Combining Perpendicular and Shape Anisotropy for Optimal Switching of Advanced Spin-Orbit Torque Memory Cells

Viktor Sverdlov[1,2] and Siegfried Selberherr[2]
[1]Christian Doppler Laboratory for Nonvolatile Magnetoresistive Memory
at the Institute for Microelectronics, TU Wien
[2]Institute for Microelectronics, TU Wien, Selberherr@TUWien.ac.at

Abstract

The spin orbit torque magnetic random access memory (SOT-MRAM) combines non-volatility, high speed, and high endurance and is suited for applications in caches. However, its development is still hindered by relatively high switching currents in in-plane magnetized structures and the need of an external magnetic field for deterministic switching of perpendicular layers. We employ the two-pulse switching scheme to achieve deterministic sub-500ps and field-free switching in in-plane cells with weak perpendicular anisotropy and perpendicular rectangular structures.

(Keywords: Spin-orbit torque; MRAM; switching; in-plane MTJ; perpendicular magnetic anisotropy)

Introduction

A comprehensive path to overturn the unfavorable trend of increasing power at stand-by is to introduce non-volatility in the circuits. Spin-transfer torque magnetic RAM (STT-MRAM) is fast (10ns), possesses high endurance (10^{12}), and has a simple structure. It is compatible with CMOS and can be straightforwardly embedded in circuits. However, the switching current for operating at a speed faster than 10ns is growing rapidly. This leads to oxide reliability issues which in turn reduces the MRAM endurance. Therefore, engineering of an electrically addressable non-volatile memory combining high speed (sub-ns operation) and high endurance suitable for replacing SRAM in higher-level caches requires the use of new physical principles.

Among the recently discovered physical phenomena suitable for the next generation of high-speed MRAM is the spin-orbit torque (SOT) assisted switching at room temperature in heavy metal/ferromagnetic [1] or topological insulator/ferromagnetic [2-4] bilayers. In this memory cell the magnetic tunnel junction's (MTJ's) free layer (FL) is grown on a material with large spin Hall angle SOT. The SOT acting on the adjacent magnetic layer is generated by passing the current through this material. The large switching current is injected in-plane along the heavy metal line and does not flow through the MTJ. To read the state of the FL, a much weaker read current is applied through the MTJ, which does not damage the tunnel barrier. It improves device reliability by eliminating correlations between the switching current, the retention time, and the endurance. Although separating the write and read current paths results in a three-terminal configuration and a larger device footprint, the high integration density is not critical as the SOT-MRAM cell competes with a typical six-transistor SRAM cell which is quite large.

Although the high switching current is not flowing through a magnetic tunnel junction but rather through a heavy metal wire under it, the current is still high [1], and its reduction is the pressing issue in the field of SOT-MRAM development.

Topological insulators (TIs) are promising materials for reducing the switching current as they are characterized by a high spin Hall angle and a remarkable efficiency of charge to spin conversion due to the peculiar perpendicular spin-momentum locking in the interface states. In addition, the strong spin-orbit interfacial Rashba field helps generating spin density in TIs boosting the charge to spin conversion efficiency above 100%. Although high charge to spin conversion efficiency in TIs has been reported, the electrical conductivity of TIs needed for practical applications to build a high-density, ultra-low power, and ultra-fast non-volatile memory was not sufficiently high because of the insulating bulk. Recent developments introduce BiSe [3] and BiSb [4] based TIs as suitable candidates for emerging SOT-MRAM, as they possess a charge to spin conversion efficiency of 18.8 and 52 times, respectively. This allows to reduce the switching current by two orders of magnitude as compared to W-based SOT-MRAM.

