HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

UDC 537.622:538.975:004.085

THE PRACTICAL SIGNIFICANCE OF HYBRID THIN FILMS FOR EXTENDING MEMORY CELLS

K. Dj. Nurmatov
Teacher, Jizzakh State Pedagogical University, Jizzakh, Uzbekistan
E-mail: mrkamol1986@gmail.com
ORCID: 0000-0002-4032-3811
doi:https://doi.org/10.5281/zenodo.24162819

Abstract. The paper considers the role of hybrid thin films, multilayer structures that combine a ferromagnet with a heavy metal, an oxide or a ferroelectric, in skyrmion-based memory cells. Each layer of a hybrid stack serves its own function: the heavy metal provides the Dzyaloshinskii–Moriya interaction (DMI) and the spin–orbit torque, the oxide barrier provides tunnelling readout and voltage control of anisotropy, and the ferroelectric localizes the skyrmion and enables its electrical switching. We estimate the write energy per unit area for three mechanisms: current-driven writing (Joule losses in the heavy-metal layer), ferroelectric polarization reversal, and capacitive control without switching. The ratio of the energies of any two mechanisms does not depend on the cell area and is set by material parameters alone. For a 50 × 50 nm² cell, current-driven writing requires 0.2 to 26 fJ depending on the skyrmion motion regime; polarization reversal costs about 1 fJ in BaTiO_{3}, 0.13 fJ in CuInP_{2}S_{6}; and capacitive control costs 0.07 fJ. We conclude that there is a trade-off between the strength of the magnetoelectric coupling needed to localize the skyrmion and the write energy, which grows with ferroelectric polarization. Recommendations for choosing materials for a hybrid cell are formulated.

Keywords: magnetic skyrmion; hybrid thin film; memory cell; magnetoelectric interaction; spin–orbit torque; ferroelectric; write energy; magnetic tunnel junction.

1. Introduction

A memory cell performs three operations: it stores a state, allows that state to be written, and allows it to be read. In conventional devices these functions are split across different elements of the circuit. Magnetic skyrmions, topologically stable vortex-like spin textures only a few nanometres in size [1, 2], make it possible to combine all three functions in a single multilayer film. No single material can do this alone, however. A ferromagnet can hold the information, but a skyrmion only appears when the Dzyaloshinskii–Moriya interaction (DMI) is present, and DMI arises only at the interface with a heavy metal. Electrical readout requires a tunnel barrier, and writing without current requires a ferroelectric or dielectric layer. This is why we use the term hybrid thin film: a stack in which layers of different physical nature jointly make one memory cell work.

The idea of storing bits in moving magnetic textures was first put forward in the racetrack-memory concept [3], and was later carried over to skyrmions [1]. The coupling between magnetic and electric order in multiferroics and heterostructures has been reviewed in detail in [4, 5]. Yet when moving from individual demonstrations to designing an actual cell, a question arises that, in our view, has received too little attention: what does each function cost in energy, and do the layers interfere with one another?

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

The aim of this work is to evaluate the practical significance of hybrid thin films for extending the functionality of skyrmion-based memory cells. To do so we address three tasks: (1) systematize the functions of the layers of a hybrid cell using the literature; (2) quantitatively compare the write energy of the current-driven and field-driven mechanisms; (3) identify limitations and formulate recommendations for choosing materials.

2. Literature Review

Ferromagnet/heavy metal. The first room-temperature skyrmions were obtained precisely in such structures. In Pt/Co/Ta and Pt/CoFeB/MgO multilayers, skyrmions were observed and moved by current [6]. In Ir/Co/Pt structures, the DMI contributions of the upper and lower interfaces add up, which stabilizes small skyrmions [7]. These films are grown by magnetron sputtering, a process compatible with microelectronics manufacturing. Work from Russian groups supports this route: micromagnetic and magneto-optical properties of ferromagnet/heavy-metal structures have been studied, including a hybrid $[CoFeB/Ir/Ta]_7/Nb$ system [8], and domain structures have been formed in CoPt multilayers with the probe of a magnetic force microscope [9].

Velocity and current. Time-resolved X-ray microscopy showed that at a current density of about 10^{11} A/m² and pulses of roughly 5 ns, a skyrmion in a multilayer film moves at a speed of about 10 m/s [10]. Fast motion requires much larger currents: in synthetic ferrimagnets, speeds of up to 400 m/s were reached at current densities of $(3.5–8)\cdot10^{11}$ A/m² and 10 ns pulses [11]. In compensated ferrimagnets, skyrmions become smaller and domain walls move faster [12]. At room temperature, antiferromagnetic skyrmions have been stabilized in synthetic antiferromagnets [13]; in them, the transverse drift characteristic of ferromagnets (the skyrmion Hall effect [14]) is, in the ideal case, compensated.

