Dramatic reduction of read disturb through pulse width control in spin torque random access memory

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Magnetizations dynamic effect in low current read disturb region is studied both experimentally and theoretically. Dramatic read error rate reduction through read pulse width control is theoretically predicted and experimentally observed. The strong dependence of read error rate upon pulse width contrasts conventional energy barrier approach and can only be obtained considering detailed magnetization dynamics at long time thermal magnetization reversal region. Our study provides a design possibility for ultra-fast low current spin torque random access memory. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4823696]

Thermal induced magnetization fluctuations in magnetic tunnel junctions (MTJs) are responsible for the bit errors in both the read (read disturb) and write operations (write error rate (WER)). Such fluctuations are often coupled with magnetization dynamic effect, which are evident in our previous studies of WER in spin torque random access memory (STT-MRAM)[1,2] and WER studies of other groups.[3–6] However, the role of magnetization dynamics in the read disturb are often ignored due to the assumption that the read disturb can be well described with a thermal activation model. In this letter, we show that, while such assumption is valid when the read pulse is long, the model fails to describe the experimental result for a short read pulse approaching magnetization dynamic scale. We further address the magnetization dynamic effect in low switching current read disturb by providing a more complete theoretical model and compare read disturb results from the two theoretical models with experimental observations. It needs to be emphasized here that the study of read disturb at short time scale is important for the design of high speed, low power STT-MRAM where the switching current is greatly reduced and sensing current margin is therefore significantly tightened.

Read disturb problem can be described with a thermal activation model where the MTJ cell thermal stability is decreased in the presence of read current. Néel-Arrhenius formula is widely used to describe long time thermal magnetization reversal.[7] In this approach, magnetization switching probability that determines the error rate can be written as

$$P = 1 - e^{-\gamma t}, \tag{1}$$

where P is the switching probability, t is the pulse duration time, and γ is the transition rate. The transition rate follows from Néel-Arrhenius formula is given by[8]

$$\gamma = f_0 e^{-\delta E/k_B T}, \tag{2}$$

where $\delta\varepsilon$ is the energy barrier, $k_B T$ is Boltzmann thermal factor at temperature T, and f_0 is the attempt frequency that could depend upon temperature and external excitation magnitude.

For thin film magnetic element with saturation magnetization M_s and volume V, magnetic energy barrier can be written by ($D_z < D_x < D_y$),

$$\varepsilon = \mathrm{E}/M_s^2 V = (D_x m_x^2 + D_y m_x^2 + D_z m_x^2)/2. \tag{3}$$

The energy barrier reduction due to read current disturbance is proportional to the normalized spin torque current amplitude I: $\delta\varepsilon \propto I$. Thus, according to Eqs. (1) and (2), pulse amplitude I contributes to switching probability P (or error rate) exponentially more significant than that of the pulse duration t. Therefore, it seems obvious to assume that controlling read pulse width is not effective in reducing read error rate as compared to controlling pulse amplitude. Note here we consider a square-wave pulse excitation with constant pulse amplitude I and pulse duration t. For general time dependent excitation $I(t)$, the energy barrier is time dependent and master equation is solved for switching probability with a time dependent transition rate.

However, it has been show that above theory only holds for relatively long pulse duration.[9–12] "Scale dilemma" results if we insist to use above formula to short current pulse duration ($\sim$GHz).[10,12] The reason is that detailed magnetization dynamics must to be included to properly describe magnetization nonvolatility as excitation frequency approaches magnetization dynamics time scale. Approach based upon transition rate with a time dependent energy barrier (formulas (1) and (2)) neglects fast magnetization dynamic and is not sufficient to describe magnetization switching probability for ultra-short pulse duration excitation.

Under the assumption that spin torque excitation magnitude is well below critical switching value and based upon stochastic Landau-Lifshiltz-Gilbert equation (LLG) with spin torque term, the switching barrier reduction due to spin torque current excitation can be derived as[11]

$$\delta\varepsilon = \min_{t_c} \int_{-\infty}^{\infty} \chi(t) I(t - t_c) dt, \tag{4}$$

where $I(t)$ is the normalized spin polarized current magnitude and $\chi(t)$ is the magnetization logarithmic susceptibility (LS).

