Thermal Brownian Motion of Skyrmion for True Random Number Generation

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Abstract—True random number generators (TRNGs) have received extensive research owing to their wide applications in information processing, transmission, and encryption. Recently, TRNGs have also been employed in emerging stochastic/probabilistic computing paradigms. TRNGs can be designed based on, for example, oscillator sampling, noise amplifying, and quantum physical effect with the aid of peripheral postprocessing circuitry. With the rapid development of emerging nanoscale devices, such as resistive devices, spintronic devices, and photonic devices, a rich variety of TRNG prototypes have been proposed in the literature. Very recently, skyrmion has emerged as a promising candidate for implementing TRNGs because of the nanometer size and, more importantly, the intrinsic thermal Brownian motion dynamics. In this article, we propose for the first time a TRNG based on the continuous skyrmion thermal Brownian motion in a confined geometry at room temperature. Random bitstream (with equal probability of ~50% for bits “0” and “1”) can be obtained by periodically detecting the relative position of the skyrmion without the need for any additional activations. Furthermore, we implemented a probability-adjustable TRNG, in which a desired probability for bit “0” and bit “1” can be acquired by adding an anisotropy gradient in the device through the voltage-controlled magnetic anisotropy (VCMA) effect. The behaviors of the proposed skyrmion-based TRNGs were studied by using micromagnetic simulations, and the generated random bitstream was tested by the National Institute of Standards and Technology (NIST) suits. Our results demonstrated that the proposed skyrmion-based TRNGs can achieve good randomness with high frequency (>1 GHz) and energy efficiency (<10 fJ/bit).

Index Terms—Skyrmion, spintronics, thermal Brownian motion, true random number generator (TRNG).

I. INTRODUCTION

INFORMATION security has become one of the most important concerns with the rapid growth of data volume by the emergence of Internet of Things and artificial intelligence. Data encryption using random numbers is an effective way to ensure the security of modern information. Some indispensable mechanisms, such as the key generation and plaintext conversion, require random numbers with good statistical properties and security, which can effectively prevent unauthorized organizations from accessing data during data transfer and storage [1], [2]. Furthermore, emerging computing paradigms, e.g., stochastic/probabilistic computing, rely on true random bitstream for good computing quality [3]–[6].

Two methods are generally used to generate the required random numbers: pseudorandom number generator (PRNG) and true random number generator (TRNG) [7]–[9]. The bit sequence generated by the former has a certain regularity and can be periodically changed when the sequence is long enough, which, however, may increase the predictability of the bit sequence [10]. In contrast, random numbers generated by a TRNG are more secure, and thus are widely used in the cryptography key to protect privacy [11].

Based on the physical source of randomness, a TRNG can be roughly divided into digital TRNG and analog TRNG [12], [13]. The source of the entropy of the digital TRNG is mainly from a pseudorandom noise, such as the frequency of the self-excited oscillator and the metastability of the circuit components [10], [12], [14]. Due to process variations, a digital TRNG faces a serious problem, i.e., bits “0” and “1” in the output sequence are not evenly distributed, leading to a serious probabilistic offset, which makes the postprocessing circuit indispensable. An additional circuitry not only reduces the output data bit rate but also brings additional power and area overhead. In addition, with the continuous downscaling of process technology, leakage current greatly increases, resulting in even more static power consumption. Therefore, digital TRNGs built by CMOS circuits generally suffer from complicated structure, large area, and power consumption.

The entropy source of an analog TRNG is typically from intrinsic thermal noise or photoelectric effect [1], [15], [16]. The stochastic dynamics caused by thermal noise are naturally random and are promising for TRNG designs. Recently,
a rich variety of analog TRNGs have been proposed with the advances of emerging nanoscale devices, such as memristors and magnetic tunnel junctions (MTJs) [7], [14], [17], [18]. However, owing to their hardware structures, complex probability tracking and precise control of the amplitude and duration of the current/voltage activations are required to produce the desired probability (50%), resulting in overhead in hardware area and power consumption. For example, the memristor-based TRNG in [17] requires a pair of SET and RESET current pulses to generate a random bit; the spin-transfer torque MTJ (STT-MTJ)-based TRNG under a certain amplitude of current has inevitable probability deviation [7], [19]. In [7], a parallel structure with multiple MTJs was proposed to generate random numbers, which significantly reduces the probability deviation but increases considerable circuit area and power consumption. Recently, a spin–orbit torque MTJ (SOT-MTJ)-based TRNG has been proposed in [14], but a correction circuit is needed to achieve the probability balance, also resulting in additional area and energy consumption. With the rapid research and development of emerging nanoscale devices, TRNG designs that are more efficient are expected.

