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Low current writing perpendicular magnetic random access memory with high thermal stability

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ABSTRACT

Spin reorientation temperature (T_{SR}) is investigated in both layers, including Co/Ni multilayer and composite layer consisting of Co/Pt multilayer with CoFeB layer. The T_{SR} of both layers can be adjusted in a wide range, and the low T_{SR} is obtained in both layers. It is also suggested a writing method based on spin transfer torque (STT) with spin reorientation, for low current writing perpendicular magnetic random memory with high thermal stability. This method is to reorient the magnetization from a perpendicular to an in-plane state, which can be caused by Joule heating the MTJ with thermal barriers above T_{SR} by the injected current pulse. This polarized current can also produce the STT to push the magnetization toward a deterministic perpendicular direction from an in-plane state, when decreasing the magnitude of current pulse. Since the perpendicular anisotropy dominates magnetization switching during cooling, the critical current density is determined by the Joule heating for realization of spin reorientation in this writing method. Macrospin modeling shows the critical current density is 2×10^6 A/cm^2, which is two orders magnitude lower than that of conventional STT switching. This writing method can be applied to the perpendicular magnetic tunnel junction comprised of Co/Ni multilayer or composite layer.

1. Introduction

A low switching current density and a high thermal stability of the memory cells are the keys for realizing high density developing gigabit magnetic random access memory (MRAM). To realize the MRAM device with bit densities of Gbit/cm^2 order, the size of the magnetic cell and the separation between adjacent cells must be below a few tens of nanometer. In such a small size, much larger magnetic anisotropy (up to a few 10^7 erg/cm^3) is required to avoid thermal instability [1]. One particularly elegant approach for gigabit cells is to align the magnetization vectors in the perpendicular direction, since perpendicular magnetic materials have magnetic anisotropy larger than that of conventional in-plane soft-magnetic materials, and can alleviate magnetization curling occurs at the edges of the small cell in in-plane magnetization as well [2,3,4,5]. Magnetization reversal by the heat in combination with applied magnetic field or STT has previously been described in magnet with perpendicular anisotropy as a low power alternative to Oersted-field magnetization switching [6–10]. Very recently, it is reported that spin orbit torque (SOT) provides an efficient way to significantly reduce the power consumption for memory [11] and logics [12]. Especially, it is very appealing writing method to achieve highly scalable MRAM cells with low power consumption and reliable writing that STT switching assisted by thermally induced anisotropy reorientation (TIAR) [1,13]. In the TIAR assisted STT method, the critical writing current is determined by minimum required current to heat the MTJ up to the T_{SR}. To further reduce the power consumption in this writing method, we propose the thermal barriers on both sides of the MTJ cell and writing by current pulse with varied magnitude. Moreover, we investigated the T_{SR} of Co/Ni multilayer and composite layer with Co/Pt multilayer and CoFeB layer, for finding the suitable materials used in MTJ for TIAR assisted STT writing method. We found that the T_{SR} can be adjusted in both films at a wide range. The film with lower T_{SR} is for storage layer to reduce critical writing current, while the high T_{SR} film is for reference layer to be kept stable even at high temperature.

2. Experimental and modeling methods

The stacks of MgO 1.4/(Co 0.3/Ni 0.3)3/Pt 3, Ta 3/Pt 20/(Co 0.5/Pt 0.4)5/CoFeB 1.5/MgO 1.6, Ta 3/Pt 20/(Co 0.4/Pt 0.4)3/CoFeB 1.5/MgO 1.6 and MTJ stack of Ta 3/Pt 20/(Co 0.3/Ni 0.4)6/MgO 1.4/(Co 0.3/Ni 0.4)3/Pt 3 (from substrate side, thickness unit in nm in this paper) were grown by conventional sputtering deposition technique. The metal was grown by DC-magnetron sputtering, while the MgO layer was deposited by rf-sputtering of an oxide target. Substrates used in this experiment are thermally oxidized silicon wafers. Post-deposition annealing was performed in a high-vacuum furnace. The stacks with

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Co/Ni multilayer was annealed at 250 °C for 30 min, whereas the stacks with Co/Pt multilayers was annealed at 350 °C for 1 h. Magnetic properties of the films were determined by anomalous Hall effect (AHE) using standard four-point Hall geometry. The magnetic hysteresis loops of the films were measured at various temperatures up to 350 °C with an out-of-plane field.

