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Laser induced sub-terahertz coherent spin dynamics in ferrimagnetic $D0_{22}$ Mn_3Ga films

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Abstract

Laser induced terahertz coherent spin precession was studied in ferrimagnetic $D0_{22}$ Mn_3Ga films with a large perpendicular magnetic anisotropy using an all-optical pump-probe method under the magnetic field of 2 T with different directions. $D0_{22}$ Mn_3Ga alloy films having the effective magnetic field of about 10 T clearly showed the coherent spin precession with the frequency of 0.3 THz. Precession amplitude was proportional to the square of in-plane component of applied field, indicating that an excitation mechanism was attributed to the thermally-induced torque by a laser pulse.

1. Introduction

Nowadays, ordered magnetic alloys with large uniaxial magnetic anisotropy, such as FePt, CoPt, and MnGa, are of quite importance for various spintronics applications, because films of this class of material have a large magnetic anisotropy with easy axis perpendicular to a film plane, namely perpendicular magnetic anisotropy, which makes magnetization stabilized upward or downward. This property is commonly used for high density memory applications, such as magnetic sequential memory (hard disk drive, HDD) [1] and spin-transfer-torque magnetic random access memory (STT-MRAM) [2].

On the other hand, the large perpendicular magnetic anisotropy, in principle, enables us to open a new way to create the high speed spintronics devices up to terahertz wave range. Spin angular momentum precesses about an internal magnetic field direction with the Larmor frequency f, which is given by the relation:

$$f = \frac{\gamma}{2\pi}\frac{2K_u^{eff}}{M_S}. \qquad (1)$$

Here, K_u^{eff}, M_S, and γ are the perpendicular magnetic anisotropy energy, saturation magnetization, and the gyromagnetic ratio, respectively. This relation indicates the magnetic films having both large perpendicular magnetic anisotropy more than 10 Merg/cm^3 and small saturation magnetization has a resonance frequency in teraherz range, which could be useful for terahertz range/wave applications. There are a few researches on terahertz spin dynamics in this context, since there are not so much materials having enough small saturation magnetization and enough large K_u.

Ferrimagnetic Mn based magnetic films with a large perpendicular magnetic anisotropy, such as $D0_{22}$ $Mn_{3-x}Ga$ [3] and $D0_{22}$ $Mn_{3+x}Ge$ [4,5], have small net magnetic moment owing to ferrimagnetism as well as small Gilbert damping constant. Furthermore, it has been known to grow epitaxial films of these alloys with good quality. In this paper, we study laser-induced terahertz spin precession in $D0_{22}$ Mn_3Ga films with applying field up to 2 T with different field angle in detail to obtain an insight into the physical origin of laser-induced ultrafast spin precession.

2. Experimental methods

The 100-nm-thick epitaxial alloy films were deposited on single-crystal (100) MgO substrates using ultra high vacuum magnetron sputtering. The base pressure was less than 1×10^{-7} Pa and the Ar pressure was 0.1 Pa. The film composition is Mn:Ga=68:32at% analyzed by inductively coupled plasma mass spectrometry and Rutherford backscattering spectrometry. The capping layer is the 5-nm-thick Ta layer deposited. The film structures were analyzed using X-ray diffraction and magnetization was measured using a vibrational sample magnetometer.

The spin dynamics was investigated using a pump-probe magento-optical Kerr effect with a Ti:sapphire femtosecond pulse laser and regenerative optical amplifier. The wavelength, width, and repetition rate of the laser pulse were 800 nm, 130 fs, and 1 kHz, respectively. The s-polarized pump beam was chopped by the mechanical chopper with a frequency of 360 Hz. The s-polarized probe beam was incident on a film. The light polarization rotation of reflected probe beam due to the polar magneto-optical Kerr effect was analyzed by a Wollaston prism and detected by a balanced photodiodes as a function of delay time between pump and probe pulse. Magnetic field of about 2 T was applied by an electromagnet with varying field direction θ_H with respect to a film normal (Fig. 1).

