Tunable Random Number Generators Implemented by Spin-Orbit Torque Driven Stochastic Switching of a Nanomagnet for Probabilistic Spin Logic

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Abstract

Probabilistic spin logic that relies on tunable random number generators (tRNGs) has attracted great interest in unconventional computing paradigm. In this work, we propose an effective tRNG based on spin-orbit torque induced stochastic switching of a nanomagnet with perpendicular magnetic anisotropy. The switching probability is dependent on both the applied in-plane magnetic fields and the currents, and is fitted well with the sigmoidal function. The result provides an alternative building block for unconventional computing systems.

(Keywords: tunable random number generators, p-bits, probabilistic computing and spin-orbit torque)

Introduction

Probabilistic spin logic (PSL) is a new computing paradigm that performs unconventional tasks such as reconfigurable logic and invertible logic, reservoir computing, deep belief networks and Bayesian networks, and integer factorization [1–7]. PSL relies on unstable stochastic bits called probabilistic bits (p-bits). A p-bit is a tunable random number generator (tRNG) that exhibits a sigmoidal response as a function of an input parameter [1, 2, 7].

Recently, several design schemes for p-bits based on spin-transfer torque (STT) or spin-orbit torque (SOT) induced stochastic switching of nanomagnets with low-barrier perpendicular magnetic anisotropy (PMA) have been proposed [1, 2, 7, 8]. However, low-barrier magnets may have a large device-to-device variation, which is a drawback in the large networks for the future application. Here, we report a tRNG based on SOT induced stochastic switching of a PMA nanomagnet without reducing anisotropy, and the switching probability has a sigmoidal response as a function of both in-plane fields and currents.

Device concept and fabrication

There is an energy barrier between the upward and downward states of the magnetization orientation of a nanomagnet with PMA, as depicted in Fig. 1(a). SOT can drive the magnetization to cross the barrier from one state to the other state with the assistance of an in-plane field, resulting in the deterministic switching. However, the current that produces SOT will induce stochastic switching of the nanomagnet when there are no fields applied, and can be utilized as a true random number generator [9]. Actually, the strength of the *z*-component of the SOT effective field acting on the nanomagnet is determined by both the charge current J and the *x*-component magnetization m_x that depends on H_x (see coordinate system in Fig. 1(b)):

$$H_z^{SOT} = \frac{\hbar}{2eM_st}\theta_{SH} J m_x \quad (1)$$

where $\hbar$ is Planck's constant, e is the electron charge, M_s is the saturation magnetization, t is the thickness of the magnetic layer, and θ_{SH} is the spin Hall angle. Therefore, one can tune H_z^{SOT} by varying H_x or J. Due to that the switching probability depends on H_z^{SOT}, there are two approaches to tuning the switching probability and corresponding two designs of tunable random number generators (tRNGs) based on field- and current-driven stochastic switching, respectively. A thin-film stack of Ta (10 nm)/CoFeB (1 nm)/MgO (1 nm)/Ta (2 nm) was sputter-deposited on a thermally-oxidized Si substrate at room temperature. The film was then processed into Hall-bar structure with a dot of 200 × 200 nm^2 at the center by electron beam lithography (EBL) and argon-ion milling (AIM). The device structure is illustrated in Fig. 1(b).

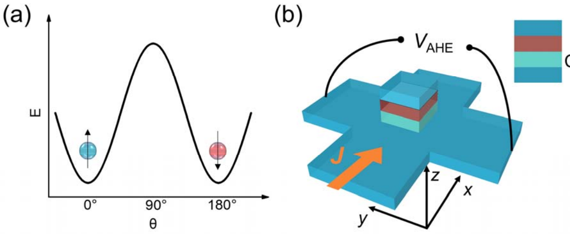

Fig. 1: (a) Energy profile between the upward and downward states of the magnetization orientation of a nanomagnet with PMA. (b) Device structure of the nanomagnet along with the schematic of the measurement setup.

Results and discussion

A. Properties of the nanomagnet

Fig. 2(a) shows the curve of the anomalous Hall effect (AHE) resistance R_H as a function of out-of-plane field H_z. The sharp switching confirms the strong PMA of the nanomagnet with a coercivity field of ~55 Oe. The SOT induced deterministic switching under an in-plane magnetic field of H_x = 200 Oe, which is parallel to the current flow, is shown in Fig. 2(b). It should be noted that there are no intermediate states during neither field or current induced switching, promising that binary bits instead of multi bits can be generated with the device.