The proposed writing methods and memory element are presented in Fig. 1. The memory element is illustrated in a geometry in which two auxiliary layers of low thermal conductivity $k_{TB,}$ playing the role of thermal barriers (TBs). They are inserted on both sides of the perpendicular MTJ to increase the storage layer heating efficiency as shown in Fig. 1(a). Both the storage layer and the pinned layer consist of a relatively thick layer Co/Pt multilayer (2.4 nm) structure with strong intrinsic perpendicular magnetic anisotropy, induced at the interface. A thinner layer CoFeB (1.5 nm) is adjacent to the tunnel barrier for enhancing the spin polarization. An adequate interlayer exchange coupling between the thicker and the thinner layers can force the magnetization of the thinner layer to be perpendicular to the film plane in overcoming the self-demagnetization field. Here, the interlayer exchange coupling is assumed to be 8.0 erg/cm^2 [14]. The basic idea of writing methods is to switch the perpendicular MRAM cell with thermal barriers by spin transfer torque under the thermal assistance, both are produced by current pulse with varied amplitude. The writing sequence is to firstly pull the magnetization of storage layer from a perpendicular to an in-plane state, which is achieved by current heating the magnetic tunnel junction with thermal barriers above T_{SR}, as shown in Fig. 1(b)–(d), and followed by decreasing the magnitude of current pulse to cool down the storage layer, which causes the magnetization gets reoriented perpendicular direction due to recovering of perpendicular magnetic anisotropy (PMA). The deterministic switching of storage layer during cooling can be achieved by the spin transfer torque, resulting from the current polarized by the reference layer which is stable in the out-of-plane direction, when the pulse current passes through magnetic tunnel junction, as shown in Fig. 1(e) and (f). Since the PMA becomes dominated during cooling, the critical current density is determined by the current density for realization of spin reorientation in this writing method.

The memory element is simulated by macrospin model. The magnetization M dynamics of the storage layer is described by the Landau–Lifshitz–Gilbert equation (Eq. (1)).

$$\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{M} \times H_{\mathrm{eff}} + \alpha \vec{M} \times \frac{\partial \vec{M}}{\partial t} + g(\theta) \frac{\gamma \hbar \mathrm{I}}{e V_{\mathrm{storage}} M_{\mathrm{s}}} \vec{M} \times \left(\vec{M} \times \vec{M}_{\mathrm{fix}} \right) \quad (1)$$

where $\vec{M}$ and $\vec{M}_{\mathrm{fix}}$ are unit vectors for the magnetization of the two ferromagnetic layers, γ the gyromagnetic ratio, $\hbar$ the reduced Planck constant, I the current, e the electron charge, and V_{storage} the volume of the storage layer. The saturation magnetization M_{s} of the storage layer is varied with the temperature and $g(\theta)$ is the unitless spin transfer efficiency. Gilbert damping constant α in our system is estimated to be about 0.15 [15], where H_{eff} is the total effective field including anisotropy field and demagnetization field.

3. Results and discussions

The critical current density in this method is determined by the heating current density for temperature driven-spin reorientation. Therefore, the spin reorientation temperature T_{SR} is the one of the critical parameters in this writing method. Co/Ni multilayer is one of good candidates for electrodes of perpendicular MTJ [3,16]. Fig. 2(a) depicts the AHE resistance (which is proportional to the M_z component) loop, as a function of the temperature with the out-of-plane field, for the post-annealed samples of MgO 1.4/(Co0.3/Ni0.3)3/Pt3. At 30 °C, the square AHE loop with coercivity of around 30 Oe, which indicates the easy axis of magnetization points out-of-plane. For the films, a strong dependence on temperature of the magnetic properties is observed, where the coercivity decreases drastically and loop becomes slant when increasing the temperature. At 100 °C, no remanence is remained at zero field. Linear behavior of the magnetic hysteresis loop was observed at 120 °C, revealing change of the magnetic easy axis from perpendicular to in-plane. This indicates that the temperature-driven spin reorientation (SRT) happens at about 120 °C for the MgO 1.4/(Co

