Reliable Sub-Nanosecond Switching of a Perpendicular SOT-MRAM Cell without External Magnetic Field

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ABSTRACT

The steady increase in performance and speed of modern integrated circuits is continuously supported by constant miniaturization of complementary metal-oxide semiconductor (CMOS) devices. However, a rapid growth of the dynamic and stand-by power due to transistor leakages becomes a pressing issue.

A promising way to stop this trend is to introduce non-volatility. The development of an electrically addressable non-volatile memory combining high speed and high endurance is essential to achieve these goals. It is particularly promising to employ non-volatility in the main computer memory as a replacement of conventional volatile CMOS-based DRAM.

To further reduce the energy consumption, it is essential to replace caches (SRAM) in modern hierarchical multi-level processor memory structures with a non-volatile memory technology. The spin-orbit torque magnetic random access memory (SOT-MRAM) combines non-volatility, high speed, high endurance, and is thus suitable for applications in caches. However, its development is still impeded by the necessity of a static in-plane magnetic field.

We propose a magnetic field-free perpendicular SOT-MRAM, based on a cross-bar architecture and the use of two consecutive orthogonal sub-nanosecond current pulses. In this way small layout footprint and high integration density are guaranteed.

Keywords: Spin-Orbit Torque, Non-Volatile Magnetoresistive Memory, Perpendicular Magnetic Anisotropy, SRAM, Sub-0.5ns Switching.

1. INTRODUCTION

To be competitive with the traditional volatile and flash memory technologies, emerging non-volatile memories must offer fast switching time, high integration density, good scalability, long retention time, high endurance, low power consumption, and be CMOS-compatible. Magnetoresistive random access memory (MRAM), in particular spin-transfer torque (STT) MRAM possesses all these advantages and is considered as a perfect candidate for future embedded non-volatile DRAM [1]. Advanced STT-MRAM is characterized by high-speed access (less than 10ns) and is thus suitable for L3 caches [1, 2], where it guarantees an about ten times power reduction as compared to DRAM [3-5]. However, STT-MRAM requires a high write current which must be supplied through a large access transistor. Reduction of the MTJ diameter can reduce the critical current, however, the MTJ characteristic's variability also increases, which severely affects the read performance. When the magnetization of the free layer is at equilibrium and thus parallel to that of the reference layer, the STT is zero. This results in an initial incubation delay which limits ultrafast switching. The dynamics of the free layer magnetization is governed by thermally activated fluctuations leading to a broad switching time distribution. Although several ways to reduce the incubation delay have been investigated and a record fast 500ps switching in MTJs has been reported, the use of STT-MRAM for ultrafast applications in L1 and L2 cache memories remains questionable as very large writing currents are required. The critical switching current reduction at faster switching represents the main challenge of STT-MRAM as this current flows through the thin dielectric tunnel barrier and causes accelerated aging of the barrier and even hard breakdown. The switching endurance is thus severely reduced for ultrafast applications.

MRAM controlled by voltage [6-9] is a viable option for last level cache applications, because the magnetization is switched fast [10] by voltage rather than current. Because of that the large control transistor is not needed and the cell size can be reduced. Regardless of this advantage, a voltage controlled MRAM cell has a large resistance compared to STT-MRAM, which results in a smaller read current and a longer read delay. To address the issue, a careful optimization of the whole circuit is required [9].

Among the newly discovered physical phenomena suitable for using in next-generation MRAM are the spin-orbit torques (SOT) generated by the spin Hall and interfacial effects in heavy metal/ferromagnetic layers [11-17]. In this memory cell the MTJ's free layer is grown on a heavy material with a large spin Hall angle. By passing the current through the heavy material the SOT acts on the free layer. In this case the large switching current is injected in-plane along the heavy metal/ferromagnetic bilayer and does not flow through the MTJ. Therefore, the read and write operations are decoupled leading to a three-terminal cell configuration. This prevents the tunnel barrier from damage and improves device reliability by eliminating correlations between the switching current and the retention time. SOT-MRAM is also free from the read error present in STT-MRAM, when the read current causes an unwanted switching. Three-terminal MRAM cells are promising candidates for future generations of non-volatile memory for fast sub-ns switching [18]. The deterministic magnetization switching by current pulses as short as 180ps in Pt/Co/AlOx dots with lateral dimensions of 90 nm was recently demonstrated [19]. The critical current needed for switching was found to be a factor of four smaller than that estimated from the macrospin switching model. This strongly indicates that the switching is governed by nucleation and fast propagation of domain walls rather than by single-domain switching. The measurements also suggest a negligible incubation time for the SOT magnetization switching scheme, when the magnetization is out of plane and thus perpendicular to the current flowing through the heavy metal/ferromagnet bilayer.

