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Dynamics of Locally Injected Spin Distribution in Undoped GaAs Quantum Wells

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Abstract

We studied the dynamics of photo-injected spin distribution in GaAs quantum wells. The time-resolved magneto-optic Kerr imaging technique revealed that the electron spins diffuse very slowly under a spin-orbit effective magnetic field. The experimentally obtained spin lifetime and diffusion coefficient values were 20 ns and 2 cm^2/s, respectively. The ability to access such locally-stored and long-lived spins allows us a plenty of time to analyze and manipulate the spin dynamics before the spin coherence vanishes.

1. Introduction

Spin-orbit interaction (SOI) plays important roles in determining the spin distribution dynamics in semiconductors. Recent studies of magneto-optic Kerr rotation microscopy have shown that spin-polarized electrons excited locally in two-dimensional electron systems visualize the characteristic stripe pattern of a persistent spin helix [1,2]. These imaging methods were possible only when the sizes of both the initial spatial spin profile and the detection resolution were smaller than the spatial period of the spin helix pattern. We expect that a similar limitation to apply when determining the detectable spin distribution dynamics for general cases such as symmetric GaAs quantum wells, which have spin-orbit interactions far from the PSH condition. Here we investigated the spatial evolution of a spin distribution injected locally in undoped 20-nm-thick GaAs/AlGaAs quantum wells (QWs). The pump-probe measurements were carried out with laser beams focused on spots smaller than the wavelength of the SOI-induced spin precession. This high spatial resolution clarified the SOI-induced spin profiles, which should not appear when we use wider spatial resolutions. We found a long-lasting decay component in time-resolved Kerr signals, which allowed us to extract a small diffusion coefficient ($D_s \sim 2$ cm^2/s).

2. Experiment

The samples studied here were grown by molecular-beam epitaxy (MBE) and contained a single undoped 20-nm-thick GaAs (001) quantum well with short-period GaAs (1.4 nm) / AlAs (0.8 nm) superlattice barriers. The two-dimensional electron gas (2DEG) mobilities in high electron mobility transistor (HEMT) structures grown in the same MBE chamber were ~100 m^2/(Vs) at 4 K. Figure 1 shows the low-temperature photoluminescence (PL) and PL excitation (PLE) spectra measured for one of the undoped samples. Each peak can be assigned to the calculated transition energies for the designed QW, and the widths of peaks assigned to the lowest exciton transitions were narrower than 1 meV. These basic electrical and optical properties indicate that the crystal quality of the present undoped GaAs QWs is sufficiently high for us to discuss photo-excited carrier dynamics.

To investigate the evolution of the local spin distribution, we carried out time and spatially resolved magneto-optic Kerr rotation measurements. We used a pair of mode-locked Ti:sapphire lasers tuned to the lowest heavy-hole exciton transition energy. A circularly-polarized pump beam from the laser excited spin polarized electrons with a spot size of ~ 6 μm, and subsequent spin density dynamics were measured through the Kerr effect of the reflected linearly polarized probe beam focused on a ~3 μm spot. These sizes are smaller than the spin-orbit length (~24 μm) estimated in similar 20-nm-thick QWs [3]. By scanning the probe position, we were able to measure two-dimensional images of spin densities at a certain pump-probe delay time Δt.

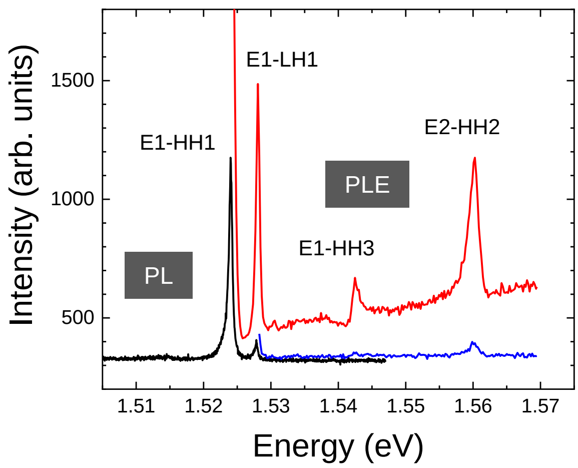

Fig. 1 PL (black line) and PLE (red and blue lines for detection energies at 1.524 and 1.528 eV, respectively) spectra measured at 8 K. The peaks are assigned to optical transitions related to the QW eigenstates as indicated by the *i*-th states of electron (E), heavy hole (HH), and light hole (LH).

3. Results and Discussion

Figure 2 (a) shows the spatial evolution of the Kerr rotation profiles that we measured by scanning the probe beam position in the Y (∥ [010]) direction at different pump-probe delay times Δt. The Kerr signal survived even with a 12 ns delay, indicating that there is a spin component with an unexpectedly long lifetime (~20 ns). This long decay time allowed us to estimate how fast the locally injected spins diffused laterally over time.