However, despite an undoubtful progress in developing SOT-MRAM, there is one important issue which has not been convincingly resolved so far. Namely, a static magnetic field is still required to guarantee deterministic switching [5] or a perpendicularly magnetized FL. Several paths to achieve the deterministic switching without magnetic fields were suggested. However, these methods either require a local intrusion into the fabrication process, or are based on solutions where scalability is questionable (antiferromagnets, shapes), which makes further large scale integration of the fabricated memory cells problematic. Here we report a two-pulse switching scheme to achieve deterministic,

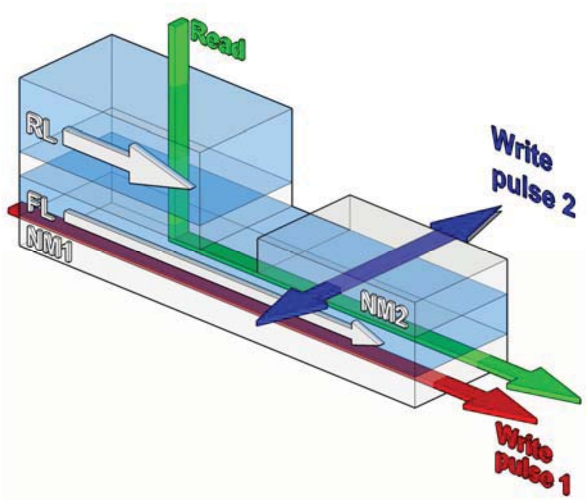

Fig. 1: Spin-orbit torque memory cell with an in-plane magnetized FL switched by current write pulses (red and blue) applied through heavy metallic wires NM1 and NM2 with a high spin Hall angle. The FL is grown on NM1.

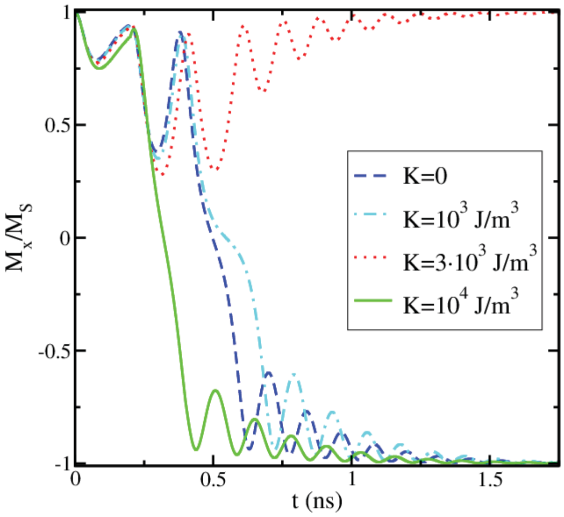

Fig. 2: Adding perpendicular magnetization in a two-pulse scheme of an in-plane structure allows reducing the switching time to sub-0.5ns, however, an engineering of the perpendicular anisotropy constant is required.

fast (sub-500ps) and magnetic field-free switching in both in-plane and perpendicular rectangular structures. To make the switching of an in-plane structure faster, it is important to add a weak perpendicular anisotropy. To make the switching of a perpendicular structure deterministic without external magnetic field, the shape in-plane anisotropy is of a paramount importance.

Perpendicular anisotropy in in-plane free layer switching

The SOT switching scheme based on the use of two consecutive orthogonal sub-nanosecond current pulses shown in Fig.1 can switch in-plane structures efficiently [6]. The first pulse deviates the magnetization from its equilibrium position, while the second, consecutive pulse completes the switching within sub-ns time. Importantly, if only one of either of the pulses is applied during a period of time equal to the switching time in the two-pulse scheme, the FL magnetization cannot be inverted. The first pulse only deviates the magnetization from its equilibrium position, where the SOT due to the second pulse becomes efficient. To further decrease the switching current at the same switching time or to reduce the switching time at a fixed current, a perpendicular magnetic anisotropy typically developed at the MgO/CoFeB interface can be introduced. The perpendicular anisotropy compensates the large demagnetizing contribution when the magnetization is out of plane during switching. However, the perpendicular anisotropy constant K_1 should not be too large to compromise the temperature stability of the in-plane structure. Fig.2 displays several switching characteristics of the in-plane magnetization along the easy axis, for several K_1. Our analyses predict that the effect of K_1 on the switching process is not monotonic as the switching time becomes longer at $K_1=10^3$J/m$^{3\cdot}$ No switching is observed at an intermediate value $K_1=3\times10^3$J/m^3. Importantly, increasing the value of the interface-induced perpendicular anisotropy to $K_1=10^4$J/m^3 results in fast, sub-500ps switching. We note that a further increase of K_1 without compromising the thermal stability is not possible as this is the critical value at which the energies of the magnetization become equal for being out of plane and in-plane along the hard anisotropy axis.

