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Spin concentration grating and electron spin ambipolar diffusion in intrinsic GaAs multiple quantum wells

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Abstract: In order to research the effect of holes on the spin electron diffusion, a method of resonant spin amplication called "Spin Concentration Grating(SCG)" is adopt to observe the process of electron spin diffusion. Transient spin grating and spin concentration grating excited by femtosecond laser beams are used to investigate electron spin diffusion and "electron spin ambipolar diffusion" in intrinsic GaAs multiple quantum wells. The measured coefficient of "electron spin ambipolar diffusion" $D_{as}=25.4\ cm^2\cdot s^{-1}$ is lower than that of electron spin diffusion $D_s=113.0\ cm^2\cdot s^{-1}$, which indicates that the influence of holes on electron spin diffusion in spin concentration grating is notable.

Key words: spin concentration grating; GaAs quantum well; electron spin ambipolar diffusion; fs laser

自旋密度光栅和本征GaAs量子阱中的电子自旋双极扩散

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摘要:为研究空穴对自旋极化电子扩散的影响,提出用自旋密度光栅方法来观察电子自旋扩散过程。由飞秒激光在本征GaAs多量子阱中激发产生瞬态自旋光栅和瞬态自旋密度光栅,并用于研究电子自旋扩散和电子自旋双极扩散。实验测得自旋双极扩散系数$D_{as}=25.4\ cm^2/s$,低于自旋扩散系数$D_s=113.0\ cm^2/s$,表明自旋密度光栅中电子自旋扩散受到空穴的显著影响。

关 键 词:自旋密度光栅;GaAs量子阱;电子自旋双极扩散;飞秒激光
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1 Introduction

The manipulation of electron spin in semiconductor electronic device offers the potential for new capabilities. The new field of spintronics involves basic and applied research in material science, and has become a focus of interest[1-6]. In spintronic devices, spin-polarized electrons must be transferred from one point to another with little loss of spin polarization. When the spin signal is transported by diffusion, it requires an adequately long spin diffusion length, which is defined by the spin diffusivity and the spin relaxation time, indicating how far the spin signal may be reliably spread out by diffusion. The spin relaxation times from several decades picoseconds[7] to nanosecond[8] and even over one hundred nanoseconds[9] have been measured in some semiconductors. The spin diffusivity of electron can be measured by the transient spin grating technique.

Transient electron spin grating technique derives from transient electron concentration grating technique. In this method, two cross-linearly polarized optical pump pulses with identical energies near the band gap overlap in the sample from different directions, exciting electron-hole pairs. Consequently, the total concentration of electron is uniform near the centre of excitation spot, while the net spin polarization alternates periodically between right and left circular spin polarizations across the excitation region. This is so-called Spin Grating(SG). The decay rate of grating amplitude can be detected by the delayed probe pulses, which are diffracted off when passing through the SG. And then, with these measured decay rates of spin gratings with different grating periods, the spin diffusion coefficient D_s and spin relaxation time τ_s can be calculated. In recent years, transient SG technique has been in common use to research on spin diffusion properties of semiconductor material or other fields[10-13]. However, because of the uniform total excited electron concentration in the excitation region, this technique, which is adapted to investigate the diffusion property of the spin polarized electrons in conduction band, is not capable of revealing the effect of the holes on electron spin diffusion process. As Flatte etc. [14] demonstrated, for the intrinsic semiconductor, the holes affected the motion of electron spin packet just as occurred in the charge packet. Therefore, it is probably hard for the spintronic devices in the future to avoid the effect of holes on the spin polarized electron diffusion. Nevertheless, in experiment, there is an almost complete lack of awareness of the property of electron spin diffusion under the influence of holes. In order to research on this phenomenon, one should set up an experiment system to observe the process of electron spin diffusion accompanied by the effect of the holes. Hence, a method of resonant spin amplication which called "spin concentration grating (SCG)" is adopted. In this method, different from the previous SG technique, two same circular polarized non-collinear pump beams intersect and interfere in the sample, producing a spatial concentration modulation of spin polarized electron, which act as a grating. The decay rate of the grating is detected by a time-delayed circular polarized beam diffracted by the grating. In this concentration grating, the density of the total electrons as well as the electron spin polarization varies across excited region with the same periods, as shown in Fig. 1(b). As a result of this, we call the transient grating as "spin concentration grating (SCG)". Unlike the characteristic of SG, both electron concentration and electron spin polarization in SCG are not uniform, then electron spin diffusion is restricted by the excited holes. This influence can be revealed by the detected decay rate of intensity of the diffracted probe beam. Since electrons and holes are injected into semiconductor simultaniously in most case , the D_s measured by this method perhaps is necessary for estimating the capability to transfer spin signal by electron spin diffusion. In this paper, we present the electron spin diffusion coefficient D_s measured by SCG technique and SG technique in intrinsic GaAs multiple quantum wells at room temperature, indicating that the spin diffusion coefficient D_s decrease due to the participation of holes in electron spin diffusion.

