Tuning of the Landé g-factor in $Al_xGa_{1-x}As/AlAs$ single and double quantum wells

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Abstract. We report on the spin dynamics of a high mobility two-dimensional electron gas in a $Al_xGa_{1-x}As/AlAs$ double quantum well structure. For high electron density samples, the g-factor was measured using time-resolved Kerr rotation technique. The g-factor tuning capability was observed by changing the aluminum content x independently in each well. Experiments demonstrated an unusual spin dephasing time robustness for high excitation power. The effect of the interaction between wells was analyzed in samples with different tunneling barriers. Results were compared with experiments on single well systems demonstrating higher spin polarization generation, longer spin dephasing time, and coupling for the double structures.

1. Introduction

The influence of a dense two-dimensional gas in the trion and exciton optical transitions of a single quantum well has been extensively studied [1, 2, 3, 4]. Determining the electronic structure of such semiconductor nanostructures requires a detailed study of their spin properties [5]. An important tool for such investigation is the Landé g-factor as it depends on the confinement potential details and chemical composition.

For example, the electron g-factor of a $Al_xGa_{1-x}As$ quantum well depends strongly on the Al content x. In a single parabolic $Al_xGa_{1-x}As/Al_{0.4}Ga_{0.6}As$ well, a gate-voltage-mediated control of coherent spin precession has already been demonstrated including g-factor sign change and vanishing values [6]. Also, the spin-beat spectroscopy in $GaAs/Al_xGa_{1-x}As$ quantum wells reveals a g-factor universal dependence on the optical transition energies [7].

Adding an extra control parameter, bilayer systems can be constructed by two parallel quantum wells with a high mobility electron gas separated by the tunneling barrier [8]. When a magnetic field is applied perpendicular to well plane, the quantum Hall states are formed. For double wells with vanishing g-factor, experiments reveal unsual magneto-transport features in the quantum Hall effect [9].

The possibility to generate direct and indirect excitonic states in double quantum wells focused great attention in optical experiments [10, 11, 12]. Furthermore, the g-factor variation with an external electric field has been observed in coupled quantum wells with unequal widths [13]. In this reference, time-resolved Faraday rotation showed a continuous g-factor tune or switch between the Larmor frequencies of the individual wells.

Here, time-resolved Kerr rotation data displays a strong tunability of the g-factor by independently adjusting the Al content in a pair of square quantum wells with equal width.

Furthermore, pump-probe spectroscopy shows that the spin polarization generation and dephasing time strongly dependent on this chemical composition control parameter. For double quantum wells, the tunneling barrier width plays the major role and allows additional tuning capability with coupling.

2. Samples

The investigated samples consist of single and double quantum wells containing a dense high-mobility two-dimensional electron gas (2DEG). Several samples were grown using the Al content (x<16%) as a g-factor engineering parameter in every individual well. The mobility and electron density were characterized through transport measurements. The sample specifications are presented in table 1. For the double quantum well structures, we denoted the sample configuration following a convention similar to reference [13].

Table 1. Single and double quantum well samples where t_b is the AlAs barrier width, n is the electron density, and μ is the mobility. The well width is 14 nm equal for all samples.

Sample	Structure	x% QW1	t_b (nm)	x% QW2	$n(\times 10^{11} cm^{-2})$	$\mu(\times 10^{3} cm^{2}/Vs)$
SQW	QW	10	-	-	4.79	35.8
10-1.4-10	DQW	10	1.4	10	4.76	12
8-5-14	DQW	8	5	14	6.63	37.9
11-5-16	DQW	11	5	16	5.0	39

3. Experimental Results and Discussions

In order to obtain the effective g-factor, time-resolved Kerr rotation (TRKR) studies were performed. For optical excitation a mode-locked Ti:sapphire laser was used emitting pulses with 100 fs duration at a rate of 75.6 MHz. The pump/probe lasers were tuned to each quantum well trion optical transitions to excite/monitor the 2DEG spin polarization. The pump beam was circularly polarized by an photo-elastic modulator with a frequency of 50 kHz. The probe beam polarization was not modulated and its change induced by the spin dynamics was detected with a brigde using coupled photodiodes. The Kerr signal was robust under high excitation power with pump-probe intensities of 10 mW and 5 mW respectively. The sample was immersed in the variable temperature insert of a superconductor magnet for fields B up to 6 T aligned perpendicular to the optical axis.

