Micromagnetic simulation of current-induced magnetization dynamics in a half-Heusler $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ alloy spin-valve nanopillar

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Abstract

We investigated the magnetization switching by means of a spin-polarized current via spin-transfer torque (STT) in a half-metallic Heusler $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ alloy by numerically solving the Landau–Lifshitz–Gilbert–Slonczewski equation including the STT term in a spin-valve nanopillar $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}/\text{Ag}/\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ using micromagnetic simulation. In this work, we use $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ film of 2 nm thickness, and then we inject a spin polarization current perpendicular to plane of the multilayers in order to flip the free layer magnetization and therefore get the magnetization switching between the two layers. Half-metallic Heusler $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ is characterized by a small Gilbert damping constant $\alpha = 0.0025$ and a complete spin polarization at the Fermi level. Using these specific parameters, we obtain the magnetization switching between the free layer and the pinned layer with a critical current density of about 10^6 A/cm^2 , as well the magnetization switching process of nanopillar are discussed and analyzed. Also, we deeply examine the behavior of magnetization switching dynamic as a function of the current density within a weak external magnetic field which helps to trig switching. Finally, we studied the impact of free layer thickness on magnetization switching dynamic and STT energy in order to immunize further the switching time and the critical current density.

Keywords Spin-transfer torque · Half-metallic Heusler alloy · Spin valve · Magnetization switching · Threshold current density

1 Introduction

Spin-transfer torque is one way of switching the magnetization when a spin-polarized current is injected between two ferromagnetic layers separated by a non-magnetic metallic layer whose thickness is adjusted to minimize the RKKY coupling between these two layers. In addition, they must have different coercive fields in order to achieve an antiparallel configuration of the magnetization, and this difference is usually achieved by blocking one of the two layers using an antiferromagnetic layer (AFM) or an artificial antiferromagnetic (AAF). This mechanism was theoretically proposed by Berger [1] and Slonczewski [2] in 1996. They established that a spin-polarized current can transfer enough angular momentum to a magnetic

system to destabilize the initial equilibrium orientation of the magnetization toward a magnetization switching. The control of the magnetization dynamics in ferromagnets at nanoscale is a key aspect from technological point of view [3, 4]. Recently, the spin-transfer torque technology has attracted considerable attention due to its application in high-density magnetic random access memory (MRAM). It has the potential to make possible MRAM devices combining reduced cost and low current through magnetization reverse of a magnetic layer via spin-polarized current [5, 6].

The magnitude of the STT is proportional to the current density passing through the device and in order that the spin-transfer effects become significant, high current densities are required. Typical threshold currents densities associated with switching and precessional

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dynamics are about 10^8 – 10^7 A/cm², depending on the device geometry and used materials [7]. High polarization, low magnetic damping α and low saturation magnetization are the main parameters influencing on the threshold current density.

Ferrites and in particular yttrium iron garnets (YIG) are among materials with the lowest damping with the typical value $\alpha \sim 10^{-4}$ [8]. In addition, the saturation magnetization in these kinds of compounds is low (0.178 T), but their insulating nature does not allow them to be used in the MTJs. Typical ferromagnetic materials have α values between 10^{-2} and 10^{-3} in bulk. These materials include, for example, centered cubic Fe [9] or face-centered cubic FeNi alloys [10] ($\alpha \sim 10^{-3}$). Unfortunately, these damping values are often increased when these materials are elaborated in thin films form. Let us add that in practice, the key building block for spintronic devices is the CoFeB/MgO/CoFeB tri-layer produced by cathodic sputtering [11]. The strong magnetoresistance (MR) effects observed in this system are due to a strong spin polarization of the electrons that tunnel through MgO [11, 12]. In addition, it is possible to make these layers with a perpendicular magnetization [12]. The main disadvantage remains the damping values obtained on this system that do not go below 10^{-2} . Some Heusler and half-metallic Heusler alloys also named half-metallic ferromagnetic (HMF), such as Co_{1.5}Fe_{1.5}Ge, Co₂MnSi and Co₂FeSi, possess these properties when they crystallize in the appropriate phase with a total spin polarization (100%), very low magnetic damping (of about 10^{-3}), sufficiently high Curie temperature, moderate magnetization [13] and high giant magnetoresistance GMR [14]. Moreover, they generally display a perpendicular anisotropy which has been experimentally carried out for certain Heusler alloys [15]. Thanks to these characteristics, recent experiences and simulations demonstrated the ability to

get the magnetization switching from a low current density of about 10^6 – 10^4 A/cm² [7, 16–19].

In this paper, we investigate the magnetization dynamics of the half-metallic Heusler Co_{1.5}Fe_{1.5}Ge (CFG) alloy spin-valve nanopillar, under the influence of a spin-polarized current perpendicular to plane (CPP) of layers by using the macrospin approximation and the micromagnetic simulation method. In Sect. 2, we present our model and put down the dynamics equation of the magnetization. Then, we briefly outline the formulas giving various contributions to the functional global energy and the effective magnetic field. In Sect. 3, numerical computation is carried out and the role of magnetic field, current density and anisotropy strength on the magnetization switching is carefully analyzed. The magnetization switching from APS to PS was done by a threshold current density injected $J_c = -8 \times 10^6$ A/cm² and for the reverse behavior (APS to PS) we get the switching for $J_c = 7 \times 10^6$ A/cm². Additionally, we examine the effect of a weak magnetic field on the threshold current density along the x-axis and on the magnetization switching time of the free layer for two cases (PS and APS), under current densities of about 10^6 A/cm² and also with a diagram representing the magnetization dynamic in a current density range of $[-20, 20] \times 10^6$ A/cm² and finally, the nanopillar size effect has been investigated through study of the impact of free layer thickness on magnetization switching dynamics and STT energy. At last, Sect. 4 presents our concluding remarks.

