Driving skyrmions with low threshold current density in Pt/CoFeB thin film

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Abstract

Magnetic skyrmions are topologically stable spin swirling particle like entities which are appealing for next generation spintronic devices. The expected low critical current density for the motion of skyrmions makes them potential candidates for future energy efficient electronic devices. Several heavy metal/ferromagnetic (HM/FM) systems have been explored in the past decade to achieve faster skyrmion velocity at low current densities. In this context, we have studied Pt/CoFeB/MgO heterostructures in which skyrmions have been stabilized at room temperature (RT). It has been observed that the shape of the skyrmions are perturbed even by the small stray field arising from low moment magnetic tips while performing the magnetic force microscopy (MFM), indicating presence of low pinning landscape in the samples. This hypothesis is indeed confirmed by the low threshold current density to drive the skyrmions in our sample, at velocities of few \( \sim 10 \text{ m s}^{-1} \).

1. Introduction

Since the proposition of employing skyrmions (chiral textures obtained in material with broken inversion symmetry) in spintronic devices [1], a collective research effort has addressed the key aspects of this subject. Skyrmions are topologically protected since the spin configuration cannot be twisted continuously to another magnetic state with a different topological number [1]. Further, their solitonic nature allows them to behave like particles under the influence of the electrical excitations. These properties make them promising candidates for logic and storage technology [1, 2]. In the experimental perspective, there are three major challenges: (i) stabilization of skyrmions at room temperature, (ii) deterministic nucleation of skyrmions, and (iii) efficient motion of skyrmions under spin Hall effect (SHE). Over the last decade, many experimental works [3–6] have been focused in the aforementioned directions to achieve the ambitious goal of skyrmion based device applications. However, controlled nucleation and motion of individual skyrmions in nanotrails with low power consumption still remain a challenge.

The topological states can emerge due to spin frustration in single-crystal or amorphous materials with large coordination number [7, 8]. However, in the non-frustrated ordered ferromagnetic materials, the neighboring spins principally exhibit collinear ordering due to Heisenberg exchange interaction. Nevertheless, the presence of large spin–orbit coupling and Dzyaloshinskii-Moriya interaction (DMI) due to broken symmetry can lead to stabilization of non-collinear spin textures viz. skyrmions [4–6, 9], since DMI lowers the texture energy and favors chirality. The most widely used combination of such system is a heterostructure of heavy metal (HM)/ferromagnet (FM)/oxide (O) [5, 6]. For spintronics, this structure also enables spin–orbit torque (SOT) to efficiently manipulate the texture [3, 10]. Recent works have revealed that the skyrmions can be stabilized,
nucleated, and driven using external magnetic field [5, 6], electrical field [11], spin polarized current pulses [3, 5, 6, 12], local field gradient [13], anisotropy gradient [14], etc. Nevertheless, a crucial criterion for device applications is to drive the skyrmions at low power. This makes materials with low pinning energy landscape indispensable. Different mechanisms (i.e. particle model based numerical analysis, current driven motion of skyrmion via nanotack, skyrmion defect interactions, etc.) suggest that a skyrmion can move around a defect as well as get pinned depending on the pinning sites, applied current density, etc [3, 15, 16]. Further, it is well established that at lower current densities, the effect of pinning on magnetic textures is more relevant than at larger current densities [17]. One way of optimizing material properties to minimize pinning is to use disordered systems [18]. However, in spite of several works in this field, the required threshold current density to drive the skyrmions is yet to reach the desired limit for real-life applications.

In this context, we chose the combination of Pt/Co$_{40}$Fe$_{40}$B$_{20}$/MgO to investigate the current driven dynamics of the skyrmions under the influence of SOT. CoFeB has been selected due to presence of lower pinning potential in comparison to polycrystalline FM layers (viz., Co, Fe, etc.) [6]. In addition, it has been observed that a CoFeB-based perpendicular magnetic anisotropic system [19] exhibits requirement of a lower threshold current density in current-induced Domain wall motion than a Co/Pt [20] or Co/Ni [21] system. Brillouin light scattering (BLS) measurements have been performed to quantify the DMI in the samples. We show that the threshold current density to drive the skyrmions is significantly lower than the existing literature.