Ferromagnet/ferroelectric. In $BaTiO_3/SrRuO_3$ heterostructures, ferroelectric order changes the DMI and thereby controls skyrmions [15]. In the multiferroic Cu_2OSeO_3, the skyrmions themselves carry an electric polarization [16]. Theory shows that a hole in the ferroelectric layer localizes a skyrmion in the magnetic layer directly beneath the hole, and that the region in which the localized state exists widens as the magnetoelectric coupling grows [17, 18]. For such structures, [17] proposes a fabrication sequence in which PZT, $BaTiO_3$ or $CuInP_2S_6$ is considered as the ferroelectric.

Ferromagnet/oxide. The oxide layer performs two roles. First, changing the voltage across it alters the interfacial anisotropy, which allows skyrmion bubbles to be switched on and off with an electric field [19]; switching of an individual skyrmion by a field has been demonstrated on the atomic scale [20]. Second, the oxide serves as a tunnel barrier: in 2024 a magnetic tunnel junction was built that reads out a single skyrmion with a signal of 20–70% and a switching energy roughly a thousand times lower than in earlier solutions [21].

The review shows that each function of the cell has already been demonstrated separately. However, comparisons of write mechanisms by energy are usually made for specific devices, which makes it hard to transfer conclusions to other materials. Below we propose a comparison that does not depend on the cell size.

3. Research Methods

Write energy was estimated per unit area of the cell for three mechanisms.

Current-driven writing. A current of density J flows through a heavy-metal layer of thickness t_{HM} and resistivity ρ for a pulse of duration τ. The Joule losses per unit area are:

$$e_I = \rho \cdot J^2 \cdot t_{HM} \cdot \tau \qquad (1)$$

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

Ferroelectric polarization reversal. When the polarization switches from −P to +P, a charge of 2P passes through a unit area at a voltage close to the coercive voltage V_c. Hence:

$$e_{FE} \approx 2P \cdot V_c \qquad (2)$$

Capacitive control. If the state changes without switching the polarization, for example through voltage control of anisotropy, the energy equals the energy stored in a capacitor with a dielectric of thickness d and permittivity ε_r:

$$e_C = \varepsilon_0 \cdot \varepsilon_r \cdot V^2 / (2d) \qquad (3)$$

It follows from (1)–(3) that the ratio of the energies of any two mechanisms, for example

$$e_I / e_C = 2\rho \cdot J^2 \cdot t_{HM} \cdot \tau \cdot d / (\varepsilon_0 \cdot \varepsilon_r \cdot V^2) \qquad (4)$$

does not contain the cell area. This allows the mechanisms to be compared without tying the result to a particular device geometry.

The parameters were taken from the literature. The resistivity of a thin Pt film is $\rho = 33$ μΩ·cm [22]. The current-writing regimes are $J = 1 \cdot 10^{11}$ A/m² with $\tau = 5$ ns [10], and $J = (3.5–8) \cdot 10^{11}$ A/m² with $\tau = 10$ ns [11]. For polarization, the remanent polarization of a $BaTiO_3$ single crystal is $P_r = 21$ μC/cm² [23], and the spontaneous polarization of $CuInP_2S_6$ is $P_s = 2.55$ μC/cm² [24]. Ferroelectricity in $CuInP_2S_6$ persists in layers about 4 nm thick [25]. The remaining quantities are order-of-magnitude estimates and are flagged as such: heavy-metal thickness $t_{HM} = 5$ nm, coercive voltage $V_c = 1$ V, and, for the capacitive case, $\varepsilon_r = 10$, $d = 1.5$ nm, $V = 1$ V. To convert the energies to a per-cell value, we took a cell area of 50 × 50 nm².

4. Results and Discussion

4.1 Functions of the layers of the hybrid cell

The literature is summarized in Table 1. Each layer of the cell performs its own operation, and it is the combination of layers that turns the film into a memory cell.