Magnetic skyrmion is a particle-like spin configuration with prominent advantages, such as nanoscale size, high motion velocity, and low depinning current density [20]–[26]. These intrinsic features of skyrmion have been studied extensively for racetrack memory both in theories and in experiments [27]–[29]. Moreover, based on the experimental reports, we found that the thermal Brownian motion of the skyrmion is intrinsically random, nonrepeatable, and unpredictable (see Supplementary Material S1 for more details) [20], [30]–[35], making it promising for the TRNG design with small area and low power consumption [36]–[38].

In this article, we propose a TRNG design based on skyrmion by utilizing the thermal noise as the entropy source to produce an unbiased random sequence without requiring additional activation or compensation circuitry. Our proposed TRNG has higher energy efficiency and smaller area than previous designs. Furthermore, we can configure the probability between bits “0” and “1” (probability adjustable) by adding an anisotropy gradient through the voltage-controlled magnetic anisotropy (VCMA) effect to modulate the average stabilized position of the skyrmion [39]–[41]. More specifically, the perpendicular magnetic anisotropy (PMA) gradient drives skyrmion from the position with large PMA to the area with small PMA and the probability of bit “0” or “1” in the random bit sequence will vary accordingly [42]–[44]. Our proposal is validated by micromagnetic simulations using the Mumax3 tool with integrated modules for Brownian motion [45]. The quality of the random numbers generated from our TRNG was tested by the National Institute of Standards and Technology (NIST) suite. Our proposal is validated by micromagnetic simulations using the Mumax3 tool with integrated modules for Brownian motion [45]. The quality of the random numbers generated from our TRNG was tested by the National Institute of Standards and Technology (NIST) suite. Our proposal is validated by micromagnetic simulations using the Mumax3 tool with integrated modules for Brownian motion [45].

### II. RESULTS

#### A. Theoretical Model

The proposed skyrmion-based TRNG appears like a chamber, consisting of a ferromagnetic (FM) layer, a heavy metal (HM) layer, and two MTJs [see Fig. 1(a)]. A skyrmion is nucleated at the center of the FM layer and performs random motion in the chamber under thermal noise [20], [30]–[35]. These two MTJs are used to detect the position of the skyrmion (left-hand side or right-hand side of the chamber) with a differential method by a sensing circuit [46]. Please note that as the MTJ on the top may affect the skyrmion dynamics, other novel methods such as topological Hall resistivity [47], [48], which has no impact on the device, can be used for skyrmion detection without affecting the core idea of this article. The magnetization dynamics of the skyrmion can be modeled by a modified Landau–Lifshitz–Gilbert (LLG) equation

$$\frac{\partial \vec{m}}{\partial t} = -\gamma \vec{m} \times \vec{H}_{\text{eff}} + \alpha\vec{m} \times \frac{\partial \vec{m}}{\partial t}$$

where the effective field $\vec{H}_{\text{eff}}$ includes the demagnetization field ($\vec{H}_{\text{demag}}$), interface PMA field ($\vec{H}_{\text{ani}}$), exchange field ($\vec{H}_{\text{ex}}$), Dzyaloshinskii–Moriya interaction (DMI) field ($\vec{H}_{\text{DMI}}$), and stochastic field ($\vec{H}_{\text{thermal}}$) due to thermal disturbance. Here, $\vec{m}$ is the unit magnetization vector of the region, $\alpha$ is the Gilbert damping constant, and $\gamma$ is the gyromagnetic ratio.

