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Stacking and polarization control of wavelength-tunable (1.55 μm region) InAs/InGaAsP/InP (100) quantum dots

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Stacking and polarization control of wavelength-tunable InAs quantum dots (QDs) embedded in lattice-matched InGaAsP on InP (100) grown by metalorganic vapor-phase epitaxy is demonstrated. Wavelength control over the 1.55 μm region at room temperature is achieved by inserting ultrathin GaAs interlayers underneath the QDs and adjusting the amount of InAs. For widely stacked QDs with a 40 nm separation layer, the linear dependence of the emission wavelength on the GaAs interlayer thickness coincides with that of single QD layers revealing the reproduction of identical QD layers. For closely stacked QDs with 4 nm separation layer, the emission wavelength as a function of the GaAs interlayer thickness is systematically redshifted and the linewidth is reduced indicating vertical electronic coupling which is proven by the linear polarization of the cleaved-side luminescence changing from in-plane to isotropic. © 2006 American Institute of Physics. [DOI: 10.1063/1.2172729]

Self-assembled InAs quantum dots (QDs) embedded in InGaAsP lattice-matched to InP are promising active materials in optical devices, such as lasers and semiconductor optical amplifiers (SOAs) operating in the 1.55 μm telecommunication wavelength region.^{1,2} However, for their successful implementation, important issues, such as wavelength control, increase of the active volume by stacking in multilayers, and polarization control need to be solved. Regarding wavelength control, InAs/InP QDs usually emit beyond 1.6 μm at room temperature (RT) due to their relatively large size, related to the small lattice mismatch of 3.2% and the presence of As/P exchange during InAs growth on the InGaAsP surface.^{3,4} We have recently solved this problem by the insertion of ultrathin (0–2 monolayers (MLs)) GaAs interlayers between the InAs QDs and the InGaAsP layer underneath which effectively suppresses As/P exchange to reduce the QD height in a controlled way. Reproducible tuning of the QD emission wavelength as a function of the GaAs interlayer thickness became possible covering the 1.55 μm wavelength region from beyond 1.6 μm to below 1.5 μm at RT.^{5,6}

In this letter, stacking and polarization control of the InAs QDs is exploited. Widely stacked QDs with 40 nm separation layer exhibit a linear dependence of the peak emission wavelength on the GaAs interlayer thickness which coincides with that of single QD layers, revealing the reproduction of identical QDs to increase the active volume. With increasing InAs amount, the wavelength is shifted to larger values with similar tuning behavior upon the GaAs interlayer thickness. For closely stacked QDs with 4 nm separation layer, the emission wavelength as a function of the GaAs interlayer thickness is systematically redshifted and the linewidth is reduced. This indicates vertical electronic coupling which is proven by the linear polarization of the cleaved-side photoluminescence (PL) changing from in-plane for widely

stacked QD layers to isotropic. Together with the high PL efficiency at RT, the successful increase of the QD active volume by stacking, and the control of the polarization of InAs/InGaAsP/InP (100) QDs emitting in the 1.55 μm wavelength region is of paramount importance for devices in fiber-optical telecommunication systems, in particular, the realization of polarization insensitive lasers and SOAs.^{7,8}

The samples were grown by low-pressure metalorganic vapor-phase epitaxy using trimethyl-indium, trimethyl-gallium, tertiarybutyl-arsine, and tertiarybutyl-phosphine as gas sources. The vicinal InP (100) substrates were misoriented by 2° toward (110). The sample structure commenced with 100 nm InP followed by single (see Ref. 6 for details) or stacked InAs QDs plus GaAs interlayers underneath placed in the center of a lattice-matched quaternary InGaAsP ($\lambda_Q=1.25 \mu\text{m}$) layer with total thickness of 200–500 nm. The growth temperature was 500 °C. The GaAs interlayer thickness was between one and two MLs, the amount of InAs for QD formation 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 assessing the QD morphology by atomic force microscopy (AFM) carried out in tapping mode in air. PL measurements were performed using a Nd:YAG laser (532 nm) as an excitation source with the samples mounted in a He-flow cryostat. The PL was dispersed by a 1 m single monochromator and recorded by a cooled InGaAs charge-coupled device. For linear polarization dependent measurements, the PL was excited on the cleaved side and the transverse electric (TE)- and transverse magnetic (TM)-polarized signals from the cleaved side were collected by setting the polarizer along the in-plane and growth direction, respectively.

