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Spin Torque Oscillator for High Performance Magnetic Memory

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ABSTRACT: A study on spin transfer torque switching in a magnetic tunnel junction with perpendicular magnetic anisotropy is presented. The switching current can be strongly reduced under a spin torque oscillator (STO), and its use in addition to the conventional transport in magnetic tunnel junctions (MTJ) should be considered. The reduction of the switching current from the parallel state to the antiparallel state is greater than in the opposite direction, thus minimizing the asymmetry of the resistance versus current in the hysteresis loop. This reduction of both switching current and asymmetry under a spin torque oscillator occurs only during the writing process and does not affect the thermal stability of the free layer.

Keywords: Magnetic random access memory; Spin transfer torque; Magnetization reversal; Magnetic tunnel junction; Spin torque oscillator**.**

شبكات المكعب البسيط (SC) والمكعب مركزي الجسم (BCC) والمكعب مركزي الوجه (FCC)المشتقة من مجموعات كوسيتر- ويل والكواتيرنيون

رشيد سبيع و خالد بوزيان

ملخص : الورقة هي دراسة عن انتقال كمية التحرك الناتج عن دوران الإلكترون (STO) لتبديل المغناطيس في تقاطع الجهاز النفقي المغناطيسي العمودي(MTJ) . تخفيض في الطاقة الكهربائية لتبديل اتجاه المغناطيس يمكن أن يتم باستعمال مذبذب ناتجة عن دوران الإلكترون (STO) هدا بالإضافة إلى وسائل النقل التقليدية في MTJ. تخفيض الطاقة الكهربائية لتبديل المغناطيس من حالة موازية الى الاتجاه المعاكس وبالتالي التقليل من التباين في المقاومة ضد التيار في حلقة التباطؤ. هذا الانخفاض كل من التحول الحالي وعدم التماثل في ظل STO يحدث فقط أثناء عملية الكتابة المعلومات في MTJ ، ولا تؤثر على الاستقرار الحراري للطبقة المتحركة في الذواكر العشوائية.

كلمات مفتاحية: ذاكرة الوصول العشوائي المغناطيسية، نقل تدور عزم الدوران، تبديل المغناطيس، الجهاز النفقي المغناطيسي و دوران الإلكترون.

1. Introduction

Spin transfer torque (STT)-based magnetic random access memory (MRAM) is considered as a potential future memory due to its non-volatility, good scalability, fast reading and writing processes and its reasonably low writing current [1–5]. The key part of STT-MRAM device is made of a magnetic tunnel junction (MTJ) where a magnetically soft layer, also called the free layer, is separated from a magnetically hard layer called the reference layer by a non-conductive tunnel barrier, as can be seen in the top part of Figure 1(a). Recently, materials with perpendicular magnetic anisotropy for the free and reference layers have been intensively investigated [6-17]. These materials have larger anisotropy energy and better thermal stability than their counterparts with in-plane anisotropy which are required for devices below 20 nm diameter. For magnetic memory to be competitive with static random access memory (SRAM) and dynamic random access memory (DRAM), the critical switching current for the free layer magnetization has to be reduced. Although current densities below 5 MA/cm^2 have been reported [9,18-21], the scalability problem still remains, as these values are for switching the magnetization of the free layer from the antiparallel state to the parallel state with respect to the reference, which has a fixed magnetization direction. In magnetoresistance devices, it is known that the free layer magnetization switching by STT effect represents a strong asymmetry, i.e. the switching current density from antiparallel state to parallel state (J_c^{AP-P}) is much smaller than the one for switching from opposite states (J_c^{P-AP}). This phenomenon is mainly due to the unbalanced rate between the polarized majority of electrons and the minority responsible for magnetization reversal. It is also important to note that in the case of perpendicular MTJ, the magnetostatic field from the reference layer could reach values larger than 0.1 mT, thus favoring parallel state and causing a strong asymmetry [11, 22]. It is crucial to reduce both J_c^{AP-P} and J_c^{P-AP}, though mainly the later , as it is the higher with a factor of two or more [9,11,14]. Different studies have aimed to reduce J_c without solving the issue of the asymmetry of the signal. In this paper, a new structure based on incorporating a spin torque oscillator (STO) to an MTJ device to reduce the switching current density of FL magnetization **M** and the asymmetry of the hysteresis loop is proposed. Moreover, it is found that for a frequency range around 2 GHz, it is possible to further reduce the value of $J_c^{P\text{–}AP}$. Minimizing the writing current and the asymmetry of the writing signal using a STO is an efficient way to make STT-MRAM competitive with other future memories. For the same applied current, both RL and STO devices induce complementary effects in reducing STT current.