In our simulations, we adopt the following CoPt material parameters [49], [50]: the exchange stiffness $A = 15$ pJ/m, saturation magnetization $M_s = 580$ kA/m, damping constant $\alpha = 0.3$, interface-induced DMI constant $D_{\text{int}} = 3$ mJ/m², and default PMA constant of the FM layer $K_{\text{p}} = 0.8$ MJ/m³. In addition, the default mesh size of 1 nm × 1 nm × 1 nm is used in our simulations. We start with an initial FM state ($m = +e_z$) and apply a 0.2-ns-long current pulse.
(5 × 10^{13} \text{A/m}^2) in the center of the chamber with a diameter of 20 nm to initiate the skyrmion.

In our system, the simulation region is an approximately elliptical chamber consisting of a rectangular region of 101 nm × 74 nm and two semicircular regions with a radius of 37 nm, as shown in Fig. 1(b). Magnetization dynamics of the skyrmion can be strongly influenced by the random thermal fluctuations. In practical situations, the output bits are assigned depending on the differential voltage ΔV (ΔV = V_{\text{left}} − V_{\text{right}}) of the two MTJs, as shown in Fig. 1(c). Specifically, if ΔV is positive, corresponding to the presence of the skyrmion on the left-hand side of the chamber, denote a bit of “0”; otherwise, a bit “1” is indicated, or vice versa.

The skyrmion Brownian motion has been studied in [20] and [30]–[35]. Please note that process variations (in the FM layer, the boundary, and the MTJ detector) as well as material defects/imperfections and so on may disturb the randomness of the skyrmion motion. However, prior experiments have proved that thermal-induced skyrmion Brownian motion is dominant if the quality of the sample can be well controlled [20], [32]. Therefore, in this article, only the thermal-induced skyrmion Brownian motion is considered in the simulation to highlight the core idea of the TRNG design. For a nonconfined 2-D system, the thermal diffusion of a skyrmion can be simply expressed as [31]

\[ \left[ r_x, y(t + t^*) - r_x, y(t) \right]^2 = \left( (\Delta r_x, y) \right)^2 = 4\mathcal{D}_{\text{dc}} t^*. \] (2)

Here, \( r_x, y \) is the position of the skyrmion center (\( x, y \)) and \( t^* \) is the time interval between two selected data points. The left-hand side of the equation expresses the mean-squared displacement (MSD) of a skyrmion. The diffusion constant \( \mathcal{D}_{\text{dc}} \) is established as

\[ \mathcal{D}_{\text{dc}} = k_B T \frac{\alpha D}{\mathcal{G}^2 + (\alpha D)^2} \] (3)

where \( \mathcal{G} \propto 4\pi Q \) is the gyrocoupling strength that is related to the skyrmion topological number \( (Q) \) and \( D \) is the dissipative factor that depends on the skyrmion profile [20], [31]. In the 2-D geometry, \( Q = -1/4\pi \int \mathbf{m} \cdot \left( \frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) dx dy \), where \( \mathbf{m} = M/M_s \) is the reduced magnetization vector and \( M_s \) is the saturation magnetization [20]. Equation (2) indicates that \( \mathcal{D}_{\text{dc}} \) can be evaluated from the linear matching of the MSD as a function of \( t^* \). Meanwhile, (3) reveals a linear dependence of \( \mathcal{D}_{\text{dc}} \) on \( T \). Therefore, we can measure \( \mathcal{D}_{\text{dc}} \) based on the linear fitting of the MSD with respect to \( T \) and \( t^* \). Fig. 2(a) shows that the MSD is linearly related to the time interval \( t^* \) when \( t^* \) is smaller than 2 ns. However, as \( t^* \) increases, the results [see Fig. 2(b)] show that the MSD no longer linearly increases as \( t^* \) increases due to the boundary effect. More specifically, as \( t^* \) increases, the distance of the skyrmion motion increases, while the displacement may decrease as the skyrmion is constrained inside the chamber, which also indicates that the MSD will not grow indefinitely with the increment of time.

In the linear region, it is difficult for a skyrmion to move from one side to the other side at a small interval. Accordingly, a fairly long continuous bit “0” or “1” will appear in the sequence and its randomness will be very poor. In the nonlinear region, a small MSD may represent a large moving distance, i.e., the skyrmion may move from one side of the chamber to the other and then move back and forth repeatedly (see Supplementary Material S2).