The electron spin precession was observed under an in-plane magnetic field by the time-resolved Kerr angle Θ_K oscillations with a frequency determined by the g-factor according to [6, 13]:

$$\Theta_K = A \exp(-\Delta t/T_2^*) \cos(2\pi f_L \Delta t + \phi) \quad (1)$$

where A is the amplitude proportional to the injected spin polarization along the optical axis, Δt is the pump-probe delay time, T_2^* is the spin dephasing time, $f_L = g\mu_B B/h$ is the Larmor frequency at a given magnetic field B, and ϕ is a phase offset. Only the magnitude of the g value will be consider in this report and not the sign ($g = |g|$).

Figure 1a shows the time evolution of the Kerr signal Θ_K for a single quantum well with Al content x=10% and for a double quantum well with x=10% in both wells separated by a narrow tunneling barrier. First, the SQW electron g-factor displays a large shift (Δg$\sim$44%) considering the calculated value of g$\sim$0.27 from reference [14]. From the SQW-DQW comparison, three

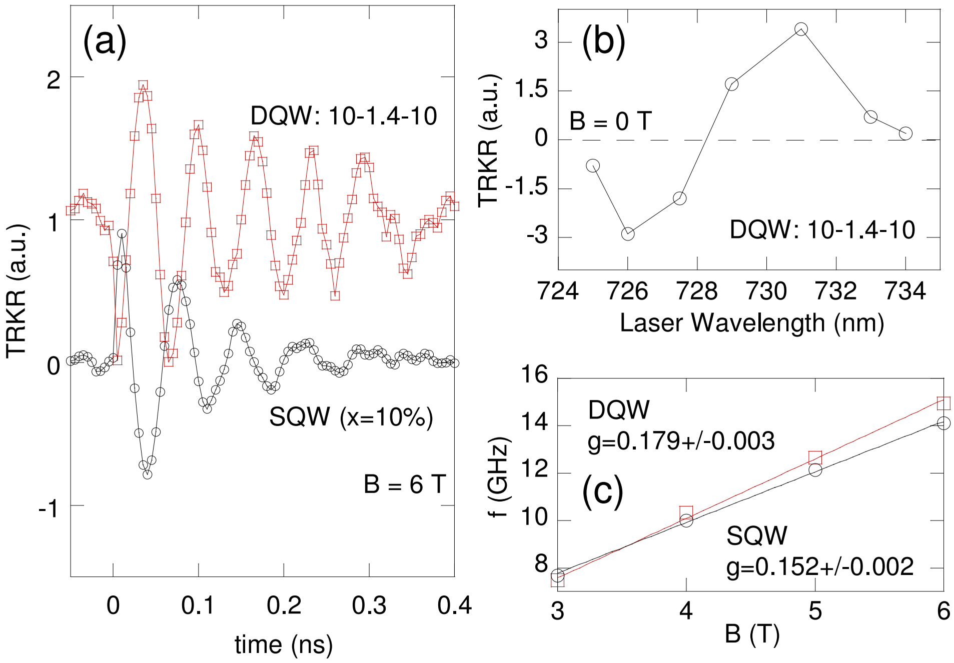

Figure 1. Single and double quantum wells with x=10%. (a) Kerr rotation at 6 Tesla. (b) Zero-field signal amplitude as function of the laser detuning at a fixed delay of 0.26 ns for sample 10-1.4-10. (c) Larmor frequency as function of the magnetic field strength. The solid line are linear fits with the g-factor as parameter.

principal features can be directly extracted: (i) the spin dephasing time appears to be longer in the double well system, (ii) the Larmor frequency is slightly larger in the double well sample, and (iii) Kerr signal oscillations display opposite phases.

To explore the opposite phase between the curves in figure 1(a), the Kerr signal amplitude was measured as function of the laser detuning for sample 10-1.4-10. Figure 1b shows that a phase change occurs leading to a maximum negative and positive amplitude a fixed time delay. In a single GaAs quantum well with the same width, the appearance of a phase change was assigned to the hole character (light/heavy) in the trion formation [4]. The electron g-factor measured for the excitation wavelength at both transitions was exactly the same (g=0.179±0.003 and g=0.178±0.002 at 726 nm and 731 nm respectively). This result indicates that this measured value is related to the electrons in the 2DEG also in accordance to this previous report. Given the fact that the larger spin polarization amplitude was obtained with excitation at the higher energy transition (light-hole trion), we plotted this data for a g-factor comparison between the SQW and the DQW 10-1.4-10 in figure 1c. The data shows that the quantum wells in the double structure with with narrow barrier must be coupled producing a considerably large g-factor magnitude enhancement from the SQW value $\Delta g \sim 15\%$.

