Origin of the resistance-area product dependence of spin transfer torque switching in perpendicular magnetic random access memory cells

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We report on an experimental study of current induced switching in perpendicular magnetic random access memory (MRAM) cells with variable resistance-area products (RAs). Our results show that in addition to spin transfer torque (STT), current induced self-heating and voltage controlled magnetic anisotropy also contribute to switching and can explain the RA dependencies of switching current density and STT efficiency. Our findings suggest that thermal optimization of perpendicular MRAM cells can result in significant reduction of switching currents.

I. INTRODUCTION

As information technology enters a new era, with Internet of Things expected to connect over 30 billion devices generating vast amount of data that need to be processed and stored, there is a rapidly growing demand for faster, denser and more power-efficient non-volatile memories that could be organized in alternative hierarchies offering better system performance and greater functionality, all at preferably lower cost. Spin transfer torque magnetoresistive random access memory (STT MRAM) is uniquely positioned to address this challenge as it is the only emerging memory that could combine the high speed and endurance of SRAM, high density of DRAM and the non-volatility of Flash. The heart of the MRAM cell is the magnetic tunnel junction (MTJ), that provides the write, read and bit storing functionality, essentially using two magnetic layers, reference layer (RL) and the free layer (FL), separated by a magnesium oxide (MgO) tunnel barrier. The two bit storage states are the parallel (P) and antiparallel (AP) magnetization orientations of the FL relative to the RL, distinguished by different resistance-area products (RA) of the MTJ: \((RA)_P \equiv RA\) for the P state, and \((RA)_{AP} = (1 + TMR)RA\) for AP state, with TMR being the tunneling magnetoresistance ratio.

For RL and FL with perpendicular magnetic anisotropy (PMA), the STT critical P \(\equiv AP\) switching voltage \(V_{c0}\) (defined at zero temperature and for infinitely long time) is, in the macrospin approximation, expressible in terms of a spin torque field \(H_{ST}\) and torque \(\tau\) as

\[
\alpha H_k = \pm H_{ST} = \pm \tau V_{c0}/RA, \tau = \frac{h}{2eM_s t}, \tag{1}
\]

where \(\alpha\), \(M_s\), \(t\), and \(H_k\) are the damping parameter, saturation magnetization, thickness, and net PMA field of the FL, respectively, and \(\eta = \sqrt{TMR(TMR + 2)/(2(TMR + 1))}\) is a polarization efficiency factor. Apart from a minor RA dependence of \(\eta\), due to \(TMR\) being a weak function of RA (see Table I), the critical current density \(J_{c0} \equiv V_{c0}/RA\) is not expected to depend on RA. Experimentally, however, an RA dependence has been observed by several groups and attributed to an RA-dependent spin pumping contribution to \(\alpha\) in Eq. (1). Here we show that the RA dependence of \(J_{c0}\) is influenced by other phenomena, in particular the current-induced self-heating of an MRAM cell which reduces the effective \(H_k\) of the FL, and, to a smaller extent, the voltage controlled magnetic anisotropy effect (VCMA). As the temperature rise of the FL is proportional to the dissipated power density, higher RA devices result in lower \(J_{c0}\). In addition, as the VCMA effect is proportional to the bias voltage \(V_b\) across the MRAM cell, for a given \(J\) VCMA effects are stronger with higher RA. The combination of heating and VCMA quantitatively explains all of our experimental findings, in particular the much stronger RA dependence of \(J_c\) for P to AP switching (P\(\rightarrow\)AP) compared to AP\(\rightarrow\)P, and the RA dependence of STT efficiency \(E_b/I_{c0}\) obtained from pulse width \(t_p\) dependent measurements of switching voltage \(V_c\) in the thermally activated (TA) regime (\(E_b\) is the energy barrier for magnetization reversal of the FL and \(I_{c0} \equiv V_{c0}/R_P\) is the critical switching current).