2 Description model

We aim to study magnetization dynamics in spin-valve device. The nanopillar structure is consisting of two asymmetric Co_{1.5}Fe_{1.5}Ge (CFG) magnetic layers with different

Fig. 1 **a** Geometry of CFG/Ag/CFG CPP-GMR nanopillar. **b** The directions schema of the main terms of the LLGS equation

thicknesses intercalated by a non-magnetic layer (Ag). Figure 1a shows a schematic description of the spin-valve GMR stack under investigation. The geometry of the nanopillar defined as CFG(8 nm) (pinned layer)/Ag(4 nm) (space layer)/CFG(2 nm) (free layer), the two diameters of the elliptical nanopillar are, respectively, 160 nm and 80 nm and the sample is discrete with cells size of $2.5 \times 2.5 \times 2 \text{ nm}^3$. The CFG layers are separated by a non-magnetic metallic layer of Ag with the x-axis related to the easy axis of the ellipse. The pinned layer is much thicker than the free layer, so it responds less strongly to the current-induced torques and its magnetization is fixed at positive x-axis. However, the free layer magnetization has two bistable states, PS or APS relatively to positive x-axis direction. We injected a spin polarization current perpendicular to plane (CPP) of the geometry, and the positive current is defined as a current that traverses the free layer to the pinned layer and for the negative from pinned to free layer. The elliptic geometry of $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ in the nanopillar causes an anisotropy along the x-axis of the ellipse, therefore favors a uniform state of magnetization.

The magnetization dynamics are described by using the extended Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation including both damping and STT terms, which can be expressed as [20, 21]:

$$\frac{d\mathbf{M}}{dt} = -\frac{\gamma}{1+\alpha^2} \left[(\mathbf{M} \times \mathbf{H}_{\text{eff}}) + \frac{\alpha}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}) \right] + \frac{g\mu_B j}{e(1+\alpha^2)M_s^2 d} g(\theta) \left[\alpha(\mathbf{M} \times \mathbf{M}_p) - \frac{1}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{M}_p) \right] \quad (1)$$

where $\mathbf{M}$ and $\mathbf{M}_p$ are, respectively, the magnetization vectors of the free and the pinned layer, α is the Gilbert damping parameter, M_s is the saturation magnetization, while M_{sp} is the saturation magnetization of the pinned layer (here, we have assumed $M_{sp} \approx M_s$), $\mathbf{H}_{\text{eff}}$ is the effective magnetic field, g is the Landé factor, while $\gamma = \frac{g|\mathbf{e}|}{2m}$, μ_B , j and d are, respectively, the electron gyromagnetic ratio, the Bohr magneton, the current density, and the thickness of the free layer.

The first term in Eq. (1) describes the precession of $\mathbf{M}$ around the effective magnetic field $\mathbf{H}_{\text{eff}}$ which drives the torque and which is resulting from the external, the demagnetizing, the anisotropy and the exchange contributions, namely $\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{ext}} + \mathbf{H}_d + \mathbf{H}_a + \mathbf{H}_e$. The second term corresponds to the energy dissipation during magnetization dynamics and tends to bring the magnetization back to its equilibrium configuration (PS or APS). The last two terms designate the spin-transfer torque, where $g(\theta)$ is the Slonczewski expression [2]:

$$g(\theta) = [-4 + (1 + \eta^3)(3 + \cos(\theta))/4\eta^{3/2}]^{-1} \quad (2)$$

with θ being the angle between the magnetization direction of the free $\mathbf{M}$ and the pinned $\mathbf{M}_p$ layers and η is the spin polarization factor which is given by [22]:

$$\eta = \frac{jPh}{4\pi\mu_0 M_s^2 ed} \quad (3)$$

where P and h are, respectively, the current polarization and the Planck constant. The third term concerns the impact of STT. Here, we are interested in the switching by STT in plane, and thus the term of $\mathbf{M} \times [\mathbf{M} \times \mathbf{M}_p]$ is the most important contribution. However, the perpendicular torque term will be weakened because of the elliptical geometry of the considered system which rather favors an in-plane magnetization arrangement (gray-plane in Fig. 1b). Consequently, the perpendicular spin torque is insignificantly small in comparison with the in-plane torque and can be neglected.

To understand how the spin-transfer torque acts on the magnetization, it is instructive to consider the total energy from which the effective field derives:

$$\mathbf{H}_{\text{eff}} = -\frac{1}{\mu_0 V} \frac{\delta E}{\delta \mathbf{M}} \quad (4)$$

where

$$E = E_e + E_z + E_d + E_a \quad (5)$$

with E_e , E_z , E_d and E_a being, respectively, the exchange, the Zeeman, the demagnetization and the anisotropy energy contributions.

Before going further, it will be convenient to recall each term in Eq. (5), in turn. The exchange energy can be written as [23]:

$$E_e = \int_V \frac{A}{M_s^2} [(\nabla \mathbf{M}(\mathbf{r}))^2] d^3 \mathbf{r} \quad (6)$$

where A is the magnetic exchange constant.

