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Practical Experiments on Fabricated TAS-MRAM Dies to Evaluate the Stochastic Behavior of Voltage-Controlled TRNGs

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ABSTRACT Noises exist in digital circuits can be leveraged as the source of entropy to design true random numbers generators (TRNGs), which is an important primitive component in cryptography and hardware-based security applications. In this paper, we present practical experiments and results of a TRNG implemented on magnetic random-access memory (MRAM) dies, fabricated by the thermally-assisted-switching MRAM (TAS-MRAM) technology. We, first, explain how one can find out a heating voltage value using that writing operations in the TAS-MRAM dies have a stochastic behavior. Then, we propose an improvement based on a feedback loop from being generated random bits. It helps to adjust the founded heating voltage value for writing operation with the aim of reaching the maximum entropy. Finally, we report the results of some post-processing methods, which are usually required in TRNGs to successfully pass the statistical test of NIST SP-800. The results show that one can generate random numbers with a high quality of randomness using the proposed TRNGs besides simple post-processing methods.

INDEX TERMS True random number generator, magnetic RAM, thermally-assisted-switching MRAM.

I. INTRODUCTION

Random numbers generators (RNGs) are a primitive component in cryptography, hardware-based security, statistical sampling, stochastic simulations such as Monte Carlo methods, etc. [1], [2]. RNGs are categorized into pseudo RNGs (PRNGs) and true RNGs (TRNGs). As the word pseudo in the name of PRNG implies, such generators do not literally output random numbers [3]. PRNGs include a deterministic algorithm and generate a sequence of numbers while applying a randomly chosen seed. One can certainly find out the output of a PRNG if its algorithm and using seed are revealed. Contrariwise, TRNGs generate truly random numbers. They take advantage of fluctuation of physical phenomena that usually appear as statistically random “noise” signals such as thermal noise, meta-stability, etc. [4]. The stochastic nature of such phenomenon makes them non-deterministic and unpredictable.

An important source of noise in integrated circuits (ICs) is the inaccuracy of their fabrication process, the so-called process variation [5]. This source can be leveraged to design TRNGs because it varies physical properties and, consequently, electrical/magnetic characteristics of a device in each of its fabricated instance. For instance, one important feature of a magnetic tunnel junction (MTJ) device in magnetic random-access-memory (MRAM) circuits is switching threshold voltage (Vth), which is the minimum voltage required to change the state of an MTJ [6]. Due to process variation, MTJ physical attributes (such as tunneling oxide thickness and cross-sectional area) and consequently the Vth in each MTJ of a fabricated MRAM is slightly different. This variability causes stochastic switching behavior in MTJs while applying a current equal to the theoretically calculated Vth.

As matter of fact, MRAMs will be dominant non-volatile memories in near future since MRAM prototypes have shown promising properties such as non-volatility, low fabrication cost, high speed, low power consumption, high reliability, etc. [7]. Therefore, researchers have studied different TRNGs designed and implemented using MRAM technologies [8]–[14]. However, most of these studies have been conducted on simulation environments. Despite the valuable knowledge
obtained in these studies, the lack of practical experiments is very tangible.

In this work, we present the analysis and results of a TRNG implemented on some fabricated MRAM dies. The technology of the used dies is thermally-assisted-switching MRAM (TAS-MRAM). In our practical experiments, the stochastic switching behavior of the TAS-MRAM bits is concerned and analyzed while a voltage near to the Vth is used.

The rest of the paper is organized as follows: Section II presents basic background on TRNG and MRAM. Section III represents the materials and methods employed in this work. Section IV explains the experiments and exhibits obtained results. Finally, Section V draws conclusions.

II. BACKGROUND

TRNGs usually include three modules: (1) a traducer makes an electrical signal from a targeted physical fluctuation; (2) an amplifier increases the amplitude of the electrical signal to a measurable level; (3) an analog-to-digital converter (ADC). Each of these modules affects on three main features of a TRNG: throughput, quality of randomness, and ease of integration.

Several fluctuations in different physical parameters of integrated circuits (ICs) make various noise in the form of an electrical signal such as clock jitter, meta-stability, etc. Thus, there is no necessity to design and employ a special traducer in ICs [15].