SOTs acting on a free ferromagnetic layer do not always provide a deterministic switching. In particular, to reverse the magnetization of a free layer with a perpendicular magnetic anisotropy [19], or with an in-plane magnetic anisotropy parallel to the current direction, an external magnetic field is required [13, 20]. Such a magnetic field reduces the thermal stability of MRAM cells. More importantly, the integration of such a field in an embedded memory is very challenging and the future of SOT-MRAMs is closely linked to the development of a reliable, scalable, and integrable field-free switching solution. The role of this external magnetic field is to break the mirror symmetry of the structure with respect to the plane formed by the easy magnetization orientation and the in-plane current direction. Several strategies were recently pursued to break this mirror symmetry:

• growth of the dielectric on the top of the heavy metal/ferromagnet bilayer [21] or of the ferromagnetic layer in a special wedge form [22]

• use of an antiferromagnetic (AF) material to bias the ferromagnetic layer [23-26]

• use of an antisymmetric magnetic dot shape which controls the switching [27]

However, even if in most of these studies a field-free switching was reported, these methods either require a local intrusion into the fabrication process, or are based on solutions whose scalability is questionable (AF, shapes), which makes the further large-scale integration of the fabricated memory cells difficult. Although an advanced technology to process SOT-MRAM on a 300mm wafer was recently presented [28], the issue of a magnetic field-free switching has not been resolved yet.

2. TWO-PULSE SWITCHING SCHEME

The configuration where the magnetization is in-plane and perpendicular to the current direction does not require an external magnetic field for deterministic switching [6] and shows a lower critical current [27]. However, the magnetization switching dynamics is similar to that of the STT-induced switching, namely, it is precessional and possesses a long initial incubation period, when the torque is not efficient.

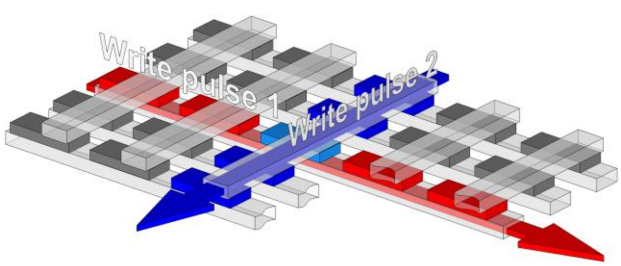

Figure 1 Schematic illustration of a cross-point architecture to realize the switching of the free magnetic layer by means of consecutive orthogonal sub-nanosecond current pulses.

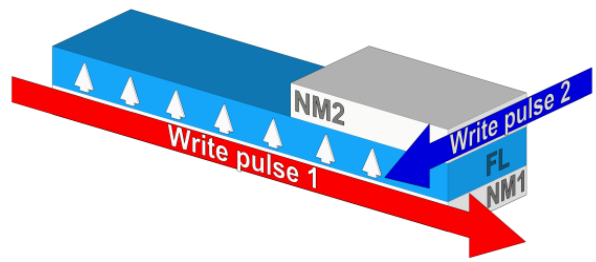

Figure 2 Perpendicular SOT-MRAM memory cell with a 52.5nm × 12.5nm ×2nm free layer. Two consecutive current pulses are applied. The duration of “Write pulse 1” is fixed at 100ps. The current amplitudes of both pulses are chosen equal to 100µA.

Employing the two-pulse switching [29], with the “Write pulse 1” running along the direction of the in-plane magnetization, generates an efficient torque and thus removes the incubation period. The SOT of the “Write pulse 2” applied after is efficient as it acts on the magnetization already deviated from its stable direction. Figure 1 illustrates a cross-point architecture in which the “Write pulse 1” is used to pre-select the memory cell (shown in light-blue; while the consecutive “Write pulse 2” is applied to complete the switching.

We apply the two-pulse scheme previously proposed for switching of an in-plane structure [29] to perpendicularly magnetized free layers. We demonstrate that the two-pulse switching scheme is suitable for sub-0.5ns SOT switching of free magnetic layers with perpendicular magnetic anisotropy. Most importantly, the idea to introduce the switching scheme with two perpendicular current pulses eliminates the need of the magnetic field [30]. The first “Write pulse 1” is efficient from the beginning thus eliminating an incubation period, while the second perpendicular “Write pulse 2” completes the switching without magnetic field. This way we use the advantages from either pulse switching and at the same time we mitigate their corresponding shortcomings because of the complementary setup. It is important that no modification of the fabrication process or the layers is required.

