Determining the sign of g factor via time-resolved Kerr rotation spectroscopy with a rotatable magnetic field*

Gu Xiao-Fang(谷晓芳), Qian Xuan(钱 轩), Ji Yang(姬 扬)†,
Chen Lin(陈 林), and Zhao Jian-Hua(赵建华)

State Key Laboratory for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, *China*

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Time-resolved Kerr rotation spectroscopy is used to determine the sign of the g factor of carriers in a semiconductor material, with the help of a rotatable magnetic field in the plane of the sample. The spin precession signal of carriers at a fixed time delay is measured as a function of the orientation of the magnetic field with a fixed strength B. The signal has a sine-like form and its phase determines the sign of the g factor of carriers. As a natural extension of previous methods to measure the (time-resolved) photoluminescence or time-resolved Kerr rotation signal as a function of the magnetic field strength with a fixed orientation, such a method gives the correct sign of the g factor of electrons in GaAs. Furthermore, the sign of carriers in a (Ga, Mn)As magnetic semiconductor is also found to be negative.

Keywords: g factor, time-resolved Kerr rotation, gallium arsenide, rotatable magnetic field

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1. Introduction

In recent years, semiconductor spintronics has attracted lots of attention and has been extensively investigated, with the aim to manipulate both the spin and the charge degree of electrons in semiconductors in order to make spin-based post-Moore devices for even more powerful information processing.[1−5] The method of g factor engineering is a candidate for efficient spin-manipulation[6,7] and it requires a knowledge of the magnitude and the sign of the g factor of the carriers. Though the magnitude of the g factor can be routinely measured with time-resolved photoluminescence (TRPL) or time-resolved Kerr rotation (TRKR) techniques,[1,8,9] it is not trivial to determine its sign. Traditionally, the sign of the g factor can be obtained by measuring the circular polarization of photoluminescence (PL) with circularly polarized excitation light in a magnetic field (Hanle effect), which is used at an oblique angle to the growth axis.[10−13] Besides this, Kalavich *et al.*[14] determined the g factor by comparing the circular polarization of the TRPL in an opposite magnetic field.[14] For these methods, the PL singals of semiconductors may have complicated origins. TRKR and time-resolved Faraday rotation (TRFR) measurement have proved to be powerful techniques in semiconductor spintronics and they are widely used to study the coherent dynamics of spin.[1,8,9] They can accurately measure the electron spin Larmor precession and, hence, the magnitude of the g factor. However, there are few reports about determining the sign of the g factor with TRKR, among which is the work by Yang *et al.*[15] In their experimental configuration, the pump beam and the probe beam had an angle and so the Kerr rotation curve of $B > 0$ had a time lag relative to that of $B < 0$, thus giving out the sign of the g factor.

2. Experimental details

Here we report on an alternative method to determine the sign of the g factor via TRKR measurement with a rotatable in-plane magnetic field. This is a natural extension of the previous methods mentioned above by Snelling *et al.*,[11] Kalavich *et al.*,[14] and Yang *et al.*[15]

The experimental setup is sketched in Fig. 1. The

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†Corresponding author. E-mail: jiyang@semi.ac.cn

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TRKR measurement part is a typical pump/probe configuration.[9,16] The pump beam and probe beam are both from one and the same mode-locked Ti: sapphire pulsed laser, which has a pulse width of 150 fs, a repetition rate of 76 MHz and a tunable wavelength between 700 nm and 980 nm. The pump beam is focused onto a spot of 100 μm in diameter and the probe beam is focused onto a spot of 30 μm in diameter. Both of them are located in a horizontal plane (y–z plane in Fig. 1), where the pump beam goes along the z axis and shines normally on a sample and the linearly polarized probe beam is incident at the same spot on the sample with an angle of $\alpha = 20°$ with respect to the pump beam. The circularly polarized pump beam is modulated by a mechanical chopper for lock-in detection. The sample is located in an Oxford microscope cryostat with a temperature range of 3 K–300 K. The cold finger of the cryostat protrudes into the hole of a permanent magnet magic ring (PMMR), which provides a magnetic field in a range of 0.05 T–0.95 T with full round 360° rotatablity in the sample plane.[17] Measurements are done at 0.77 T unless otherwise noted. The rotation angle of the magnetic field, β, is defined as the angle between the orientation of the magnetic field (from the north pole to the south) and the positive y axis ($\beta = 0°$) as shown in Fig. 1.

