Speed and stability of magnetic chiral motion in a chain of asymmetric thin nanodots

To cite this article: Kyeong-Dong Lee et al 2015 Appl. Phys. Express 8 103003

View the article online for updates and enhancements.

Related content
- Topical Review
  June W Lau and Justin M Shaw
- Ratchet effect of virtual domain wall motion in discrete magnetic nanodot chains
  Xiao-Ping Ma, Seon-Dae Kim, Hong-Guang Piao et al.
- The 2014 Magnetism Roadmap
  Robert L Stamps, Stephan Breitkreutz, Johan Åkerman et al.

Recent citations
- Field-controllable injection of virtual magnetic domain wall in discrete magnetic nanodot chains
  Xiao-Ping Ma et al.
- Ratchet effect of virtual domain wall motion in discrete magnetic nanodot chains
  Xiao-Ping Ma et al.
- Techniques in micromagnetic simulation and analysis
  D Kumar and A O Adeyeye
Speed and stability of magnetic chiral motion in a chain of asymmetric thin nanodots

Kyeong-Dong Lee¹, Young Min Kim¹, Hyon-Seok Song², Chun-Yeol You³, Jung-Il Hong², and Byong-Guk Park¹*

¹Department of Materials Science and Engineering, KI for the Nanocentury, KAIST, Daejeon 305-701, Korea
²Department of Emerging Materials Science, DGIST, Daegu 711-873, Korea
³Department of Physics, Inha University, Inchon 402-751, Korea

E-mail: bgpark@kaist.ac.kr

Received August 17, 2015; accepted September 9, 2015; published online September 29, 2015

The speed and stability of magnetic chiral motion are numerically investigated in a chain of asymmetric thin nanodots. The chirality of the magnetization rotation in an asymmetric nanodot plays a significant role in the velocity at low critical field, and there exists a stable operating magnetic field at the intermediate level, irrespective of the arrangement of asymmetric nanodots. Additionally, with induced in-plane anisotropy, we find that the chiral motion yields more stability with a lower critical field at room temperature. We ascribe the shift of the energy barrier as a major contribution to the thermal stability, high speed, and low critical field of chiral motion. © 2015 The Japan Society of Applied Physics

With the advancement of recent nanofabrication technology, the shape engineering of isolated magnetic nanodots¹ has opened a way to magnetic quantum cellular automata (MQCA): magnetic logic operation² and the transmission³ of a magnetic soliton⁴,⁵ or magnetic orientation along the dot chain. The advantages of MQCA are ultrahigh density, high speed, low power consumption, and room-temperature operation.⁶–¹⁸

In the nanodot system, the clock frequency of magnetic rotational motion has been expected to exceed 100 GHz with a large saturation magnetization.¹⁹ On the other hand, stability is enhanced by introducing magnetocrystalline biaxial anisotropy.¹⁶,¹⁹ Alternatively, shape control of an individual nanodot could also be a viable approach to enhance speed, stability, and energy-saving.¹⁷,¹⁸,²⁰,²¹ In this case, the nanodot shape needs to be fabricated uniformly, which is still a challenging issue. This could be less sensitive using high-speed regime with a strong driving field, especially in the presence of extrinsic spin wave damping such as Cherenkov radiation²²,²³ or in the presence of spin wave emission in the wake of soliton propagation.²⁴–²⁷ However, this high field regime is undesirable for achieving low power consumption.

In the present study, we introduce asymmetric elements and their arrangement in order to investigate the effect of the rotational chirality of magnetization reversal on the speed, stability, and critical field of magnetic soliton motion.

A soliton, which is head-to-head magnetization orientation in a dot chain, was simulated using single domain disks with diameters of 80 nm and thicknesses of 4 or 6 nm. The simulations were performed by using mostly MuMax3²⁸—a GPU-accelerated micromagnetic simulator, together with the object oriented micromagnetic framework (OOMMF).²⁹ We used an absolute value of the gyromagnetic ratio, \(\gamma_\mu\), of 17.6 MHz/Oe, an exchange stiffness, \(A_{\text{ex}}\), of 15 pJ/m, and a cell size of \(2 \times 2 \times 4\) or \(2 \times 2 \times 6\) nm³ according to the thickness of the dot. The gap distance, \(d\), was set to 10 nm in order to ensure sufficient strength of the dipolar interaction. Note that large \(d\) values reduce the dynamic field range due to the decrease of dipolar coupling strength, but the underlying physics is nearly the same when we suitably increase the dipolar strength by increasing the saturation magnetization \(M_s\), the thickness, or the diameter. To introduce asymmetry in the shape of the dot, the edge of the disk was cut by 10 nm with respect to the diameter of 80 nm, and a chain of 37 dots was used. All simulations were performed at \(T = 0\) K except for the case of thermal stability test, which was performed at room temperature (300 K). To form a soliton state near the first dot on the left end of the chain, an elliptical aspect ratio of 3 was used for the first fixed dot in order to guarantee a fixed magnetic state as depicted in Fig. 1. Similarly, the end dot also had an elliptical aspect ratio of 3 to compensate for the reduced dipole field due to the void of next-neighboring dots at the right end of the chain. Individual dots were identified with numbers ranging from 0 (fixed dot) to 36 (end dot). To create the initial state with a single soliton next to a fixed dot, a simulated energy relaxation process was applied.