Analog circuits suffer from various noises, some of which are completely random and appropriate for designing TRNGs. However, employing these circuits imposes to use an amplifier and ADC and, consequently, impedes easy integration [16]. On the contrary, one can eliminate the need for these two modules in digital circuits. For this purpose, those noises must be employed that can stochastically make values in state elements (i.e. flip-flops) of digital circuits. One popular type of digital circuits is MRAM, which these days their usage as elements (i.e. flip-flops) of digital circuits.

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The main device of a memory bit in all MRAM technologies is a magnetic tunnel junction (MTJ). A simple schematic of an MTJ is shown in Fig. 1.b. It consists of two ferromagnetic layers separated by a thin insulating barrier. If this barrier is thin enough, electrons can tunnel from one layer into the other. The resistance of MTJs changes significantly when their ferromagnetic layers have a parallel (P) or anti-parallel (AP) magnetic orientation [17]. This phenomenon is called the Tunnel magnetoresistance (TMR) effect [18]. In other words, TMR causes MTJs to operate like a switch. In fact, if the two ferromagnetic layers of an MTJ have the parallel magnetic orientation the junction resistance is low; in the antiparallel configuration, it is high [19], shown in Fig. 1.a as Rp and Rap.

In each MTJ, one of the two ferromagnetic layers has a fixed magnetic orientation. This layer is usually called pinned layer (PL). Contrary, the other layer, the so-called free layer (FL) has an easy-changeable magnetic orientation. In each MRAM technology, a specific method is designed to change the magnetic orientation of FL. For example, in the spin transfer torque MRAM (STT-MRAM) technology a polarized current is used to change the magnetic orientation of FL [21].

In the TAS-MRAM technology, which is considered and focused in this work, the magnetic orientation of FL is changed by increasing the temperature through the MTJ while applying an external magnetic field. In this technology, one antiferromagnetic layer (AFML) with high blocking temperature (Tb) is adjoined to PL; Another AFML with low Tb is adjoined to FL. The magnetic orientation of FL and PL remains fixed and insensitive to external magnetic fields for temperatures below these blocking temperatures. Fig 1.b shows the schematic of an MTJ device in the TAS-MRAM technology. This MTJ has AFML1 and AFML2 with Tb1 = 300 °C and Tb2 = 160 °C corresponding to the PL and FL, respectively. In order to change the magnetic orientation of the FL in Fig. 1.b, AFML2 must heat up 160 °C. For this purpose, a voltage is applied to TAS-MRAM cells. This voltage is called “heating voltage” in literature.

The writing process in a TAS-MRAM cell is depicted in Figure 2. At first, the cell heats up. When it is enough warmed up, its FL becomes ready to store ‘0’ or ‘1’. Then, a field line current is applied to the cell. The direction of this current determines the direction of the FL. Finally, a short time space is required to cool down the cell by stopping the heating while maintaining the field line current.

Due to process variation, the threshold of the amplitude and duration of the heating voltage is not identical for all the memory bits of a chip. In addition, due to the environmental variation and aging effects, this threshold is not always a fixed value even for a bit. Thus, one needs to use a value...
for the heating voltage more than the threshold in order to reliably set/reset a TAS-MRAM cell. Employing a value near to the threshold may cause failures in the set/reset operations. If one can find a value that causes a failure probability of 50%, this value can be used to design a TRNG. However, broadly speaking, having exactly 50% is not practically feasible.

A problem exists in all TRNGs is their bias. A TRNG is called biased if the probability of one or some of its outputs is not equal to the probability of other outputs. In order to remove the bias of TRNGs, several post-processing procedures have been proposed. Two well-known procedures are Von-Neumann [22] and Exclusive OR (XOR) post-processing [23]. In addition, the authors in [8]-[11] proposed an approach that helps MRAM-based TRNGs generate numbers with less bias. In our experiments and analysis, we used these procedures and approach. In the following, they are briefly explained.

A. VON-NEUMANN PROCEDURE
It is a simple post-processing procedure and results in perfectly unbiased outputs [22]. It consecutively groups the bits of a binary stream in subsequences of non-overlapping pairs and generates outputs as follows:

- If a pair is 00 or 11, it is discarded.
- If a pair is 01 or 10, the output is the first bit of the pair.