II. DEVICE FABRICATION

The MRAM film stacks used in this study consist of a seed layer, synthetic antiferromagnet RL, MgO tunnel barrier, CoFeB-based FL, MgO cap layer for enhancing

| RA (\(\Omega \mu m^2\)) | TMR (%) | \(M_s t\) (memu/cm²) | \(H_k\) (kOe) | \(\alpha\) |
|-----------------|---------|-----------------|----------|---------|
| 5               | 133     | 0.232           | 2.71     | 0.0100  |
| 10              | 147     | 0.227           | 2.72     | 0.0102  |
| 15              | 156     | 0.220           | 2.69     | 0.0100  |
| 20              | 156     | 0.232           | 2.69     | 0.0094  |

TABLE I. Transport and magnetic properties of free layer films used in this study.
FIG. 1. (a) TEM image of an MRAM cell used in this study. (b) Measured $J_c$ vs $RA$ (symbols) and calculated (lines) using fit parameter values described in text. Each $J_c$ data point value is median from >500 devices. Measured (c) $R$ vs $H$ and (d) $R$ vs $V_b$ of an MRAM cell with $RA_{10}$.

$H_k$, and Ru/Ta cap layer. The films were deposited by magnetron sputtering in an Anelva C-7100 system and then annealed at 335°C for 1 hour. The MgO layers were rf-sputtered from a MgO target. The $RA$ and $TMR$ values measured on the annealed films by current-in-plane tunneling (CIPT) are shown in Table I. Variation of $RA$ values in the range 5 - 20 $\Omega \mu m^2$ was achieved by adjusting the sputter time of the MgO barrier, and consequently, the $TMR$ ratio increased from 133 to 156 %, respectively. For this range of $RA$ values, $M_s,t$ measured by vibrating sample magnetometry, as well as $H_k$ and $\alpha$ of the FL measured by full film ferromagnetic resonance (FMR) are identical (see Table I).

MRAM test device cells are fabricated using 193 nm deep UV optical lithography, followed by reactive ion etching a hard mask, ion milling the MRAM film, SiO$_2$ refill and chemical mechanical planarization. Median electrical device diameters $D$, determined by fitting $R_P$ vs $RA$ for the given optical mask size, are ~120, 100, 80 and 60 nm. A transmission electron microscopy (TEM) image of a representative device is shown in Fig. 1(a). Fig. 1(c) shows $R$ vs. perpendicular external magnetic field $H$ for an MRAM cell with $RA = 10 \Omega \mu m^2$ ($RA_{10}$) and $D \approx 60$ nm measured at constant $V_b = 50$ mV, showing $TMR \approx 140 \%$, coercive field $H_c = (H_{SW}^{P\rightarrow AP} - H_{SW}^{AP\rightarrow P})/2 \approx 2$ kOe ($H_{SW}$ is the switching field) and offset field $H_{offs} = (H_{SW}^{P\rightarrow AP} + H_{SW}^{AP\rightarrow P})/2 \approx 300$ Oe that favors the P state. Fig. 1(d) shows $R$ vs $V_b$. One can see that $P\rightarrow AP$ and $AP\rightarrow P$ occur at $V_c^{P\rightarrow AP} = -0.54$ V and $V_c^{AP\rightarrow P} = +0.58$ V, respectively.

FIG. 2. (a) $R$ vs $H$ for $-0.95 V < V_b < +0.95$ V for a MRAM cell with $RA_{20}$ and $D = 80$ nm. (b) $H_{SW}$. (c) $H_{offs}$ and (d) $H_c$ vs $V_b$ obtained from the measurements shown in (a) (symbols) and the corresponding dependencies calculated using Eqs. (2) and (3) (lines) with $H_{so} = 1.85$ kOe, $H_{RL} = 225$ Oe, $\tau/\alpha = 18.6$ kOe$\mu m^2$/A, $\epsilon = 0.37$ kOe/V and $\zeta = 37.8$ kOe$\mu m^2$/W.

III. RESULTS AND ANALYSIS

Fig. 1(b) shows $J_c = I_c/(D^2\pi/4)$, determined by ramping $V_b$ with a dwell time of ~10 ms and measuring current $I_c$ just before switching, as a function of $RA$. $J_c$ decreases with increasing $RA$ for both $AP\rightarrow P$ and $P\rightarrow AP$. The dependence, however, is much stronger for the latter, with $J_c$ decreasing ~50% from $RA_5$ to $RA_{20}$, while for $AP\rightarrow P$ the decrease is only ~15%. Also, $J_c$ at a given $RA$ increases with decreasing $D$. This is contrary to what one would expect in the TA switching regime of these measurements, as smaller devices are more thermally unstable.