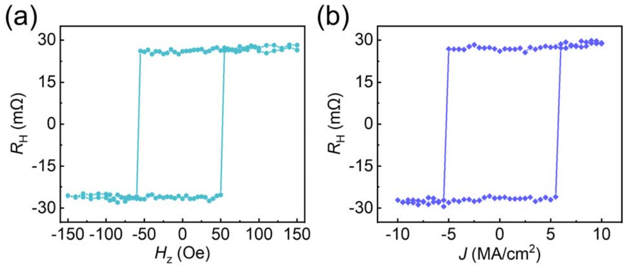

Fig. 2: Characteristics of the nanomagnet. (a) Anomalous Hall resistance R_H as a function of the perpendicular magnetic field H_z. (b) Current-induced switching of the R_H due to SOT under a constant in-plane magnetic field H_x = 200 Oe.

B. Field driven tRNG

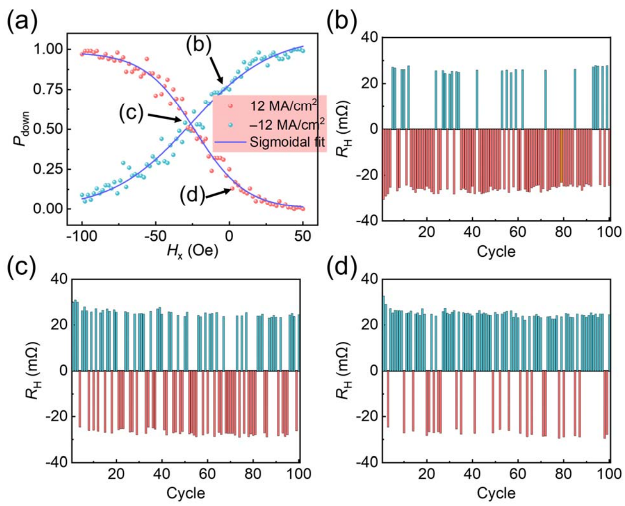

Fig. 3: Characteristics of the field driven tRNG. (a) The probability of downward states P_{down} over 100 stochastic switching cycles as a function of H_x under J = 12 MA/cm^2 (pink dots) and –12 MA/cm^2 (blue dots). The data is fitted with a sigmoid function (purple lines). Three indicative points in detail are shown in (b), (c), and (d), respectively.

To implement stochastic switching, a write current of 12 MA/cm^2 (–12 MA/cm^2) is applied to the device under smaller fields ($|H_x|$ < 100 Oe). A read current of 0.5 MA/cm^2 is followed by the write current to detect the magnetization orientation in every cycle. We performed 100 cycles under different in-plane fields and the resulted downward states are counted as N_{down}. We define $P_{down} = N_{down}/(N_{down}+ N_{up})$, and plot P_{down} as a function of H_x at J_{write} = ±12 MA/cm^2, as shown in Fig. 3(a). Three indicative points in detail are shown in (b), (c), and (d), respectively. Furthermore, the switching probability could be fitted with a sigmoid function (purple lines in Fig. 3 (a)).

C. Current driven tRNG

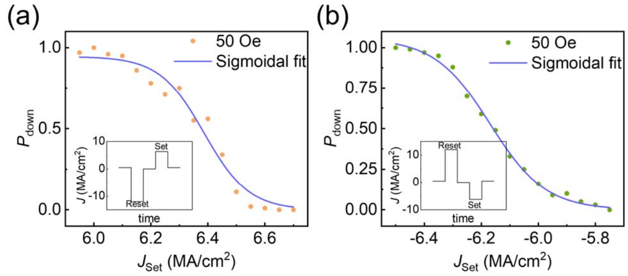

Fig. 4: The current driven tRNG under H_x = 50 Oe. (a) P_{down} vs. J_{Set} while the J_{Reset} is fixed to –12 MA/cm^2. (b) P_{down} vs. J_{Set} while the J_{Reset} is fixed to 12 MA/cm^2. The insets in (a) and (b) shows the programming current pulses in each cycle. A small read current is followed by the programming pulses to detect the R_H. Similarly, P_{down} is extracted from 100 switching cycles.

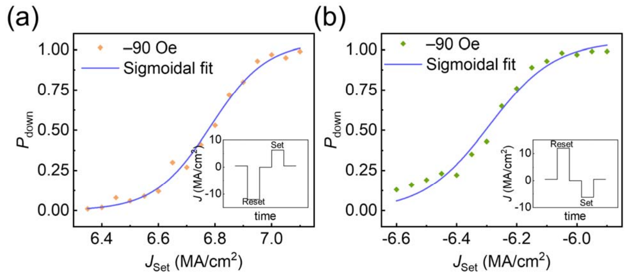

Fig. 5: The current driven tRNG under H_x = –90 Oe. (a) P_{down} vs. J_{Set} while the J_{Reset} is fixed to –12 MA/cm^2. (b) P_{down} vs. J_{Set} while the J_{Reset} is fixed to 12 MA/cm^2.