Suppose the bits of a given stream have the bias \( \epsilon \); this means each bit of the stream has the probability of being ‘0’, \( P(0) \), equal to \( '0' \). This stream as the input of the Von-Neumann procedure results the output ‘y’ with the probability of being ‘0’ as following:

\[
P(y = 0) = \frac{P(‘01’)}{P(‘01’) or ‘10’)} = \frac{(0.5 - \epsilon)(0.5 + \epsilon)}{(0.5 - \epsilon)(0.5 + \epsilon) + (0.5 - \epsilon)(0.5 + \epsilon)} = \frac{1}{2}
\]

This is the best result for the output probability. However, the stream output of the Von-Neumann procedure is shorter than its inputs. The length of the output is at most 25% of the length of the raw input stream.

B. XOR PROCEDURE
The probability bias decreases when an XOR operation is performed between two independent bits. Suppose two independent bits ‘x1’ and ‘x2’ have the probability bias ‘\( \epsilon_1 \)’ and ‘\( \epsilon_2 \)’, respectively. The XOR of ‘x1’ and ‘x2’, \( ‘x1 \otimes x2’ \) has the probability of being ‘0’:

\[
P(x_1 \otimes x_2 = 0) = P(x_1 = x_2 = 0) \text{ OR } P(x_1 = x_2 = 1)
\]
\[
= P(x_1 = 0)P(x_2 = 0) + P(x_1 = 1)P(x_2 = 1)
\]
\[
= (0.5 + \epsilon_1)(0.5 + \epsilon_2) + (0.5 - \epsilon_1)(0.5 - \epsilon_2) = 0.5 + 2\epsilon_1\epsilon_2
\]

C. REAL-TIME OUTPUT PROBABILITY TRACKING (RTOPT)
The authors in [11] proposed the RTOPT approach to generated numbers with less bias. As observed in Fig. 3, this method consists of a feedback from a bit memory cell, probability calculator, and decision unit. As mentioned, in order to design a TRNG based on an MRAM technology, one can try to set (or reset) an MTJ cell using a current or voltage that causes a failure probability of 50% for the set (or reset) operation. In the RTOPT method, the decision block adjusts the value of the current or voltage in the set (reset) operation such that the set (or reset) operations fail with a 50% chance. This method somewhat compensates the low rate of the output of the Von-Neumann corrector and XOR post-processing.

III. MATERIALS AND METHODS
A. MATERIALS: TAPE-OUT TAS-MRAM
In our experiments, we employed TAS-MRAM dies designed and fabricated by CROCUS Technology. Each die includes 1K bits arranged in a 32 × 32 array such that each bit is individually addressed and accessed. One of the used die and its holding package is shown in Fig. 4. The architecture of the dies is shown in Fig. 5. IOF, IOM, and IOR are sense pads being used during the read operation. As seen in Fig. 5, IOF is on the top of the MTJ; IOM is connected right below the MTJ, and IOR is between a poly 500 \( \Omega \) resistance and a select transistor. The total impedance of a cell holding ‘0’ can be changed from \( R_{\text{min}} \) to \( R_{\text{max}} \) using the write ‘1’ (W1) operation. Likewise, the write ‘0’ (W0) operation changes the MTJ resistance from \( R_{\text{max}} \) to \( R_{\text{min}} \). The both operations require three voltages: \( V_{\text{Heat}}, V_{\text{Field1}}, \) and \( V_{\text{Field2}} \). The first one is needed to locally heat the selected MTJ, whereas the second and third ones allow changing the magnetic orientation of FL in the desired state after heating. In order to have a certain \( W_0 \), one needs to apply 2V, 3.3V, and 0V to \( V_{\text{Heat}}, V_{\text{Field1}}, \) and \( V_{\text{Field2}} \), respectively. Likewise, the certain \( W_1 \) operation needs to apply 2V, 0V, and 3.3V to \( V_{\text{Heat}}, V_{\text{Field1}}, \) and \( V_{\text{Field2}} \), respectively. The duration of these three signals, \( T_{\text{heat}}, T_{\text{Field1}}, \) and \( T_{\text{Field2}} \) must be 30 ns. In these cases, one can be sure that the write operations are
done without any fail. We call these operations “Certain Write 0” (CW₀) and “Certain Write 1” (CW₁). The read operation need \( V_{\text{Field1}} = 0V, V_{\text{Field2}} = 0V, V_{\text{Heat}} = 0.3V, \) and \( T_{\text{Heat}} = 30 \) ns.