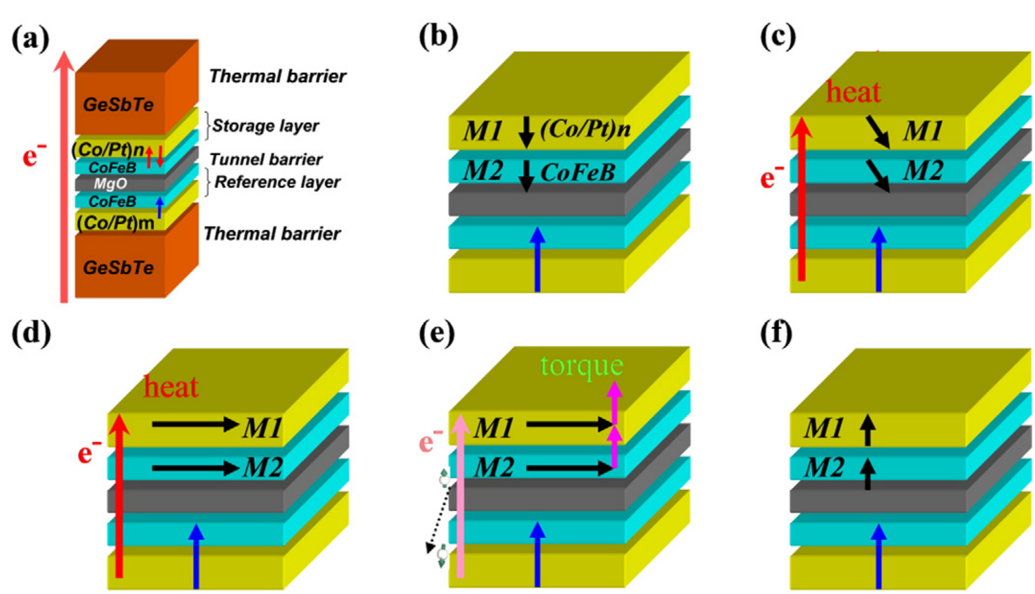

Fig. 1. Schematic description of magnetization switching by spin transfer torque with spin reorientation. (a) the memory cell comprised of magnetic tunnel junction with thermal barriers (GeSbTe), (b) the magnetic tunnel junction stack, in which the storage layer is made up of exchange coupled media with soft (CoFeB) and hard (Co/Pt multilayers) magnetic layers, (c) the magnetization of storage layer is pulled toward an in-plane by heating produced by current pulse, (d) the magnetization is totally in plane when the temperature is above spin reorientation temperature, (e) The current magnitude is reduced to cool down the MTJ so that the magnetization of storage layer returns out-of plane, in the direction determined by the STT from current polarized by reference layer, (f) the storage layer is switching from downward to upward by applying current flowing from storage layer to reference layer (electrons flowing from reference to storage layer).

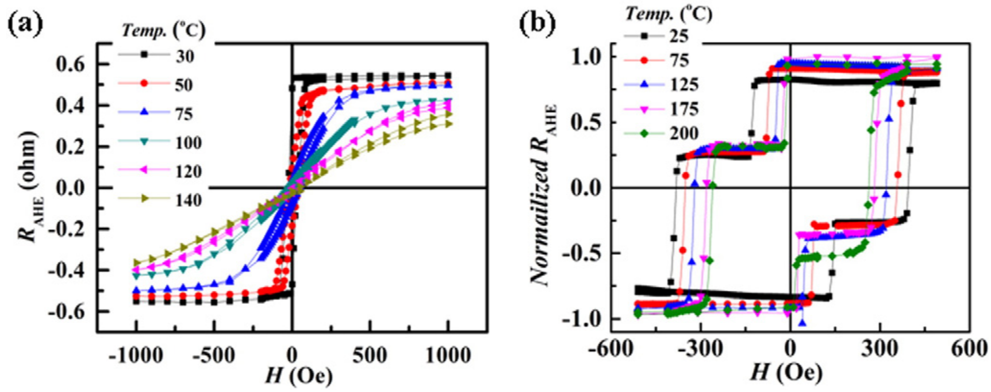

Fig. 2. Out-of-plane hysteresis loops as a function of temperature for (a) MgO 1.4/(Co 0.3/Ni 0.3)3/Pt 3 samples after annealing at 250 °C for 30 min, (b) Ta 3/Pt 20/(Co 0.3/Ni 0.4)6/MgO 1.4/(Co 0.3/Ni 0.4)3/Pt 3 samples after annealing at 250 °C for 30 min (thickness unit is nm).

