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Y. C. Wu , W. Kim, S. Couet, K. Garello , S. Rao, S. Van Beek, S. Kundu, S. Houshmand Sharifi , D. Crotti, J. Van Houdt, G. Groeseneken, and G. S. Kar
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AFFILIATIONS
1IMEC, Kapeldreef 75, 3001 Heverlee, Belgium
2Department of Electrical Engineering, KULeuven, Kasteelpark Arenberg 10, 3001 Heverlee, Belgium

ABSTRACT
We study the characteristics of the precessional switching induced by voltage control of magnetic anisotropy (VCMA) in back-end-of-line (BEOL)-compatible perpendicular magnetic tunnel junction devices. Using micromagnetic simulation, we find three operation regimes differentiated by zero excess energy, lower boundary, zero energy barrier, and upper boundary. Experimentally, the switching speed ($f_s$) is characterized by two phases: non-precession and acceleration. Non-precession is a thermal mediated phase, where $f_s$ cannot be deduced, while in acceleration, both the higher electric field ($E_F$) and in-plane field ($B_x$) increase $f_s$ progressively. We find that the intrinsic thresholds can be retrieved by linear extrapolation of $f_s$ as a function of $E_F$. Those thresholds and experimental results are in good agreement with the simulation. In addition, we numerically calculate the characteristic switching speed of $2\gamma^* m_z^* B_x$ and verify it experimentally. This work provides insights into the VCMA-induced precessional switching, including detailed understandings of the switching mechanism and modeling of switching speed for reliable write duration control for practical applications.

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Among the emerging memories, magnetic random access memory (MRAM) has great potential to be introduced as cache memories in the advanced technology nodes due to its complementary metal-oxide-semiconductor (CMOS) process compatibility and scalability. Its non-volatile feature enables a reduction in the static power in comparison with dynamic RAMs. In the past decades, the spin-transfer-torque (STT) effect, as the write mechanism, has been extensively studied, and STT-based magnetic tunnel junction (MTJ) devices have achieved a reliable writing time down to few nanoseconds. However, the required switching current is dramatically increased for gigahertz operation, causing degradation and reliability issues in the MgO tunnel barrier. Magnetization switching utilizing the voltage control of magnetic anisotropy (VCMA) effect is an alternative mechanism that allows drastic reduction in energy consumption and sub-nanosecond writing of the MRAM. While various origins are studied, the electronic-based VCMA effect is commonly explained by applying an electric field ($E_F$) that charges the oxide/ferromagnet interface and redistributes the electrons between the 3d orbitals, resulting in enhancement or weakening of the interfacial perpendicular magnetic anisotropy (iPMA). By such a principle, in perpendicular MTJ (p-MTJ) devices, magnetization switching is executed by applying an $E_F$ that removes the energy barrier ($E_b$) between the anti-parallel (AP) and the parallel (P) states; simultaneously, an external in-plane magnetic field ($B_z$) induces an oscillation of the free-layer ($F_L$) about this field direction, allowing for precessional switching control. A successful switching relies on an accurate control of pulse duration ($t_P$), which should match with half of the precession period. This type of $E_F$-driven device has merits as follows: (1) the time scale of the half period usually falls in the range of sub-nanoseconds, in correspondence to
gigahertz writing, and (2) the thickness of the MgO barrier is intentionally made thicker than that of the STT-driven devices; hence, the current flowing through the device is suppressed, and the switching energy can reach the scales of femto-joules.

In such a writing scheme, the switching speed ($f_s$) varies with both $EF$ and $B_k$. These three mutual-related parameters ($EF$, $B_k$, and $f_s$) are the key parameters to achieve a successful writing process as they control the optimum switching time window with a maximized switching probability ($P_{sw}$). Therefore, fundamental understanding of the switching threshold and the parameters to control $f_s$ is crucial to enable reliable modeling for applications. In this work, we first discuss the estimation of the VCMA properties. Based on the first discussion, in the second section, we simulate and analyze the operation regimes with energy consideration and correlate them to our experimental results. Finally, we discuss the parameters that allow the numerical calculation of the switching speed for applications.

