ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理 Chinese Physics B

The unique magnetic damping enhancement in epitaxial $Co_2Fe_{1-x}Mn_xAl$ films

Shu-Fa Li(李树发), Chu-Yuan Cheng(程樗元), Kang-Kang Meng(孟康康), Chun-Lei Chen(陈春雷)
Citation: Chin. Phys. B . 2019, 28(9): 097502 . **doi:** 10.1088/1674-1056/28/9/097502
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Influence of additives on the magnetic damping constant of CoIr soft magnetic thin films with negative magnetocrystalline anisotropy

Tianyong Ma(马天勇), Zhi Luo(罗智), Zhiwei Li(李志伟), Liang Qiao(乔亮), Tao Wang(王涛), Fashen Li(李发伸)
Chin. Phys. B . 2019, 28(5): 057505 . **doi:** 10.1088/1674-1056/28/5/057505

Effect of Sb-doping on martensitic transformation and magnetocaloric effect in Mn-rich $Mn_{50}Ni_{40}Sn_{10-x}Sb_x$ (x=1, 2, 3, and 4) alloys

Ishfaq Ahmad Shah, Najam ul Hassan, Jun Liu(刘俊), Yuanyuan Gong(龚元元), Guizhou Xu(徐桂舟), Feng Xu(徐锋)
Chin. Phys. B . 2017, 26(1): 017501 . **doi:** 10.1088/1674-1056/26/1/017501

Interplay of Rashba effect and spin Hall effect in perpendicular Pt/Co/MgO magnetic multilayers

Yun-Chi Zhao(赵云驰), Guang Yang(杨光), Bo-Wen Dong(董博闻), Shou-Guo Wang(王守国), Chao Wang(王超), Young Sun(孙阳), Jing-Yan Zhang(张静言), Guang-Hua Yu(于广华)
Chin. Phys. B . 2016, 25(7): 077501 . **doi:** 10.1088/1674-1056/25/7/077501

Shape-manipulated spin-wave eigenmodes of magnetic nanoelements

Zhang Guang-Fu, Li Zhi-Xiong, Wang Xi-Guang, Nie Yao-Zhuang, Guo Guang-Hua
Chin. Phys. B . 2015, 24(9): 097503 . **doi:** 10.1088/1674-1056/24/9/097503

Magnetic entropy change involving martensitic transition in NiMn-based Heusler alloys

Hu Feng-Xia, Shen Bao-Gen, Sun Ji-Rong
Chin. Phys. B . 2013, 22(3): 037505 . **doi:** 10.1088/1674-1056/22/3/037505

The unique magnetic damping enhancement in epitaxial $Co_2Fe_{1-x}Mn_xAl$ films*

Shu-Fa Li(李树发)[1,2,†], Chu-Yuan Cheng(程楝元)[2], Kang-Kang Meng(孟康康)[3], and Chun-Lei Chen(陈春雷)[1]

[1] College of Electronics and Information Engineering, Guangdong Ocean University, Zhanjiang 524000, China
[2] State-Key Laboratory of Optoelectronic Materials and Technologies, School of Physics, Sun Yat-Sen University, Guangzhou 510275, China
[3] State Key Laboratory for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

(Received 12 June 2019; revised manuscript received 24 July 2019; published online 23 August 2019)

Uniform precession dynamics and its magnetic damping are investigated in epitaxial $Co_2Fe_{1-x}Mn_xAl$ films by using the time-resolved magneto–optical Kerr effect under out-of-plane configuration. The decay time of uniform precession mode decreases, and thus the magnetic damping increases with the increase of external field. Moreover, the decay time decreases as x decreases, so that the enhancement of magnetic damping occurs in Fe-rich sample. Furthermore, the decay time decreases as the excitation fluence increases, which drops rapidly at low magnetic field comparing with the slow reduction at high magnetic field. This unique magnetic damping enhancement is attributed to the enhancement of homogeneous magnetization.