### B. METHODS: VOLTAGE-CONTROLLED TRNG

In this work, we aimed to explore a Voltage-Controlled TRNG (VC-TRNG) implemented on the TAS-MRAM dies. VC-TRNGs leverage one or some noises on controlling signals designed to set/reset a memory cell. This type of TRNGs can be efficient if noises on controlling signals cause that write operations fail with a probability of 50%.

In the previous section, it was explained that the signals \( V_{\text{Heat}}, V_{\text{Field1}}, \) and \( V_{\text{Field2}} \) are employed in the TAS-MRAM dies for the \( W₀ \) and \( W₁ \) operations. In addition, the required properties of these to have the \( CW₀ \) and \( CW₁ \) operations were introduced. In order to design a VC-TRNG, we use \( CW₀ \) and the “Uncertain Write 1” (\( UW₁ \)) in which a voltage in the range of \([0V, 2V)\) is selected for applying to \( V_{\text{Heat}} \). In this case, the probability that a cell have ‘1’ after performing the sequence of \( CW₀-UW₁ \) depends on (1) the selected voltage and (2) the effects of the process variation on the cell. In order to have an efficient VC-TRNG, one must select a value from the mentioned range such that it results in a failure probability of 50%.

### IV. EXPERIMENTS AND RESULTS

#### A. PRIMARY EXPERIMENT

In order to find out a voltage value by which 50% of the \( UW₁ \) operations fail, experiments begin from a test voltage equal to 1V. For this voltage, the sequence of \( CW₀-UW₁ \) was executed on an MTJ \( 10³ \) times; and the switching probability, \( P(1) \), is calculated. Then, 0.01 V is added to the test voltage and again the \( 10³ \) times the sequence of \( CW₀-UW₁ \) is executed. This procedure is continued until the test voltage reaches 2V. The results of this procedure applied to two MTJs of a die are presented in Fig. 6. As observed, the switching probability depends on the value of the heating voltage. It gradually increases for voltages between 1.5V and 1.7V. The difference between the curves in this figure is due to cell-to-cell process variations.

#### B. EXPLORING TRNG ON A SINGLE MTJ

The results shown in Fig. 6 inform us that a random bit (Rb) with a probability of 50% can be generated by adjusting \( V_{\text{Heat}} \). In order to have an efficient TRNG, a switching activity of 50% however is necessary, it is not sufficient. High-quality Rbs require equiprobability of each switching event. In other words, the statistical distribution of the switching probability of Rbs should be the same as the binomial distribution. However, the switching probability fluctuates a lot around the nominal value of \( P = 50\% \) due to environmental effects such as thermal and voltage fluctuations. Figure 7 shows the histogram of the equiprobability paucity of switching probability for two MTJs, MTJ1 (red) and MTJ2 (blue). For each histogram, \( 10⁷ \) bits are generated. These bits are gathered in \( 10³ \) groups including \( 10⁴ \) bits. Each group makes a switching probability value. In the histograms, each point in the x-axis presents a switching probability; and the y-axis shows how many times a switching probability happens among the \( 10³ \) groups. For MTJ1, the mean and the standard deviation are 54.22% and 8.66%; and for MTJ2, these values are 53% and 6.79% respectively. The same experiments on other cells in the dies results (almost) the same as MTJ1 and MTJ2.

#### C. USE OF POST-PROCESSING PROCEDURES TO ENHANCE OUTPUT PROBABILITY

As mentioned in Section II, the randomness quality of raw Rbs generated by TRNGs can be enhanced using post-processing procedures, like Von-Neumann and XOR ones.
Fig. 7 shows that the designed VC-TRNG needs such procedures to obtain high-quality Rbs.

By applying the Von-Neumann corrector to the raw Rbs generated by both MTJ1 and MTJ2, less than $9 \times 10^5$ processed Rbs is obtained from a total of $10^7$ raw Rbs generated by each MTJ. The processed Rbs are less than 9% of the initial raw Rbs. Fig. 8 shows the switching probability obtained for each $8 \times 10^3$ Rbs from a total of $8 \times 10^5$ raw Rbs for both MTJ1 (red) and MTJ2 (blue) after the Von-Neumann correction. The mean P value and standard deviations are 49.97% and 0.48% for MTJ1 and 50.008% and 0.49% for MTJ2. As observed, the bias is considerably reduced but the output rate is quite low.

Performing one XOR post-processing on the raw Rbs generated by MTJ1 and MTJ2 results in the mean 49.5% and standard deviation of 1.37%. These results confirm a good enhancement provided by an XOR post-processing. The histogram of switching probability is depicted in Fig. 9.

