• **Supplementary File** •

Reconfigurable Physical Unclonable Function Based on Spin Orbit Torque Switching of Nanomagnets

Shuai Zhang, Jian Zhang, Shihao Li, Yaoyuan Wang, Zhenjiang Chen, Jeongmin Hong, Long You*

Wuhan National Laboratory for Optoelectronics and School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, China

*Corresponding author (email: lyou@hust.edu.cn)

Appendix A Deterministic switching of the nanomagnets

The deterministic magnetization switching of the nanomagnets was investigated. The anomalous Hall effect (AHE) resistance as a function of out-of-plane (OOP) magnetic fields is plotted in Figure S1a. The sharp switching at the coercivity field of ±80 Oe indicates the strong perpendicular magnetic anisotropy (PMA) of the CoFeB magnet. Figure S1b shows the current induced deterministic magnetization switching under an appropriate in-plane (IP) field (H_x) of −100 Oe. It can be seen that the crucial current is 0.5 mA. When the applied current exceeds 0.5 mA, the SOT induced switching is deterministic, where the positive current favors downward switching and negative current prefers upward switching.

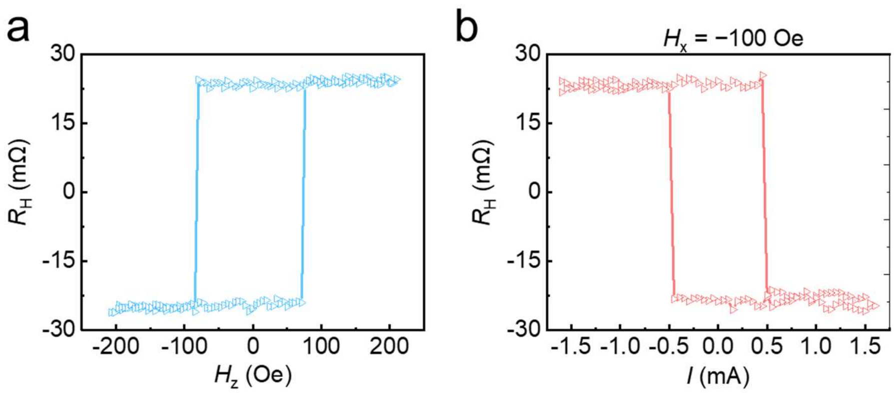

Figure S1. Deterministic switching of the nanomagnets induced by (a) OOP fields and (b) SOT with the assistance of an IP field.

Appendix B Switching probability under different current and in-plane fields

Next, we investigated the switching probability under a series of writing currents (I_w) and IP fields. The number of upward magnetization states (N_{up}) extracted from 100 test cycles versus I_w under a small IP field of 10 Oe and sweeping H_x are plotted in Figure S2a and b, respectively. The results show that a current below 0.9 mA is not efficient enough to drive the nanomagnet to generate random numbers, because the probability deviates from 50%. Figure S2b shows the relationship between N_{up} and the IP fields under $I_w > 0.9$ mA. One can see that the probability at these currents has a similar trend with increasing H_x. The N_{up} at $H_x = -50$ Oe and +50 Oe is approximately 0 and 100, respectively. In other words, upward switching is preferred if the current flow is along the field direction, while downward switching is favored if the current is antiparallel to the field direction, which is consistent with Figure S1b. Such bipolar switching behavior demonstrates that SOT, instead of *Joule* heating, is dominant during the current induced magnetization switching in the Ta/CoFeB/MgO heterostructure due to spin Hall effect and/or Rashba effect [1, 2]. Moreover, the optimum probability occurs at $H_x = 10$ Oe, instead of $H_x = 0$. This may be related to the fabrication process, including film deposition and nanometer device fabrication, which introduces a bias field to the devices [3, 4]. Therefore, the implementation of the true random number generator (TRNG) requires a small in-plane field to compensate for the bias field.

