Simulations on the effect of magnetic anisotropy on switching of an easy cone magnetized free layer

Angshuman Deka, Katsunori Sato, Iori Tanaka and Yasuhiro Fukuma*

Department of Computer Science and Electronics, Kyushu Institute of Technology
680-4 Kawazu, Iizuka 820-8502, Japan
* Member, IEEE

***Abstract*—The easy cone state of magnetization that arises as a result of a competition between second and fourth order perpendicular magnetic anisotropies has the advantage of a non-zero electric-field torque without the application of a bias magnetic field and is thus a potential candidate for purely voltage driven magnetic storage devices. In this study, the onset of the easy cone state of magnetization are simulated in a ferromagnet film. Subsequently the switching field and time for voltage controlled magnetization switching process are studied as a function of the inclination angle of easy cone state from the film normal in the range of 0 to 45 degrees. The switching field is found to decrease with decreasing anisotropy. The switching time is found to become faster for higher inclination angle of the easy cone state due to an increase in its torque.**

Keywords*— Magnetic anisotropy, cone state, voltage controlled magnetization switching, magnetic random-access memory.

I. Introduction

Magnetic tunnel junction (MTJ) based magnetoresistive random access memory (MRAM) have emerged as a promising candidate for high performance non-volatile storage devices. Magnetization direction in the free layer of the MTJs has been controlled by magnetic fields [1], spin transfer torques [2, 3] and spin orbit torques [4, 5], all of which require a flow of charge current in close proximity or inside the device. As a result, when the device sizes are scaled down, the need to remove unwanted Joule heating caused by the flow of charge currents becomes very important in order to maintain the device performance. Recently the effect of magneto-electric coupling through selective electron-hole doping in interfacial bonding states of ferromagnetic metal-oxide interfaces by application of voltage was demonstrated [6]. As a result, perpendicular magnetic anisotropy (PMA) could be modulated to give rise to a variety of effects such as ferromagnetic resonance [7] – [10], spin wave generation [11] and magnetization switching [12] – [14]. The advantage of such a control of magnetization via voltage in metallic ferromagnets is that it has the potential to eliminate the charge currents required for magnetization switching and in turn help in development of ultralow power MRAMs.

Typical MTJs have a free layer that has either an in-plane or out-of-plane magnetic easy axis. However, the torque exerted by electric field on magnetization is zero for an in-plane and out-of-plane magnetized film [7]. Therefore, an external bias magnetic field is typically used to tilt the magnetization away from the film plane or the normal during magnetization switching via electric fields [12] – [14]. One of the potential solution to overcome the need for this bias magnetic field is by substituting the free layer of the MTJs with a ferromagnetic layer that has an easy cone state of magnetization [15, 16]. This easy cone state arises out of the competition between the second and fourth order PMA [17, 18]. In this study, we investigated the transition of a ferromagnetic thin film from an out-of-plane easy axis into an easy cone state due to PMA. We also investigated thermal stability of the same samples as a function of the PMA. The magnetization switching mechanism is studied. A comparison of the switching fields and times as a function of inclination angle from the film normal θ of the easy cone state is made.

II. Easy Cone State and Thermal Stability

Simulations were performed on samples of dimensions 50 nm × 50 nm × 1 nm using the LLG micromagnetic simulator. The saturation magnetization was kept fixed at $\mu_0 M_s$ = 1.50 T. The second order PMA is varied from $K_{u,2}$ = 1.0×10^3 kJm^{-3} to 1.8×10^3 kJm^{-3}, while the fourth order PMA $K_{u,4}$ is changed from 0 to – 4×10^2 kJm^{-3}. The effective magnetic anisotropy of a ferromagnet can be taken to be of the form:

$$E(\theta) = K_{u,eff} \cos^2 \theta - K_{u,4} \cos^4 \theta, \quad (1)$$

where, the first term $K_{u,eff} = K_{u,d} - K_{u,2}$ and $K_{u,d}$ is the demagnetization energy.

In the absence of $K_{u,4}$, the magnetic easy axis is determined by the competition between $K_{u,d}$ and $K_{u,2}$, both of which have a $\cos^2\theta$ dependence. As a result, easy axis is possible either in the in-plane or out-of-plane directions, depending on the sign of $K_{u,eff}$. When H_p, the field corresponding to second order PMA, overcomes the field corresponding to the demagnetizing energy i.e. $K_{u,eff} < 0$, the minimum of E is along the normal to the film plane (θ = 0 degree) which gives rise to a perpendicular easy axis. In this state, when a negative $K_{u,4}$ is introduced, a special kind of minimum for (1) is possible wherein it lies at a value of θ between 0 and 90 degree because $K_{u,4}$ has a $\cos^4\theta$ dependence. This state is called the easy cone state because the easy axis forms a cone of angle θ around the film normal as shown in the inset of Fig. 1.

