Control of spins in a nano-sized magnet using electric-current

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With the development of spintronics, spin-transfer torque control of magnetic properties receives considerable attention. In this paper the Landau–Lifshitz–Gilbert equation including the torque term is used to investigate the magnetic moment dynamics in the free layer of the ferromagnet/non-magnetic/ferromagnet (FM1/N/FM2) structures. It is found that the reverse critical time τ_c decreases with the current increasing. The critical time τ_c as a function of current for the perpendicular and parallel easy magnetic axes are the same. The critical time τ_c increases with the damping factor α increasing. In the case of large current the influence of the damping factor α is smaller, but in the case of little torque the critical time τ_c increases greatly with the damping increasing. The direction of the magnetization in the fixed layer influences the critical time, when the angle between the magnetization and the z direction changes from 0.1π to 0.4π, the critical time τ_c decreases from 26.7 to 15.6.

Keywords: magnetization switching, spin transfer torque, Landau–Lifshitz–Gilbert (LLG) equation

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1. Introduction

Efficient control of magnetization switching and dynamics is a crucial issue in spintronics. Recent rapid development in nanotechnology, such as thin film growth and nano-fabrication, has provided new approaches to the control of magnetization, such as voltage induced by magnetic anisotropy change and spin-transfer torque (STT)[1,2] control of magnetic properties induced by an injection of spin-polarized current in particular. The mechanism behind the spin-transfer effect is based on the conservation of spin angular momentum. A nano-scale sandwich structure is composed of FM1/N/FM2 three layers, in which FM1 is a ferromagnet with fixed magnetization, N is a non-magnetic layer and FM2 is a thin ferromagnet called free layer, whose magnetization can be changed. As the injected electrons move from the bottom ferromagnetic electrode (FM1) to the top one (FM2), the electrons have definite spin polarization P determined by the magnetization of FM1. The electrons move through the non-magnetic layer, and enter the FM2 layer, where there are local anisotropic magnetic fields inside instead of the external magnetic field. The spin-polarized electrons will precess around the local magnetic field. Due to damping effect the electrons will approach the localized spin. Based on the conservation law of angular momentum, the localized spin in FM2 feels opposite torque. As a result, the process can be used to control magnetization precessing or even switching.

In order to develop the magnetoresistance devices, it is important to characterize the spin dynamics. The Landau–Lifshitz–Gilbert (LLG) equation with spin-transfer torque included is useful. In the analysis with the application of the LLG equation, the macro-spin approximation is an important one. In this approximation, spins in the magnetic layer are treated as a single spin. The macrospin model is useful since the spin dynamics are described only by a few essential physical parameters. The spin dynamics in the magnetic free layer of micro-fabricated magnetoresistance devices are found consistent with the model.

Magnetization reversal with electric current[3–8] is essential for future magnetic data storage technology, such as magnetic random access memories. Diao *et al.*[9] presented experimental and numerical results of current-driven magnetization switching in magnetic tunnel junctions, and showed that the tunneling magnetoresistance ratio is as large as 155% and the intrinsic switching current density is as low as 1.1×10^6 A·cm^{-2}, otherwise, three magnetization switching modes, thermal activation, dynamic reversal, and precessional process, play significant roles in determining the spin transfer torque-induced magnetization switching. Safeer *et al.*[10] reported a new approach to control magnetization reversal, which is compatible with any physical mechanism that uses spin orbit torque and allows the magnetization to be reversed by transferring angular momentum directly from the crystal lattice. The current flow is no longer restricted to a single direction and can have any orientation within the magnetic thin film plane. Zhang *et al.*[11] determined that both the in-plane ($T_\parallel$) and field-like ($T_\perp$) spin transfer torque effect played a significant role in enhancing the reliable magnetization switching of the free layer. By combining both the E-field pulse and STT current, the power cost for deterministic magnetization switching could be significantly reduced by two orders of magnitude if both the in-plane and field-like torques are considered.