The magnetization logarithmic susceptibility is defined as the ratio of reversal barrier reduction to external spin torque current excitation magnitude. "t_c" in Eq. (4) is the "best" time for the magnetization reversal to happen. Periodic external forcing lifts the time degeneracy of escape path. It synchronizes optimal escape trajectories, one per period, to minimize the activation energy of escape. Magnetization logarithmic susceptibility $\chi(t)$ can be obtained from optimal reversal path $z_0(t)$, which is the minimization of action functional of Landau-Lifshiltz-Gilbert equation with spin torque term.[11,12]

Although the word "switching barrier reduction" is used in describing logarithmic susceptibility concept, the "barrier reduction" obtained through logarithmic susceptibility considers detailed magnetization dynamics. The LS switching barrier is not a static or time dependent energy barrier based upon magnetization energy surface analysis. In magnetization LS approach, through considering detailed magnetization dynamics, the dynamics time scale at high frequency (~GHz) is retained for long time thermal magnetization reversal process. Thus, long time thermal magnetization reversal dependence upon excitation frequency (up to GHz) is properly characterized.

In order to illustrate pulse duration effect on long time thermal magnetization reversal, we consider a thin film element with cylindrical symmetry $(D_y = D_x)$.[11] This corresponds to perpendicular MTJ stack. In this case, analytical formula can be obtained for logarithmic magnetization susceptibility

$$\chi(\mathrm{t}) = [D_x - D_z]\alpha\cos\{\tan^{-1}[e^{\alpha(D_x-D_z)t}]\} \times \{1 - \cos\{\tan^{-1}[e^{\alpha(D_x-D_z)t}]\}^2\}, \tag{5}$$

where α is the damping parameter and time is normalized by gyromagnetic ratio multiplying saturation magnetization. For a square–wave read pulse with constant amplitude I_0 and pulse duration t_d, the reversal barrier reduction due to polarized spin current excitation (from Eqs. (4) and (5)) is

$$\delta\varepsilon = -\min_{t_c} \; I_0\int_{t_c}^{t_c+t_d} dt[D_x - D_z]\alpha\cos\{\tan^{-1}[e^{\alpha(D_x-D_z)t}]\} \times \{1 - \cos\{\tan^{-1}[e^{\alpha(D_x-D_z)t}]\}^2\}. \tag{6}$$

For infinite long pulse duration $t_d \to \infty$, Eq. (6) can be integrated out explicitly as

$$\delta\varepsilon = -I_0\int_{-\infty}^{\infty} dt[D_x - D_z]\alpha\cos\{\tan^{-1}[e^{\alpha(D_x-D_z)t}]\} \times \{1 - \cos\{\tan^{-1}[e^{\alpha(D_x-D_z)t}]\}^2\} = -I_0. \tag{7}$$

This gives the well-known reversal barrier formula for read disturbance with long time read pulse: $\frac{(D_x-D_z)M_s^2V}{2k_BT}(1-2\frac{I_0}{I_c})$. The corresponding switching probability formula is

$$P = 1 - \exp\left(-t_d f_0 e^{\frac{(D_x-D_z)M_s^2V}{2k_BT}\left(1-2\frac{I_0}{I_c}\right)}\right). \tag{8}$$

For a pulse with finite duration t_d, reversal barrier Eq. (6) can be written as $\frac{(D_x-D_z)M_s^2V}{2k_BT}\left[1-2r(t_d)\frac{I_0}{I_c}\right]$, where $r(t_d)$ is the switching barrier reduction factor due to finite pulse width

$$r(t_d) = -\min_{tc} \int_{t_c}^{t_c+t_d} dt|D_x - D_z|\alpha\cos\{\tan^{-1}[e^{\alpha(D_x-D_z)t}]\} \times \{1 - \cos\{\tan^{-1}[e^{\alpha(D_x-D_z)t}]\}^2\}. \tag{9}$$

Switching probability Eq. (8) then needs to be generalized to

$$P = 1 - \exp\left(-t_d f_0 e^{\frac{(D_x-D_z)M_s^2V}{2k_BT}\left(1-r(t_d)2\frac{I_0}{I_c}\right)}\right). \tag{10}$$

Figure 1 shows the switching barrier reduction factor as a function of pulse duration calculated from Eq. (9). The magnetic element has $M_s = 1400\ emu/cc$, $D_z - D_x = 0.48$, and a thermal stability factor $(D_z - D_x)M_s^2V/k_BT$ of 40. Damping parameter and the attempt frequency is assumed to be 0.02 and 10 GHz. The vertical axis is normalized to the switching barrier reduction at long pulse width limit. With constant pulse amplitude, it can be seen from the figure that switching barrier reduction factor strongly depends upon pulse duration as pulse width reaches 10 ns and below.

