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High-density self-assembled quantum dots of InGaAs for ultrafast and efficient spin injection

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Abstract

High-density self-assembled quantum dots (QDs) of InGaAs have been studied for the purpose of applying to optical active layers suitable for ultrafast and efficient spin injection. We show that spin blocking in the injection process can be resolved in high-density QDs. Ultrafast spin injection from a two-dimensional electron system into the high-density QDs is observed via tunneling, which is affected by the excitation-spin density.

1. Introduction

III-V compound semiconductor quantum dots (QDs) show desirable properties for highly energy-saving optical devices such as light-emitting and laser diodes (LEDs and LDs), since strong quantum confinements make the density of the carrier states discrete. Moreover, in these QDs, carrier-spin states can be temporarily maintained during radiative recombination, because of sufficient suppression of the major spin-relaxation mechanism due to momentum relaxation of carriers acting on the spin state. These advantages for utilizing the QDs in active layers motivate one to develop spin-functional optical devices, such as a spin-polarized LED or LD, emitting circularly polarized lights reflecting electron-spin polarizations injected.

However, efficient spin injection with highly conserving the spin state into the QDs has not been established yet. The spin states can easily relax in spin transport across semiconductor barrier layers and potential steps during the injection into the QDs. The spin-injection dynamics can play an important role to solve this issue, since the spin state is a strong function of time and therefore ultrafast spin injection is highly required before spin relaxation. We have studied the spin injection dynamics including an injection time and spin relaxation during the injection from GaAs barriers into InGaAs self-assembled QDs, by using circularly polarized time-resolved photoluminescence (PL) after optical spin generation in the barrier [1]. Effects of the dot structure, such as the dot density, have been studied on the spin injection dynamics [2]. Then, we have applied the high-density QD system to a spin receiver from a two-dimensional (2D) electron system via tunneling [3]. The high-density QDs are appropriate for ultrafast spin injection from the 2D electron system. The spin-density dependence is studied in the tunneling process.

2. Experimental procedure

Crystal growth of self-assembled InGaAs QDs

Self-assembled $In_{0.5}Ga_{0.5}As$ QDs were grown on GaAs(100) substrates by molecular beam epitaxy. Growth conditions were examined, where the substrate temperature was changed ranging from 470 to 510 deg. C. The dot density increased with decreasing temperature, and high-density dots with the sheet density of 7×10^{10} cm^{-2} were obtained at 470 deg. C. In addition, we examined an effect of inserting a 2D electron system of $In_{0.1}Ga_{0.9}As$ quantum well (QW) with a thickness of 20 nm, which was coupled with the QD layer through a GaAs barrier, for the purpose of efficient capture of spin-polarized electrons. This coupling of electronic states is a function of barrier thickness. The high-density QD system can increase the number of coupling path between the QW and QDs.

Time-resolved PL measurement

The spin-density dependence of the spin-injection dynamics into InGaAs QDs was measured by time-resolved PL using a streak camera after pulsed optical excitation of spin-polarized carriers in barriers. Time-dependent PL at excited states in the QDs was detected, where these states lay slightly below the barrier level and thus allowed one to detect the spin dynamics just after the injection from the barrier. The excitation and detection of spins were made by using circular polarization. The degree of circular polarization (CPD) of PL, reflecting spin polarization, was defined using circularly polarized PL intensities: $I(\sigma^{\pm})$, as follows;

$$\rho = \frac{I(\sigma^{+}) - I(\sigma^{-})}{I(\sigma^{+}) + I(\sigma^{-})} . \qquad (1)$$

3. Results and discussion

Dot-density dependence of spin-injection dynamics

Circularly polarized time-resolved PL in QDs showed to depend on the dot density. We have taken the following factors of the spin-injection dynamics in analyzing these PL data into account; the initial spin polarization and injection time from the barrier, the state-filling effect at the limited density of the spin states in the QD, and the subsequent relaxation dynamics to the lower-lying energy levels. From rate-equation calculations, these parameters were deduced as a function of excitation-spin density.