Similarly, Fig. 3(a) displays that the MSD is also linearly dependent on the temperature in the case of small \( t^* \), which is consistent with (3). Here, the thermal effect induced by temperature plays a dominant role on the displacement of the skyrmion. In contrast, the boundary effect has a greater impact on the skyrmion if \( t^* \) is larger than 3 ns, leading to the nonlinearity [see Fig. 3(b)]. To obtain an output sequence with good randomness, a relatively large MSD is necessary. Furthermore, the interval will affect the randomness. If the interval between two observations is long enough, the randomness caused by thermal disturbance will make the generated random numbers independent of each other. In our simulations, we find that the average distance of the skyrmion motion in every 20 ps is about 1.4 nm by focusing in the \( x \)-axis direction. Correspondingly, the distance of the skyrmion motion in 10 ns is about 700 nm. The maximum displacement of the skyrmion in the chamber is about 120 nm [see Fig. 4(a)] in the \( x \)-axis direction. In this case, the skyrmion can move several times back and forth in the chamber in 10 ns, denoting that every two adjacent bits can be considered independent of each other if the interval \( t^* \) is long enough. Therefore, a high temperature or (and) a long interval \( t^* \) is preferred to keep good randomness of the generated bits. On the other hand, increasing \( t^* \), however, will influence the frequency. In our simulations, we detect the position of the skyrmion in every 10 ns at room temperature (300 K). As indicated, higher frequency can be obtained by raising the temperature without increasing \( t^* \), e.g., \( t^* = 1 \) ns with \( T = 320 \) K. In addition, in our design, we only need to detect the skyrmion position without any activations to generate random numbers. Based on
rather low power consumption (our circuit simulation results, the detection circuit can achieve under thermal disturbance. (a) Left panel shows the trajectory of the skyrmion and the right panel shows the corresponding position of the skyrmion. (b) Bit sequence of length 580 obtained by detecting the position of the skyrmion in the x-axis direction. (c) Theoretical outputs from 3.9 to 4.39 μs.

our circuit simulation results, the detection circuit can achieve rather low power consumption (<10 fJ/bit) and high speed (<200 ps) to read the device state [46].

B. TRNG With Equally Distributed bit “0” and bit “1”

As discussed above, an isolated skyrmion will randomly diffuse in the chamber under the combined effect of the thermal disturbance and the boundary effect. Random bit sequence can then be obtained by locating the position of the skyrmion. Fig. 4(a) shows the trajectory of the skyrmion within 5.7 μs (570 stages). As can be seen, the skyrmion is located 286 times on the left-hand side of the chamber and 284 times on the right-hand side of the chamber, resulting in about equal probability (50%) of bits “0” and “1.” Fig. 4(b) shows the positions of the skyrmion in the x-axis in order to observe clearly the arrangement of “0” and “1” in the sequence. Fig. 4(c) presents 50 output samples selected from our random bit sequence. Please note that the skyrmion size may change and the shape may deform as a function of time and temperature [51]. However, in our design, we only focus on the relative skyrmion position for the TRNG design, so the size and shape of the skyrmion will not affect the output.

Furthermore, the quality of our random numbers is evaluated by the NIST suite. The NIST suite is a statistical package that focuses on the nonrandomness possibly existing in the tested data [52]. The test can only be performed normally, if the “0” and “1” in the American Standard Code for Information Interchange (ASCII) sequence are evenly distributed, that is, the unbiased sequence is a prerequisite for ensuring the success of the test. The NIST test results of our TRNG are shown in Table I, where nine tests were performed. The value of P calculated during each test is to evaluate the randomness and a large P indicates a better randomness. Specifically, if P is smaller than 0.01, the test is successfully passed. As can be seen, the random bits generated by our proposed skyrmion-based TRNG can pass the NIST test.