We study bottom-pinned p-MTJ stacks of [Co/Pt]-multilayer-based hard-layer/spacer/reference-layer/MgO(1)/CoFeB(1.7)/Ta(20)/Ru(50) sputter deposited on 300 nm thermally oxidized Si(100) wafers using a Canon-ANELVA EC7800 cluster tool. Numbers in parentheses are the nominal thicknesses in nanometers. The reference-layer (RL) is a CoFeB-based multilayer. Two MgO thicknesses, $t = 1.4$ nm and 1.1 nm, are prepared to target the resistance-area (RA) products at 1000 $\Omega\mu m^2$ and 100 $\Omega\mu m^2$, respectively. Devices with high RA products are used to estimate the VCMA coefficient under direct current (DC) conditions without the disturbance of the STT effect, while a device with a lower RA product aims at fast assessment of the electrical switching properties. After deposition, the films are annealed at 400°C for 30 min in vacuum under 2T out-of-plane magnetic field. Stacks are then patterned into 100 nm circular pillars using 193 nm immersion lithography and ion beam etch (IBE). Saturation magnetization of the different layers in the stack is characterized using a MicroSense vibrating sample magnetometer (VSM) on blanket 8 $\times$ 8 mm$^2$ samples. Electrical pulse switching experiments are carried out in a constantly applied external magnetic field (see the supplementary material for the configuration of the electrical switching setup).

To study and model the VCMA switching characteristics, fundamental parameters such as the saturation magnetization of the FL ($M_{s,FL}$), the effective perpendicular magnetic anisotropy field ($B_{k,eff}$), and the $EF$-dependence of the perpendicular anisotropy field ($dB_{k,eff}/dEF$) must be quantified. We measure the $M_{s,FL}$ on 8 $\times$ 8 mm$^2$ blanket samples, and it is $1.45 \times 10^6$ A/m considering the presence of a 0.7 nm magnetic dead layer (see the supplementary material for the VSM measurements). Such a dead layer thickness is comparable to the value obtained from the similar stack. Next, to evaluate $B_{k,eff}$ and $dB_{k,eff}/dEF$, we measure devices with high RA products using an out-of-plane magnetic field sweep method to obtain the switching probability distributions. Figure 1(a) shows the AP-to-P switching field distributions of 500 switching events. Due to the VCMA effect, the FL is switched at weaker (stronger) fields. There is also a Rashba field that can lead to a change in PMA. Therefore, for the current perpendicular to the plane measurements, the Rashba field is not generated because the cross product of the wave vector and the electric field is zero. In addition, we observe a linear VCMA response indicating that such an effect is attributed to the depletion/accumulation effect, in contrast to the Rashba splitting which has a quadratic reaction. Since we obtain a linear dependence, $B_{k,eff}$ at zero bias and $dB_{k,eff}/dEF$ are estimated to be 80 mT and 60 mT/V/nm, respectively. The VCMA coefficient ($\xi$) is then evaluated as $\xi = \frac{M_{s,FL} dB_{k,eff}}{2 dB_{k,eff}/dEF} \equiv 43.5 fJ/Vm$. By linear extrapolation, $B_{k,eff}$ is expected to be removed at $-1.3$ V/nm approximately, which we define it as the characteristic electric field ($EF_{C,0}$). These parameters obtained from the experiments will be applied to the micromagnetic simulation for in-depth analyses.

In the following, we study the characteristics of the VCMA switching from both simulation and experiment and afterward correlate the results to get insights into the switching properties. In the simulation, we focus on the analyses of energy diagrams under
different $E_F$ and $B_s$ conditions, and we summarize them into corresponding operation regimes. We perform the Object Oriented Micro-Magnetic Framework (OOMMF) project using the experimental parameters listed in Table I to calculate the total magnetic energy by aligning the FL magnetization to various angles. Here, two terms are considered: the excess energy ($E_{ex}$) and the energy barrier ($E_b$). The $E_{ex}$ is defined as the difference between the energy along $B_s$ under a given $E_F$ ($E_{0,EF}$) and the initial equilibrium energy without an $E_F$ ($E_0$), which describes the energy that allows us to drive the FL to precess across the horizontal plane. The $E_b$ is the difference between $E_{0,EF}$ and the equilibrium energy under the $E_F$ ($E_{0,EF}$), which is the barrier that prevents the FL from switching if the system is relaxed. Figures 2(a)–2(c) show the representative diagrams under different $E_F$ conditions at $B_s = 20$ mT as examples, which correspond to the three different operation regimes. In regime I, both $E_{ex}$ and $E_b$ are positive, and the FL cannot switch over the barrier. When increasing the $E_F$ up to regime II, $E_{ex}$ becomes negative, while $E_b$ remains positive. Since the $E_F$ pulse is considered as a square pulse with a negligible rise time, there is a minimum relaxation of the FL toward the equilibrium state. In the case of ideal systems, i.e., extremely low damping and without thermal disturbance, the FL has sufficient energy to switch even with a barrier present. This energy is consistent with $E_{ex}$; hence, $E_{ex} = 0$ defines the lower boundary of switching. If the $E_F$ is further increased up to regime III, $E_b$ is completely removed. In this regime, switching should be induced in any system, since there is no barrier to prevent switching. For instance, in the real systems, there is finite damping which causes energy dissipation. While it results in the relaxation of the FL toward the equilibrium states, the precessional switching characteristics can be properly observed. Accordingly, the upper boundary can be defined at $E_b = 0$. In addition, we observe a linear dependence of $E_{ex}$ on the $E_F$, as shown in Fig. 2(d), indicating that the switching characteristics of the FL will be varied linearly as well. This behavior will be confirmed in the observation of the following experiments.