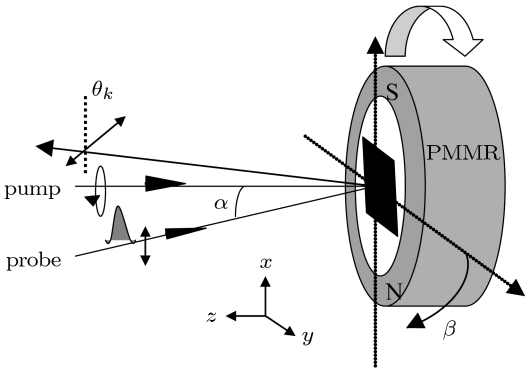


Fig. 1. Schematic diagram of the experimental configuration for the TRKR signal measurement. The magnetic field lies in the sample plane. The angle between the pump beam and the probe beam is $\alpha = 20°$. The PMMR forms a rotatable in-plane magnetic field, which can rotate 360° in the x–y plane.

3. Results and discussion

The spin precession of carriers, generated by the pump beam, is monitored by the Kerr rotation of the time-delayed linearly polarized probe pulse. The TRKR signal is proportional to the projection of the net spin along the probe direction, which may be described as[1,15]

$$\theta_k(\Delta t, \beta) = A\exp(-\Delta t/T_2)(\cos\varphi\cos\omega\Delta t - \sin\varphi\sin\omega\Delta t\sin\beta), \quad (1)$$

where A is a constant that describes the initial amplitude of the spin, T_2 is the spin lifetime, $\omega = g\mu_B B/\hbar$ is the Larmor precession frequency (where g is the g factor of carriers, μ_B is the Bohr magneton, B is the magnetic field and $\hbar$ is the Planck constant), and φ is a phase shift that depends on the angle α between the pump beam and the probe beams, and determined by the refraction law of light

$$\frac{\sin\alpha}{\sin\varphi} = \frac{1}{n}, \quad (2)$$

where n is the refractive index of the sample.

Two samples are used here. One is a thin layer of GaAs grown by molecular beam epitaxy (MBE) on a (001) semi-insulating GaAs substrate. Since the sign of the electron g factor in such a material is known to be negative, it is used to verify the equivalence of our method to the previous methods.[11,12,15] The other is a 200-nm thick dilute magnetic semiconductor (DMS) (Ga, Mn)As with Mn mole concentration of 6%, which is grown on a (001) semi-insulating GaAs substrate by low temperature MBE. The sign of the g factor in such a material is not known,[18,19] yet despite that it was argued to be negative.[17]

The TRKR signals of the two samples were measured each as a function of the delay time under four different orientations of the PMMR, as shown in Fig. 2. We fitted the curves with the formula (1), then we could extract the g factor of GaAs and (Ga,Mn)As from the precession period ω of the Kerr rotation data, i.e., $g = 0.42$ for GaAs and $g = 0.2$ for (Ga,Mn)As.

Two methods were used to obtain the sign of the g factor. One is what was described by Yang *et al.*:[15] the configurations of $\beta = 90°$ and $\beta = 270°$ PMMR are exactly what were used in their work. In that case, formula (1) should be $\theta_k(\Delta t) = A\exp(-\Delta t/T_2)\cos(\omega\Delta t + \varphi)$ for 90° and $\theta_k(\Delta t) = A\exp(-\Delta t/T_2)\cos(\omega\Delta t - \varphi)$ for 270°. As shown in Fig. 2(a), the curve for the 90° configuration lags 5 ps behind that for the 270° configuration, which corresponds to a phase shift $\varphi = 12°$ for a precession period of 150 ps, thus indicating that the sign of the electron g factor in GaAs is negative. As described by formula (2), the phase shift φ depends on α, which is 20° in our experimental setup. With the refractive index $n = 3.6$ of GaAs, the φ can be calculated to be 5.45°, and so the phase shift between 90° and 270°

should be 10.9°, which is in good agreement with our experimental result 12°.

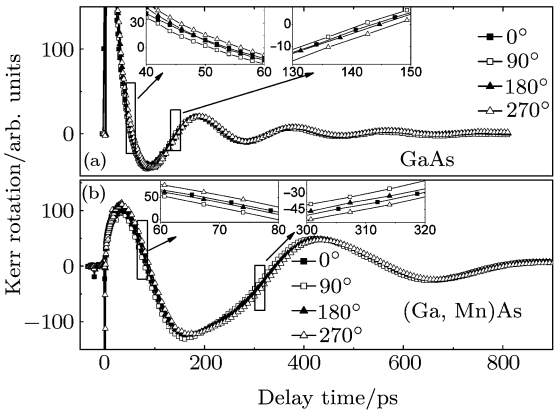


Fig. 2. The TRKR signals of the GaAs (a) and (Ga,Mn)As (b) thin films with different directions of the in-plane magnetic field. The direction 0° is along the positive y axis and the magnetic field is 0.77 T. For different directions, the change in the TRKR signal of (Ga,Mn)As is similar to that of GaAs, thus indicating that the sign of the g factor of (Ga,Mn)As is the same as that of GaAs, which is well known to be negative. Inserts show the magnified rectangular region.

