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研究課題名（和文）Dynamics-based neuromorphic properties of spintronics devices

研究課題名（英文）Dynamics-based neuromorphic properties of spintronics devices

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研究成果の概要（和文）：本研究課題では、強磁性／反強磁性積層構造におけるスピン軌道トルク磁化反転を決める微視的な機構に関する理解を構築することを目指した。強磁性／反強磁性層界面における交換バイアスは系全体で分散しており、これがアナログ的な振る舞いの原因となっていることを明らかにした。またこの分散自体は15 nm程度の結晶粒のスケールで生じている。一つの結晶粒内では交換バイアスの方向は揃っており、その大きさは数100ミリテスラ程度であり、以前にマクロスケールで観測されていた20-40ミリテスラ程度の交換バイアスは、交換バイアスの方向の分散が平均化された結果として説明されることが明らかになった。

研究成果の学術的意義や社会的意義
The new picture of EB in polycrystalline systems, confirmed experimentally and with simulations, is crucial for understanding and engineering of EB both for fundamental studies and neuromorphic applications.

研究成果の概要（英文）：We have clarified the microscopic mechanism behind spin-orbit torque switching in ferromagnet/antiferromagnet (FM/AFM) stacks. It was found that exchange bias (EB) at the FM/AFM interface varies throughout the system and causes non-binary behavior. This variation happens at a fine scale of the stack grain size i.e. ~ 15 nm. Within a grain, the FM/AFM interface can be assumed to be monocrystalline and it can give EB as large as hundreds of mT. Much weaker EB of ~20-40 mT, previously measured at the FM domain level (~ 200 nm in effective diameter) can be explained by averaging effects. EB in each site is determined by crystallographic orientation of the grain and the quality of the FM/AFM interface, which leads to a wide dispersion of values in polycrystalline non-epitaxial systems.

研究分野：Neuromorphic computing with spintronics

キーワード：neuromorphic computing　synapse　neuron　spintronics　exchange bias　antiferromagnet　ferromagnet

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１．研究開始当初の背景

The paradigm of neuromorphic computing, which is computing using principles inspired by the biological brain, holds a great promise for capable and efficient cognitive systems. However, scaling and development in this area is considerably impeded by the prohibitive cost of running neuromorphic algorithms on conventional von-Neumann hardware. Development of new functional unit elements with properties similar to those of their biological counterparts became essential in recent years. To replicate the biological units of the brain, synapses and neurons, one needs to reproduce their mathematical description. The neurons can be described as leaky integrating and firing units [Izhikevich et al., PNAS (2008)] (Fig. 1). They are connected via synapses, which attenuate strengths of propagating signals according to their variable weights [Boyn et al., Nat. Commun. (2017)] (Fig. 1). Functionality of both elements is based on delays between electrical pulses, which arrive to them. The delays are measured in the “local time” of each neuron and synapse, which is what presents the main hindrance against building their artificial analogues with CMOS, which is typically controlled by one or a handful of clocks (for the whole circuit). Therefore, the challenge is to find novel material systems in which time intervals can be measured naturally.

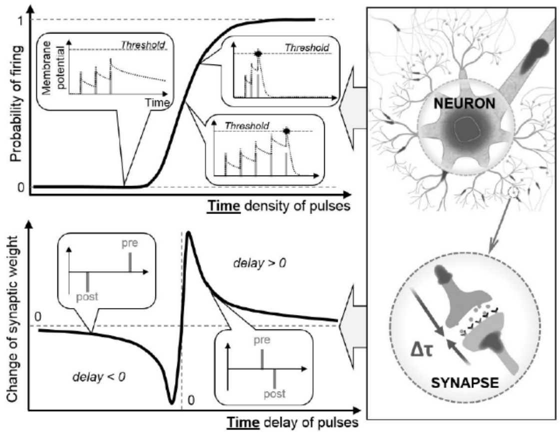

Fig. 1. Neuron and synapses in a biological SNN (right inset) and their functions (on the left). Signals (darker) propagate between neurons via synapses, where they get attenuated. Attenuation strength is adjusted depending on the delay between the moments at which signals arrive to the synapse (lower function). Neurons integrate incoming signals and fire once the integration exceeds a threshold. The process is leaky, which makes it strongly time-dependent (upper function).

