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Citation: Chin. Phys. B . 2018, 27(6): 067502. **doi:** 10.1088/1674-1056/27/6/067502

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Voltage control of magnetization switching and dynamics*

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(Received 22 November 2017; revised manuscript received 9 March 2018; published online 10 May 2018)

The voltage controlled magnetic switching effect is verified experimentally. The Landau–Lifshitz–Gilbert (LLG) equation is used to study the voltage controlled magnetic switching. It is found that the initial values of magnetic moment components are critical for the switching effect, which should satisfy a definite condition. The external magnetic field which affects only the oscillation period should be comparable to the internal magnetic field. If the external magnetic field is too small, the switching effect will disappear. The precessions of m_x and m_y are the best for the tilt angle of the external magnetic field $\theta_t = 0°$, i.e., the field is perpendicular to the sample plane.

Keywords: magnetic switching, voltage control, spin transfer torque, Landau–Lifshitz–Gilbert (LLG) equation

PACS: 75.78.–n, 75.30.Gw, 77.80.Fm **DOI:** 10.1088/1674-1056/27/6/067502

1. Introduction

Efficient control of magnetization switching is crucial for a magnetic storage device, and it has been an important topic in magnetism from the viewpoints of both fundamental physics and practical applications.[1–10] In recent decades, the spin-transfer-torque (STT) switching[11–14] of magnetic nanostructure has been extensively explored due to its potential for high performance magnetic memory technologies. The STT induced manipulation of spin in a nanoscale ferromagnet has accelerated the development of novel spintronics devices. However, in order to further reduce the operating power, an innovative approach to controlling the magnetization direction and dynamics solely by using voltage [15,16] is required.

One possible solution is the voltage control of the perpendicular magnetic anisotropy in an ultrathin 3d transition ferromagnetic metal layer. Weisheit *et al.* first demonstrated that the magnetocrystalline anisotropies of ordered FePt and FePd intermetallic compounds can be reversibly modified by an applied electric field when immersed in an electrolyte.[17] A voltage variation of -0.6 V on a 2-nm thick film changed the values by -4.5 and $+1\%$ in FePt and FePd, respectively. The modification of the magnetic parameters was attributed to a change in the number of unpaired d electrons in response to the applied electric field.

Two years later Maruyama *et al.* demonstrated that this effect can be observed in a solid state device consisting of Au/ultrathin Fe/MgO/polyimide/ITO junctions.[18] A relatively small electric field (less than 100 mV·nm^{-1}) can cause a change ($\sim 40\%$) in the magnetic anisotropy of a bcc Fe (001)/MgO (001) junction. Simulations confirm that voltage-controlled magnetization switching in the magnetic tunnel junction is possible by using the anisotropy change. Because the influence of the electric field on the perpendicular anisotropy is effective only at the interface, the ferromagnetic layer is composed of only a few monatomic layers. The anisotropic energy of the film consists of a surface anisotropy term $\Delta K_{\mathrm{mS}}(V)$ induced by application of a voltage V. When the voltage decreases from $+200$ V to -200 V, the magnetic anisotropy energy was changed from -31.3 kJ·m^{-3} to -13.7 kJ·m^{-3}, corresponding to the perpendicular anisotropy field 22 kA·m^{-1} and 12 kA·m^{-1}, respectively. An external magnetic field of 8 kA·m^{-1} was applied in the direction normal to the film plane to tilt the magnetization towards the perpendicular direction. In these conditions, the Landau–Lifshitz–Gilbert (LLG) equation simulations show that a dynamic precession and switching to another energetically stable point is achieved if the pulse rise time is short enough (less than 1 ns).

Shiota *et al.* also demonstrated a coherent processional magnetization switching by using an electric field in nanoscale magnetic cells adjacent to an MgO barrier.[19] The ultrathin FeCo layer sandwiched between the Au and MgO layers exhibits considerable perpendicular magnetic anisotropy (PMA). A macro-spin model simulation based on the LLG equation is performed, where the damping constant $\alpha = 0.01$, the perpendicular anisotropy field $H_{\mathrm{s,perp}} = 1400$ Oe (1 Oe = 79.5775 A·m^{-1}) under a zero electric field and 600 Oe under a pulsed electric field of -1.0 V·nm^{-1}. An opposite-direction external magnetic field of 700 Oe at a tilt angle of 6° with respect to the film normal direction is applied. The simulation results showed that the magnetization can be switched by 180° when the pulse duration $\tau_{\mathrm{pulse}} = 0.4$ ns, while it is switched back to the initial state by rotating through an angle

*Project supported by the Advanced Research Plan of the Chinese Academy of Sciences (Grant No. QYZDY-SSW-JSC015).

