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Growth of InAs Quantum Dots with Various Charged States on a Wafer Utilizing Concentric Distribution

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1. Introduction

Epitaxially grown InAs quantum dots (QDs) have been attractive for applications in photonics and quantum information technology [1-3]. For these applications, low density for spatial separation from other QDs, distinctive emissions from excitonic states in single QD, and control of its charged excitonic state are required. Among these requirements, control of the charged states in single QDs becomes one of critical objects for generation of entangled photon pair and single spin manipulation. In the former case, cascade emission from neutral biexciton to exciton [3] is essential, and negative or positive excitonic states as trions are required in the latter case [4, 5]. In previous studies, electric field with applying bias voltage has been generally utilized for control of charged excitonic states [6-8]. However, this way is not convenient because of fabrication of electrode and kind of applying of bias voltage.

On the other hand, delta doping is a conventional way to supply electron or hole directly into QDs. In addition, external devices such as electrode and power supply are not required if delta doping enables to control charge states. Delta doping method will have advantages for applying bias voltage with electrode. Furthermore, control of charged states between positive and negative states by delta doping has not been reported, as far as we know.

In this study, we apply Si delta doping to InAs QDs with positively charged states and carry out micro-photoluminescence (μ-PL) measurements for these delta doped samples. Using concentric distribution of QD density on a wafer, we obtain a series of QDs with charged excitonic states from positive to negative via neutral states at a time. As a result, we succeed in growth of InAs QDs with selectively charged states on a same wafer by only Si doping.

2. Experimental

InAs QD samples are grown on (001) GaAs wafer with 3-inch diameter by molecular beam epitaxy. Growth temperature (T_g), rate, and nominal coverage of InAs QDs are 485 ^oC, 0.0042 ML/sec, and 2.1 ML, respectively. Emission wavelength is tuned to less than 1μm at low temperature by In-flush method [10]. T_g of GaAs partial cap in In-flush process is 423 ^oC. Si sheet layer for delta doping is sited at 20 nm below InAs QDs layer and its sheet density is $5x10^{10}cm^{-2}$. Distribution of QD density along a radius is evaluated by atomic force scanning microscopy.

A reference sample is grown by same conditions without a Si delta doping layer. After processing these wafers to mesa structures, μ-PL measurements are performed at 7K with $Ti:Al_2O_3$ laser of 780 nm for optical pumping. PL peaks are assigned by power dependence, photon correlation measurement and consideration by energy diagram with taking account of charged state and its total spin. The detail of assignments will be published elsewhere [11, 12].

3. Results and discussions

QD density increases from ~$1x10^7$ to ~$2x10^9$ cm^{-2} with distance from center of wafer along the radius as shown in figure 1. This means that effective doping concentration per a QD increases with closing to center of wafer from edge. We use QDs in the different regions showing the averaged QD density of ~$5x10^8$ and ~$5x10^7$ cm^{-2}, respectively. These regions are defined as regions (H) and (L) and also shown in figure 1 as dark and light shaded areas. Reference QDs have dominant emission from positively charged excitonic states (X^+ and XX^+) in low density region corresponding to region (H) and (L), although the QDs are not intentionally doped. Therefore, reference QDs is appropriate to ascertain effect of n-type delta doping. Typical μ-PL spectrum from positively charged state of reference sample is shown in figure 1 as the inset.

Figure 2 (a) and (b) show typical μ-PL spectra of delta doped QDs in region (H). Typical features of these spectra are neutrally and positively charged excitonic states. In contrast to reference, showing that positively charged state are dominant, emissions from neutral excitonic states (X^0 and XX^0) are dominant. Emissions from the other states remain slightly.

Figure 2 (c) and (d) show typical μ-PL spectra of delta doped QDs in region (L). In contrast to reference and region (H), emissions from positively charged excitonic states disappear completely. Emissions from neutral and negatively charged states have been dominant. And moreover, emissions from negatively biexcitonic state (XX^-)

have appeared. These results indicate that positively charged states turn to neutrally and negatively charged states with increasing of effective doping concentration.

In region (H) and (L), nominal doping concentration is ~100 and ~1000 Si atoms per a QD, respectively. In comparison with the QD density, they are relatively high values. In the simplest case, one electron is required for neutralization of one QD (X^+), so that doping concentration should be comparable to that of QD density. Although precise mechanism of high doping concentrations is not clear, it is probably due to low activity of Si atoms as dopant at low temperature, trap states of electron around QDs, and faster capture rate of hole than that of electron in a QD. In the present, this remains further subject.

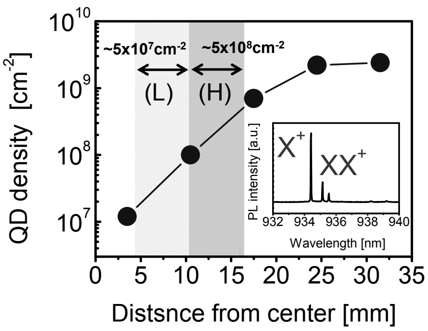

Fig. 1 QD density as a function of distance from center of wafer. Two regions of (H) and (L) for μ-PL are shaded by dark and light gray. The inset is typical μ-PL spectrum of undoped QD as reference.

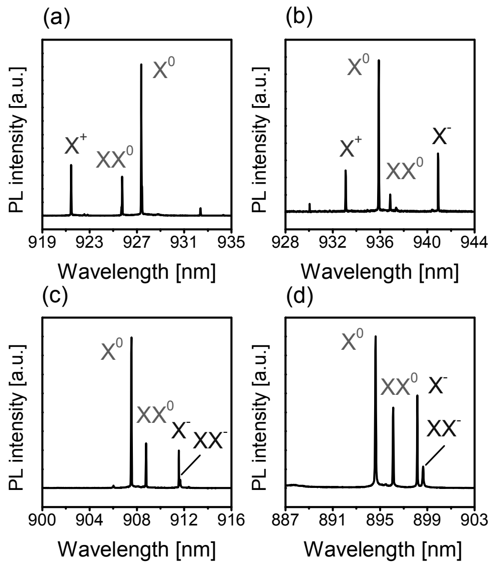

Fig. 2 Measured μ-PL spectra of delta doped single InAs QDs for region (H) [(a) and (b)] and for region (L) [(c) and (d)]

Thus, we have obtained a series of QDs with charged excitonic states from positive to negative via neutral states. Being a series of variation in charge states enables to chose QDs with preferred charge state on a wafer. In other words, we succeed growth of InAs QDs with selectively three charged states, which is positive, neutral and negative, on a same wafer at a time by only Si delta doping for the first time. These InAs QDs can be widely applicable to photonics and quantum information technology such as generation of entangled photon pair and single spin manipulation.

4. Conclusions

We have applied Si delta doping method to low density InAs QDs with positively charged states, and carried out μ-PL measurements for these doped samples. We have successfully demonstrated growth of InAs QDs with selectively multi-charged states on a wafer by Si delta doping. Delta doping, which is simple and conventional method, will improve yielding of preferred QDs and promote related studies in photonics and quantum information technology.

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