Table 1. Functions of the layers of a skyrmion-based hybrid memory cell

Layer	Function in the cell	Physical mechanism	Source
Ferromagnet (Co, CoFeB)	Bit storage	Skyrmion as a topologically stable state	[6, 7]
Heavy metal (Pt, Ir, Ta)	Stabilization and motion	Interfacial DMI; spin–orbit torque	[10, 11]
Oxide (MgO and others)	Readout; voltage control	Tunnel magnetoresistance; anisotropy change	[19, 21]
Ferroelectric ($BaTiO_3$, $CuInP_2S_6$)	Localization and electric writing	Magnetoelectric coupling; DMI change	[15, 17]
Compensated magnetic layers	Size reduction, acceleration, drift compensation	Ferrimagnetic and antiferromagnetic order	[12, 13]

4.2 Write energy

The results of the calculations with formulas (1)–(3) are given in Table 2 and Figure 1. The calculation is reproduced in the accompanying workbook (Table2_write_energy.xlsx).

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

Table 2. Estimated write energy (author's calculations)

Mechanism	Parameters	e, J/m²	Energy per 50 × 50 nm² cell, fJ
Current, slow motion	$J = 1 \cdot 10^{11}$ A/m², $\tau = 5$ ns	0.083	0.21
Current, fast motion	$J = 3.5 \cdot 10^{11}$ A/m², $\tau = 10$ ns	2.0	5.0
Current, fast motion	$J = 8 \cdot 10^{11}$ A/m², $\tau = 10$ ns	10.6	26
Polarization reversal, $BaTiO_3$	$P_r = 21$ μC/cm², $V_c = 1$ V	0.42	1.05
Polarization reversal, $CuInP_2S_6$	$P_s = 2.55$ μC/cm², $V_c = 1$ V	0.051	0.13
Capacitive control	$\varepsilon_r = 10$, d = 1.5 nm, V = 1 V	0.030	0.074

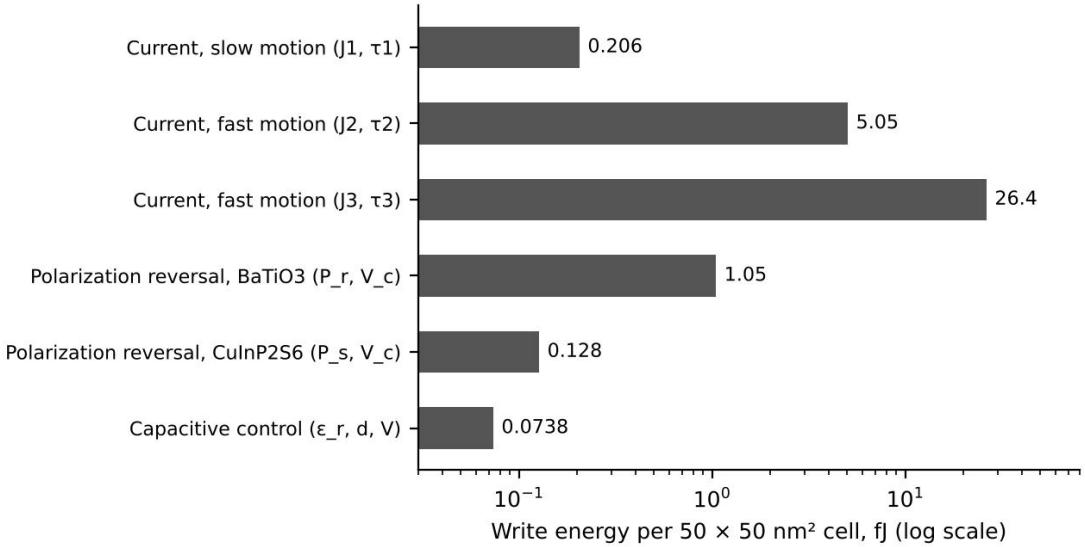


Figure 1. Write energy for a 50 × 50 nm² cell under different mechanisms, computed from the formulas in Section 3 (log scale).

The result is less clear-cut than is often assumed. A common view holds that an electric field always beats current. Our estimates show that this is only partly true. In the fast-motion regime of the skyrmion (hundreds of m/s), current-driven writing is indeed 40–360 times more expensive than polarization reversal in $CuInP_2S_6$ or capacitive control. But in slow motion (about 10 m/s), current-driven writing requires only about 0.2 fJ, which is comparable to polarization reversal in $CuInP_2S_6$ and five times less than polarization reversal in $BaTiO_3$. In other words, a ferroelectric with large polarization does not by itself guarantee energy savings.

