Terahertz electric-field induced Franz-Keldysh effect and magnetization modulation in the ferromagnetic semiconductor GaMnAs

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Generally, it takes more than a few hundred ps to reverse the magnetization direction [1]. Meanwhile, using a terahertz light pulse, we can induce strong fluctuations of electromagnetic fields in ferromagnetic films within an extremely short time less than ~1 ps. Thus, we can expect ultrafast magnetization reversal within a few ps because the energy relaxation of spin is too slow to follow it [2]. Previous studies of terahertz pump probe measurements for ferromagnetic metals have detected ultra-fast magnetization modulation ($\Delta\theta$) of the polarization rotation of the probe pulse and claimed that the response is induced by the Landau-Lifschitz-Gilbert torque [3-5], demagnetization due to heating [4,6], or the electro-optic effect [5]. However, the origin of the terahertz response has not been clarified yet.

Ferromagnetic semiconductor GaMnAs is quite sensitive to an external optical stimulus [7]. In this study, to clarify the effect of the electro-optic effect in GaMnAs, we compare the terahertz response of GaMnAs with that of GaAs:Be. The GaMnAs sample consists of $Ga_{0.94}Mn_{0.06}As$ (20 nm)/ $In_{0.2}Al_{0.8}As$ (500 nm)/ GaAs (100 nm) grown on a semi-insulating GaAs (001) substrate by low-temperature molecular beam epitaxy. This sample was annealed at 180 ºC for 68 h. The Curie temperature T_C of the film was 125 K. The GaMnAs film has a perpendicular easy magnetization axis and coercivity of 15 mT at 10 K. The GaAs:Be sample consists of GaAs:Be (Be: 10^{19} cm^{-3}, 40 nm)/ $In_{0.2}Al_{0.8}As$ (500 nm)/ GaAs (100 nm) grown on a semi-insulating GaAs (001) substrate. The terahertz-pump probe measurements were performed using a pulsed-light source with a repetition rate of 1 kHz. Both pump and probe pulses were linearly polarized. The strong terahertz-pump pulse with the centered frequency of 1 THz, whose electric field $\boldsymbol{E}_{THz}$ was along the [110] axis, was generated by the optical rectification using a $LiNbO_3$ crystal. The time duration of the probe pulse was 130 fs and the wavelength was 800 nm.

We have found that $\Delta\theta$ is induced by $\boldsymbol{E}_{THz}$ even in the non-magnetic GaAs:Be sample. This result indicates that $\boldsymbol{E}_{THz}$ induces the birefringence, which is the difference in the refractive indices for two orthogonally polarized light beams, in the GaAs:Be film. This difference can cause $\Delta\theta$ when the electric field vector $\boldsymbol{E}_{probe}$ of the probe pulse and $\boldsymbol{E}_{THz}$ are not parallel. In fact, when the angle between $\boldsymbol{E}_{probe}$ and $\boldsymbol{E}_{THz}$ is 30 deg, the maximum value of $|\Delta\theta|$ observed in the time-evolution of $\Delta\theta$ (not shown) tends to saturate as the field intensity ($\boldsymbol{E}_{THz}^2$) increases (Fig.1(a)), which is a typical behavior observed in the transient reflectivity induced by the Franz-Keldysh effect [8]. For the GaMnAs film, we observed similar saturating behavior (Fig.1(b)). These results indicate that $\Delta\theta$ is mainly attributed to the birefringence due to the Franz-Keldysh effect. When $\boldsymbol{E}_{probe}//\boldsymbol{E}_{THz}$, $\Delta\theta$ induced by the birefringence should become negligible. Actually, the observed $\Delta\theta$ was almost symmetric around $\Delta\theta$=0 when the direction of the external magnetic field applied perpendicular to the sample surface was reversed (Fig.1(c)). This indicates that $\Delta\theta$ mainly originates from the Polar Kerr effect, which is thought to be induced by the Franz-Keldysh effect, when $\boldsymbol{E}_{probe}//\boldsymbol{E}_{THz}$. Our results show that the Franz-Keldysh effect plays an important role while the terahertz pulse is irradiated to the GaMnAs film.

This work was partly supported by Giants-in-Aid for Scientific Research (No.26103003) and Spintronics Research Network of Japan. T.I., H.Y., and T.K. were supported by JSPS through the Program for Leading Graduate Schools (MERIT). T.I. thanks the JSPS Research Fellowship Program for Young Scientists for support.
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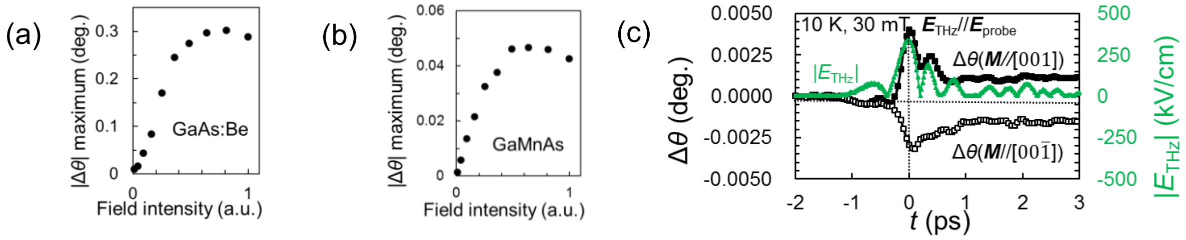

Fig. 1 (a)(b) Maximum value of $|\Delta\theta|$ observed in the time-evolution of $\Delta\theta$ (not shown) measured for (a) GaAs:Be and (b) GaMnAs as a function of the field intensity ($\boldsymbol{E}_{THz}^2$) at 10 K when the angle between $\boldsymbol{E}_{probe}$ and $\boldsymbol{E}_{THz}$ is 30 deg. (c) Black ■ and □ express $\Delta\theta$ measured at 10 K for the $Ga_{0.94}Mn_{0.06}As$ thin film when $\boldsymbol{E}_{probe}//\boldsymbol{E}_{THz}$ with a magnetic field of 30 mT applied in the [001] and [00$\bar{1}$] directions, respectively. $|\boldsymbol{E}_{THz}|$ is shown by green ▲.