Methods for reducing write error rate in voltage-induced switching having prolonged tolerance of voltage-pulse duration

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ABSTRACT
Simulating the magnetization dynamics in a perpendicularly-magnetized free layer with Langevin equation, we investigated methods for reducing write error rate (WER) in voltage-induced switching with long tolerance of voltage-pulse duration ($t_p$). The simulation results show that WER can be reduced by increasing the perpendicular anisotropy ($K_u$) before and after the application of voltage or by increasing both $K_u$ and the in-plane external magnetic field.

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I. INTRODUCTION

Voltage-induced magnetization switching$^{1-14}$ has been attracting a great deal of attention because it enables low-power-consumption writing in magnetoresistive random access memory (MRAM). In voltage-induced magnetization switching, anisotropy field is reduced through voltage control of magnetic anisotropy (VCMA) effect,$^{1-5}$ which induces magnetization precession around external magnetic field.$^{15}$ The switching can be completed by turning off the voltage after a half period of precession.$^6$-$^{12}$

However, this dynamic switching requires the adjustment of the voltage-pulse duration ($t_p$) to stop the precessional motion of the magnetization and to obtain low write error rate (WER). The range of $t_p$ where WER is below $1 \times 10^{-3}$ is as narrow as several hundred picoseconds.$^{10,11}$ We call this range of $t_p$ as the tolerance of $t_p$ just for convenience. Broadening the tolerance of $t_p$ is desirable because of the distribution of $t_p$ from pulsed power supply in MRAMs and the distribution of precession periods among the MRAM cells. In the dynamic switching, the tolerance of $t_p$ has been prolonged by decreasing minimum WER of perpendicular MRAMs. The WER has been improved by increasing external in-plane magnetic field ($H_{ext}$),$^7$ or by increasing the perpendicular anisotropy constant ($K_u$) before and after the application of writing voltage pulse,$^{12,16,17}$ or by increasing both $K_u$ and $H_{ext}$.$^{10,14}$

In our previous study,$^{18}$ we proposed the voltage-induced magnetization switching having prolonged tolerance of $t_p$ in perpendicularly magnetized free layer at room temperature. In this switching, the switched state is kept even under the persistent application of the voltage, and so the precise adjustment of $t_p$ is not required. This prolonged tolerance of $t_p$ can be realized by the energy dissipation through damping torque during the precessional motion of magnetization.$^2$ However, the WER around $10^{-4}$ in the large free-layer volume ($V_F$) of $140^2 \pi \times 2 \text{ nm}^3$ needs further improvement.$^2$

In this letter, we simulated the magnetization dynamics in the free layer with smaller $V_F$ using Langevin equation and found that the WER in the switching with prolonged tolerance of $t_p$ can be reduced by increasing $K_u$ before and after the application of writing voltage pulse and by increasing both $K_u$ and $H_{ext}$. 

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II. MODEL

The system we consider is schematically shown in Fig. 1(a). The lateral size of the nano-pillar is assumed to be so small that the magnetization dynamics can be described by the macrospin model. The direction of the magnetization in the free layer is represented by the unit vector \( \mathbf{m} = (m_x, m_y, m_z) = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta) \), where \( \theta \) and \( \phi \) are the polar and azimuthal angles of \( \mathbf{m} \). The \( x \)-axis is parallel to the direction of external in-plane magnetic field \( \mathbf{H}_{\text{ext}} \), hence the equilibrium azimuthal angle at 0 K \( (\phi^{(0)}) \) is \( \phi^{(0)} = 0^\circ \). Here and hereafter \( (\theta^{(0)}, \phi^{(0)}) \) are equilibrium angles at zero-bias voltage and 0 K. The magnetization in the reference layer is fixed to align in the positive \( z \)-direction.

The energy density of the free layer is given by\(^{19} \)

\[
\mathcal{U}(m_x, m_y, m_z) = \frac{1}{2}\mu_0 M_s^2 (N_x m_x^2 + N_y m_y^2 + N_z m_z^2) + K_u (1 - m_z^2) + \mu_0 M_s H_{\text{ext}} m_z.
\]  

(1)