The spin-transfer torque (STT) control of magnetic properties has been verified by a series of experiments.[12–19]

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Current-driven magnetization reversal in a ferromagnetic semiconductor-based (Ga, Mn)As/GaAs/(Ga, Mn)As magnetic tunnel junction is determined at 30 K.[12] Magnetoresistance measurements combined with current pulse application on a rectangular 1.5 μm×0.3 μm device revealed that magnetization switching occurs at low critical current densities of 1.1×10^5 A/cm^2–2.2×10^5 A/cm^2. The spin-transfer magnetization switching properties of CoFe/Pd-based perpendicularly magnetized giant magnetoresistance cells have also been reported.[17] A two-dimensional color map of the spin-transfer switching probability from AP (anti-parallel) to P (parallel) states as a function of the pulse current amplitude I and width $t_{\rm pulse}$ was given. A perpendicular MTJ (magnetic tunnel junction) consisting of Ta/CoFeB/Mgo/CoFeB/Ta shows a high tunnel magnetoresistance ratio over 120%, high thermal stability at dimension of diameter as low as 40 nm and of a low switching current of 49 μA.[18]

To fabricate the MRAM (magnetic random access memory) with MTJs, the MTJs need to meet several requirements: a high TMR ratio over 100% for high-speed reading operation, a low intrinsic critical current $I_{\rm c}$ for low-power writing operation, and a high thermal stability factor Δ to ensure years of non-volatility. It is demonstrated that the CoFeB-MgO-based MTJs with a perpendicular magnetic easy axis[17] of TMR ratio = 120%, $I_{\rm c}=49$ μA, and $\Delta=43$, basically meet the major requirements. To ensure a 10-years retention time for multiple bits, however, one needs to further increase Δ. Sato *et al.* investigated the $I_{\rm c}$ and Δ as functions of junction diameter D as D decreases from 56 nm to 11 nm.[19] They found that Δ is basically a constant, and starts to decrease when D is smaller than 30 nm. $I_{\rm c}$ reduces along with the decrease of D in the entire investigated D range. A ratio of Δ to $I_{\rm c}$ shows continuous increase when D decreases to 11 nm.

This paper will discuss the spin switching properties as functions of material parameters, electric current parameter, etc theoretically with the application of LLG equation.

2. LLG equation

In the presence of SST, the LLG equation is written as

$$\frac{1}{\gamma}\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} = -\boldsymbol{m}\times\boldsymbol{H}_{\rm eff}+\left(\frac{\alpha}{\gamma}\right)\boldsymbol{m} \times\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t}-a_J\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{n}_s), \tag{1}$$

where $\boldsymbol{m}$ is the unit vector of the macro magnetic moment in the free layer, $\gamma\approx 2\mu_{\rm B}/\eta$ is the gyromagnetic ratio, α is the phenomenological LLG damping constant, $H_{\rm eff}$ is the local magnetic field, $n_{\rm s}$ is the unit vector of the magnetization in the fixed layer and a_J is a torque constant relative to the spin-polarized current,

$$a_J=\left(\frac{\hbar}{2e}\right)\eta\left(\frac{I}{\mu_0 S\mathrm{d}M_{\rm s}}\right), \tag{2}$$

where η is the spin polarization of electrons, I is the current, $M_{\rm s}$ is the saturated magnetization, S and d are the area and width of the free layer, respectively.

Inserting $\mathrm{d}\boldsymbol{m}/\mathrm{d}t$ at the left side of Eq. (1) into the right side of Eq. (1), after arranging we obtain

$$\frac{1}{\gamma_0}\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} = -\boldsymbol{m}\times\boldsymbol{H}_{\rm eff}-\alpha\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{H}_{\rm eff}) -a_J\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{n}_s)+\alpha a_J(\boldsymbol{m}\times\boldsymbol{n}_s), \tag{3}$$

where

$$\gamma_0=\frac{\gamma}{1+\alpha^2}. \tag{4}$$

In order to transfer Eq. (3) into the dimensionless form, we take the unit of the magnetic field as H_0, $H_{\rm eff}=h_{\rm eff}H_0$. The time unit is taken as $\tau_0=1/\gamma H_0$, $t=\tau\tau_0$. In this paper we took $H_0=10^4$ A/m$\sim1.257\times10^{-2}$ T, $\gamma H_0=176$ GHz/T$\times1.257\times10^{-2}$ T$=2.21$ GHz, $\tau_0=0.45$ ns. With variable τ, equation (3) becomes

$$(1+\alpha^2)\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}\tau} = -\boldsymbol{m}\times\boldsymbol{h}_{\rm eff}-\alpha\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{h}_{\rm eff}) -a_{JH}\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{n}_s)+\alpha a_{JH}(\boldsymbol{m}\times\boldsymbol{n}_s), \tag{5}$$

where $a_{JH}=a_J/H_0$. $\boldsymbol{H}_{\rm eff}$ represents the sum of the internal and external fields on the magnet. In the absence of any external fields, internal fields still present, it refers to what is responsible for keeping the magnetization pointing along the easy axis. For example, a thin-film magnet oriented in the xy plane with easy axis along z axis is characterized by

$$H_{\rm eff}=H_z m_z\hat{z}+H_x m_x\hat{x}, \tag{6}$$

representing the internal "uniaxial anisotropy" effective field. It is noticed that the internal field is dependent on the magnetic moment $\boldsymbol{m}$.