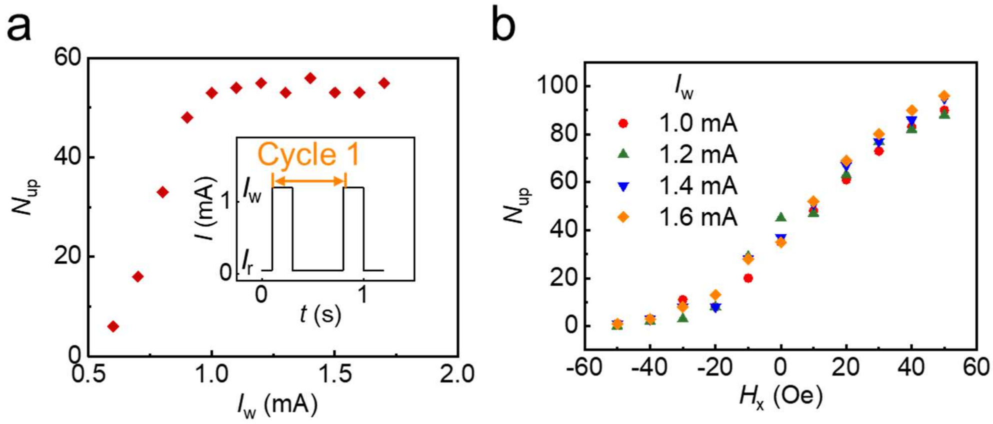

Figure S2. Switching probability under different (a) current amplitudes I_w and (b) IP fields H_x.

Appendix C Micromagnetic simulations of the magnetization evolution during the stochastic switching

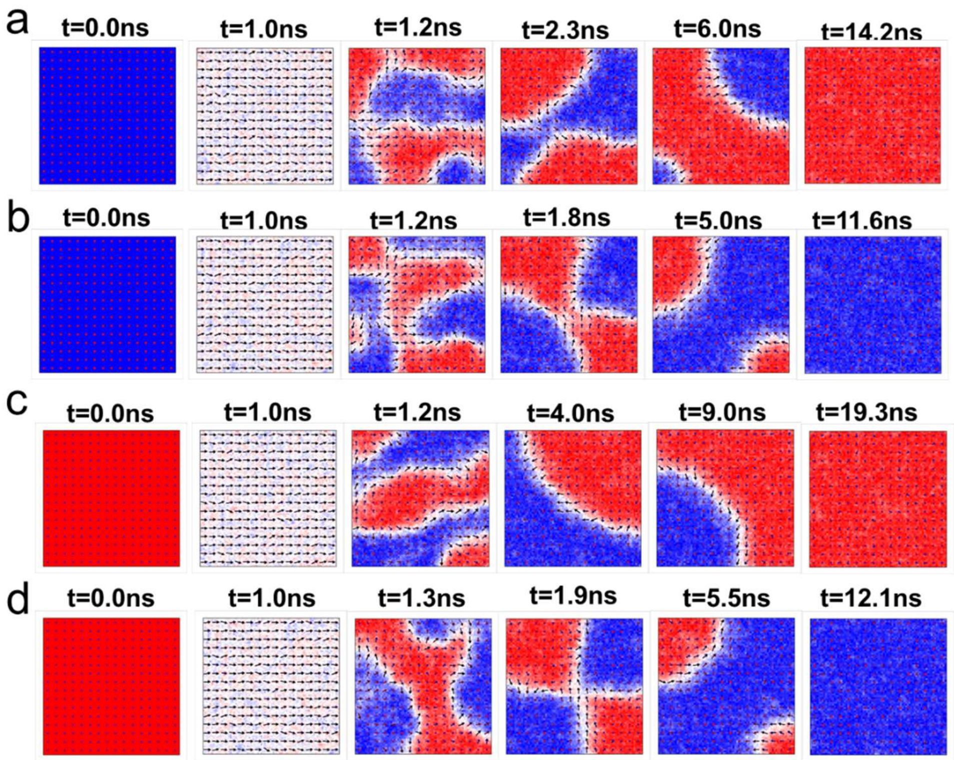

Figure S3. Object-Oriented Micro-Magnetic Framework micromagnetic simulations of the magnetization evolution based on the generalized Landau–Lifschitz–Gilbert theory, using a current density of 5×10^{12} A/m^2 (1 ns). Red (blue) for positive (negative) OOP component, while the arrows indicate the IP component of the magnetization.