Figure 2a and b shows double quantum well samples with different Al composition in each well. Since the x parameter changes the energy gap, we can identify the emission peaks associated with the individual quantum wells in the photoluminescence spectra. These peaks are separated by the large x difference. The laser tuning near every peak position allow to observe the two opposite phase components in the Kerr signal as in figure 1b. In a similar manner, both data plots (figure 2a and b) display a larger g-factor and longer spin dephasing time for increasing x.

A possible coupling between the wells is indicated by the presence of the higher g-factor into

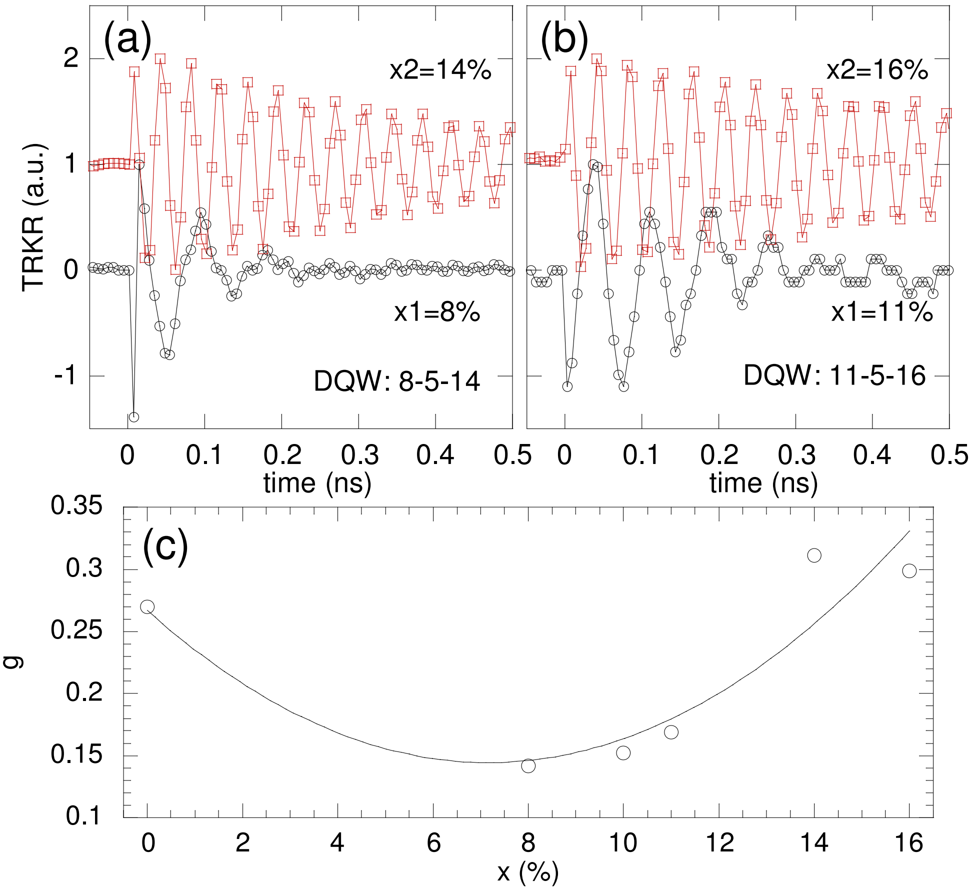

Figure 2. Kerr rotation signal in double structures using resonant excitation with each single quantum well for sample (a) DQW: 8-5-14 and (b) DQW: 11-5-16. (c) g-factor dependence on the Al content. The data point at x=0 was extracted for a 14 nm quantum well width from reference [14]. The solid line is a fitted parabolic function.

the other well signal in the same pair. This faster frequency appears with lower amplitude, as it is far from resonance, at a long delay time ($\sim$ 0.3 - 0.5 ns in the black curves). We can conclude that the double wells with a hard AlAs tunneling barrier of 5 nm still present coupling. However, this coupling results in the mixing of the individual g-factors and may not produce a shift in the individual values. Following this assumption, the g-factor associated to an individual well was plotted in figure 2c including a parabolic fitting as trend line. We extracted the value for a GaAs well (x=0) with the same width from reference [14] and we use the SQW data for x=10%. From the fitted function, it is expected a lower magnitude of the g-factor around 7%. We must note that the g-factor sign is considered in our present analysis. Nevertheless, if we take the know negative value at x=0, a vanishing g-factor if expected near x=7% as obtained in reference [6].

We conclude that the composition engineering in $Al_xGa_{1-x}As$ single and double square quantum wells allows to tuned the g-factor in large range as well as the spin polarization efficiency and dephasing time. For the double wells, the tunneling barrier adds another control parameter in a coupling regime. A detailed study of the indirect exciton in double quantum wells with unequal aluminum content as well as the excitation power dependence study will be published elsewhere [15].

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