D. USE OF RTOPT TO ENHANCE OUTPUT PROBABILITY

The histogram of switching probability obtained from every $10^4$ Rbs from a total of $10^7$ Rbs generated by the RTOPT method is shown in Fig. 10. This figure shows the improvement of the distribution. P (1) fluctuate around 47.45% and 52.47% with a mean value of 50.12% and a standard deviation of 0.78%. This compensation method has the advantage of being immune against thermal or voltage fluctuation while keeping the output bit-stream rate to 100% of initial bit-stream.

E. NIST TEST RESULTS

In order to qualify an RNG, the randomness of its generated Rbs is studied. This is done through statistical tests that compare the RNG outputs with those, theoretically, have a sequence of truly Rbs. For instance, the National Institute of Standard and Technology (NIST) has developed a suite of tools available online that can statistically test the randomness
TABLE 1. Result of NIST test on the generated raw Rbs and the outputs of the XOR², XOR³, and Von Neumann.

<table>
<thead>
<tr>
<th>Test name</th>
<th>Raw Rbs</th>
<th>XOR²</th>
<th>XOR³</th>
<th>Von Neumann</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Block frequency</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Run</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Longuest Run</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Cumulative Sums</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Binary Rank</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>FFT</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Serial</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Approximate Entropy</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Non-Overlapping Template</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

TABLE 2. Results of NIST test on the Rbs generated by an RTOPT structure (in column 2), and the XOR³ function of 4 RTOPT structures (in column 3).

<table>
<thead>
<tr>
<th>Test name</th>
<th>RTOPT Rbs</th>
<th>XOR³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Block frequency</td>
<td>Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>Run</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Longuest Run</td>
<td>Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>Cumulative Sums</td>
<td>Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>Binary Rank</td>
<td>Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>FFT</td>
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<td>Pass</td>
</tr>
<tr>
<td>Approximate Entropy</td>
<td>Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>Non-Overlapping Template</td>
<td>Fail</td>
<td>Pass</td>
</tr>
</tbody>
</table>

of any RNG [24]. For this purpose, we organize sequences of Rbs as follows:

1) 100 sequences of \(10^5\) bits generated by a single MTJ (raw Rbs)
2) 100 sequences of \(8 \times 10^3\) bits obtained by performing the Von Neumann correction on raw Rbs
3) 100 sequences of \(10^5\) bits generated by RTOPT accompanying a single MTJ
4) 100 sequences of \(10^5\) bits obtained by XORRing 8 MTJs (XOR³ on Raw Rbs)
5) 100 sequences of \(10^5\) bits obtained by XORRing 4 MTJs in 4 RTOPT architectures (XOR² on RTOPT Rbs).

Results are reported in Table 1 and 2. All the 10 applicable tests failed for the initial raw Rbs. However, four of them passed for the Rbs generated after XOR². When applying Von Neumann correction or the XOR³ post-processing procedure, all the tests passed. As a result, one needs to use such post-processing procedures to have a high-quality TRNG based on VC-TAS-MRAM.

RTOPT results better, as seen in Table 2. Two out of 10 tests can be passed no need any post-processing; and in order to pass all the test, one only needs to perform XOR².

F. THROUGHPUT

As mentioned in Section II, one important feature for TRNGs is throughput. The throughput of the studied TRNG in this work is determined by the minimum required time to consecutively perform the CW₀, UW₁, and Read operations. Thus, according to the datasheet of the used TAS-MRAM technology, the throughput is calculated to 11 Mb/s. This throughput can be tripled if one uses three TAS-MRAM cells, and make a pipeline for the CW₀, UW₁, and Read operations.

In order to have a fair comparison between the throughput of the TAS-MRAM-based TRNG proposed in this work and that of STT-MRAM-based TRNGs, we chose the works [10] and [12]. In these two works, the CW₀, UW₁, and Read operations were performed on fabricated STT-MRAM dies. Based on the required time for these operations in the STT-MRAM technology, the throughput of the TRNGs in [10] and [12] is about 66 Mb/s.

It is noteworthy to mention that in the STT-MRAM technology, the maximum working frequency is higher than that of TAS-MRAM; nonetheless, the throughput of TRNGs based on these two technologies are in the same decade range. In addition, the TAS-MRAM technology has its own benefits, like the capability of designing Magnetic Logic Unit [25].

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