C. Probability-Adjustable TRNG

On the other hand, the nonuniform distribution of “0” or “1” bitstream (preferred in stochastic/probabilistic computing) can be implemented with peripheral circuits, such as cascading XOR gates after the TRNG [2], [10], [12]. However, such peripheral circuits typically consume a large amount of energy and occupy additional hardware area. In contrast, our proposed skyrmion-based TRNG can generate unbalanced bit bitstream simply by a PMA gradient, which can be generated either by the VCMA effect through employing multiple electrodes [53], [54] or by fabricating a wedge structure [55]. In this article, we choose the former one. The voltage changes the value of PMA (K_A) of the material, thus producing an anisotropy gradient of the FM of the chamber, which drives the skyrmion from the area with high PMA to the lower counterpart [56]. Here, the PMA value follows a linear increase with respect to the position of the chamber, i.e., K_A(ξ) = K_{A0} + ΔK_A ξ, in which K_{A0} is the initial PMA value at the origin (i.e., ξ = 0), ΔK_A is the PMA increasing rate, and ξ is the relative distance from the origin. As discussed above, regardless of the influence of the thermal disturbance, the average stabilized position of the skyrmion is the center of the chamber. With the combination of the anisotropy gradient and the boundary effect, the average stabilized position of the skyrmion will move a distance (d) away from the center to the low PMA region, depending on the PMA difference ΔK_A = K_{A max} - K_{A min}, where K_{A max} is the maximum value and K_{A min} is the minimum value of the PMA [see Fig. 5(a)]. Considering the thermal disturbance, the skyrmion moves around the new average stabilized position, so the probability of the skyrmion appearing on the left-hand or the right-hand side of the chamber will be different. It can be seen from Fig. 5(b) that the average stabilized position of the skyrmion is constantly shifted to the left-hand side of the chamber with the increase in K_{A min}. The uneven distribution of the skyrmion positions for 1000 intervals (τ* = 1 ns) is displayed in Fig. 5(c)-(f), in which the skyrmion position locating in left-hand side of the chamber is much denser than that in the right-hand side.

The probability of bit “0” or “1” in the output bitstream can be precisely controlled by a negative feedback circuit that includes a counter, a probability calculator, a comparator, and a decoder, as shown in Fig. 5(g). The counter is used to count the number of “0” or “1” in the random sequence. The probability of “0” is obtained by a division operation in the

| Test                  | P-value   | Success/Fail |
|-----------------------|-----------|--------------|
| Frequency             | 0.716998  | Success      |
| Block Frequency       | 0.119433  | Success      |
| Runs                  | 0.337499  | Success      |
| Longest Run of Ones   | 0.809269  | Success      |
| FFT                   | 0.105078  | Success      |
| Approximate           | 1.000000  | Success      |
| Cumulative Sums       | 0.604709  | 0.329112     |
| Serial                | 0.824844  | 0.907266     |
| Non-Overlapping       | All sub-test success |       |
| Template Matching     |           |              |

TABLE I
NIST TEST RESULTS OF THE RANDOM NUMBERS

Fig. 4. Random sequence generated by the skyrmion Brownian motion under thermal disturbance. (a) Left panel shows the trajectory of the skyrmion. (b) Bit sequence of length 580 obtained by detecting the position of the skyrmion in the x-axis direction. (c) Theoretical outputs from 3.9 to 4.39 μs.
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Fig. 5. (a) Schematic of the anisotropy gradient when $K_{uv} = 0.82 \text{ MJ/m}^3$. The average stabilized position of the skyrmion moves away a distance of $d = 38.5 \text{ nm}$ from the center of the chamber. (b) Average stabilized position of the skyrmion as a function of $K_{uv}$. (c)–(e) Skyrmion position distribution when $K_{uv} = 0.81 \text{ MJ/m}^3$, $K_{uv} = 0.85 \text{ MJ/m}^3$, and $K_{uv} = 0.89 \text{ MJ/m}^3$, respectively. (f) Probability of "0" in the output bitstream as a function of $K_{uv}$. (g) Flowchart used to control the distribution of the output bitstream.

probability calculator. The comparator transmits a signal that is the result of comparing the calculated real-time probability and the target probability to the decoder. The core of the decoder is a CMOS transistor array that converts the signal into a voltage generating the PMA gradient. A bigger (smaller) voltage is supplied when the calculated probability is smaller (bigger) than the target probability to generate a bigger (smaller) anisotropy gradient, thereby the probability can be adaptively configured according to the application requirement.

