Wavelength Tuning (1.55-µm Region), Stacking, and Polarization Control of InAs/InGaAsP/InP (100) Quantum Dots Grown by Metalorganic Vapor-Phase Epitaxy

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Abstract: We achieved wavelength tuning of InAs quantum dots (QDs) embedded in InGaAsP/InP (100) grown by metalorganic vapor-phase epitaxy over the 1.55-µm region at room temperature by inserting GaAs interlayers. The interlayer, together with reduced V/III ratio and extended growth interruption, suppresses As/P exchange to reduce the QD height in a controlled way. The linear dependence of the PL wavelength on the interlayer thickness of stacked QDs reveals the successful reproduction of identical QD layers. Systematic redshift and linewidth reduction of closely-stacked QDs indicate vertical electronic coupling which is proven by the linear polarization of the cleaved-side luminescence changing from in-plane to isotropic.

Introduction

Quantum dot (QD) active regions in optical devices such as lasers and semiconductor optical amplifiers have great potential due to the QD singular density of states. Controlling, however, the emission wavelength of self-assembled InAs/InP QDs in the 1.55-µm region is still a challenge. This is primarily due to the small lattice mismatch, resulting in relatively large QDs and the presence of As/P exchange during InAs growth on InP-based materials,[1] shifting the emission wavelength beyond 1.6 µm at room temperature (RT). The QD wavelength control is anticipated to be most critical in metalorganic vapor-phase epitaxy (MOVPE) due to enhanced As/P exchange related to the higher growth temperature, high reactor pressure, long gas-phase diffusion, and complex gas exchange processes. Up to now, only a few attempts to fabricate InP-based QD structures by MOVPE have been reported with typical emission wavelengths around 1.6 µm.[2,3]

In this paper, we report the growth of InAs QDs embedded in an InGaAsP matrix, lattice matched on InP by MOVPE with tunable emission in the 1.55-µm wavelength region. Stacking and polarization control of InAs QDs, which are crucial for increasing the active volume and applicability of photonic devices in fiber-optical communication system, are exploited.

Experiment

The samples were grown on InP (100) substrates by MOVPE using trimethyl-indium (TMI), trimethyl-gallium (TMG), tertiarybutyl-arsine (TBA), and tertiarybutyl-phosphine (TBP) as gas sources. The sample structure commenced with 100 nm InP followed by single or stacked InAs QDs plus GaAs interlayers underneath placed in the center of a lattice-matched InGaAsP (Q1.25) layer with total thickness of 200-500 nm grown at 500 ºC. The GaAs interlayer thickness (d_{GaAs}) was 0 - 2 MLs, the nominal amount of InAs for QD growth was 3 and 3.5 MLs, and the InGaAsP separation layer

thickness between the stacked QD layers was 40 and 4 nm. On the sample surface the InAs QDs plus GaAs interlayer were repeated for atomic force microscopy (AFM) measurement.

Wavelength tuning by GaAs interlayer

Figure 1 summarizes the photoluminescence (PL) spectra at 4.8 K of the InAs QDs without and with GaAs interlayer and an additional flushing step under various TBA flows. The QD morphology without GaAs interlayer is similar to that obtained by CBE.[4] The PL peak emission wavelength of the QDs (λ_{QD}), however, is beyond 1600 nm both at RT and 4.8 K. In order to shift the λ_{QD} to shorter values, 2 MLs GaAs are inserted on the InGaAsP layer underneath the QDs. The 2 MLs GaAs interlayer thickness is the upper limit for defect free structures.[4] The average QD height (h_{QD}) in the presence of the GaAs interlayer is reduced from 6.0 to 3.1 nm, and λ_{QD} is blue-shifted to 1580 nm. The GaAs interlayer effectively suppresses As/P exchange and consumes surface segregated In adatoms, leading to a drastic reduction of h_{QD} and λ_{QD}. The shoulder observed on the short-wavelength side of the PL spectrum of Fig. 1 (b) is attributed to composition inhomogeneities in the QD layer, caused by a memory effect due to residual gas species in the reactor. A TMG flushing step (45 seconds) under TBA flow after GaAs interlayer growth, to ensure pure TMI as group-III source, results in smaller QD size and generates an additional blue-shift to 1558 nm. No shoulder is observed in the corresponding PL spectra of the QDs [Fig. 1 (c)].