The demagnetization energy is given by the following equation [23, 24]:

$$E_d = -\mu_0 \int_V \mathbf{H}_d \cdot d\mathbf{M} = -\mu_0 N_d \int_V \mathbf{M} \cdot d\mathbf{M} \quad (7)$$

where N_d is the demagnetization tensor depending on the sample shape is given by [25, 26].

$$N_d = \langle N \rangle_{ij} = \frac{1}{8\pi^3 V} \int d^3 \mathbf{k} \frac{|D(\mathbf{k})|^2}{k^2} k_i k_j \quad (8)$$

where V , k and $D(k)$ are, respectively, the volume of the body, the wave vector and the shape amplitude in Fourier space. We can express the shape amplitude for elliptic cylinder as:

$$D(\mathbf{k}) = 2V \frac{J_1(a\mathbf{k})}{ak} \frac{\sin(dk_z)}{dk_z},$$

where $J_1(x)$, a and d are Bessel function, major semi axis and the half-thickness [24].

The anisotropy energy of $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ in the elliptical geometry of nanopillar CFG/Ag/CFG is [23]:

$$E_a = \int \left[K_1 (1 - m_x^2(r)) + K_2 (1 - m_x^2(r))^2 \right] d^3r \quad (9)$$

where K_1 and K_2 are the magnetocrystalline anisotropy coefficients and x is the easy axis and $m_x(r) = M_x(r)/M_s$. (Here, we assume a uniaxial anisotropy, and thus K_2 is neglected.)

Zeeman energy is written [23]:

$$E_Z = -\mu_0 M_s \int_V [\mathbf{H}_{\text{ext}} \cdot \mathbf{m}(r)] d^3r \quad (10)$$

where $\mathbf{H}_{\text{ext}}$ is the external magnetic field.

The effective field due to the STT is given by [20, 21]:

$$\mathbf{H}_{\text{STT}} = 2\mu_B j g(\theta) \mathbf{m} \times \mathbf{m}_p / (\gamma e d M_s) \quad (11)$$

where $m_p = M_p/M_{\text{sp}}$, $m = m/M_s$ and the corresponding energy is:

$$E_{\text{STT}} = -\mu_0 M_s \int [\mathbf{H}_{\text{STT}} \cdot \mathbf{m}(r)] d^3r \quad (12)$$

Obtained results are based on the micromagnetic simulation by numerically solving the Landau–Lifshitz–Gilbert–Slonczewski (LLGS) Eq. (1) including the STT term and the effective field resulting from the exchange, the Zeeman, the demagnetization and the anisotropy field contributions using Mumax3 code [27]. The chosen geometry for spin-valve device is nanopillar CFG/Ag/CFG at sufficiently low temperature in order to minimize the thermal agitation and guarantee a total spin polarization. The simplest approach is to assume that the magnetization of each layer is separately uniform. This assumption is the basis of the macrospin model. The simplicity of the resulting equation lends itself to analytic determination of the threshold current density [28, 29] and permits exhaustive exploration of the system behavior as a function of field and current [30–33]. The magnetic parameters of the used half-metallic Heusler $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ alloy are. Thickness $d = 2$ nm, saturation magnetization $M_s = 9.2 \times 10^5$ A/m, exchange constant $A = 1.3 \times 10^{-11}$ J/m, Gilbert damping parameter $\alpha = 0.0025$, magnetocrystalline anisotropy constant $K_1 = 0.5 \times 10^4$ J/m³ [14] and our calculated value of the spin polarization factor

$\eta = 0.81$, which is significantly higher than for full-Heusler alloy $\text{Co}_2\text{FeAl}_{0.5}\text{Si}_{0.5}$ ($\eta = 0.76$) [34].

3 Results and discussion

3.1 Impact of current density on the magnetization switching dynamics and the STT energy

This section is devoted to the micromagnetic simulations of the magnetization behavior of the free layer $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ in a spin-valve nanopillar CFG/Ag/CFG. In this geometry, we have applied different values of current density flow perpendicular to plane (see Fig. 1a). Figure 2 shows the evolution of the three magnetization components of the free layer with $\mathbf{m} = \mathbf{M}/M_s$ being the normalized vector of the magnetization and $\mathbf{M} = (M_x, M_y, M_z)$. The minimum value of current allowing the switching is the threshold current density or the critical current density J_c . It is influenced by a set of parameters including the thickness of the free layer, saturation magnetization, Gilbert damping parameter, anisotropy constant and exchange stiffness. We point out that the spin-transfer torque can take or supply energy to the system according to the sign of the applied current. The negative threshold current density favors the anti-parallel configuration, while the positive one leads to a parallel configuration. As shown in Fig. 2a, for $J_c = -8 \times 10^6$ A/cm² the current density is from the pinned layer to the free layer, and therefore the magnetization flips from the PS ($M_x/M_s = 1$) to APS ($M_x/M_s = -1$) with a magnetization switching time equal to 5.7 ns under a zero external magnetic field. In Fig. 2b, we have applied a current density flow of $J_c = 7 \times 10^6$ A/cm² and a reverse behavior is shown where the magnetization flipped from APS to PS with a magnetization switching time equal to 3.8 ns. As a comparison with the classical ferromagnetic materials in particular Co and Fe in a spin-valve system, it is necessary to apply a current density of about 10^8 A/cm² to trig the switching, and that due to their high Gilbert damping constant 10^{-2} and saturation magnetization of order of 10^6 A/m [35].

The switching process of magnetization according to m_x , m_y and m_z is accompanied by drastic magnetization oscillations with different amplitudes and frequencies. As shown, m_y and m_z for the two cases (PS and APS) have a similar behavior. Where they begin with weak oscillations and close to the reverse shift, become high and tend progressively into zero. The special thing is that the m_z amplitudes are very smaller than m_x and m_y , by reason of the thickness of the free layer (2 nm) is significantly smaller than the lateral size (160×80 nm²), resulting an inequality of the demagnetizing energy along the

Fig. 2 The temporal evolution of the average magnetization m_x , m_y and m_z under two current densities: **a** For the negative threshold current density of $J_c = -8 \times 10^6$ A/cm² (PS to APS). **b** For the positive threshold current density $J_c = 7 \times 10^6$ A/cm² (APS to PS)

x -, y - and z -axis which causes a much strong demagnetization fields in the z -axis.

