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Effects of Band Mixing on Hole-Spin Superposition in GaAs/AlGaAs Quantum Wells

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Abstract

The relaxation mechanism of hole-spin superpositions was investigated in order to obtain hole-spin qubits with better characteristics than conventional electron-spin qubits. The excitation energy dependence of hole-spin superpositions in GaAs/AlGaAs quantum wells (QWs) was measured through polarization- and time-resolved photoluminescence (PL) measurements. The initial degree of polarization and decay time of the linear polarization decreased with increasing excitation energy in three kinds of QWs of different well width. The effects of band mixing on hole-spin superpositions were examined by comparing the excitation photon energy and energy splitting between heavy- and light-hole states.

1. Introduction

Spin-related phenomena in semiconductor quantum-confinement structures have been investigated not only for fundamental physics but also for quantum information technology. Especially, hole-spin states and their superpositions are expected to use as quantum bits because hole-spin states are not affected by nuclear spin polarization. A hole-spin superposition can be observed by photoluminescence (PL) measurements under resonant excitation [1, 2]. In this study, we have performed polarization- and time-resolved PL measurements to investigate the creation and relaxation of hole-spin superpositions in quantum wells. Hole-spin superpositions are destroyed by phonon scattering and band mixing effects in the valence band. Excitation energy dependences of the linear polarization were measured to investigate the effect of band mixing to the spin superposition.

2. Experimental

The samples used in the present study were GaAs/AlGaAs multiple quantum wells (MQWs). 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 thicknesses of the well layers were 4, 8, and 12 nm. Linear polarization- and time-resolved PL measurements were performed to observe the dynamics of spin polarization at 18 K. In the experiment, the MQW samples were irradiated by a Ti-doped sapphire pulse laser with an excitation power of 2 mW. The average input power density on the sample surface was approximately 20 W/cm^2. The duration and repetition rate of the laser pulses were 2 ps and 80 MHz, respectively. Linearly polarized laser pulses were used to excite electron-hole pairs with superpositions composed of up and down spins. The linearly polarized components of the PL emitted from the samples were selectively measured using a half-wave plate and a polarizer. The spectrally and temporally resolved intensity of the linear component was measured with a spectrometer and a streak camera.

3. Results and Discussion

Figure 1 shows the time traces of PL intensity of the parallel (I^+, black thick curve) and cross (I^-, red thin curve) components from a MQW with a well width of 4 nm. The excitation photon energies were 1.650 and 1.657 eV, respectively 4 and 11 meV higher than that of the heavy-hole state. The intensity difference between the parallel and cross components was clearly observed at the excitation energy of 1.650 eV. However, the difference clearly decreased at the energy of 1.657 eV. To analyze how spin polarization is formed by linearly polarized excitation light we calculated the time traces of the degree of polarization, $(I^+ - I^-)/(I^+ + I^-)$, from the polarized PL components (I^+, I^-) and plotted them as a function of time (thin curves in Fig.2). The excitation photon energies are shown in the figure. The time trace of the degree of polarization was fitted by a single exponential decay, as shown by the thick lines in Fig.2. The initial degree of polarization and decay time decreased with increasing excitation photon energy. Similar measurements were performed for the MQWs with well widths of 8 and 12 nm.

Linear polarization is not observed after the electron- or hole-spin superposition decays [2]. A hole-spin superposition promptly decays under non-resonant excitation conditions because of the complex band structure of the valence band. To illustrate the effect of band mixing for the decay of the hole-spin superposition, the decay time for each sample is plotted in Fig. 3 as a function of the energy difference, E_{ex} - E_{hh}, and of that normalized by the light-hole energy, $(E_{ex} - E_{hh})/(E_{lh} - E_{hh})$, where E_{ex}, E_{hh}, and E_{lh} are the excitation, heavy-hole state, and light-hole state energy, respectively. The decay time strongly depends on the excitation energy. The decay rates appear to decrease with decreasing well width. However, the decay time dependence on the normalized energy difference showed the same trend. This indicates that hole-spin relaxation is caused by the same mechanism for all QWs. The observed linear polarization reflects the lifetime of the hole spin, which is mainly determined by the effect of band mixing of heavy- and light- hole states in the valence band. Excitation energy control and band engineering in the valence band are important for suppressing the hole-spin relaxation.

4. Conclusions

The excitation energy dependence of linear polarization was observed by polarization- and time-resolved PL measurements. The degree of linear polarization decreased when the excitation energy approached the heavy-hole state. Band mixing in the valence band affects the creation and relaxation of hole-spin superpositions. Excitation energy control and engineering of valence-band structures are necessary to obtain hole-spin qubits with better characteristics than those of conventional electron-spin qubits. These results can contribute to the advancement of quantum information technology with hole-spin quantum bits.

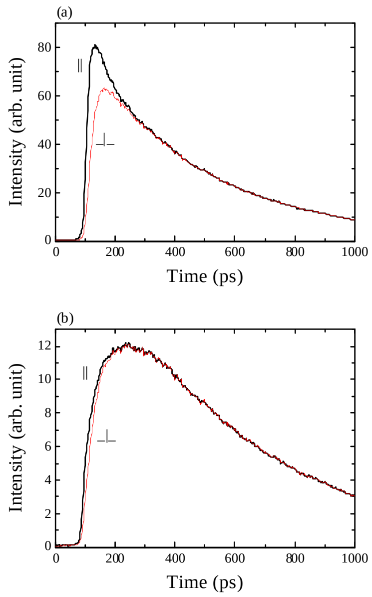

Fig. 1 Time traces of PL intensity of parallel (black thick curve) and cross (red thin curve) components for MQW with a well width of 4 nm. The excitation energies were (a) 1.650 eV and (b) 1.657 eV.

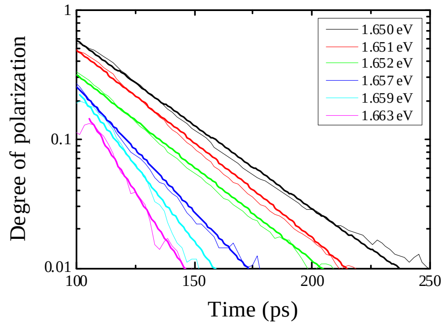

Fig. 2 Time traces of degree of polarization (thin curves) for MQW with a well width of 4 nm. The thick lines indicate results of a single exponential decay fitting. The corresponding excitation energies are shown in the figure.

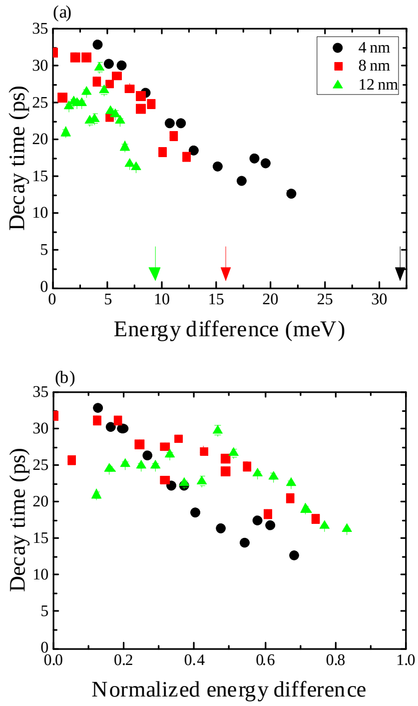

Fig. 3 (a) Energy difference and (b) normalized energy difference dependence of the decay time. The well widths of the measured MQW were 4 (black circles), 8 (red squares), and 12 nm (green triangles). The arrows in (a) indicate the energy of the light-hole states.

Acknowledgements

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