III. CONCLUSION

We implement a skyrmion-based TRNG utilizing the thermal-induced skyrmion Brownian motion property. Random number sequence with a 50% distribution can be obtained without additional excitations, which is more energy-efficient than other TRNG designs. The NIST test results indicate that the random numbers from our TRNG have fairly good randomness. Furthermore, our proposed TRNG can be adjusted to produce an output sequence with the desired probability of "0" and "1" using the anisotropy gradient. This article provides a new perspective to implement an efficient TRNG for information processing and nonvon Neumann computing paradigms. In the next step, we will study a more practical skyrmion-based TRNG design by considering also the process variations and material defects/imperfections.

REFERENCES

[1] Y. Liu, R. C. C. Cheung, and H. Wong, “A bias-bounded digital true random number generator architecture,” IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 64, no. 1, pp. 133–144, Jan. 2017, doi: 10.1109/TCSI.2016.2606353.

[2] A. P. Johnson, R. Subhra Chakraborty, and D. Mukhopadhyay, “An improved DCM-based tunable true random number generator for xilinx FPGA,” IEEE Trans. Circuits Syst. II, Exp. Briefs, vol. 64, no. 4, pp. 452–456, Apr. 2017, doi: 10.1109/TCSI.2016.2566262.

[3] A. Alaghi, W. Qian, and J. P. Hayes, “The promise and challenge of stochastic computing,” IEEE Trans. Comput.-Aided Design Integr. Circuits Syst., vol. 37, no. 8, pp. 1515–1531, Aug. 2018, doi: 10.1109/TCAD.2017.2778107.

[4] K. Mee Song et al., “Magnetic skyrmion artificial synapse for neuromorphic computing,” 2019, arXiv:1907.00957. [Online]. Available: http://arxiv.org/abs/1907.00957

[5] D. Prychynenko et al., “Magnetic skyrmion as a nonlinear resistive element: A potential building block for reservoir computing,” Phys. Rev. A, Gen. Phys., vol. 9, no. 1, 2018, Art. no. 014034, doi: 10.1103/PhysRevApplied.9.014034.

[6] G. Bourianoff, D. Pinna, M. Sitte, and K. Everschor-Sitte, “Potential implementation of reservoir computing models based on magnetic skyrmions,” AIP Adv., vol. 8, no. 5, 2018, Art. no. 055602, doi: 10.1063/1.5006918.

[7] Y. Qu, J. Han, B. F. Cockburn, W. Pedrycz, Y. Zhang, and W. Zhao, “A true random number generator based on parallel STT-MTJs,” in Proc. Design, Autom. Test Eur. Conf. Exhib. (DATE), Mar. 2017, pp. 606–609, doi: 10.23919/DATE.2017.7927058.

[8] J. Katz, A. J. Menezes, P. C. van Oorschot, and S. A. Vanstone, Handbook of Applied Cryptography. Boca Raton, FL, USA: CRC Press, 1996.

[9] J. Han, H. Chen, J. Liang, P. Zhu, Z. Yang, and F. Lombardi, “A stochastic computational approach for accurate and efficient reliability evaluation,” IEEE Trans. Comput., vol. 63, no. 6, pp. 1336–1350, Jun. 2014, doi: 10.1109/TC.2012.276.

[10] M. Alcin, I. Koyuncu, M. Tuna, M. Varan, and I. Pehlivan, “A novel high speed artificial neural network-based chaotic true random number generator on field programmable gate array,” Int. J. Circuit Theory Appl., vol. 47, no. 3, pp. 365–378, Mar. 2019, doi: 10.1002/cta.2581.

[11] N. Oliver, M. C. Soriano, D. W. Sukow, and I. Fischer, “Fast random bit generation using a chaotic laser: Approaching the information theoretic limit,” IEEE J. Quantum Electron., vol. 49, no. 11, pp. 910–918, Nov. 2013, doi: 10.1109/JQE.2013.2280917.
[12] K. Yang, D. Blauw, and D. Sylvester, “An all-digital edge racing true random number generator robust against PVT variations,” IEEE J. Solid-State Circuits, vol. 51, no. 4, pp. 1022–1031, Apr. 2016, doi: 10.1109/JSSC.2016.2519383.