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of 360° when $\tau_{\rm pulse} = 0.8$ ns. The experiments verified that for a negative voltage pulse of -0.76 V with $\tau_{\rm pulse} = 0.55$ ns, the switching between the parallel (P) and antiparallel (AP) states was observed until the pulse number = 50. On the other hand, for a positive voltage pulse of $+0.76$ V, no switching event was observed no matter what the initial magnetization configuration is.

Nozaki *et al.* demonstrated electric-field-induced ferromagnetic resonance (FMR) excitation by means of voltage control over the magnetic anisotropy in a few monolayers of FeCo at room temperature,[20] as the radiofrequency-voltage-induced anisotropy change can be considered as an effective radiofrequency field $H_{\perp}(V_{\rm RF})$, applied perpendicularly to the film plane. The electric-field induced FMR has been observed,[20] where the external magnetic field strength was varied from 0.04 T to 0.3 T, with an elevation angle $\theta_{\rm H} = 55°$. In the whole magnetic field range a clear resonance spectrum was observed, and the resonance frequency is a linear function of the external magnetic field.

Switching of the magnetic easy axis between the in-plane and the out-of-plane directions was demonstrated by controlling the sign of the direct current (DC) bias voltage.[21] In this paper we simulate the voltage control of magnetization switching by using the LLG equation, and study the voltage controlled magnetic switching effect (Section 2) and the effects of various parameters on the design of a new magnetic memory device, including the effects of initial values of magnetic moment components (Section 3), external magnetic field (Section 4), and the tilt angle of the external magnetic field (Section 5). Section 6 is devoted to the summary.

2. Voltage-controlled magnetic switching effect

We use the following LLG equation to study the voltage control of magnetization switching and dynamics,

$$\frac{1}{\gamma}\frac{{\rm d}m}{{\rm d}t} = -m \times H_{\rm eff} + \left(\frac{\alpha}{\gamma}\right) m \times \frac{{\rm d}m}{{\rm d}t}, \tag{1}$$

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 total magnetic field, including external magnetic field and internal anisotropic magnetic field. Like Ref. [19], we take the external magnetic field $\boldsymbol{H}_0 = (H_{0x},\ 0,\ H_{0z})$, where

$$H_{0x} = H_0 \sin\theta_{\rm t}, \quad H_{0z} = H_0 \cos\theta_{\rm t}, \tag{2}$$

where $\theta_{\rm t}$ is the tilt angle of the external magnetic field with respect to the film normal direction. We take the internal anisotropic field $\boldsymbol{H}_1 = (H_{1x},\ 0,\ H_{1z})$, and it is mainly in the perpendicular direction, of which the magnitudes are assumed to be 1400 Oe under a zero electric field and 600 Oe under a pulsed electric field of -1.0 V·nm^{-1}, respectively. The external field is set to be 700 Oe at a tilt angel of 6° with respect to the film normal direction.[19]

In this paper we take the dimensionless physical quantities in the LLG equation (1):[22] the magnetic field unit $h_0 = 10^4$ A/m$\sim 1.257 \times 10^{-2}$ T and $\gamma h_0 = 176$ GHz/T$\times 1.257 \times 10^{-2}$ T = 2.21 GHz. The time unit is taken as $\tau_0 = 1/\gamma h_0 = 0.45$ ns, and $t = \tau\tau_0$. With τ equation (1) becomes

$$\left(1+\alpha^2\right)\frac{{\rm d}\boldsymbol{m}}{{\rm d}\tau} = -m \times H_{\rm eff} - \alpha \boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{H}_{\rm eff}), \tag{3}$$

where the unit of $H_{\rm eff}$ is h_0. The dimensionless external field $H_0 = 5.5704$, the internal field $H_{1z} = -4.7747$ (under pulsed electric field), and -11.1409 (under zero electric field) (unit: h_0). It is noted that the external field is always opposite to the internal field. The internal in-plane field is much smaller than the perpendicular field; here we take $H_{1x} = 0.05$.

