Nonequilibrium skyrmion accumulation induced by direct current in Ir/Co/Pt heterostructure

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We investigated the current-induced dynamics of magnetic skyrmions in Pt/Co/Ir trilayer thin films. Skyrmions segregate in the transverse direction to the current flow via the skyrmion Hall effect, which shows scalability for current density and wire width. We also found the non-local accumulation of nonequilibrium skyrmions under charge current, which has an analogy with the spin accumulation in the nonlocal configuration.

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Magnetic skyrmions1) are a new class of spin textures which arise from competition between the aligning direct exchange interaction and the skew Dzyaloshinskii–Moriya interaction (DMI),2–5) the latter of which is generated by strong spin–orbit coupling and broken inversion symmetry. They are known to show nontrivial topological effects, such as the topological Hall effect,4,5) skyrmion Hall effect (SkHE),6,7) and unusual skyrmion spin-wave excitation.8) Furthermore, their compelling attributes suit memory devices that may have excellent characteristics, including current-drive with low threshold current density,9) and good scalability with small size and dense population.10,11)

Most of the early works on skyrmions were implemented on non-centrosymmetric compounds hosting bulk DMI.12,13) Nowadays, skyrmions generated by the DMI at a thin-film interface14,15) hold the prospect of inherent tunability by using the existing spintronics engineering.16) Interfacial DMI, which can host Néel-type skyrmions, typically emerges in heterostructures of thin ferromagnetic (FM) films and nonmagnetic metals (NM).5)δ transition metals (e.g., Ta, W, Pt, Ir, Os) are mainly utilized for NM because of their high atomic number and hence of large spin–orbit coupling.17,18) To date, skyrmions have been observed in Ta/CoFeB/TaOx,18) Ta/CoFeB/MgO,19) Pt/Co/Os/Pt,20) and multilayers composed of repetitions of Pt/Co/Ta,19) Pt/Co/Ir,21) and Ir/Fe/Co/Pt multilayers.22)

Here, we report the current-induced dynamics of skyrmions in Pt/Co/Ir trilayer thin films. We observed nonequilibrium skyrmion segregation under the direct current (DC), which is a consequence of SkHE. The skyrmion segregation shows scalability via wire width and current density. We also demonstrated non-local skyrmion accumulation, which has an analogy with the spin accumulation in the nonlocal configuration.

Pt/Co/Ir trilayers were grown by combining dc and rf magnetron sputtering on thermally oxidized silicon substrates at room temperature. The magnetization measurement was performed on film stacks consisting of substrate/Ta (1 nm)/Pt (5 nm)/Co (δ/Ir (5 nm)) with varying Co thicknesses between 0.5 and 3.0 nm. The saturation magnetization Ms and the magnetic anisotropy field Hk were obtained by vibrating sample magnetometry at room temperature. The effective magnetic anisotropy Ku was evaluated as Ku = HkMs/2. The corresponding domain morphology was examined by making magneto-optical and transport measurements on devices microfabricated with a film stack consisting of substrate/Ta (1 nm)/Pt (5 nm)/Co (δ/Ir (0.8 nm)/Pt (5 nm)), where the Co layer thickness was continuously varied in the range of 0.5 ≤ δ ≤ 3.0 nm by the linearly moving shutter under the deposition process. The top Pt capping layer worked as a protective layer during the microfabrication process. Our magneto-optical Kerr effect (MOKE) microscopy is equipped with a 50× magnifying lens with a spatial resolution of 250 nm/pixel, and precise magnetic hysteresis loops were investigated via measurements of the Hall resistance. All experiments were performed at room temperature.

The stabilization of skyrmions can be described by the competition between the exchange interaction, magnetostatic energy, interface perpendicular anisotropy, and DMI. The critical material parameter κ is given through the domain wall surface energy,23,24) as

κ = πD/4√AKu, (1)

where A is the exchange stiffness constant, D the normalized DMI per unit area, and Ku the effective PMA energy. When κ > 1, skyrmions are thermodynamically stable, forming a lattice at equilibrium. In contrast, when 0 ≤ κ ≤ 1, skyrmions are metastable, existing as isolated particles. It should be noted that a large value of κ results in appearances of stripes or labyrinth domains at the ground state, and not the sufficient condition to stabilize skyrmion lattice phases. However, skyrmions are usually emerged by applying magnetic filed to such DMI-induced domains, and hence increasing κ is a straightforward approach to realize the skyrmion phase. In terms of material engineering, modulation of Ku is the simplest approach with changing the film thickness t, written as

Ku,t = 2Ku = 2πMt,t, (2)

where 2Ku is the sum of the interface PMA energy at the top and bottom interfaces.
Figure 1(a) shows the thickness $t$ dependence of the saturation magnetization $M_s$ and the effective perpendicular anisotropy $K_u$ multiplied by $t$. Blue dashed lines exhibit linear fitting by $M_s t = M_{s, \text{bulk}}(t - t_{\text{dead}})$ (top panel) and Eq. (2) in the text (bottom panel). (b) Polar-MOKE microscope images at three different thicknesses: #A with $t = 0.655$ nm, #B with $t = 0.650$ nm, and #C with $t = 0.647$ nm. (c) Field dependence of Hall resistance $\Delta R_{xy}$ obtained at the exact thickness of region: #A, #B, and #C.