The morphology of the InAs QDs with different GaAs interlayer thicknesses and InAs amounts is shown in Figs. 1(a)–1(c). The QD density is $\sim 3 \times 10^{10} \text{ cm}^{-2}$ independent of the GaAs interlayer thickness and the InAs amount. An in-

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FIG. 1. (Color online) AFM image of the surface QDs with GaAs interlayer thickness and InAs amount of (a) 1.2 MLs and 3 MLs, (b) 2.0 MLs and 3 MLs, and (c) 1.2 MLs and 3.5 MLs. The height contrast is 10 nm in all images.

crease in the GaAs interlayer thickness decreases the average QD height from 5.5 to 4.5 nm [Figs. 1(a) and 1(b)] due to suppressed As/P exchange,⁶ while the average QD height is increased for larger InAs amount from 5.5 nm to 5.7 nm [Figs. 1(a) and 1(c)]. The PL peak wavelengths at RT of the QD samples as a function of GaAs interlayer thickness are summarized in Fig. 2. The inset shows the RT PL spectra of the three-fold widely stacked QDs with an InAs amount of 3 MLs as an example. The GaAs interlayer thickness is kept above one ML to avoid the formation of quantum dashes.⁶ The peak wavelengths of all samples are consistently reduced for increasing GaAs interlayer thickness due to the reduced QD height. The linear dependence of the peak wave-

FIG. 2. PL peak wavelength at RT as a function of GaAs interlayer thickness of the QD samples with various InAs amounts, InGaAsP separation layer thicknesses, and number of stacked QD layers. Inset: RT PL spectra of the three-fold stacked QDs with InAs amount of 3 MLs, 40 nm InGaAsP separation layers, and GaAs interlayer thickness of 1.5, 1.2, and 1 MLs (from left to right). The detection limit of the cooled InGaAs detector is at 1600 nm.

length of the three-fold widely stacked 3 MLs InAs QDs as a function of GaAs interlayer thickness (open circles) almost coincides with that of the single QD layers (open squares). The PL linewidths of the single and stacked QD layers are similar (compare inset in Fig. 2 and Ref. 6). Increasing the InAs amount of the three-fold widely stacked QDs to 3.5 MLs shifts the peak wavelength by about 20 nm to larger values (solid circles), due to the larger QD height. The wavelength tuning with GaAs interlayer thickness remains unchanged, identifying the InAs amount together with the V-III ratio⁶ as other parameters to adjust the QD emission wavelength in combination with the GaAs interlayer providing the highest PL efficiency slightly above 1 ML thickness. The peak wavelength of the five-fold widely stacked 3.5 MLs InAs QDs with 1 ML GaAs interlayer lies on the same line (open diamond). These results reveal identical reproduction and wavelength tuning of the InAs QD layers during wide stacking where vertical strain and electronic coupling can be neglected to increase the active volume without structural degradation.

The PL peak wavelength of the three-fold closely stacked 3.5 MLs InAs QDs (solid squares in Fig. 2) is redshifted by about 90 nm compared to that of the widely stacked ones and the PL linewidth at 5 K is reduced by more than 30 meV. The PL redshift 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 wave functions.^{9–11} Tuning of the QD peak wavelength with the GaAs interlayer thickness behaves very similar also for the closely stacked QDs.

