Magnetic skyrmions

Your passion for physics: What are you curious about?

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Abstract

This paper summarises the current developments in magnetic skyrmions and their possible application as a computational platform. In theory skyrmions could increase the speed and information density of future computational devices, while also decreasing their power consumption.

1 Introduction

The theoretical construct of a skyrmion was first introduced by Tony Skyrme in 1961 [1]. In 2009 skyrmions were observed in magnetic materials for the first time [2]. They are topologically protected spin arrangements in two dimensional magnetic materials under the presence of a broken spatial inversion symmetry. They can be described as repulsive quasi-particles.

The energy of the exchange interaction for two neighbouring spins in a magnetic material is given by equation 1. This interaction is favouring their parallel alignment.

$$E_{ex} = J \cdot (\boldsymbol{S}_1 \cdot \boldsymbol{S}_2) \tag{1}$$

$$E_{DM} = -\boldsymbol{D}_{12} \cdot (\boldsymbol{S}_1 \times \boldsymbol{S}_2) \tag{2}$$

Under the presence of a broken spatial inversion symmetry an additional energy term arises, due to the so called Dzyaloshinskii-Moria interaction (DMI), as given in equation 2. This interaction favours an orthogonal alignment of neighbouring spins. Its magnitude is dependant on material properties. The result of this additional energy term is a stable spin arrangement with a flipped inner spin in respect to the exterior spins, called a skyrmion.

To achieve stable skyrmions both the magnetic field and the DMI within the two dimensional magnetic material have to be tuned carefully. Using multilayered substrates, both of these properties can be changed. In 2020 skyrmions were observed at room temperature and zero external magnetic field for the first time within such a multilayered system [3].

2 Application in storage devices

One promising future application of skyrmions could be within storage devices. Their small size of a few nanometers and high stability might lead to a high density storage device. One proposal for such a storage device is a linear racetrack memory [4]. Representing logical "0" and "1" by the existence or nonexistence of a skyrmion in a given space, the write operations could be conducted by creating or annealing skyrmions. This has been shown to be possible in a deterministic way using external magnetic fields [5], or spin polarised electrical currents [6]. Skyrmions could be detected in an electrical device using Topological Hall Resistivity [7] or Magnetic Tunnel Junctions [6]. Moving the skyrmions along the racetrack memory could be realised using spin orbit torques [8, 9]. In addition to the driving force, spin orbit torques induce a force orthogonal to the direction of movement. This effect is called the skyrmion Hall effect [9]. To prevent the skyrmions escaping from any storage devices due to this skyrmion Hall effect the edge-repulsion can be used by placing a boundary layer to control the skyrmion motion.

Due to their massless properties skyrmions can be transported efficiently. It has been shown, that they can be moved using currents that are orders of magnitudes smaller than for magnetic domain based devices [8].

3 Application as computational device

Besides using skyrmions in a future storage device, they could also be used as a computational platform. Although this concept has not been tested until the present day, multiple theoretical proposals and simulations have been brought forward. Using different properties of skyrmions, logical gates capable of being used for different operations – such as AND, NAND, OR, NOR – could be manufactured [10]. A potential speedup of about three orders of magnitude could be possible.

References

[1] T.H.R. Skyrme. A unified field theory of mesons and baryons. *Nuclear Physics*, 31:556–569, 1962.

[2] S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böni. Skyrmion lattice in a chiral magnet. *Science*, 323(5916):915–919, 2009.

[3] K. Gaurav Rana, A. Finco, F. Fabre, S. Chouaieb, A. Haykal, L. D. Buda-Prejbeanu, O. Fruchart, S. Le Denmat, P. David, M. Belmeguenai, T. Denneulin, R. E. Dunin-Borkowski, G. Gaudin, V. Jacques, and O. Boulle. Room-temperature skyrmions at zero field in exchange-biased ultrathin films. *Phys. Rev. Applied*, 13:044079, 2020.

[4] Riccardo Tomasello, E. Martinez, R. Zivieri, Luis Torres, Mario Carpentieri, and Giovanni Finocchio. A strategy for the design of skyrmion racetrack memories. *Scientific reports*, 4:06784–1, 2014.

[5] Niklas Romming, Christian Hanneken, Matthias Menzel, Jessica E. Bickel, Boris Wolter, Kirsten von Bergmann, André Kubetzka, and Roland Wiesendanger. Writing and deleting single magnetic skyrmions. *Science*, 341(6146):636–639, 2013.

[6] Xichao Zhang, Yan Zhou, Kyung Mee Song, Tae-Eon Park, Jing Xia, Motohiko Ezawa, Xiaoxi Liu, Weisheng Zhao, Guoping Zhao, and Seonghoon Woo. Skyrmion-electronics: writing, deleting, reading and processing magnetic skyrmions toward spintronic applications. *Journal of Physics: Condensed Matter*, 32(14):143001, 2020.

[7] Davide Maccariello, William Legrand, Nicolas Reyren, Karin Garcia, Karim Bouzehouane, Sophie Collin, Vincent Cros, and Albert Fert. Electrical detection of single magnetic skyrmions in metallic multilayers at room temperature. *Nature Nanotechnology*, 13(3):233–237, 2018.

[8] Luqiao Liu, Chi-Feng Pai, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman. Spin-torque switching with the giant spin hall effect of tantalum. *Science*, 336(6081):555–558, 2012.

[9] Seonghoon Woo, Kyung Song, Hee-Sung Han, Min-Seung Jung, Mi-Young Im, Ki-Suk Lee, Kun Song, Peter Fischer, Jung-Il Hong, Jun Choi, Byoung-Chul Min, Hyun Koo, and Joonyeon Chang. Spin-orbit torque-driven skyrmion dynamics revealed by time-resolved x-ray microscopy. *Nature Communications*, 8:15573, 2017.

[10] Shijiang Luo, Min Song, Xin Li, Yue Zhang, Jeongmin Hong, Xiaofei Yang, Xuecheng Zou, Nuo Xu, and Long You. Reconfigurable skyrmion logic gates. *Nano Letters*, 18(2):1180–1184, 2018.