3. Experimental results and discussion

Figure 2(a) shows typical pump-probe Kerr rotation measurement for the film with applying field of 1.96 T at θ_H = 45 deg. When the pump beam shines the film surface, Kerr rotation decreases within the time less than 1 ps due to the ultrafast heating of electron and spin system. Then, Kerr signal gradually recovers because of the electron and spin system cooled by heat diffusion. Simultaneously, the oscillation signal is observed, which corresponds to the change in Kerr rotation due to spin precession. Figure 2(b) displays

the spectrum power density of signal in Fig. 1(a) obtained by fast Fourier transform (FFT) analysis after subtracting background signals. The FFT data clearly shows spin precession frequency is more than 0.3 THz. It was found that the spin precession frequency f was proportional to the perpendicular component of magnetic field $H_{\perp}$ with the offset (not shown here), thus the observed oscillation has magnetic origin. From the fitting to f vs. $H_{\perp}$ data using eq. (1) with including the applied field, the g factor of 2.0 and the effective internal field (= $2K_u^{eff}/M_S$) of 9.6 T were obtained, which are consistent with those obtained in the previous work [6].

Figure 3 displays oscillation amplitudes in the time domain measurement as a function of the in-plane component of applied field $H_{//}$. The amplitudes non-linearly increase with increasing $H_{//}$. We calculated the precession spin dynamics using Landau-Lifshitz-Gilbert equation by talking account of the torque induced by the pulse laser heating, as expressed below.

$$\frac{d\boldsymbol{m}}{dt} = -\gamma \boldsymbol{m} \times \left(\boldsymbol{H} + \boldsymbol{H}_{eff}\right) + \alpha \boldsymbol{m} \times \frac{d\boldsymbol{m}}{dt} + \Delta \boldsymbol{T}_{\text{laser}}(t). \qquad (2)$$

Here, $\boldsymbol{m}$, H, H_{eff}, and α are a unit vector of magnetization, the applied field, the effective anisotropy field, and Gilbert damping constant, respectively. The last term represents the additional torque induced by the pulse laser heating. In the case of ultra-short pulse heating and small precession amplitude excited, this theory predicts that spin precession amplitude is proportional to the square of $H_{//}$. Solid curve in Fig. 3 represents a function proportional to $H_{//}^2$ fitted to the experimental data. The fitting is well enough, thus the experiments basically can be explained by eq. (2). The more detailed experiments and analysis will be discussed elsewhere.

4. Conclusion

Laser induced terahertz coherent spin precession was studied in ferrimagnetic $D0_{22}$ Mn_3Ga films with a large perpendicular magnetic anisotropy using an all-optical pump-probe method under the magnetic field of 2 T with different directions. The films clearly showed the coherent precession with the frequency of 0.3 THz. The excitation mechanism is attributed to the thermally-induced torque by a laser pulse.

Acknowledgements

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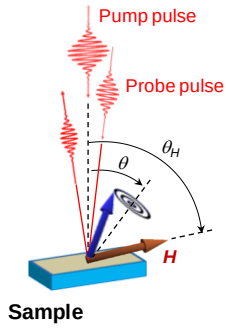

Fig. 1 Schematic illustration of the all-optical pump-probe Kerr rotation measurement.

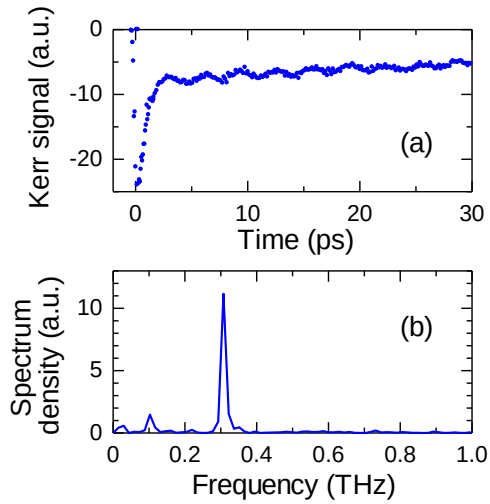

Fig. 2 (a) The laser induced spin dynamics observed in the time domain. (b) Corresponding spectrum power density in the frequency domain obtained by the fast Fourier transform.

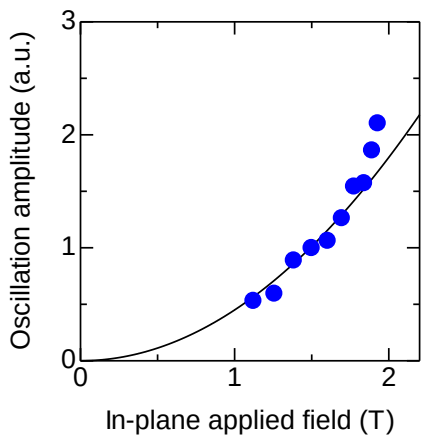

Fig. 3 Oscillation amplitude as a function of in-plane component of applied magnetic field. Solid curve is fitted to the data.