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Spin relaxation property after spin transfer from a semiconductor superlattice barrier to quantum dots

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Abstract

Spin transfer from a semiconductor superlattice barrier to quantum dots and spin relaxation property after spin injection were investigated via circularly polarized time-resolved photoluminescence under the selective photoexcitation of the superlattice miniband. A reversal of the optical spin polarity was observed at the ground state of the quantum dots. We found that this reversal was attributed to the existence of residual electron spins at this state, which was generated by the spin-polarized electron transport and the faster transport of the electrons as compared to the holes. In addition, we observed a clear recovery of the optical spin polarity by eliminating the existence of the residual electron spin through heavy p-doping.

1. Introduction

In recent years, III-V semiconductor quantum dots (QDs) have attracted much attention due to the significant suppression of the electron-spin relaxation obtained via their strong quantum confinements [1]. By using QDs as the optically active layer, spin-functional optical devices such as a spin-polarized light emitting diode [2], that can directly convert electron-spin property into circularly polarized light, can be realized. For that purpose, a spin-conserved transport of electrons from a ferromagnetic electrode to an optically active layer is essential. However, since electron spins are rapidly depolarized in semiconductor barriers, it is necessary to suppress the electron-spin relaxation during the transport. We have recently demonstrated a spin-conserved transport to InGaAs QDs using quantum waves in the superlattice (SL) minibands [3]. In this study, we mainly focused on the spin relaxation property in QDs after the spin-conserved transport by using circularly polarized time-resolved photoluminescence (PL).

2. Experimental

Sample growth

A single layer of self-assembled $In_{0.5}Ga_{0.5}As$ QDs with a $GaAs/Al_{0.15}Ga_{0.85}As$ SL barrier laid on top was grown by molecular beam epitaxy on the GaAs(100) substrates. Figure 1 (a) shows a schematic of the sample structure. First, a 400-nm-thick GaAs buffer layer was grown on the substrate at 853 K, followed by a 30-nm-thick $Al_{0.15}Ga_{0.85}As$ barrier grown at 853 K as a blocking layer to confine the photoexcited electrons and holes in proximity to the QDs. Then, a 9-nm-thick GaAs layer was grown at 853 K with the subsequent growth of $In_{0.5}Ga_{0.5}As$ QDs at 773 K. The QDs were capped with a 11-nm-thick GaAs layer with or without Be doping at 773 K. Finally, 11 periods of GaAs quantum well (QW) (10 nm)/$Al_{0.15}Ga_{0.85}As$ barrier (5 nm) layers were grown at 853 K. The structural analysis of the reference QDs grown under the same condition revealed an areal density of 1.3×10^{10} cm^{-2} with an average diameter of 22 nm. The nominal p-doping concentration in the capping layer was 3×10^{17} cm^{-3}, corresponding to ~23 holes per QD based on the areal density.

Circularly polarized time-resolved PL measurement

Figure 1 (b) shows a schematic of circularly polarized time-resolved PL system. Circularly polarized PL and its time-resolved spectra were measured by streak camera under σ^+-polarized excitation at 6 K. The excitation energy was tuned to 1.63 eV to selectively excite the second miniband states, as shown in Fig. 1(a). Both the excitation and detection directions coincided with the sample growth direction. A mode-locked Ti:Sapphire pulsed laser with an 80-MHz repetition rate, < 100-fs pulse width, and 10-nm spectral width was used as the excitation source. The diameter of the excitation laser spot was approximately 0.1 mm. Time resolution of the streak camera was 10 ps. For polarization-resolved optical characterization, a linear polarizer and quarter-wave plate were inserted into the excitation (detection) beam paths to generate (detect) circularly polarized excitation (emission). Here, the polarization of electron spins generated in the GaAs

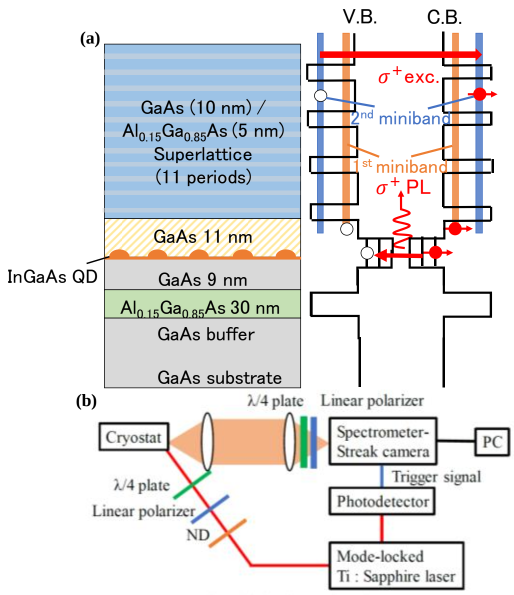

Fig. 1 (a) Schematic of sample structure and PL measurement principle in this study. Capping layer was undoped or p-doped. (b) Schematic of circularly polarized time-resolved PL system.

QW is expected to be 50% according to the optical selection rule when taking the valence-band mixing into account [4]. The circular polarization degree (CPD) measured in QDs is defined as $(I_{\sigma+}-I_{\sigma-})/(I_{\sigma+}+I_{\sigma-})$ using the circularly polarized PL intensity $I_{\sigma\pm}$, reflecting the polarization of electron spins at QD emissive states [3].