Figure 1 shows the components of magnetic moment $\boldsymbol{m}$ in the free layer each as a function of time in τ, the parameters are taken as $H_{0z} = 5.54$, $H_{0x} = 0.5821$, $\alpha = 0.01$, $H_{1z} = -4.7747$ (on state), and -11.14 (off state), and $H_{1x} = 0.05$. The initial values of the magnetization components are taken as (0.866, 0, 0.5). From Fig. 1(a) (on state) we see that the magnetization components m_x and m_y precess around the z axis periodically, then the z component m_z keeps basically constant. From Fig. 1(b) (off state) we see that the three components of the magnetization keeping near their initial values have no movement. In the case of on state, the three-dimensional (3D) trajectory of the magnetic moment is shown in Fig. 1(c). It can be seen from the figure that the magnetic moment is always in the space of the positive z axis, and rotates around the z axis. If we take the pulse duration to be half of the magnetic moment oscillation period, then the magnetic moment $\boldsymbol{m}$ will stop at the opposite position relating to the original position. This finishes the switching once. Later on if the voltage pulse with the same duration is added again, the magnetic moment will rotate 180°, returning to the original position. The on and off states can be modulated by the voltage pulse.

From Fig. 1(a) we see that under the pulsed voltage the magnetization components m_x and m_y move periodically in the x–y plane, and the in-plane magnetization vector changes its sign in a period, resulting in the switching. While under the zero electric field (off state), this switching effect does not emerge. From Fig. 1(a) we also see that the amplitudes of the m_x and m_y oscillations decrease with time going by, which results from the damping factor α: especially when $\tau > 30.4$ (13.7 ns) the m_x becomes positive, the trajectory of the magnetic moment is in the positive x-axis space with no change in sign, and no switching will emerge. It is found that the oscillation period varies slightly as τ increases from 3.4 to 22.6.

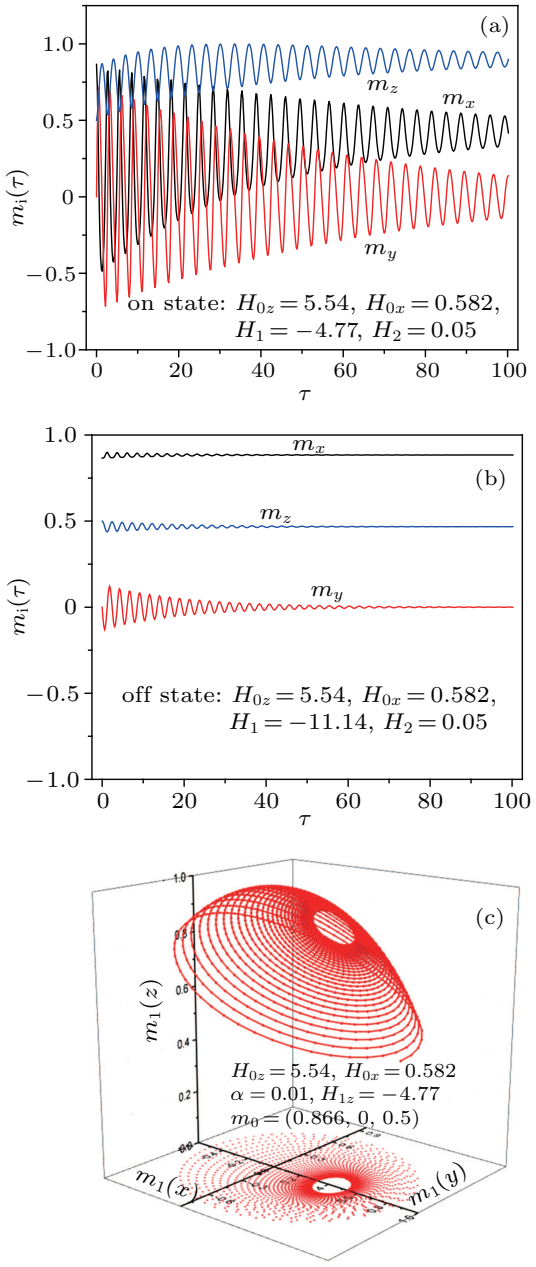


Fig. 1. (color online) Components of magnetic moments each as a function of time τ in the cases of (a) 'on state' ($H_1 = -4.77$) and (b) 'off state' ($H_1 = -11.14$), and (c) 3D trajectory of magnetic moments in the case of 'on state'.

