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Proton Irradiation Effects on Spin Orbit-Torque and Spin Transfer-Torque Magnetic Tunnel Junctions

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Abstract—**This paper aims to investigate proton irradiation effects on a new class of emerging devices: Perpendicular-Magnetic Anysotropy (PMA) Spin Orbit (SOT) Torque Magnetic Tunnel Junctions (MTJ).**

I. Introduction

The recent successful landing of the Mars Perseverance Rover with on board the high performance, space qualified, 16 Mb toggle-MRAM (UT8MR2M8) based on proven technology from Everspin, demonstrate that Non-Volatile (NV) Magnetic Random Access memory (MRAM) is a key element for future space missions. Certainly, the mission will provide very interesting data on the memory's radiation hardness, however, the main drawbacks of toggle MRAM remain: huge size, writing complexity and poor scalability are unlikely to make it a suitable candidate for future applications [1]. For this reason, looking ahead, a good alternative seems to be the spintronic-based memories, particularly attractive on the market due to their high scalability, good performance, high endurance and low power consumption. The most common device from this family is the Spin-Tranfer Torque (STT) Magnetic Tunnel Junction (MTJ) a nanometric multi-layer pillar. For the sake of simplicity, it is possible to grouping these layers by recognizing: two ferromagnetic layers with perpendicular magnetic anisotropy (PMA) and a thin oxide tunnel barrier, typically MgO. By construction, one of the two layers has a free switchable orientation (FL) while the other, consisting of pinned oriented spin, is used as reference layer (RL). This way, by allowing a current to flow through the pillar, it is possible to switch the orientation of the FL so that it becomes parallel or antiparallel with respect to the RF, allowing the storage of bit "0" or "1". Indeed, due to the ferromagnetic properties of the CoFeB layer the MTJ cell exhibits low/high resistance depending on the mutual magnetic orientation of these two layers. By means of a current, usually equal to one-third of the writing current, it is possible to sense the state of the device by leveraging on the tunnel magneto-resistance effect (TMR). The main drawback of STT-MRAM is the shared read/write path which can impair the read reliability. Indeed, the write current can impose a severe stress for the memory cell leading to a possible time dependent degradation of the MTJ. Trying to go beyond this limit, a new proof of concept was presented in [2] and [3] hereby providing a new approach for controlling magnetic device: Spin Orbit Torque Magnetic Tunnel Junction. The latter is a three terminal device where reading and writing paths are decoupled thereby enhancing the robustness of the simple STT-MTJ pillar. Indeed, it no longer needs to be traversed by a large write current, which, instead, passes through a strip of metal underneath, called the SOT channel. This separation significantly enhances the reliability of the device [4] since the write current does not flow through the tunnel barrier, which is sensitive to electrical breakdown. For this motivation SOT devices gained the attention of industry [5] and academia [6] confirming attractive qualities such as a very fast switching, a quasi-infinite endurance and the elimination of the read disturbance. A very attractive design for high density application was recently proposed in [7], where the SOT channel is shared among different device. In [8] they propose radiation hardening by design techniques to enhance the robustness of the complementary metal oxide semiconductor (CMOS) peripheral circuitry needed to write and read the SOT devices. To the best of our knowledge there is only one study on the irradiation of PMA-MTJ SOT devices and none on the protons irradiation effects, which is the focus of this study. Indeed in [9] it was observed that gamma ionizing dose up to 1 Mrad(Si) does not alter the magnetic switching behavior, while very high Ta^{1+} ion irradiation (over 10^{12} p/cm^2) modified some magnetic properties.

II. Device under test

SOT-MTJ is a three terminal geometry devices where a traditional PMA-STT MTJ is placed on top of a heavy metal strip made of an hard metal such as Pt, W or Ta. Two physical phenomena are understood to be at the origin of the spin-orbit torques: a bulk component, the Spin Hall Effect, and an interfacial component, commonly known as the Rashba Effect. The Spin Hall effect induces a spin current transverse to the charge current flowing in the SOT strip layer, leading to a spin accumulation at the SOT interfaces, which then diffuses into magnetic materials. The Rashba effect originates from the uncompensated electric field at the interface, resulting in an effective magnetic field directly acting on nearby magnetizations. Both effects lead to magnetic torques, that can control the magnetization direction of an adjacent magnetic free layer. This way, it is possible to write a binary "0" or

Parameter	Symbol	SOT Value range	STT Value range
Critical Diameter [nm]	$\mathcal{CD}$	60-200	60-1000
Tunnel Magnetoresistance [%]	$\mathcal{TMR}$	10-90	15-140
Barrier Thickness [nm]	$\mathcal{T}_{ox}$	0.8-1	1.1-1.3
Channel lengh [nm]	$\mathcal{T}_c$	4	-
Channel high [nm]	$\mathcal{W}_c$	50	-
Channel high [nm]	$\mathcal{L}_c$	180	-
Channel resistivity [Ω cm]	ρ	20	-

Fig. 2. Photomicrograph of the purely magnetic SOT memory. The 4 pads and the MTJ device are highlighted as well as the correspondence with the device cartoon