Although the sign of the electron g factor in GaAs is well known to be negative,[20,21] the sign of the hole g factor in (Ga,Mn)As is not that clear-cut.[18,19] A similar measurement is made with (Ga,Mn)As, and the resulting TRKR signal is shown in Fig. 2(b). The curve of the 90° configuration lags behind that of the 270°, indicating that the sign of the hole g factor is negative in (Ga,Mn)As. The time lag between the two configurations is approximately 13 ps: this corresponds to a phase shift of 10° for a precession period of 470 ps. The Mn mole concentration is just 6%, and the refractive index $n = 3.6$ of (Ga,Mn)As is the same as that of the GaAs. The phase shift of 10° is in agreement with the calculated result 10.9°.

The sign of the g factor can also be determined by measuring the TRKR signal as a function of the orientation of the PMMR, at a fixed magnetic field strength and a fixed time delay between the pump pulse and the probe pulse. There is a simple relationship between the Kerr rotation and the orientation of the PMMR magnetic field when Δt is fixed, and it is expressed as

$$\theta_{\rm k}(\beta) = \theta_{\rm k}(0) - b\sin\beta, \tag{3}$$

where $\theta_{\rm k}(0)$ is the amplitude of the Kerr rotation when $\beta = 0°$, and $b = A\exp(-\Delta t/T_2)\sin\varphi\sin\omega\Delta t$. Figure 3 shows the dependencies of TRKR signal on the orientation of the magnetic field at the fix delay time for the GaAs and (Ga, Mn)As thin films. For the GaAs sample $\Delta t = 30$ ps (Fig. 3(a)), $B = 0.77$ T, the values of $\theta_k(0)$ and b can be

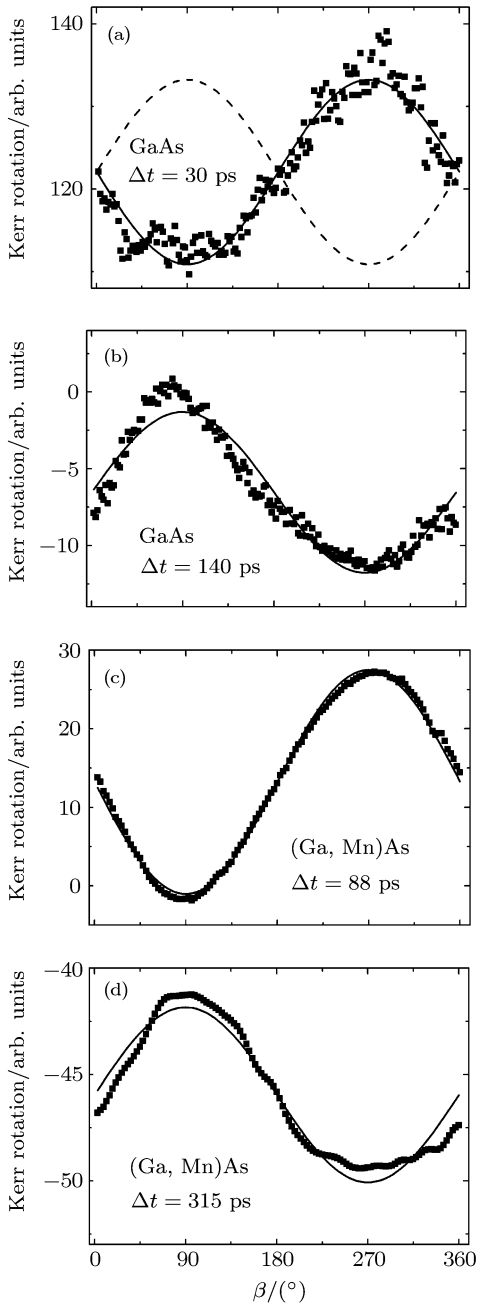


Fig. 3. Dependencies of the TRKR signal on the rotation angle (β) of the magnetic field at the fix delay time. The initial direction (0°) of the magnetic field is along the y axis and the magnetic field is 0.77 T. Panel (a) is for GaAs film at $\Delta t = 30$ ps, panel (b) for GaAs at $\Delta t = 140$ ps, panel (c) for (Ga, Mn)As at $\Delta t = 88$ ps, and panel (d) for (Ga, Mn)As at $\Delta t = 315$ ps. The black dots refer to the experimental data and the black lines represent the fitting results with formula (3), which are in good agreement with the calculations. The dashed line in panel 3(a) denotes the theoretical result with the sign of g being set to positive. The experimental data are in good agreement with the $g < 0$ fitting results, thus indicating that the g factor in GaAs is negative.

calculated to be 1.25×10^{-4} and 1.12×10^{-5}, respectively. Fitting the experimental curve with formula (3), their values are 1.22×10^{-4} and 1.12×10^{-5}, respectively, in good agreement with calculations. With the same method, we calculated the values and fitte them to the corresponding curve for the $\Delta t = 140$ ps (Fig. 3(b)), and the two curves are both in good agreement with each other. For (Ga, Mn)As, we also calculated the values for two different fixed delay times (88 ps and 315 ps), as shown in Figs. 3(c) and 3(d). We obtained a similar result, thereby indicating that the sign of the g factor is also negative: the g factor in (Ga, Mn)As has the same sign as that in GaAs.