The change in $J_c$ with $RA$ cannot be attributed to an $RA$-dependent spin-pumping contribution to $\alpha$ as our film FMR measurements show that $\alpha$ is independent of $RA$ (see Table I). It also cannot be explained by any dependence of $M_s$ or $H_k$ of the FL on $RA$ as they are also measured to be $RA$-independent (Table I). In order to understand the origin of these dependencies we performed additional $R$ vs $H$ measurements as a function of $V_b$.

Fig. 2(a) shows representative $R$ vs $H$ data for different $V_b$ from a single cell. $V_b$ is varied from −0.95 V (bottom curve) to +0.95 V (top curve) in 0.1 V steps. The obtained $V_b$ dependencies of $H_{SW}$ for $P\rightarrow AP$ and $AP\rightarrow P$, $H_{offs}$ and $H_c$ are shown in Figs 2(b), 2(c) and 2(d), respectively. While the near-linear $V_b$-dependence of $H_{offs}$ shown in Fig. 2(c) is close to expected from...
STT, Fig. 2(d) shows that $H_c$ exhibits a quadratic component of $V_b$-dependence that strongly suggests self-heating. Indeed, in the macrospin approximation, STT alone predicts no dependence of $H_c$ on $V_b$. A more careful inspection of Fig. 2(d) shows that $H_c$ also exhibits a smaller linear component of $V_b$-dependence, which could be due to VCMA.

Alternatively, the $V_b$-dependence of $H_k$ can be measured more directly (see Fig. 3) from device-level thermally induced FMR (mag-noise) spectra. The expected peak resonance frequency $f_0 \approx \gamma \sqrt{\left( (H_k + H_z)^2 + H_{ST}^2 \right) \left( 1 - (H/y/H_c)^2 \right)}$ where $\gamma \approx 3$ GHz/kOe is the gyromagnetic ratio, $H_y$ and $H_z$ are the total in-plane and perpendicular magnetic fields, respectively, and $H_{ST} = (\alpha H_k)(V_b/V_0)$ (see Eq. 1). For the measurements in Fig. 3 (near the AP state), $V_b < V_0$, thus $H_{ST}$ is negligible, $H_y \approx 0$, and $H \approx 1$ kOe $\ll f_0/\gamma$ makes only a small correction to $H_k$. As shown in Fig. 3 for an RA20 cell, $f_0(V_b)$ has both a quadratic and linear (VCMA) contributions, the latter more clearly visible than indicated by $H_c$ vs $V_b$ shown in Fig. 2(d). One can fit this dependence by expressing $H_k = H_{k0} + eV_b - \zeta V^2_{b}/RA$ where $RA' = RA(1 + TMR(V_b=0)(1 - 0.5|V_b|)$ is the approximate expression for $V_b$-dependent $RA$ in the AP state (see Fig. 1(d)). The values obtained are $H_{k0} = (3.76 \pm 0.01)$ kOe, $\epsilon = (0.42 \pm 0.01)$ kOe/V and $\zeta = 44.0 \pm 0.5$ kOe$^2$/W. The sign of the VCMA is positive, i.e. it increases $H_k$ for positive $V_b$ (AP→P polarity).

Having established that VCMA and self-heating are present, $H_{SW}(V_b)$ is explicitly expressed as

$$H_{SW}^{P\rightarrow AP} = H_{k0} + H_{RL} + \frac{\tau}{\alpha RA} V_b + \epsilon V_b - \zeta V^2_{b}/RA',$$

and $H_{SW}^{AP\rightarrow P}$

FIG. 3. (a) Normalized mag-noise root mean square power spectral density measured for different $V_b$. (b) The resonance frequency $f_0$ vs $V_b$ corresponding to the measurements shown in (a). The line is fit to the data using a model that includes VCMA and self-heating contributions, as described in text.
FIG. 5. (a) Measured $R$ vs $H$ for different $T$s for an MRAM cell with $R_{20}$, $D = 100$ nm. (b) $H_c$ vs $T$ for the data shown in (a) (symbols) and linear fit (line) with slope $dH_c/dT \approx 10$ Oe/K. (c) FL $T$ vs $V_c$ for $H_c$ determined for the P state for different $R_A$s. (d) $T$ vs dissipated power density for different $R_A$s. The line is linear fit to the data, i.e. $T = T_0 + R_{th}AV^2_c/R_A$ with $T_0 = (28 \pm 2)^\circ$C and $R_{th}A = (4.0 \pm 0.1)$ Kμm$^2$/mW. Each data point in (c) and (d) is the median from ~25 measured cells averaged over $D = 60, 80, 100$ and $120$ nm devices.