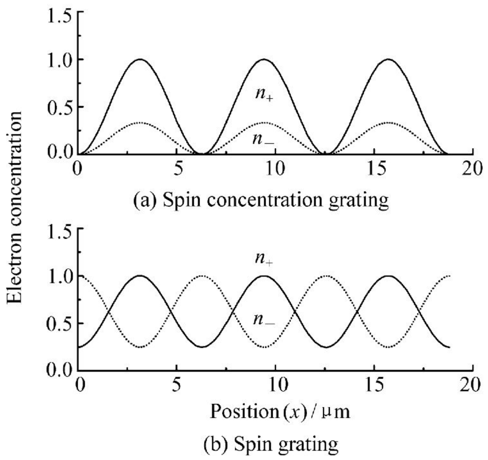

Fig. 1 Polarization modulation for (a) spin concentration grating and (b) spin grating. The n_+ and n_- refer to concentration of spin-up and spin-down electrons excited by polarized light

2 Experiments

The sample grown by molecular beam epitaxy (MBE), consists of 11 periods of 6-nm-thick GaAs wells and 10-nm-thick AlGaAs barrier layers. The GaAs substrate was removed and the structure was adsorbed on a sapphire base for mechanical stability. The heavy hole exciton absorption peak is at about 1.5 eV[15].

The experiments were performed at room temperature using a self-mode-locked Ti:sapphire laser producing 150 fs pulses at 96 MHz . The linearly polarized beam from Ti:sapphire laser was split into two pump pulses and a probe pulse by beam splitters. Two pump pulses with same intensity arrived at the sample simultaneously with diameters at the focus of 100 μm, and the probe pulse, whose arrival was delayed by a delay line, formed a spot in the center of the pump spot with diameter of 60 μm. The average power in every pump beam was 8 mW with 2 mW in probe beam. The beam chopper was not inserted into pump beams but probe beam in order to decrease the effect on the detected signal from the scattered incident light, because of much less intensity of probe beam than that of pump beams. By wave plates in each beam, it is convenient to change the polarization of pump and probe lights. In SG experiments, a half-wave plate was set in one of pump beams to make two pump beams cross-linear-polarized. The decay rate of the SG was detected with a delayed probe beam with linear (horizontal) polarization. The diffracted beam of probe beam passed through a linear polarizer oriented vertically in order to filter scattered light from probe beam. In SCG experiments, a quarter-wave plate was set in each pump beam to make pump beams same circular polarized. We used a delayed probe beam with the same circular polarization (SCP) first and then the opposite circular polarization (OCP) to monitor the decay rate of the SCG, respectively. Actually, spin concentration grating consist of spin-up electron concentration grating and spin-down electron concentration grating with different modulated amplitude [see Fig. 1(a)]. More over, the results of FWM experiment detected with the SCP or OCP probe beam only relate to the corresponding electron concentration gratings respectively, which will be illuminated further in the following section.

3 Results and discussion

For SCG, the kinetics of the plasma grating following the excitation are described by[16]:

$$\frac{\partial m(x,t)}{\partial t} = D_s \nabla^2 m(x,t) - \frac{m(x,t)}{\tau}, \quad (1)$$

where $1/\tau = 2/\tau_s + 1/\tau_r$, τ_s is spin relaxation time and, τ_r is electron recombination time; D_s is spin diffusion coefficient; $m(x,t) = n_+(x,t) - n_-(x,t)$ is the net spin density at point x and time t, $n_+(x,t)$ and $n_-(x,t)$ are value of density of up and down-spin electrons at point x and time t. The key part of solution for Eq. (1), which denotes the relation between spin polarization modulated amplitude and time t, can be written as[17-18]:

$$\delta(t) = \delta(0)\exp[-(\frac{4\pi^2 D_s}{\Lambda^2}+\frac{1}{\tau})t] , \quad (2)$$