Shape in-plane anisotropy in perpendicular free layer switching

The two-pulse scheme is also applicable for switching perpendicularly magnetized free magnetic layers of rectangular shape (Fig.3) [7]. After the 200ps thermalization period the magnetization dynamics is modeled with a random magnetic field and a set of different microscopic magnetization realizations is obtained. Then the first 100ps short pulse with a current larger than the critical current [1] is applied. Due to this pulse the SOT puts the magnetization in-plane perpendicular to the current direction. If the second pulse with a current larger than the critical current is applied, it would orient the magnetization in-plane parallel to the long side of the rectangular FL. In this case the magnetization would relax up or down with an equal probability, and no deterministic switching is achieved. However, if the current in the second

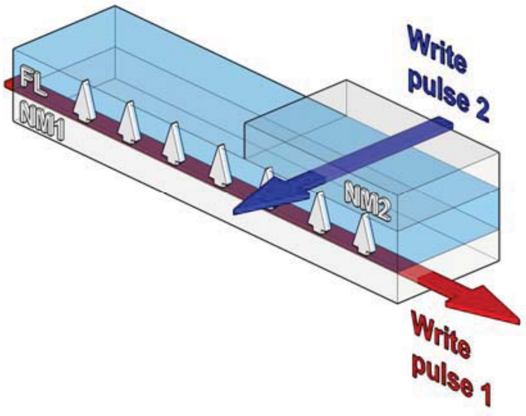

Fig. 3: The switching scheme based on two short consecutive orthogonal current pulses provides fast, deterministic, and magnetic field-free magnetization reversal of a perpendicularly magnetized FL.

consecutive pulse is weaker, it only deviates the magnetization in-plane from the axis parallel to the short FL axis. At this point the magnetization experiences the effective magnetic field due to the shape anisotropy, which completes the switching. A sub-300ps, 100% reliable, and magnetic field-free switching is obtained when the overlap of the NM2 wire with the FL is about 30%. (Fig.4). For this overlap the switching time is not sensitive to small variations of the NM2 width and the second current pulse duration.

Conclusion

The two-pulse switching scheme is demonstrated suitable for switching both in-plane and perpendicularly magnetized flat magnetic layers of rectangular shape by means of spin-orbit torques. A partial overlap of the second wire is efficient in reducing the switching current in the in-plane structure keeping it fast, and adding an interface-induced perpendicular magnetization further improves the switching speed. For perpendicularly magnetized structures, the first current pulse puts the magnetization in-plane, while the second pulse, depending on its direction, deviates the magnetization to either end of the structure. Then the magnetization experiences the shape anisotropy magnetic field, which puts the magnetization up or down, depending on the second pulse direction, and sub-300ps, 100% reliable, and magnetic field-free switching is achieved.

Acknowledgments

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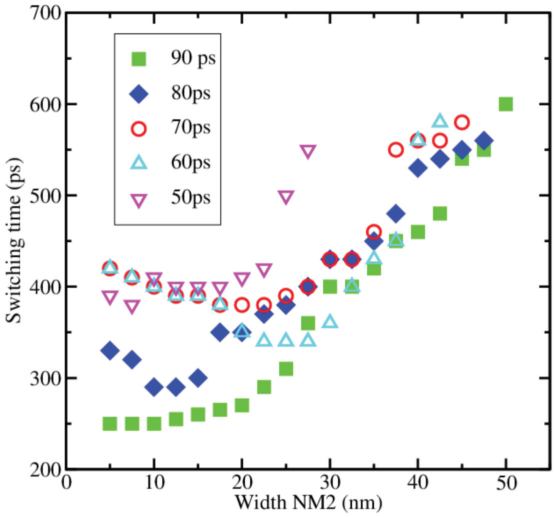

Fig. 4: Spin-orbit torque memory cell with an in-plane magnetized FL switched by current write pulses (red and blue) applied through the heavy metallic wires NM1 and NM2 with a high spin Hall angle. The FL is grown on NM1.

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