We write Eq. (5) in the component form,

$$\begin{aligned}
&(1+\alpha^2)\frac{\mathrm{d}m_x}{\mathrm{d}t}\\
&= -m_y m_z H_z-\alpha\left(-m_x m_y^2 H_x-m_x m_z^2 H_x+m_x m_z^2 H_z\right)\\
&\quad -a_{JH}\left[m_x m_y n_y+m_x m_z n_z-\left(m_y^2+m_z^2\right)n_x\right]\\
&\quad +\alpha a_{JH}\left(m_y n_z-m_z n_y\right),\\
&(1+\alpha^2)\frac{\mathrm{d}m_y}{\mathrm{d}t}\\
&= m_x m_z H_z-m_x m_z H_x-\alpha\left(m_y m_x^2 H_x+m_y m_z^2 H_z\right)\\
&\quad -a_{JH}\left[m_x m_y n_x+m_y m_z n_z-\left(m_x^2+m_z^2\right)n_y\right]\\
&\quad +\alpha a_{JH}\left(m_z n_x-m_x n_z\right),\\
&(1+\alpha^2)\frac{\mathrm{d}m_z}{\mathrm{d}t}\\
&= m_x m_y H_x-\alpha\left[m_z m_x^2 H_x-\left(m_x^2+m_y^2\right)m_z H_z\right]\\
&\quad -a_{JH}\left[m_x m_z n_x+m_z m_y n_y-\left(m_x^2+m_y^2\right)n_z\right]
\end{aligned}$$

$$+\alpha a_{JH}\left(m_x n_y - m_y n_x\right). \tag{7}$$

The torque coefficient a_{JH} in Eq. (7) is calculated from Eq. (2) as follows: if we suppose that the volume $\Omega = S \times d = v$ (9000 nm^3), the electric current $I = i$ mA, saturated magnetization $M_s = m_s \times 10^6$ A/m, then

$$\begin{aligned}
\mu_0 S \mathrm{d} M_s &= 1.257\times10^{-6}\ \frac{\mathrm{V\cdot s}}{\mathrm{A\cdot m}} \times v\,(9000) \\
&\quad \times \left(10^{-9}\ \mathrm{m}\right)^3 \times m_s 10^6\ \frac{\mathrm{A}}{\mathrm{m}} \\
&= 1.13\times10^{-23} v m_s\ \mathrm{V\cdot m\cdot s}, \\
\mu_0 S \mathrm{d} M_s &= 1.13\times10^{-23}\ \mathrm{V\cdot m\cdot s} \times 10^4\ \frac{\mathrm{A}}{\mathrm{m}} \\
&= 1.13\times10^{-19} \times v m_s\ \mathrm{V\cdot A\cdot s}\,(J), \\
a_{JH} = \frac{a_J}{H_0} &= \eta \frac{1.0544\times10^{-34}\ \mathrm{J\cdot s} \times i\times10^{-3}\ \mathrm{A}}{2\times1.602\times10^{-19} C \times 1.13\times10^{-19} \times v m_s\ \mathrm{J}} \\
&= 2.91\frac{\eta i}{v m_s}.
\end{aligned} \tag{8}$$

3. Some calculation results

3.1. Spin torque effect

Figure 1 shows the components of magnetic moment $\boldsymbol{m}$ in the free layer as functions of time in τ, the parameters are taken as $h_z = 0.5$, $h_x = 0.02$, $\alpha = 0.02$, $a_{JH} = 0.08$. From Fig. 1 we see that first the magnetic moment precesses around the magnetic field in the z axis, then the z component decreases due to the electric current, and then becomes negative. At the same time, the amplitudes of x and y components decrease gradually, meaning the magnetization of the free layer reverses. The turning point (critical time) is at $\tau_c = 16.7$.