Experimentally, we investigate the VCMA switching speeds using a device with a lower RA product for faster assessment of the FL states. At this designed RA product, the STT effect has a negligible impact on the spin dynamics in the precessional switching regime, and any switching behavior is solely induced by the VCMA effect. Furthermore, there is no noticeable difference in the fundamental properties such as coercive fields, thermal stability factors, and VCMA coefficients between the devices with lower and higher RA products. The experiments are carried out by measuring the switching probability ($P_{sw}$) as a function of pulse duration ($t_p$), with 1000 switching events per condition. We observe the oscillatory behavior in $P_{sw}$, as exemplified in Fig. 3(a). Theoretically, the spin dynamics is described by the Landau–Lifshitz–Gilbert (LLG) equation,

$$\frac{d\vec{M}}{dt} = -\gamma(\vec{M} \times \vec{B}_{eff}) + \alpha \left(\vec{M} \times \frac{d\vec{M}}{dt}\right),$$

where $\gamma$ is the gyromagnetic ratio (considering as 29.4 GHz/T m), $B_{eff}$ is the effective field, and $\alpha$ is the damping constant. The first term on the right-hand side of Eq. (1) describes the precessional motion of the magnetization about $B_{eff}$, from which the oscillating probability originates when switching is executed. In general, the precession frequency ($f_p$) corresponds to the Larmor frequency $\gamma B_{eff}$. To systematically assess $f_p$, we apply a periodic equation, e.g., a cosine function, to fit the first period of the probability curve. The maximum of the fitting equation is a floating value which can be greater than 100, implying that the normalized out-of-plane component of the FL does not necessarily be one to achieve 100% switching. The error is minor in the fitting, and it has a negligible impact on $f_p$. Figure 3(b) summarizes the switching speed $f_s$ ($= 2f_p$) as a function of $E_F$ under various $B_s$ conditions, where the factor of two indicates that a reliable switching occurs at the period of a half precession. $f_s$ is characterized into two phases. First, below the critical electric field ($E_{C0}$), corresponding to approximately $f_s < 0.5$ GHz, there is a non-precessional phase where no oscillation is observed in the switching probability curves; hence, $f_s$ cannot be deduced. This can

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**TABLE I. OOMMF simulation parameters.**

| Parameter                | Value          |
|--------------------------|----------------|
| Junction diameter        | 100 nm         |
| FL thickness             | 1 nm           |
| Mesh size                | $2 \times 2 \times 1$ nm$^3$ |
| Saturation magnetization | $1.45 \times 10^6$ A/m |
| Interfacial anisotropy   | $1310 \mu$m$^2$ |
| Exchange stiffness       | 25 fJ/m         |
| VCMA coefficient         | $45 fJ/Vt$      |

**FIG. 2.** (a)–(c) Representative energy diagrams at different $E_F$s under $B_s = 20$ mT, corresponding to the operation regimes I–III. Dotted curves indicate the energy profiles without the $E_F$, and solid curves are the energy profiles at −0.5 V/nm, −0.8 V/nm, and −1.3 V/nm, respectively. $E_i$ is the initial energy state, $E_{0,EF}$ is the energy along $B_s$ under the $E_F$, and $E_{0,EF}$ is the equilibrium energy under the $E_F$. (d) Dependence of $E_{ex}$($k_BT$) as a function of $E_F$, where $k_B$ is the Boltzmann constant and $T$ is the temperature in Kelvin.
be attributed to the thermal fluctuation effect dominating over the precessional switching characteristics. Specifically, for perpendicularly magnetized devices, $B_{\text{eff}}$ is expressed as Eq. (2) to account for the VCMA effect.