２．研究の目的

The most minimalistic and efficient way to measure time intervals is to use a time-evolving physical process. The requirements for this process are that a) one should be able to excite it (e.g. by an electric pulse), b) it should monotonously change the system after excitation and c) one should be able to capture the amount of this change after a given time interval (e.g. by applying another pulse). The purpose of this research was to use magnetization dynamics as the named process and to check whether it can be used for local measurements of time intervals. In the previous work, we have demonstrated that Joule heating produced by current pulses can be used for local time measurements and for artificial synapses and neurons [Kurenkov et al., Adv. Mater. (2019)]. The used in that work material system, antiferromagnet (AFM) / ferromagnet (FM) heterostructure, has shown suitable properties for the task due to the presence of both binary and analogue-like switching. Thus it is meaningful to use the same system for magnetization dynamics-based time measurements. The idea is that a current pulse, applied to the system, excites magnetization dynamics in the FM. This is due to a torque from spin current, which flows in the FM from the AFM with strong spin-orbit interaction. The

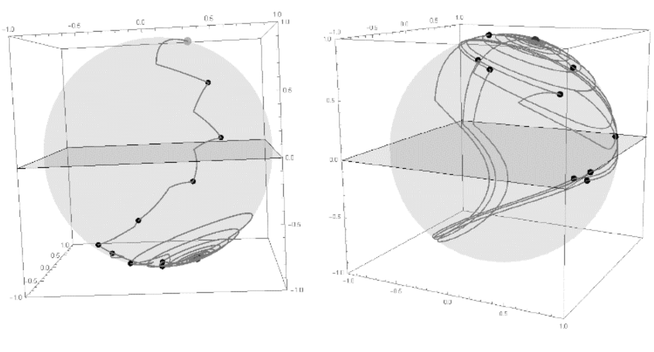

Fig. 2. LLG simulations of binary switching by a train of 10 pulses of 50 ps each. Left side: pulses, separated by 50 ps intervals, induce switching. Right side: pulses, separated by 450 ps, do not induce switching.

excited dynamics continues to evolve even after the initial current pulse has finished. This creates the time-measuring capability, because if a second pulse is applied, its effect will differ depending on the application time (i.e. on the state of the still-changing magnetization when the second portion of spin-orbit torque arrives). This opens a way towards synapse- and neuron-like functionalities. For example, when a bunch of small pulses are applied in a sparse sequence, the magnetization has enough time to relax to almost its initial state and will not switch (equals to "not firing" of a neuron). However, if the time between pulses is decreased, they may gradually push the magnetization further and further until it switches. The simulated trajectories for these cases are shown in Fig. 2. The described behavior is like that of a biological neuron as shown in Fig. 1. The purpose of this research was to check if the described idea could be used to build artificial synapses and neurons.

３．研究の方法

The research method includes both simulations and experiment. Simulations consist of modelling the system in the approximation of coherent magnetization rotation ("macrospin") and more plausible micromagnetic simulations. Experimental part consists of clarifying the details of switching in the chosen AFM/FM system, and then optimization of the system and demonstration of the desired behavior. To achieve the latter, it is necessary to comprehensively understand dynamics of magnetization in the system when current pulses are applied. Once it is understood, the physics can be simulated to determine the optimal system and pulses configurations. Thus, the simulations and the experiment need to go hand in hand until a precise enough model is developed.

The simulations were done using mumax3 for micromagnetic simulations and using custom written Landau-Lifshitz-Gilbert (LLG) simulator. The experimental methods included magnetron sputtering, electron-beam lithography, ion milling for device fabrication; vibrating sample magnetometry, X-ray diffraction and electrical measurements for device characterization. However, it tuned out that the laboratory-based techniques were not enough to clarify the complex magnetic structure of the AFM/FM heterostructures. To do it, we used X-ray magnetic circular and linear dichroism coupled with photo-emission electron microscopy (XMCD and XMLD PEEM) in collaboration with Diamond Light Source in the UK and ETH Zurich in Switzerland.