For the GaAs $\Delta t = 30$ ps (Fig. 3(a)), if $g > 0$, formula (3) should be $\theta_{\rm k}(\beta) = \theta_{\rm k}(0) - b\sin(-\beta)$. Figure 3(a) also shows a fitting curve (the dash line) with the sign of the g factor being positive, and other parameters being the same as those used above ($\theta_{\rm k}(0) = 1.25 \times 10^{-4}$ and $b = 1.12 \times 10^{-5}$). As can be seen, it has an entirely opposite shape in contrast with the experimental data and the fitting curve with $g < 0$ (black line), which again indicates that we can determine the sign of the g factor with the phase-shift and the sign of the GaAs g factor is not positive but negative.

4. Conclusions

According to a similar configuration to that of Yang *et al.*[15] and a rotatable in-plane PMMR magnetic field, we extend the method to determine the sign of the electron g factor with TRKR measurement. At a fixed delay time, the dependence of the TRKR signal on the direction of the magnetic field in the sample plane shows a sine-like form, which can be used to determine the sign of the g factor of carriers. After verifying this method with a GaAs sample, whose g factor is well known to be negative, we also carry out the measurement in (Ga, Mn)As and find that its g factor has a negative sign.

References

[1] Awschalom D D, Loss D and Samarth N 2002 *Semiconductor Spintronics and Quantum Computation* (Berlin: Springer) **107** 152

[2] Awschalom D D and Flatté M E 2007 *Nat. Phys.* **3** 153

[3] Žuti I, Fabian J and Sarma S D 2004 *Rev. Mod. Phys.* **76** 323

[4] Dyakonov M I 2008 *Spin Physics in Semiconductors* (Berlin: Springer) p. 1

[5] Wu M W, Jiang J H and Weng M Q 2010 *Phys. Rep.* **493** 61

[6] Salis G, Kato Y, Ensslin K, Driscoll D C, Gossard A C and Awschalom D D 2007 *Nature* **414** 619

[7] Li F Z and Li Z M 2002 *Chin. Phys.* **11** 940

[8] Elezzabi A Y and Freeman M R 1996 *Appl. Phys. Lett.* **68** 3546

[9] Syperek M, Yakovlev D R, Greilich A, Misiewicz J, Bayer M, Reuter D and Wieck A K 2007 *Phys. Rev. Lett.* **99** 187401

[10] Snelling M J, Flinn G P, Plaut A S, Harley R T, Tropper A C, Eccleston R and Philips C C 1991 *Phys. Rev.* B **44** 11345

[11] Snelling M J, Blackwood E, Mcdonagh C J, Harley R T and Foxon C T B 1992 *Phys. Rev.* B **45** 3922

[12] Kalevich V K, Ivchenko E L, Shiryaev A Y, Afanasiev M M, Egorov A Y, Ikezawa M and Masumoto Y 2008 *Semicond. Sci. Technol.* **23** 114008

[13] Malinowski A, Guerrier D J, Traynor N J and Harley R T 1999 *Phys. Rev.* B **60** 7728

[14] Kalevich V K, Zakharchenya B P, Kavokin K V, Petrov A V, Jeune P L, Marie X, Robart D, Amand T, Barrau J and Brousseau M 1997 *Phys. Solid State* **39** 681

[15] Yang C L, Dai J F, Ge W K and Cui X D 2010 *Appl. Phys. Lett.* **96** 152109

[16] Luo H H, Qian X, Ruan X Z and Ji Y 2009 *Phys. Rev.* B **80** 193301

[17] Qian X, Gu X F and Ji Y 2010 *Rev. Sci. Instrum.* **81** 106106

[18] Zhu Y G, Zhang X H, Li T, Chen L, Lu J and Zhao J H 2009 *Appl. Phys. Lett.* **94** 142109

[19] Zhou R, Sun B Q, Ruan X Z, Gan H D, Ji Y, Wang W Z, Zhao J H 2008 *Acta Phys. Sin.* **57** 5244 (in Chinese)

[20] Hopkins M A, Nicholas R J, Pfeffer P, Zawadzki W, Gauthier D, Portal J C and DiForte-Poisson M A 1987 *Semicond. Sci. Technol.* **2** 568

[21] Xu H H, Jiao Z X, Liu X D, Lei L, Wen J H, Lin W Z and Lai T S 2006 *Acta Phys. Sin.* **55** 2618 (in Chinese)