The need for control of magnetic parameters for energy efficient performance of magnetic tunnel junctions

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Abstract. Optimizing energy performance of Magnetic Tunnel Junctions (MTJs) is the key for embedding Spin Transfer Torque-Random Access Memory (STT-RAM) in low power circuits. Due to the complex interdependencies of the parameters and variables of the device operating energy, it is important to analyse parameters with most effective control of MTJ power. The impact of threshold current density, \(I_{co}\), on the energy and the impact of \(R\) on \(I_{co}\) are studied analytically, following the expressions that stem from Landau-Lifshitz-Gilbert-Slonczewski (LLGS-STT) model. In addition, the impact of other magnetic material parameters, such as \(M_s\), and geometric parameters such as \(t_{free}\) and \(\lambda\) is discussed. Device modelling study was conducted to analyse the impact at the circuit level. Nano-magnetism simulation based on NMAG\(^\text{TM}\) package was conducted to analyse the impact of controlling \(R\) on the switching dynamics of the film.

1. Introduction and motivation

STT-RAM memory technology shows potential in improving the performance and scaling challenges of current memory technologies [1, 2]. Optimizing the energy performance of MTJ is crucial to further incorporation of MTJs into STT-RAM and related low power spintronics nanoelectronics devices platforms. Figure 1 shows an illustration of an MTJ, where geometrical parameters are defined on the device shown. The electrical energy required for switching the MTJ state, \(E_W\), is defined as [3-5]:

\[
E_W = J_c^2 \delta \Delta t = I_{co} \left[ 1 - \left( \frac{k_B T}{\Delta E} \ln \left[ \frac{\tau_p}{\tau_0} \right] \right) \right] \delta \Delta t,
\]

where \(J_c\) is the critical current density, \(I_{co}\) is the threshold current density, \(k_B\) is Boltzmann constant, \(T\) is temperature, \(\Delta E\) is energy barrier, \(\tau_p/\tau_0\) is the temporal signature of the switching process, \(\delta\) is the resistance-area product (RA), \(A\) is the cross-sectional area of the junction and \(t\) is the duration of the applied voltage. For in-plane MTJs (IMTJ), \(I_{co}\) is defined as [6]:

\[
I_{co} = \left( 2e\alpha/\hbar \eta \right) t_{free} M_s \left( H_{applied} + H_K + 2\pi M_s \right),
\]

where \(e\) is the charge of an electron, \(\alpha\) is the Gilbert damping coefficient, \(\hbar\) is the reduced Planck constant, \(\eta\) is spin polarization, \(t_{free}\) is the free layer thickness, \(M_s\) is the magnetization saturation, \(H_{applied}\) is the external applied field and \(H_K\) is the effective anisotropy field. For perpendicular-to-plane MTJ (PMTJ), \(I_{co}\) is defined as [7, 8]:

\[
I_{co} = \left( 2e\alpha/\hbar \eta \right) t_{free} M_s \left( H_{applied} + H_K \right).
\]

Magnetic material parameters and geometrical parameters are considered. In addition, we focus on an additional control on the energy performance of the device by controlling effective anisotropy field \(H_K\). Due to the quadratic dependence of \(E_W\), equation (1), on \(I_{co}\), equations (2-3), this report focuses on optimizing \(E_W\) through optimizing \(I_{co}\).
In section 2, the expressions of \( J_{co} \), equations (2-3), are analyzed as functions of geometric and magnetic parameters. Model predictions were compared with points from literature. Section 3 discusses circuit level device modelling of MTJ, where the impact of \( H_K \) on the device performance is studied at the circuit level. In section 4, nano-magnetic dynamics simulations are performed for simple MTJ devices, illustrating the impact of controlling anisotropy energy on the device nanomagnetic dynamics. Section 5 concludes with summary and future work.

![Figure 1. Basic MTJ device and parameters/notations used in this paper.](image)

![Figure 2. Dependence of \( J_{co} \) for IMTJs on \( t_{free} \) with varied \( H_K \) and \( M_s \).](image)

2. \( J_{co} \) analytical expression

Given the multivariate and multiparametric nature of this problem, it is understandable that some features of the overall findings from the nano-magnetism community on optimizing such nanodevices are not readily presentable in simple 2D graphs. We therefore used either parametric 2D plots or equivalent 3D plots. In figure 2, we present the dependence of \( J_{co} \) for IMTJ devices as a function of \( t_{free} \), while controlling \( R \) and \( \alpha \). It is found that as \( t_{free} \) increases, \( J_{co} \) increases, where controlling \( R \) results in lowering \( J_{co} \) by ~20%. \( \alpha \) impact on \( J_{co} \) is stronger, where ~30% reduction in \( J_{co} \) can be obtained by controlling \( \alpha \). The data points presented in figure 2 are from [9-14].

In figure 3 the behaviour of \( J_{co} \) \( (t_{free}, H_K) \) for both types of MTJs is shown. Although MTJ devices such as those in references here are bounded by model curves in figure 2, one can see in figure 3 that the model predictions can only be considered semi-quantitatively valid. Figure 3 (a) predicts that as \( t_{free} \) increases, the dependence of \( J_{co} \) on \( H_K \) increases, reaching ~20% decrease in \( J_{co} \) for high \( t_{free} \) values. Similarly, higher \( M_s \) values result in stronger dependence of \( J_{co} \) on \( t_{free} \) and \( H_K \) (faded plane in figure 3 (a)).

