This article has been accepted for publication in IEEE Electron Device Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LED.2024.3515147

Bipolar Random Signal Generation with Electrical Operation Based on Two Magnetic Tunnel Junctions

Jiajia Jian, Xihui Yuan, Zheng Chai, Xue Zhou, Yongjie Luo, Yingtong He, Xin Yue, Jian Fu Zhang, Weidong Zhang and Tai Min

***Abstract*—The generation of high quality bipolar random signal for unconventional computing and artificial neural networks remains challenging. In this study, we proposed a new method to generate bipolar random signals using two industrial-viable magnetic tunnel junctions (MTJs) operated solely by electrical operations compatible to the conventional memory program/read circuits. The bipolar random signals demonstrate excellent randomness and this method shows satisfying controllability over the average dwell times (ADTs), with good adjustability in bit generation speed and power consumption. This study provides a new practical hardware solution to the generation of high-quality random signals in the post-Moore era.**

***Index Terms*—random bit generation, magnetic tunnel junction, probabilistic switching, spintronic**

I. Introduction

BIPOLAR signals with positive (“+1”), negative (“-1”) and zero (“0”) elements carry more information than their binary counterparts (“1” and “0”) [1] [2], and were initially used in telecommunication [3] [4]. Recently, bipolar random signals, whose “+1”, “-1” and “0” bits are randomly distributed, are attractive in unconventional computing paradigms such as stochastic computing (SC) and spiking neural networks (SNNs). In SC, they facilitate the scaled subtraction and the stochastic tanh function [5] [6] [7]. In SNNs, they naturally mimic the biological spikes that transmit both excitatory and inhibitory information [8] [9] [10] [11] [12], leading to improved learning efficiency and recognition accuracy [13].

Random signals, including the bipolar random signals, if generated from stochastic physical phenomenon within devices, are considered naturally unpredictable with higher quality. CMOS-based random signal generators (RSGs), unfortunately, require complex circuits for entropy extraction and post-processing [14] [15] [16]. Thanks to the advancements in spintronics, various RSGs based on the MTJs [17] [18] have emerged through exploiting the stochastic switching of MTJ driven by operation currents below the critical threshold [19].

Most existing RSGs are designed for binary signal with only two states [20] [21] [22]. For bipolar random signal made up of “+1”, “0” and “-1”, [23] utilizes a spin-orbit torque (SOT) MTJ with a heavy metal layer and requires a rather large device area and a four-port circuit. [24] proposes a circuit consisting of MTJs and carbon nanotube field-effect transistors (CNTFET), but the mess production of the latter remains a challenge. [25] employs two MTJs driven by simultaneous magnetic fields and electrical bias, but the magnetic field is not easy to realize in high density circuits.

In this work, we propose a hardware solution for bipolar random signal generation, based on two industrially viable MTJs operated solely by electrical operations compatible with the standard memory program/read circuits. The signals demonstrate good randomness and controllability across a wide range of speed and power consumption. This study provides a unique perspective on the generation of random signals using emerging memory technologies.

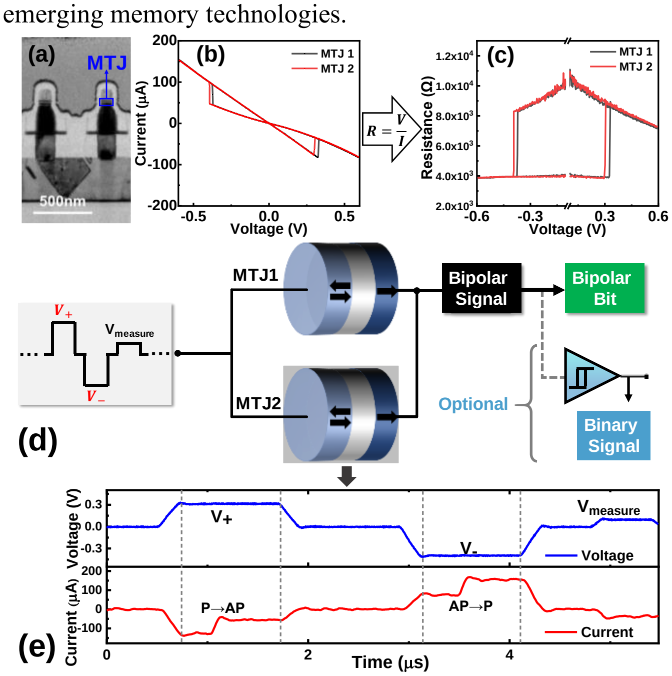


Fig.1. (a) Cross section scanning electron microscope (SEM) of MTJ. (b) I-V and (c) R-V curves show the magnetic-resistive switching of two MTJs with similar AP-/P-state resistances. (d) Schematic of the proposed MTJ-based bipolar random signal generator. (e) The real-time currents in a MTJ during the voltage pulse waveform.