$$
\bar{B}_{\text{eff}} = \left[ B_{\text{eff}}(0) + \frac{dB_{\text{eff}}}{dE_{\text{F}}} \times E_{\text{F}} \right] \cdot m_z + B_x + B_{\text{thermal}},
$$

where $B_x$ is the applied in-plane magnetic field and $B_{\text{thermal}}$ is the ambient temperature-driven thermal fluctuation field (Joule heating effect is much less pronounced in VCMA devices due to the thick MgO). When the magnitude of $B_{\text{eff}}$ is small, the random thermal field dominates the spin dynamics such that the precession characteristics are concealed. Such $E_{\text{F}}$ can be reduced by increasing $B_x$ because it contributes in lowering the energy barrier along its direction. Subsequently, there is an acceleration phase above $E_{\text{F}}$, where the effective field is stable against the thermal fluctuation and the oscillatory features become clear. Here, we observe that the higher $E$ increases $f_s$ progressively. This is explained with Fig. 2(d) since $f_s$ is linearly increased with the $E$. By linear extrapolation of $f_s$ to zero, the intrinsic thresholds ($E_{\text{F}_{\text{th}}}$) without thermal agitation can be retrieved.

Regarding the discussions above, we correlate the results from both simulation and experiments. The landscape of $E_{\text{in}}$ is plotted as functions of $EF$ and $B_x$, and the operation regimes are distinguished by the two boundaries, as shown in Fig. 3(c). The experimental data and the extrapolated $E_{\text{F}_{\text{th}}}$ are attached in the same plot for comparison. We observe that $E_{\text{F}_{\text{th}}}$ are in regime II. The deviation of $E_{\text{F}_{\text{th}}}$ from $E_{\text{F}_{\text{ex}}}$ = 0 can be attributed to the finite damping in the real systems. Additionally, it can be attributed to the non-square pulse shape in the switching experiments which can induce relaxation during the pulse rising edge and falling edge (see the supplementary material for the pulse shape). Those measured datapoints situate in regime III, indicating that a certain amount of overdrive is required to overcome the thermal fluctuation. These experimental results show good agreement with the analyses of the fundamental switching mechanism.

Finally, we remark the characteristic speed which can be computed numerically. From the estimation of $B_{\text{eff}}$ and $dB_{\text{eff}}/dE_{\text{F}}$, it is foreseen that the PMA can be completely removed without the assistance of $B_x$ at $E_{\text{F}_{\text{CO}}}$. At such a condition, $B_{\text{eff}}(E_{\text{F}_{\text{CO}}})$ is approximately $B_x$ according to Eq. (2), for $B_x \gg B_{\text{thermal}}$. Accordingly, the corresponding characteristic frequency is $\gamma M \times B_x$. Considering
that the FL can be tilted by $B_x$, the effective torque applied on the FL is then scaled to $m_z^* B_x$, with $m_z = \sqrt{1 - \left| B_x / B_{\text{eff}}(0) \right|^2}$ using the macro-spin approximation. Hence, the characteristic $f_i$ is predicted as $2y^* m_z^* B_x$. In Fig. 4, $f_i$ measured at $E_{\text{FD}}$ are in good agreement with this hypothesis. Speeds at other EFs are also demonstrated. However, since $B_{\text{eff}}$ is non-zero in those cases, $B_{\text{eff}}$ and $f_i$ can only be solved analytically. Nevertheless, these results demonstrate that characteristic speeds can be modeled numerically, which enables reliable prediction of the write duration for practical applications.

In summary, we investigate the VCMA properties with both simulation and experiments. From the simulation, three operation regimes are distinguished by the two boundaries: $E_{\text{ex}} = 0$ and $E_B = 0$. Experimentally, the variation of $f_i$ is studied under various EF and $B_y$ conditions. The measured and extrapolated datapoints correspond to the second and third operation regimes, respectively, which are consistent with the fundamental switching mechanism. For the prediction of speeds, we demonstrate that the characteristic $f_i$ at $E_{\text{FD}}$ can be numerically estimated, enabling reliable control of the write duration to maximize the switching probability for practical applications.

See the supplementary material for the electrical setup for the pulse voltage controlled magnetization switching, magnetic properties of the CoFeB free-layer, and effective perpendicular magnetic anisotropy extraction.

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