Appendix D Evaluation of Intra-HD of the RPUF

We firstly investigated the retention property of a single device under room temperature. Figure S4a shows the retention data of the two resistance states, and both of them can be well sustained for 10^4 s under 50 μA read current, indicating that either the single device or the building block of the proposed PUF has a good retention property.

The intra-HD of a PUF reveals the variations between the responses of two tests under the same challenge for all device units. The ideal intra-HD is 0. To approximately evaluate the intra-HD of the PUF, we chose 15 devices, acting as a single unit, to investigate the difference between two read operations. After a write current of 1.2 mA was applied to each device, AHE resistances were detected twice by the same read current (50 μA). By encoding the upward state as logic ‘1’ while the downward state as logic ‘0’, two 15-bit responses are generated, as shown in Figure S4b. The two binary bits are coincided well with each other, meaning that the Hamming Distance of the two responses of the device unit is zero.

Furthermore, we applied the write current for 99 times to the unit and read the AHE resistances twice during each cycle. Then two corresponded bitmaps of 100 (rows) × 15 (columns) were constructed, as shown in Figure S4c. Similarly, the results show that there is no difference between the two bitmaps, confirming that the Hamming Distance of the two tests for the device unit remains zero over reconfigure cycles. According to above experimental results, we can clearly see that the testing or measurement using low current doesn't affect the magnetic properties (or stored information) of nanomagnets for all measured devices. Therefore, we can expect that there would be no difference between different tests for any one device, and estimate that the intra-HD of the proposed RPUF, which consists of 15 units, is very close to 0.

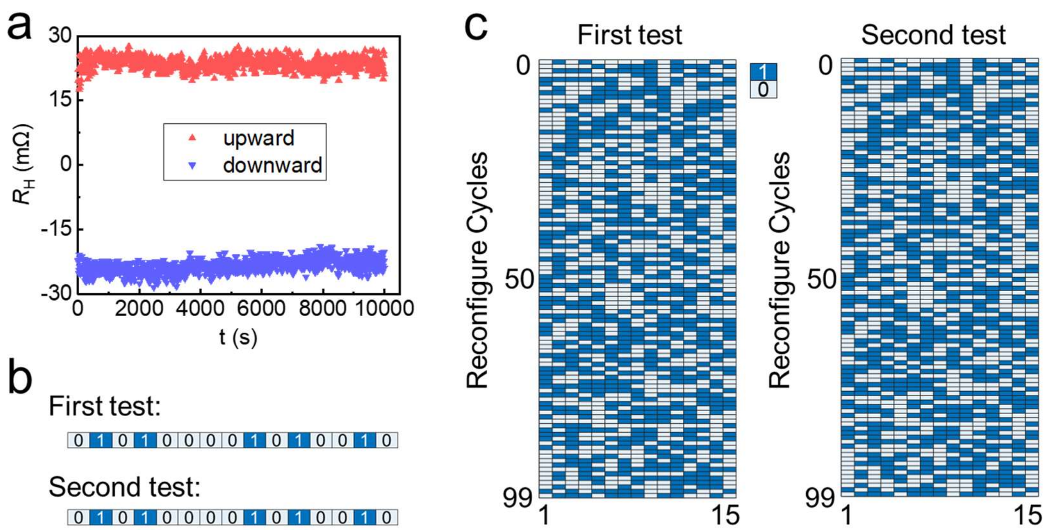

Figure S4 (a) Retention characteristic of the two different resistance levels, measured under 50 μA read current for 10^4 s. (b) Bitmaps of 1 × 15 binary bits for two tests. (c) Bitmaps of 100 × 15 binary bits for two tests.