Manuscript received xx. This work is supported by the National Key R&D Program of China (Grant No. 2022YFB4400200), the National Natural Science Foundation of China (Grant No. 62104188 and 12327806). (Jiajia Jian and Xihui Yuan contributed equally to this work.) (Corresponding authors: Zheng Chai, Tai Min.)

Jiajia Jian, Xihui Yuan, Zheng Chai, Xue Zhou, Yongjie Luo, Yingtong He, Xin Yue, Weidong Zhang and Tai Min are with the Center for Spintronic and Quantum Systems, State Key Laboratory for Mechanical Behavior of Materials, and School of Materials Science and Engineering, Xi’an Jiaotong University, Xi’an, China, and also with the Peng Cheng Laboratory, Shenzhen, Guangdong 518055, China, and also with the Pazhou Laboratory (Huangpu), Guangzhou, Guangdong 510555, China (e-mail: zheng.chai@xjtu.edu.cn, tai.min@mail.xjtu.edu.cn).

Jian Fu Zhang and Weidong Zhang are with the School of Engineering, Liverpool John Moores University, L3 3AF Liverpool, U.K.

This article has been accepted for publication in IEEE Electron Device Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LED.2024.3515147

II. Device and Experiment

The MTJs are bottom pinned perpendicular magnetization anisotropy (PMA) devices with a diameter of 78 nm (**Fig. 1a**). I-V curve **(Fig. 1b)** and R-V curve **(Fig. 1c)** show the magneto-resistive switching between the low resistance (P) state and the high resistance (AP) state. **Fig. 1e** illustrates that for each MTJ, there is only one probabilistic switching event per pulse, as the industrial-ready device is thermally stable. Such probabilistic switching below the threshold voltage can be attributed to the thermal fluctuations causing random initial polarization angles of the free layer [26]. The electrical measurements were conducted using a Keithley 4200 semiconductor analyzer with embedded pulse measurement units (PMUs).

III. Results and Discussions

A. Bipolar Random Signal Generation

In this work, a series of waveforms consisting of three sequential square pulses are repeatedly applied to the top electrodes of two parallel MTJs sharing similar P-/AP-state resistances (**Fig. 1d**). The 1st pulse (V_+) intends to probabilistically switch the MTJ from P to AP, while the 2nd pulse (V_-) works in the opposite direction. The 3rd pulse measures the total current flowing through the parallel MTJs. As shown in **Fig. 2a**, after the stochastic switching induced by the 1st and 2nd pulse [27] [28], the 3rd pulse generates a current signal with three states in **Fig. 2b**: the lowest state indicates that both MTJs are at AP state, which can be represented as [AP, AP]. The highest state indicates [P, P], while the intermediate state indicates either [P, AP] or [AP, P]. This current signal is then digitized into a bipolar bit stream formed by "+1", "-1" and "0", as **Fig. 2b** shows. Moreover, if necessary, such bipolar signal can be further converted into a binary bit stream via a Schmitt trigger (**Fig. 2c**), which can be used for the quality assessment with the National Institute of Standards and Technology Statistical Test Suite (NIST STS) [29].

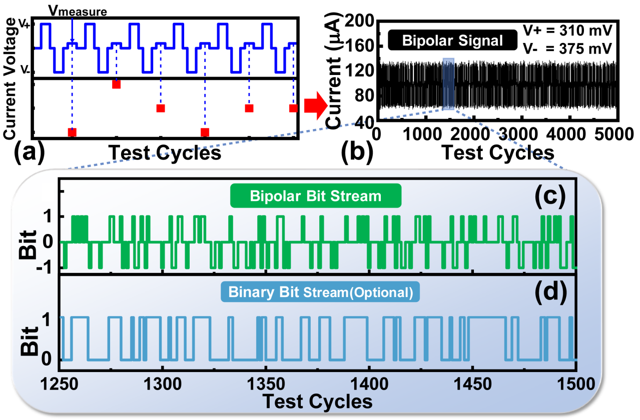


Fig.2. (a) The timing process of bipolar random bit generation per cycle. (b) The 3-state bipolar current signal generated at V_+ =310 mV and V_- = 375mV with pulse width of 500 ns. (c) The digitized bipolar random signal and (d) binary bit stream for optional randomness evaluation.