We adopted Slonczewski's model, which only takes into account the interface spin-flip scattering between the layers, and the relationships between spin-transfer torque and θ are plotted in Fig. 3 for $J_c = -8 \times 10^6$ A/cm², with θ is the angle between the two magnetizations, H_{STT} is the effective field of spin-transfer torque. In our simulation, we initialized the angle θ at 0.1° for the PS and at 179.9° for APS, with H_{STT} equal to zero in these cases ($\mathbf{M} \times \mathbf{M}_p = 0$).

The H_{STT} is not symmetrical at 90° , because the spin-current scattering from the free layer is dependent also on the direction of the two magnetizations, and the H_{STT} in this angle is equal to 1.72×10^4 A/m. Therefore, it is larger than the magnetocrystalline anisotropy field of the $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ layer at the same angle. Consequently, the H_{STT} overcomes the barrier of the magnetocrystalline anisotropy field and keeps on to increase until it reaches to its maximum value of $H_{STT} = 2.875 \times 10^4$ A/m at $\theta = 144.2^\circ$ which makes the switching easier from the antiparallel to the parallel state than from parallel to

Fig. 3 **a** The relationships between STT and θ in Slonczewski's model. **b** (Color online) Snapshots of the domain configuration during the reversal process under a negative threshold current density

of $J_c = -8 \times 10^6$ A/cm² (160×80 nm²). Color coding: positive (red) and negative (light blue) average magnetization following the x -axis

the antiparallel state. After that, H_{STT} decreases when θ increases, but it remains larger than the magnetocrystalline anisotropy field and therefore making the magnetization switch to the APS.

When the magnetization is in the PS, the Gilbert damping is too high, the magnetization has difficulties to move from the equilibrium. But, the magnetization moving the Gilbert damping loses little by little its energy. As a result, the STT easily controls the magnetization and when it gets closer to APS, the Gilbert damping becomes again large, but toward the switching.

We get the magnetization switching through a competition between spin-transfer and Gilbert torques (Fig. 4). As long as the STT is greater than Gilbert damping torque, we are reaching the magnetization switching (Fig. 4d). As an example, for $J = -1 \times 10^7 \text{ A/cm}^2$, we get the switching at $t = 3.5 \text{ ns}$. But in the reverse case, when the STT energy is lower than the Gilbert damping (Fig. 4b), the magnetization comes back to its equilibrium state after few oscillations around it, which is mainly due to the fact that the energy of the spin-transfer torque is insufficient to overcome the Gilbert damping, and therefore the Gilbert damping continually loses energy to the system and tends to reduce the magnetization to a minimum of energy. In the third case, when we apply a higher current density but on the flip side, there is a stable precession, in this case the magnetization usually precesses (Fig. 4b), such as for $J = -2 \times 10^6 \text{ A/cm}^2$, the magnetization continues to oscillate around the PS. We point out that the precession state is reached when the Gilbert energy dissipation equals

the STT energy. Thus, the magnetization switching time depends on the applied current and as shown in Fig. 4e. For the threshold current density $J_c = -8 \times 10^6 \text{ A/cm}^2$, we can get the magnetization switching at 5.5 ns. However, $J = -1.2 \times 10^7 \text{ A/cm}^2$ is at 2.3 ns. Consequently, whenever the current is greater than the threshold current density we get the switching faster.

3.2 Impact of a weak applied field on the magnetization switching dynamic and the current density

As mentioned before, the magnetization switching time could change by the influence of the current density applied on the tri-layer; whenever the current is larger than the threshold current density, we get the switching quickly. In addition, the magnetization switching time is also influenced by the external magnetic field applied in plane of the geometry; the magnetization dynamics becomes more intricate when there is a magnetic field applied along the x-axis. Depending on the values and the signs of the applied magnetic field, the magnetization can either turn around and reach a new static stable state or keep to process continuously around the constant average energy orbit. As shown in Fig. 5, we have applied different values of external magnetic fields: $H_{\text{ext}} = -0.057M_s$, $-0.115M_s$, $0.0115M_s$ and $-0.0251M_s$, for a constant current density $J_c = -8 \times 10^6 \text{ A/cm}^2$. In the absence of the magnetic field, we are in the normal case where the STT energy is larger than the Gilbert damping, and thus we

Fig. 4 **a** The temporal evolution of magnetization m_x under different current densities and also the evolution of the threshold current density as a function of the magnetization switching time with

the illustration of the magnetization movement for three cases. **b** Low current density (damped motion), **c** average current density (stable precession) and **d** high current density (switching)

Fig. 5 The temporal behavior of magnetization m_x under constant current density $J_c = -8 \times 10^6$ A/cm² with different values of the magnetic field along the x-axis

get the magnetization switching easily at $t = 5.7$ ns. The application of a magnetic field following the negative direction of the x-axis which favors the APS produces a new energy term to the system which modifies the energy equilibrium state of the free layer, through reduces the H_{eff} which favors the reverse configuration (PS), therefore with second term in Eq. (1) linked between the Gilbert damping and H_{eff} , the Gilbert damping effect becomes very low, for weak fields $H_{\text{ext}} = -0.115 M_s$, $-0.057 M_s$ and $-0.0251 M_s$ with a threshold current density applied favors the same configuration, we get the switching at $t = 1.8$ ns, 3.4 ns and 2.3 ns, respectively; therefore, they are very smaller than before under zero magnetic field. For $H_{\text{ext}} = 0.115 M_s$, the switching becomes more difficult by reason of the magnetic field which favors the PS; consequently, the Gilbert damping becomes very important and the threshold current density becomes also insufficient to flip the magnetization to the APS. Thus, the magnetization remains wedged around its initial state.