[13] M. M. Abutaleb, “A novel true random number generator based on QCA nanocomputing,” Nano Commun. Netw., vol. 17, pp. 14–20, Sep. 2018, doi: 10.1016/j.nccn.2018.04.001.

[14] Y. Liu, Z. Wang, Z. Li, X. Wang, and W. Zhao, “A spin orbit torque based true random number generator with real-time optimization,” in Proc. IEEE 18th Int. Conf. Nanotechnol. (IEEE-NANO), Jul. 2018, pp. 1–4, doi: 10.1109/NANO.2018.8626347.

[15] C. S. Petrie and J. A. Connolly, “A noiseless IC random number generator for applications in cryptography,” IEEE Trans. Circuits Syst. I, Fundam. Theory Appl., vol. 47, no. 5, pp. 615–621, May 2000, doi: 10.1109/81.847365.

[16] A. Uchida et al., “Fast physical random bit generation with chaotic semiconductor lasers,” Nature Photon., vol. 2, no. 12, pp. 728–732, 2008, doi: 10.1038/nphoton.2008.227.

[17] H. Jiang et al., “A novel true random number generator based on astochastic diffusive memristor,” Nature Commun., vol. 8, no. 1, p. 882, 2017, doi: 10.1038/s41467-017-00869-x.

[18] J. S. Friedman and A. V. Sahakian, “Complementary magnetic tunnel junction logic,” IEEE Trans. Electron. Devices, vol. 61, no. 4, pp. 1207–1210, Apr. 2014, doi: 10.1109/TED.2014.2306395.

[19] E. I. Vatajelu, G. Di Natale, and P. Prinetto, “STT-MTJ-based TRNG with on-the-fly temperature/current variation compensation,” in Proc. IEEE 22nd Int. Symp. On-Line Test. Robust Syst. Design (IOLTS), Jul. 2011, pp. 649–654, doi: 10.1109/IOLTS.2011.6104694.

[20] L. Zhao et al., “Spin-topology dependent Brownian diffusion of skyrmions,” arXiv:1901.08206. [Online]. Available: http://arxiv.org/abs/1901.08206

[21] M. Kim, U. Ha, K. J. Lee, Y. Lee, and H.-J. Yoo, “A 82-nW chaotic map true random number generator based on a sub-ranging SAR ADC,” IEEE J. Solid-State Circuits, vol. 52, no. 7, pp. 1953–1965, Jul. 2017, doi: 10.1105/10.1109/JSSC.2017.2694833.

[22] A. Fert, N. Reyren, and V. Cros, “Magneto skyrmions: Advances in physics and potential applications,” Nature Rev. Mater., vol. 2, no. 7, pp. 170–181, Jul. 2017, doi: 10.1038/s41578-017-0014.

[23] T.-E. Park et al., “Observation of magnetic skyrmion crystals in a van der Waals ferromagnet Fe3GeTe2,” 2019, arXiv:1907.01425. [Online]. Available: http://arxiv.org/abs/1907.01425

[24] W. Kang, Y. Huang, X. Zhang, Y. Zhou, and W. Zhao, “Skyrnon-electronics: An overview and outlook,” Proc. IEEE, vol. 104, no. 10, pp. 2040–2061, Oct. 2016, doi: 10.1109/JPROC.2016.2591578.

[25] Y. Huang, W. Kang, X. Zhang, Y. Zhou, and W. Zhao, “Magnetic skyrmions-based synaptic devices,” Nanotechnology, vol. 28, no. 8, Feb. 2017, Art. no. 08LT02, doi: 10.1088/1361-6528/aa8383.

[26] L. Shen et al., “Dynamics of the antiferromagnetic skyrmion induced by a magnetic anisotropy gradient,” Phys. Rev. B, Condens. Matter, vol. 98, no. 13, Oct. 2018, Art. no. 134448, doi: 10.1103/PhysRevB.98.134448.