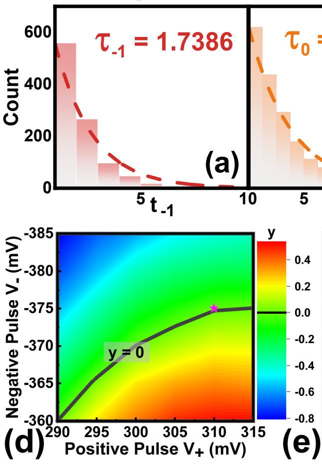
B. Randomness Quality Evaluation

The quality of randomness means how unpredictable the next signal is despite any knowledge of the previous signals in a sequence. Here, we use the mathematical distribution of the bipolar random signal to evaluate its quality: as shown in **Fig. 3(a-c)**, the exponential distribution of Dwell Times (DTs) t supports that the transitions among the three states follow Poisson processes. This suggests that the bipolar signals are stochastic because it can be mathematically described as a discrete three-state "memoryless" Markov process, which is a fundamental type of random process [30]. The average values of the DTs are called average dwell times (ADTs) and represented by τ.

Furthermore, another way to evaluate the randomness quality is the average output: it is expected that in bipolar random signals, the distribution of "-1" and "+1" should be as balanced as possible. This is often called "bias-free", where the "bias" is commonly evaluated with the average output [25]:

$$y = \frac{(-1)*\tau_{-1}*n_{-1}+\tau_1*n_1}{t_{test}} \quad (1)$$

where t_{test} refers to the number of cycles for testing; n_{-1} and n_1 respectively denote the occurrences of the low and high current state. Apparently, the closer y is to 0, the smaller the bias of the bipolar bit stream.



Test Name	P-Value	Test Name	P-Value
Approximate Entropy	0.9812	LongestRun	0.7400
BlockFrequency	0.0576	NonOverlapping Template	0.4313
CumulativeSums	0.0209	Overlapping Template	0.5544
FFT	0.4629	Rank	0.6484
Frequency	0.0104	Runs	0.1019
LinearComplexity	0.3720	Serial	0.4841

Fig.3. Histograms indicate that (a) t_{-1}, (b)t_0, and (c)t_1 follow exponential distributions. (d) The average output y under different combinations of V_+ and V_-. The line satisfies y=0. (e) NIST results of the binary random bit stream converted from a bipolar one generated under V_+=310 mV and V_-=375 mV.

Moreover, NIST STS was used to examine the randomness quality of data by comparing its certain characteristics with the expected test statistic that is precomputed for random infinite sequences [29]. Bipolar random signals are generated across a wide amplitude range of V_+ and V_-, where V_+ ranges from 290 mV to 315 mV and V_- ranges from 360 mV to 385 mV. The generated bipolar signals are converted into 20,000-bit binary stream for NIST STS. In **Fig. 3d**, the line represents the (V_+, V_-) combinations where y = 0. In fact, the binary bit streams generated using conditions near this line pass more NIST tests than that farther away. **Fig. 3e** demonstrates the NIST results for V_+=310 mV and V_-=375 mV and y=0.01, showing that 12 tests passed the criteria of p-value > 0.001, supporting the high-quality of bipolar random signals. The remaining three tests in NIST were not implemented because of the huge amount of data required.

This article has been accepted for publication in IEEE Electron Device Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LED.2024.3515147

C. Timing Parameter Modulation

For bipolar random signals, the flexible modulation of timing parameters is also important. For example, in artificial neural networks, e.g. SNN, information is encoded into a random time-series spike sequence, [31] in the form of spike rate [32] or inter-spike intervals [33]. If information is encoded in the form of spike rate which corresponds to the proportion of "+1" and "-1" in a bipolar random signal, **Fig. 4a&c** shows that with V_+ fixed, the proportion of "+1" and "-1" in the bipolar streams approximately covers 0~100% by adjusting V_-. Thus, the intensity of information can be encoded as the frequency of excitation of bipolar bits.

