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PAPER

Femtosecond laser-heating effect on the magnetization dynamics in perpendicularly magnetized Ta/CoFeB/MgO film

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Supplementary material for this article is available online

Abstract

We have studied the effect of ultrafast laser-heating on the magnetization dynamics of perpendicularly magnetized CoFeB film by means of the time-resolved magneto-optical Kerr rotation effect. The effective perpendicular magnetic anisotropy field H_K is significantly decreased with enhancing the pump laser-fluence in a moderate range of 5–12 mJ cm^{-2}. The Gilbert damping, however, is found to be independent of the pump fluence. These findings provide a new method of separately manipulating the Gilbert damping and perpendicular magnetic anisotropy.

1. Introduction

The magnetic films with perpendicular magnetic anisotropy (PMA) are the promising candidates in the application of the next-generation, high-density magnetic information storage technology due to their high thermal stability. One of the prevailing magnetic random access memories (MRAM) is switched by spin transfer torque (STT) due to its good down-scalability [1, 2]. With STT, the critical current density for magnetization switching in the case of perpendicular magnetized magnetic tunneling junctions (MTJs) is directly proportional to the Gilbert damping constant and PMA. This proportionality shows that a balance between the thermal stability and writability of magnetization is required. Therefore, materials with large PMA and weak Gilbert damping are preferred. The CoFeB/MgO/CoFeB MTJ with PMA is extensively investigated due to its high tunneling magnetoresistance ratio [3]. However, from a physical point of view, magnetic anisotropy and Gilbert damping both arise from the same origin, namely the spin–orbit coupling, as evidenced by previous results [4, 5]. Usually, materials with large PMA exhibit large damping values such as Co/Pt multilayers [6] and CoCrPt alloys [7].

At the same time, the PMA and the Gilbert damping can also be influenced by various other factors, such as capping layer, [8–10] annealing temperature, [11, 12] element compositions, [5, 13, 14] and film thickness [15, 16]. For instance, Liu *et al* [10] observed a 35% increase in PMA by replacing the Ta buffer layer, with Devolder *et al* [17] reported that, similar to the annealing effect, the effective anisotropy field increased in proportion to the irradiation fluence of light ions, while the Gilbert damping constant was almost invariant. These studies suggest that there is a possibility of tuning the anisotropy and damping constant in a separate way. In the practical application of STT–MRAM, the magnetization switching generally takes place within a timescale of nanoseconds (ns) and thermal effect arising from the writing current is inevitably introduced into a given device. It remains an open question that how the transient thermal effect influences the anisotropy and Gilbert

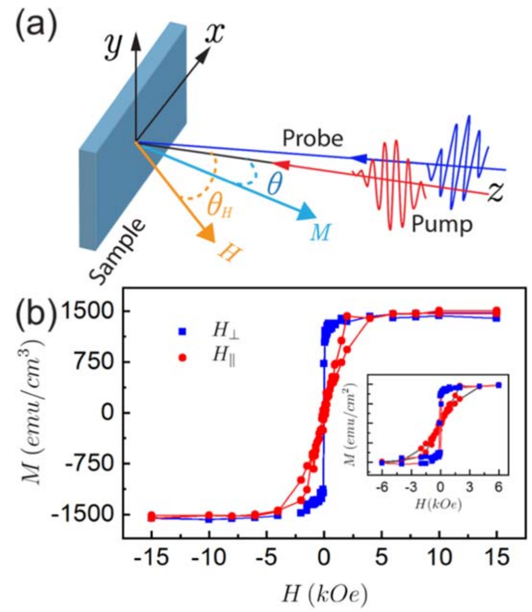

Figure 1. (a) Schematic of the measurement geometry of the time-resolved Kerr rotations. The pump beam is along the normal direction *z* of the sample plane. The θ_H and θ represent the angles away from the *z* direction for the external magnetic field and the initial equilibrium magnetization, respectively. (b) Magnetic hysteresis loops with the magnetic field parallel and perpendicular to the sample plane, respectively. The inset shows a zoom-in of the hysteresis loop near the saturation field.

damping. It has been previously reported that the damping constants in ferromagnetic thin films with in-plane magnetic anisotropy can be transiently enhanced by increasing the fluence of femtosecond laser-pulses [18, 19]. The results showed that the transient thermal effect induced by the ultrafast laser-pulses within the ns timescale plays an important role in transiently manipulating damping parameter. However, studies of transiently tailoring the PMA and Gilbert damping by this kind of thermal effect are still lacking. In this letter, we report the effect of transient laser heating on the magnetic anisotropy and Gilbert damping in perpendicularly magnetized Ta/CoFeB/MgO film by using the time-resolved magneto-optical Kerr effect (TRMOKE) techniques. The effective perpendicular anisotropy field H_K has been found to be strongly dependent on the fluence of the ultrafast laser-pulses. The Gilbert damping, however, remains stable within a pump fluence range of 5–12 mJ cm^{-2} where the saturation magnetization remains constant.

