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Observation of Phase Relaxation in Spin Superposition by Polarization- and Time-Resolved Pump and Probe Measurements

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Abstract

Phase relaxation in spin superposition created by linearly polarized light in GaAs/AlGaAs quantum well was observed by polarization- and time-resolved pump and probe measurements. The spin superposition decays when population of polarized spin or phase in spin superposition changes. To study these two origin of spin relaxation we compared temperature dependence of relaxation time of the phase relaxation in spin superposition transferred by linearly polarized light with that of spin state created by circularly polarized light. The result shows that band mixing in the valence state mainly contribute to the change of the phase in superposition of hole-spin states and relaxation time is different from that of hole-spin polarization generated by circularly polarized light. The spin relaxation is caused by changing the population of polarized hole spin or the phase in superposition of hole spins and these process show different relaxation time.

1. Introduction

Electron and hole spin in semiconductor nanostructure is expected for the quantum information technologies. This superposition is created by the arbitrary superposition of two types of polarized light [1]. Understanding of superposition of electron- and hole-spin states and their relaxation mechanism is indispensable for coherent transfer of the quantum bit in the photon states to carrier states in semiconductor.

When electrons and holes in the QW sample are irradiated by right-handed circularly polarized light, polarized electron ($\uparrow_e$) and hole spin states ($\downarrow_h$) are excited,

$$|\uparrow_e\rangle|\downarrow_h\rangle. \quad (1)$$

This spin polarized state decays by decreasing the population of polarized electron ($\uparrow_e$) and hole spin states ($\downarrow_h$) and results in showing two decay components in time resolved measurements. In the same manner, the superposition is transferred to electron ($\uparrow_e, \downarrow_e$) and hole states ($\uparrow_h, \downarrow_h$) in QW by linearly polarized light which is the superposition of right- and left-handed circularly polarized light,

$$\left|\uparrow_e + e^{i\varphi}\downarrow_e\right\rangle\left|\uparrow_h + e^{i(\varphi+\pi)}\downarrow_h\right\rangle. \quad (2)$$

This polarized states disappear when the population of polarized spin state or the phase φ in superposition changes. In this study, we have measured temperature dependence of relaxation time of carrier spin created by circularly polarized light and that of superposition of spin states created by linearly polarized light by polarization- and time-resolved pump and probe measurements and compared these relaxation process for further understandings of spin relaxation mechanism in spin superposition.

2. Experiments

GaAs/AlGaAs multiple quantum wells were used for the present study. Each quantum well (QW) consisted of 20 periods of GaAs wells and $Al_{0.35}Ga_{0.65}As$ barrier layers grown on a (001) GaAs substrate. The thickness of the well layer were 4, 8, and 12 nm. Polarization- and time-resolved pump and probe measurements were performed to observe temperature dependence of spin relaxation time using Ti-doped sapphire laser with a pulse duration and repetition rate of 2 ps and 80 MHz, respectively.

Figure 1 (a) and (b) show time traces of degree of polarization (DOP) measured by using right-handed circularly polarized light and linearly polarized light as pump light, respectively. DOP was obtained by $(I_1 - I_2)/(I_1 + I_2)$, where I_1 and I_2 are parallel and anti-parallel component to pump light, respectively. Figure 1 (a) shows two relaxation components which correspond to electron and hole spin relaxation. On the other hand, Fig. 1 (b) shows one relaxation components. In linearly pump experiments, entangled state of electron and hole written by Eq. (2) is created. The linearly polarization disappear after either electron- or hole-spin phase (φ) changing [2]. To confirm the mechanism of spin relaxation transferred by linearly polarized light written by Eq. (2), we measured temperature dependence of relaxation time for linearly and circularly polarized excitation.

3. Results and Discussion

Figure 2 shows temperature dependence of slow spin relaxation time obtained by exponential fitting of DOP when QW with a well width of 4, 8, and 12 nm were pumped by right-handed circularly-polarized light. In low temperature region (~50 K), relaxation time increases

with increasing the temperature. This tendency is consistent with motional narrowing in D'yakonov-Perel' (DP) mechanism which is predominant in strong phonon scattering condition. The relaxation time decreased with decreasing the well width. This tendency also consistent with that effective magnetic field in DP mechanism is strongly contribute to spin relaxation in strong confinement condition. Since DP mechanism is mainly observed in the conduction band rather than the valence band, slow relaxation time of the Fig. 1 (a) is concluded to be electron spin relaxation.