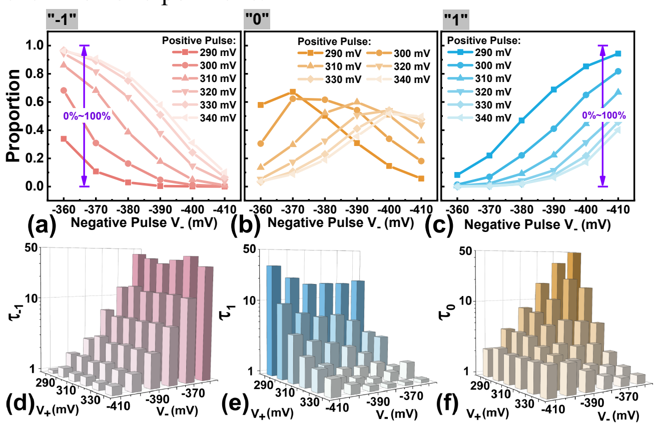


Fig.4. The proportion of (a) "-1", (b) "0" and (c) "1" in a bipolar bitstream under different V- with V+ fixed. The dependence of (d) τ_{-1} , (e) τ_1 and (f) τ_0 on both V+ and V- amplitudes, respectively.

If information is encoded in the form of inter-spike intervals, which can be closely linked to the ADT of the bipolar random signals, **Fig. 4(d-f)**, demonstrates how the ADTs are determined by V_+ and V_-: τ_1 is affected by both V_+ and V_-, while τ_{-1} is solely dependent on V_- and independent of V_+. This inspires that a target combination of τ_{-1} and τ_1 could be reached following a two-step procedure similar to what we have proposed for binary random bit streams [27]: set τ_{-1} with V_- and then set τ_1 with V_+.

D. Speed and Energy Adjustability

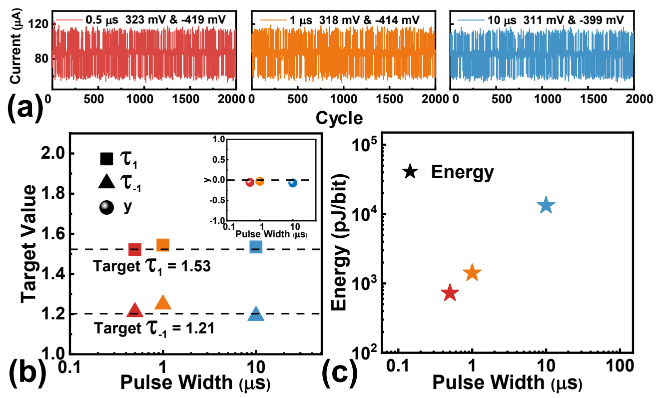


Fig.5. (a) Bipolar signal generated with different pulse widths exhibits scalability from 10 μs to 500 ns, with (b) τ_{-1} and τ_1 of bipolar signal unchanged and y≈0, after pulse amplitude modulation. (c) Energy consumption per bit can be conveniently modulated by pulse width.

It is worth noting that the time per bit of bipolar signal generation can be conveniently scaled by using shorter pulse (**Fig. 5a**), while maintaining the same ADTs and keeping y≈0 **(Fig. 5b)**. Energy consumption per bit also can be modulated according to pulse width due to the linear relationship between them. Thus, the bit generation speed and energy consumption can be flexibly controlled according to the specific application requirements.

E. Across Multiple Devices Test

Finally, the versatility of the methods is validated through tests conducted across multiple devices. 9 pairs of MTJs across the 12-inch wafer were randomly picked in **Fig. 6a**, to generate bipolar random signal under the same condition (V_+=340 mV, V_-= 380mV, pulse width = 500 ns). As shown in **Fig. 6b,** the y-values of the generated bipolar signals are all around 0, with the outcome of τ_{-1} displayed uniformity, as did those for τ_1 and τ_0. This supports that our method is applicable on multiple devices.