4.3 The trade-off between localization and energy

A contradiction emerges here, and in our view it is the main practical conclusion of the work. In the model of [17], the magnetoelectric coupling is proportional to the polarization of the ferroelectric layer, and the region in which the skyrmion stays localized beneath the hole widens as that coupling

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

grows. The energy of polarization reversal (2) is also proportional to the polarization. It follows that reliable localization calls for a "strong" ferroelectric, while economical writing calls for a "weak" one. We see two ways out. The first is to separate the functions: a ferroelectric layer with large polarization is used only as a fixed "template" that sets the skyrmion's position, while writing is done by capacitive control through a thin oxide. The second is to use layered ferroelectrics with small polarization, such as $CuInP_2S_6$, and offset the weaker coupling with a stronger DMI.

4.4 Readout and integration

The magnetic tunnel junction [21] solves the problem of reading out an individual skyrmion, and at the same time adds an oxide layer to the cell that can be used for capacitive writing. For this reason, we believe that a heavy-metal/ferromagnet/oxide stack with an additional ferroelectric template is the most balanced hybrid cell.

4.5 Limitations of the estimates

Formula (1) takes into account only the losses in the heavy-metal layer and does not consider that current flows along the whole track rather than through a single cell. This makes the current-driven values a lower bound. Formula (2) assumes a rectangular hysteresis loop; in real films the coercive voltage depends on thickness and interface quality. The values of t_{HM}, V_c, ε_r and d are typical estimates and need to be refined for a specific structure. Finally, we did not estimate the lifetime of a written state at finite temperature. That question requires separate analysis [26], as does the broader question of localized structures in magnets without inversion centre [27].

5. Conclusions

A hybrid thin film makes it possible to combine storage, writing and readout in one cell. The ferromagnet stores the bit as a skyrmion, the heavy metal provides the DMI and current-driven control, the oxide provides readout and voltage control, and the ferroelectric provides localization and electrical writing.

The ratio of write energies for different mechanisms does not depend on cell area (formula 4), which allows materials to be compared without reference to device geometry.

For a 50 × 50 nm² cell, the write energy is 0.2–26 fJ for current-driven writing, depending on the skyrmion motion regime; about 1 fJ for polarization reversal in $BaTiO_3$; 0.13 fJ in $CuInP_2S_6$; and 0.07 fJ for capacitive control.

Electrical writing offers a 40–360-fold advantage only over the fast current-driven regime. A ferroelectric with large polarization may turn out to be less energy-efficient than slow current-driven writing.

There is a trade-off between the strength of the magnetoelectric coupling needed to localize the skyrmion and the energy of polarization reversal. We recommend separating the functions: use the ferroelectric as a fixed template and perform writing by capacitive control through a thin oxide, or use layered ferroelectrics with small polarization.

Future work should refine these estimates with micromagnetic simulations that account for finite temperature, and test the proposed scheme on experimental samples.

Funding: [Specify the funding source, or state: "The study received no sponsorship."]

Conflict of interest: The author declares no conflict of interest.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