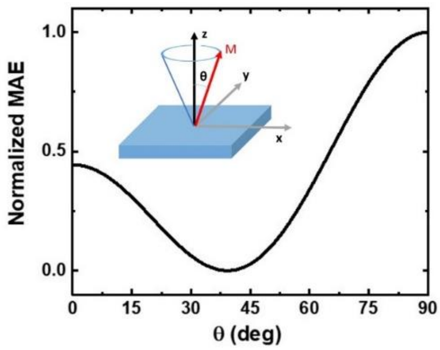

Fig. 1. Schematic to illustrate the magnetic anisotropy energy (MAE) as a function of the angle of the magnetization from the film normal θ for a thin film with an easy cone state. Inset shows the coordinates used in the study along with a definition of θ.

We estimated the equilibrium state of magnetization as a function of PMA and the evolution of the easy axis from a perpendicular to an easy cone state is shown by the dependence of θ with PMA in Fig. 2. The value of θ can be analytically estimated by minimizing (1) to be of the form:

$$\theta = \cos^{-1}\sqrt{\frac{K_{u,eff}}{2K_{u,4}}} \quad . \qquad (2)$$

Upon fitting the values of θ obtained from the simulations as a function of PMA to (2), we can obtain a good accuracy with theory as shown by the lines in Fig. 2. It can be seen

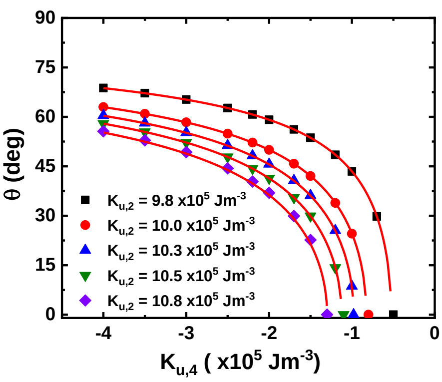

Fig. 2. Evolution of θ as a function of the second $K_{u,2}$ and fourth $K_{u,4}$ order perpendicular magnetic anisotropy energy (symbols) for a thin film with a fixed saturation magnetization $\mu_0 M_s$= 1.5 T. Lines are fits to (2) in the main text.

from (2) that the out-of-plane easy axis state (θ = 0 degree) transitions into an easy cone state when $K_{u,4} \geq K_{u,eff}/2$.

Subsequently the thermal stability factor Δ which gives a measure of the energy barrier separating the easy cone state from the in-plane hard axis can be estimated as follows [14]:

$$\Delta = \frac{E(90\ \mathrm{deg}) - E(\theta)}{k_B T} A, \qquad (3)$$

where A is the volume of the device, k_B is the Boltzmann's constant and T is the temperature of operation which is taken as 300 K.

During calculation of Δ for the easy cone state, we initialized our simulation with the magnetization in the film plane and allow the magnetization vector to relax to the nearest lowest energy state. The difference in the energies between the initial and final states gives us: E(90 deg) – $E(\theta)$. Substituting this value in (3), we obtain the value of Δ as shown in Fig. 3. It can be seen from (1) that a negative $K_{u,4}$, can also result in a decrease in E which in turn reduces the thermal stability factor that is a key parameter of memory devices. Typically, for the condition of non-volatility in memory devices, Δ = 60 is required for a retention period of about 10 years. Therefore, during the discussion of magnetization switching conditions for easy cone magnetized samples in the subsequent section, we ensured that the samples have $\Delta \geq 60$.

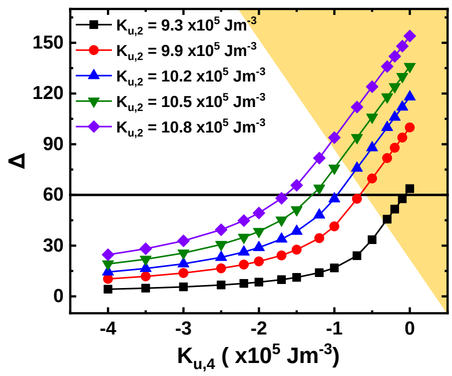

Fig 3. Evolution of thermal stability Δ as a function of the second $K_{u,2}$ and fourth $K_{u,4}$ order perpendicular magnetic anisotropy energy for a thin film with a fixed saturation magnetization $\mu_0 M_s$= 1.5 T.