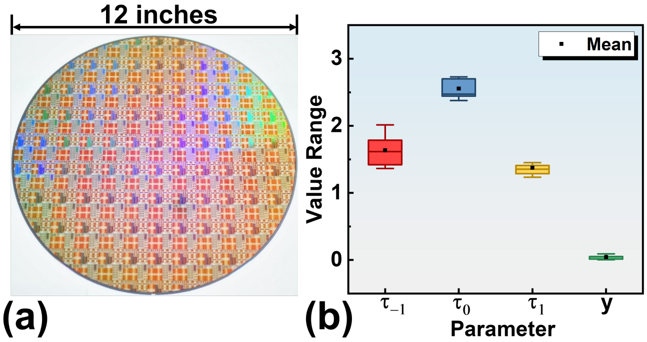


Fig.6. (a) Multiple devices were selected from the 12-inch MTJ wafer for testing. (b) The ADTs (τ_{-1}, τ_1, τ_0) and y of the bipolar random signals generated from the randomly selected 9 pairs of MTJs. Each of the parameters is narrowly distributed on its own. These signals are measured at V_+ =340 mV and V_-= 380mV with pulse width of 500 ns.

IV. CONCLUSIONS

In this study, we proposed a new method to generate bipolar random signals using two industrial-ready MTJs operated solely by electrical operations compatible with the memory program/read circuits. This method produces bipolar random signals with good randomness, and also shows controllability over the timing parameters, together with good adjustability in bit generation speed and power consumption, which provides new prospects for single-channel transmission of positive and negative signals in neural networks.

REFERENCE

[1] A. Amirany, K. Jafari and M. H. Moaiyeri, "High-Performance Spintronic Nonvolatile Ternary Flip-Flop and Universal Shift Register," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems,* vol. 29, no. 5, pp. 916-924, 2021, doi: 10.1109/TVLSI.2021.3055983.

[2] S. Kim, S. -Y. Lee, S. Park, K. R. Kim and S. Kang, "A Logic Synthesis Methodology for Low-Power Ternary Logic Circuits," *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 67, no. 9, pp. 3138-3151, 2020, doi: 10.1109/TCSI.2020.2990748.

[3] W. H. Lob, R. I. Laming, A. D. Ellis, and D. Atkinson, "10 Gb/s transmission over 700 km of standard single-mode fiber with 10-cm chirped fiber grating compensator and duobinary transmitter," IEEE Photon. Technol. Lett., vol. 8, no. 9, pp. 1258–1260, Sep. 1996, doi: 10.1109/68.531855.

[4] X. Gu, L. C. Blank, S. J. Dodds, A. D. Ellis, D. M. Spirit, and S. J. Pycock, "Duobinary technique for dispersion reduction in high capacity

optical systems—Modelling, experiment and field trial," IEEE Proc.-Optoelectron., vol. 143, no. 4, pp. 228–236, Aug. 1996, doi: 10.1049/ip-opt:19960511.

[5] B. D. Brown and H. C. Card, "Stochastic neural computation. I. Computational elements," *IEEE Transactions on Computers,* vol. 50, no. 9, pp. 891-905, 2001, doi: 10.1109/12.954505.

[6] P. Li and D. J. Lilja, "Using stochastic computing to implement digital image processing algorithms," in *IEEE 29th International Conference on Computer Design (ICCD)*, Amherst, MA, USA, 2011, doi: 10.1109/ICCD.2011.6081391.

[7] P. Li, D. J. Lilja, W. Qian, K. Bazargan and M. D. Riedel, "Computation on Stochastic Bit Streams Digital Image Processing Case Studies," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems,* vol. 22, no. 3, pp. 449-462, 2014, doi: 10.1109/TVLSI.2013.2247429.

[8] C. Hong, X. Wei, J. Wang, B. Deng, H. Yu and Y. Che, "Training Spiking Neural Networks for Cognitive Tasks: A Versatile Framework Compatible With Various Temporal Codes," *IEEE Transactions on Neural Networks and Learning Systems,* vol. 31, no. 4, pp. 1285-1296, 2019, doi: 10.1109/TNNLS.2019.2919662.

[9] L. Guo, Y. Song, Y. Wu and G. Xu, "Anti-interference of a small-world spiking neural network against pulse noise," *Applied Intelligence,* vol. 53, no. 6, pp. 7074-7092, 2023, doi: 10.1007/s10489-022-03804-w.