$H_{k0} \approx 1.9$ kOe characteristic of the Fig. 4 data. The former is a passive measurement under quiescent macrospin conditions, and should better represent the true device FL PMA compared to the latter, which likely involves a nucleated magnetization reversal process not resembling uniform macrospin rotation. In the macrospin picture (see Eq. 1), $\tau/\alpha = H_{k0}/J_{c0} = (h\eta)/(2\alpha M_t)$. Using Table I, one then estimates $\tau/\alpha \approx 65$ kOeμm$^2$/A. This is about 3.5 times larger than the value found from fitting the data in Fig. 4. More than half of this discrepancy may be ascribed to the aforementioned factor of two difference between macrospin $H_{k0}$ and $H_{k0}$ obtained by fitting the same non-macrospin data of Fig. 4 used to fit $\tau/\alpha$.

In order to determine how the cell temperature $T$ depends on $V_c$, we performed $R$ vs $H$ measurements over $T$ range 30 – 120$^\circ$C. Figs. 5(a) and 5(b) show representative results obtained from single cells. A typical value $dH_c/dT \approx 10$ Oe/K is obtained that is within 10% of the $dH_c/dT$ found from thermal FMR measurements analogous to those shown in Fig. 3. The measured $dH_c/dT$ factors convert $H_c$ vs $V_c$ data into $T$ vs $V_c$ and $T$ vs $V_c^2/R_A$, as is illustrated in the figure and described in the caption.

We also measured $V_c$ vs $t_p$ in the range 10 ns to 5 ms and evaluated $J_{c0}$, thermal stability factor $\Delta = E_b/k_BT$ ($k_B$ is the Boltzmann constant) and $E_b/I_{c0}$ using the TA model.$^{12,18}$ Fig. 6(a) shows an example of the data from a RA10 cell, which in the range $t_p \geq 5$ μs is fit to the TA model $\ln (t_p/(\tau_0 \ln 2)) = \Delta_{eff} = \Delta (H_k/H_{k0}) (T_0/T)$ using the following two forms:

$$H_k = H_{k0} \left(1 \pm \frac{V_c}{V_{c0}} \right), \quad T = T_0$$

(solid lines) and

$$H_k = H_{k0} \pm \frac{\tau V_c}{\alpha R_A} - \epsilon V_c - \frac{\epsilon V^2}{2R_A}, \quad T = T_0 + R_{th}A \frac{V^2}{R_A}$$

(dashed lines) where $\tau_0 = 1$ ns is taken to be the inverse attempt frequency, $H_{k0}$ and $T_0$ are $H_k$ and $T$ at $V_c = 0$. $R_{th}A$ is the effective thermal resistance-area product and $\epsilon$ and $(-)$ sign correspond to P→AP and AP→P, respectively. Eq. (4) is commonly found in the literature,$^{12,17,18}$ where only STT influence is accounted for, while Eq. (5) incorporates the additional $V_c$ dependencies of $H_k$ from both VCMA and self-heating, as well as the explicit $V_c$ dependence of cell $T$, as described earlier via Eqs. (2), (3) and Figs. 4 and 5. Along with fit parameter $\Delta$ (both forms), Eq. (4) uses the second fit parameter $V_{c0}$. When using Eq. (5), $H_{k0}$ is the only additional fit parameter, while the values for $\tau/\alpha$, $\epsilon$ and $\Delta$ are determined from the data of Fig. (4), $T_0 = 303$ K and $R_{th}A \approx 4$ Kμm$^2$/mW is determined from data in Fig. 5. For Fig. 6(c), $J_{c0} = V_{c0}/RA$ for Eq. (4) case and $J_{c0} = (\tau/\alpha)^{-1}/H_{k0}$ for Eq. (5) case. Note that, in both cases, AP→P and P→AP branches are fit separately and $V_{c0}$ and $\Delta$ are determined as their average. One can see in Fig. 6(a) that both models fit the data well (the solid and dashed lines are indistinguishable).