Keywords: ultrafast dynamics, pump-probe, magnetic damping, Heusler alloy

PACS: 75.40.Gb, 76.50.+g, 78.20.Ls **DOI:** 10.1088/1674-1056/ab38ad

1. Introduction

The magnetic relaxation of ultrafast magnetization dynamics in ferromagnetic films is a challenging subject for engineering the ultrafast magnetic processes in magnetic information storage and spintronic applications, which can be triggered by magnetic field pulses, femtosecond laser pulses, or spin-polarized currents.[1–5] As a half metal, cobalt-based full-Heusler ferromagnetic alloy film is the promising material for spintronics,[6–8] owing to their high spin polarization and Curie temperature, and the existence of multiple spin-wave modes.[9,10] Moreover, such alloy normally presents low Gilbert damping,[11] which is a key parameter for transporting, storing, and processing information in magnonics. Therefore, understanding and controlling the magnetic damping in Heusler alloys becomes crucial importance. Up to now, its behind mechanism is still controversial. The extrinsic uniform precession mode in Heusler alloys is normally attributed to the mechanism of inhomogeneous magnetization.[12–14] In Co_2FeAl film, this inhomogeneity can only explain the magnetic damping in the low-field regime, but fails to explain the damping of the high-field regime.[15] In addition, multiple spin wave modes typically exist in Heusler alloys,[16–19] and then the two-magnon scattering should be the dominant origin. For example, the two-magnon scattering attributes to the damping in Co_2FeSi Heusler alloys,[20] and induces extrinsic magnetic damping for half-metals at low magnetic field.[21,22] Recently, in half metal Fe_3O_4 films,[23] the population of the perpendicular standing spin wave (PSSW) mode increases the magnetic damping of uniform precession mode with the increase of external field, and acts as an additional channel for the dissipation of uniform precession mode. However, in many Co-based Heusler alloy films,[12–15,21] the magnetic damping of uniform precession mode normally decreases with the increase of external field, and does not transfer its energy to the PSSW mode, although we should observe the uniform precession mode and PSSW mode simultaneously.

To explore the magnetic damping behaviors of Heusler alloys and get insight to its behind mechanism, we investigate the uniform precession dynamics in the thinner $Co_2Fe_{1-x}Mn_xAl$ films epitaxially grown on GaAs (001) substrate with the time-resolved magneto–optical Kerr effect under out-of-plane configuration. Surprisingly, the decay time of uniform precession mode decreases with the increase of external magnetic field, so that the enhancement of external field-dependent magnetic damping is observed. In addition, the decay time decreases and then its magnetic damping increases as x decreases. Furthermore, the decay time decreases with the increase of excitation fluence, and it reduces rapidly at the low-field regime comparing with the slow drop at the high-field regime. This unique magnetic damping enhancement in $Co_2Fe_{1-x}Mn_xAl$ films is attributed to the enhancement of homogeneous magnetization, but not the inhomogeneous magnetization.

2. Sample and experimental setup

The Heusler alloy films $Co_2Fe_{1-x}Mn_xAl$ ($x = 0$, 0.3 and 0.7) studied here were deposited on a GaAs (001) substrate

*Project supported by the Natural Science Foundation of Guangdong Province, China (Grant No. 2015A030310003) and the Program for Scientific Research Start-up Funds of Guangdong Ocean University, China.

†Corresponding author. E-mail: lishufa310@163.com

© 2019 Chinese Physical Society and IOP Publishing Ltd

using molecular beam epitaxial at a temperature of 280 °C. The thickness of the deposited film was set to 10 nm, and these films were capped with a 2-nm aluminum in order to prevent oxidation. All the three elements Co, Fe, and Mn show ferromagnetic states and contribute ferromagnetism to the film with the help of x-ray magnetic circular dichroism measurement. The magnetic measurement with a superconducting quantum interference device also represents the pure ferromagnetic property in these films, and further indicates the coexistence of in-plane uniaxial and fourfold magnetic anisotropies. More details on the preparation and magnetic properties of the sample were shown in Ref. [24].