Figure 1 shows a schematic and snapshots of soliton propagation utilized in this study. To initiate soliton propagation, an external field \(B\) was applied globally along the +z-axis. This external field had a logistic step function shape with a rising time of 100 ps. Solitons move faster as the amplitude of the applied external field increases. To quantitatively analyze the soliton propagation along the chain, we plotted the change of average magnetization of each dot, \(M_s/M_{\text{sat}}\), in the

![Fig. 1. Magnetic chiral motion in an asymmetric nanodot chain. Two different types of arrangement of an asymmetrically edge-cut dot: (a) C and (b) U. (a) C aligns the edge-cut side in an alternated way. A magnetic soliton localized at head-to-head magnetization propagates upon application of an external magnetic field, \(B = 7.5\) mT, along the +z-axis. Three snapshots are shown with color codes for magnetization angle, \(\phi\). (b) U changes dot 1 for a different alignment from that of C, which reverses the rotational chirality from dot 2 to the end dot between U and C. The reversal of dot 1 depends on its cut-side, whereas reversals from dot 2 show cog-wheel rotational motion.](image-url)
B is denoted by I and II according to the magnitude of the external magnetic field, $B$. $B'$ drives the same $v$, irrespective of its chirality.

Two possible types of array arrangements of an asymmetrically edge-cut dot are shown in Figs. 1(a) and 1(b). As a result, the bottom rows in Figs. 1(a) and 1(b) depict two rotational chiralities of the cog-wheel magnetization motion of an asymmetric dot. The array arrangement of type C, shown in Fig. 1(a), represents an anti-parallel array with alternating orientation of the edge-cut side of an asymmetric dot. Type U, shown in Fig. 1(b), changes dot 1 for a different alignment from that of type C, which reverses the rotational chirality from dot 2 to the end dot between types U and C. We find that the reversal of dot 1 depends on its cut side, whereas reversals from dot 2 show cog-wheel rotational motion, which governs magnetic soliton motion in this system. By comparing the soliton velocity of these arrays, we investigate the effect of asymmetry in shape as well as chirality in magnetization rotation.

Figure 2 shows the soliton velocity as a function of the external magnetic field, $B$, for C and U when $M_s = 800 \text{ emu/cm}^3$, $r = 4 \text{ nm}$, and $d = 10 \text{ nm}$. In this graph, two regions can be inferred according to the magnitude of $B$. In region II, the strong $B$ drives the velocity towards saturation and shows no particular difference between the two types since the $B$ field is dominant. Interestingly, we find that there is a stable operating field of $B'$, irrespective of chiral motion or the arrangement of the asymmetric dots. In region I, the solitons move with different velocities depending on the spin rotation direction. Intriguingly, in region I, U exhibits an abnormally faster velocity than C.

We will attempt to provide insight into the high speed in region I of U because it could be relevant for device application. First, as shown in the inset of Fig. 3(a), we discovered that in all types of arrays, the spins exhibit a cogwheel-like rotation. For example, in C, when the spins rotate towards the cut-side boundary in the first dot, the spins in the second dot rotate towards the cut-side boundary and vice versa to continue a cogwheel-like rotation. In U, the spins in the first dot also rotate around the cut-side boundary due to the shape anisotropy. However, because of the alternating pattern thereafter and dipolar coupling, the spins in the second dot rotate around the uncut-side boundary, and then the spins in the next dots also rotate around the uncut-side boundary. Impressively, in Fig. 3(a), we can see a direct relationship between the intergap time and the velocity. Obviously, as seen by the smallest inter-gap or minimal time-lapse, a fast velocity is observed when the spins rotate around the uncut-side boundary in the U array. In contrast, the solitons in C with cut-side rotation are shown to move slowly (comparative animation of U and C shown in Video S1 in the online supplementary data at http://stacks.iop.org/APEX/8/103003/mmedia). As plotted in this figure, we could infer from the time-dependent chiral rotational motion of dots 1 to 6 for C and U that rotating around the uncut-side boundary is energetically more favored, yielding a greater velocity than that of the opposite case C. The small inter-gap time in the U array can be understood in terms of the following. As shown in the inset dot of Fig. 3(b), we use here two macrospins to describe the magnetization of one dot, $m_{\text{left}}$ and $m_{\text{right}}$, and consider two energy contributions from shape anisotropy and exchange as the energy density. In the dipolar field $H_d \propto 1/r^3$, $H_d$ of a rotating soliton
dot towards the +x-axis affects mainly the partial left side of the next-neighboring dot in the chain. Therefore, the energy density of a single dot as a function of magnetization angle $\phi$ could be shifted by $\phi_s$ due to the dominant contribution of its partial left-side area. The energy density of left-side area ($m_{\text{left}}$) is shown by the orange curve. In contrast, the sum of the energy density of $m_{\text{left}}$ and $m_{\text{right}}$ is not shifted due to the compensation between the left- and right-side area of the dots. With this model, the easy axis of the edge-cut single dot will remain in the $x$-axis. However, the absolute value of the shape anisotropy energy of the left and right side of the dot could be different because of the strong localized field. This spatial dependence represents the curved shape anisotropy $K_s$ effect of thermal fluctuation strength according to Brown\(^{36}\) was checked by using a different value of the Gilbert damping constant as the thermal fluctuation field, $H_{\text{therm}} \propto \sqrt{\alpha}$.\(^{29,34}\)

