodic width modulation for Co/Ni-nanowires.[2] The experimental results reveal that the combination of built-in potential energy valley and current-pulse-DW-driving effectively compensates DW-position fluctuation induced by CIDWM. We have also demonstrated the multi-bit read out operation utilizing a magnetic tunnel junction (MTJ) integrated on the nanowire.[3] Thanks to the Co/Pt-based synthetic antiferromagnetic structure for the reference layer of MTJ, no magnetic field was needed to achieve the data readout from the MTJ-integrated MSR.

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The numerical analysis of standing spin wave configurations controlled with a domain wall in nanowires

Xiaorui Ya, Mao Fukuzono, Terumitsu Tanaka, Kimihide Matsuyama

Department of electronics, ISEE, Kyushu University, Fukuoka 819-0395, Japan

1. Introduction

Spin dynamics in nanostructured magnetic system have attracting intense research interests from view point of fundamental physics and practical applications. The geometrically confined standing spin wave resonance (SSWR) is one of the most power efficient excitation modes. Various kinds of SSWR modes have been observed in wires [1], squares [2] and rectangular dots [3], made of in-plane magnetization films. In the present study, the SSWR properties of nanowires with perpendicular anisotropy have been numerically investigated. Especially, the effect of the domain wall (DW) on the SSWR is focused, aiming at the application to a novel memory and logic applications.

2. Numerical model

Fig. 1 (a) presents a designed device structure, consists of a nanowire and inductively coupled conductors for the SWs generators (GE1, GE2) and detector (DE). Material parameters of large perpendicular and low damping ferromagnets, such as MnGa, MnAl, were assumed in the micromagnetic simulations: M_s = 1000 emu/cm^3, H_k = 13 kOe, α = 0.01. Pulsed microwave currents with phase lag $\Delta\phi = \pi$ and the duration of 930 ps (37.2 ps (=1/(26.9 GHz)) × 25 periods) were assumed to be applied through GE1 and GE2, which excite the 2nd mode SSW along the nanowire. The inductive output waveform when the DW located at the nanowire center is shown as Fig. 1(b).

3. Results and discussions

The maximum amplitude Vout computed for various locations of the DW (x_{DW}) is shown in Fig. 2(a). The significant dependence of the Vout reflects the modification of the SSW configuration due to the DW location, as shown in Fig. 2(b), (c). The DW located under the GE locally suppresses the magnetization precession, reflecting lower Vout, while the influence from the DW located at the nanowire center (node of the SSW) is subtle, reflecting higher Vout. The obtained numerical results demonstrate feasibility of the domain wall location as a state variable of nanowires.

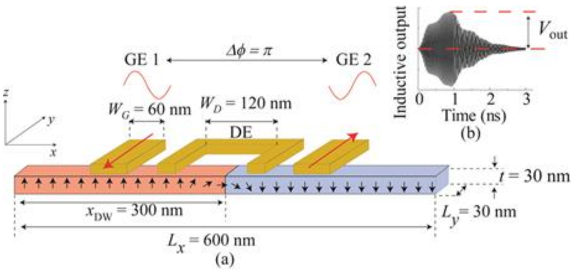

Fig. 1. Schematic of a designed nanowire with DW (a) and the V_{out} waveform (b).

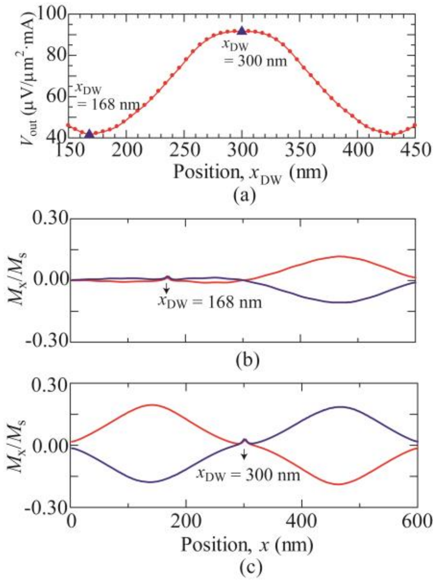

Fig. 2. Dependence of the Vout on the x_{DW} (a), and the comparison of the SSW profile for different DW position; x_{DW} = 168 nm (b) and = 300 nm (c).