We fitted the data with a simple Gaussian function for all Δt values. As plotted in Fig. 2(b), the widths obtained for the data do not show clear expansion during the time range of ~10 ns. The spatial diffusion of spins in a two-dimensional plane can be expressed by the diffusion equation, $\partial f / \partial t = D_s \nabla^2 f$, which has a Gaussian solution expressed by,

$$f(x, y, \Delta t) = A \exp[-(x^2+y^2) / (2\sigma^2)]. \qquad (1)$$

Here σ is the standard deviation, which increases over time in accordance with,

$$\sigma(\Delta t) = [\sigma_0{}^2 + 2\, D_s \Delta t]^{1/2}. \qquad (2)$$

A comparison of the data with the lines calculated from eq. (2) for different D_s values (Fig. 2(b)) indicates that the relevant spins are completely localized ($D_s = 0$), or that D_s has a non-zero value but its order does not exceed 1 cm^2/s.

An analysis of the spin precession in an external magnetic field ($\mathbf{B}_{ext}$) provided us with an additional clue with which to identify the D_s value. We applied B_{ext} = 49 mT in the X (∥[100]) direction and scanned the probe positions in the X and Y directions. Figure 3 shows the time-resolved Kerr rotation for different probe positions. The oscillations at X = 0 and Y = 0 correspond to the spin precession determined by B_{ext}. The precession frequency Ω increases linearly in the X direction whereas it is constant in the Y direction. This behavior cannot be explained without including spin diffusion, and its direction dependence is consistent with the symmetry of the k-linear Dresselhaus spin-orbit interaction. A linear fit to $\Omega(X)$ provided $d\Omega/dX$ = 7.7 MHz/μm, from which we obtained $D_s \sim 2$ cm^2/s according to the theory [4]. This D_s value is consistent with the Gaussian expansion in B_{ext} = 0 T, which was discussed in Fig. 2. These results suggest that the long-living electron spins diffuse very slowly under the spin-orbit effective magnetic field.

4. Conclusions

We investigated the diffusion dynamics of spins that were generated locally in an undoped GaAs quantum well. The Kerr rotation profile revealed the contribution of spin states with a long lifetime of 20 ns. Our analysis of spin precession dependence on probe position enabled us to extract a spin diffusion coefficient of D_s = 2 cm^2/s. The ability to access such locally-stored and long-lived spins allows us sufficient time to analyze and manipulate the spin dynamics before the spin coherence vanishes.

Acknowledgements

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References

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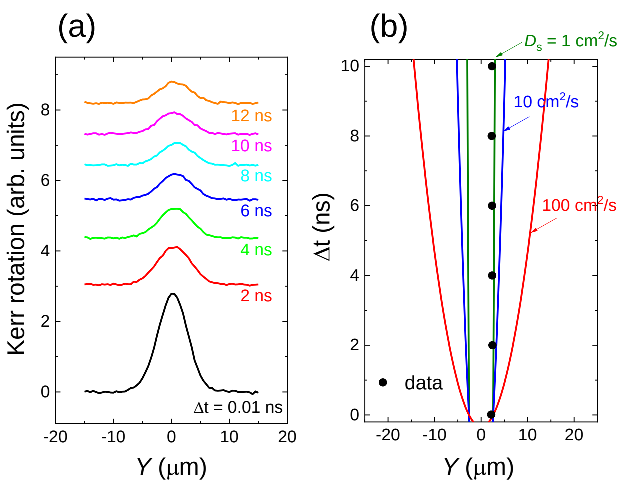

Fig. 2 (a) Spatial evolution spin density measured with Kerr rotation microscopy. The data are offset for clarity. (b) The symbols indicate the widths of the spin density profile obtained by fitting the data to a Gaussian function. The lines are the solutions of the diffusion equation calculated for different diffusion coefficients D_s.

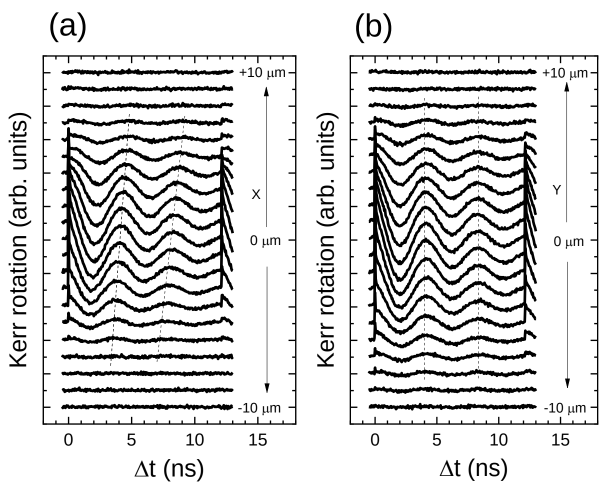

Fig. 3 Time resolved Kerr rotation measured at different probe positions, which were scanned in X (a) and Y directions (b). The data are offset for clarity. The dotted lines indicate precession phases 2π and 4π, whose timings change with probe position.