2. Experimental details

We have prepared Ta (5 nm)/Pt (6 nm)/Co$_{40}$Fe$_{40}$B$_{20}$($t_{\text{CoFeB}}$)/MgO (2 nm)/Ta (3 nm) heterostructure on thermally oxidized Si/SiO$_2$ (100 nm) substrates. The schematic of the sample structure is shown in figure 1(a).

We choose SiO$_2$ 100 nm since it leads to better signal in the optical measurements [22]. A Ta seed layer has been chosen to promote the (111) growth of Pt as well as to reduce the strain between Pt and the substrate. We also use a 3 nm Ta layer on the top as a capping layer. The samples are named as S1, S2 for $t_{\text{CoFeB}} = 1.5$ and 1.6 nm, respectively. However, $t_{\text{CoFeB}}$ has been scanned from 1.1 to 1.7 nm to find the spin reorientation transition (SRT) and then we kept the $t_{\text{CoFeB}}$ values close to the SRT to balance the total energy of the system favorable to host skyrmions. The sample preparation was performed in a high-vacuum chamber consisting of sputtering and e-beam evaporators. The base pressure of the chamber was better than 8 × 10$^{-8}$ mbar. Ta, Pt, and CoFeB layers were deposited using DC magnetron sputtering while e-beam evaporation technique was employed to prepare MgO. The substrate has been rotated with 10 rpm during deposition to improve uniformity of the layers.

Further, for deposition of CoFeB the Ar flow was kept at 10 sccm which allows uniform growth of the thin film. The growth pressure and rate of deposition for CoFeB were 8 × 10$^{-4}$ mbar and 0.01 nm s$^{-1}$, respectively. We have used a commercially purchased Co$_{40}$Fe$_{40}$B$_{20}$ stoichiometric target to prepare our thin films. However, from the Energy Dispersive x-ray (EDX) analysis measurements (data shown in supplementary information, figure S1) for sample S2, it is observed that the amounts of Co, Fe, and B are found to be 43%, 41%, and 16%, respectively. The roughness of the sample is observed to be 0.2 nm from AFM measurements. In order to promote the interfacial perpendicular magnetic anisotropy (PMA), all the samples were annealed in-situ at 600°C for 1 h in vacuum (~1 × 10$^{-7}$ mbar), after deposition. The hysteresis behaviour of the samples have been performed via the magneto optical Kerr effect based microscopy (MOKE) in polar mode. To quantify the spontaneous magnetization ($M_s$) of the samples we have performed hysteresis measurements via a superconducting quantum interference device (SQUID) magnetometer. Microfabrication of the tracks and the contacts in the samples has been performed using a two-step electron beam lithography (EBL) and Ar ion etching. We deposited Ti (5 nm) and Au (50 nm) contact pads for transport measurements using e-beam
evaporation. The imaging of skyrmions and their dynamics under the application of current has been performed by magnetic force microscopy (MFM) using homemade CoCr/Cr tip coating, to minimize tip induced perturbations[12, 23]. BLS measurements have been performed in Damon-Eshbach geometry to quantify the interfacial DMI (iDMI) in the samples.

3. Results and discussion

The crystalline nature of the samples has been investigated using x-ray diffraction (XRD) measurements. From grazing incidence x-ray diffraction (GIXRD) data, we obtained peaks with low intensity in both the samples at ~45° and ~68°, which are not present in the virgin substrate (see figure S3 in supplementary information). These peaks have been associated to CoFe (110) and (002)-oriented bcc phase previously reported in the literature [24–26]. The partial crystallization of the CoFeB due to in situ annealing originates the perpendicular magnetic anisotropy in the system. We observe that the sample with 1.1 nm thick CoFeB leads to PMA with a square hysteresis loop, whereas the sample with $t_{\text{CoFeB}} = 1.7$ nm shows hysteresis with in-plane anisotropy (see figure S4 in supplementary information). However, the shape of the hysteresis in figure 1(b) for samples S1 ($t_{\text{CoFeB}} = 1.5$ nm) and S2 ($t_{\text{CoFeB}} = 1.6$ nm) show a sharp change in magnetization (from one saturated state) followed by a relative slow variation before reaching the other saturated state. Usually, in the presence of a finite iDMI and vanishing magnetic anisotropy, such hysteresis loop indicates the presence of a textured (stripes, bubbles, skyrmions) phase as the ground state in the sample [27]. Further, at the part of the hysteresis where the saturation is progressive after the initial drop in magnetization, skyrmion like textures are likely to be stabilized under the presence of a finite external magnetic field. This has been further confirmed by imaging the magnetic states in samples S1 and S2 as shown in figure 2.