Appendix E RPUF performance under different writing currents

In addition to investigating the RPUF at a writing current of I_w = 1.2 mA in the main text, here, we discuss the dependence of the RPUF performance on the amplitude of the writing current. Figure S5 shows the bitmaps of the original keys after a current pulse is applied to every device and the corresponding normalized inter-Hamming distance (inter-HD) with Gaussian fitting. The distribution of the HDs of 100 reconfigure cycles together with the mean normalized inter-HDs and standard deviations extracted from Gaussian fitting are shown in Figure S6. The mean inter-HDs range from 0.45 to 0.55, except in the case of $I_w = 0.8$ mA. The standard deviations are below 0.18. These two parameters can be further improved by expanding the length of keys, where the mean inter-HDs fluctuate at the center of 0.5 with standard deviations close to 0. To evaluate the reconfigurability, Figure S7 gives the bitmaps together with reconfigure HDs and correlation matrixes when considering all the keys generated in every reconfigure cycle. In each cycle, $15 \times 15 = 225$ binary bits are produced, which are extracted as row data in the bitmap. Using these bitmaps, we can calculate reconfigure HDs and correlation coefficients between every two reconfigure cycles. Figure S7i plots the mean reconfigure HDs extracted from Figure S7b, d, f, and h. One can see that the mean reconfigure HDs and correlation matrix at $I_w = 0.8$ mA are not as good as those when $I_w \geq 1.0$ mA, which coincides with Figure S2a. Therefore, high reconfigurability requires high-quality probability from relatively large currents when using TRNGs to implement an RPUF.

Besides, we have calculated the uniformity (the proportion of “1”) of the 100 reconfigure cycles of binary bits. The distribution of the uniformity under $I_w = 1.2$ mA is show in Figure S8a. The mean uniformity for the RPUF is 0.5113 with a standard deviation of 0.0335. The mean values of uniformities along with standard variations under different reconfigure currents are plotted in Figure S8b. All the mean values are close to 0.5, indicating that the binary bits have a good randomness.

On the other hand, here, the work current range of the proposed RPUF is from 1.0 mA to 1.6 mA. The results under the currents above 1.6 mA is not shown, because devices are likely to be destroyed from *Joule* heating at larger currents. The maximum of the work current range depends on the deposit quality of films in devices. General speaking, high performance from RPUFs can be obtained as long as the writing current is higher than 1.0 mA.