where $\delta(t) = [m_{max}(t) - m_{min}(t)]/2$ is the spin polarization modulated amplitude at time t, $m_{max}(t)$ and $m_{min}(t)$ are the maximum and minimum of net spin density at time t in SCG; Λ is the transient grating periods; Since SCG consist of up-spin electron concentration grating and down-spin electron concentration grating, we obtain $\delta(t) = \delta_+(t) - \delta_-(t)$, where $\delta_+(t) = [n_{+max}(t) - n_{+min}(t)]/2$ and $\delta_-(t) = [n_{-max}(t) - n_{-min}(t)]/2$ are the electron density modulated amplitude for up-spin electron concentration grating and down-spin electron concentration grating at time t, respectively, $n_{+max}(t)$ and $n_{+min}(t)$ ($n_{-max}(t)$ and $n_{-min}(t)$) are the maximum and minimum of density of electron in up-spin (down-spin) electron concentration grating, respectively; $\delta(0)$, as the proportional coefficient between $\delta(t)$ and $\exp[-(4\pi^2 D_s/\Lambda^2 + \tau^{-1})t]$, is the spin polarization modulated amplitude at time $t = 0$. As was mentioned above, our results of SCG experiments include $S_+(t)$ and $S_-(t)$ corresponding to the SCP and OCP probe beams. It is common knowledge that, the diffracted signal is proportional to the square of the modulated amplitude, namely $S_\pm(t) = \alpha^2 \times [\delta_\pm(t)]^2$, where α^2 is the proportional coefficient between $S_\pm(t)$ and $[\delta_\pm(t)]^2$. Notice that the proportional coefficient between $S_+(t)$ and $[\delta_+(t)]^2$ is the same as that between $S_-(t)$ and $[\delta_-(t)]^2$ because of the same intensity of SCP and OCP probe beams used in our experiments. Hence, the difference between the square roots of $S_+(t)$ and $S_-(t)$ can be expressed by Eq. (3):

$$\sqrt{S_+(t)} - \sqrt{S_-(t)} = \alpha\delta_+(t) - \alpha\delta_-(t) = a\delta(t) . \quad (3)$$

Substituting Eq. (2) in Eq. (3), we obtain:

$$\sqrt{S_+(t)} - \sqrt{S_-(t)} = \alpha\delta(0)\exp[-(\frac{4\pi^2 D_s}{\Lambda^2}+\frac{1}{\tau})t] . \quad (4)$$

Eq. (4) indicates that the difference between the square roots of $S_+(t)$ and $S_-(t)$ decays with rate:

$$\Gamma_{SCG} = \frac{4\pi^2 D_s}{\Lambda^2}+\frac{1}{\tau} . \quad (5)$$

For SG experiments, the well-known relation between decay rate of diffraction (2Γ) and delay time(t) can be expressed by Eq. (6)[10]:

$$2\Gamma_{SG} = \frac{8\pi^2 D_s}{\Lambda^2}+\frac{2}{\tau} . \quad (6)$$

To make a distinction, we define D_{as} and D_s as electron spin diffusion coefficient in SCG and SG, respectively. Then, Eq. (4) and Eq. (5) may be rewritten as Eq. (7) and Eq. (8):

$$\sqrt{S_+(t)} - \sqrt{S_-(t)} = \alpha\delta(0)\exp[-(\frac{4\pi^2 D_{as}}{\Lambda^2}+\frac{1}{\tau})t] . \quad (7)$$

$$\Gamma_{SCG} = \frac{4\pi^2 D_{as}}{\Lambda^2}+\frac{1}{\tau} . \quad (8)$$

To sum up, Eq. (6) and Eq. (8) act as fitting functions for the results of SG and SCG experiments, respectively.

We determined the coefficient D_s of electron spin diffusion without the effect of holes by monitoring the decay of diffraction signal of SG. The experimental results of time-resolved measurement of the diffracted probe signals for the $\Lambda = 6.8$ μm SG are shown in Fig. 2(a), from which the decay time of SG $\tau = 17$ ps can be determined. The measured decay rate of diffraction signal for SG with some other grating periods are plotted in the inset of Fig. 2. A linear fitting to the scattered points with the Eq. (6) gives a spin diffusion constant of $D_s = 113.0\ \mathrm{cm^2 \cdot s^{-1}}$, which is in agreement with previous study[10,11].

Subsequently, we performed a measurement of spin diffusion in SCG, which provided us with time delay diffracted signal S_+ and S_- corresponding to SCP and OCP probe beams. The kinetics of S_+ and

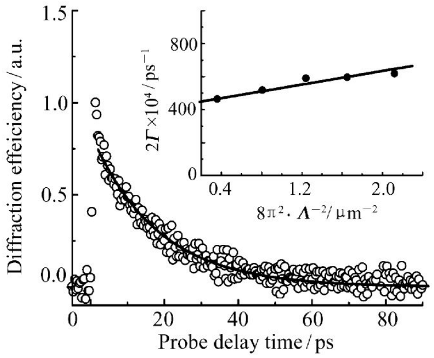

Fig. 2 Measured diffracted signal (open dots) as a function of probe delay time for Λ = 6.8 μm spin grating. Inset, measured decay rates (dots) of the diffracted signal against $8\pi^2 \cdot \Lambda^{-2}$

S_- for the SCG with Λ = 6.8 μm is shown in Fig. 3. The diffraction efficiency decrease with t for SCP probe beam, while increase with t for OCP probe beam, and then converge at a little more than $\Delta t \approx$ 100 ps, which indicate the electron spin relax during the spin polarized electron diffuse and recombine.