III. Magnetization Switching

Whenever the effective magnetic field H_{eff} in a ferromagnet changes, the magnetization M precesses around the new H_{eff} and aligns parallel to it to reach the new energy minima. This process is well defined by a sum of precessional and damping torques given by the Landau-Lifshutz-Gilbert (LLG) equation below:

$$\frac{dM}{dt} = -\frac{\gamma}{1+\alpha^2}(M \times H_{eff}) - \frac{\gamma\alpha}{(1+\alpha^2)M_s}(M \times (M \times H_{eff})), \quad (4)$$

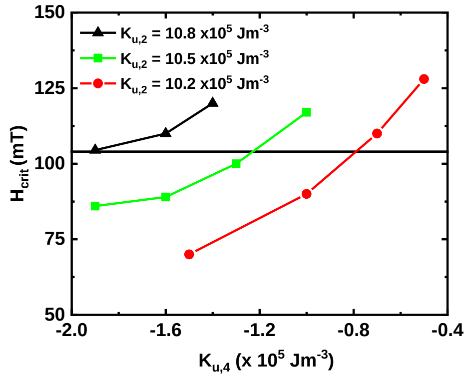

Fig 4. Switching fields H_{s0} as a function of 4^{th} order perpendicular anisotropy energy $K_{u,4}$ for different values of second order perpendicular anisotropy fields $K_{u,2}$.

where the term on the left represents the time t derivative of M, γ is the gyromagnetic ratio taken as 0.0176 GHz.mT^{-1} and α is the damping constant of the ferromagnet which is taken as 0.05.

In the presence of an electric field at the interface of the ferromagnet, PMA can be modified by the change of electron occupancies in its interfacial 3d orbitals [6]. Such an effect is typically quantified by the voltage controlled magnetic anisotropy (VCMA) coefficient ζ which represents the change in magnetic anisotropy energy per unit electric field at the interface of the ferromagnet. The application of a voltage results in a change of E. As a result, H_{eff}, which can be estimated from the derivative of $E(V)$ with respect to the magnetization vector m, changes and the magnetization precesses to the new minimum. If ζ of the ferromagnet is sufficient enough, so that during this precession M crosses the equatorial film plane, the magnetization can be switched from the upper (lower) cone to the other side by turning off the voltage. Typical reported values of ζ for second order PMA range from about 0.01 pJV^{-1}m^{-1} for CoFeB/MgO junctions [19] upto about 0.25 pJV^{-1}m^{-1} for FePt/MgO junctions [20]. Based on this, corresponding voltage induced change in the second order PMA field of up to 150 mT can be expected in such materials.

The electric field effect can be modelled as a change in H_{eff} due to the presence of a z-axial field pulse H_z which is equivalent to the change in PMA in presence of an interfacial voltage. Before applying H_z, we apply a small bias field of 1 mT along x-axis to ensure that azimuthal angle ϕ = 0 degree and let the sample relax to its equilibrium state which is determined by its effective anisotropy energy. Subsequently, a z-axial magnetic field pulse with a fixed duration of 10 ns and rise and fall times of 0.1 ns is applied at t = 0 ns and the resultant magnetization trajectory is observed. Switching condition of the samples are studied by varying the field pulse

Sample Name	$K_{u,2}$ (kJm^{-3})	$K_{u,4}$ (kJm^{-3})	θ (degree)
S-1	10.22	-0.80	4
S-2	10.35	-0.99	19
S-3	10.50	-1.20	29
S-4	10.65	-1.51	34
S-5	10.80	-1.90	41

Table 1. Second and fourth order anisotropy constants and the corresponding inclination angles for samples S-1 to S-5.

amplitudes. Switching time t_{swit} is taken as the time when the z-component of magnetization m_z crosses the equator defined by m_z = 0.

H_{s0}, which is defined as the minimum amplitude of H_z required for switching the magnetization vector, was estimated as a function of PMA. As shown in Fig. 4, it is observed that the H_{s0} decreases with a decrease in $K_{u,2}$ and $K_{u,4}$. This can be understood in terms of a reduced potential barrier between the easy and hard axes. Also, as can be seen in Fig. 4, it is possible for samples with different combinations of $K_{u,2}$ and $K_{u,4}$ to have equal values of H_{s0}. Therefore, for discussing the magnetization switching times, we selected samples S-1 to S-5 that have an equal value of H_{s0} = 104 mT. The values of $K_{u,2}$ and $K_{u,4}$ for these samples, as given in Table 1, are such that they have equal Δ and corresponding θ = 4, 19, 29, 34 and 41 degrees respectively. This enables us to make a comparison of the magnetization switching dynamics as a function of θ.