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薄膜ヘテロ構造におけるカイラル磁気構造とその制御

Chiral magnetism in thin film heterostructures

林　将光 [1,2]
[1] 東京大学大学院理学系研究科物理学専攻
[2] 物質・材料研究機構
M. Hayashi[1,2]
1, Department of Physics, The University of Tokyo, Japan
2, National Institute of Materials Science, Japan

スピン軌道相互作用が大きい遷移金属層と強磁性層の界面では、ジャロシンスキー・守谷相互作用によってカイラル磁気構造が形成されることが近年明らかになった。また、カイラル磁気構造を有する細線に電流を流すと、電流と同じまたは逆方向に磁区パターン（磁壁）が平行移動できることが実証された。磁区パターンの移動速度は界面ジャロシンスキー・守谷相互作用の大きさに比例するため、その効果を最大化できる積層構造の探索や背後にある物理・材料力学的理解が必要不可欠である。

本講演では、薄膜ヘテロ構造を構成する材料や膜厚が界面ジャロシンスキー・守谷相互作用に及ぼす影響について報告する。また、カイラル磁気構造を自在に制御するために必要となる磁壁の生成と磁壁間相互作用[1]に関する実験について議論する。

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Magnetic nanowire memory for realizing ultra-fast data transfer rate: Magnetic and magneto-optical detection of current-driven domain motion

M. Okuda, M. Kawana, Y. Miyamoto and N. Ishii
(*NHK* Science & Technology Research Laboratories, Tokyo 157-8510, Japan)

To record the video data of 8K ultra-high definition TV, future storage devices require not only a large capacity but an ultra-high data transfer rate. In fact, an enormous transfer rate of more than 144 Gbps is required for recording the uncompressed full-featured 8K video, and of course, an extremely high data transfer rate over 1 Tbps may be required for the future 3D video recording. However, there is no way to treat such terrible “data flood” using conventional memories. For example, even solid-state drives (SSDs), which use semiconductor memory and are currently the fastest commercially available storage devices, have a fundamental data transfer rate of only several Gbps. As a result, SSDs are incapable of recording the uncompressed full-featured 8K video unless multiple devices are used simultaneously.

The racetrack memory[1)] that utilizes the high-speed current-driven domain walls motion[2)] in the magnetic nanowire (NW) has been proposed as a non-volatile random access memory with large capacity. Here, by limiting the direction of current-driven domain motion in one way for the racetrack memory, sequential memory architecture suitable for video recording can be constructed. We have proposed this new sequential “magnetic nanowire memory” consisting of parallel aligned magnetic NWs, as shown in Fig. 1. Each magnetic NW acts as a recording medium, and a pair of write and read head (writer and reader) is attached on. The data are stored along the magnetic NWs direction as the magnetic domains with upward or downward magnetization directions. These troops of domains are shifted quite fast by applying optimum current pulses along the NW direction for data writing and reading purposes. The ultra-high speed storage device will be achieved if the domains in thousands of parallel aligned NWs can be controlled synchronously by applied current pulses.

To demonstrate the operational principle of this NW memory, we adopted a magnetic recording head, in which a pair of write head and read head is equipped, as the writer and the reader in NW memory element. We have succeeded in recording, shifting and detecting the domain motion along the fabricated NW with perpendicular magnetic anisotropy by a magnetic head with current pulses application in our previous work[3)].

In this study, in order to search the artificial lattice NW materials with high domain wall velocity, the multiple magnetic domains motion along an entire NW area was observed by magneto-optical Kerr effect microscopy (MOKE), since a magnetic head can detect only the change in magnetization beneath the reader. As shown in Fig. 2, we could observe the current-driven magnetic domains toward the electron flow along a NW with 1.5 μm-width in real-time. Since an MOKE can detect the multiple domains motion in the entire NW area, it is suitable for investigating the control of synchronous current driven magnetic domains. For realizing parallel aligned magnetic nanowire memory, both magnetic and magneto-optical detection methods are essential to study micron to sub-micron behavior of current driven domain motion.

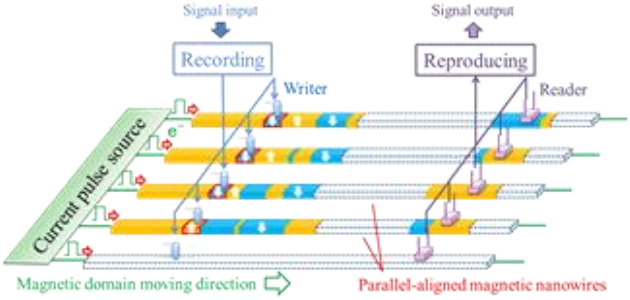

Fig. 1 Schematic illustration of magnetic NW memory consisting of parallel aligned NWs.

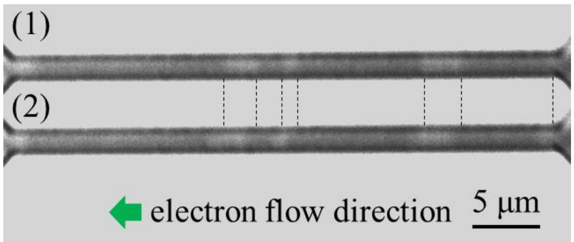

Fig. 2 (1) Initial MOKE image and (2) MOKE image after injection of current pulse. The width of NW is 1.5 μm. Queue of written domains moves along the electron flow direction.

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