2. Experimental methods

The sample was prepared by using the magnetron sputtering method with a base pressure of 10^{-5} Pa. After the sample was deposited, a post-annealing process at 300 °C was performed. Further growth information can be found in our previous paper [20]. The stacking structure is Si substrate/Ta(5 nm)/$Co_{40}Fe_{40}B_{20}$(1 nm)/MgO(3 nm)/Ta(5 nm). The numbers in brackets represent film thickness. The magnetization dynamics was measured using the TRMOKE at room temperature. In our measurements, the laser pulses were generated by a Ti: sapphire regenerative amplifier with a central wavelength of 800 nm, a repetition rate of 1 kHz, and a pulse duration of ∼50 fs. The output of the amplifier was divided into two beams. One was used as the pump beam and the other was frequency-doubled (3.1 eV) as the probe beam. The spot diameters of the pump and probe beams focused onto the sample are ∼500 and 200 μm, respectively.

Figure 1(a) shows the experimental geometry employed in our measurements. The pump beam is incident normally and the incident angle of probe beam is ∼5° with respect to the normal direction of the sample. The applied magnetic field *H* is along the direction of $\theta_H = 47.5°$. Figure 1 (b) shows the hysteresis loops with the magnetic field parallel and perpendicular to the film plane. These magnetization curves were measured by a quantum design superconducting quantum interference device. The saturation magnetization M_s is around 1500 emu/cc, which coincides with other results [21, 22]. The experimental H_K is approximately 3 kOe obtained from the closed area between the in-plane and out-of-plane hysteresis loops.

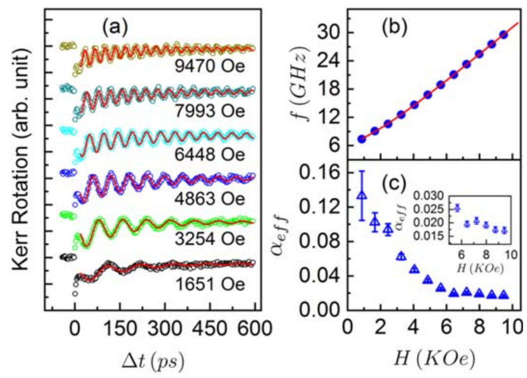

Figure 2. (a) Time-resolved Kerr rotation traces for the PMA CoFeB film measured at different external magnetic fields with $\theta_H = 47.5°$. The pump fluence F is fixed at 7 mJ cm^{-2}. Solid lines are the fitting lines according to equation (1), which are used to obtain values of magnetization precession frequency f and spin relaxation time τ. (b) The obtained magnetization precession frequency f as a function of external field H. The red solid line is the fitting line based on equations (2) and (3). (c) The external field H dependence of the effective damping constant α_{eff}. The inset shows a zoom-in of α_{eff} in the range of 5–10 KOe.

3. Results and discussions

Figure 2(a) shows the Kerr rotations of the CoFeB film as a function of the time-delay Δt, which were measured at the pump fluence of 7 mJ cm^{-2} under different magnetic fields. The instantaneous decrease of Kerr signal at $\Delta t = 0$ ps is characterized as the ultrafast demagnetization [23]. This ultrafast demagnetization behavior modifies the effective magnetic anisotropy field within a few ps and thus triggers a magnetization precession which last for hundreds of ps. The oscillations shown in figure 2(a) correspond to the magnetization precession that strongly depends on the external field H. In addition, the measured data of Kerr rotations also include a non-oscillating component, which can be described by a single-exponential function. Thus, the experimental Kerr dynamics can be modeled as the following equation [24]:

$$\Delta\theta/\theta \sim a\exp(-t/\tau)\cos(2\pi ft + \phi) + b\exp(-vt), \tag{1}$$

where a τ, f, ϕ are the initial amplitude, spin relaxation time, precessional frequency and phase, respectively. b is the background amplitude and v is the recovery rate of the magnetization. In figure 2(a), the red solid lines are the fitting results. The extracted parameter of precession frequency f is plotted in figure 2(b) as a function of H. We reproduce f using the following equations as used in previous results [25, 26]:

$$f = (\gamma/2\pi)\sqrt{H_1H_2} \tag{2}$$

with $H_1 = H\cos(\theta_H - \theta) + H_K\cos^2\theta$ and $H_2 = H\cos(\theta_H - \theta) + H_K\cos 2\theta$. Here, γ is the gyromagnetic ratio defined as $\gamma = g\mu_B/\hbar$, where g, μ_B and $\hbar$ are the Lande's g-factor, Bohr magneton, and the reduced Planck's constant, respectively. The H_K here equals $2K_U/M_S - 4\pi M_S$, where K_U is the uniaxial magnetic anisotropy constant. The equilibrium magnetization angle θ is calculated by the equation:

$$\sin 2\theta = (2H/H_K)\sin(\theta_H - \theta). \tag{3}$$

The value of $H_K = 2$ kOe at 7 mJ cm^{-2} is obtained by fitting the extracted precession frequencies f in figure 2(b) with the equation (2). The solid line in figure 2(b) is the fitting curve. In figure 2(c), the effective damping constant α_{eff}, defined as $\alpha_{\text{eff}} = 1/2\pi f\tau$, is calculated using the fitted values of f and τ. The α_{eff} shows an obvious dependence on magnetic field, reaching its minimum at the highest field of 9600 Oe. The α_{eff} values under high fields suppress the extrinsic contributions such as the inhomogeneous anisotropy and thus approximately equals the intrinsic α_0 [5, 26]. Here, we treat the α_{eff} at the highest field of 9600 Oe as the intrinsic damping constant α_0.

To study the femtosecond laser-heating effect on the α_0 and H_K in our PMA film, we performed systematic measurements of time-resolved Kerr rotation as a function of magnetic fields under different pump fluences, where the H_K and α_0 can be derived. The raw data of fluence-dependent Kerr rotations are shown in the supplementary material (SM) is available online at stacks.iop.org/NJP/21/053032/mmedia. The upper threshold of pump fluence is carefully checked to assure the magnetization dynamics are reversible as the pump fluence is tuned back to the lowest value. Thus, within the pump fluence range of 5–12 mJ cm^{-2}, the CoFeB film is protected from degradation. The average heating effect from the pump pulses can be ignored by measuring the magnetization at $\Delta t = -6$ ps with and without the pump beam (see figure S4 in the supporting information).

Figures 3(a) and (b) show the derived H_K and α_0 values as a function of pump influence F, respectively. The α_0 of 0.0165 is found to be independent of F while the H_K is monotonously decreased from 2.4 ± 0.5 to

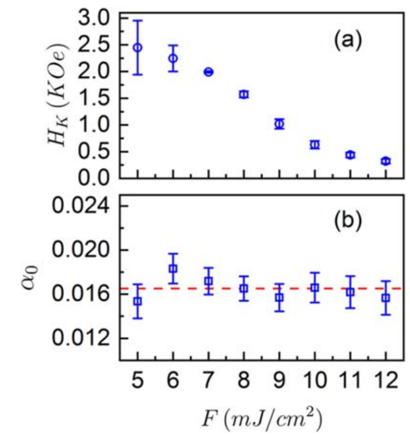

Figure 3. (a) The derived effective perpendicular anisotropy field H_K and (b) intrinsic damping constant α_0 of the PMA CoFeB thin film as a function of the pump fluence *F*.

0.32 $\pm$ 0.04 KOe with the increase of *F*. Throughout the transient magnetization precession process, both M_S and K_U are changing. However, in comparison with M_S, the reduction of K_U should contribute to the decrease of H_K. Because, according to the definition of H_K mentioned above, if the reduction of M_S is dominant, the resultant H_K would increase. This contradicts the obtained results. In addition, as shown in previous results [18, 19], the variation of M_S is negligible for analyzing the pump-fluence dependence of the effective magnetic anisotropic field. Therefore, the PMA K_U is proportional to H_K. The pump fluence dependent results of K_U and α_0 demonstrate that the perpendicular interfacial anisotropy can be varied independently with damping constant. Such a separate tunability cannot be simultaneously achieved in most cases [27, 28] because ferromagnetic materials with large anisotropy constant usually have large damping factor due to spin–orbital coupling (SOC).