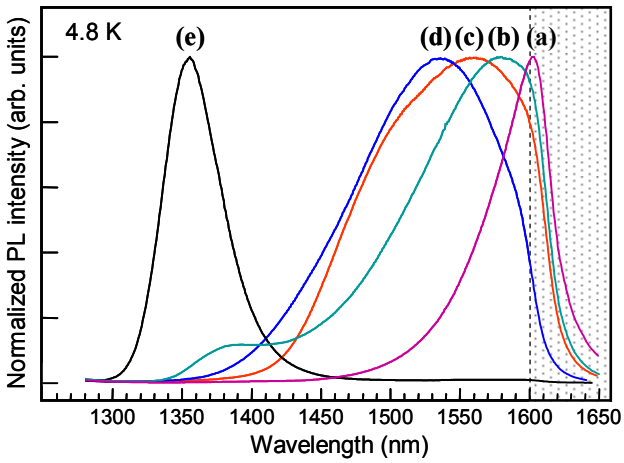

Fig. 1. Normalized PL spectra taken at 4.8 K of 3 MLs InAs single QD layers grown (a) without and (b) with 2 MLs GaAs interlayer at TBA flow of 6.1 sccm. (c)-(e) PL spectra of QDs with 2 MLs GaAs interlayer and TMG flushing grown at TBA flow of 6.1, 2.0 and 1.0 sccm, respectively. The shaded area is above the detection limit at 1.6 μm.

To study the effect of the V/III ratio on QD formation, the TBA flow rate is reduced from 6.1 to 2.0 and 1.0 sccm, while the TMI flow rate is kept constant. For 6.1 sccm TBA flow rate, λ_{QD} is 1558 nm at 4.8 K and beyond 1600 nm at RT despite of the small QD sizes. With reduction of the TBA flow, λ_{QD} continuously shifts to shorter wavelengths, reaching 1355 nm for the TBA flow rate of 1.0 sccm [Fig. 1 (e)]. Simultaneously, the PL linewidth becomes smaller, pointing toward reduced As/P exchange under low TBA flow, reducing size fluctuations of the QDs. However, the QDs are wider due to the larger In adatom migration length at low TBA flow.

After establishing the growth conditions such as gas switching sequences and V/III ratio, the QDs emit at 1480 nm at RT in the presence of a 2 MLs GaAs interlayer. The QD emission is then tuned over the 1.55-μm wavelength region by reducing d_{GaAs}. When d_{GaAs} is decreased from 2 MLs to 1.2 MLs, λ_{QD} continuously shifts to larger values reaching 1560 nm for 1.2 MLs GaAs, covering the 1.55 μm wavelength region [□ in Fig.

2 (a)]. Simultaneously, the PL efficiency improves, which is attributed to the reduction of tensile strain for thinner d_{GaAs}, improving the structural quality. The average h_{QD} increases from 4.5 nm for 2 MLs to 5.6 nm for 1.2 MLs GaAs [Fig. 2 (b)]. This confirms the continuous reduction of As/P exchange and consumption of surface segregated In with GaAs interlayer thickness to continuously reduce h_{QD} and, hence, λ_{QD}. Surprisingly, λ_{QD} shortens for $d_{GaAs} < 1$ ML. This is understood by the gradual shape transition from QDs to quantum dashes elongated along [0-11] for $d_{GaAs} < 1$ ML. Obviously the low group-V flow changes the properties of the InGaAsP surface to cause anisotropic surface diffusion leading to dash formation and, moreover, favors P incorporation into the quantum dashes causing the PL blue-shift. The minimum of λ_{QD} around $d_{GaAs} = 0.4$ MLs is, thus, attributed to the interplay between shape transition, shortening λ_{QD}, and As/P exchange, increasing the quantum dash height and PL emission wavelength. Only the combination of low growth temperature and V/III ratio with the insertion of GaAs interlayers ($d_{GaAs} > 1$ ML) allows continuous tuning of λ_{QD} over the 1.55 μm region without forming dashes.

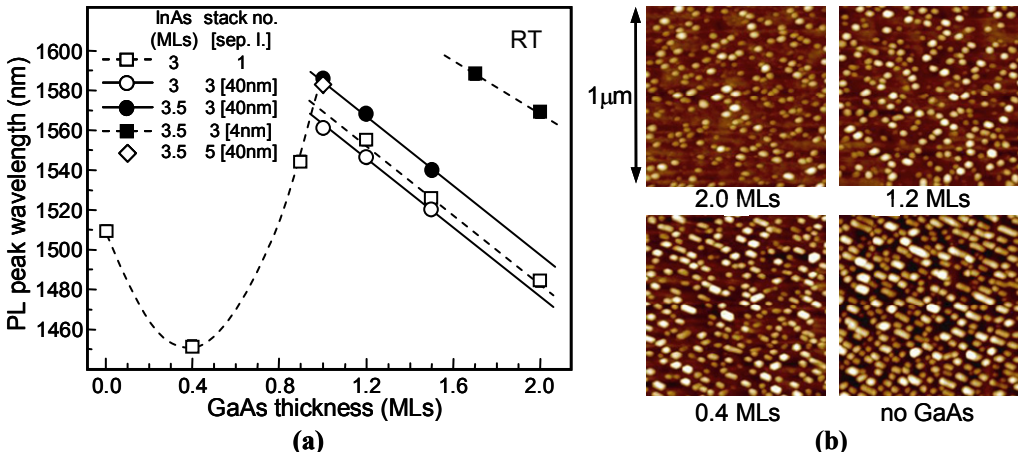

Fig. 2. (a) PL peak wavelength at RT as a function of GaAs interlayer thickness of the QDs formed by various InAs amount, InGaAsP separation layer thickness, and number of stacked QD layers. (b) AFM images of the 3 MLs InAs surface QDs with different GaAs interlayer thickness. The height contrast is 10 nm.

