Switching Performance of Mo-based pMTJ and dsMTJ structures

B.Pruckner[1] S.Fiorentini[1], N.Jorstad[2], T.Hadamek[1], S.Selberherr[2], W.Goes[3], and V.Sverdlov[1,2]
[1] Christian Doppler Laboratory for Nonvolatile Magnetoresistive Memory and Logic at the
[2] Institute for Microelectronics, TU Wien, Gußhausstraße 27–29, A-1040 Wien, Austria
[3] Silvaco Europe, Cambridge, United Kingdom
e-mail: pruckner@iue.tuwien.ac.at

Abstract: **We investigate the switching performance of Mo/CoFeB magnetic tunnel junctions depending on the configuration of the magnetization of the ferromagnetic layers and number of fixed layers at low temperatures.**

Mo-based perpendicular magnetic tunnel junctions (Mo-pMTJs) have demonstrated superior performance in terms of perpendicular magnetic anisotropy (PMA) and thermal tolerance. Ultrafast sub-ns switching of Mo-pMTJs has been demonstrated at low temperature, making them a potential option for future memory applications [1]. Here we focus on comparing Mo-pMTJs with structures containing two pinned layers (PLs) and a nonmagnetic spacer layer. As the free layer in these structures experiences the torques from both PLs, they are termed double-spin MTJs (dsMTJs). dsMTJs have shown promising results in reducing the switching current and cell size [2]. We used the Finite-Element-Method (FEM) micromagnetic framework which allows evaluating the spin torques produced in bulk as well as at interfaces [3] in multilayered structures which include ferromagnetic layers separated by tunnel barriers and non-magnetic spacers.

We have used [1] to determine material parameters summarized in Table 1. The accuracy of the extracted parameters (saturation magnetization M_S, magnetic anisotropy constant K) is demonstrated in Fig 1, where the experimental hysteresis curve has been accurately reproduced by simulations. Spin drift-diffusion transport model parameters (e.g. spin flip, spin dephasing and exchange lengths) for CoFeB have been taken from [4][5].

We calculate the critical current densities as a function of the switching time for three different structures: (i) a Mo-pMTJ, (ii) a dsMTJ with the two PLs being anti-parallel, and (iii) a dsMTJ* with the two PLs being parallel to each other. We assumed 1nm Mo normal spacer between the free layer and the second PL in the dsMTJ and the dsMTJ*. Fig.2 demonstrates that the critical switching current density is inversely proportional to the switching time τ, which is in agreement with the experimental [1] observations and theoretical predictions [5]. Fig.2 shows that the pMTJ switching from the anti-parallel to the parallel (AP→P) configuration between the free and the pinned layers is faster than the P→AP switching, in agreement with [1].

Fig. 2 proves that the (AP→P) switching is also faster for dsMTJs. As in dsMTJs the spin torques from the two PLs are additive, the switching is faster than that of pMTJs. Similarly, the torques from the PLs act against each other in a dsMTJ*, which leads to a slower switching than in a pMTJ switching (Fig.2). These results are valid for both P→AP and AP→P switching.

The switching acceleration in a dsMTJ with a Mo spacer is about 20-40% and is thus not as impressive as in previously studied structures [7] where the gain was two-fold. This is due to reduced spin torque from the second PL as indicated in Fig.3. Finally, Fig.4 and Fig.5 compare the switching times as a function of the voltage applied to Mo-pMTJs and dsMTJs with a Mo spacer for AP→P and P→AP switching, respectively.

Conclusion: While the dsMTJ using a Mo spacer layer shows faster switching, the speed up depends on the proper choice of materials for the spacer.

REFERENCES

[1] D. Lyu, P. Khanal, Y. Lv et al., Sub-ns switching and cryogenic-temperature performance of Mo-based perpendicular magnetic tunnel junctions, IEEE Elelctron Dev. Lett. 43, 1215-1218 (2022). doi: 10.1109/LED.2022.3184278

[2] G. Hu, C. Safranski, J. J. Sun et al., Double spin-torque magnetic tunnel junction devices for last-level chache applications, in Proceedings IEDM, 10.2.1-10.2.4 (2022) doi: 10.1109/IEDM45625.2022.10019402.