Ultrafast magnetization dynamics was measured by using a time-resolved magneto–optical polar Kerr (TR-MOKE) configuration. The femtosecond laser pulse from a Ti:sapphire regenerative amplifier is linearly polarized, and has a maximum energy of 0.5 mJ per pulse with a duration of 150 fs at the central wavelength of 800 nm. The laser pulse with a repetition rate of 1 kHz is split into a stronger pump pulse and a weaker probe pulse with their fluence ratio larger than 30. The two pulses are incident almost perpendicularly and focused on the surface of the sample. The diameter of focused pump spot is approximately 150 μm, while that of probe pulse is about a half of the pump pulse. The Kerr rotation $\theta_k(t)$ is measured by a probe pulse delayed by a time t after excitation. The optical balanced bridge combined with the lock-in amplifier is used to detect the Kerr signal. To modulate the pump beam, the lock-in amplifier is set to synchronize with a 340-Hz optical chopper. An electromagnet generates a variable magnetic field, which is nearly applied in out-of-plane to cause a larger precession angle induced by the pump pulse, as shown in the inset of Fig. 1(a). In Ref. [25], this time-resolved Kerr setup was described in details. All pump-probe measurements are taken at room temperature.

3. Results and discussion

The pump-induced magnetization dynamics of $Co_2Fe_{0.7}Mn_{0.3}Al$ film ($x = 0.3$) with a constant fluence of 12.5 mJ·cm^{-2} under the out-of-plane external field applied to eliminate external field orientated dependence of in-plane magnetic anisotropies were shown in Fig. 1(a). These dynamics curves exhibit a significant cosine oscillation, and their amplitude increases greatly with magnetic field, while they exponentially decay faster under high magnetic field. These data were fitted to the following function with an exponentially decreasing harmonic function in order to extract their frequency f and decay time τ of the precession,

$$\Delta\theta_k(t) = A\cdot\exp(-t/\tau_{de}) + B\cdot\exp(-t/\tau)\cdot\sin(2\pi ft+\varphi). \quad (1)$$

Here the first part comes from the recovery from ultrafast demagnetization, while the last term corresponds to damped magnetization precession. The calculated $\Delta\theta_k$ fit well to the experimental data, as plotted in Fig. 1(a) by the solid curve. The frequency and decay time were extracted and plotted in Fig. 1(b). A fast Fourier transform (FFT) was also performed on the dynamics curve, as shown in the inset of Fig. 1(b), and shows two peaks. Comparing with external field-dependence of low frequency peak, the high frequency peak remains constant at 43.9 GHz. The value of low frequency peak was extracted and plotted in Fig. 1(b), which agrees well with the frequency of fitting and further proves the correctness of the fitting. It is noted that the external field-independent frequency peak in FFT comes from the coherent acoustic phonons,[16] and its amplitude is much smaller and thus neglected compared to that of spin waves in the fitting. In addition, the ultrafast magnetization dynamics for other films with $x = 0$ and 0.7 was also measured at 12.5 mJ·cm^{-2} under various external fields and fitted with Eq. (1) to extract f and τ.

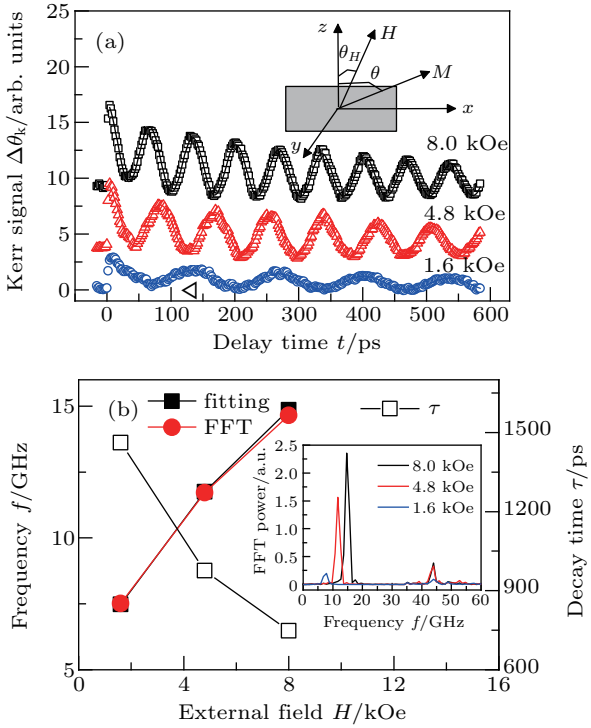


Fig. 1. (a) External field-dependent magnetization dynamics of 10-nm $Co_2Fe_{0.7}Mn_{0.3}Al$ film (open dot) under 12.5 mJ·cm^{-2}, and their fittings (solid line). The schematic measurement configuration is shown in the inset. (b) The frequency (black solid dot) and decay time (black open dot) were extracted from the fitting and FFT (red solid dot), respectively. The inset shows FFT spectrum.