The time-integrated CPD value increases from 15 % with increasing the excitation power density from 16 to 48 Wcm^{-2}, where the maximum value depends on the growth temperature and thus the dot density; 25 % in the dots with the growth temperature of 480-490 deg. C (4-5 × 10^{10} cm^{-2}), and 28 % with 470 deg. C (7×10^{10} cm^{-2}). Above this power, the CPD decreases monotonically down to less than 15 %. The dots grown on 500 deg.C (2×10^{10} cm^{-2}) shows different power dependence, where the maximum CPD of 20 % is observed at the lowest power and then monotonically decreases down to 3 %. The state-filling effect at the spin-split excited state is found to be responsible for the spin-injection efficiency. The spin polarization is reduced when the majority-spin state is fully occupied by spins, because the majority spins cannot be injected due to the Pauli exclusion principle while the minority spins can be continuously injected. Therefore, the high-density QDs show an advantage for high-density spin injection, which will be necessary for spin-LED and LD applications.

Spin-injection dynamics and the spin-density dependence in coupled QDs

Effects of the excitation-spin density were studied in coupled QDs with QWs, where the spins were initially excited in the QW and subsequently injected into the QDs via tunneling driven by the potential difference. The CPD value in QD emission significantly increases from 5 to 18 % with decreasing barrier thickness from 8 to 2 nm, originating from decreasing a tunneling time from 20 to 5 ps.

The CPD in QD emission decreases with increasing the spin density initially excited in the QW. Figure 1 shows circularly polarized time-resolved PL in the QDs. The CPD value monotonically decreases with increasing delay time after the pulsed excitation at lower excitation powers. However, at higher powers, a steep decrease in the CPD value is observed after the excitation, which coincides with a plateau-like behavior on the time dependence of σ^+-polarized PL intensity corresponding to the majority spin state. Therefore, this CPD degradation originates from the spin-state filling in the QDs. At the same time, the filling effect is observed also in the QW PL, which can be attributed to localized states of carriers originating from potential fluctuations in the well possibly due to atom-scale interface roughness and compositional inhomogeneities. In this case, the injection path of spin is limited by tunneling, and therefore this filling effect appears particularly with thicker tunneling barriers. The total spin polarization in the well prior to the spin injection can be reduced when the localized majority-spin states are filled with spins. Results of the excitation-spin density dependence with varying the tunneling barrier thickness will be presented.

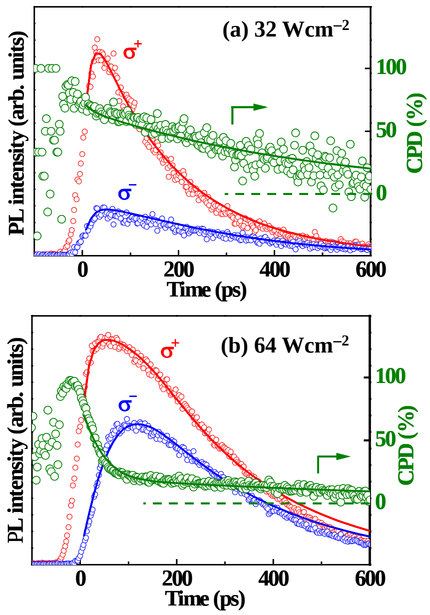

Fig. 1 Circularly polarized transient PL and the corresponding CPD in InGaAs QDs coupled with an InGaAs QW and a 4 nm-thick barrier of GaAs as a function of excitation power (a: 32 Wcm^{-2}, b: 64 Wcm^{-2}). Solid lines are rate-equation calculations.

4. Conclusions

High-density self-assembled InGaAs QDs have been studied for ultrafast and efficient spin injection. We show that spin blocking in the injection process can be resolved in the high-density QDs. Ultrafast spin injection is observed from a 2D electron system into the high-density QDs via tunneling, where the initial spin density affects the spin-injection dynamics and the resultant injection efficiency of spin.

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