2. Theoretical model

The proposed structure is shown in Figure 1(a), where an MTJ is separated from an STO by a non-magnetic spacer. In this study only the magnetization dynamics of the free layer will be discussed and no details of the STO will be presented. It is assumed that the STO is made of a perpendicular magnetic anisotropy ferromagnetic layer with a fixed magnetization direction and an oscillating magnetic layer (OSL) with magnetization $\mathbf{M}_{osc}$ as sketched in Figure 1(a). When a polarized electric current is applied, $\mathbf{M}_{osc}$ forms an angle φ from z-axis perpendicular to the film plane and rotates with an angular frequency $\omega = 2\pi f$. In this geometry, the free layer magnetization is under two STT effects, $\mathbf{H}_{ST1}$ and $\mathbf{H}_{ST2}$, originating from the reference layer and the oscillating layer, respectively. The current is assumed to flow perpendicularly to the layers and to have a uniform distribution. The dynamics of the free layer magnetization is described by the Landau-Lifshitz-Gilbert (LLG) equation:

$$\frac{\partial \mathbf{M}}{\partial t} = -\frac{\gamma}{M_S}(\mathbf{M}\times\mathbf{H}_{eff}) + \alpha(\mathbf{M}\times\frac{\partial \mathbf{M}}{\partial t}) \quad (1)$$

where γ is the gyromagnetic ratio and α is the effective damping constant. The effective field $\mathbf{H}_{eff}$ in Eq. (1) includes the anisotropy field, the exchange field and the magnetostatic field, as well as $\mathbf{H}_{ST1}$ and $\mathbf{H}_{ST2}$. The two STT fields can be expressed as:

$$\mathbf{H}_{ST1(2)} = -H_{ST1(2)}(\mathbf{M}\times\mathbf{P}_{1(2)}) \quad (2)$$

$$H_{ST1(2)} = \frac{\hbar\varepsilon_{1(2)}}{2eM_S^2 d}J \quad (3)$$

The MTJ device in Figure 1(a) is the main part, and the oscillating layer functions only to assist the switching of **M**. To avoid a reduction of read-back signal due to the existence of the STO, the spacer between the MTJ and STO parts is of Cu, which helps in writing and will not affect the tunnel magnetoresistance signal (TMR). The thickness of the Cu spacer between the free layer and oscillating layer is about 2 nm, but could be made slightly larger. This range of thickness is enough to reduce the magnetostatic field from the oscillating layer which could change the magnetization dynamics of the free layer. In the case of the spin valve, 1.8 nm Cu was is used to minimize the magnetostatic field between RL and FL [23]. Because there is a conductive spacer between the oscillating layer and the free layer, the magnetoresistance signal from this part (OSL/Cu/FL) is much smaller than the TMR signal from FL/tunnel barrier/RL. In Eq. 3, M_S and d are the saturation magnetization and the thickness of the free layer, which were fixed to 800 emu/cm^3 and 2 nm, respectively. The efficiencies of spin polarization from RL and OSL, ε_1 and ε_2 were also fixed in this work to 0.5 and 0.4, respectively. This difference was because the efficiency of a STT in a MTJ is larger than in all conductive magnetoresistive devices, as reported by switching current values in both structures. For the calculation of the magnetization dynamics using Eq. 1, the anisotropy field H_k and exchange constant were kept constant at 9 kOe and 1.6×10^{-6} erg/cm, respectively. These values are similar to those for materials commonly used for perpendicular MTJs, such as CoFeB single layer or a laminated CoFeB with Ta [9,24,25]. Finally, α = 0.007, as reported from ferromagnetic resonance measurements in the case of CoFeB [26], was used throughout this study. In this simulation, the lateral size of the device, which includes FL, RL and OSL, was fixed to 40 nm by 40 nm.

3. Results and discussions

Firstly, the out-of plane component of the normalized free layer magnetization, m_Z, when there is only a reference layer (polarizer P_1) was evaluated. For an electric current with a pulse duration τ of 2 ns, m_Z decays with the current density, as can be seen from Figure 2. It is important to note that m_Z was calculated at time t = 2ns. A critical value $J_c^{AP\text{–}P}$ of about 12 MA/cm^2 for switching **M** was obtained. This value is about 2.5 times smaller than $J_c^{P\text{–}AP}$. Before considering the case where a STO is added, the case where the magnetic layer is below the free layer (Figure 1) was studied. It can be seen from Figure 2 that the switching of **M** occurs at a lower $J_c^{AP\text{–}P}$ of about 6 MA/cm^2, but is not sensitive to the angle φ (up to 30° investigated in this study). If one could make a fixed magnetization direction instead of a STO device, the reduction of the electrical current for switching the free layer magnetization could still be improved. However, practically, it is challenging to have a good thermal stability with a tilted angle of more than15°. In the proposed scheme, conventional perpendicular anisotropy materials could be used for an OSL with good thermal stability and it would then only be when the current is applied, that $\mathbf{M}_{osc}$ starts to oscillate, thus forming an angle φ from the z-axis. In a second part of this study, we investigate the effect of frequency f on $\mathbf{M}$ dynamics. From Eq. (2), the three components of $\mathbf{H}_{ST2}$ are