Here, the demagnetization coefficients, \( N_x, N_y \) and \( N_z \) are assumed to satisfy \( N_z \gg N_x = N_y \). \( \mu_0 \) is the vacuum permeability, and \( M_s \) is the saturation magnetization of the free layer. \( K_u \) and \( K_{\text{eff}} \) are the perpendicular anisotropy constant and its effective perpendicular anisotropy constant. \( K_{\text{eff}} \) is defined as \( K_{\text{eff}} = K_u - 1/2\mu_0 M_s^2 (N_x - N_z) \) where the demagnetization energy is subtracted from \( K_u \). The value of \( K_u \) can be varied by applying bias voltage, \( V \), through the voltage-control of magnetic anisotropy (VCMA) effect. In this letter, \( K_{\text{eff}} \) indicates \( K_{\text{eff}} \) at zero-bias voltage, and \( K^{(\text{ext})}_{\text{eff}} \) indicates \( K_{\text{eff}} \) during \( t_p \) as illustrated in Figs. 1(b) and (c). Throughout this letter, we assume the perpendicularly magnetized free layer with the saturation magnetization of \( M_s = 1400 \text{ kA/m} \), \( V_F = \pi r^2 t_F = 7854 \text{ nm}^2 \), \( N_x = N_y = 0.0175 \), and \( N_z = 0.9650.\)\(^{20} \) Here \( r = 50 \text{ nm} \) is the radius of a junction area, and \( t_F = 1 \text{ nm} \) is the thickness of the free layer.

The thermally-agitated magnetization dynamics was simulated with the following Langevinequation,\(^{11} \)

\[
(1 + \alpha^2) \frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m} \times (\mathbf{H}_{\text{eff}} + \mathbf{h}) + a\{\mathbf{m} \times (\mathbf{H}_{\text{eff}} + \mathbf{h})\} + \delta(\mathbf{m}(t) - \mathbf{m}(t-\Delta t)).
\]

(2)

\( \mathbf{h} \) represents the thermal agitation field satisfying the following relations: \( \langle h_x(t) \rangle = 0 \) and \( \langle h_y(t) h_y(t') \rangle = [2k_B T/(\gamma_0 \mu_0 M_s V_F)] \delta(t - t') \), where \( T \) is the temperature assumed as \( T = 300 \text{ K} \), \( \alpha = x = y, z \), \( t \) is time, and \( (X) \) denotes the statistical average of \( X \). Unless noted otherwise, we assumed the time evolution of voltage and \( K_{\text{eff}} \) shown in Figs. 1(b) and (c). Here, \( t_p \) and the relaxation time \( (t_{\text{relax}}) \) before and after \( t_p \) are \( t_p = t_{\text{relax}} = 10 \text{ ns} \).

III. RESULTS

Fig. 1(d) shows an example of \( m_z(t) \) obtained in the simulations where \( H_{\text{ext}}(= 3 \text{ kOe}) = 239 \text{ kA/m} \), \( K^{(0)}_{\text{eff}} = 1200 \text{ kJ/m}^3 \), \( K^{(\text{ext})}_{\text{eff}} = 275 \text{ kJ/m}^3 \), and \( \alpha = 0.17 \) are assumed. The magnetization \( \mathbf{m} \) completes the switching without going back to \( m_z > 0 \) even for \( t_p = 10 \text{ ns} \). \( K^{(\text{ext})}_{\text{eff}} \) vs. \( \alpha \) dependence of WER is shown in Fig. 2(a). Low-WER region in \( K^{(\text{ext})}_{\text{eff}} < K^{(\text{ext})}_{\text{eff}} < K^{(\text{ext})}_{\text{eff}} \) appears as a result of the switching with the prolonged tolerance of \( t_p \).\(^{18} \) \( K^{(\text{ext})}_{\text{eff},1} \) and \( K^{(\text{ext})}_{\text{eff},2} \) are the lower and upper boundaries of \( K^{(\text{ext})}_{\text{eff}} \) where the voltage-induced switching with the prolonged tolerance of \( t_p \) can be induced at appropriate \( \alpha \), and analytical expressions of \( K^{(\text{ext})}_{\text{eff},1} \) and \( K^{(\text{ext})}_{\text{eff},2} \) were given in Ref. 18. In the low-WER region, the WER is minimized down to \( 1.5 \times 10^{-4} \) at the conditions of Fig. 1(d). Hereafter the minimized WER in the \( K^{(\text{ext})}_{\text{eff}} \) vs. \( \alpha \) dependence is indicated as WER_{min}.

Assuming constant \( K^{(0)}_{\text{eff}} = 600 \text{ kJ/m}^3 \), we calculated the \( H_{\text{ext}} \) dependence of WER_{min}, and show the results as blue solid circles on a blue curve in Fig. 2(b). WER_{min} was reduced up to \( H_{\text{ext}}(= 2.5 \text{ kOe}) = 199 \text{ kA/m} \) is because the magnitudes of the field torque and damping torque increase with \( H_{\text{ext}} \) overwhelming the magnitude of the field torque by \( h \). The other reason is shorter switching time at high \( H_{\text{ext}} \). On the other hand, the further increase of \( H_{\text{ext}} \) deteriorated WER_{min}.