In conclusion, we studied the effect of asymmetric elements and their arrays on the chiral motion of a magnetic soliton. With a well-defined dot shape, speed could be enhanced by a factor of 6 at low field regimes with proper rotational chirality. For a situation with shape non-uniformity, there existed a stable operating magnetic field irrespective of the arrangement of the asymmetric nanodots. The model system with the asymmetric nanodot array enabled us to seek out a new thermal stability factor of the induced in-plane anisotropy, which afforded a more flexible energy barrier shift in the asymmetric nanodot, thereby improving thermal stability and lowering the critical field. This implies that an understanding of magnetic soliton chiral motion is essential for enhancing the speed, critical field, and thermal stability in magnetic nanodot devices.

In another sense, type U could be used as a measure of the stability of the chiral soliton motion since this is sensitive to the misalignment of the magnetization angle induced by external perturbation, as shown by the large difference of $v$ between C and U at region I in Fig. 2. Especially at the low-field regime I in uncut-side rotation mode, the misalignment might cause the change of rotation chirality, thereby resulting in a large deviation from the initial speed owing to the transition from U mode to C mode in the middle of propagation.

To verify it with the thermal fluctuation, simulations were performed at 300 K.\(^{33-35}\) An array type of U was tested under a near-threshold magnetic field due to the large sensitivity of misalignment. To see the reliability, fifty repetitive simulations were performed with random thermal seed numbers from 1 to 50.

The effect of the weakly induced in-plane anisotropy, $K_{u,y}$, was also considered since this could change the energy-barrier shift of $\phi_s$, as shown in Fig. 4(a). For simplicity, we carried out the simulation with parameters that $T = 300 \text{ K}$, $M_s = 800 \text{ emu/cm}^3$, $t = 6 \text{ nm}$, and $d = 10 \text{ nm}$. The effect of thermal fluctuation strength according to Brown\(^{36}\) was checked by using a different value of the Gilbert damping constant as the thermal fluctuation field, $H_{\text{therm}} \propto \sqrt{\alpha}$.\(^{29,34}\)

Figures 4(b)–4(e) show the histogram of the velocity distribution. Without $K_{u,y}$ of Fig. 4(b), the histogram shows several distinct counts of fail. In the case of a larger damping constant of 0.05, shown in Fig. 4(c), the mean value of the velocity distribution decreases due to a more dissipative motion, and its variance becomes wider with more counts of fail. However, in the presence of $K_{u,y}$, shown in Figs. 4(d) and 4(e), the histograms show no distinct count of fail, even with a large damping constant of 0.05 (comparative animation with and without fail is shown in Video S2 in the online supplementary data at http://stacks.iop.org/APEX/8/103003/mmedia). This means that $K_{u,y}$ improves the thermal stability of the chiral motion of type U by shifting the energy barrier, which results in more probable activation through $0 \rightarrow U \rightarrow 1$ in Fig. 3(b). In addition, the net anisotropy along the $x$-axis is decreased, as shown in Fig. 4(a), thereby reducing the threshold critical field from approximately 12 to 6 mT.

**Acknowledgments** This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2014R1A2A1A11051344, 103003-3 © 2015 The Japan Society of Applied Physics
NRF-2015M3D1A1035354, NRF-2014R1A2A2A01003709, NRF-2012K1A4A3053565 and Education, Science and Technology (NRF-2013R1A1A2011103). It was also supported by the DGIST R&D Program of the Ministry of Science, ICT & Future Planning of Korea.

5) V. G. Bar'yakhtar and M. V. Chetkin, Dynamics of Topological Magnetic Solitons (Springer, Berlin, 1994).
31) Thetaevolve module is used in OOMMF, which is written by Oliver Lemcke, to model finite temperature via a differential equation of the Langevin type.33)
32) MuMax version 3.6 or higher is used, which is contributed by Jonathan Leliaert for finite-temperature simulations with a large time step.