Stacking and polarization control

Upon stacking the 3 MLs InAs QDs with 40 nm InGaAsP separation layers up to five layers, the linear dependence of λ_{QD} as a function of d_{GaAs} coincides with that of the single QD layers [○ in Fig. 2 (a)]. Increasing the InAs amount to 3.5 MLs consistently shifts λ_{QD} by about 20 nm to larger values due to larger h_{QD}. The wavelength tuning with d_{GaAs} remains unchanged, identifying the InAs amount together with the V/III ratio as another parameters to adjust the QD emission wavelength in combination with the GaAs interlayer thickness. These results reveal reproduction and wavelength tuning of identically widely stacked QD layers where vertical strain and electronic coupling can be neglected, to increase the active volume without structural degradation, see Fig. 3 (a). On the other hand, λ_{QD} of the 3-closely-stacked 3.5 MLs InAs QDs with 4 nm InGaAsP separation layer thickness is red-shifted by about 90 nm compared to the widely-stacked ones. The PL linewidth at 4.8 K is reduced by more than 30 meV. Such PL red-shift and linewidth reduction are well documented to originate from efficient strain- and electronic coupling resulting in vertically aligned QDs with strong overlap of the electron wavefunctions. Tuning of λ_{QD} with d_{GaAs} is unaltered for the coupled QDs.

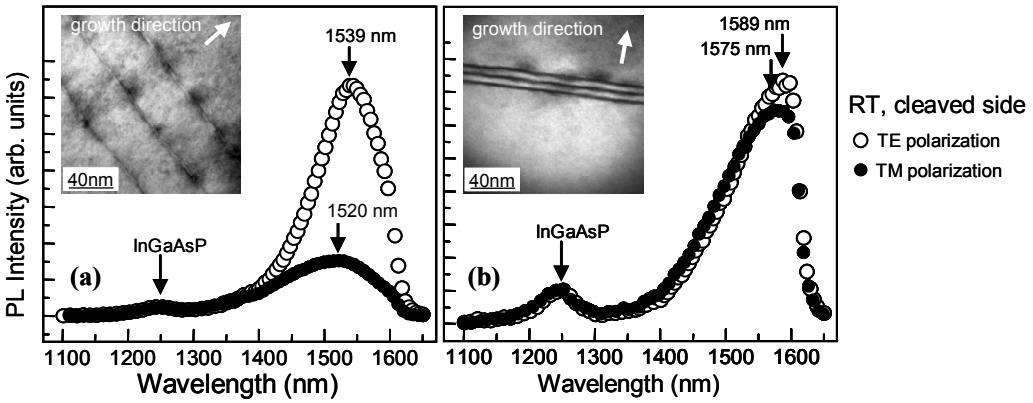

Fig. 3. Linear polarized cleaved-side PL spectra at RT of the 3-stacked QDs with InAs amount of 3.5 MLs. GaAs interlayer and InGaAsP separation layer thickness are (a) 1.5 MLs and 40 nm and (b) 1.7 MLs and 4 nm. The detection limit of the cooled InGaAs detector is at 1.6 μm. Insets: Cross-sectional transmission electron micrographs of the stacked QDs.

Vertical electronic coupling of the 3-closely-stacked QDs (4 nm InGaAsP separation layer) is proven by the linear polarization properties of the cleaved-side PL in comparison with those of the widely-stacked QDs [Fig. 3]. For the 3-widely-stacked QDs, the PL is TE polarized (in-plane) with a degree of linear polarization $P = (I_{TE}-I_{TM})/(I_{TE}+I_{TM})$ at the PL peak position of 0.7. In these compressively strained QD structures with valence band ground state of dominantly heavy-hole character, this anisotropy of the linear polarization is governed by the shape anisotropy of the QDs having an averge height-to-diameter ratio around 0.1 as measured by AFM. In contrast, P for the closely-stacked QDs at the PL peak position is reduced to 0.1. Hence, the shape anisotropy of the closely-stacked QDs is effectively reduced due to strong vertical electronic coupling. The PL efficiency of the 3-closely-stacked QDs at RT is one order of magnitude larger than that of the single QD layer, confirming the high structural and optical quality of the QDs without introduction of defects upon stacking.

In summary, we achieved wavelength tuning of MOVPE-grown InAs/InGaAsP/InP(100) QDs over the 1.55-μm region at RT by inserting GaAs interlayers, together with reduced V/III ratio, suppressing As/P exchange to reduce the QD height. Morevover, the successful increase of the QD active volume by stacking and the polarization control of emitted light prove these QDs of paramount importance for devices in fiber-optical telecommunication systems and, in particular, for the realization of polarization insensitive lasers and SOAs.

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