[10] X. Lin, J. Shen, J. Wen and H. Tang, "Bipolar Population Threshold Encoding for Audio Recognition with Deep Spiking Neural Networks," in *2023 International Joint Conference on Neural Networks (IJCNN)*, Gold Coast, Australia,, 2023, doi: 10.1109/IJCNN54540.2023.10191235.

[11] K. Burelo, G. Ramantani, G. Indiveri and J. Sarnthein, "A neuromorphic spiking neural network detects epileptic high frequency oscillations in the scalp EEG," *Scientific Reports,* vol. 12, no. 1, p. 1798, 2022, doi: 10.1038/s41598-022-05883-8.

[12] Y. Guo, Y. Chen, X. Liu, W. Peng, Y. Zhang, X. Huang and Z. Ma, "Ternary Spike: Learning Ternary Spikes for Spiking Neural Networks," in *Proceedings of the AAAI conference on artificial intelligence*, 2024, doi: 10.48550/arXiv.2312.06372.

[13] X. Yang, in, J. L W. Zheng, J. Zhao, M. Ji, Y. Lei and Z. Chai, "Research on learning mechanism designing for equilibrated bipolar spiking neural networks," *Artificial Intelligence Review,* vol. 53, pp. 5189-5215, 2020, doi: 10.1007/s10462-020-09818-5.

[14] K. Hayakawa, S. Kanai, T. Funatsu, J. Igarashi, B. Jinnai, W. A. Borders, H. Ohno, and S. Fukami, "Nanosecond Random Telegraph Noise in In-Plane Magnetic Tunnel Junctions," *Phys. Rev. Lett.,* vol. 126, p. 117202, 2021, doi: 10.1103/PhysRevLett.126.117202.

[15] K. Yang, D. Fick, M. B. Henry, Y. Lee, D. Blaauw and D. Sylvester, "16.3 A 23Mb/s 23pJ/b fully synthesized true-random-number generator in 28nm and 65nm CMOS," in *2014 IEEE International Solid-State Circuits Conference Digest of Technical Papers (ISSCC)*, San Francisco, CA, USA, 2014, doi: 10.1109/ISSCC.2014.6757434.

[16] K. Yang, D. Blaauw and D. Sylvester, "An All-Digital Edge Racing True Random Number Generator Robust Against PVT Variations," *IEEE Journal of Solid-State Circuits,* vol. 51, no. 4, pp. 1022-1031, 2016, doi: 10.1109/JSSC.2016.2519383.

[17] A. Fukushima, T. Seki, K. Yakushiji, H. Kubota, H. Imamura, S. Yuasa, and K. Ando, "Spin dice: A scalable truly random number generator based on spintronics," Application of Phys. Exp., vol. 7, p. 083001, 2014, doi: 10.7567/APEX.7.083001.

[18] W. H. Choi, Y. Lv, H. Kim, J. -P. Wang and C. H. Kim, "An 8-bit Analog-to-Digital Converter based on the voltage-dependent switching probability of a Magnetic Tunnel Junction," 2015 Symposium on VLSI Technology (VLSI Technology), Kyoto, Japan, 2015, pp. T162-T163, doi: 10.1109/VLSIT.2015.7223662.

[19] H. Zhao, A. Lyle, Y. Zhang, P. K. Amiri, G. Rowlands, Z. Zeng, J. Katine, H. Jiang, K. Galatsis, K. L. Wang, I. N. Krivorotov and J.-P. Wang, "Low writing energy and sub nanosecond spin torque transfer switching of in-plane magnetic tunnel junction for spin torque transfer random access memory," *Journal of Applied Physics ,* vol. 109, p. 07C720, 2011, doi: 10.1063/1.3556784.

[20] J. Yang, D. Wu, A. Lee, S. -A. Razavi, P. Gupta, K. -L. Wang and S. Pamarti, "A Calibration-Free In-Memory True Random Number Generator Using Voltage-Controlled MRAM," in *IEEE 47th European Solid State Circuits Conference (ESSCIRC)*, Grenoble, France, 2021, doi: 10.1109/ESSCIRC53450.2021.9567766.

[21] K. Yang, Q. Dong, Z. Wang, Y. Shih, Y. Chih, T. Chang, D. Blaauw and D. Sylvester, "A 28NM Integrated True Random Number Generator Harvesting Entropy from MRAM," in *IEEE Symposium on VLSI Circuits*, Honolulu, HI, USA, 2018, doi: 10.1109/VLSIC.2018.8502431.