[27] R. Tomasello et al., “Nanoscale X-ray photon correlation spectroscopy on magnetic skyrmions,” Phys. Rev. Lett., vol. 119, no. 6, Aug. 2017, Art. no. 067403, doi: 10.1103/PhysRevLett.119.067403.

[28] H. Du, W. Ning, M. Tian, and Y. Zhang, “Field-driven evolution of chiral spin textures in a thin helimagnet nanodisk,” Phys. Rev. B, Condens. Matter, vol. 87, no. 1, Jan. 2013, Art. no. 014401, doi: 10.1103/PhysRevB.87.014401.

[29] A. Vansteenkiste, J. Leliaert, M. Dvornik, M. Helsen, F. Garcia-Sanchez, and B. Van Waeyenberge, “The design and verification of MuxMax3,” AIP Adv., vol. 4, no. 10, Oct. 2014, Art. no. 107133, doi: 10.1063/1.4891986.

[30] W. Kang et al., “Separated precharge sensing amplifier for deep submicrometer MTJ/CMOS hybrid logic circuits,” IEEE Trans. Magn., vol. 50, no. 6, pp. 1–5, Jun. 2014, doi: 10.1109/TMAG.2013.2297393.

[31] K. Hamamoto, M. Ezawa, and N. Nagaosa, “Purely electrical detection of a skyrmion in constricted geometry,” Appl. Phys. Lett., vol. 108, no. 11, Mar. 2016, Art. no. 112401, doi: 10.1063/1.4943949.

[32] C. Hanneken et al., “Electrical detection of magnetic skyrmions by tunneling through a ferromagnetic-collinear magnetoelectric nanofilm,” Nanotechnology, vol. 10, no. 12, pp. 1039–1042, Dec. 2015, doi: 10.1103/10.1038/nano.2015.218.

[33] J. Sampaio, V. Cros, S. Rohart, A. Thiaville, and A. Fert, “Nucleation, stability and current-induced motion of isolated magnetic skyrmions in nanostructures,” Nature Nanotechnol., vol. 8, no. 11, pp. 839–844, Nov. 2013, doi: 10.1038/nano.2013.210.

[34] X. Zhang, M. Ezawa, and Y. Zhou, “Magnetic skyrmion logic gates: Conversion, duplication and merging of skyrmions,” Sci. Rep., vol. 5, no. 1, p. 8, Aug. 2015, doi: 10.1038/srep09040.

[35] R. Tomasello et al., “Origin of temperature and field dependence of magnetic skyrmion size in ultrathin nanodots,” Phys. Rev. B, Condens. Matter, vol. 97, no. 6, Feb. 2018, Art. no. 060402, doi: 10.1103/PhysRevB.97.060402.

[36] L. E. Bassham et al., “A statistical test suite for random and pseudorandom number generators for cryptographic applications,” NIST, Gaithersburg, MD, USA, Special Publication SP 800-22 Rev. 1a, 2010, doi: 10.6028/nist.sp.800-22r1a.

[37] Y. Liu et al., “Voltage-driven high-speed skyrmion motion in a skyrmion-shift device,” Phys. Rev. A, Gen. Phys. Appl., vol. 11, no. 1, Jan. 2019, Art. no. 014004, doi: 10.1103/PhysRevApplied.11.014004.

[38] X. Wang, W. L. Gan, J. C. Martinez, F. N. Tan, M. B. A. Jail, and W. S. Lew, “Efficient skyrmion transport mediated by a voltage controlled magnetic anisotropy gradient,” Nanoscale, vol. 10, no. 2, pp. 733–740, 2018, doi: 10.1039/C7NR06482A.

[39] C. Ma et al., “Electrical field-induced creation and directional motion of domain walls and skyrmion bubbles,” Nature Nanotech., vol. 19, no. 1, pp. 353–361, 2018, doi: 10.1038/s41565-018-00938-3.

[40] Y. Zhang et al., “Magnetic skyrmions without the skyrmion Hall effect in a magnetic nanotrack with perpendicular anisotropy,” Nanoscale, vol. 9, no. 29, pp. 10212–10218, 2017, doi: 10.1039/c7nr01980d.