$$H_{ST2}^{x} = H_{ST2}.(\cos\varphi.m_y - \sin\varphi.\sin 2\pi f.m_z) \tag{4.a}$$

$$H_{ST2}^{y} = H_{ST2}.(\sin\varphi.\cos 2\pi f.m_z - \cos\varphi.m_x) \tag{4.b}$$

$$H_{ST2}^{z} = H_{ST2}.\sin\varphi.\cos 2\pi f.my \tag{4.c}$$

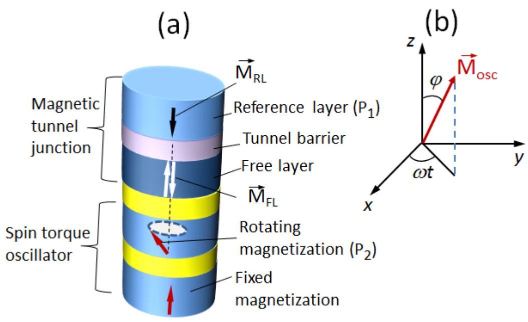

Figure 1. (a) Schematic diagram of the proposed structure made of a magnetic tunnel junction (top part) and a spin torque oscillator (bottom part). The order of the two parts could be reversed. The free layer and reference layer have perpendicular magnetic anisotropy and (b) the oscillating magnetization in the spin torque oscillator part is shown in spherical coordinates. The current is flowing perpendicular to the film plane.

These components are added to $\mathbf{H}_{ST1}$ leading to an increase of the efficiency of the STT effect in reversing $\mathbf{M}$. Figure 3 shows the dependence of m_Z on the frequency f of STO for two applied current densities. As mentioned earlier, we did not investigate the dynamics of $\mathbf{M}_{osc}$ but it is assumed that for a given current density J a frequency f could be reached. This is possible by adjusting the intrinsic properties of STO such as saturation magnetization, anisotropy field and damping constant. In addition, the efficiency of STT from the in-plane layer and spin polarization of the two magnetic layers of a STO are two other parameters that could tune the frequency f [27–29]. For J = –12 MA/cm^2, FL magnetization has a z-component of –0.7 and could not be reversed from P state to AP state with respect to reference layer magnetization. Values of J = –12 MA/cm^2 and –14 MA/cm^2 for this part of the study were selected so as not to have a switching of FL magnetization without STO.

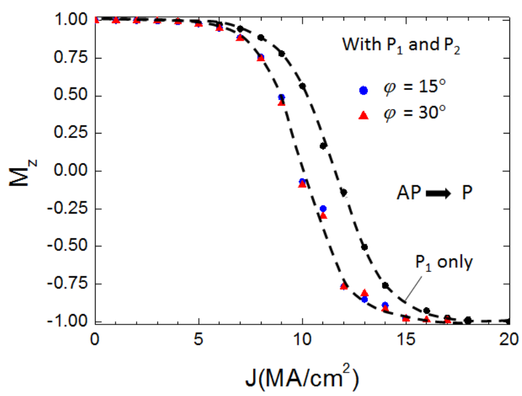

Figure 2. Out-of-plane component of free layer magnetization as a function of the current density J for cases where there is only polarizer P_1, and for both P_1 and P_2 with φ = 15° and 30°. In this calculation, the current pulse duration is 2 ns and P_2 is considered not oscillating (f = 0).

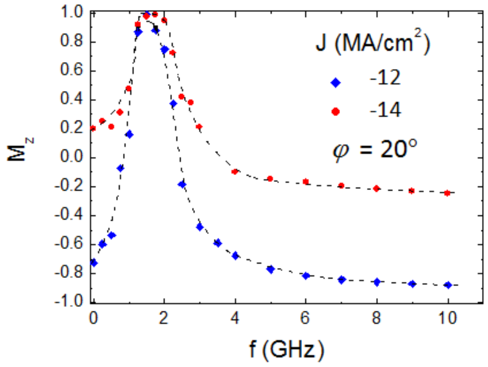

Figure 3. Out-of-plane component of free layer magnetization versus frequency f of spin torque oscillator for different current densities. The current pulse duration is fixed to 2 ns and the switching is from parallel state to antiparallel state.