The frequency of the precession dynamics for the $Co_2Fe_{1-x}Mn_xAl$ films was plotted in Fig. 2(a), which increases as magnetic field increases. One can see that, it decreases as x increases, revealing the lower frequency at Mn-rich sample. This external field-dependent frequency mode was best determined by the dispersion of Kittel mode (or uniform precession mode) in the following,[26] taking the in-plane

uniaxial and fourfold magnetic anisotropy effective fields H_2 and H_4 into consideration, and setting the external field H and magnetization M restricted in x–z plane for simplicity,

$$f = \frac{\gamma}{2\pi} \cdot (H_a H_b)^{1/2}, \tag{2}$$

$H_a = H\cos(\theta - \theta_H) - (M_{eff} - H_2)\cos 2\theta$, and $H_b = H\cos(\theta - \theta_H) - (M_{eff} - H_2)\cos^2\theta - H_2 + H_4\sin^2\theta$. Here $M_{eff} = 4\pi M_s - 2k_\perp/M_s$, in which M_s is the saturated magnetization and $k_\perp$ is the out-of-plane uniaxial anisotropy constant. $\gamma = \gamma_e g/2$ is the gyromagnetic ratio, where $\gamma_e = 1.76 \times 10^7$ Hz/Oe (1 Oe = 79.5775 A·m^{-1}) and $g = 2.08$.[13] θ is the angle between the equilibrium magnetization and the normal of film plane, and θ_H is a angle of external field projecting to the out-of-plane, as shown in the inset of Fig. 1(a). The projected angle θ_H remains constant, while the magnetization direction θ changes and is evaluated by balancing the torque condition provided by external field, yielding the equilibrium equation $2H\sin(\theta - \theta_H) - (M_{eff} - H_2)\sin 2\theta = 0$. Figure 2(a) shows the best fitting, giving the parameter $M_{eff} = 14200$, 12120, and 11100 Oe for $x = 0$, 0.3, and 0.7, respectively. The fitted values of H_2 and H_4 were plotted in the inset of Fig. 2(a). As x increases, H_2 slightly increases, but H_4 rapidly decreases, showing the Mn composition modulation of magnetic anisotropy.

The relaxation rate of dissipating magnetization dynamics can be represented with the parameter of Gilbert damping, which is critical for engineering the magnetization dynamics involving ultrafast magnetic processes in future magnetic applications, and will be studied in the following. Figure 2(b) shows the decay time τ of uniform precession mode extracted from Eq. (1). It is surprising that in all samples, τ is obviously decreases with the increase of magnetic field, which is consistent with the decay time in Co_2FeSi.[20] In contrast, the decay time observed in many Heusler alloys normally increases with external magnetic field.[14,15,27] More interestingly, the extracted decay time reduces rapidly at low magnetic field comparing with the slight drop at high magnetic field. In addition, it increases as x increases, indicating the slow decay of uniform precession mode in Mn-rich sample.

The Gilbert damping α and the decay time τ are related by the following function:[28]

$$\frac{1}{\alpha} = \frac{\tau \cdot \gamma}{2}(H_a + H_b). \tag{3}$$

Figure 2(c) shows the Gilbert damping α obtained from Fig. 2(b) based on Eq. (3). One can see that, α is strongly dependent on magnetic field, showing the extrinsic feature. Interestingly, it increases rapidly at low magnetic field, but slowly increases at high magnetic field. This extrinsic damping of uniform precession mode does not come from the inhomogeneous magnetization, which always results in the reduced damping with magnetic field. Actually, the homogeneity enhances as the external field increases, and thus the increased damping is related to the enhancement of the homogeneity. Moreover, α increases with the decrease of x. As x reduces, H_2 slightly decreases while H_4 remarkably increases, as shown in the inset of Fig. 2(a), leading to the weak competition between H_2 and H_4 and thus the enhancement of homogeneity.[29] This further proves that the increase of α is related to the enhancement of homogeneity.