"1" in the MRAM cell. Indeed, SOT-MRAM devices feature switching of the free magnetic layer done by injecting an in-plane current in the SOT channel. Unlike STT-MRAM, where the current is injected perpendicularly into the magnetic tunnel junction and the read and write operation is performed through the same path, the Spin Orbit Torque effect converts charge into spin current, which enables also ultra-fast switching (see Fig. 1). The read principle is the same as for the STT: a charge-flow through the MTJ is employed to sense the magnetization state of the device through the magneto-resistance phenomena, i.e. the change in the material conductivity depending on the mutual magnetization state of the reference and free layer. SOT uses the same core MTJ as the existing STT and can thus be easily implemented in the same manufacturing environment as STT. In this study, we irradiated both SOT and STT devices
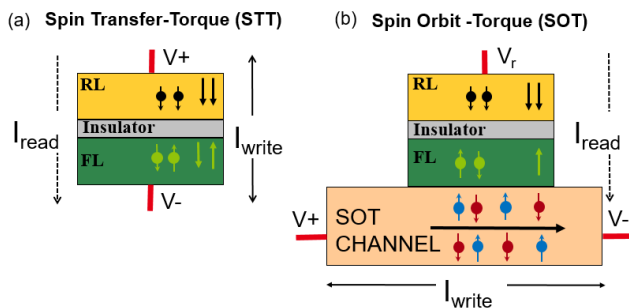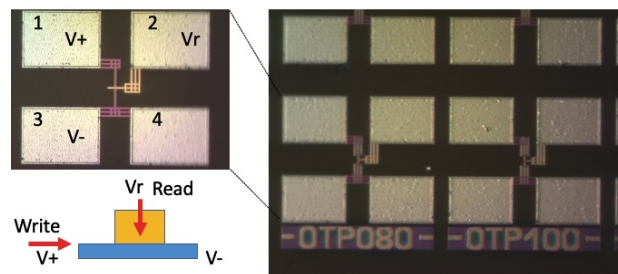

Fig. 1. Schematic view of STT and SOT reading/writing paths

so that we can make a comparison on the irradiation response of these two technologies. The devices were organized in 2 groups: first group was irradiated with 62 MeV protons to a fluence of 1.2 x 10^{11} p/cm^2 (F1), while a fluence of 1.2 x 10^{12} p/cm^2 (F2) was chosen for the second group. The flux was set to the maximum value the facility could provide: 2 x 10^8 p/cm^2/s. Each group of SOT and STT consisted of 25 magnetic elementary memory arrays arranged in 6 column x 9 rows. Each row hosted different MTJ sizes as highlighted in Table I. They were fabricated by a SPINTEC partner to guarantee an industrial process using the most advanced CoFeB-MgO technology. As depicted Fig. 2 samples have a cross bridge structure of two metal wires for the top and bottom electrodes, which have been used to make three-terminal measurements. Indeed, prior to irradiation a set of measurements were done:

- The resistance and TMR
- The coercive field H_c, i.e. the field value needed to switch the magnetization from one stable state to the other, which in a perfectly symmetrical situation, corresponds to one half of the whole hysteresis loop width. Its value is considered as positive for the P to AP transition, and negative conversely.
- The offset field H_{off}, which quantifies the hysteresis loop shift with respect to a symmetrical situation.

Each measurement is the result of a 300 times cycle performance, which were made in partnership with Hprobe, a company leader in characterization and testing of MRAM. All the MTJs were set in the parallel state (R_{min}) because in these devices, by construction, the favored (i.e. more stable) configuration is the antiparallel (R_{max}). This is due to choices made at the level of the multi-layer stack to compensate dipolar fields across the device.

III. EXPERIMENTAL RESULT

Devices exposed to the lowest proton fluence do not show any relevant change in their parameters. Fig. 3 reports resistance inter quartile range (IQR) distributions before (a) and after (b) irradiation at the largest proton fluence. These evidences suggest that the smaller devices experienced the biggest distribution modifications. However, the overall modification is still negligible. Indeed, our data analysis shows how median value and standard deviation of resistance (Fig. 4 a and b) and TMR (Fig. 4 c and d) are immune to protons irradiation both for SOT and STT- MTJs. On the contrary, as Fig. 5 a and b show, the median value of H_c after irradiation is larger than before both for SOT and STT devices. However, to gain more insights, these data should be analyzed together with the H_{off} ones. Concerning SOT devices, the fact that H_{off} absolute value increased (Fig. 5d) means that, statistically, the majority of the hysteresis loop shifted towards the left. On the contrary, for the STT MTJs, the change of H_{off} sign, from negative to positive values (Fig. 5 c), implies that the P to AP transition now takes place at higher field for most of the devices. Further analysis are on going and they will be presented in the final paper.

IV. Conclusion

Protons irradiation of SOT devices seems to suggested that scaled devices are more sensitive to resistance changes. A comparative study on SOT and STT elementary structures demonstrates electrical properties to be unaffected up to the highest proton fluence used in this campaign, i.e. 1.2×10^{12} p/cm^2. Simultaneously, an increase of the coercive field is observed for both the categories of devices. The offset field variations are more noticeable for STT devices, where this parameter changes its sign, than for SOT MTJ. This could be explain as a consequence of the fact that the writing current in SOT devices does not flow into the MTJ, thence any structural changes in the MgO barrier or other layers will affect less the writing process. The latter consideration, seems to suggest SOT devices as possible better candidate than STT ones for future space applications.

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