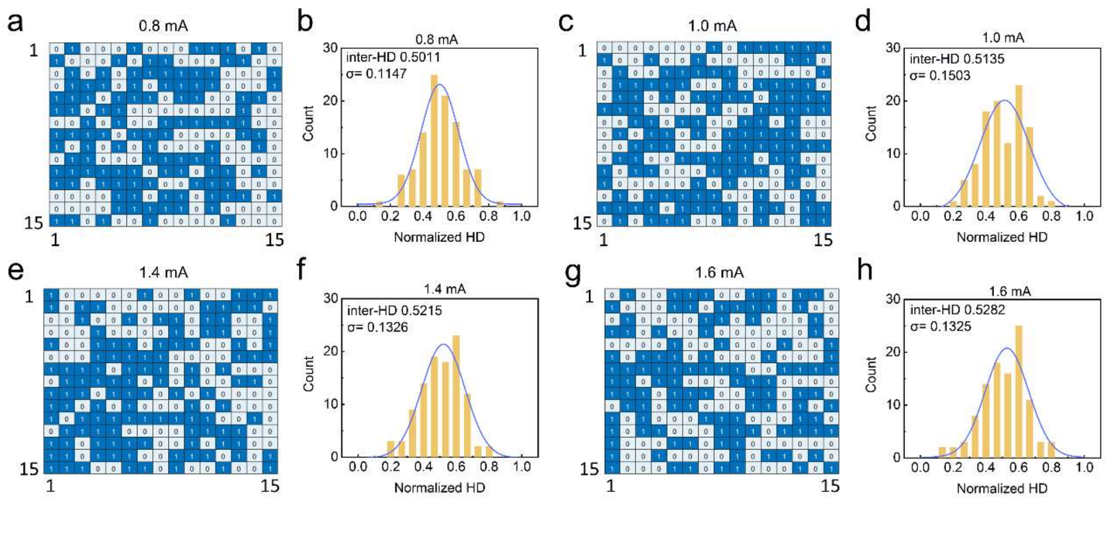

Figure S5. Bitmaps and inter-HDs of RPUFs under different writing currents.

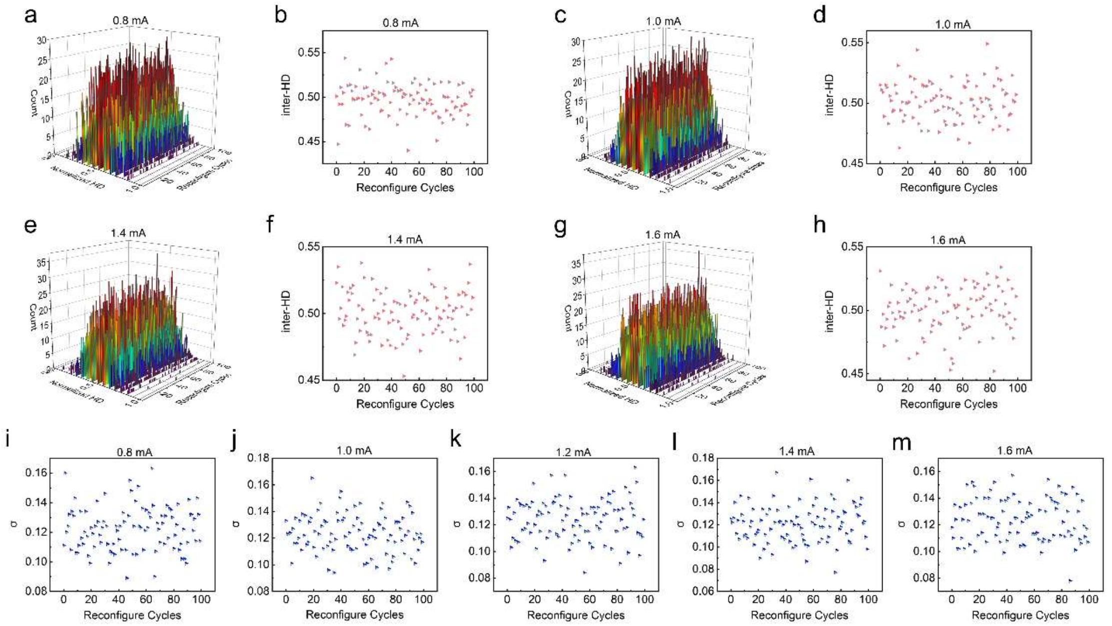

Figure S6. Distribution of the HDs of 100 reconfigure cycles under different writing currents. (a-h) Inter-HDs of 100 reconfigure cycles with their mean values and (i-m) standard deviations extracted from Gaussian function fitting under different writing currents.