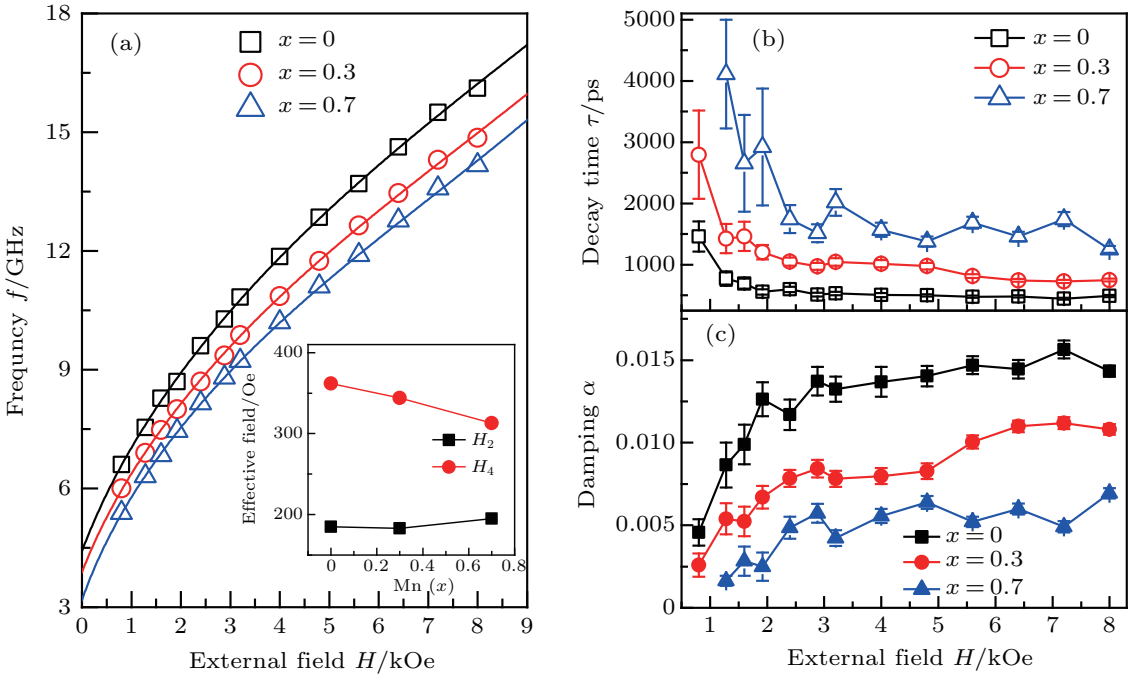


Fig. 2. External field-dependent frequency (a), decay time (b), and damping (c) for 10-nm $Co_2Fe_{1-x}Mn_xAl$ films with different x. The solid line in panel (a) represents the fitting, and the fitted parameters H_2 and H_4 are shown in the inset.