４．研究成果

The initial simulation was done based on coherent magnetization approximation and LLG equation. Like in the previous work [Kurenkov et al., Adv. Mater. (2019)], we chose a smaller single-domain device for a neuron and larger device with multi-domain switching for a synapse. The simulation was done based on the understanding of the system available in the beginning of this project, i.e. that the system consists of multiple areas with different exchange bias (EB), and that the areas switch independently [Fukami, Kurenkov et al., Nat. Mater. (2016); Kurenkov et al., APL (2017)]. For the neuron, the simulation consisted of calculating magnetization dynamics and its final state for a sequence of 10 pulses of 50 ps separated by intervals from 50 ps to 450 ps. As Fig. 3a shows, the final state strongly depends on the density of applied pulses and roughly resembles the S-shaped characteristic of a neuron (see Fig. 1). For the synapse, the simulation consisted of calculating magnetization dynamics of 500 independent domains when a couple of pulses of opposite polarities is applied with delays from -10 ns to +10 ns. As Fig. 3b shows, the final sample magnetization (given by the ratio of "up" and "down" domains) is indeed determined by the delay. The dependence has non-linear features similar to the biological synaptic weight update function (see Fig. 1), although does not fully reproduce it. It should be noted that a) the simulation assumed 0 K temperature, thus the curves are expected to smoothen at a finite temperature as schematically shown by the red lines in Fig. 3 and b) even though the weight update function is not exactly the same as in the biological case, it can still be used for computation [C. Zamarreño-Ramos et al., Front. Neurosci. (2011)].

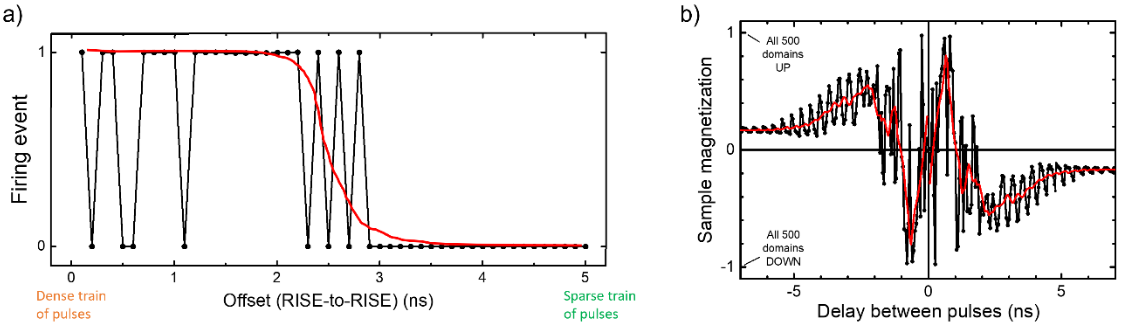

Fig. 3. a) LLG simulation of switching of a binary device with realistic material properties by a train of 10 pulses of 50 ps each. b) LLG simulation of switching of a multi-domain device by two pulses of opposite polarities applied with a variable time interval.

After this initial confirmation of the idea, we performed several beamtimes at Diamond Light Source to image evolution of magnetic structures in the FM and AFM layers and possible correlations between them. We found that, unlike it had been expected, the switching of the FM is dominated by domain wall propagation. However, it is different from what is usually observed: the feature size is smaller, the shapes of the domains are patchy and with rough edges and the domain patterns are very reproducible over multiple cycles of pulses of opposite polarities [Krishnaswamy, Kurenkov et al., Phys. Rev. Appl. (2020)] (Fig. 4).