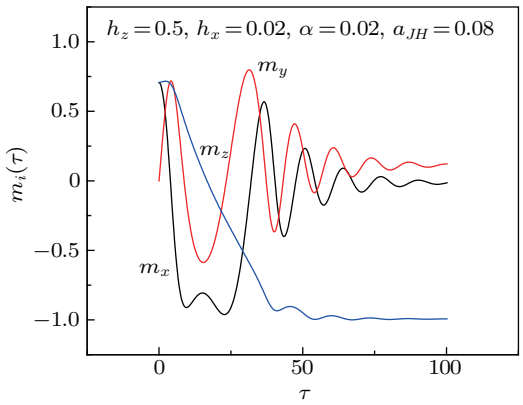


Fig. 1. (color online) Components of magnetic moments as functions of time τ in the case of easy magnetic axis in the z direction.

For a concrete concept, from Eq. (5) the critical time is $t_c = 16.7\tau_0 = 7.5$ ns. The torque coefficient $a_{JH} = 0.08$, from Eq. (8), if we take $\eta = 0.5$, $v = 50$, $m_s = 1$, then the critical current $I_c = 2.75$ mA. Equation (8) gives a scaling relation between the critical current and the volume of the free layer (area and thickness). If we fix the thickness, then the critical current I_c will be proportional to the area of the free layer, as shown in Ref. [19].

Figure 2 shows the trajectory of magnetic moment $\boldsymbol{m}$ in the free layer, and the parameters are taken as the same as Fig. 1, $h_z = 0.5$, $h_x = 0.02$, $\alpha = 0.02$, $a_{JH} = -0.08$. When the STT torque surpasses damping torque in the opposite direction, the precession trajectory opens up till it crosses the equator, leading to the magnetization reversal.

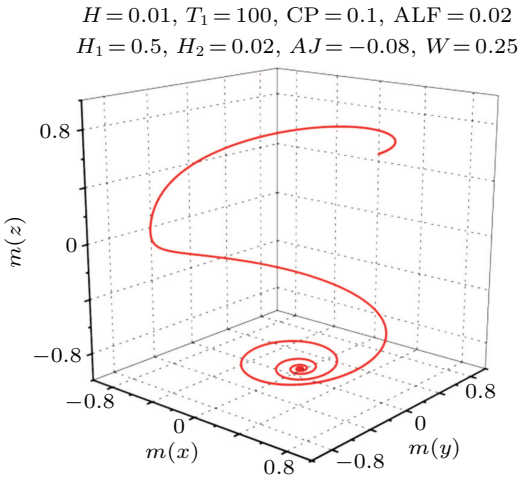


Fig. 2. (color online) The trajectory of magnetic moment $\boldsymbol{m}$ in the free layer.

3.2. Dependence of current

If we fix all other parameters and only change current, we obtain the dependence relation of the critical times on the current. Figure 3 shows the variations of the z components of magnetic moment $\boldsymbol{m}$ with time for different current a_{JH}, the other parameters are $h_z = 0.5$, $h_x = 0.02$, $\alpha = 0.02$. From Fig. 3 we see that the critical time decreases with the current (a_{JH}) increasing.

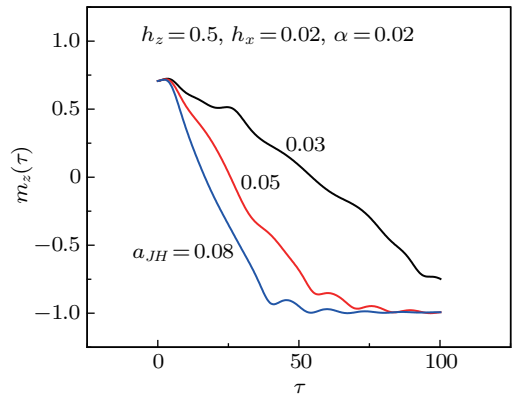


Fig. 3. (color online) Variations of the z components of magnetic moment $\boldsymbol{m}$ with time for different current a_{JH}.

Figure 4 shows the critical time τ_c as a function of a_{JH}, the other parameters are h_z =0.5, h_x =0.02, $\alpha = 0.02$. From Fig. 4 we see that when the current is larger, the critical time is shorter. But when the current is larger than a definite value, in our case $a_{JH} = 0.05$, the critical time decreases slowly. On the other hand, when the current is smaller than the $a_{JH} = 0.05$ value, the critical time increases rapidly. This trend is consistent with the experimental results.[17]

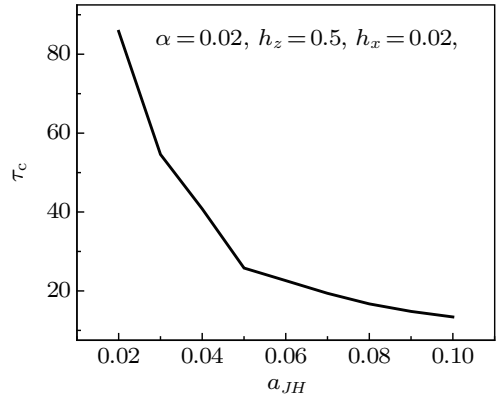


Fig. 4. Critical time τ_c as a function of a_{JH}, for $\alpha = 0.02$, $h_z = 0.5$, $h_x = 0.02$.

