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Electron-spin dynamics in tunnel-coupled structures of InGaAs well and dot with different p-doping concentrations applied with electric field

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Abstract

Controlling spin polarization by applying an electric field has been studied in InGaAs quantum well-dot coupled structures with different p-doping concentrations. We observed an extremely fast CPD switching time of 71 ps at ground state (GS) of quantum dots (QDs) for lightly p-doped sample as compared to 140 and 386 ps for undoped and heavily p-doped sample with low excitation power. This result means that a spin-reversal injection into the QD-GS can be promoted under the condition of moderate p-doping concentration.

1. Introduction

Opto-spintronic device is one of the key components of technological platforms for future information processing. III-V semiconductor quantum dot (QD) has been studied as an optically active layer of opto-spintronic devices due to its longer electron-spin relaxation time compared to radiative lifetime as a result of the strong quantum confinements. Furthermore, since the QD has the discrete density of the state of electrons, it is possible to realize ultra-low-energy-consumption optical devices. However, in the layered device structures, electron spins are rapidly relaxed in three-dimensional semiconductor barrier layers due to the spin relaxation mechanisms [1] before arriving at an active layer. Therefore, it is necessary to efficiently transport and inject spins into QDs before spin relaxation. We have proposed quantum well (QW)-QD coupled structure and demonstrated ultrafast and highly spin-conserved spin injection from QW to QDs [2]. Also, we fabricated optical spin devices that can control the spin polarity in ultrafast spin injection into QDs from a tunnel-coupled QW by applying an electric field [3]. Since the spin relaxation can be suppressed in p-doped QDs owing to the weaken electron-hole exchange interaction [4], we have studied p-doping effects on QW-QD coupled structure applied with electric field [5]. We found that light p-doping concentration is the appropriate condition that can greatly control the spin polarization. In this study, we focused on the electron-spin dynamics in QW-QD coupled structure with different p-doping concentrations applied with electric field using circularly polarized time-resolved photoluminescence (PL).

2. Experimental

Sample growth

Figure 1(a) shows a schematic of the optical device structure in this study. The $In_{0.1}Ga_{0.9}As$ QW and $In_{0.5}Ga_{0.5}As$ QD were grown on the p-doped GaAs(100) substrates by molecular beam epitaxy. A 10-nm thick GaAs capping layer was grown with or without Be doping. The $Al_{0.1}Ga_{0.9}As$ layer acts as a blocking layer to suppress carrier injection from a top Ti/Au electrode for electric-field application. Figure 1(b) shows an atomic force microscopy (AFM) image of the reference QDs grown under the same condition, from which an areal density of 1.9×10^{10} cm^{-2} was revealed. The nominal p-doping concentration in the capping layer was 1×10^{17} and 3×10^{17} cm^{-3}, which corresponded to 5 and 15 holes per QD, respectively. Figure 1(c) shows a high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image of the QW-QD coupled structure, where the structure is observed as designed.

Circularly polarized time-resolved PL measurement

Circularly polarized PL spectra and their time profiles were measured by CCD and time-correlated single photon counting respectively under σ^--polarized excitation at 4 K. A mode-locked Ti:Sapphire pulsed laser with a 76-MHz repetition rate, 150-fs pulse width was used as the excitation source. The full width at half maximum of instrument response function was 100 ps. A combination of quarter-wave plate with a linear polarizer was used for σ^--polarized excitation, as well as for discriminating the circular polarization of PL emission from the device. The excitation energy was tuned to 1.46 eV to generate spin-polarized carriers in the $In_{0.1}Ga_{0.9}As$ QW according to the optical selection rule. An excitation power was changed from 80 to 640 μW. A voltage with a range of −3 V ~ +3 V was applied along the growth direction, but in this study we focused on the specific voltages that showed the characteristic negative circular polarization degree (CPD)

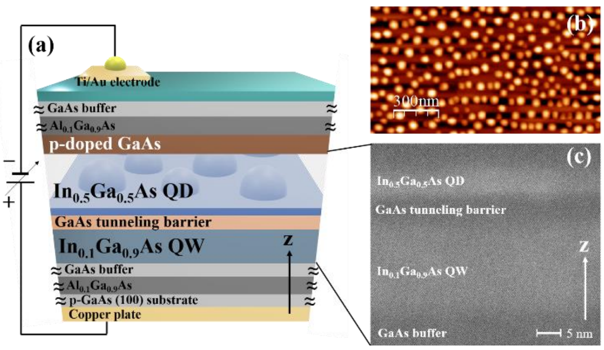

Fig. 1 (a) Schematic of optical device structure. (b) Typical AFM image of reference $In_{0.5}Ga_{0.5}As$ QDs. (c) HAADF-STEM image of QW-QD coupled structure.

properties of PL at 0 V, −0.4 V, and −2.2 V for 0, 5, and 15 hole/QD samples. Spin-polarized carriers generated in the QW were injected into the QDs through spin-conserving tunneling, and then were detected by circularly polarized PL from the QDs. Here, the CPD was defined as $(I_{\sigma^-} - I_{\sigma^+})/(I_{\sigma^-} + I_{\sigma^+})$ using circularly polarized PL intensity $I_{\sigma^\pm}$. The CPD measured in QDs reflects the electron-spin polarization at QD emissive states.

