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Improvement of the optical property and uniformity of self-assembled InAs/InGaAs quantum dots by layer-by-layer temperature and substrate rotation

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ABSTRACT

The influence of layer-by-layer temperature and substrate rotation on the optical property and uniformity of self-assembled InAs/$In_{0.2}Ga_{0.8}As$/GaAs quantum dots (QDs) gown with an As_2 source was investigated. An improvement in the optical property of QDs was obtained by the precise control and optimization of growth temperature utilized for each layer, i.e., InAs QDs, InGaAs quantum wells, GaAs barriers and AlGaAs layers, respectively. By using a substrate rotation, the QD density increased from $\sim1.4\times10^{10}$ to $\sim3.2\times10^{10}\,cm^{-2}$ and its size also slightly increased, indicating a good quality of QDs. It is found that the use of an appropriate substrate rotation during growth improves the room-temperature (RT) optical property and uniformity of QDs across the wafer. For the QD sample with a substrate rotation of 6 rpm, the RT photoluminescence (PL) intensity is much higher and the standard deviation of RT-PL full-width at half-maximum is decreased by 35% compared to that grown without substrate rotation.

1. Introduction

There has been a growing interest in achieving long-wavelength emission to ~1.3–1.6 μm at room temperature (RT) from self-assembled InAs quantum dots (QDs) on GaAs substrate for applications of optical communications [1,2]. Recently, the InAs QDs embedded in an InGaAs quantum well instead of a GaAs matrix, i.e., dots in a well (DWELL) structure, have exhibited light emission at 1.3 μm with high performance due to the enhanced carrier capture and the increase of QD density [3–5]. The structural and optical properties of InAs/InGaAs QDs depend strongly on the growth parameters, such as sample temperature, group III/V ratio, deposition rate, growth interruption, strain and composition of structure layers [6–8]. Particularly, the growth temperature has a key influence on the kinetics of QD formation during growth, thus appropriate temperature should be maintained for each layer to maximize the quality of QD structure.

In practical applications, the uniformity and reproducibility in the optical properties of QDs across a wafer are very important for low-cost manufacture. Although, lots of researches on the size uniformity of QDs were carried out, there are very few reports on the uniformity in terms of emission wavelength, intensity and linewidth of the photoluminescence (PL) spectrum of QDs [9–12]. The uniformity of QDs is correlated to the distribution of elemental fluxes arriving on the sample surface and the diffusion process of adatoms. For molecular beam epitaxy (MBE), the source cells are equipped to be positioned at an angle to the horizontal. To achieve a uniform flux distribution of elements over the sample, the substrate needs to be rotated during the growth at a moderate rate.

In this paper, we optimized the layer-by-layer temperature for each layer of self-assembled InAs/InGaAs asymmetric DWELL structures under different growth conditions. The effect of substrate rotation throughout the growth on the optical property and uniformity of the QD structures grown by MBE using an As_2 flux was studied.

2. Experimental details

The cross-sectional schematic diagram of the self-assembled InAs/$In_{0.2}Ga_{0.8}As$ asymmetric DWELL structure employed in this experiment was shown in Fig. 1(a). The layers were grown on semi-insulating (1 0 0) GaAs substrate by a VG Semicon V80H MBE system with an As_2 flux. It is noted that the QDs grown with the As_2 flux has better properties than those grown with the As_4 flux

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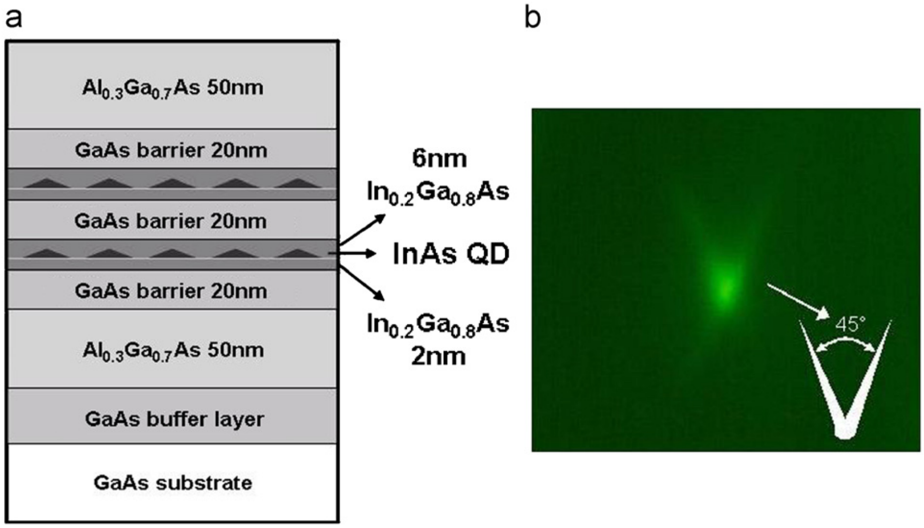

Fig. 1. (a) The cross-sectional schematic diagram of the self-assembled InAs/$In_{0.2}Ga_{0.8}As$ asymmetric DWELL structure employed in this experiment, (b) the observed chevron pattern from the RHEED during the growth of InAs/$In_{0.2}Ga_{0.8}As$ QDs.