The physical mechanism of the off state is as follows. The total magnetic field applied to the magnetic moment is the sum of the external field and the internal field, in the z direction, i.e.,

$$H_{\text{total}} = H_0 - H_1 m_z. \tag{4}$$

In the 'off state', $H_0 = 700$ Oe, $H_1 = 1400$ Oe, so that if $m_z = 0.5$, then $H_{\text{total}} \approx 0$. While in the 'on state', $H_1 = 600$ Oe and $H_{\text{total}} \approx 400$ Oe.

3. Effect of magnetic moment initial value

Because of the physical mechanism (Eq. (4)) of the last section we took the initial values of the magnetization components as $\boldsymbol{m}_0 = (0.866, 0, 0.5)$. In this section we study the effect of the initial values of the magnetization components. Figures 2(a) and 2(b) are the components of magnetization each as a function of time τ in the case of 'on state' and 'off state', respectively. The parameters are the same as those in Fig. 1, except the initial values of the magnetization components $\boldsymbol{m}_0 = (0.714, 0, 0.7)$.

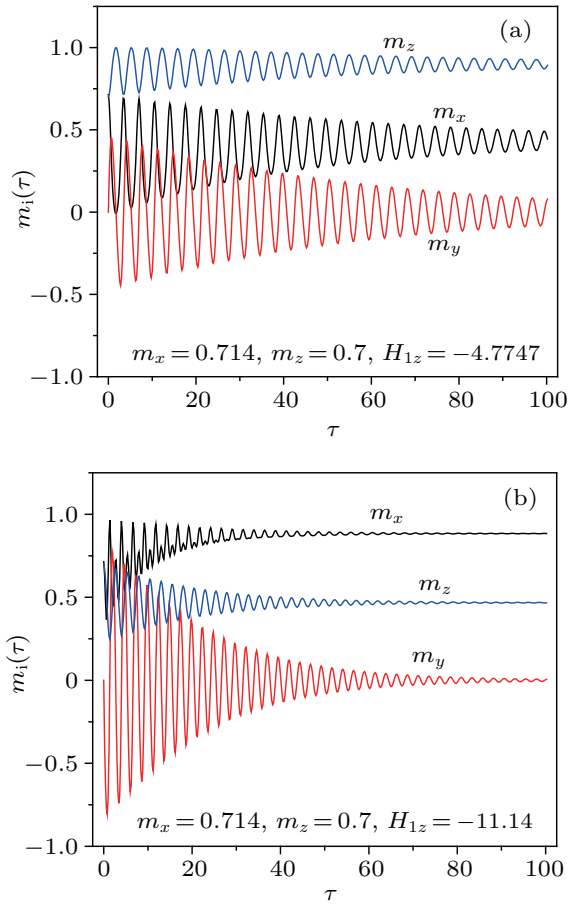


Fig. 2. (color online) Components of magnetic moments each as a function of time τ in the cases of (a) 'on state' and (b) 'off state', with $H_1 = -11.14$ and initial values of magnetization components $\boldsymbol{m}_0 = (0.714, 0, 0.7)$.

Comparing Fig. 2(b) with Fig. 1(b), we find that under the same condition the movements of the magnetic moment at the "off state' are differently dependent on the initial value of the m_z. If $m_z = 0.5$, which satisfies Eq. (4), the movements of the magnetic moment components are completely 'off' as shown in Fig. 1(b). However, if $m_z = 0.7$, deviating from Eq. (4), none of the movements of the $\boldsymbol{m}$ components is completely 'off', they still oscillate as shown in Fig. 2(b), especially m_y. Therefore, the voltage controlled magnetic switching depends sensitively on the initial value of the magnetization component. In the experiment there is a problem regarding how to modulate the initial values of the magnetization components.

Fortunately, however, from Fig. 2(b) it is noted that at the 'off' state the three magnetic moment components approach finally to the suitable initial values (0.866, 0, 0.5), satisfying

Eq. (4). Therefore, we only keep the off state for a short time, and we can obtain the ideal magnetic moment initial values.

4. Effect of external magnetic field

In order to study the effect of external magnetic field we increase the external magnetic field from 5.57 A·m^{-1} to 7.0 A·m^{-1}, and the initial values of the magnetization change into $\boldsymbol{m}_0 = (0.778, 0., 0.628)$, the other parameters are the same as those in Subsection 2.1.