For better understanding the behavior of H_K and α_0 in the PMA CoFeB thin film under different pump irradiation fluences, we provide a possible explanation for the irrelevance between α_0 and H_K. As demonstrated in our previous work of 10 nm CoFeB film with in-plane anisotropy [19], the α_0 increased with the increase of *F* while the effective demagnetization field remained constant. The enhancement of α_0 upon laser heating is attributed to the transient rising values of T/T_C. Here *T* is the electronic temperature and T_C means Curie temperature. However, in the case of 1 nm thick CoFeB film, besides the similar electron temperature rise under different pump fluences, the interfacial effect has to be taken into consideration. The origin of PMA for the 1 nm CoFeB film is attributed to the hybridization of Fe and oxygen's orbitals at the CoFeB/MgO interface due to the interfacial SOC [29, 30]. As a consequence, the decrease of PMA as increasing the pump fluence indicates the loss of interfacial SOC. We attribute this reduction of interfacial SOC to the transient thermal effect induced by the pulsed laser excitations. Similar quenching of PMA caused by high temperature was also reported in previous works [31]. Based on the discussions above, in the PMA CoFeB film, both the interfacial SOC and the T/T_C ratio are obviously modulated by the thermal effect caused by the pulsed laser. These two factors should be responsible for the different behaviors of H_K and α_0 of the 1 nm thin film case.

Before showing how the two factors lead to our experimental results, it is essential to approximately quantify the transient thermal effect. Illuminated by the laser pulses of different fluence, the corresponding equilibrium temperatures of the sample was estimated to be ~815–1310 K. The temperatures were obtained according to the ratios of the reduced magnetic order $\Delta\theta/\theta_0$ at $\Delta t = 5$ ps (see figure 4) as well as the published M–T curves [32]. Here, we used the values of $\Delta\theta/\theta_0$ at 5 ps because at this time-delay the thermal equilibrium among electron, spin and lattice subsystems usually has been reached. The detailed information of the temperature estimation is given in the supplementary material (SM). Since the temperatures raised by the laser pulses in both the 10 and 1 nm thick CoFeB films are in the same order of magnitude, we expect a similar increase of damping constant in the 1 nm film due to the rising values of T/T_C. We denote this damping term that increases with the increase of pump fluences as α_{ratio}. The damping term α_{ratio} originates from the bulk properties of the film. As a consequence, to assure the fluence-independent nature of α_0, another damping term is required to compensate the increase of α_{ratio}.

Considering the proportional correlation between the SOC and damping parameter, it is reasonable to define a damping term α_{inter} that arises from the interfacial SOC. As also recently demonstrated by Okada *et al* [35], the interfacial PMA is found to be correlated with the Gilbert damping manifested by monitoring the ferromagnetic resonance linewidths with varying temperatures and sample thickness. According to the

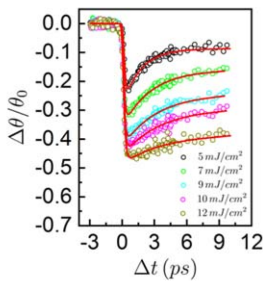

Figure 4. The normalized pump-induced Kerr rotations of CoFeB thin film measured at different pump fluences. An external field of 100 Oe is applied with $\theta_H = 0°$. The red solid lines are the fitting lines and the details of fitting procedure are given in SM. The fitting equation is from previously published [33, 34].

discussions above, both the interfacial damping term $\alpha_{\rm inter}$ and the bulk damping term $\alpha_{\rm ratio}$ contribute to the total intrinsic damping constant α_0, namely $\alpha_0 = \alpha_{\rm inter} + \alpha_{\rm ratio}$. Therefore, we think that upon strengthening the transient thermal effect the decreasing trend of $\alpha_{\rm inter}$ compensates the enhancement of $\alpha_{\rm ratio}$, leading to the stabilization of α_0 within the measured pump fluence range.

4. Conclusion

In conclusion, the femtosecond laser-heating effect on the magnetization dynamics in the perpendicularly magnetized CoFeB film is investigated by the TRMOKE techniques. The equilibrium temperature of the CoFeB film with PMA is quantitatively scaled from 815 to 1310 K in the pump fluence range of 5–12 mJ cm^{-2}. Within such a high temperature regime, the effective perpendicular anisotropy field decreases with increasing the pump fluence while the Gilbert damping constant remains stable. The possible reasons for fluence-independent behavior of α_0 are discussed in terms of the interfacial SOC and electronic temperature. Our finding provides an approach for controlling separately the perpendicular anisotropy field and the damping constant, which is critical for achieving the best performance of STT–MRAM devices.

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