References

1. Fert A., Reyren N., Cros V. Magnetic skyrmions: advances in physics and potential applications. Nature Reviews Materials, 2017, Vol. 2, Art. 17031.
2. Back C., Cros V., Ebert H. et al. The 2020 skyrmionics roadmap. Journal of Physics D: Applied Physics, 2020, Vol. 53, Art. 363001.
3. Parkin S. S. P., Hayashi M., Thomas L. Magnetic domain-wall racetrack memory. Science, 2008, Vol. 320, pp. 190–194.
4. Pyatakov A. P., Zvezdin A. K. Magnetoelectric and multiferroic media. Physics-Uspekhi, 2012, Vol. 55, pp. 557–581.
5. Spaldin N. A., Ramesh R. Advances in magnetoelectric multiferroics. Nature Materials, 2019, Vol. 18, pp. 203–212.
6. Woo S., Litzius K., Krüger B. et al. Observation of room-temperature magnetic skyrmions and their current-driven dynamics in ultrathin metallic ferromagnets. Nature Materials, 2016, Vol. 15, pp. 501–506.
7. Moreau-Luchaire C., Moutafis C., Reyren N. et al. Additive interfacial chiral interaction in multilayers for stabilization of small individual skyrmions at room temperature. Nature Nanotechnology, 2016, Vol. 11, pp. 444–448.
8. Zdoroveyshchev A. V., Vikhrova O. V., Demina P. B., Dorokhin M. V., Kudrin A. V., Temiryazev A. G., Temiryazeva M. P. Micromagnetic and magneto-optical properties of ferromagnetic/heavy metal thin film structures. Physics of the Solid State, 2019, Vol. 61, p. 1628.
9. Temiryazev A. G., Temiryazeva M. P., Zdoroveyshchev A. V., Vikhrova O. V., Dorokhin M. V., Demina P. B., Kudrin A. V. Formation of a domain structure in multilayer CoPt films by magnetic probe of an atomic force microscope. Physics of the Solid State, 2018, Vol. 60, p. 2158.
10. Woo S., Song K. M., Han H.-S. et al. Spin-orbit torque-driven skyrmion dynamics revealed by time-resolved X-ray microscopy. Nature Communications, 2017, Vol. 8, Art. 15573.
11. Mallick S., Sassi Y., Figueiredo Prestes N. et al. Driving skyrmions in flow regime in synthetic ferrimagnets. Nature Communications, 2024, Vol. 15, Art. 8472.
12. Caretta L., Mann M., Büttner F. et al. Fast current-driven domain walls and small skyrmions in a compensated ferrimagnet. Nature Nanotechnology, 2018, Vol. 13, pp. 1154–1160.
13. Legrand W., Maccariello D., Ajejas F. et al. Room-temperature stabilization of antiferromagnetic skyrmions in synthetic antiferromagnets. Nature Materials, 2020, Vol. 19, pp. 34–42.
14. Jiang W., Zhang X., Yu G. et al. Direct observation of the skyrmion Hall effect. Nature Physics, 2017, Vol. 13, pp. 162–169.
15. Wang L., Feng Q., Kim Y. et al. Ferroelectrically tunable magnetic skyrmions in ultrathin oxide heterostructures. Nature Materials, 2018, Vol. 17, pp. 1087–1094.
16. Seki S., Yu X. Z., Ishiwata S., Tokura Y. Observation of skyrmions in a multiferroic material. Science, 2012, Vol. 336, pp. 198–201.
17. Abdrakhmanov D. I., Sharafullin I. F., Yuldasheva A. R., Nugumanov A. G., Nurmatov K. J. Surface defects and skyrmions in magnetoelectric bilayers. Journal of Physics: Condensed Matter, 2025, Vol. 37, Art. 345403.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

18. Sharafullin I. F., Nugumanov A. G., Nugaeva N. M., Diep H. T. Skyrmions and phase transitions in ferromagnetic/ferroelectric superlattices with triangular lattice. IEEE Magnetics Letters, 2020, Vol. 11, pp. 1–5.
19. Schott M., Bernand-Mantel A., Ranno L. et al. The skyrmion switch: turning magnetic skyrmion bubbles on and off with an electric field. Nano Letters, 2017, Vol. 17, pp. 3006–3012.
20. Hsu P.-J., Kubetzka A., Finco A., Romming N., von Bergmann K., Wiesendanger R. Electric-field-driven switching of individual magnetic skyrmions. Nature Nanotechnology, 2017, Vol. 12, pp. 123–126.
21. Chen S., Lourembam J., Ho P. et al. All-electrical skyrmionic magnetic tunnel junction. Nature, 2024, Vol. 627, pp. 522–527.
22. Zhu L., Sui M., Ralph D. C., Buhrman R. A. Intrinsic nature of the giant spin Hall conductivity in Pt. arXiv, 2019, arXiv:1905.04573.
23. Shieh J., Yeh J. H., Shu Y. C., Yen J. H. Hysteresis behaviors of barium titanate single crystals based on the operation of multiple 90° switching systems. Materials Science and Engineering: B, 2009, Vol. 161, pp. 50–54.
24. Belianinov A. et al. $CuInP_2S_6$ room temperature layered ferroelectric. Nano Letters, 2015, Vol. 15, pp. 3808–3814.
25. Liu F., You L., Seyler K. L. et al. Room-temperature ferroelectricity in $CuInP_2S_6$ ultrathin flakes. Nature Communications, 2016, Vol. 7, Art. 12357.
26. Lobanov I. S., Potkina M. N., Uzdin V. M. Stability and lifetimes of magnetic states of nano- and microstructures (brief review). JETP Letters, 2021, Vol. 113, p. 833.
27. Borisov A. B. Localized structures in magnetic systems without an inversion center. Physics-Uspekhi, 2020, Vol. 63, pp. 269–288.