3. Results and Discussion

Figure 2(a) shows the circularly polarized transient PL and the corresponding CPD of the QD ground state (GS) measured at 80 μW for 5 and 15 hole/QD samples. A positive CPD of +25%, corresponding to a luminescence co-polarized to the initial excitation, was observed in the initial time region, whereas the reversal of the CPD polarity appeared during light emission for both samples. Here, we refer to the CPD switching time as τ_{cs}. A much faster τ_{cs} was obtained for 5 hole/QD sample compared to 15 hole/QD sample, at 71 and 386 ps, respectively (see the black arrows). This value is also shorter than 140 ps for 0 hole/QD sample (data not shown). The reversal of CPD polarity is attributed to the spin-flip scattering at the QD excited state (ES) [6]. When excess electrons are injected from QW into QD by potential gradient due to the electric field, residual electron spins are generated at the QD-GS [3]. Then, the parallel electron spins injected into the QD-ES cannot be relaxed to the QD-GS owing to the Pauli blocking, after which the electron and hole with simultaneous flips of their spins occurs. The spin-flipped electron and hole are relaxed to the unoccupied QD-GS and radiatively recombine, emitting negative CPD of PL. Here, the negative CPD reached a maximum of −50% during light emission for 5 hole/QD sample as compared to −5% for 15 hole/QD sample. This result means that residual electron spins are dominantly generated at the QD-GS in the moderate p-doping condition.

The τ_{cs} largely changed with increasing excitation power, as shown in Fig. 2(b). The excitation power dependence of τ_{cs} is shown in Fig. 3. For 0 and 5 hole/QD samples, τ_{cs} was increased to 186 ps and 198 ps at 640 μW. At high

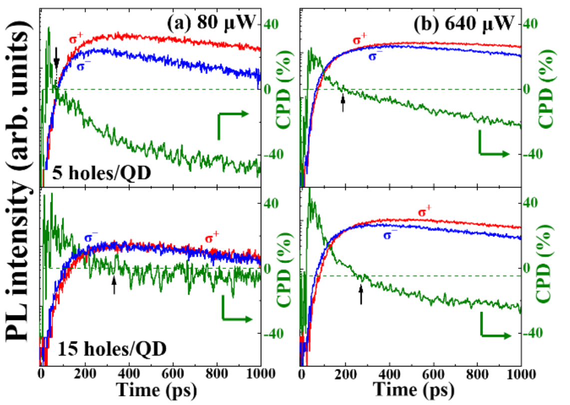

Fig. 2 Circularly polarized transient PL and corresponding CPD of the QD-GS at (a) 80 μW and (b) 640 μW for 5 (upper) and 15 hole/QD (lower) samples. The black arrows indicate the time points (τ_{cs}) in which the CPD polarity was switched.

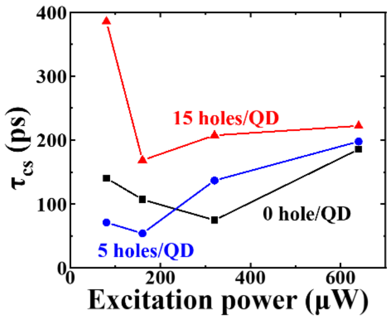

Fig. 3 Excitation power dependence of τ_{cs} for 0 (0 V), 5 (−0.4 V), and 15 (−2.2 V) hole/QD samples.

excitation powers, the QD-ES as well as the QD-GS is occupied by both electron spins, i.e., the spin injection into the QD-ES increases. This state-filling effect prevents the energy relaxation from the QD-ES to the QD-GS as well as the spin-flip scattering at the QD-ES [7]. As a result, the maximum of negative CPD decreased to −21% at 640 μW for 5 hole/QD sample [see Fig. 2(b)]. By contrast, for 15 hole/QD sample, τ_{cs} was decreased to 163 ps at 640 μW, and thus the maximum of negative CPD increased to −20%. In spite of the dominant hole escape from the QDs to the QW due to the strong potential gradient by applied bias voltage of −2.2 V, heavy p-doping can eliminate the existence of residual electron spins at the QD-GS at low excitation powers, whereas at high excitation powers, residual electron spins are easily generated due to the accelerated injection of electron spins into QDs.

4. Conclusions

We have studied the p-doping effects on electron-spin dynamics when the electric-field was applied to the QW-QD coupled structures. The degree of optical spin polarity was found to be strongly affected by p-doping concentration. For 5 hole/QD sample, the fastest τ_{cs} = 71 ps and the largest negative CPD of −50% were observed. These results indicate that a spin-reversal injection into the QD-GS can be accelerated under the condition of moderate p-doping concentration.

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