The result shows here has great implication on predicting read disturb probability behaviour. In conventional approach, the energy barrier would not dependent on the pulse duration; therefore, the pulsing duration only contributes to the switching probability by determining the time length for thermal agitated magnetization reversal, which is a second order parameter compared to pulse amplitude as can been seen in Eq. (10). However, with the consideration of the dynamic behaviour at short time scale, the reversal barrier shows a strong nonlinear dependence on pulse duration t_d, which makes it an even more dominant factor in determining disturbing probability as compared to pulse amplitude.

To experimentally demonstrate the dependence of read error rates on read pulse duration, the read disturb rate has been measured on a MTJ cell with different pulse width ranging from 2 ns to 50 ns. Figure 2 shows the main results of this article. Figure 2(a) shows experimental results on the voltage dependence of pulse durations for three different error rate levels as indicated on the graph. Figure 2(b) replots the result in the format of inverse pulse duration as a

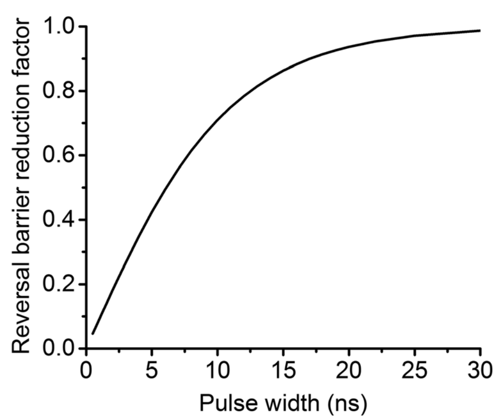

FIG. 1. Reversal Barrier reduction factor as a function of current pulse duration.

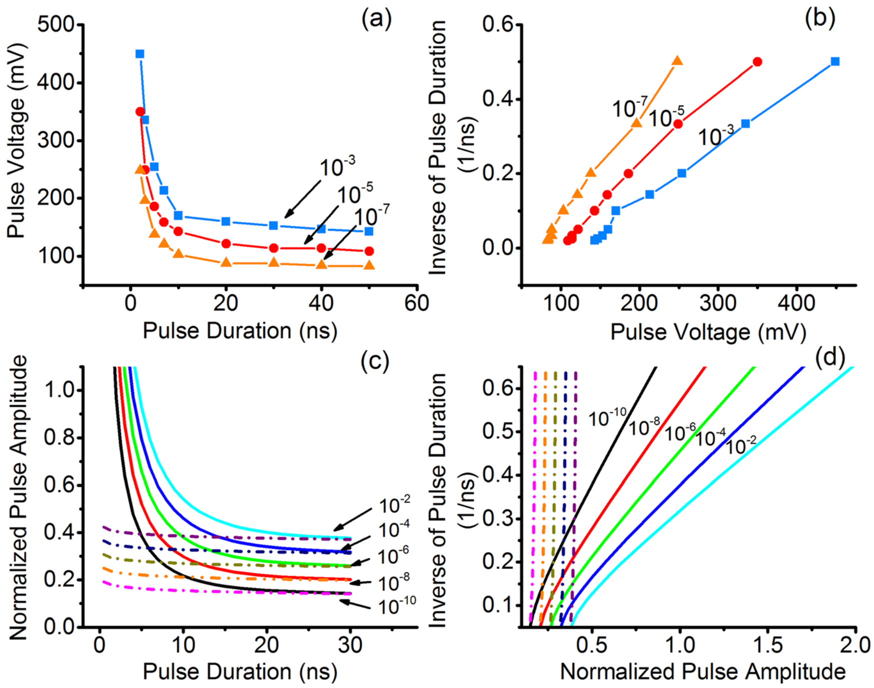

FIG. 2. Pulse voltage versus pulse duration for a certain read error rate. Graphs (a) and (b) show the experimental results. Graphs (c) and (d) show the theoretical calculation of pulse amplitude versus pulse duration at different read bit error rate. The solid line shows the calculation using dynamic logarithmic susceptibility approach and the dashed line shows the calculation with time varying energy barrier approach.

function of pulse voltage level. Figure 2(c) shows the theoretical calculation of pulse amplitude dependence on pulse duration for five different read error levels as indicated on the graph. Here, the solid line shows the calculation using dynamic logarithmic susceptibility approach and dashed line shows the calculation with time varying energy barrier approach. Figure 2(d) re-plots the theoretical results in the format of inverse pulse durations as a function of pulse amplitude.