Considering the operating complexity of the field driven tRNG in the future application, we design another operating mode that tunes switching probability by current under a fixed field. What's different is that the device should be Reset at the beginning of each cycle. We firstly fixed the J_{Reset} is fixed to –12 MA/cm^2 to initialize the nanomagnet to downward state and observe the failure rate of down-to-up switching, P_{down}, as a function of J_{Set} (inset of Fig. 4(a)) under H_x = +50 Oe, as shown in Fig. 4(a). Similarly, each data point is obtained by $P_{down} = N_{down}/(N_{down}+ N_{up})$ over 100 cycles. Fig. 4(b) shows the other scenario when the J_{Reset} is fixed to 12 MA/cm^2 but the J_{Set} is changing. Next, we performed the same experimental measurements under a different magnetic field of H_x = –90 Oe, as shown in

Fig. 5. All the experimental data is fitted well with sigmoidal function, indicating that the current driven tRNG can work as a p-bit for probabilistic computing. To further decreasing the power consumption and device consumption, the tRNG can be developed by utilizing the technologies of SOT induced field-free switching, such as exchange bias, interlayer coupling and breaking of geometrical symmetry [10–12].

Conclusion

In conclusion, we have reported field and current driven tRNGs based on SOT induced stochastic switching of the PMA Ta/CoFeB/MgO heterostructure without reducing anisotropy. It is experimentally demonstrated that the devices exhibit sigmoidal responses as a function of both fields and currents, indicating that the proposed tRNGs can be used to construct probabilistic computing. The result provides an alternative way to implementing the building block for unconventional computing systems.

Acknowledgments

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References

[1] K. Y. Camsari, R. Faria, B. M. Sutton, and S. Datta, "Stochastic p-bits for invertible logic," Physical Review X, vol. 7, 031014, July 2017, doi: 10.1103/PhysRevX.7.031014.

[2] A. Z. Pervaiz, L. A. Ghantasala, K. Y. Camsari, and S. Datta, "Hardware emulation of stochastic p-bits for invertible logic," Scientific reports, vol. 7, 1-13 September 2017, doi: 10.1038/s41598-017-11011-8.

[3] S. Ganguly, K. Y. Camsayi, and A. W. Ghosh. "Reservoir computing using stochastic p-bits," arXiv preprint arXiv:1709.10211 (2017).

[4] R. Zand, K. Y. Camsari, S. D. Pyle, I. Ahmed, C. H. Kim, and R. F. DeMara, "Low-energy deep belief networks using intrinsic sigmoidal spintronic-based probabilistic neurons," Proceedings of the 2018 on Great Lakes Symposium on VLSI, pp. 15-20, May, 2018, doi: 10.1145/3194554.3194558.

[5] Z. Zhang, Y. Zhang, R. Wang, L. Zeng, and R. Huang, "Reconfigurable Logic based on Voltage-Controlled Magnetic Tunnel Junction (VC-MTJ) for Stochastic Computing," In 2018 14th IEEE International Conference on Solid-State and Integrated Circuit Technology (ICSICT), October 2018, doi: 10.1109/ICSICT.2018.8564959.

[6] R. Faria, K.Y. Camsari, and S. Datta, "Implementing Bayesian networks with embedded stochastic MRAM," AIP Advances, vol. 8, 045101, April 2018, doi: 10.1063/1.5021332.

[7] W. A. Borders, A. Z. Pervaiz, S. Fukami, K. Y. Camsari, H. Ohno, and S. Datta, "Integer factorization using stochastic magnetic tunnel junctions," Nature, vol. 573, 390-393, September 2019, doi: 10.1038/s41586-019-1557-9.

[8] P. Debashis, R. Faria, K. Y. Camsari, S. Datta, and Z. Chen, "Correlated fluctuations in spin orbit torque coupled perpendicular nanomagnets," Physical Review B, vol. 101, 094405, March 2020, doi: 10.1103/PhysRevB.101.094405.

[9] 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," 2018 IEEE International Electron Devices Meeting (IEDM), 36-5, December 2018, doi: 10.1109/IEDM.2018.8614638.

[10] S. Fukami, C. Zhang, S. DuttaGupta, A. Kurenkov, and H. Ohno, "Magnetization switching by spin–orbit torque in an antiferromagnet–ferromagnet bilayer system," Nature Materials, vol. 15, 535-541, May 2016, doi: 10.1038/NMAT4566.

[11] Y. C. Lau, D. Betto, K. Rode, J. M. D. Coey, and P. Stamenov, "Spin–orbit torque switching without an external field using interlayer exchange coupling," Nature Nanotechnology, vol. 11, 758-762, May 2016, doi: 10.1038/nnano.2016.84.

[12] L. You, O. J. Lee, D. Bhowmik, D. Labanowski, J. Hong, J. Bokor, and S. Salahuddin, "Switching of perpendicularly polarized nanomagnets with spin orbit torque without an external magnetic field by engineering a tilted anisotropy," Proceedings of the National Academy of Sciences, vol. 112, 10310-10315, August 2015, doi: 10.1073/pnas.1507474112.