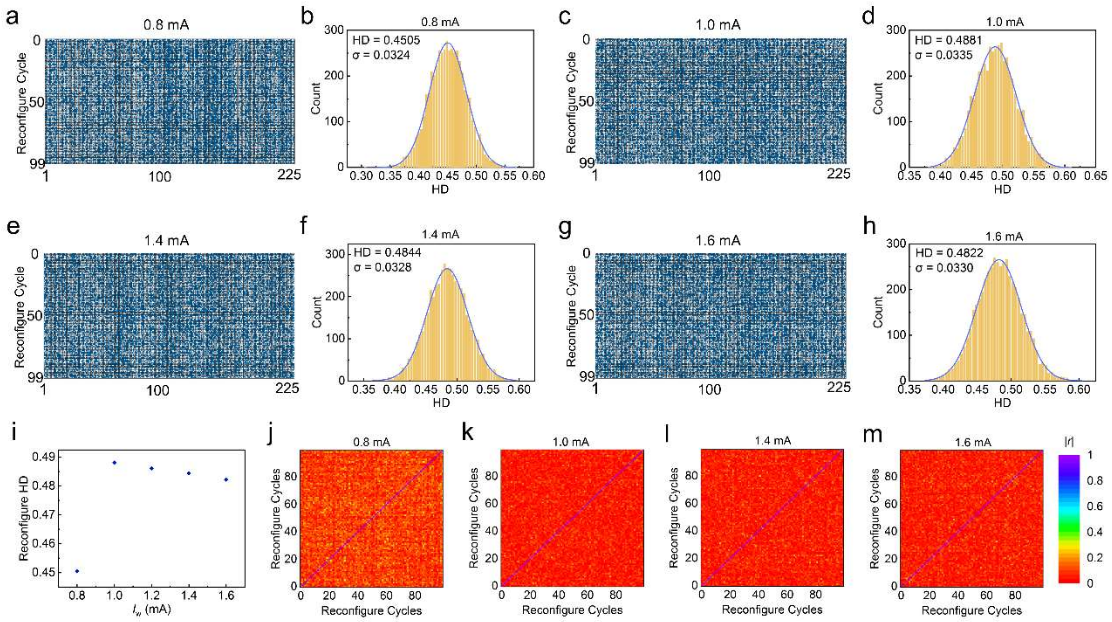

Figure S7. Evaluation of reconfigurablity of the RPUF under a series of writing currents. (a)(c)(e)(g) Bitmaps of 225 × 100 binary bits after 100 reconfigure cycles. (b)(d)(f)(h) Reconfigure-HDs distribution between 100 reconfigured keys with Gauss fitting (blue line). (i) Mean Reconfigure-HDs as a function of currents. (j-m) Correlation matrix of 100 reconfigured keys.

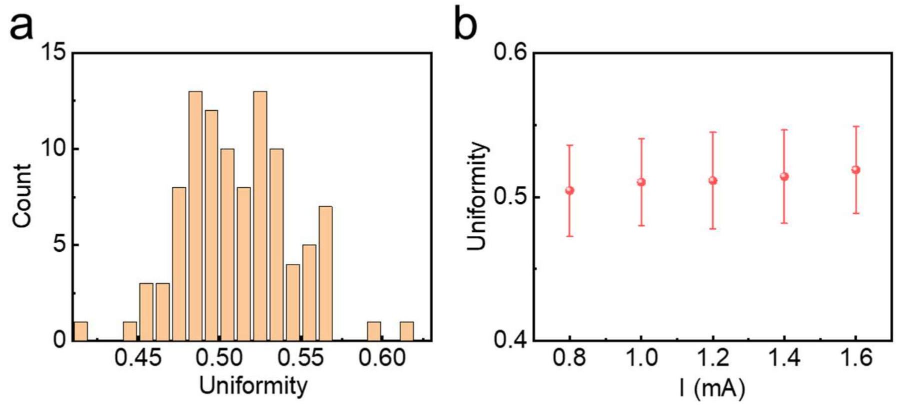

Figure S8. (a) Distribution of the uniformity test run over 100 response strings under 1.2 mA. (b) Mean values of uniformities along with standard variations under different reconfigure currents.