Figure 1(a) shows the $t$ dependence of $M_s t$ and $K_u t$. Based on the phenomenological description, the bulk saturation magnetization $M_{s, \text{bulk}}$, and magnetic dead layer $t_{\text{dead}}$, and $2 K_u$ were estimated as $1.24 \times 10^6$ A m$^{-1}$, and $0.52 \pm 0.02$ nm, and $1.65 \pm 0.03$ erg cm$^{-2}$, respectively. For $t < 1.2$ nm, $K_u t$ no longer shows a linear dependence on $t$. Such a behavior is observed for ultrathin films$^{25}$ where the volume of the dead layer $t_{\text{dead}}$ is not negligible with respect to the net FM volume. Our interest lies in this ultrathin region with decreasing $K_u$ where $K$ is expected to increase according to Eq. (1).

To identify the actual spin texture, we performed polar-MOKE imaging and Hall resistance measurements on a Pt/Co ($t$)/Ir/Pt heterostructure. Figure 1(b) summarizes the domain morphology for three different Co thickness (labeled #A, #B, and #C). Snapshots in Fig. 1(b) were captured in the vicinity of the coercivity field where the spin texture starts to flip from the negative magnetization ($-m_z$) (colored black in the figure) to positive magnetization ($+m_z$) (colored gray) under a perpendicular field of $H = +8.4$ Oe for #A, $H = +3.3$ Oe for #B, and $H = +4.1$ Oe for #C. The corresponding field dependence of Hall resistances $\Delta R_{xy}$ is plotted in Fig. 1(c).
Although the thickness differences between these three regions are extremely small ($\Delta d < 0.01$ nm), their domain morphologies are completely different. #A indicates typical weak PMA, where a tiny but clear hysteresis loop is observed, whilst #C behaves more in a paramagnetic manner where magnetization continuously rotates with no clear hysteresis. Only for #B with small and distorted hysteresis loop, uniformly distributed sub-micrometer dark spots were observed as shown in Fig. 1(b). They were successful stabilizations of core-down skyrmions at room temperature.18)

Figure 2 shows snapshots of DC $j$ responses for (a) core-up skyrmions (obtained at $H = -3.7$ Oe), (b) stripe domains (at $H = +0.9$ Oe), and (c) core-down skyrmions (at $H = +4.0$ Oe) in a microfabricated device with a width of 15 μm. The right images show the responses for negative current injection: $j = -6.7 \times 10^{10}$ A m$^{-2}$, whereas the right ones for positive current injection: $j = +6.7 \times 10^{10}$ A m$^{-2}$. Skyrmions/stripes always flow along with the electron flow, as illustrated using blue (negative current) or red arrows (positive current). This current-driven motion can be mainly attributed to spin–orbit torque arising from the Co/Pt interface26) whereas the spin-transfer torque generated in the Co layer is considered to be negligible at this ultrathin FM layer.

Apart from the longitudinal drive of the spin textures along the wire ($x$-direction in Fig. 4), both moving core-up and core-down skyrmions deviate toward the y-direction, causing a significant imbalance in the spin texture density along the top or bottom edge of the strip channel. The direction of such DC-induced segregation depends on the electron flow direction and core directions of skyrmions, which indicates this feature can be ascribed to SkHE.6) It should be further noted that there observed a following relaxation process, i.e., the segregation is solved before (initial) and after (remanence) DC application, resulting in uniform distributions as shown in Fig. 2(d). Then, this phenomenon should be attributed to the nonequilibrium state under the current. We named this unique DC response as a nonequilibrium skyrmion accumulation, to distinguish the remnant accumulation of skyrmions reported in CoFeB-based system.6) Besides, the average drive velocity along the longitudinal direction ($x$) are plotted in Fig. 3(a), where the obtained longitudinal velocities results in almost one or two orders of magnitude smaller than previous reports of other interfacial skyrmions.6,19,20) This is possibly due to the relatively large transverse ($y$) velocity rather than longitudinal one, which results in the enhancement of skyrmion segregation here.

To gain further insight, we have also investigated the wire width $w$ dependence of nonequilibrium skyrmion accumulation, as shown in Figs. 3(a) and 3(b). The observed skyrmion density becomes larger with approaching the top edge both for $w = 15$ μm and $w = 50$ μm, as shown in the histograms, indicating that the skyrmions repel each other. The skyrmion density gradients normalized by the wire width $n(y)/w$ are similar for these two different-width devices. Such scalability is general for accumulation phenomena including spin accumulation.27)
A clear analogy between spin accumulation and nonequilibrium skyrmion can be observed in the non-local configuration as shown in Fig. 4, where current is injected only at the bottom wire while the top pocket structure is left as a zero-current region. Results of three different current densities and their remanence after turning off current are presented in Fig. 4(a). As is clear from these snapshots, skyrmions also accumulate in the top pocket and increase their number density with current, although this area is free from any current-induced driving forces. These current-free accumulations can be regarded as the non-local accumulation of nonequilibrium skyrmions, similar to the non-local spin accumulation performed at lateral spin valves.27) In conclusion, we have explored the formation of magnetic skyrmions in Pt/Co/Ir trilayers, and their collective dynamics driven by DC. Room-temperature skyrmions are observed at the ultrathin thickness range of the Co film where the perpendicular magnetic anisotropies start to decrease, even though the thickness range for skyrmion is extremely narrow, smaller than the order of 0.1 Å. These skyrmions are driven under DC, and segregate along to the transverse direction to the current flow following SkHE. However, this phenomenon should be regarded as the nonequilibrium one under the charge current, different from conventional demonstrations which focused on remnants of current pulses. Under this
nonequilibrium state, we successfully observed the non-local skyrmion accumulation, which has an analogy with the non-local spin accumulation.

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