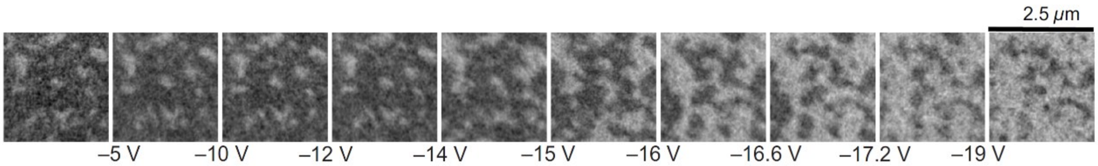

Fig. 4. The current-induced domain switching of PtMn/[Co/Ni]2.5. The domain structure as a function of the pulse voltage imaged by XMCD at the Co L3 edge. The first image shows the initial state prepared by applying 20 consecutive pulses with amplitude +20 V. The amplitude of the voltage pulses is then varied in steps of 0.2 V between +20 V and −20 V. The XMCD images are taken at intermediate voltage steps, as indicated in the figure. Repeated measurements show reproducibility of the domain structures.

These observations indicated that spin-orbit torque switching in AFM/FM structures is governed not only by the torque itself, Dzyaloshinskii–Moriya interaction and Joule heating, but also by some "pattern", which is imprinted in the device and cannot be erased with neither current nor magnetic field (at least of amplitudes below 1 Tesla). A pattern with such properties should most probably exist in the AFM. As we had already known that the EB varies throughout the sample, it was most probable that the variation in the interface or the AFM led to variation of EB, which created potential energy barriers for a propagating DW and resulted in its strong pinning. This hypothesis was supported by the dependence of domain pattern on the stack. Weaker EB due to thinner AFM; or thinner FM with weaker anisotropy led to larger domain size (Fig. 5).

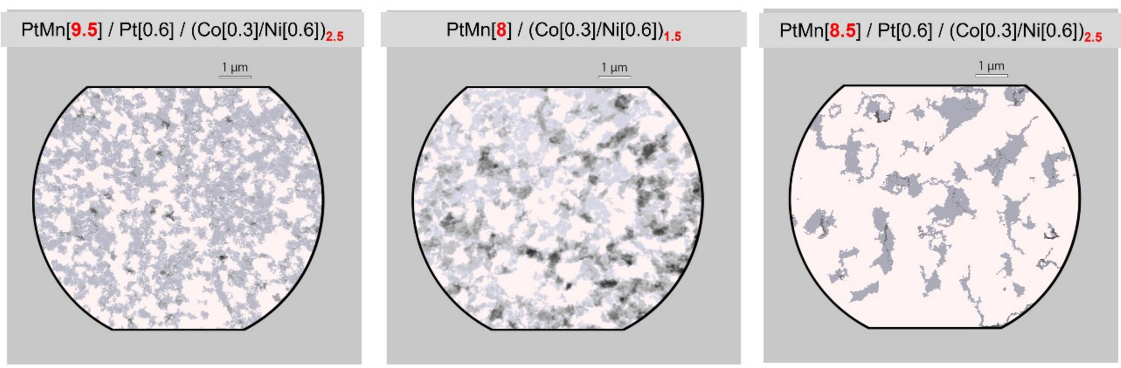

Fig. 5. Dependence of the ferromagnetic domain patterns on the stack properties (pink color shows part of the sample that has not switch after applying several current pulses of increasing amplitude, light gray color shows parts that have switched once, while the darker shades show areas that has switched back-and-forth multiple times).

Consequently, we tried to image magnetic structure of the AFM but despite several attempts could not obtain a convincing result. The explanation for this comes from the micromagnetic simulations. Having most parameters of the system obtained experimentally, including domain sizes from XMCD PEEM and variation of EB between the domains from electrical measurement, one could simulate the switching observed by means of XMCD. However, the simulation result did not match the experimental one (Fig. 6, compare *simulation result 1* and *XMCD PEEM image*).