[3] S. Fiorentini, J. Ender, S. Selberherr et al., Coupled spin and charge drift-diffusion approach applied to magnetic tunnel junctions, Solid-State Electron. 186, 108103 (2021). doi: 10.1016/j.sse.2021.108103.

[4] S. X. Huang, T.Y. Chen, C. L. Chien, Spin polarization of amorphous CoFeB determined by point-contact, Andreev reflection, Appl. Phys. Lett. 92, 242509 (2008). doi: 10.1063/1.2949740

[5] D. M. Lattery, D. Zhang, J. Zhu et al., Low Gilbert Damping Constant in Perpendicularly Magnetized W/CoFeB/MgO Films with High Thermal Stability, Scientific Reports 8, 13395 (2018). doi: 10.1038/s41598-018-31642-9

[6] J. Z. Sun, Spin-transfer torque switching probability of CoFeB/MgO/CoFeB magnetic tunnel junctions beyond macrospin, Physical Review B 104, 104428 (2021), doi: 10.1103/PhysRevB.104.104428

[7] W. J. Loch, S. Fiorentini, N. Jorstad, et al., Double reference layer STT-MRAM structures with improved performance, Solid-State Electron. 194, 108335 (2022). doi: 10.1016/j.sse.2022.108335.

Table 1: Extracted parameters used in the FEM simulation.

Resistance Anti-Parallel (R_{AP})	6.5	kΩ
Resistance Parallel (R_P)	4	kΩ
Diffusion Coefficient Non-magnetic Layers (D_{eNM})	$1.1*10^{-2}$	m^2/s
Diffusion Coefficient Ferromagnetic Layers (D_{eFM})	$1.1*10^{-3}$	m^2/s
Exchange Length (λ_J)	2	nm
Spin-flip Length (λ_{sf})	1	nm
Spin Dephasing Length (λ_ϕ)	0.1	nm
Diffusivity Spin Polarization (β_D)	0.7	
Conductivity Spin Polarization (β_σ)	0.52	
Conductivity Non-magnetic Layers (σ_{NM})	$2*10^7$	A/Vm
Conductivity Ferromagnetic Layers (σ_{FM})	$4*10^6$	A/Vm
Anisotropy Constant (K)	$7.34*10^5$	J/m^3
Exchange Constant (A)	$2*10^{-11}$	J/m
Saturation Magnetization (M_S)	$1.47*10^6$	A/m
Damping constant (α)	0.02	