3.3. Effect of field anisotropy

Above we assumed that the easy magnetic axis in the free layer is in the z direction, we have taken that $h_z = 0.5$, $h_x = 0.02$. In the case of the easy magnetic axis in the parallel x direction we take $h_z = 0.02$, $h_x = 0.5$. Figure 5 shows the components of magnetic moment $\boldsymbol{m}$ in the free layer as functions of time in τ, the parameters are taken as $h_z = 0.02$, $h_x = 0.5$, $\alpha = 0.02$, $a_{JH} = 0.08$. From Fig. 5 we see that the components m_y and m_z oscillate with τ, they precess around the strong magnetic field in the x direction. The component m_x decreases with τ, and becomes negative at a critical time τ_c (16.7), i.e., the magnetization reverses. This behavior is the same as the case of the easy axis in the z direction (see Fig. 2), only the m_z and m_x exchange.

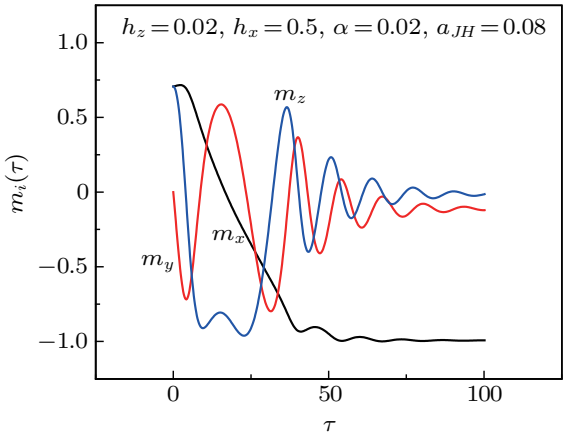


Fig. 5. (color online) Components of magnetic moments as functions of time τ in the case of easy magnetic axis in the x direction.

Figure 4 shows the critical time τ_c as a function of a_{JH} for the case of easy magnetic axis in the z direction. The calculation found that the critical time τ_c as a function of a_{JH} for that the easy magnetic axis in the x direction is the same as that in the z direction, i.e., as shown in Fig. 4.

3.4. Effect of damping factor α

In the absence of current, the effect of the damping is to decrease the amplitude of the precession of the magnetic moment, and to make the magnetic moment approach to the fixed magnetic field. In the presence of current the damping decreases the torque due to the current, and increases the critical time τ_c of magnetization reversion.

Figure 6 shows the components of magnetic moment $\boldsymbol{m}$ in the free layer as functions of time in τ, the parameters are the same as Fig. 1, but the damping factor increases to $\alpha = 0.08$. Comparing Fig. 6 with Fig. 1 we see that the variation of the components of $\boldsymbol{m}$ are basically the same, only the critical time τ_c increases from 16.7 to 20.7 when α increases from 0.02 to 0.08.

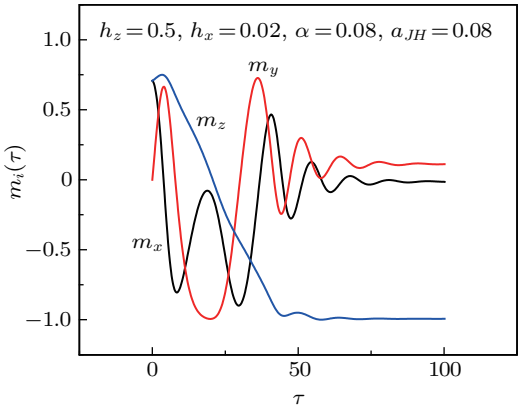


Fig. 6. (color online) Components of magnetic moment $\boldsymbol{m}$ in the free layer as functions of time τ, the parameters are the same as Fig. 1, but the damping factor α =0.08.

Figure 7 shows the τ_c as a function of α for $a_{JH} = 0.05$ and 0.10. From Fig. 7 we see that the τ_c increases when α does the same, but the increasing speeds vary with regards to different a_{JH} (current). In the case of large current the torque caused by the current is large, so the robustness against the damping is strong. On the other hand, in the case of little torque the robustness against the damping is weak when the damping increases, which makes the critical time τ_c increase greatly.