Figure 3 shows the components of magnetization $\boldsymbol{m}$ in the free layer each as a function of time τ. From Fig. 3(a) (on state) we see that the magnetization components m_x and m_y precess around the z axis periodically, then the z component m_z keeps basically constant. However, when $\tau > 26$, then $m_x > 0$, the switching effect disappears. From Fig. 3(b) (off state) we see that the three components of the magnetization keep near their initial values, having no movement.

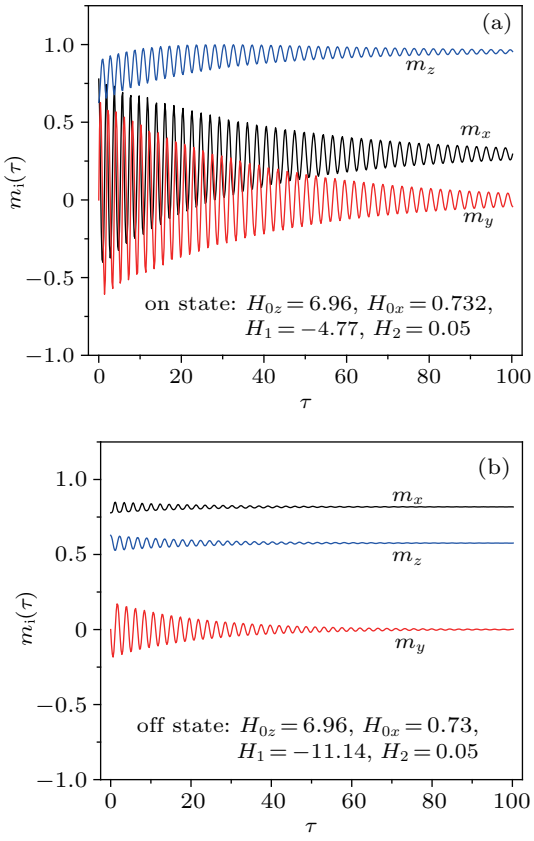


Fig. 3. (color online) Components of magnetization each as a function of time τ in the cases of (a) 'on state' ($H_1 = -4.77$) and (b) 'off state' ($H_1 = -11.14$), in external field $H_0 = 7$.

Figure 4 shows the components of magnetization $\boldsymbol{m}$ in the free layer as a function of time τ in a smaller external magnetic field $H_0 = 4$, where the other parameters are the same as those in Subsection 2.1. The initial values of magnetization components are taken as (0.933, 0, 0.359).

From Fig. 4(a) we see that m_x and m_y also oscillate with τ, but with a larger period. When $\tau > 14.6$, then $m_x > 0$, the switching effect disappears. For the larger external fields, for example, $H_0 = 5.57$, 7.0, the m_x becomes positive at larger τ values of 30.4 and 26, respectively. Therefore, the external magnetic field cannot be taken to be too small: it should be comparable to the internal magnetic field.

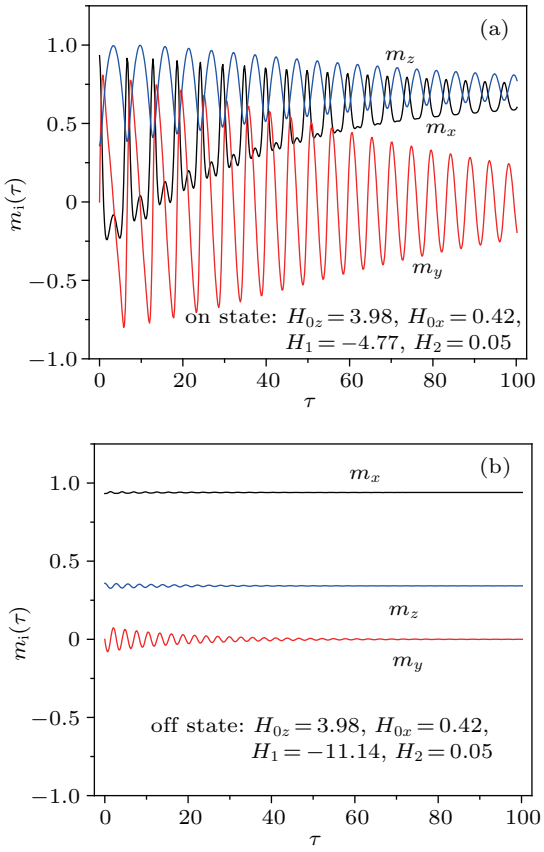


Fig. 4. (color online) Components of magnetization each as a function of time τ in the cases of (a) 'on state' ($H_1 = -4.77$) and (b) 'off state' ($H_1 = -11.14$), in external field $H_0 = 4$.