First of all, it needs to be emphasized here that in conventional time dependent energy barrier approach as shown in Eq. (8), read disturb rate has a very weak dependence upon pulse duration, as shown by dashed curves in Figures 2(c) and 2(d). This is because current amplitude directly affects energy barrier while pulse duration only affects pre-factor of exponential of energy barrier. However, in reality, the experimental results in Figure 2(a) show a rather dramatic reduction of read error at small pulse width (<10 ns). Figure 2(b) further shows for a constant error rate, pulse amplitude is linearly proportional to the inverse of pulse duration.

While such result cannot be explained by a conventional time-dependent energy barrier theory, the dynamic approach as shown in Eq. (10) reproduced the experimental data very well. The solid curve in Figure 2(c) obtained from Eq. (9) shows a very strong dependence of error rate upon pulse duration when pulse duration reaches magnetization dynamics time scale. Also, Figure 2(d) shows at nanosecond time scale, for a constant error rate, current amplitude is linearly proportional to current duration, which all agree very well with the experimental data. Note here that although experimental measurement and theoretical prediction of Eq. (9) agrees very well in trend, we do not want to fit theoretical calculation of Eq. (9) exactly to measurement because the experiment is performed on a MTJ thin film structure without cylindrical symmetry.

The difference between Eqs. (7) and (9) is fundamentally rooted in the frequency dependence of logarithmic susceptibility.[12] Formula (7) holds true only for relatively long pulse where only DC components of logarithmic susceptibility contributes to switching barrier reduction. As pulse duration decreases, the high frequency component of the pulse becomes dominant. Therefore, high frequency component of the magnetization logarithmic susceptibility, where the magnetization dynamic becomes important, needs to be taken into account, which significantly changes reversal barrier reduction behaviour.

In order to demonstrate this concept, the frequency dependent reduction of switching voltage is measured on the same MTJ cell. Here, the switching voltage of the MTJ is measured in the presence of a constant amplitude modulation microwave, where the modulation amplitude of the microwave is kept constant at 50 mV and the frequency is swept from 20 to 400 MHz. The energy barrier reduction due to the presence of microwave is then estimated from the switching voltage. The result is shown in Figure 3. Fig. 3(a) shows the switching voltage as a function of modulation frequency and Fig. 3(b) shows the normalized energy barrier reduction as a function of frequency. Here, the energy barrier reduction value is normalized to the 20 MHz data point, which is the lowest frequency available.

The data in Figure 3 shows a fast roll of energy barrier reduction as a function of modulation frequency and quickly approach zero for frequency above 100 MHz. Notice here that the frequency scale for saturation (100 MHz) matches the read disturb results very well where a dramatic reduction of read disturb rate is observed for pulse width less than 10 ns. This result shows directly that high frequency modulation has a minimum impact on the reduction of energy barrier. Theoretical calculation of logarithmic susceptibility also shows the same trend.[12]

In summary, in this article we showed the magnetic dynamic effect played an important role in read disturb behaviour especially for read pulses with short duration. As a result, the read disturb rate reduced dramatically at short

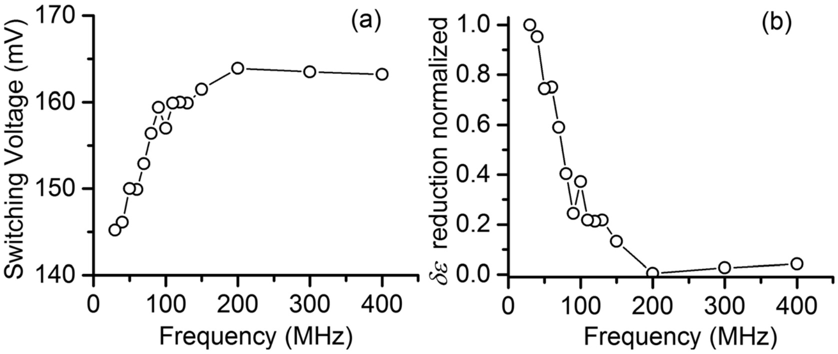

FIG. 3. Switching voltage and reversal barrier reduction dependence on modulation microwave frequency. Graph (a) shows the switching voltage as a function of modulation frequency. Graph (b) shows the normalized reduction of reversal energy barrier as a function of modulation microwave frequency.

pulse widths. Such effects shed light on ultra-fast, low current STT-RAM design. Due to the significant reduction of programming current for STT-MRAM with improvement of MTJ material and structure,[13–15] the sense current margin for STT-MRAM design has been greatly tightened. Controlling read pulse duration opens a path to design STT-RAM read/write besides controlling read/write current amplitude ratio. Detailed STT-RAM design based upon our dynamic approach is beyond the scope of this letter and will be pursued in future publications.

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