Fig. 6(b) shows $H_{k0}$ values as a function of $RA$. We see that, as expected, $H_{k0}$ is independent of $RA$ with $RA$-averaged values $H_{k0}^{P\rightarrow AP} = (2.77 \pm 0.07)$ kOe and $H_{k0}^{P\rightarrow AP} = (2.32 \pm 0.12)$ kOe. These values are higher than the $H_{k0}$ values obtained from the $H$-driven magnetization reversal measurements described by Eqs. (2) and (3) (see Figs. 2 and 4), but are lower than $H_{k0}$ values obtained in thermal FMR measurements which do not involve any magnetization reversal. This is not surprising considering the different magnetization excitation and reversal processes in these measurements. Note that the difference $(H_{k0}^{P\rightarrow AP} - H_{k0}^{P\rightarrow AP})/2 \approx 220$ Oe agrees well with the value of $H_{RL}$ obtained from fitting the data of Fig. 4.

Figs. 6(c)-6(e) compare $RA$ dependencies of $J_{c0}$, $\Delta$ and $E_b/I_{c0}$, obtained by fitting experimental data using Eqs. (4) and (5). We find strong $RA$ dependence of all those quantities when $t_p$ dependent $V_c$ data is fit to Eq. (4). In particular, we observe large increase of $E_b/I_{c0}$ with increasing $RA$, similar to previous reports.$^{11,12}$ However, when the data is fit using Eq. (5), which takes into account VCMA and self-heating effects, all quantities become $RA$-independent. This means that STT switching parameters are intrinsically not $RA$ dependent, but their apparent $RA$ dependence is due to an error from fitting the $t_p$ vs $V_c$ assuming that STT is the only mechanism responsible for switching, without including contributions from VCMA and self-heating effects.
From Fig. 6(e), the fitting model of Eq. (5) predicts an \( RA \)-independent value of \( E_b/I_o \cong 0.1 \) \( k_B T/\mu A \). However, from the macrospin model of Eq. (1), taking \( E_b = M_s H_k A/2 \), \( E_b/I_o = h\eta/(4\alpha) \cong 1.8 \) \( k_B T/\mu A \), using the values in Table I. This 18 times discrepancy for \( E_b/I_o \) is far greater than the aforementioned 3.5 time one for \( \tau/\alpha \) despite that both expressions, derived from Eq. (1), share the same physical parameters \( h\eta/(2\epsilon) \). The immediate cause of this is that the value \( \Delta \cong 70 \) obtained by fitting the experimental data using Eq. (5) (see Fig. 6(d)) is much smaller than the value \( \Delta = 474 \) obtained by calculating \( E_b \) using the parameter values in Table I for average \( D = 90 \) nm. Further explanations are beyond the physics of the macrospin model\textsuperscript{21,23}.

It is noted that the self-heating term \(-\zeta V_c^2/RA'\) of Eq. (5) explicitly violates the assumption that \( E_b \) is a \( T \)-independent quantity, as is commonly implied by Arrhenius-type models such as the TA model in the case of Eq. (4)\textsuperscript{24}. In the Eq. (5), the parameter \( H_{k0} \) is the room \( T \) value, rather than that at \( T \to 0 \), and \( E_b \propto H_k \) will vary with \( T \) due to self-heating regardless of the presence of VCMA and STT effects. This implies that \( M_s H_k \) of the cell effectively has additional \( T \) dependence\textsuperscript{23} besides that attributable solely to thermal fluctuations in the FL magnetization direction, which is otherwise treated by the denominator \( k_B T \) in the expression for \( \Delta_T \). This could result from the failure of the macrospin model to account for non-uniform (spin-wave mode) magnetization fluctuations.

**IV. CONCLUSION**

In conclusion, we point out that using the obtained values for \( \tau/\alpha \), \( \epsilon \), and \( \zeta \), we find that STT and self-heating contribute comparably to FL switching at \( RA_{10} \), and the latter is the dominant switching mechanism for larger \( RAs \). As \( \zeta = (R_{th}A)dH_c/dT \), higher \( R_{th}A \) values should result in lower \( J_s \). Two times higher \( R_{th}A \) values than measured in our cells have been reported in the literature\textsuperscript{16,26}, which suggests that further reduction of \( J_s \) should be possible with thermal optimization of perpendicular MRAM cells.

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