0.3/Ni 0.3)3/Pt 3 films. Furthermore, we investigated the temperature dependence of magnetic properties for MTJ stack of Ta 3/Pt 20/(Co 0.3/Ni 0.4)6/MgO 1.4/(Co 0.3/Ni 0.4)3/Pt 3. Fig. 2(b) plots the normalized AHE resistance loops of this MTJ stack dependence of temperature. Note that, the top electrode being the softest one. This attributes that much less anisotropy from the MgO/(Co/Ni) interface than that from the Pt/(Co/Ni) one [3]. The coercivity of both of the top (storage) and bottom (reference) electrodes decreases with increase of the temperature. At 200 °C, the AHE hysteresis loop in the top electrode exhibits the reversible linear behavior, which indicates the perpendicular component is to be the hard axis. Whereas, the AHE hysteresis loop of bottom electrode has an almost square easy-axis loops even at 200 °C. We can clearly see that the spin reorientation temperature T_{SR} can be modulated at wide range in the Co/Ni multilayer, meanwhile, the low T_{SR} around 120 °C can be obtained in Co/Ni multilayer for storage layer. Its effective anisotropy is about 3×10^6 erg/cm^3 from our previous measurements [3]. When the lateral dimension of device scale down to 30 nm × 30 nm, the switching energy barrier is around 4.86×10^{-19} J, which is approximately two orders of magnitude greater than the thermal energy K_BT (4.14×10^{-21} J) at ambient temperature. This reveals that Co/Ni multilayers are good candidate materials for temperature driven SRT.

Since the temperature-driven SRT is generally caused by the change of magnetic anisotropy with temperature, it is expected that T_{SR} can be also easily adjusted in composite storage layer having exchange coupled layers with in-plane and out-of-plane competing anisotropies [8]. Fig. 3(a) shows the AHE resistance dependence of the magnetic field applied out of plane at varied temperature from room temperature (RT) to 350 °C for the stack of Ta 3/Pt 20/(Co0.5/Pt0.4) 5/CoFeB 1.5/MgO 1.6. It is observed that the coercivity decreases from 460 to 180 Oe when increasing the temperature from RT to 350 °C. The high remanence ratio (M_r/M_s) indicates the perpendicular component still remain even at 350 °C. However, the stacks of Ta 3/Pt 20/(Co 0.4/Pt 0.4)3/CoFeB 1.5/MgO 1.6 shows the very fascinating temperature dependence of the magnetic properties including coercivity and magnetization remanence, as shown in Fig. 3(b). At 250 °C, both of the coercivity and remanence drop to zero. Above this temperature, the AHE loops are hard-axis-like. This reveals that the temperature-driven SRT happens at about 250 °C. From above, these results confirm that T_{SR} can be adjusted by varying the Co thickness and multilayer repetition number of Co/Pt in composited layers consisting of Co/Pt multilayer with perpendicular magnetic anisotropy and a CoFeB with in plane anisotropy. Therefore, the composite layers can be used as storage and reference electrodes in the MTJ structure for TIAR assisted STT writing method.

Next, we macrospin model the switching dynamic using spin transfer torque assisted by thermal-driven SRT. In this modeling, we use the composite layer as electrodes in the MTJ. Fig. 4 shows a calculated magnetization switching hysteresis loop for composite layers. For the Co/Pt multilayer (M_1), the thickness is assumed to be 2.4 nm. The perpendicular anisotropy constant of M_1 is10^7 erg/cm^3. The saturation magnetization of M_1 is assumed to be 6.0×10^5 A/m. While, for the CoFeB layer (M_2), the thickness is assumed to be 1.5 nm, and the in-plane anisotropy is 5.0×10^5 erg/cm^3. The saturation magnetization of M_2 is 8.2×10^5 A/m. At the above conditions, an out-of-plane switching field is around 1.28 T. The calculation also shows that the interlayer exchange coupling (8.0 erg/cm^2) is strong enough to align the magnetization of CoFeB to be out-of-plane in overcoming the self-demagnetization.

