Effect of resistance-area product on spin-transfer switching in MgO-based magnetic tunnel junction memory cells

Z. M. Zeng,1,a, P. Khalili Amiri,2 G. Rowlands,3 H. Zhao,4 I. N. Krivorotov,5 J.-P. Wang,4 J. A. Katine,5 J. Langer,6 K. Galatsis,2 K. L. Wang,2 and H. W. Jiang1

1Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA
2Department of Electrical Engineering, University of California, Los Angeles, California 90095, USA
3Department of Physics and Astronomy, University of California, Irvine, California 92697, USA
4Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, Minnesota 55455, USA
5Hitachi Global Storage Technologies, San Jose, California 95135, USA
6Singulus Technologies, Kahl am Main 63796, Germany

(Received 24 November 2010; accepted 29 January 2011; published online 18 February 2011)

We use ultrafast current-induced switching measurements to study spin-transfer switching performance metrics, such as write energy per bit ($E_w$) and switching current density ($J_c$), as a function of resistance-area product (RA) (hence MgO thickness) in magnetic tunnel junction cells used for magnetoresistive random access memory (MRAM). $E_w$ increases with RA, while $J_c$ decreases with increasing RA for both switching directions. The results are discussed in terms of RA optimization for low write energy and current drive capability (hence density) of the MRAM cells. Switching times <2 ns and write energies <0.3 pJ are demonstrated for 135 nm×65 nm CoFeB/MgO/CoFeB devices. © 2011 American Institute of Physics. [doi:10.1063/1.3556615]

The spin-transfer torque (STT) effect, predicted by Slonczewski1 and Berger,2 shows great promise for enabling high density magnetoresistive random access memory (MRAM).3–5 In STT-MRAM bits, the spin torque can reverse the free layer magnetization if the current density is sufficient, resulting in spin-transfer-induced switching (STS). Remarkable progress in STS in giant magnetoresistive nanopillars6 and magnetic tunnel junctions (MTJs),7 particularly in MgO-based MTJs with large magnetoresistance (MR) ratio,8,9 has been achieved in recent years, but challenges remain to be overcome in terms of write current and write energy. High values for the critical current density required for STS, $J_c$, complicate the integration with complementary metal-oxide-semiconductor (CMOS), requiring larger transistors to increase the current drive capability. Moreover, present-day CMOS operates at speeds in the low gigahertz range, but $J_c$ increases drastically with decreased switching time $\tau_p$ in the subnanosecond current pulse regime.10,11

In this work, we study the effect of resistance-area (RA) product on the MTJ switching performance through ultrafast switching measurements. In our experiments, all conditions except MgO thickness of MTJ cells are controlled to be the same. We find that the write energy increases, while $J_c$ decreases with increasing RA values, as described below.

MTJs with stacks of composition PtMn (15)/CoFe (2.5)/Ru (0.85)/CoFeB (2.4)/MgO (wedge: 0.8–1.0)/CoFeB (1.8) (thickness in nanometers) were deposited using a Singulus TIMARIS PVD system and annealed at 300 °C for 2 h in a magnetic field of 1 T. The films were subsequently patterned into ellipse-shaped pillars. In this letter, we show data from devices with 135 nm×65 nm nominal dimensions. Our previous works2,11 suggest that these MTJ cells have low $J_c$ values and high thermal stability based on measurements of the magnetic anisotropy field. Similar results were observed in devices with other sizes. Our experimental setup with short pulse capability is briefly described as follows. The MTJ cell is contacted by a one-port ground-signal-ground configuration microwave (40 GHz) probe. A short pulse and a dc are applied to the MTJ cell through a bias $T$ and the resistance is recorded by a Keithley Instruments meter. Note that the real pulse voltage across the MTJ cells presented below was calibrated by considering the reflection and the loss $L$ (in our system, $L=0.0279$) in the cables and probe as $V_p=2V_{in}(1−L)R/(R+50 Ω)$, where $V_{in}$ is the input pulse amplitude and $R$ is the resistance of the MTJ cell. During the pulse measurements, the polarity of the pulse and the initial orientation of free layer are fixed, while $V_{in}$ and pulse duration $\tau$ are varied. In our convention, positive voltage corresponds to electrons traveling from the fixed to free layers favoring parallel state.

Figure 1(a) represents the RA (hence MgO thickness) dependence of the MR ratio. Note that the RA presented below corresponds to the parallel (P) state. It can be seen that the MR variation is relatively large when RA is below 4.0 $Ω $ μm², while MR becomes stable around 150% for RA > 4.0 $Ω $ μm². Figure 1(b) depicts the field hysteresis loop for one typical MTJ cell with MR of 147% and RA of 4.9 $Ω $ μm². The coupling or interaction field ($H_{int}$) between the fixed and the free layer favors parallel alignment in our devices and is found to be ~60–120 Oe in our measured cells. We believe that the decrease in $H_{int}$ with higher RA is due to reduced Néel coupling in the thicker barriers. The sharp resistance transition suggests that the free layer magnetization has an almost single-domain structure. Figure 1(c) shows the dc current-voltage ($I$−$V$) curves for the corresponding MTJ cell when the magnetizations of the fixed and free layers are aligned in the antiparallel (AP) and parallel (P) states as well as the switching state. In the dc switching loop, resistance shows abrupt changes at +144 μA ($I^*$) and

aElectronic mail: zhungming.zeng@gmail.com.
Here, MR is defined as \( MR = \frac{100}{H_{11003}} \rightarrow H_{9270} \).