Vertical electronic coupling in the three-fold closely stacked QDs is proven by the linear polarization properties of the cleaved-side PL in comparison with those of the widely stacked QDs, shown in Figs. 3(a) and 3(b). For the three-fold widely stacked 3.5 MLs InAs QDs with 1.5 MLs GaAs interlayer, TE polarization is dominant with a degree of linear polarization $P = (I_{TE} - I_{TM}) / (I_{TE} + I_{TM})$ at the peak position of 0.7. In these compressively strained QD structures with a valence-band ground state of dominantly heavy-hole character, this anisotropy of the linear polarization is attributed to the shape anisotropy of the QDs (Ref. 8) having a height-to-diameter ratio of approximately 0.1 as measured by AFM for the surface QDs.

In contrast, for the three-fold closely stacked 3.5 MLs InAs QDs with a 1.7 MLs GaAs interlayer (chosen for similar structural properties), the degree of linear polarization P at the PL peak position is reduced to 0.1. Hence, the shape anisotropy of the closely stacked QDs is effectively reduced due to the strong vertical electronic coupling. Figure 3(c) shows the degree of linear polarization P for the widely and closely stacked QDs as a function of wavelength. In both cases, P increases toward the PL peak wavelength indicating some reduction of the QD height-to-diameter ratio over the Gaussian QD size distribution toward the average (peak) value. This leads to isotropic PL emission ($P=0$) around 1.55 μm for the closely stacked QDs having a peak wavelength of 1.58 μm . In fact, a slightly longer PL peak wavelength is beneficial also in view of polarization insensitive device operation in the 1.55 μm region where lasing from QDs is commonly observed at wavelengths slightly shorter (30–40 nm) than the PL peak wavelength.^{4,12} Polarization insensitive emission is observed from the closely stacked QDs, though the total QD height-to-diameter ratio, including

FIG. 3. Linear polarized PL spectra at RT taken from cleaved sides of the three-fold stacked QDs with InAs amount of 3.5 MLs and InGaAsP separation layer thickness of (a) 40 nm and (b) 4 nm. The GaAs interlayer thickness is (a) 1.5 MLs and (b) 1.7 MLs. (c) Degree of linear polarization as a function of wavelength for 40 nm (open circles) and 4 nm (closed circles) separation layer thickness. The detection limit of the cooled InGaAs detector is at 1600 nm.

the InGaAsP separation layers is ~ 0.4 , i.e., less than unity. This might be related to inhomogeneous strain in the QDs varying from compressive toward tensile from the base to the apex.¹³ As a consequence, the electron-light hole transition is shifted down in energy to contribute to TM-polarized PL, which also explains the blueshift of 10 meV for both the closely and widely stacked QDs.

The PL efficiency of the closely stacked QDs is high and only degrades when the number of QD layers is increased above three. The PL efficiency of the three-fold closely stacked QDs is constant between 5 and 140 K, where it undergoes an exponential decrease due to a thermally activated carrier escape into the InGaAsP barriers, similar to the

single⁶ and widely stacked QDs. The drop in PL efficiency between 5 K and RT depends on the sample structure and is, e.g., reduced to one to two orders of magnitude when completed with a 40 nm InP barrier. The PL efficiency at RT of the three-fold closely stacked QDs is one order of magnitude larger than that of the single QD layers confirming high structural and optical quality of the QDs without the introduction of defects upon stacking.

In summary, we have studied stacking and polarization control of wavelength tunable InAs QDs embedded in lattice-matched InGaAsP on InP (100) grown by MOVPE. Insertion of ultrathin GaAs interlayers, together with fine adjustment by the amount of InAs, allows wavelength tuning of the QD emission at RT over the technologically important 1.55 μm wavelength region. For widely stacked QDs with 40 nm separation layer, the linear dependence of the emission wavelength on the GaAs interlayer thickness coincides with that of single QDs revealing the reproduction of identical QD layers to increase the active volume. For closely stacked QDs with 4 nm separation layer, vertical electronic coupling is demonstrated by the systematic redshift of the emission wavelength, the linewidth reduction, and the linear polarization of the cleaved-side PL changing from in-plane to isotropic. Together with the high PL efficiency at RT, this is of paramount importance for the realization of polarization insensitive optical devices, such as lasers and SOAs, required in fiber-optical telecommunication systems.

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