Appendix F Circuit scheme of the CMOS/SOT-MTJ based RPUF

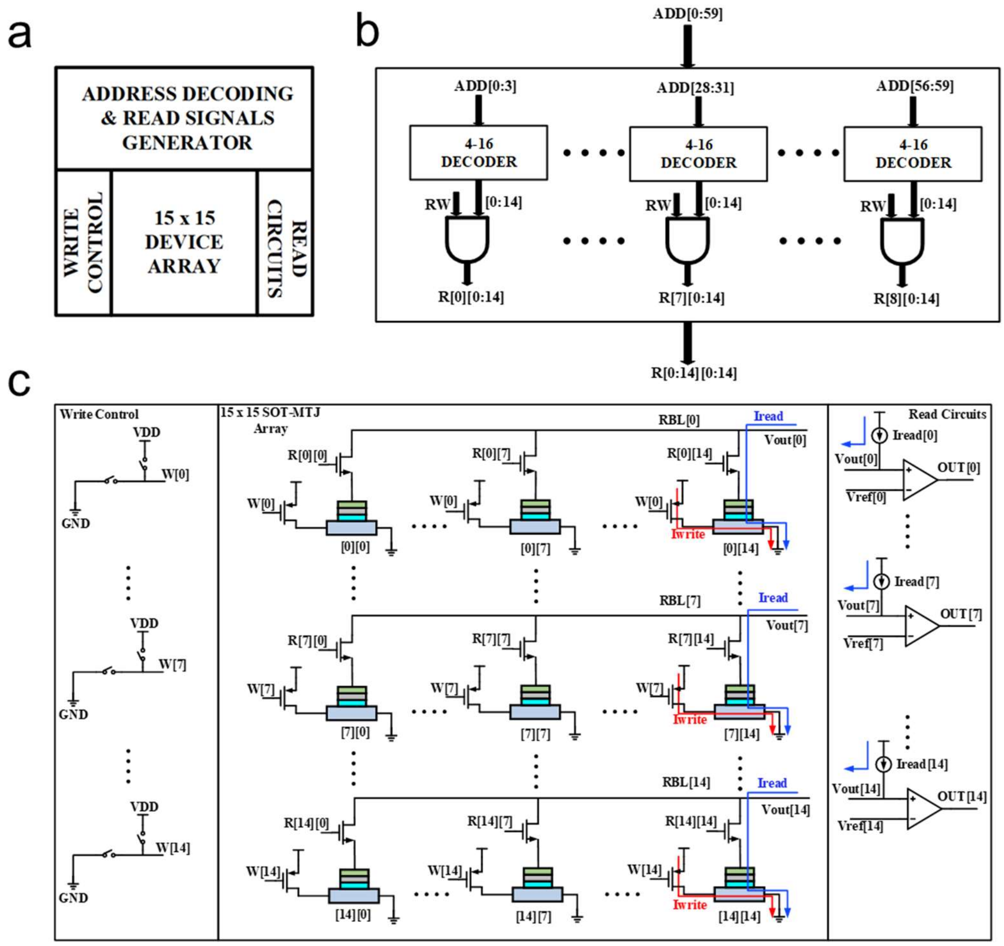

Figure S9. Circuit scheme of the CMOS/SOT-MTJ based RPUF: (a) block diagram, (b) block of address decoding & read signals generator, and (c) details of the circuit for the device array block along with write control block and read circuits.

References

1 Miron I M, Garello K, Gaudin G*, et al.* Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection. Nature, 2011, 476: 189-193

2 Liu L, Pai C-F, Li Y*, et al.* Spin-torque switching with the giant spin Hall effect of tantalum. Science, 2012, 336: 555-558

3 Yu G, Upadhyaya P, Fan Y*, et al.* Switching of perpendicular magnetization by spin–orbit torques in the absence of external magnetic fields. Nat Nanotechnol 2014, 9: 548

4 You L, Lee O, Bhowmik D*, et al.* Switching of perpendicularly polarized nanomagnets with spin orbit torque without an external magnetic field by engineering a tilted anisotropy. Proc Natl Acad Sci USA, 2015, 112: 10310-10315