We have performed the BLS measurements to quantify the iDMI of the samples. The detailed analysis of calculating the iDMI values from the BLS measurements is shown in the supplementary information. The iDMI constants are $0.33 \pm 0.03$ mJ m$^{-2}$ and $0.32 \pm 0.02$ mJ m$^{-2}$ for S1 and S2, respectively, which is similar to previous reports [28, 29].

In order to stabilize isolated skyrmions, we need to fine tune the domain wall (DW) energy [9] between two limiting cases: (a) a large positive energy which causes the collapse of the skyrmions, and (b) a large negative wall energy which destabilizes the collinear order, leading to isolated skyrmions only at large external magnetic field [12]. One way of achieving this is to keep the FM layer thickness near the SRT to reduce the effective anisotropy energy of the system to near zero. For this work, the thickness of the samples S1 ($t_{\text{CoFeB}} = 1.5$ nm) and S2 ($t_{\text{CoFeB}} = 1.6$ nm) are chosen close to the SRT. This is confirmed by the presence of skyrmionic states in samples S1 and S2 as observed using MFM. Wormlike stripe domains are observed in the demagnetized state indicating that the ground state is the spin spiral state (figure 2(a)). By applying OOP fields of 1 and 3 mT (figures 2(b) and (c)), isolated skyrmions have been observed in the samples S1, and S2, respectively. The average size of the skyrmions (measured within the accuracy of the MFM) varies in the range of 200–500 nm and 150–300 nm for samples S1 and S2, respectively. We note from figures 2(b), and (c) that the shape of the skyrmions is significantly perturbed even by the stray field of the lowest moment magnetic tips. In the area marked by cyan circle in figure 2(b), we note that there is a ‘flat domain’ ~500 nm on the left at the level of the skyrmion which is cut into two domains (skyrmions). This indicates that the skyrmions have jumped to a different pinning points for a few scanning lines. Further, it should be noted that the skyrmions are elongated along the slow scan axis (transverse axis/Y-axis). The reason of such elongation is because the skyrmion has more time to interact with the magnetic tip along the slow scan axis and hence can be dragged progressively providing an elongated shape. Such significant tip induced perturbations indicate the presence of low pinning landscape in the samples. A detailed discussion of the moment of the MFM tips and their effect on the magnetic textures is discussed in figure S7 of the supplementary information file. The low pinning landscape of CoFeB can be understood from its structural

Figure 2. (a) and (b) MFM images of sample S1 at demagnetized state and at an applied out-of-plane field of 1 mT, respectively. (c) MFM image of sample S2 at an applied field of 3 mT. The cyan circled area in (b) is a guide to the eye for the distorted shape of the skyrmion induced by tip perturbation (horizontal scanning).
intrinsically amorphous CoFeB crystallizes into bcc structure after annealing beyond 300 °C. It has been reported that the amorphous phase (and subsequently crystallized bcc phase) may be expected to lead to a low density structural defects acting as pinning sites in compared to conventional fcc textured 3d ferromagnetic materials [6, 19, 25, 30]. Burrows et al [30], reported that the depinning field in Ta/CoFeB/MgO films can be as low as 2–3 mT which is an order of magnitude lower than the depinning field for Co/Pt [31] or Co/Ni [32]. The mean spacing between the consecutive stable pinning sites in CoFeB is 300 nm [33]. This observed low pinning can be corroborated to the low interface roughness, low density of grain boundaries, and better structural coherence in the CoFeB films as compared to other materials hosting skyrmions [13, 19, 25, 34–36].