\[ J_c \text{bit} = \frac{d}{H_{20849}} \]

state the coupling field, thus the total field \( H \).

\[ E_w \text{marks the} \]

Ew obtained at a 1 ns pulse. During the pulse measurement, the obtained from dc- \( I \) curve, as shown in Fig. 1(e) at 1 ns pulse is \( \sim 8 \text{ MA/cm}^2 \), indicating that \( J_c \) increases drastically with decreased switching time \( \tau_p \). In Figs. 2(a) and 2(b), the switching probabilities \( P_{sw} \) are plotted as a function of pulse duration \( \tau = 0.3-2 \text{ ns} \) for P \( \rightarrow \) AP and AP \( \rightarrow \) P switching of the free layer for the corresponding MTJ cell at various pulse amplitudes. It can be seen that for both switching directions, the switching time \( \tau_p \) decreases with increasing pulse amplitude. The energy per write for a given pulse amplitude can be estimated from

\[ E_w = \frac{V_p^2 \tau_p}{R}, \]

where \( \tau_p \) is the mean switching time corresponding to \( P_{sw} = 50\% \), as shown by the dashed line in Fig. 2. A minimum \( E_w \) for AP \( \rightarrow \) P(\( P \rightarrow \) AP) switching of 0.28 (0.52) pJ is obtained in this MTJ, as indicated in Fig. 2. Since our measurements are not in the thermal activation regime, the switching is dominated by angular momentum transfer rather than temperature, and according to an adiabatic precessional model, the switching time is given as

\[ \tau_p = \tau_0 \ln \left( \frac{\pi/2}{\theta_0} \right) \left( \frac{V_p}{V_0} - 1 \right), \]

where \( V_0 \) is the zero temperature instability voltage, \( \tau_0 \) is the relaxation time, and \( \theta_0 \) is the initial misalignment between spin polarization and the macrospin to be reversed. We found that \( t_p(V_p) \) is consistent with our experiment, as shown in Fig. 3. By assuming \( \theta_0 = (k_B T/2E)^{1/2} = (1/2 \Delta)^{1/2} = 0.0745 \) [\( \Delta = 90 \text{ (Ref. 12)} \)], \( V_0 = 0.26(0.30) \) V and \( \tau_0 = 0.42(0.34) \) ns for AP \( \rightarrow \) P(\( P \rightarrow \) AP) switching are obtained as fitting parameters.

Through measuring the switching probability \( P_{sw} \) of MTJ cells as mentioned above, we can get the energy per write for different RA values. Figure 4(a) shows the results of \( E_w \) as a function of RA. It can be clearly seen that \( E_w \) increases with increasing RA values for both switching direc-

![Figure 1](image1.png)

FIG. 1. (Color online) (a) MR ratio as a function of the resistance-area (RA) product; the inset is plotted as a function of the MgO thickness. The field hysteresis loop (b), current-voltage curves for AP, P, and switching states (c), and pulse voltage loop (d) in a typical MgO-MTJ cell with RA = 4.9 \( \Omega \mu m^2 \). Here, MR is defined as MR = 100 \( (R_{P0} - R_P)/R_P \) and the solid line in (a) is added for clarity.

![Figure 2](image2.png)

FIG. 2. (Color online) Switching probabilities (\( P_{sw} \)) as a function of the pulse width at various pulse amplitudes for AP \( \rightarrow \) P state (a) and P \( \rightarrow \) AP state (b) in the MgO-MTJ cell with RA = 4.9 \( \Omega \mu m^2 \). The write energy per bit (\( E_w \)) is calculated at \( P_{sw} = 50\% \) (dashed line) and the dashed line box marks the \( E_w \) minima.
tions. The increase in $E_w$ is accompanied by an increase in the write voltage for larger RA values and is thus undesirable in terms of integration with low-power CMOS. Furthermore, write voltage (pulse amplitude) corresponding to the minimum $E_w$ increases from $-0.35$ V for $RA=3.0$ $\Omega \, \mu m^2$ to $-0.9$ V for $RA=11.0$ $\Omega \, \mu m^2$ (not shown) because of the increase in the MTJ resistance with RA. The larger voltage across MTJ cell increases the probability of tunnel barrier degradation and breakdown, lowering write endurance of the cell. RA optimization is thus essential for integration of the MTJ cell into a practical STT-MRAM circuit.

We also investigated the effect of RA on the switching current density $J_c$. The $J_c$ values were determined by performing pulse induced switching loops for $>20$ times with 1 ns pulse, as shown in Fig. 1(d). In contrast to the write energy dependence of RA, $J_c$ is found to decrease with increasing RA, as shown in Fig. 4(b). The reduction in $J_c$ may originate from the decrease in effective damping due to spin pumping effect. Since this effective damping depends on the effective spin mixing conductance, high RA reduces the spin diffusion and spin mixing conductance.

In summary, we have investigated the effect of the resistance-area product on the spin-transfer switching in MgO-based MRAM cell. The write energy and write voltage are found to increase, while switching current density is reduced with increasing RA (i.e., MgO thickness), MTJ cells with switching times $<2$ ns and write energies $<0.3$ pJ are demonstrated with RA in the range of $-4$ to $-8$ $\Omega \, \mu m^2$ and MR $>140\%$.

We would like to acknowledge fruitful discussions with Y. Huai. This work was supported by the DARPA STT-RAM program (HR0011-09-C-0114) and the Nanoelectronics Research Initiative (NRI) through the Western Institute of Nanoelectronics (WIN).