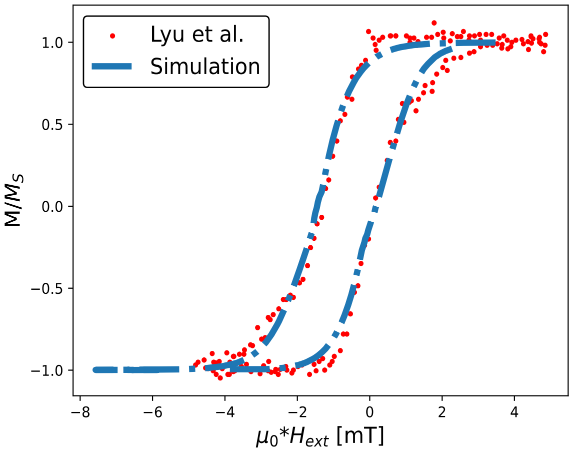

Figure 1: Hysteresis curve for a CoFeB/Mo MTJ by Lyu et al[1] and our simulation

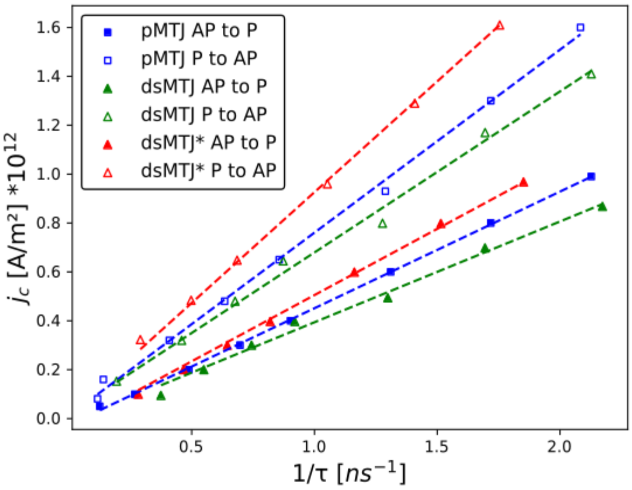

Figure 2: Switching current j_c for AP→P and P→AP switching respectively. The configuration of the magnetization of the fixed layers was antiparallel (dsMTJ) and parallel (dsMTJ*)

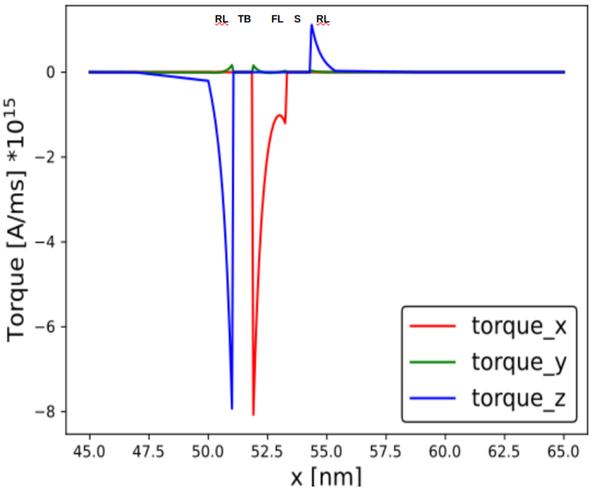

Figure 3: Spin Torque for the structure fixed reference layer (RL) - tunnel barrier (TB) - free layer (FL) - spacer (S) - fixed reference layer (RL)

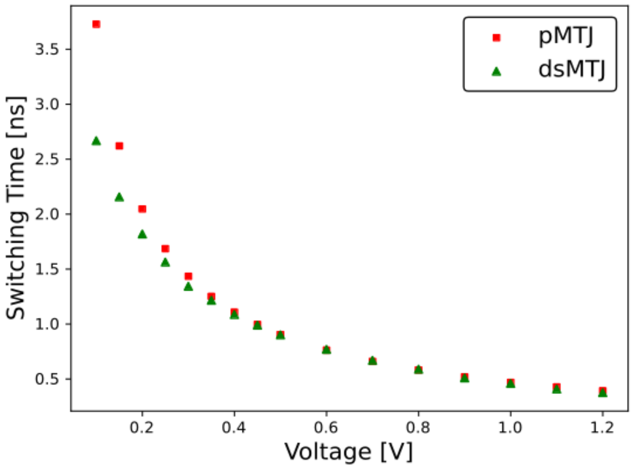

Figure 4: Switching time for AP→P switching, at different voltages

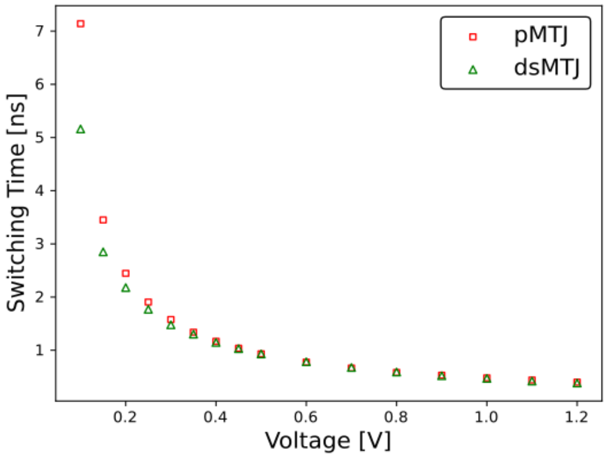

Figure 5: Switching time for P→AP switching, at different voltages