Figure 3 shows temperature dependence of relaxation time obtained by exponential fitting of DOP when QW with a well width of 8 nm was pumped by right-handed circularly- and linear-polarized light. In circularly polarization pump measurements fast relaxation component is plotted. The relaxation time monotonously decreased with increasing the temperature. This tendency is assumed to be consistent with Elliott-Yafet (EY) mechanism owing to complexity of valence band structure which cause strong band mixing. So, the fast relaxation component in circular polarization pump measurements is caused by hole spin relaxation. Temperature dependence of relaxation time in linear polarization pump measurements shows same tendency. Phase change in Eq. (2) is concluded to be EY mechanism in hole spin state.

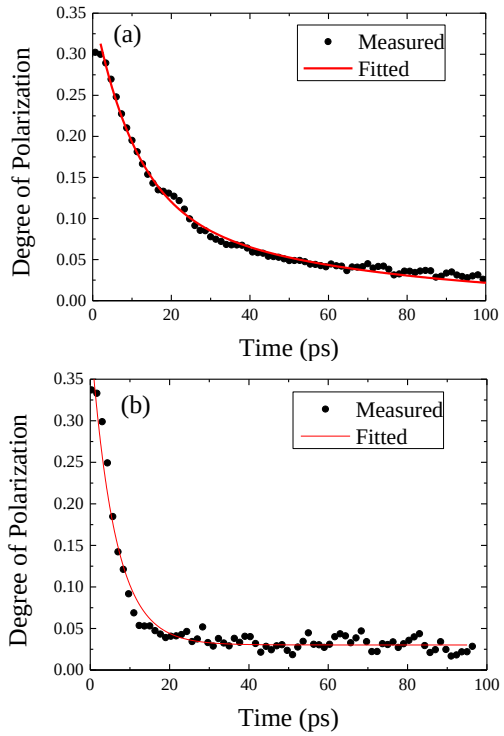

Fig. 1 Time trace of DOP obtained from measurement using (a) right-handed circularly- and (b) linearly-polarized light as pump pulse for QW with a well width of 8 nm.

The decay time of hole spin relaxation is longer than that of superposition of spin state, even though the temperature dependence shows same tendency. When QWs were pumped by right handed circularly polarized light, the polarization state in photon transferred to hole spin state in Eq. (1) is remained until the population of polarized hole spin state completely decays. On the other hand, when QWs were pumped by linearly polarized light, the polarized light transferred to superposition of up and down spin written by Eq. (2) disappears if the phase (φ) changes in hole spin state. The difference in relaxation time reflects the difference in the origin of spin relaxation for each polarization.

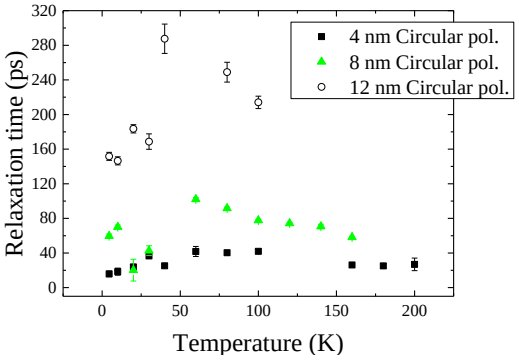

Fig. 2 Temperature dependence of slow spin relaxation time obtained by exponential fitting of DOP for QW with a well width of 4 (solid squares), 8 (green triangles), and 12 nm (open circles) in right-handed circularly- polarized pump measurements.

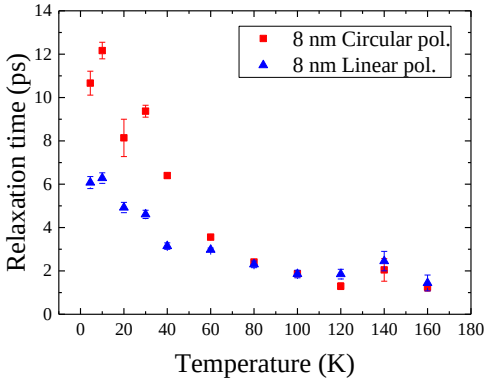

Fig. 3 Temperature dependence of relaxation time of fast component in Fig. 1 (a) (red squares) and (b) (blue triangles) obtained by exponential fitting of DOP for QW with a well width of 8 nm.

4. Conclusion

Temperature dependence of relaxation time of carrier spin created by circularly polarized light and that of superposition of spin states created by linearly polarized light were measured by polarization- and time-resolved pump and probe measurements, and compared these relaxation process. The result shows that band mixing in the valence state mainly contribute to the decay of the phase in superposition of electron- and hole-spin states and relaxation time is different from that of hole-spin polarization generated by circularly polarized light. This comparison and consideration will crucially contribute to coherent transfer of photon state to electron and hole states in quantum information technologies.

Acknowledgements

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5. References

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