![Figure 3. 3D plot of \( J_{co} \) as a function of \( t_{free} \) and \( H_K \) for (a) IMTJ and (b) PMTJ.](image)

Figure 3 (b) depicts the behaviour of \( J_{co} \) for PMTJs, where similar behaviour as in figure 3 (a) is observed. However, a stronger impact of \( H_K \) on \( J_{co} \) is observed for PMTJs. The magnetic properties, such as \( M_s \), have a strong impact on \( J_{co} \). Controlling \( M_s \) is achieved by changing the materials used. However, in figure 4, we considered \( M_s \) as a more broadly controllable variable. A stronger dependence of \( J_{co} \) on \( M_s \) is found compared to its dependence on \( H_K \) for IMTJ devices. However, PMTJ devices
show linear dependence on $M_s$, with the $H_K$ impact being stronger. Even for very broad range of values of $t_{\text{free}}$, $H_K$ and $M_s$, only a limited validity of the model predictions is achieved.

![3D plot of $J_{co}$ as a function of $M_s$ and $H_K$ for (a) IMTJ and (b) PMTJ.](image)

Figure 4. 3D plot of $J_{co}$ as a function of $M_s$ and $H_K$ for (a) IMTJ and (b) PMTJ.

Due to the limited validity predictions of $J_{co}$ equations (2-3) stemming from LLGS-STT approach, the utilization of $J_{co}$ equations (2-3) is limited to predicting the range of the current density, and the trend of $J_{co}$ behavior when controlling different parameters, as shown in figures 2-4.

3. MTJ circuit device modeling

We have modelled the I-V curves of the MTJ to explore the effect of controlling $R$ on the overall power (energy) needed to operate the device. Zhao et al. MTJ circuit model was modified to account for the impact of $H_K$ [21]. We modelled the device for several different parameter families. Some salient features are shown in figure 5, where the change in resistance-area product ($\delta$) and $R$ induces a change in switching current ($I_{SW}$) and voltage ($V_{SW}$) of the device. Figure 5 shows typical I-V hysteresis curves of the device, for two values of $\delta$, 25 and 100 $\Omega\text{m} \mu \text{m}^2$ and two values of $H_K$, 100 and 1000 Oe. Manipulating $\delta$ has greater impact on $V_{SW}$ compared to $I_{SW}$.

![I-V hysteresis loop of MTJ device model.](image)

Figure 5. I-V hysteresis loop of MTJ device model.

![Effect of $H_K$ and $\delta$ on $V_{SW}$, $I_{SW}$ and $P_{SW}$.](image)

Figure 6. Effect of $H_K$ and $\delta$ on $V_{SW}$, $I_{SW}$ and $P_{SW}$.

A set of simulations have been performed, where $V_{SW}$ and $I_{SW}$ are extracted and plotted as a function of $H_K$, (figure 6). We find that $V_{SW}$ shows stronger dependence on $H_K$. The switching power ($P_{SW}$ ($H_K$)) is calculated by multiplying $V_{SW}$ and $I_{SW}$ curves, figure 6. Since the impact of $\delta$ is stronger, we accounted for the impact of $\delta$ (solid and dashed lines are for $\delta = 25$ and 100 $\Omega\text{m} \mu \text{m}^2$, respectively.).

Controlling $\delta$ also affects the $H_K$, where larger $\delta$ values results in stronger impact on the control of $H_K$, and both are partially interface-controlled. For $\delta = 100$ $\Omega\text{m} \mu \text{m}^2$, changing $H_K$ by $\sim 40\%$ results in decreasing $V_{SW}$ by $< 5\%$, while $I_{SW}$ decreases by $\sim 10\%$. Therefore, controlling $H_K$, in addition to the control of $\delta$, should result in further controlling the power consumption and energy performance.

4. Nano-magnetic simulations of magnetization reversal

Given that the need for a better control of $H_K$ is one of the main suggestions of this report, we examined the influence the changes in anisotropy have on the elementary process of magnetization reversal in an elliptically shaped disk that is a model of one ferromagnetic layer of an MTJ. We used NMAG package
[21], and we modelled devices $20 \times 10 \text{ nm}^2$ in size ($\lambda = 2$). The initial results of the magnetization dynamics are shown in figure 7. Two panels of the figure differ from each other only in the change of the effective second order anisotropy (by 30%). We note that both devices have completely “flipped”.

**Figure 7.** Nano-magnetic simulation for $20 \times 10 \text{ nm}^2$ free layer, where $H_K$ for (b) is lower by 30%.

5. Conclusions and future work

It is shown that geometric and magnetic parameters can be tuned to minimization operating energy of MTJs. The role of $H_K$, $t_{\text{free}}$ and $M_e$ on the threshold current density, $J_{\text{co}}$, are demonstrated in the light of the need to control $J_{\text{co}}$ for a more efficient energy performance of MTJs. We further emphasize the role of $H_K$ as the key operating parameter that is tuneable, potentially via surface nanoengineering of MTJ layers.

Acknowledgement

The work in this paper has been supported by the Mubadala-SRC grant 2012-VJ-2335. Part of the work has been supported by Brookhaven National Laboratory, BNL-CFN, supported by the US DoE, Office of Basic Energy Sciences. We acknowledge support from A. Stein (BNL), K. Ng (SRC) and A. Jacob (GlobalFoundries). We are thankful to I. Zutic (SUNY-Buffalo) for useful advice in the early stages of the report.

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