The reverse orientation is also studied where the magnetization flips from APS to PS. In Fig. 6, we have injected the threshold current density $J_c = 7 \times 10^6$ A/cm² under different values of the external magnetic fields: $H_{\text{ext}} = 0.1156 M_s$, $0.0112 M_s$, $0.05812 M_s$ and $-0.0756 M_s$. We observe similar behavior of the magnetization in the last curve (see Fig. 5) with an irreversible increase in the magnetization associated with the reversal of the magnetization. Looking at the positive values of the magnetic field, for $H_{\text{ext}} = 0.1156 M_s$, the switching time is at 1.5 ns. Thus, this magnetization switching is faster than before (PS $\rightarrow$ APS). On the other hand, for the negative magnetic field $H_{\text{ext}} = -0.0756 M_s$, the magnetization finds a difficulty to reach the magnetization switching. The competition between spin-transfer and Gilbert torques leads to

Fig. 6 The magnetization trajectories from APS to PS of m_x under the threshold current density of $J_c = 7 \times 10^6$ A/cm² within different values of the magnetic field along the x-axis

know if the magnetization switching is possible or not. However, when an external magnetic field is applied, the magnetization orientation of free layer depends mainly on the direction of magnetic field. In the positive values ($H_{\text{ext}} = 0.115 M_s$) the strong Gilbert damping stopped the magnetization switching and making magnetization dynamics lie in the multidomain state. However, for the negative ($H_{\text{ext}} = -0.115 M_s$) the field reinforced the threshold current density to lead the magnetization to the switching through weakening of Gilbert damping. In fact, the types of magnetization dynamics are mainly influenced by the competition between STT and the Gilbert damping.

In addition to the switching time, the external field has also an influence on the threshold current density. As shown in Fig. 7, we presented the threshold current density evolution for the PS and the APS under different external field values.

The simulation showed that in the absence of the external field, we reach a threshold current density of -8×10^6 A/cm² for the APS and 7×10^6 A/cm² for PS. But, when we increase the external field, we noticed a critical current density decrease (Fig. 7b) to -4.8×10^6 A/cm² which can be considered as a minimal value of the threshold current density that we could reach under a low external field of $0.25 M_s$. Although when the external field decreases, the threshold current density increases gradually up to $J_c = 17 \times 10^6$ A/cm² for $H_{\text{ext}} = -0.167 M_s$. As a result, we confirm the great ability of a weak field to influence on the threshold current density value as well as on the STT energy. For the magnetization switching from the PS to the APS in Fig. 7b and for an external field that favors the PS, the threshold current density increased again to

Fig. 7 The relationship of the switching threshold current density versus external field for **a** switching to the APS and **b** switching to the PS

$J_c = 18 \times 10^6 \text{ A/cm}^2$ as a maximal value at $H_{\text{ext}} = 0.156 M_s$. However, it came down to $J_c = 5.1 \times 10^6 \text{ A/cm}^2$ for $-0.25 M_s$.

Consequently, the low field has two roles, the first is to promote the magnetization switching by decreasing the switching time which was clearly explained in Figs. 5 and 6. The second, as we have pointed out in Fig. 7, is it can enhance the critical current density.

In this subsection, we studied the magnetization dynamic as a function of the current density range of $-20 \times 10^6 \text{ A/cm}^2 \leq J \leq 20 \times 10^6 \text{ A/cm}^2$ under different weak magnetic fields typically lower than the coercive field H_c : $H_{\text{ext}} = 0, -0.115 M_s$ and $0.115 M_s$ (Fig. 8a) where the magnetization can be hysterically reversed by the current (the weak field regime). To elucidate this figure, we divided the magnetization dynamic into four sections as a function of the current density ranges (Fig. 8b). Switching state (SS), multidomain state (MDS), precession state (PS) and unchanging state (US). Thus, we are going to study the behavior of these sections with the magnetic field.

In the absence of the magnetic field and for $J \leq -8 \times 10^6 \text{ A/cm}^2$ and $J \geq 7 \times 10^6 \text{ A/cm}^2$, the magnetization lies in the switching state where the magnetization reaches the switching ($\theta = 0^\circ$ for PS or $\theta = \pi$ for APS). But as long as the current applied includes the range of $-8 \times 10^6 \text{ A/cm}^2 < J \leq -2.2 \times 10^6 \text{ A/cm}^2$ and $1.5 \times 10^6 \text{ A/cm}^2 \leq J < 7 \times 10^6 \text{ A/cm}^2$, the magnetization begins to divide into multi-domains, by change in the distribution of the initial equilibrium state ($\theta = \frac{\pi}{6}$ for APS, $\theta = \frac{5\pi}{6}$ for PS), with a frequency and an amplitude of oscillations not constant. For the range of $-2.2 \times 10^6 \text{ A/cm}^2 < J < 1.5 \times 10^6 \text{ A/cm}^2$, the current is insufficient to destabilize the initial equilibrium, and therefore the magnetization doesn't

change its equilibrium states. In the range of $0.9 \times 10^6 \text{ A/cm}^2 \leq J < 1.5 \times 10^6 \text{ A/cm}^2$, the magnetization lies in the steady precessional state (PS) where it can precess around the effective field, with oscillations at constant amplitude and frequency.