The oscillation periods are inversely proportional to the external magnetic field, and they are approximately $\tau = 2.3$, 3.6, 5.0 for $H_0 = 7.0$, 5.6, 4.0, respectively.

5. Effect of tilt angle of external magnetic field

In Ref. [18] an external magnetic field was applied to the direction normal to the film plane. In Ref. [19] the external field was set to be at a tilt angle of 6° with respect to the film normal direction, while in Ref. [20] the tilt angles were 0° and 35°. In the above calculations we took the tilt angle of 6°, and in this section we study the effect of the tilt angle θ_t.

Figure 5 shows the components of magnetic moment $\boldsymbol{m}$ in the free layer each as a function of time τ, the parameters are the same as those in Subsection 2.1, except the tilt angle of the external magnetic field $\theta_t = 0°$. The initial values of magnetization components are taken to be (0.866, 0, 0.5). From Fig. 5(a) (on state) we see that the magnetization components m_x and m_y precess around the z axis periodically, and the z component m_z keeps basically constant. From Fig. 5(b) (off

state) we see that the three components of the magnetization keep near their initial values, having no movement. Comparing Fig. 5(a) with Fig. 1(a), we find that the precessions of m_x and m_y in the case of $\theta_t = 0°$ are better than those in the case of $\theta_t = 6°$, for the latter when $\tau > 30.4$, m_x becomes positive (see Fig. 1(a)), the switching effect disappears. While for the case of $\theta_t = 0°$, there is no such behavior occurring, though the amplitudes decrease due to the damping.

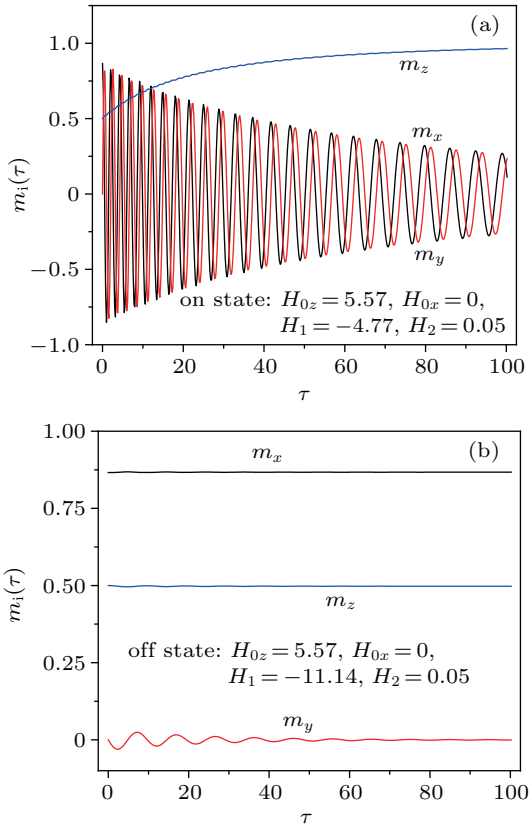


Fig. 5. (color online) Components of magnetic moments each as a function of time τ in the cases of (a) 'on state' ($H_1 = -4.77$) and (b) 'off state' ($H_1 = -11.14$), with $\theta_t = 0°$.

When we increase the tilt angle to $\theta_t = 10°$, the results are worse than those in Fig. 1(a), and when $\tau > 4$ the m_x becomes positive, there will no switching effect. Therefore, according to our calculation results it is better to take the tilt angle $\theta_t = 0°$, in Ref. [19] the authors took $\theta_t = 6°$, they may have other considerations.

6. Summary

We have used the LLG equation to study the voltage controlled magnetic switching, and obtained some results as follows.

(i) The initial values of magnetic moment components are critical for the switching effect, which should satisfy Eq. (4). But at the 'off' state the three magnetic moment components approach finally to the suitable initial values.

(ii) The external magnetic field which affects only the oscillation period should be comparable to the internal magnetic field, and the switching effect will disappear if the external magnetic field is too small.

(iii) The precessions of m_x and m_y are the best for the tilt angle of the external magnetic field $\theta_t = 0°$, i.e., the field is perpendicular to the sample plane. The larger the tilt angle, the worse the result is.

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