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Highly efficient electron-photon spin conversion using InGaAs quantum dots with p-doped capping barrier

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Abstract

III-V semiconductor quantum dots (QDs) have attracted much attention as an optically active layer of optical spin devices that transmit electron-spin information superimposed on light. However, at high temperatures, electron spins are thermally excited to the barrier and the spin polarization in QDs is significantly reduced as a result of the reinjection of electron spins depolarized in barriers. In this study, we have demonstrated highly efficient electron-photon spin conversion using InGaAs/GaAs QDs with p-doped capping barrier. This enhanced spin polarization was mainly attributed to the suppressed relaxation of the electron spins reinjected from the p-doped capping barrier, where the D'yakonov-Perel' spin relaxation was potentially weakened through impurity scattering.

1. Introduction

III-V semiconductor quantum dots (QDs) have attracted great attention as an active layer of spin-functional optical devices which utilize electron-spin states because carrier spin relaxation can be significantly suppressed in QDs owing to their three-dimensional quantum confinements [1]. At low temperatures, QD excited states (ESs) show a temporally amplified spin-polarization due to the selective relaxation of minority spins from the QD-ESs to the QD ground state (GS) with respect to the blocked relaxation of majority spins by the Pauli blocking [2]. QD-ESs can also suppress the spin-state filling effect in QDs, which largely reduces the electron-spin polarization during light emission [3]. However, the QD-ES is energetically close to the barrier compared to the QD-GS, and thus carriers are thermally excited to the barrier, which leads to thermal quenching of QD luminescence at high temperatures. In addition, the electron-spin polarization at QD emissive states also decreases as a result of the reinjection of electron spins that are depolarized in the barrier [4].

In this study, we mainly focused on the suppression of thermal electron-spin relaxation in the p-doped capping barrier based on the previous theoretical study [5]. The effects of the p-doped capping barrier on the electron-spin properties of the QD-ES were investigated by means of circularly polarized time-resolved photoluminescence (PL) measurement.

2. Experimental

Sample growth

Figure 1 (a) shows a schematic of the sample structure in this study. Self-assembled $In_{0.5}Ga_{0.5}As$ QDs were grown by molecular beam epitaxy on GaAs(100) substrates. First, a 300 nm-thick GaAs buffer layer was grown at a substrate temperature of 580°C, followed by a single layer of $In_{0.5}Ga_{0.5}As$ QDs with 7.5 monolayers grown at 520°C. Then a 10-nm thick GaAs capping barrier was grown at 520°C with or without Be doping. The nominal doping concentration was 3×10^{17} cm^{-3}, which corresponds to approximately 20 holes per QD based on the areal QD densities described below. The QDs were further capped with a 30-nm thick GaAs layer. Additional QDs were grown on the capping layer for structural characterization via atomic force microscopy (AFM). Figure 1(b) shows a typical AFM image of the $In_{0.5}Ga_{0.5}As$ QDs, from which an areal QD density of 1.3×10^{10} cm^{-2} was revealed.

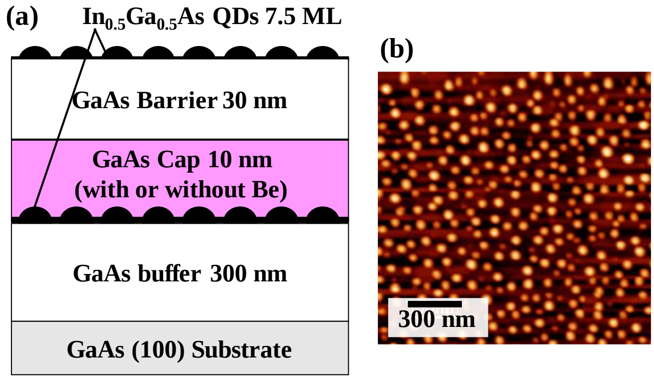

Fig. 1 (a) Schematic drawing of the QD sample structure. (b) Typical AFM image of the $In_{0.5}Ga_{0.5}As$ QDs.

Circularly polarized time-resolved PL measurement

Circularly polarized time-resolved PL was measured from 6 to 293 K. A mode-locked Ti:sapphire pulsed laser with a repetition rate of 80 MHz and a pulse width of <100 fs was used as the excitation source. The diameter of the excitation laser spot was approximately 0.1 mm. The excitation energy was set to 1.55 eV to generate spin-polarized carriers in GaAs barriers. According to the optical-transition selection rule, the initial degree of the electron-spin polarization generated in GaAs barriers was expected as 50%. Here, the circularly-polarization degree (CPD) of a QD-PL, corresponding to the electron-spin polarization at QD emissive states, was defined as CPD (%) = $100 \times (I_{\sigma+} - I_{\sigma-})/(I_{\sigma+} + I_{\sigma-})$ using circularly polarized PL intensity $I_{\sigma\pm}$.