For $H_{\text{ext}} = 0.115 M_s$, the threshold current density changed from $J_c = -8 \times 10^6 \text{ A/cm}^2$ to $J_c = -15 \times 10^6 \text{ A/cm}^2$ (PS $\rightarrow$ APS) and from $J_c = 7 \times 10^6 \text{ A/cm}^2$ to $J_c = 5.3 \times 10^6 \text{ A/cm}^2$ (APS $\rightarrow$ PS). Under these currents, we have the MDS section in a range of $-15 \times 10^6 \text{ A/cm}^2 < J \leq -2.5 \times 10^6 \text{ A/cm}^2$ which is larger than the MDS section in $H_{\text{ext}} = 0$ for PS to APS, by the reason that the magnetization orientation is influenced by a resistance of the magnetic field which favors the PS. To the PS, the MDS section becomes very short with a range of $1.5 \times 10^6 \text{ A/cm}^2 \leq J < 5 \times 10^6 \text{ A/cm}^2$. For the US and PS sections, there is no a big change.

However, under a negative magnetic field ($H_{\text{ext}} = -0.115 M_s$), the magnetization dynamic has a reverse behavior in comparison with the positive magnetic field, the magnetization lies in the switching state in the ranges of $J \geq 14 \times 10^6 \text{ A/cm}^2$ (APS $\rightarrow$ PS) and $J \leq -5.5 \times 10^6 \text{ A/cm}^2$ (PS $\rightarrow$ APS). The magnetic field promotes the STT to trig switching for the APS and weaken it for the PS. Thus, the MDS section becomes large in the positive current but very short for the negative current.

3.3 Impact of free layer thickness on the magnetization switching dynamic and the STT energy

In this section, we simulated the magnetization reversal and dynamics of $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ -free layer with different

Fig. 8 **a** Hysteresis loop of the magnetization dynamic of the free layer $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ under a current density range of $[-20, 20] \times 10^6 \text{ A/cm}^2$ and with different magnetic fields applied along the x -axis. **b** Diagrams of the magnetization dynamic divided into four colors, and each section represents a type of the magnetization dynamic under the same current density range with $H_{\text{ext}} = 0, -0.115M_s$ and $0.115M_s$

thickness as $T = 1 \text{ nm}, 1.5 \text{ nm}, 2 \text{ nm}, 4 \text{ nm}, 2 \text{ nm}$ and 5 nm , and then we injected a current density of $J = -0.8 \times 10^6 \text{ A/cm}^2$. As shown in Fig. 9, we have different magnetization switching processes from the PS to the APS, depending on the free layer thickness.

The thickness of free layer plays a key role in reducing the switching time of the device. For the smallest thicknesses, we reach the magnetization switching quickly with a small switching time equal 2.7, 4.9 and 5.7 ns, respectively, for $T = 1, 1.5$ and 2 nm , through a precessional dynamics until trig the switching with oscillations around the x -axis controlled by STT. While that, for the higher thicknesses as $T = 4 \text{ nm}$ and 5 nm , we do not get the switching, and therefore the magnetization remained to oscillate near to the PS by reason of the STT which is very weak in this case and also accumulation phenomena

appear which leads to loss in spin polarization. According to Eq. (1), when the thickness is large, the STT energy becomes insufficient to flip the magnetization to the APS. However, the damping effect develops into against the magnetization switching where it becomes very important for the large thicknesses. So, by reason of the competition between spin-transfer and Gilbert torques, STT loses the control on the magnetization, and consequently we do not trig the switching.

Although when the free layer is ultra-thin ($T = 1 \text{ nm}, 1.5 \text{ nm}$ and 2 nm), the STT again becomes great, while that the Gilbert damping and the magnetization switching time decrease as the free layer thickness is small; therefore, the control of the magnetization is becoming easy. On the other hand, the issue of thermal instability arises. However, high thermal stability can be achieved via large

Fig. 9 The temporal evolution of the average magnetization m_x for different thicknesses of free layer under constant current density $J_c = -8 \times 10^6 \text{ A/cm}^2$

Fig. 10 The relationships of STT versus θ in Slonczewski's model for different free layer thicknesses

magnetocrystalline anisotropy and also large saturation magnetization which is realizable for our alloy $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ layer where it presents a large magnetocrystalline anisotropy, in addition to a saturation magnetization up to $9.2 \times 10^5 \text{ A/m}$ in the nanometer scales.

The simulation results of Fig. 9 are clearly explained in Fig. 10. We studied the thickness effect on the STT energy. We point out that more STT energy is great as we trig the magnetization switching quickly with a weak switching time. The spin-transfer torque as a function of the angle θ is plotted in Fig. 10 under a critical current density of $J_c = -8 \times 10^6 \text{ A/cm}^2$. The results show that the STT energy varies with different thicknesses of $T = 1 \text{ nm}$, 1.5 nm , 2 nm ,

4 nm , 4.5 nm , 5 nm up to 5.5 nm . First, we observe a slow increase in the energy of STT with the angle θ for all thicknesses because the Gilbert damping is too high in the PS and APS. But, whenever the magnetization moving the Gilbert damping loses little by little its energy, therefore, the STT energy starts to increase and as a result, the STT controls the magnetization.

For $T = 1 \text{ nm}$, the STT energy in $\theta = 90^\circ$ is equal to $1.125 \times 10^4 \text{ A/m}$ which is large enough to overcome the barrier of the magnetocrystalline of the $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ layer. However, when we increased the thickness, the STT energy also decreased, and therefore it becomes insufficient to trig the magnetization switching.