Figure 5 shows estimated t_{swit} as a function of H_z for S-1 to S-5. Switching times decreased with increasing amplitude of the field pulse and inclination angle. In order to explain such a switching behavior, we plot the time dependence of the magnetization components of S-3 and S-5 in Fig. 6. Interestingly, even though all the samples have the same H_{s0} = 104 mT, for any fixed field amplitude, the

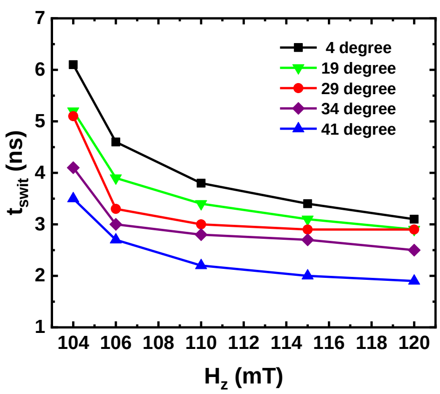

Fig. 5. Switching time t_{swit} as a function of the amplitude of the field pulse H_z which shows a longer switching time for sample with θ = 4 degree (S-1), θ = 19 degree (S-2), θ = 29 degree (S-3), θ = 34 degree (S-4) and θ = 41 degree (S-5).

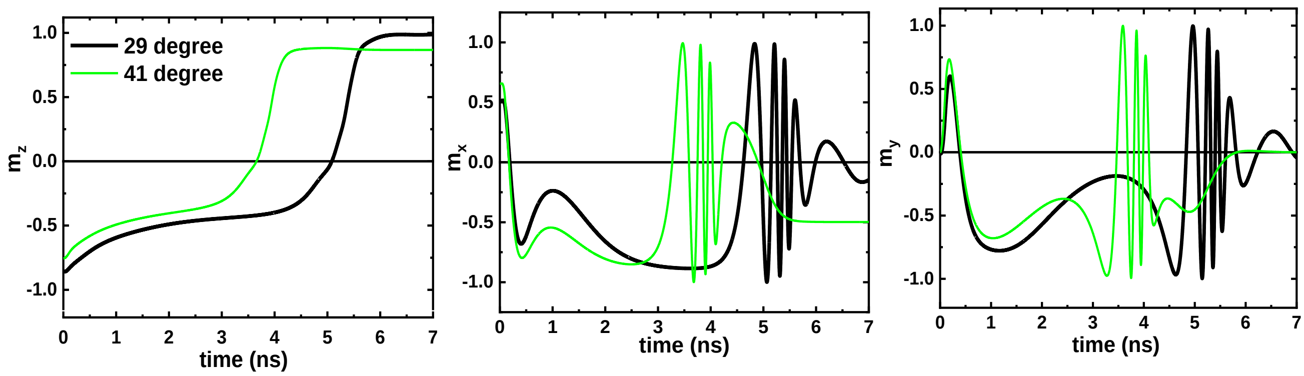

Fig 6. Time evolution of the (a) z- component m_z, (b) x-component m_x, and (b) y-component m_y of magnetization vector when a z-axial field pulse H_{s0} = 104 mT is applied on a sample with θ = 29 degree (S-3) and θ = 41 degree (S-5). Rise and fall times of the pulse are 0.1 ns and pulse duration is 10 ns.

switching process depends on the inclination angles of the easy cone state. While the switching time at H_{s0} is lowest for S-5 that has θ = 41 degree, it increases as θ decreases. This points towards an increase in torque on magnetization when θ is increased. Such an increase is confirmed from a faster magnetization precession for S-5 compared to S-3, as shown in the time evolution of m_x and m_y in Fig. 6. The torque on m is applied in the film plane because H_{eff} is perpendicular to the film. For a fixed damping factor, an increase in the torque will consequently increase the Gilbert damping torque that is orthogonal to the torque. This in turn gives rise to a lower switching time as the inclination angles are increased.

IV. Conclusion

The dependence of the magnetic state on perpendicular magnetic anisotropy was investigated. It showed that a competition between the second and fourth order PMA can give rise to an easy cone state of magnetization due to differences in angular dependences of the magnetic anisotropy energies. Thermal stability was found to decrease with decreasing effective anisotropy due to a decrease in the energy barrier separating the easy cone state from the in-plane direction. Upon comparison of samples with equal values of minimum switching fields but different θ, varying from 4 to 41 degrees, switching time was found to be lowest for the sample with an easy cone angle of 41 degrees. This could be understood in terms of an increase in the torque with an increase of the inclination of the easy cone state with respect to the film normal.