We consider that a gradient current flow perpendicularly to the film plane shown in Fig. 1. The higher amplitude part produces heating that causes the perpendicular anisotropy of Co/Pt multilayer decrease, and consequently in-plane anisotropy of CoFeB layer forces the

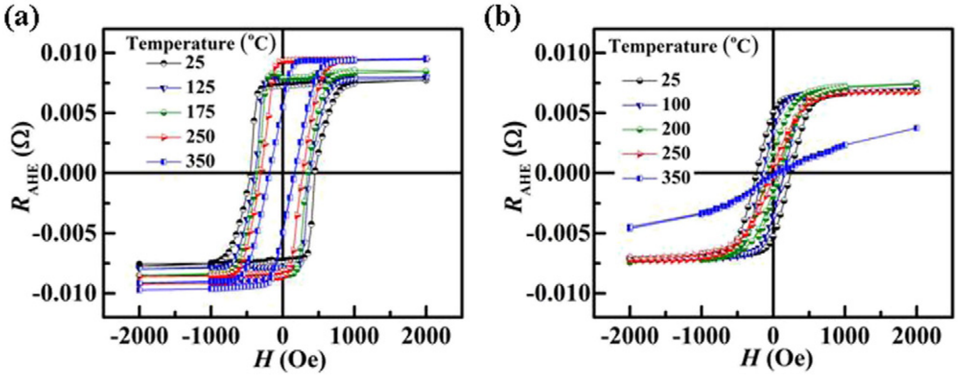

Fig. 3. Out-of-plane hysteresis loops as a function of temperature for (a) Ta 3/Pt 20/(Co 0.5/Pt 0.4)5/CoFeB 1.5/MgO 1.6 samples after annealing at 350 °C for 1 h, (b) Ta 3/Pt 20/(Co 0.4/Pt 0.4)3/CoFeB 1.5/MgO 1.6 samples after annealing at 350 °C for 1 h (thickness unit is nm).

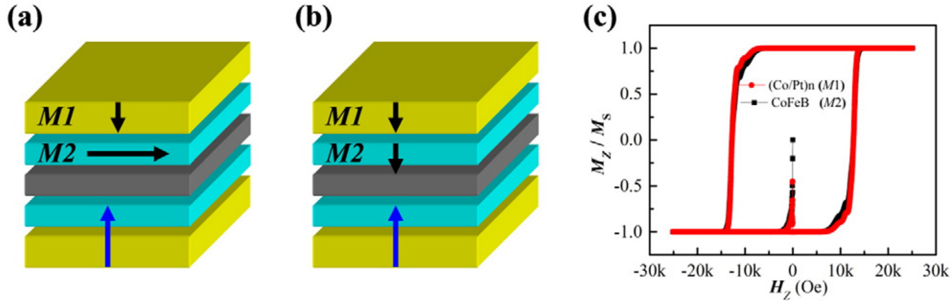

Fig. 4. Macrospin simulation of magnetic switching under an out-of-plane magnetic field for storage layer in MTJ structure. (a) The storage layer consists of Co/Pt multilayer ($M1$) with perpendicular anisotropy constant of 10^7 erg/cm^3 at room temperature (RT), and CoFeB layer ($M2$) with in plane anisotropy constant of 5.0×10^5 erg/cm^3 at RT. The thickness of $M1$ and $M2$ is 2.4 and 1.5 nm, respectively. The saturation magnetization of $M1$ and $M2$ is 6.0×10^5 and 8.2×10^5 A/m at RT, respectively. The interlayer exchange coupling between two layers is 8.0 erg/cm^2. (b) The magnetization of the $M2$ is forced to be perpendicular to the film plane due to the exchange coupling between $M1$ and $M2$. (c) Calculated magnetic hysteresis loops at room temperature as a function of perpendicular applied field for the storage layer (composited layers).

magnetization of the storage layer from out of the film to in-plane. In the following, the lower amplitude part of the pulse cools the system and the magnetization should be pulled back into its original easy axis direction (out of film) by perpendicular anisotropy of Co/Pt multilayer. If positive current specifies electron flow from the storage layer to the reference layer, the spins polarized carried by negative current can force the storage layer from in-plane into parallel (P) alignment compared with the reference layer even when the current is so low during cooling. Otherwise a positive current is necessary. The macrospin modeling results are shown in Fig. 5.