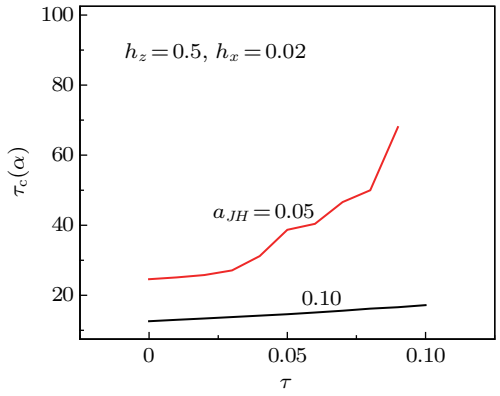


Fig. 7. (color online) τ_c as a function of α for $a_{JH} = 0.05$ and 0.10.

3.5. Effect of magnetization direction n_s in the fixed layer

In LLG equation n_s is the unit vector of the magnetization in the fixed layer. In the above calculation we have taken

$$\boldsymbol{n}_s = \cos\omega\hat{k} + \sin\omega\hat{i}, \tag{9}$$

$\omega = 0.25\pi$, and corresponding to initial values of the components of magnetic moment in the free layer. When ω changes, so does the direction of the magnetization relative to the z axis, i.e., corresponding initial values of the components of magnetic moment in the free layer.

Figure 8 shows the components of magnetic moment $\boldsymbol{m}$ in the free layer as functions of time in τ, the parameters are the same as Fig. 1, but the $\omega = 0.1\pi$ instead of 0.25π. The initial values of the $\boldsymbol{m}$ are (0.309, 0., 0.9511), and when $\omega = 0.25\pi$, the initial values are (0.7071, 0, 0.7071). From Fig. 8 we see that the components m_x and m_y increase first, reach their maximum near τ_c, then decrease. The critical time $\tau_c = 26.7$ is larger than that in the case of $\omega = 0.25\pi$, $\tau_c = 16.7$ (see Fig. 1). The critical times τ_c for different ω are shown in Table 1, from the table we see that the τ_c decreases when ω increases. Physically, because the angle between the initial magnetic moment and the magnetic field becomes larger, it is easy to reverse the magnetic moment.

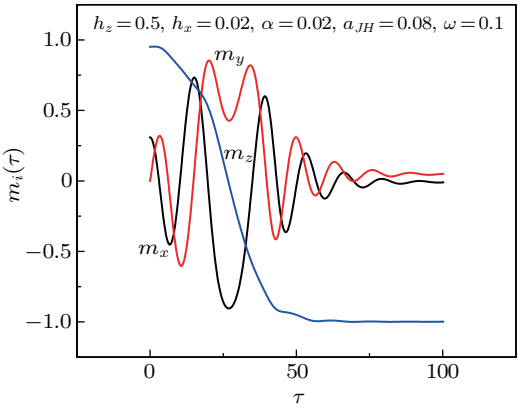


Fig. 8. (color online) Components of magnetic moment $\boldsymbol{m}$ in the free layer as functions of time τ, the parameters are the same as Fig. 1, but for $\omega = 0.1\pi$.

Table 1. Critical times τ_c for different ω.

ω	0.1	0.2	0.25	0.3	0.4
τ_c	26.7	18.3	16.7	15.6	16.7

4. Summary

In this paper the LLG equation including the STT torque term is employed to investigate the magnetization dynamics in the free layer of the FM1/N/FM2 structures. Firstly, we change the LLG equation into the dimensionless form, in which the unit of time is the degree of magnitude of ns, and the dimensionless torque coefficient a_{JH} including the scaling relation between the critical current and the volume, saturated magnetization of the free layer, and the spin polarization of electrons. When the current is larger than a definite value, the critical time τ_c decreases slowly. On the other hand, when the current is smaller than the definite value, the critical time increases rapidly. The reverse critical time τ_c as a function of a_{JH} for the perpendicular and parallel easy magnetic axes are same. The τ_c increases along with the increase of damping factor α, but the increasing speeds vary with regards to different a_{JH} (current). In the case of large current the influence of α is smaller. On the other hand in the case of little torque the critical time τ_c increases greatly with the damping increasing. The direction of the magnetization in the fixed layer influences the critical time, when the angle between the magnetization and the z direction changes from 0.1π to 0.3π and the τ_c decreases from 26.7 to 15.6.

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