[22] W. -H. Choi, Y. Lv, J. Kim, A. Deshpande, G. Kang and J. -P. Wang, "A Magnetic Tunnel Junction based True Random Number Generator with conditional perturb and real-time output probability tracking," in *IEEE International Electron Devices Meeting*, San Francisco, CA, USA, 2014, doi: 10.1109/IEDM.2014.7047039.

[23] H. Chen, S. Zhang, N. Xu, M. Song, X. Li, R. Li, Y. Zeng, J. Hong and L. You, "Binary and Ternary True Random Number Generators Based on Spin Orbit Torque," in *IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2018, doi: 10.1109/IEDM.2018.8614638.

[24] F. Khodayari, A. Amirany, M. H. Moaiyeri and K. Jafari, "A Variation-Aware Ternary True Random Number Generator Using Magnetic Tunnel Junction at Subcritical Current Regime," *IEEE Transactions on Magnetics,* vol. 3, no. 1-8, p. 59, 2023, doi: 10.1109/TMAG.2022.3233891.

[25] Y. Lv, B. R. Zink and J. -P. Wang, "Bipolar Random Spike and Bipolar Random Number Generation by Two Magnetic Tunnel Junctions," *IEEE Transactions on Electron Devices,* vol. 69, no. 3, pp. 1582-1587, 2022, doi: 10.1109/TED.2022.3144117.

[26] R. Carboni, W. Chen, M. Siddik, J. Harms, A. Lyle, W. Kula, G. Sandhu and D. Ielmini, "Random Number Generation by Differential Read of Stochastic Switching in Spin-Transfer Torque Memory," *IEEE Electron Device Letters,* vol. 39, no. 7, pp. 951-954, 2018, doi: 10.1109/LED.2018.2833543.

[27] X. Yuan, J. Jian, Z. Chai, H. Wei, X. Zhou, Y. Wen, Y. Liu, W. Yan, Y. He, J. -F. Z, W. Zhang and T. Min, "Arbitrary Modulation of Average Dwell Time in Discrete-Time Markov Chains based on Tunneling Magnetoresistance Effect," *IEEE Electron Device Letters,* vol. 45, no. 7, pp. 1349-1352, 2024, doi: 10.1109/LED.2024.3394711.

[28] X. Yuan, J. Jian, Z. Chai, S. An, Y. Gao, X0 Zhou, J.- F. Zhang, W. Zhang and T. Min, "Markov Chain Signal Generation Based on Single Magnetic Tunnel Junction," *IEEE Electron Device Letters,* vol. 44, no. 12, pp. 1963-1966, 2023, 10.1109/LED.2023.3322194.

[29] L. E. Bassham, A. L. Rukhin, J. Soto, J. R. Nechvatal, M. E. Smid, S.-D. Leigh, M. Levenson, M. Vangel, N. A. Heckert and D. L. Banks, "A Statistical Test Suite for Random and Pseudorandom Number Generators for Cryptographic Applications," NIST, Gaithersburg, MD, USA, Tech. Rep. SP 800-22, 2010. [Online]. Available: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=906762.

[30] J. F. C. Kingman, Poisson processes, Oxford : Clarendon Press, 1993, doi: 10.1093/oso/9780198536932.001.0001.

[31] A. Azarfar, N. Calcini, C. Huang, F. Zeldenrust and T. Celikel, "Neural coding:a single neuron's perspective," *Neurosci. Biobehav. Rev.,* no. 94, pp. 238-247, 2018, doi: 10.1016/i.neubiorev.2018.09.007.

[32] K.-H. Srivastava, C.-M. Holmes, M. Vellema, A.-R. Pack, C.-P. Elemans, I. Nemenman and S.-J. Sober, "Motor control by precisely timed spike patterns," *Proc Natl Acad Sci USA.,* vol. 114, no. 5, pp. 1171-1176, 2017, doi: 10.1073/pnas.1611734114.

[33] T. Gollisch and M. Meister , "Rapid Neural Coding in the Retina with Relative Spike Latencies," *Science,* vol. 319, pp. 1108-1111, 2008, doi: 10.1126/science.1149639.