Figure 2 schematically illustrates the proposed SOT-MRAM cell. The first pulse runs through the nonmagnetic metal line NM1 and tilts the magnetization away from its equilibrium position. The “Write pulse 1”, however, cannot reliably switch the magnetization as there is no magnetic field. A second pulse is then injected along the nonmagnetic line NM2 perpendicular to the first one completing the switching. It is important that the second pulse runs not under the whole free layer but through a part of it. This is needed to break the mirror symmetry. Indeed, as it was demonstrated recently, the switching of Permalloy free layer in a WTe_2/Permalloy was observed, when the mirror symmetry of the transition-metal dichalcogenide layer was broken [17].

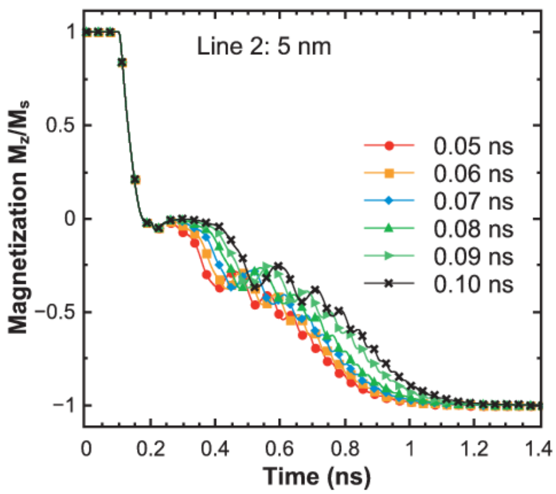

Figure 3 Magnetization switching dynamics as a function of time, for several durations of the second current pulse. The first pulse with fixed duration 100ps is applied with a delay of 0.1ns needed for thermalization. The width of Line 2 for the second pulse is 5nm (see Figure 2).

3. RESULTS AND DISCUSSION

Results of simulations are shown in Figure 3 to Figure 7. It is assumed that the duration of the first pulse is 0.1ns. For simplicity the currents I_1=I_2=100µA of the pulses are assumed to be equal.

The dynamics of the magnetization (or, to be more precise, its projection on the hard perpendicular magnetic anisotropy axis) is shown in Figure 3. The first current “Write pulse 1” is applied after 0.1ns delay. One can see that this pulse quickly brings the magnetization in-plane. The in-plane magnetization is then brought through the equator by means of the second current “Write pulse 2”, which runs not under the whole structure but through a part thus exerting the spin-orbit torque only on this part. The second pulse is applied without delay after the first current pulse. It is concluded that the duration of the second pulse affects the duration of switching. Unexpectedly, the switching is faster for shorter pulse durations.

Similar dependencies of the magnetization dynamics are observed for the part under which the current runs with widths

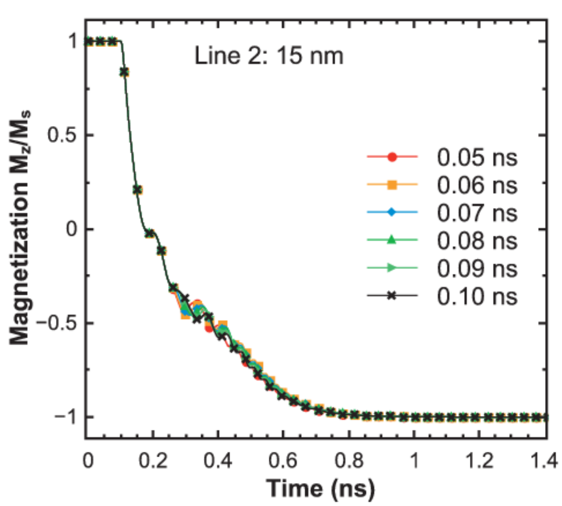

Figure 4 Magnetization switching dynamics for several durations of the second current pulse. The width of Line 2 for the second pulse is 15nm (see Figure 2). The switching becomes fast and nearly independent on the “Write pulse 2” duration.