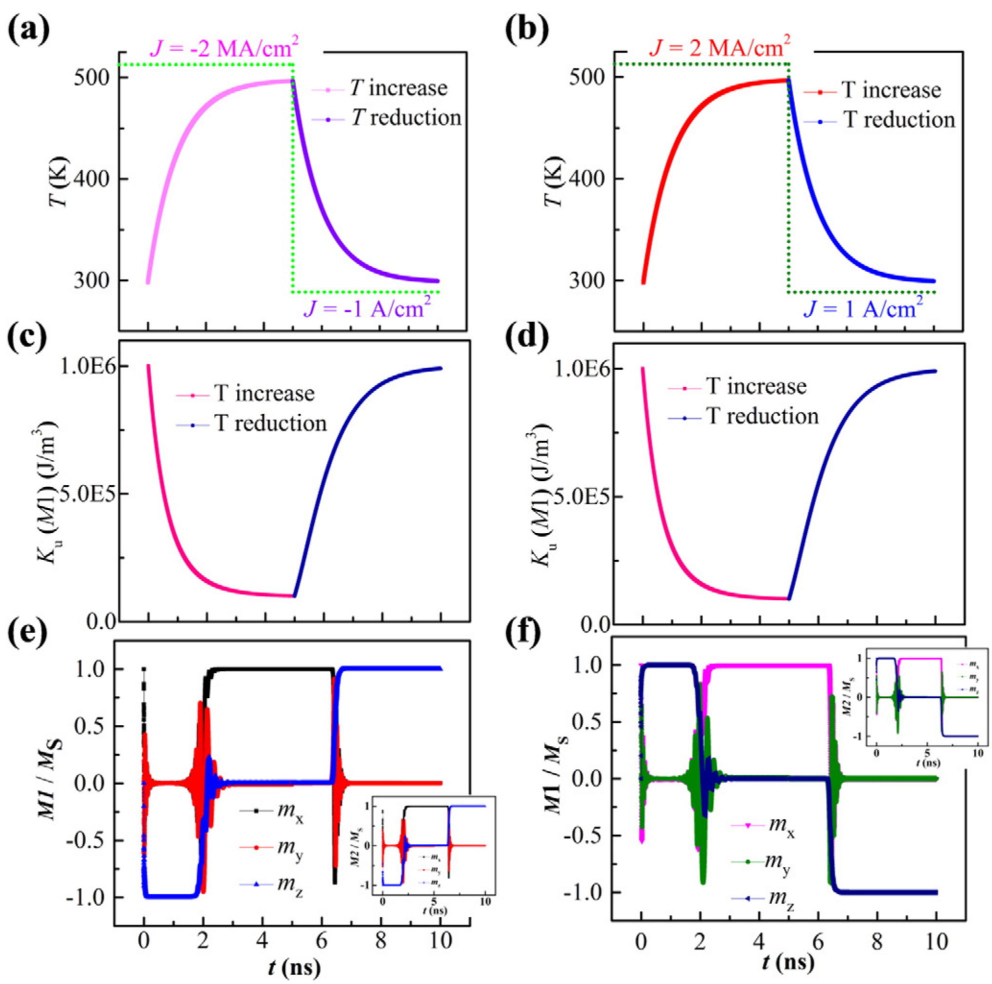

Fig. 5. Simulation of magnetization reversal of the composited layers with a lateral area of 50×50 nm^2, in the presence of the gradient current pulse for (a), (c), (e) negative and (b), (d), (f) positive direction, while positive current defines the current flowing from reference layer to storage layer and magnetization of reference layer is kept in upward. Temperature evolution with time using gradient current pulse (the dotted line in the figures), as plotted in (a) and (b). The temperature in MTJ structure with 20 nm thermal barriers (GeSbTe) increased to 200 °C, where the spin reorientation happens at the composited layer, after applying current of 2.0×10^6 A/m^2 for 5 ns. The evolution of out-of-plane magnetic anisotropy of Co/Pt multilayer in storage layer with time, as shown in (c) and (d) corresponding to negative and positive current, respectively. The corresponding magnetization component (x, y, z) of Co/Pt multilayer ($M1$) in the composited layers evolves with time, as plotted in lower panel of (e) for negative and (f) for positive current. The insets in (e) and (f) are the evolution curves of $M2$ in the composited layers with time. Actually, $M2$ and $M1$ in one composited layer is kept in same pace during magnetization switching due to the strong exchange coupling between two magnet.