3. Results and Discussion

Figure 2(a) shows the circularly polarized time-integrated PL spectra and the corresponding CPD measured at 2 mW. We attribute the sharp PL at 1.55 eV and another PL at 1.52 eV to the SL first miniband and to the GaAs QW surrounding the QDs, respectively [5]. The broad PL emission at 1.20–1.40 eV comes from the ground state (GS) and excited state (ES) of QDs. Here, a high positive CPD of +30% was observed at a higher QD-ES (around at 1.37 eV), which is closer to the SL. Figure 2(b) shows the circularly polarized PL time profiles and the corresponding CPD of the QD-ES. An initial CPD of 50%, which is the same as the initial polarization of electron spins generated in the SL, was obtained. This result demonstrates a spin-conserved electron transport from the SL to the QDs, as reported in a previous study [3]. By contrast, remarkable negative CPD values down to −15% appear at QD-GS during the entire radiative lifetime, as shown in Fig. 2(b). The spin-polarized electron transport and the faster transport of the electrons as compared to the holes owing to the lower effective mass generate the residual majority electron spins at the QD-GS [5]. The residual electron spins induce the electron-hole spin flip-flop interactions at the QD-ES, leading to the negative CPD properties of GS-PL [6].

We also investigate the effect of p-doping on the PL-CPD properties. Figure 3(a) shows the circularly polarized time-integrated PL spectra and the corresponding CPD measured at 2 mW for the p-doped sample. We observed the disappearance of negative CPD properties at QD-GS by p-doping. This

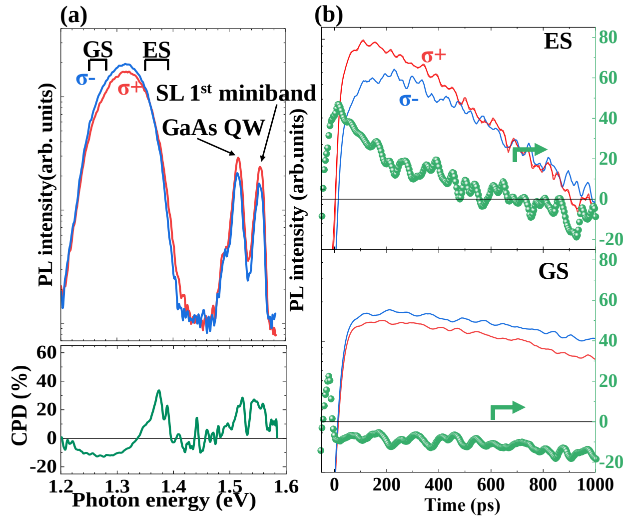

Fig. 2 (a) Circularly polarized time-integrated PL spectra and corresponding CPD at 2 mW for undoped sample. (b) Circularly polarized PL time profiles and corresponding CPD for ground state (GS) and excited state (ES) of QDs at 2 mW.

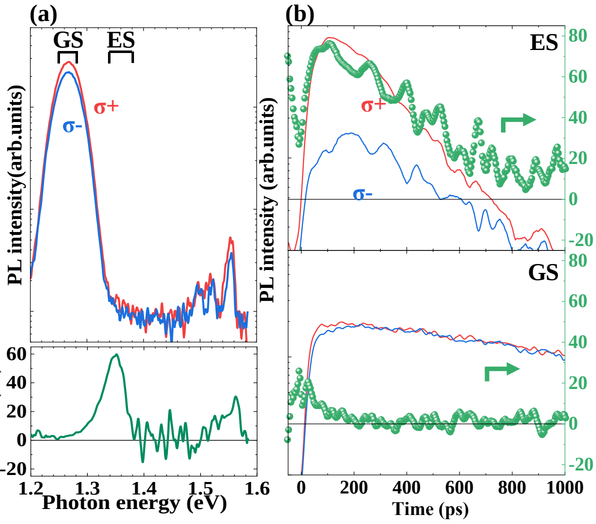

Fig. 3 (a) Circularly polarized time-integrated PL spectra and corresponding CPD at 2 mW for p-doped sample. (b) Circularly polarized PL time profiles and corresponding CPD for ground state (GS) and excited state (ES) of QDs at 2 mW.

result demonstrates that p-doping fully eliminates the existence of the residual electron spins at the QD-GS, leading to a luminescence co-polarized to the initial excitation [5]. P-doping also significantly enhances the positive CPD values of the QD-ES. Figure 3(b) shows the circularly polarized PL time profiles and the corresponding CPD of the QD-ES. We observed the amplification of CPD from 50% to 75% in the initial time region. The amplification of electron-spin polarization was attributed to the selective relaxation of minority spins from the QD-ES to the QD-GS relative to the blocked relaxation of the majority spins by the Pauli blocking [7].

4. Conclusions

A spin relaxation process in the QDs adjacent to the SL was studied using spin- and time-resolved PL with a selective excitation of the SL miniband. A clear reversal of the optical spin polarity, originating from the residual electron spins in QDs, appeared at the QD-GS. We also observed a recovery of the optical spin polarity by heavy p-doping. These results indicate that the optical spin property of the QDs strongly depends on the existence of the residual electron spins.

Acknowledgements

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