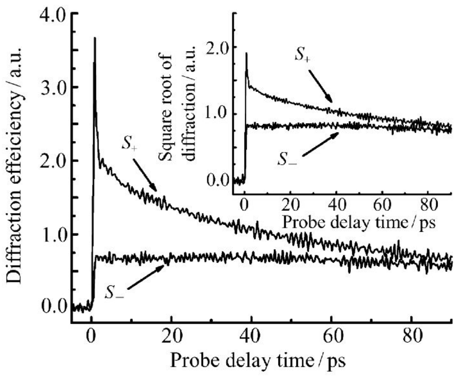

Fig. 3 Diffracted signal as a function of probe delay time for Λ = 6.8 μm spin-up electron concentration grating measured by same circular polarized (SCP) probe beam (S_+) and spin-down electron concentration grating measured by opposite circular polarized (OCP) probe beam (S_-). Inset, square root of the diffracted signal, corresponding to modulated amplitude of each electron concentration grating, as a function of probe delay time

As was discussed above, the diffraction efficiency $S\pm$ correspond to the square of the amplitude modulation of spin-up electron concentration grating and spin-down electron concentration grating. Accordingly, in the inset of Fig. 3, we present kinetics of the square root of S_+ and S_- for the Λ = 6.8 μm.

Kinetics of the difference of the square root of S_+ and S_- ($\sqrt{S_+} - \sqrt{S_-}$) is shown in Fig. 4, which gives a time constant τ = 35.7 ps. The double decay rate of $\sqrt{S_+} - \sqrt{S_-}$ versus $8\pi^2/\Lambda^2$ for several SCG periods Λ are plotted in the inset of Fig. 4. The fit procedures, as shown in the inset of Fig. 4, yield spin diffusion coefficients D_{as} = 25.4 cm^2/s, which is prominently lower than the value of D_s in SG. These results indicate that the electron spin diffusion velocity in SCG is much lower than that in SG. Since the experiments are performed using laser beams with the same exciting power and the same wavelength to excite the same sample, we attribute this phenomenon to the influence from holes. In SCG experiment, the spin polarized holes imported with spin polarized electrons, with the same distribution as the excited electrons, relax rapidly in sub-pico-second[19], and accordingly act as a charge packet during spin polarized electrons diffuse. Because

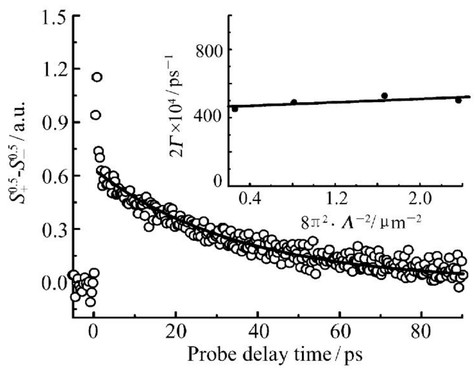

Fig. 4 Date (open dots), showing the decay of Λ = 6.8 μm SCG, obtained (from Fig. 3) by subtraction of the diffraction curve for OCP from the diffraction curve for SCP. The line is a fit of the date with time constant of 35.7 ps. Inset, double decay rate (dots) of the SCG against $8\pi^2 \cdot \Lambda^{-2}$

the density of holes should equal to that of electrons, namely, the electrical neutrality should be met everywhere in pump spot, the spread of electron packet by diffusion is necessarily accompanied by holes whose diffusion velocity much lower than electrons in GaAs. Consequently, the electron spin diffusion velocity in spin concentration grating is decreased. This case is analogous with the ambipolar diffusion of charge, hence we define the coefficient of electron spin diffusion dragged by holes as "spin ambipolar diffusion coefficient" D_{as}. Conversely, as indicated in Fig. 1(b), in SG experiment, although the density of the electron with certain spin orientation alternates periodically, the total density of electrons is uniform in pump region. As a result, even though there exist spin current in SG, the total diffusion current density of electron at any point near the center of excitation spot equal to 0. In this case, the electrical neutrality is met by electron itself during electron spin diffusion without the participation of holes. This spin diffusion of relatively free electron is the so-called single band electron spin transport[9], which result in a relatively larger spin diffusion coefficient D_s.

4 Conclusion

In conclusion, we investigate the electron spin diffusion in SCG, which gives a spin diffusion coefficient $D_{as} = 25.4\ \mathrm{cm^2 \cdot s^{-1}}$ lower than that measured by SG technique. This SCG technique was used to detect electron spin diffusion. The results indicate the influence of holes on electron spin diffusion, which should be taken into account when the ability of spin diffusion of a certain semiconductor material is referred.

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