During the application of a heating current at room temperature ($T_{RT}=298$ K), the temperature increase in the storage layer ΔT_{ST} is proportional to power density P based on a proposed one-dimensional (1D) model of heat diffusion, that is expressed by $\Delta T_{ST}=cP[1-\exp(-\frac{t}{\tau})]$ with time t [17]. Here, c and τ are the proportional constant and characteristic time, respectively. Low thermal conductivity GeSbTe ($k_{TB}=0.5\ \mathrm{W\,(m\,K)^{-1}}$) with 20 nm thickness d_{TB} is assumed to be used as thermal barrier here [18]. The parameters of c and τ are estimated to be $8.0\times10^{6}\ \mathrm{K\,W^{-1}}$ and 1 ns respectively [17].

The Co/Pt multilayer, exhibiting a strong dependence of magnetic properties on temperature, is chose in storage layer. The saturation magnetization is assumed to be a power-law dependence on the temperature, $M_s\ (T)=M_s\ (0)(1-BT^{3/2})$ [19], where M_s (0) stands for the magnetization at 0 K, and B represents Bloch constant and is estimated to be $6.17\times10^{-5}\ \mathrm{K^{-3/2}}$ for nanoscale Co/Pt multilayer. Anisotropy K follows a simple power law dependence on the magnetization M(T), $K(\mathrm{T})\propto M^{2}(\mathrm{T})$ here [20]. Compared to the Co/Pt multilayer, the Curie temperature of CoFeB is much higher and around 1025 °C [21]. Therefore, the CoFeB layer is insensitive to temperature during heating process, in which temperature is less than 225 °C. Here, we can consider their magnetic properties are kept as constant during heating. The spin polarization factor $P=0.25$ is assumed for enhancing CoFeB layers in adjacent to the tunnel barrier [9]. The resistance area product $R\times A$ of the junction is assumed to be $25\ \Omega\ \mu\mathrm{m}^2$.

If we assume the total width of current pulse is 10 ns, and the pulse duration with high and low magnitude is half of the total pulse width (5 ns). The critical current density for realization of spin reorientation for the storage layer is around $2\times10^{6}\ \mathrm{A/cm^2}$, which is independent of current polarizer since Joule heating is dominant at this process. Around 225 °C can be reached after 5 ns, as shown in Fig. 5(a) and (b). At this temperature point, the anisotropy of Co/Pt multilayer in storage layer is reduced from $1\times10^{7}\ \mathrm{erg/cm^3}$ ($1\times10^{6}\ \mathrm{J/m^3}$) to around $1\times10^{6}\ \mathrm{erg/cm^3}$ ($1\times10^{5}\ \mathrm{J/m^3}$), which is comparable to the in-plane energy contributing from in-plane anisotropy and demagnetization energy of CoFeB in storage layer. These are plotted in Fig 5(c) for negative current and Fig. 5(d) for positive current. Therefore, the temperature driven spin reorientation happened at around 225 °C. The magnetization is in the film plane, as revealed in the Fig 5(e) and (f) that the x component of both of unit vector magnetization (M_1 and M_2 plotted in the inset) is "1", while the z component is "0" during a period from 2 to 5 ns. If the low amplitude current is less than $3.0\times10^{5}\ \mathrm{A/cm^2}$, the magnetization can go back out of the film plane during cooling. It is interesting that very small current density even less than $1\ \mathrm{A/cm^2}$ with correct polarizer direction is enough to switch the storage layer to desired perpendicular direction. For example, $+1\ \mathrm{A/cm^2}$ current can switch the magnetization to parallel state relative to pinned layer, whereas the $-1\ \mathrm{A/cm^2}$ did switch the magnetization to antiparallel state relative to reference layer, as shown in Fig. 5. As described above, it is obvious that the critical current density is determined by the realization of spin reorientation in composite storage layer of MTJ, in which the temperature increased by Joule heating. The T_{SR} is intrinsic property of storage layer. The temperature increase in the MRAM cell is determined by power density, produced by current density j, and proportional constant c. The response time of temperature increase is dependent on characteristic time τ. Both c and τ are proportional to thickness division of thermal conductivity ((d_{TB}/k_{TB}) of thermal barrier, and exactly described by $c\propto\frac{d_{TB}}{k_{TB}A}$. Therefore both parameters can be adjusted by thickness (d_{TB}) and/or thermal conductivity (k_{TB}) of thermal barrier. The total power density is essentially determined by the $R\times A$ product of the junction and the current density j, as $P=(R\times A)\,j^2$. So, the temperature increase in the stack cell can be expressed by:

$$\Delta T_F\propto cP\propto\frac{d_{TB}}{k_{TB}}Rj^2\left[1-\exp\left(-\frac{t}{\tau_{TB}}\right)\right],$$

where $R=\rho\frac{t1}{A}$. If the thickness $t1$ and resistivity ρ in MTJ stack are invariable, in other worlds, $R\times A$ is kept to a constant, the resistant R is inverse proportional to lateral area A. It indicates that the required current density in this writing method should be decreased with the decrease in lateral area. It is advantage over conventional spin transfer torque method in required current density, since the critical current density in conventional STT writing is independent of area.