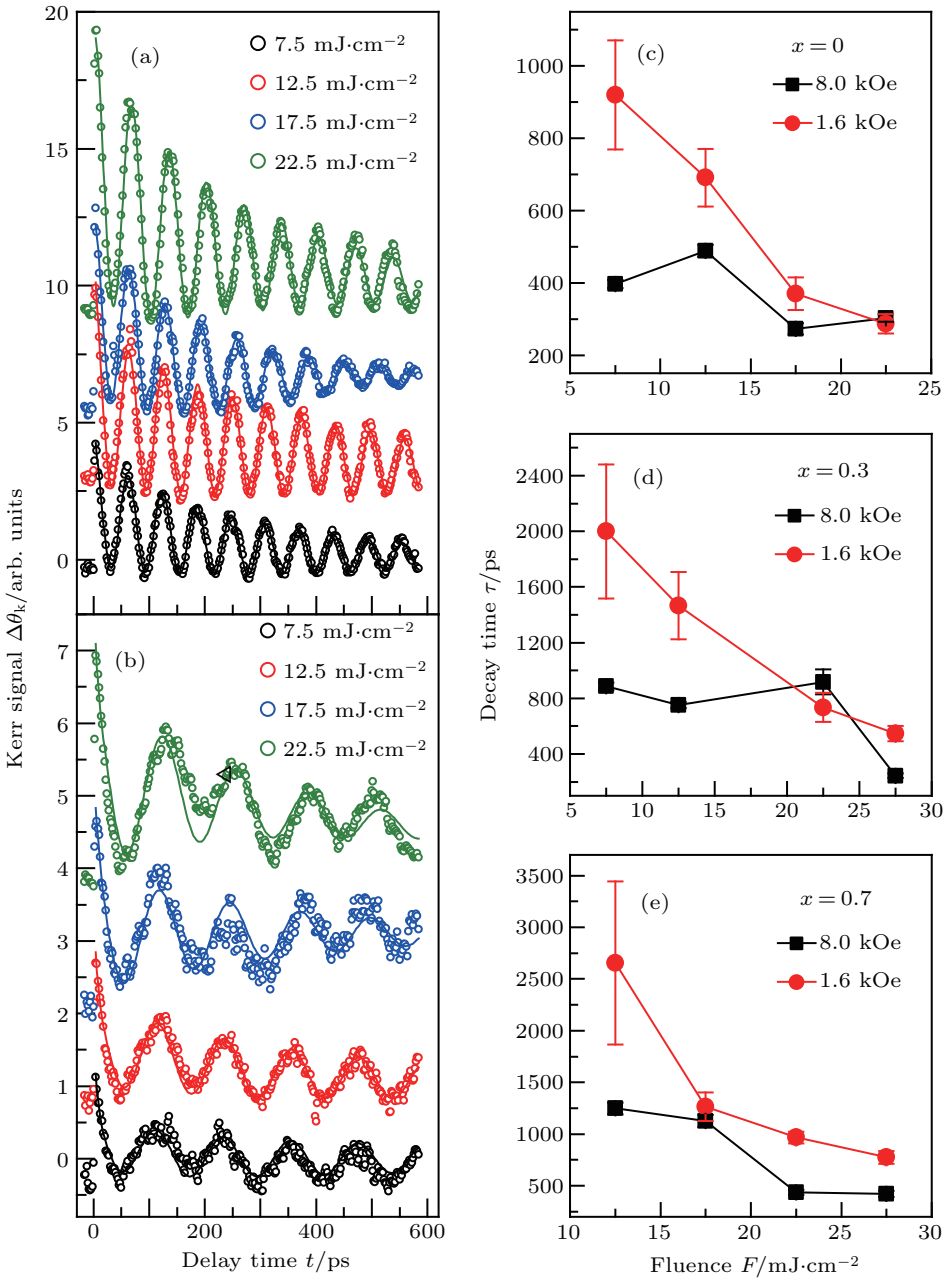


Fig. 3. Excitation fluence-dependent magnetization dynamics of Co_2FeAl film under 8.0 kOe (a) and 1.6 kOe (b), respectively. The extracted decay time for $x = 0$ (c), 0.3 (d), and 0.7 (e), respectively.

We further measure the excitation fluence-dependent precession dynamics of $Co_2Fe_{1-x}Mn_xAl$ films under a constant magnetic field. Figure 3(a) shows the fluence-dependent dynamics for Co_2FeAl at 8.0 kOe. For comparison, the dynamics was measured at 1.6 kOe and plotted in Fig. 3(b). These dynamics were fitted with Eq. (1) to extract their frequency and decay time. The extracted frequency decreases with increasing the excitation fluence at both fields (not shown here). Figures 3(c)–3(e) shows the extracted decay time τ under different excitation fluences. We can see that, the decay time decreases with the increase of excitation fluence. Yet, it drops rapidly at low magnetic field comparing with the reduced one at high magnetic field. As x increases to 0.3 and 0.7, the decay times of uniform precession mode under various excitation fluences (F) were also extracted and plotted in Figs. 3(d) and 3(e), respectively. We further confirm the fact that the rapid reduction of decay time occurs at low magnetic field, but the slow reduced one presents at high magnetic field. In other word, the slope of τ–F curve at low magnetic field is larger than that at high magnetic field. As the excitation fluence increases, the magnetic anisotropy effective field decreases with the rising of equilibrium temperature, so that the applied magnetic field drives a more uniform magnetization. At high magnetic field, the heating induced reduction of the magnetic anisotropy effective field does not result in a more uniform magnetization, since the external magnetic field is much larger than the anisotropy effective field. Yet, at low magnetic field, this reduced effective field causes a significant trend from a

nonuniform to a uniform magnetization state.[29] Therefore, the enhancement of homogeneity with the increase of excitation fluence at low magnetic field relates to the rapid decay of uniform precession mode.