Sample S1 is selected for the study of current-induced dynamics due to its lower pinning energy landscape and better control under applied magnetic field. We start from the demagnetized state and apply a small external field of 1.0 mT to stabilize the skyrmions in the tracks. Subsequently, we apply ~19ns current pulses with increasing amplitude. Figure 3(a) shows the schematic of the sample structure with the AFM images of the nanotacks (3 parallel tracks with width ~1.2 μm separated by ~2.8 μm from each other) along with Ti/Au contact pads. The current is injected in the tracks using the point-like contacts on the left and collected at the right. We observe that at J ∼ 0.56 × 10^11 A m^−2, the skyrmions in the track do not move and beyond a threshold current density of ∼0.8 × 10^11 A m^−2, the skyrmions start moving. The measurements for each current density are repeated in between 3-5 times depending on the number of skyrmions inside the tracks. The velocity of skyrmions is calculated by averaging the movement of these 4–7 number of skyrmions which move due to the pulses. The motion of the skyrmions, opposite to the electron motion direction, confirms the dynamics due to SOT [3, 5, 6, 37]. In order to confirm that the stray field originating from the magnetic tip has minimal/no effect on the motion of the skyrmions, we have checked using no pulse applied where the skyrmions were stable (a detailed discussion is given in figure S8 of SI). Figures 3(b) and (c) show the skyrmion displacements marked by different colours before and after the application of one current pulse. It should be noted that both at lower as well as at higher current densities, the displacements of all the skyrmions are not equal. This is the consequence of the skyrmion hopping due to the presence of defects within the potential landscape [38]. The skyrmions advance in the track until they are either pinned or face strong skyrmion-skyrmion repulsion from another pinned skyrmion. We have plotted the average velocity of all the skyrmions present in the track for a particular current density (figure 3(d)). The error bar (green) in figure 3(d) corresponds to the standard deviation. The high current velocity data indicate, within the deviation range of the data, that a regime is reached, where defects plays a minor role, analogue to a flow regime [39]. We obtain skyrmion velocity up-to ~40 m s^−1 for a current density of ~2 × 10^11 A m^−2. Application of higher current densities led to burning of the contacts due to application of large (19 ns) current pulses through the tracks (see figure S9 in supplementary information for details). The threshold current density reported in this work is lower than the
ones reported in the literature (see table 1 in supplementary information) whereas the corresponding velocity (>10 m s\(^{-1}\)) is comparable to previous reports.

### 4. Conclusions

In conclusion, we have shown that skyrmions are stabilized at very low field in Pt/CoFeB/MgO heterostructures at room temperature. We have quantified the iDMI value for our thin films which is similar to earlier reports. We observe significantly lower threshold current densities to drive the skyrmions. Larger skyrmion velocity under shorter current pulses can be expected in similar samples. Here, we have used a single set of optimized deposition conditions (growth pressure, deposition rate, annealing temperature) to prepare the samples. However, the impact of various deposition conditions on pinning potential can be investigated in the future. We believe that the work presented here may be helpful to utilize such low pinning materials for skyrmionic applications at low power consumption.

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### Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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### References