[13]. The As_2 fluxes were generated from a valved crack cell with the cracking zone and base zone kept at 900 and 420 °C, respectively. After deoxidizing the sample surface under As_2 overpressure, a GaAs buffer layer was grown at 580 °C. Then, the active InAs/InGaAs QDs, which consist of 2 periods of InAs QDs grown on a 2 nm $In_{0.2}Ga_{0.8}As$ strained buffer layer, covered by a 6 nm $In_{0.2}Ga_{0.8}As$ strain-reducing layer, were embedded in 20 nm GaAs barriers and 50 nm $Al_{0.3}Ga_{0.7}As$ cladding layers. The growth temperature was optimized for each layer of QD structures. The III/V ratios were fixed at optimum values of ~60 and 9 for InAs and GaAs, respectively. The InAs QDs on the thin wetting layer of ~1–1.5 monolayer (ML) were formed with an indium (In) beam equivalent pressure (BEP) of 1.28×10^{-8} mbar (measured by monitoring ion gauge), indicating a growth rate of approximately 0.089 ML/s. The GaAs barrier was grown with a gallium (Ga) BEP of 3.89×10^{-8} mbar and the growth rate of $Al_{0.3}Ga_{0.7}As$ was ~2.83 ML/s. For a sufficient migration time of In adatom, the growth interruption time was 30 s before and after the formation of each InAs QD layer under As_2 overpressure. For atomic force microscopy (AFM) measurements, the substrate temperature was reduced quickly to freeze the islands after the growth of InAs QDs. All epitaxial layers were grown without stopping the As_2 flux of a BEP of 1×10^{-8} mbar. The InAs/InGaAs QD structures were grown with and without substrate rotation under the same growth conditions.

The *in-situ* reflection high energy electron diffraction (RHEED) is very useful to monitor the change in shape and surface morphology in initial stages of QD formation [14,15]. The observed chevron pattern from the RHEED during the growth of InAs/$In_{0.2}Ga_{0.8}As$ QDs is shown in Fig. 1(b). The chevron angle of approximately 45° indicates a typical pyramid-like QD shape. The substrate rotation did not lead to a considerable change in the RHEED patterns. The structural and optical properties of QD structures were analyzed by optical microscope, AFM, transmission electron microscopy (TEM), scanning tunneling microscopy (SEM), low-temperature PL measurements and RT-PL mapping. The PL at low temperature was measured by a 632 nm HeNe laser of 25 mW and emitted light was detected by a He-cooled InGaAs detector located at the exit of a monochromater. The RT-PL mapping was carried out with a 532 nm semiconductor diode

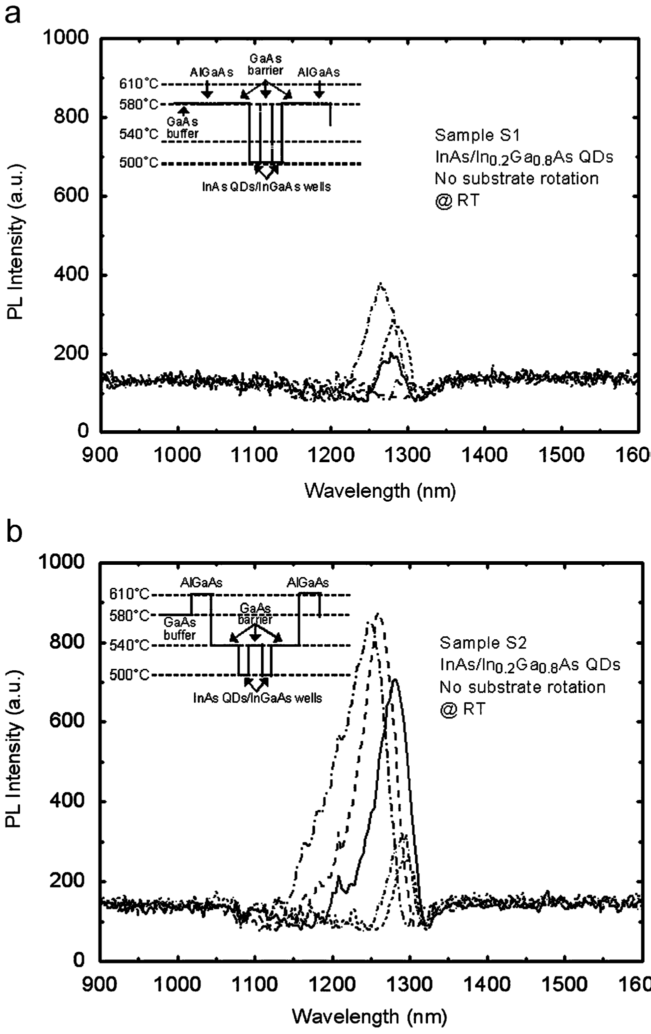

Fig. 2. RT-PL spectra of the InAs/$In_{0.2}Ga_{0.8}As$ double QD structures grown without substrate rotation for (a) the sample S1 and (b) sample S2 growth temperature sequences for each layer.