The magnetic damping observed in our experiment significantly differs from the results reported in many Heusler alloys,[12–14] which is dominant by the mechanism of inhomogeneous magnetization. In contrast, it is consistent with the increased magnetic damping observed in Fe_3O_4 films due to the enhancement of homogenous magnetization.[23] As reported, the homogeneous magnetization facilitates the excitation of spin wave mode,[27] and then the uniform precession mode can transfer its energy to the spin wave mode.[23] In the low-field regime, the inhomogeneity dominated by the competition between H_2 and H_4 hinders the energy transfer from uniform precession mode to spin wave mode, leading to the small magnetic damping. In the high-field regime, this transfer increases since the magnetization precession becomes more uniform owing to the neglecting magnetic anisotropy effective field compared to external field, so that the magnetic damping increases. Therefore, the magnetic damping increases with magnetic field as the inhomogeneity of sample changes to homogeneity. As x decreases, the competition between H_2 and H_4 becomes weak due to the larger H_4,[29] leading to the enhancement of homogeneity of sample. So that, the magnetization precession becomes more uniform, which thus causes the increased magnetic damping. Meanwhile, as the excitation fluence increases, the magnetic anisotropy effective field decreases owing to the heating, and thus the magnetization of sample becomes more uniform. This process occurs significantly at low magnetic field, so that more energy dissipates from the uniform precession mode to the spin wave mode, leading to more rapid increase of the magnetic damping. We therefore indicate that the increased magnetic damping of uniform precession mode in 10-nm $Co_2Fe_{1-x}Mn_xAl$ films is attributed to the enhancement of homogeneous magnetization, but not the inhomogeneous magnetization. In 10-nm $Co_2Fe_{1-x}Mn_xAl$ films, the PSSW mode can be excited and acts as an additional channel for the energy relaxation of uniform precession mode. So that one possible origin of such increased magnetic damping could be the energy transfer from uniform precession mode to PSSW mode. The frequency of this PSSW mode is huge, on the order of 250 GHz, due to the inverse relationship of square of the thickness.[16,27] It is difficult to detect this huge-frequency PSSW mode in our experiment because of the very small period and very fast decay. Therefore, in future, more experiments are needed to study the characteristics of this increased magnetic damping in uniform precession mode, and then to deeply understand the behind mechanism.

4. Conclusion

In conclusion, the unique magnetic damping enhancement of uniform precession mode was observed in 10-nm epitaxial $Co_2Fe_{1-x}Mn_xAl$ films by using the time-resolved magneto–optical Kerr effect under out-of-plane configuration. The magnetic damping increases with the increase of external magnetic field, which increases rapidly at low magnetic field comparing with that at high magnetic field. In addition, the magnetic damping increases as x decreases due to the weaker competition between in-plane uniaxial and fourfold magnetic anisotropy. Moreover, the excitation fluence-dependent magnetic damping shows the rapid reduced decay time at low magnetic field than the one at high magnetic field. These therefore indicate that the increased magnetic damping of uniform precession mode in 10-nm $Co_2Fe_{1-x}Mn_xAl$ films is attributed to the enhancement of homogeneous magnetization, but not the mechanism of inhomogeneous magnetization. These observations enrich the magnetic damping property for Heusler alloy films, although its origin remains subject of speculation. However, its future understanding could enable the magnetization characteristics of Heusler alloy films to the needs of the given application.