We calculated the critical current density using spin transfer torque switching without considering Joule heating in same simulation condition as described above. A critical current density is required to be around $-2.5\times10^{8}\ \mathrm{A/cm^2}$ for switching this composite storage layer from antiparallel to parallel state relative to reference layer. On the other hand, $5.5\times10^{8}\ \mathrm{A/cm^2}$ current is required for switching this composite storage layer from parallel to antiparallel state relative to reference layer for 10 ns pulse duration (Fig. 6).

We also note that it is possible to use thicker storage layer for high thermal stability in this writing method, since the required current density is independent of thickness of storage layer if we assume that thickness does not affect spin reorientation temperature. The critical current density can be further reduced by reducing the spin reorientation temperature.

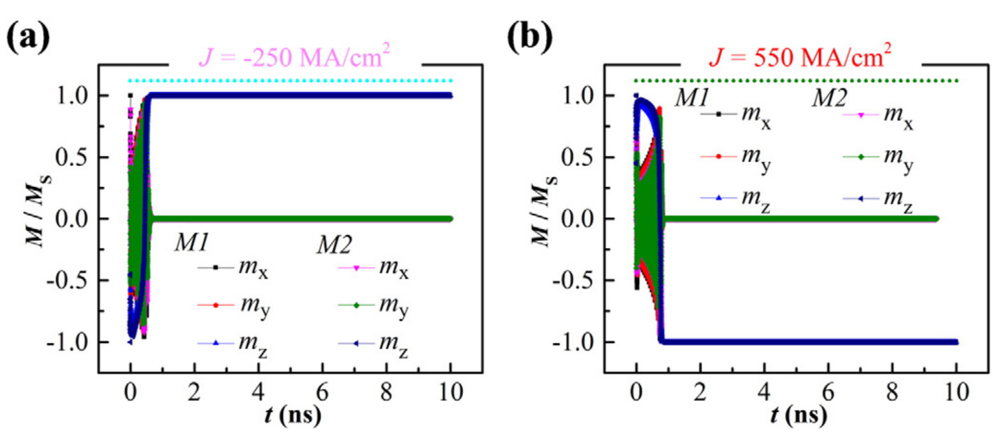

Fig. 6. Time evolution of magnetization component (x, y, z) of $M1$ and $M2$ in the composited layers with a lateral area of $50\times50\ \mathrm{nm^2}$, considering the current pulse only generate the spin transfer torque without Joule heating. (a) The negative current switches the magnetization to antiparallel state relative to reference layer, (b) positive current can switch the magnetization to parallel state relative to pinned layer. The critical current density is $-2.5\times10^{8}\ \mathrm{A/cm^2}$ and $5.5\times10^{8}\ \mathrm{A/cm^2}$ for switching magnetization to antiparallel and parallel state relative to reference layer, respectively.

4. Conclusion

In summary, the lower T_{SR} can be experimentally obtained in Co/Ni multilayer (around 120 °C), with thermal stability factor Δ ($=K_{eff}V$ / k_BT) at ambient temperature greater than 100 even when the lateral dimension of device scale down to 30 nm × 30 nm. The T_{SR} of composite layer with Co/Pt multilayer and CoFeB can be adjusted as low as 250 °C from our experiments. From macrospin modeling, the critical current density is about 2.0×10^6 A/cm^2 using current pulse with 10 ns pulse width, to switch around 4 nm storage layer in the perpendicular MRAM cell with high anisotropy field of 1.28 T, by the switching method of spin transfer torque assisted with spin reorientation. This switching method shows great potential to obtain high thermal stability and low critical current density for future ultrahigh density MRAM, since critical current density reduced with decrease in lateral area for perpendicular MRAM cell with certain spin reorientation temperature, and independent of thickness of element cell.

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