Please note that, in the case of the switching of a micron-size magnet which holds the spatial distribution of \( \Delta K_{\text{eff}} = K^{(0)}_{\text{eff}} - K^{(\text{ext})}_{\text{eff}} \), the increase of \( H_{\text{ext}} \) excites spatially-inhomogeneous magnetization oscillations.\(^{15} \) The inhomogeneous oscillations tends to disturb the switching with prolonged tolerance of \( t_p \).\(^{13} \) In the case of an iron garnet,\(^{15} \) however, the inhomogeneous oscillations increased effective \( \alpha \) during \( t_p \), and the increased \( \alpha \) facilitated the switching with prolonged tolerance of \( t_p \). The combination of low \( \alpha \) during \( t_{\text{relax}} \) and high \( \alpha \) during \( t_p \) might be advantageous for the reduction of WER.
in the switching with prolonged tolerance of \( t_p \), but the detailed analysis on micron-size magnet is beyond the scope of this letter.

Please also note that the thermal agitation of \( m \) during \( t_{\text{relax}} \) hardly deteriorated WER_{min} even though the thermal stability was reduced at the high \( H_{\text{ext}} \). In order to eliminate the thermal agitation during \( t_{\text{relax}} \), we conducted the simulations where \( t_{\text{relax}} = 0 \) ns and \( m \) starts the motion from \((\theta, \phi) = (\theta^{(0)}, 0^\circ)\). \( \theta^{(0)} \) is given by \( \theta^{(0)} = \sin^{-1}\left(\frac{\mu_0 M_{\text{eff}}}{2 K_{\text{eff}}^{(0)}}\right) \) and \( \theta^{(0)} \) was varied from \( 3^\circ \) (for \( H_{\text{ext}} = 0.5 \) kOe) to \( 36^\circ \) (for \( H_{\text{ext}} = 5 \) kOe) in Fig. 2(b). Those results are indicated as green open squares on a green curve in Fig. 2(b). The green curve and the blue curve show similar results. This result indicates that the dominant cause of write errors for the blue curve is the thermal agitation during \( t_p = 10 \) ns rather than that during \( t_{\text{relax}} \). The angles \((\theta^{(0)}, 0^\circ)\) from which \( m \) starts the motion at the beginning of \( t_p \) seems to take a crucial role for the dynamics of \( m \) during \( t_p = 10 \) ns and WER_{min}.

In order to investigate the effect of \( \theta^{(0)} \) on WER_{min}, we calculated \( K_{\text{eff}}^{(0)} \) dependence of WER_{min} at constant \( H_{\text{ext}} \) as shown in Fig. 3(a). Here, in order to decrease \( \theta^{(0)} \) from \( 30^\circ \) to \( 2^\circ \), \( K_{\text{eff}}^{(0)} \) was increased from \( 140 \) to \( 2000 \) kJ/m\(^3\) at constant \( H_{\text{ext}} = 1 \) kOe. In Fig. 3(a), the calculated \( K_{\text{eff}}^{(0)} \) dependence of WER_{min} is indicated as blue solid circles on a blue curve and the simulation results calculated at \( t_{\text{relax}} = 0 \) ns is indicated as green open circles on a green curve. The results show that the WER_{min} decreases with the increase of \( K_{\text{eff}}^{(0)} \) (Fig. 3(a)) and the decrease of \( \theta^{(0)} \) (the inset in Fig. 3(a)). This is because, at high \( K_{\text{eff}}^{(0)} \) and subsequently small \( \theta^{(0)} \), \( m \) can avoid the switching trajectories where \( m \) is sensitive to \( h \). Especially around \((\theta, \phi) = (90^\circ, 0^\circ)\), the anisotropy field by \( K_{\text{eff}}^{(0)} \) is small. Around this point, \( m \) is fluctuated by \( h \) rather than being driven by the fields from \( K_{\text{eff}}^{(0)} \) and \( H_{\text{ext}} \).

Varying \( H_{\text{ext}} \) and \( K_{\text{eff}}^{(0)} \) and subsequently maintain \( \theta^{(0)} = 10^\circ \), we calculated \( H_{\text{ext}} \) dependence of WER_{min}, as shown in Fig. 3(b). Here, for example, \( K_{\text{eff}}^{(0)} = 200 \) kJ/m\(^3\) was assumed for \( H_{\text{ext}} = 500 \) Oe, and \( K_{\text{eff}}^{(0)} = 2000 \) kJ/m\(^3\) was assumed for \( H_{\text{ext}} = 5 \) kOe. The WER_{min} monotonically decreases with increase of \( H_{\text{ext}} \). This is because, even at high \( H_{\text{ext}} \), \( m \) can avoid the switching trajectories where \( m \) is sensitive to \( h \).

IV. CONCLUSION

We theoretically investigated methods for reducing WER in voltage-induced switching with prolonged tolerance of \( t_p \). The simulations using Langevin equation show that WER can be reduced by increasing \( K_{\text{eff}}^{(0)} \) or by increasing both \( K_{\text{eff}}^{(0)} \) and \( H_{\text{ext}} \).

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