References

[1] Slonczewski J C 1996 *J. Magn. Magn. Mater.* **159** L1
[2] Gerrits Th, van den Berg H A M, Hohlfeld J, Bär L and Rasing Th 2002 *Nature* **418** 509
[3] Schumacher H W, Chappert C, Sousa R C, Freitas P P and Miltat J 2003 *Phys. Rev. Lett.* **90** 17204
[4] Kiselev S I, Sankey J C, Krivorotov I N, Emley N C, Schoelkopf R J, Buhrman R A and Ralph D C 2003 *Nature* **425** 380
[5] Kaka S, Pufall M R, Rippard W H, Silva T J, Russek S E and Katine J A 2005 *Nature* **437** 389
[6] Sukegawa H, Wen Z C, Kondou K, Kasai S, Mitani S and Inomata K 2012 *Appl. Phys. Lett.* **100** 182403
[7] Sebastian T, Ohdaira Y, Kubota T, Pirro P, Brächer T, Schultheiss K, Serga A A, Naganuma H, Oogane M, Ando Y and Hillebrands B 2012 *Appl. Phys. Lett.* **100** 112402
[8] Loong L M, Hyun J, Deorani P, Yu C N T, Hirohata A and Yang H 2014 *Appl. Phys. Lett.* **104** 232409
[9] Kubota T, Tsunegi S, Oogane M, Mizukami S, Miyazaki T, Naganuma H and Ando Y 2009 *Appl. Phys. Lett.* **94** 122504
[10] Li S F, Cheng C Y, Meng K K and Chen C L 2019 *Jpn. J. Appl. Phys.* **58** 040903
[11] Mizukami S, Watanabe D, Oogane M, Ando Y, Miura Y, Shirai M and Miyazaki T 2009 *J. Appl. Phys.* **105** 07D306
[12] Yuan H C, Nie S H, Ma T P, Zhang Z, Chen Z H, Wu Y Z, Zhao J H, Zhao H B and Chen L Y 2014 *Appl. Phys. Lett.* **105** 072413
[13] Qiao S, Nie S H, Zhao J H, Huo Y, Wu Y Z and Zhang X H 2013 *Appl. Phys. Lett.* **103** 152402
[14] Liu Y, Shelford L R, Kruglyak V V, Hichen R J, Sakuraba Y, Oogane M, Ando Y and Miyazaki T 2007 *J. Appl. Phys.* **101** 09C106
[15] Qiao S, Nie S H, Zhao J H and Zhang X H 2014 *Appl. Phys. Lett.* **105** 172406
[16] Cheng C Y, Meng K K, Li S F, Zhao J H and Lai T S 2013 *Appl. Phys. Lett.* **103** 232406
[17] Schneider T, Serga A A, Leven B, Hillebrands B, Stamps R and Kostylev M P 2008 *Appl. Phys. Lett.* **92** 022505
[18] Kuboa T, Hamrle J, Sakuraba Y, Gaier O, Oogane M, Sakuma A, Hillebrands B, Takanashi K and Ando Y 2009 *J. Appl. Phys.* **106** 113907
[19] Belmeguenai M, Zighem F, Roussigne Y, Cherif S M, Moch P, Westerholt K, Woltersdorf G and Bayreuther G 2009 *Phys. Rev. B* **79** 024419

[20] Zhu W H, Zhu Z D, Li D, Wu G J, Xi L, Jin Q Y and Zhang Z Z 2019 *J. Magn. Magn. Mater.* **479** 179
[21] Liu Y, Shelford L R, Kruglyak V V and Hicken R J 2010 *Phys. Rev. B* **81** 094402
[22] Mizukami S, Watanabe D, Kubota T, Zhang X, Naganuma H, Oogane M, Ando Y and Miyazaki T 2010 *Appl. Phys. Express* **3** 123001
[23] Lu X Y, Atkinson L J, Kurebanjinag B, Liu B, Li G Q, Wang Y C, Wang J L, Ruan X Z, Wu J, Evans R F L, Lazarow V K, Chantrell R W and Xu Y B 2019 *Appl. Phys. Lett.* **114** 192406
[24] Meng K K, Wang S L, Xu P F, Chen L, Yan W S and Zhao J H 2010 *Appl. Phys. Lett.* **97** 232506
[25] Liu X D, Xu Z, Gao R X, Hu H N, Chen Z F, Wang Z X, Du J, Zhou S M and Lai T S 2008 *Appl. Phys. Lett.* **92** 232501
[26] Tao X D, Wang H L, Miao B F, Sun L, You B, Wu D, Zhang W, Oepen H P, Zhao J H and Ding H F 2016 *Sci. Rep.* **6** 18615
[27] Li S F, Meng K K, Cheng C Y, Zhao J H and Lai T S 2018 *J. Phys.: Condens. Matter* **30** 485802
[28] M uller G M and Munzenberg M 2008 *Phys. Rev. B* **77** 020412(R)
[29] Hamrle J, Blomeier S, Gaier O, Hillebrands B, Schafer R and Jourdan M 2006 *J. Appl. Phys.* **100** 103904