V. Acknowledgements

We would like to thank B. Rana and S. Gupta for helpful discussions. This work was supported by Grants-in-Aid (18H01862) from MEXT and Materials Science Foundation, Hitachi Metals

References

[1] S. Chikazumi, “International series of monographs on physics 94: Physics of Ferromagnetism”, Oxford University Press (2009).

[2] J. Slonczewski, “Current-driven excitation of magnetic multilayer”, J. Magn. Magn. Mater., vol. **159**, L1 (1996).

[3] L. Berger, “Emission of spin waves by a magnetic multilayer transversed by a current”, Phys. Rev. B, vol. **54**, 9353 (1996).

[4] I. M. Miron, *et al.*, “Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection”, Nature, vol **476**, 189 (2011).

[5] L. Liu, *et al.*, “Spin-torque switching with the giant spin Hall effect of tantalum”, Science, vol **336**, 555 (2012).

[6] T. Maruyama, *et al.*, “Large voltage-induced magnetic anisotropy change in a few atomic layers on iron”, Nature nanotech., vol 1**8**, 158 (2009).

[7] T. Nozaki, *et al.*, “Electric-field-induced ferromagnetic resonace excitation in an ultrathin ferromagnetic metal layers”, Nature Phys., vol **8**, pp. 491–496 (2012).

[8] J. Zhu, *et al.* “Voltage-induced ferrromagnetic resonance in magnetic tunnel junctions”, Phys. Rev. Lett., vol **108**, 19720 (2012).

[9] S. Kanai, *et al.* “Elecric field-induced ferromagnetic resonace in a CoFeB/MgO magnetic tunnel junction under dc bias voltages”, Appl. Phys. Lett., vol **105**, 242409 (2014).

[10] K. Miura, *et al.* “Voltage-induced magnetization dynamics in CoFeB/MgO/CoFeB magnetic tunnel junctions”, Sci. Rep., vol **7**, 42511 (2017).

[11] B. Rana, Y. Fukuma, K. Miura, H. Takahashi, and Y.C. Otani, “Excitation of coherent propagating spin wave in ultrathin CoFeB

film by voltage-controlled magnetic anisotropy", Appl. Phys. Lett., vol **111**, 052404 (2017).

[12] Y. Shiota, *et al.*, "Induction of coherehnt magnetization switching in a few atomic layers of FeCo using voltage pulse", Nature Mat., vol **13**, 39 (2012).

[13] S. Kanai, *et al.* "Electric-field-induced magnetization switching in CoFeB/MgO magnetic tunnel junctions with high junction resitance", Appl. Phys. Lett., vol **108**, 192406 (2016).

[14] C. Grezes, *et al.* "Ultra-low switching energy and scaling in electric-field-controlled nanoscale magnetic tunnel junctions with high resistance-area product", Appl. Phys. Lett., vol **108**, 012403 (2016).

[15] R. Matsumoto, T. Nozaki, S. Yuasa and H. Imamura, "Voltage-Induced Precessional Switching at Zero-Bias Magnetic Field in a Conically Magnetized Free Layer", Phys. Rev. Appl., vol **9** 014026 (2018).

[16] A. A. Timopheev, R. Sousa, M. Chshiev, H. T. Nguyen, and B. Dieny, "Second order anisotropy contribution in perpendicular magnetic tunnel junctions", Sci. Rep., vol **6**, 26877 (2016).

[17] H. Stillrich, C. Menk, R. Frömter and H.P. Oepen, "Magnetic anisotropy and the cone state in Co/Pt multilayer films", J. Appl. Phys., vol **105**, 07C308 (2009).

[18] J. M. Shaw, *et al.*, "Perpendicular magnetic anisotropy and easy cone state in Ta/Co60Fe20B20 /MgO", IEEE Magn. Lett., vol. **6**, pp. 1-4 (2015).

[19] Alzate, J. G. *et al.* "Temperature dependence of the voltage-controlled perpendicular anisotropy in nanoscale MgO/CoFeB/Ta magnetic tunnel junctions", Appl. Phys. Lett., vol **104**, 112410 (2014).

[20] Miwa, S. *et al.*, "Voltage controlled interfacial magnetism through platinum orbits", Nat. Commun., vol **8**, 15848 (2017).