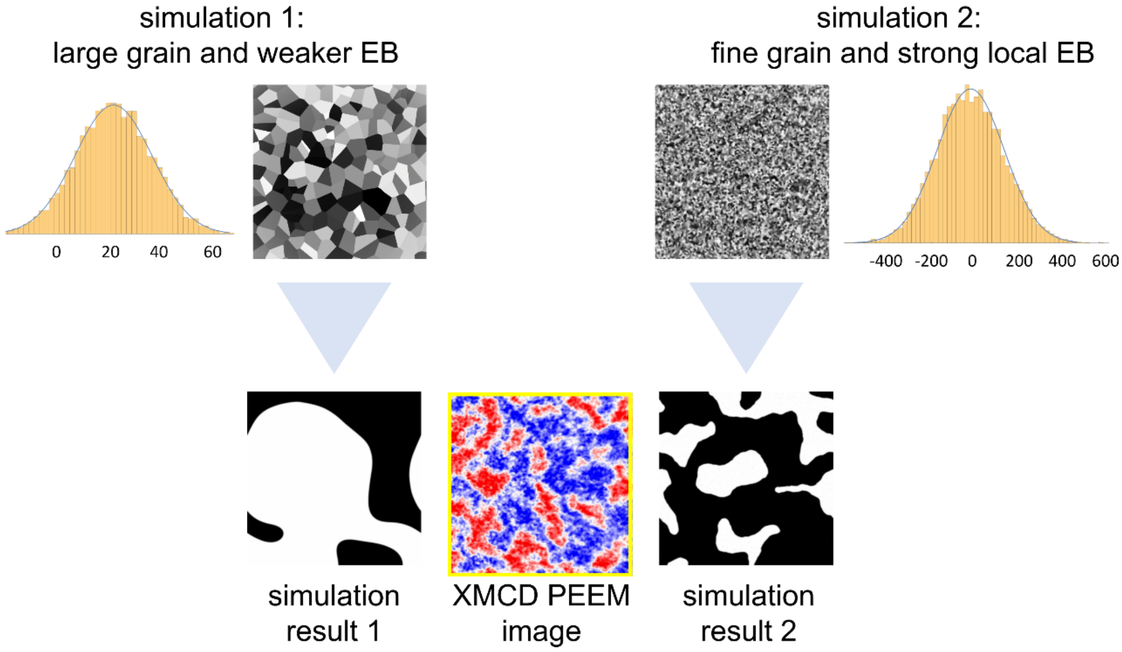

Fig. 6. Micromagnetic simulations versus experimental observation. When simulated with EB varying at the FM domain scale (simulation 1), switching does not reproduce what is observed experimentally. However, once recalculated to the scale of AFM grains (simulation 2), the simulated switching generally matches the XMCD result. The histograms are distributions of EB, measured experimentally at the FM domain scale (simulation 1) and recalculated to the scale of AFM grains (simulation 2).

Both the mismatch in the simulations and lack of magnetic XMCD signal can be explained by the scale of variations in the magnetic structure of the AFM, which should be of the grain scale. Transmission electron microscopy study of the stack showed the grain size of ~15 nm. Since this is below the resolution limit of the PEEM, the signal could not be detected. This also means that EB must vary at the same scale (Fig. 6, simulation 2) and not at the scale of the FM domains (roughly 205 nm of effective diameter, as in the tessellation of Fig. 6, simulation 1). The distribution of EB amplitude measured electrically (histogram in Fig 6, simulation 1) are not incorrect, but averaged over multiple grains. Once recalculated for the grain size (histogram in Fig. 6, simulation 2), it becomes considerably wider (i.e. EB at the grain size is much larger that what can be measured at coarser scales). After these considerations are considered, the micromagnetic simulations gives a plausible result (*simulation result 2* in Fig. 6).
This picture of EB in AFM/FM systems is an important addition to the understanding of EB phenomenon. It could not be obtained in the previous years because spin-orbit torque switching had not been established at that time. At the same time, these findings hint that AFM/FM heterostructures may not be the most suitable system for magnetization dynamics-based neuromorphic functionality. This is because the discovered switching mode, dominated by domain wall propagation, cannot be described by predictable macrospin approximation. On the contrary, switching in the presence of EB is, although reproducible from cycle to cycle, rather random from device to device (due to the unique structure of the pinning sites) and thus can hardly be used for reliable neuromorphic functionality. This, however, may mean that other spintronic systems, such as granular media, may be promising for the proposed approach due to independent switching of the grains (interacting dipolarly but not by exchange interaction).

5．主な発表論文等

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

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