The STT energy keeps up to increase until it reaches to its maximum value at $\theta = 145.2^\circ$, and this maximum depends mainly on the thickness where it is up to $2.625 \times 10^4 \text{ A/m}$ for $T = 1 \text{ nm}$ and comes down into the value of $1.3125 \times 10^4 \text{ A/m}$ for $T = 5 \text{ nm}$. After that, H_{STT} decreases when θ increases; therefore, the energy of STT and the Gilbert damping making the magnetization switch to the APS.

4 Conclusion

In this paper, we studied the magnetization switching of half-metallic Heusler $\text{Co}_{1.5}\text{Fe}_{1.5}\text{Ge}$ (CFG) alloy in a spin-valve nanopillar CFG/Ag/CFG. By micromagnetic simulation, we numerically solved the Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation including the STT term in the spin-valve system. The magnetization switching is due to the competition between the STT and Gilbert energy. For the current densities $J_c^{\text{PS} \rightarrow \text{APS}} = -8 \times 10^6 \text{ A/cm}^2$ or $J_c^{\text{APS} \rightarrow \text{PS}} = 7 \times 10^6 \text{ A/cm}^2$, the STT overcomes the Gilbert damping and consequently leads the free layer magnetization to the switching (PS or APS). In addition, we have optimized the threshold of these current densities and the magnetization switching time using different free layer thicknesses and with the application of a weak magnetic field that promotes the same switching.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

References

- Berger L (1996) Emission of spin waves by a magnetic multi-layer traversed by a current. *J Phys Rev B* 54:9353. <https://doi.org/10.1103/PhysRevB.54.9353>