[1] Fert A, Reyren N and Cros V 2017 Nature Reviews Materials 2 17031  
[2] Nagaosa N and Tokura Y 2013 Nat. Nanotechnol. 8 899–911  
[3] Sampaio J, Cros V, Rohart S, Thiaville A and Fert A 2013 Nat. Nanotechnol. 8 839  
[4] Soumyanarayanan A et al 2017 Nat. Mater. 16 896–904  
[5] Jiang W et al 2015 Science 349 283–6  
[6] Woo S et al 2016 Nat. Mater. 15 501–6  
[7] Zhang X, Xia J, Zhou Y, Liu X, Zhang H and Ezawa M 2017 Nat. Commun. 8 1717  
[8] Streubel R et al 2021 Adv. Mater. 33 2004830  
[9] Rohart S and Thiaville A 2013 Phys. Rev. B 88 184422  
[10] Thiaville A, Rohart S, Sue E, Cros V and Fert A 2012 EPL (Europhysics Letters) 100 57002  
[11] Ma C, Zhang X, Xia J, Ezawa M, Jiang W, Ono T, Piramanayagam S, Morisako A, Zhou Y and Liu X 2018 Nano Lett. 19 353–61  
[12] Hrabec A, Sampaio J, Balmagiudan M, Gross I, Weil R, Chérief S, M, Stashkevich A, Jacques V, Thiaville A and Rohart S 2017 Nat. Commun. 8 15765  
[13] Casiraghi A, Corte-León H, Vafaee M, Garcia-Sanchez F, Durin G, Pasquale M, Jakob G, Kläui M and Kazakova O 2019 Communications Physics 2 145  
[14] Tomasello R, Komineas S, Sircusanso G, Carpentieri M and Finocchio G 2018 Phys. Rev. B 98 024421  
[15] Reichhardt C, Ray D and Reichhardt C O 2015 Phys. Rev. Lett. 114 217202  
[16] Lin S Z, Reichhardt C, Batista C D and Saxena A 2013 Phys. Rev. B 87 214419  
[17] Hanneken C, Kubetzka A, Von Bergmann K and Wiesendanger R 2016 New J. Phys. 18 055009  
[18] Kim J V and Yoo M W 2017 Appl. Phys. Lett. 110 132404  
[19] Fukami S, Suzuki T, Nakatani Y, Ishiwata N, Yamanouchi M, Ikeda S, Kasai N and Ohno H 2011 Appl. Phys. Lett. 98 082504
[20] Moore T A, Miron I, Gaudin G, Serret G, Aufrêt S, Rodmacq B, Schuhl A, Pizzini S, Vogel J and Bonfim M 2008 Appl. Phys. Lett. 93 262504
[21] Fukami S, Nakatani Y, Suzuki T, Nagahara K, Ohshima N and Ishiwata N 2009 Appl. Phys. Lett. 95 232504
[22] Hrabec A, Belmeguenai M, Stashkevich A, Chérif S, Rohart S, Roussigné Y and Thiaville A 2017 Appl. Phys. Lett. 110 242402
[23] Chauleau J Y, Weil R, Thiaville A and Militat J 2010 Phys. Rev. B 82 214414
[24] Kanak J, Wiśniowski P, Stobiecki T, Zaleski A, Powroźnik W, Cardoso S and Freitas P 2013 J. Appl. Phys. 113 023915
[25] Ikeda S, Miura K, Yamamoto H, Mizunuma K, Gan H, Endo M, Kanai S, Hayakawa J, Matsukura F and Ohno H 2010 Nat. Mater. 9 721–4
[26] Huang T, Cheng X, Guan X and Miao X 2014 IEEE Trans. Magn. 50 1–4
[27] Mallick S, Panigrahy S, Pradhan G and Rohart S 2022 Physical Review Applied 18 064072
[28] Tacchi S, Troncoso R, Ahlberg M, Gubbotti G, Madami M, Åkerman J and Landeros P 2017 Phys. Rev. Lett. 118 147201
[29] Khan R, Shepley P, Hrabec A, Wells A, Ocker B, Marrows C and Moore T 2016 Appl. Phys. Lett. 109 132404
[30] Burrowes C et al 2013 Appl. Phys. Lett. 103 182401
[31] Metaxas P, Jamet J, Mougin A, Cormier M, Ferré J, Baltz V, Rodmacq B, Diény B and Stamps R 2007 Phys. Rev. Lett. 99 217208
[32] Burrowes C et al 2010 Nat. Phys. 6 17–21
[33] Tetienne J P et al 2014 Science 344 1366–9
[34] Zhang X, Vernier N, Zhao W, Vila L and Ravelosona D 2018 AIP Adv. 8 056307
[35] Tetienne J P et al 2015 Nat. Commun. 6 1–6
[36] Jaiswal S et al 2017 Appl. Phys. Lett. 111 022409
[37] Büttner F et al 2017 Nat. Nanotechnol. 12 1040–4
[38] Kim K J, Lee J C, Ahn S M, Lee K S, Lee C W, Cho Y J, Seo S, Shin K H, Choe S B and Lee H W 2009 Nature 458 740–2
[39] Berges L, Haltz E, Panigrahy S, Mallick S, Weil R, Rohart S, Mougin A and Sampaio J 2022 Phys. Rev. B 106 144408