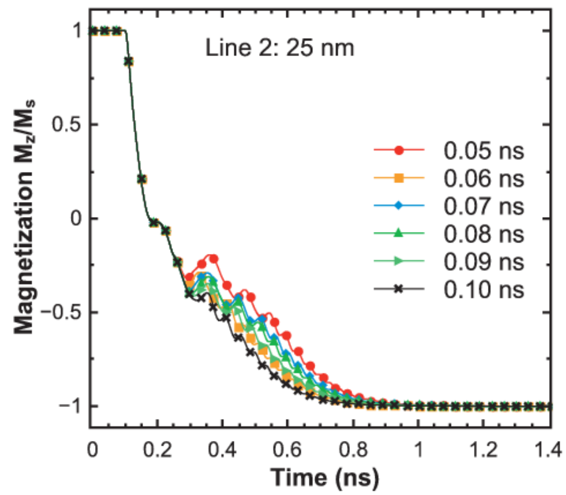

Figure 5 Magnetization switching dynamics for several durations of the second current pulse. The width of Line 2 for the second pulse is 25nm (see Figure 2). The switching becomes dependent on the “Write pulse 2” duration again. For shorter pulse duration it also becomes slower.

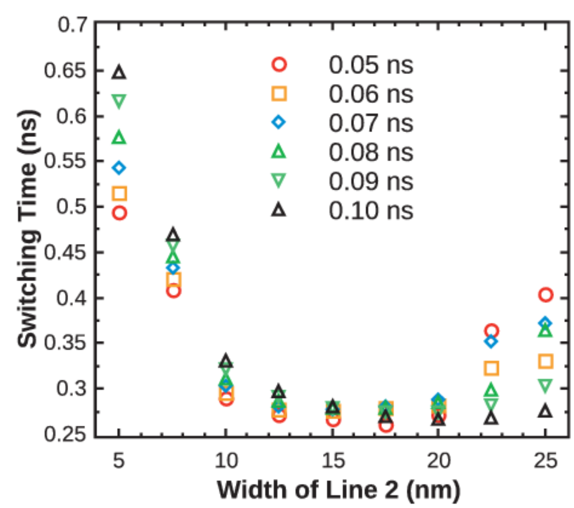

Figure 6 Switching time as a function of the second line width, for several durations of the second pulse, I_1=I_2=100µA. Temperature is 300K. Each point is a result of averaging over 20 realizations.

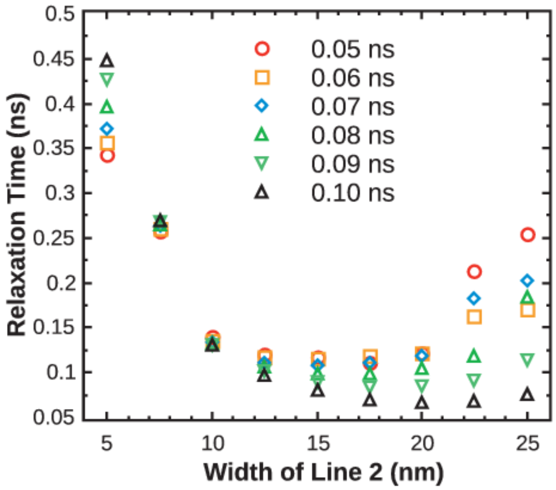

Figure 7 Relaxation time obtained by extraction the "Write pulse 1" and "Write pulse 2" durations from the switching time from Figure 5. The relaxation time is the largest contribution to the switching time.

of 15nm (Figure 4) and 25nm (Figure 5). As it is seen from Figure 3, there is almost no dependence of the magnetization dynamics for the second current pulses' durations between 50ps and 100ps. In the case when the current carrying part is 25nm wide, the longer pulses result in a faster switching, as expected.

Figure 6 shows the dependence of the switching time on the width of the current carrying part, for several durations of the second current pulse. The switching time is the sum of the durations of the first and second pulses plus the relaxation time needed for the average magnetization to develop the projection of one-half from the saturation magnetization in the direction opposite to the initial orientation. It is concluded that an optimal width of the current carrying part to achieve the fastest switching is around 30% from the total width of the free layer. Figure 7 indicates that the largest contribution in the switching time is due to the magnetization relaxation. As it follows from Figure 6, the switching time is not sensitive to the second pulse duration when the width of the wire for the second pulse is around 30% of the width of the free layer. Therefore, it easies constraints on the pulse quality and synchronization exactly at the configuration yielding the fastest switching.

4. CONCLUSIONS

The presented two-pulses scheme is shown to be working very well for SOT-assisted switching of a free magnetic layer with perpendicular magnetic anisotropy. The switching is free from an external magnetic field; it is efficient and fast as the switching time for various values of the parameters studied (the second pulse duration, the width of Line 2) is below 0.5ns. It is demonstrated that the fastest switching is achieved, when the width of the second current carrying wire is about one third of the free layer width. Importantly, requirements to the pulse duration and synchronization are also relaxed when the width of the second wire is around 30% of the free layer width.

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