3. Results and Discussion

Figure 2(a) shows PL spectra of undoped and p-doped QDs measured at 6 K. We observed a high-energy shift of the PL peak and a stronger PL emission from the QD-ESs for p-

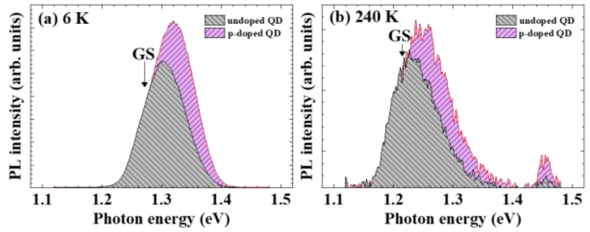

Fig. 2 PL spectra of undoped and p-doped $In_{0.5}Ga_{0.5}As$ QDs measured at (a) 6 K and (b) 240 K.

doped QDs. This result indicates that the excess holes provided by strong p-doping ensure that not only the hole GS but also many of the hole ESs are filled. The large supply of holes in the QDs can enhance the efficiency of the radiative recombination at the QD-ES. The dominant light emission from the QD-ESs promoted through p-doping was observed even at 240 K, as shown in Fig. 2(b). We anticipate that an increase in the PL intensity from the QD-ESs at high temperature is attributed to the high efficiency of a radiative recombination at the QD-ES against the thermal escape of carriers from the QDs [6].

Figures 3(a) and 3(b) show the circularly polarized transient PL and the corresponding CPD of the QD-ES measured at 6 and 240 K, respectively. Here, a QD-ES is defined as an energy range of 1.32–1.36 eV at 6 K. The analyzed energy range was shifted with a change in temperature according to Varshni's law using the parameters of $In_{0.5}Ga_{0.5}As$ [7]. We carried out a rate-equation fit analysis to investigate the net electron-spin relaxation time (τ_s) based on previous study [3]. In this rate equation, the spin-injection time, spin relaxation during injection, relaxation time from the emissive states including the radiative and nonradiative decaying processes, spin relaxation in the QDs, and spin-state filling effects are all considered. At 6 K, τ_s was estimated as 1550 and 2480 ps for undoped and p-doped QDs, respectively. This increased τ_s was due to the suppression of the electron-hole exchange interaction owing to a filling of the holes up to the high QD-ESs, which is the same mechanism known as the suppression of electron-spin relaxation at the QD-GS [8]. When the temperature increased to 240 K, τ_s also increased from 97 ps to 163 ps by p-doping. At high temperatures, the CPD decay of the QD-ES mainly reflects the electron-spin relaxation in the barriers because the electron spins are easily reinjected from the barriers into the QDs after a thermal escape from the QDs [4]. Therefore, this increased electron-spin lifetime was mainly attributed to the suppressed relaxation of the electron spins reinjected from the p-doped capping barrier, where the D'yakonov-Perel' spin relaxation, which was dominant at high temperatures, was potentially weakened through impurity scattering [6].

4. Conclusions

In conclusion, we have demonstrated highly efficient electron-photon spin conversion using InGaAs QDs with p-doped capping barrier. P-doped QD-ESs showed an increased PL intensity owing to the enhanced radiative recombination efficiency, originating from the filling of holes up to the high QD-ESs. In addition, a higher CPD value was observed for p-doped QDs at low and high temperatures. At low temperature, filling of holes up to the high QD-ESs suppressed the electron-hole exchange interaction. At high temperature, the enhanced spin polarization was mainly attributed to the suppressed relaxation of the electron spins reinjected from the p-doped capping barrier, where the D'yakonov-Perel' spin relaxation was potentially weakened by impurity scattering.

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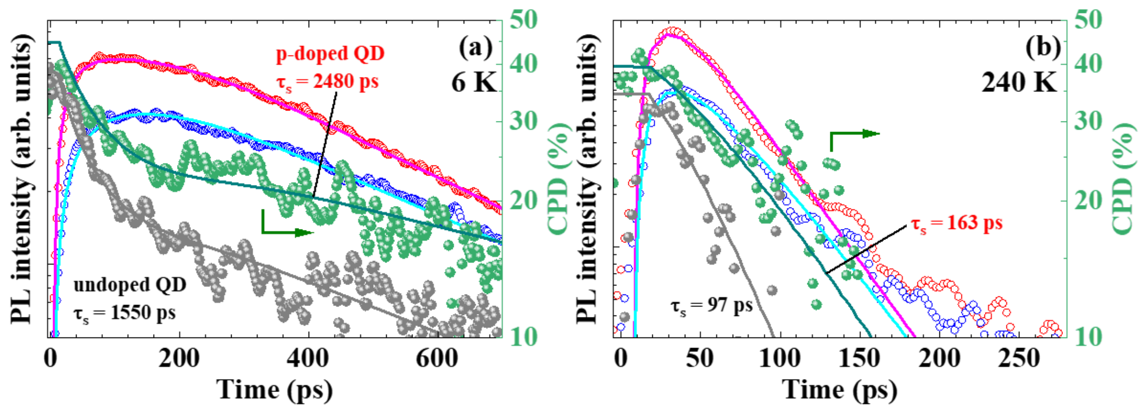

Fig. 3 Circularly polarized transient PL and corresponding CPD of p-doped QD-ES measured at (a) 6 K and (b) 240 K. The solid lines show the best-fitted results of rate equations. The gray symbols show the corresponding CPD time profiles of undoped QDs.