2. Slonczewski JC (1996) Current-driven excitation of magnetic multilayers. *J Magn Magn Mater* 159:L1. [https://doi.org/10.1016/0304-8853\(96\)00062-5](https://doi.org/10.1016/0304-8853(96)00062-5)
3. Kiselev SI, Sankey JC, Krivorotov IN, Emley NC, Schoelkopf RJ, Buhrman QA, Ralph DC (2003) Microwave oscillations of a nanomagnet driven by a spin-polarized current. *J Nat*. <https://doi.org/10.1038/nature01967>
4. Tulapurkar AA, Suzuki Y, Fukushima A, Kubota H, Maehara H, Tsunekawa K, Djayaprawira DD, Watanabe N, Yuasa S (2005) Spin-torque diode effect in magnetic tunnel junctions. *J Nat* 438:339. <https://doi.org/10.1038/nature04207>
5. Grollier J, Cros V, Hamzic A, George JM, Jaffrs H, Fertl A (2001) Spin-polarized current induced switching in Co/Cu/Co pillars. *J Appl Phys Lett* 78:3663. <https://doi.org/10.1063/1.1374230>
6. Katine JA, Albert FJ, Buhrman RA, Myers EB, Ralph DC (2000) Current-driven magnetization reversal and spin-wave excitations in Co/Cu/Co pillars. *J Phys Rev Lett* 84(14):31493152. <https://doi.org/10.1103/PhysRevLett.84.3149>
7. Huang HB, Ma XQ, Liu ZH, Meng FY, Xiao ZH, Wu PP, Shi SQ, Chenc LQ (2011) Micromagnetic simulation of spin-transfer switching in a full-Heusler $\text{Co}_2\text{FeAl}_{0.5}\text{Si}_{0.5}$ alloy spin-valve nanopillar. *J Appl Phys Lett* 110:033913. <https://doi.org/10.1063/1.3619773>
8. Sun Y, Chang H, Kabatek M, Song Y-Y, Wang Z, Jantz M, Schneider W, Wu M, Montoya E, Kardasz B, Heinrich B, te Velthuis SGE, Schultheiss H, Hoffmann A (2013) Damping in yttrium iron garnet nanoscale films capped by platinum. *J Phys Rev Lett* 111:106601. <https://doi.org/10.1103/PhysRevLett.111.106601>
9. Devolder T, Tahmasebi T, Eimer S, Hauet T, Andrieu S (2013) Compositional dependence of the magnetic properties of epitaxial FeV/MgO thin films. *J Appl Phys Lett* 103:242410. <https://doi.org/10.1063/1.4845375>
10. Ogiwara M, Iihama S, Seki T, Kojima T, Mizukami S, Mizuguchi M, Takashi K (2013) Magnetization damping of an L10-FeNi thin film with perpendicular magnetic anisotropy. *J Appl Phys Lett* 103:242409. <https://doi.org/10.1063/1.4845035>
11. Huang SX, Chen TY, Chien CL (2008) Spin polarization of amorphous CoFeB determined by point-contact Andreev reflection. *J Appl Phys Lett* 92:242509. <https://doi.org/10.1063/1.2949740>
12. Ikeda S, Miura K, Yamamoto H, Mizunuma K, Gan HD, Endo M, Kanai S, Hayakawa J, Matsukura F, Ohno H (2010) A perpendicular-anisotropy CoFeB-MgO magnetic tunnel junction. *J Nat Mater* 9:721–724. <https://doi.org/10.1038/nmat2804>
13. Graf T, Felser C, Parkin SSP (2011) Simple rules for the understanding of Heusler compounds. *J Prog Solid State Chem* 39:150. <https://doi.org/10.1016/j.progsolidstchem.2011.02.001>
14. Maat S, Carey MJ, Childress JR (2008) Current perpendicular to the plane spin-valves with CoFeGe magnetic layers. *J Appl Phys Lett* 93:143505. <https://doi.org/10.1063/1.2993213>
15. Ding M, Poon SJ (2012) Perpendicular magnetization of $\text{Co}_{20}\text{Fe}_{50}\text{Ge}_{30}$ films induced by MgO interface. *J Appl Phys Lett* 101:122408. <https://doi.org/10.1063/1.4754001>
16. Sukegawa H, Kasai S, Furubayashi T, Mitani S, Inomata K (2010) Spin-transfer switching in an epitaxial spin-valve nanopillar with a full-Heusler $\text{Co}_2\text{FeAl}_{0.5}\text{Si}_{0.5}$ alloy. *J Phys Rev Lett* 96:042508. <https://doi.org/10.1063/1.3297879>
17. Huang HB, Ma XQ, Liu ZH, Zhao CP, Chen LQ (2013) Micromagnetic simulation of high-power spin-torque oscillator in half-metallic Heusler alloy spin valve nanopillar. *J AIP Adv* 3:032132. <https://doi.org/10.1063/1.4796189>
18. Huang HB, Ma XQ, Liu ZH, Zhao CP, Shi SQ, Chen LQ (2013) Simulation of multilevel cell spin transfer switching in a full-Heusler alloy. Spin-valve nanopillar. *J Appl Phys Lett* 102:042405. <https://doi.org/10.1063/1.4789867>
19. Huang HB, Ma XQ, Liu ZH, Zhao CP, Chen LQ (2014) Modeling current-induced magnetization switching in Heusler alloy Co_2FeAl -based spin-valve nanopillar. *J Appl Phys* 115:133905. <https://doi.org/10.1063/1.4870291>
20. Finocchio G, Azzerboni B, Fuchs GD, Buhrman RA, Torres L (2007) Micromagnetic modeling of magnetization switching driven by spin-polarized current in magnetic tunnel junctions. *J Appl Phys* 101(6):063914. <https://doi.org/10.1063/1.2496202>
21. Finocchio G, Carpentieri M, Azzerboni B, Torres L, Martinez E, Lopez-Diaz L (2006) Micromagnetic simulations of nanosecond magnetization reversal processes in magnetic nanopillar. *J Appl Phys* 99(8):08G522. <https://doi.org/10.1063/1.2177049>
22. Boule O (2007) Magnetization precession by spin transfer in magnetic nanopillars. Ph.D. thesis, Pierre and Marie Curie University, Paris VI
23. Miltat JE, Donahue MJ (2007) Handbook of magnetism and advanced magnetic materials, volume micromagnetism. In: Miltat JE, Donahue MJ (eds) Numerical micromagnetic: finite difference methods. Wiley, London. <https://doi.org/10.1002/9780470022184.hmm202>
24. Labrune M, Miltat J (1995) Wall structures in ferro/antiferromagnetic exchange-coupled bilayers: a numerical micromagnetic approach. *J Magn Magn Mater* 151(12):231245. [https://doi.org/10.1016/0304-8853\(95\)00328-2](https://doi.org/10.1016/0304-8853(95)00328-2)
25. Tandon S, Beleggia M, Zhu Y, De Graef M (2004) On the computation of the demagnetization tensor for uniformly magnetized particles of arbitrary shape. Part I: analytical approach. *J Magn Magn Mater* 271:9. <https://doi.org/10.1016/j.jmmm.2003.09.011>
26. Beleggia M, De Graef M (2005) General magnetostatic shape-shape interactions. *J Magn Magn Mater* 285:L1. <https://doi.org/10.1016/j.jmmm.2004.09.004>
27. Software Mumax3. <http://mumax.github.io/>
28. Bazaliy Ya B, Jones BA, Zhang SC (2001) Towards metallic magnetic memory: how to interpret experimental results on magnetic switching induced by spin-polarized currents. *J Appl Phys* 89:6793. <https://doi.org/10.1063/1.1362642>
29. Xi H, Gao K, Shi Y (2004) Microwave generation by a direct current spin-polarized current in nanoscale square magnets. *J Appl Phys* 84:4977. <https://doi.org/10.1063/1.1762981>
30. Katine JA, Albert FJ, Buhrman RA, Myers EB, Ralph DC (2000) Current-driven magnetization reversal and spin-wave excitations in Co/Cu/Co pillars. *J Phys Rev Lett* 84:3149. <https://doi.org/10.1103/PhysRevLett.84.3149>
31. Kiselev SI, Sankey JC, Krivorotov IN, Emley NC, Rinkoski M, Perez C, Buhrman RA, Ralph DC (2004) Current-induced nanomagnet dynamics for magnetic fields perpendicular to the sample plane. *J Phys Rev Lett* 93:03660. <https://doi.org/10.1103/PhysRevLett.93.036601>
32. Koch RH, Katine JA, Sun JZ (2004) Time-resolved reversal of spin-transfer switching in a nanomagnet. *J Phys Rev Lett* 92:088302. <https://doi.org/10.1103/PhysRevLett.92.088302>
33. Xiao J, Zangwill A, Stiles MD (2005) Macrospin models of spin transfer dynamics. *J Phys Rev. B* 72:014446. <https://doi.org/10.1103/PhysRevB.72.014446>
34. Huang HB, Ma XQ, Liu ZH, Meng FY, Xiao ZH, Wu PP, Shi SQ, Chen LQ (2011) Micromagnetic simulation of spin-transfer switching in a full-Heusler $\text{Co}_2\text{FeAl}_{0.5}\text{Si}_{0.5}$ alloy spin-valve nanopillar. *J Appl Phys* 110:033913. <https://doi.org/10.1063/1.3619773>
35. Sabareesan P, Daniel M (2011) Magnetization reversal in nanopillar devices. *J Phys Scr* 84:035706. <https://doi.org/10.1088/0031-8949/84/03/035706>