As shown in Figure 3, to reverse **M** either a large J should be applied to improve STT efficiency or $\mathbf{M}_{osc}$ should be allowed to oscillate with a frequency f around 2 GHz under our calculation conditions. It is difficult to correlate between f and FL resonance frequency f_R. Heinonen et *al.* reported that f_R decreases linearly with the bias voltage or applied current [30]. More interestingly, from ferromagnetic resonance (FMR) measurements they showed that f_R is higher for a negative bias voltage compared to positive voltage. In the case of CoFeB with 2 nm, it was found that f_R is around 2.5 GHz without applying an electric current [26]. Nevertheless, the intrinsic properties such as H_k and M_S may have a strong effect on f, in addition to the device size and applied current magnitude. In fact, while **M** is precessing under STT from RL, an additional STT from STO helps **M** to become reversed. The z-component of FL magnetization evolves with time t as $m_Z \sim \exp(-\Omega t).\cos(\Omega t)$ for a small amplitude limit and with no STO (only RL as a polarizer) [31]. When a STO is added to assist magnetization switching Ω should be synchronized with f of **M**, but this is not straightforward, as can be seen from Eq. 4, where both ωt and the three components of **M** which are also time dependent exist. In Figure 3, it can be seen that for a larger frequency (f > 3 GHz), the oscillation of $\mathbf{M}_{osc}$ is not effective in the reversal process, and thus m_Z drops to an even lower value than where $f = 0$. Similar behavior of m_Z versus f was observed for $J = -14$ MA/cm^2. By plotting the calculated hysteresis loop for each value of applied current density, it can be seen from Figure 4 that there is a strong asymmetry δ for the case of conventional MTJ (only polarizer P_1). A J_c^{P-AP} of -28.5 MA/cm^2 is required to reverse **M** from P state to AP state, which leads to a change of device resistance from low value to high value, respectively (plotted as normalized resistance in Figure 4). It we assume that the STO is replaced by a layer with fixed magnetization direction $\varphi = 30°$ without any oscillation ($f = 0$), a reduction of both J_c^{P-AP} and J_c^{AP-P} to -13.6 MA/cm^2 and 9.9 MA/cm^2, respectively, could be achieved. The strong reduction of J_c^{P-AP} compared to J_c^{AP-P} leads to a minimization of asymmetry δ. When a STO is acting on the free layer magnetization, a further reduction of J_c^{P-AP} with almost no change in J_c^{AP-P} value was is observed. For $f = 2$ GHz, J_c^{P-AP} was further reduced to -10.7 MA/cm^2 which represents an approximately 60% reduction. In fact, for a/the STT-MRAM application, it is mainly the reduction of J_c^{P-AP} which remains a challenge, thus causing an asymmetry between J_c from parallel and antiparallel states. It is known that **M** takes less time to switch from antiparallel to parallel states than for the reverse case. The STO is then more effective for reducing J_c^{P-AP} than J_c^{AP-P}.

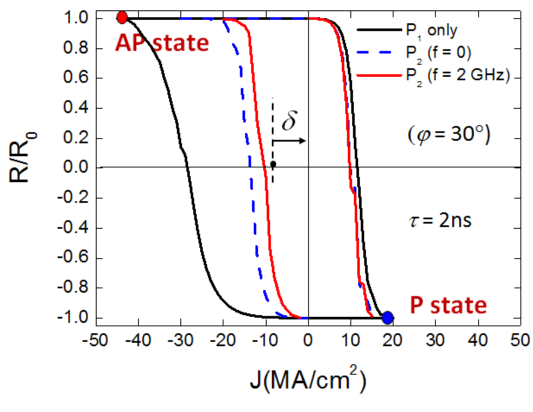

Figure 4. Normalized resistance versus current density for cases where there is only P_1, and when P_2 is added with no oscillation ($f = 0$), and with a frequency of oscillations of 2 GHz. The magnetization of the oscillating layer has a fixed angle $\varphi = 30°$ around the z-axis.

4. Conclusion

Integrating a spin torque oscillator to a magnetic tunnel junction with perpendicular anisotropy could help to improve the efficiency of the STT effect. The study revealed a stronger reduction of switching current from parallel state to antiparallel state compared to the reverse transformation. This is important in reducing the asymmetry in the resistance-current hysteresis loop. It is also shown from this study that the critical switching current is not very sensitive to the opening angle of STO oscillations. More interestingly, the oscillation frequency is another key parameter to further reduce the current from parallel state to antiparallel state. The proposed structure does not require an additional lithography process or special electrical circuit and thus offers an efficient way to reduce the STT switching current and asymmetry in perpendicular magnetic tunnel junctions.

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