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Self Assembled InAs/InP Quantum Dots for Telecom Applications in the 1.55 μm Wavelength Range: Wavelength Tuning, Stacking, Polarization Control, and Lasing

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Wavelength-tunable InAs quantum dots (QDs) embedded in lattice-matched InGaAsP on InP(100) substrates are grown by metalorganic vapor-phase epitaxy (MOVPE). As/P exchange, which causes a QD size and an emission wavelength that are very large, is suppressed by decreasing the QD growth temperature and V–III flow ratio. As/P exchange, QD size and emission wavelength are then reproducibly controlled by the thickness of ultrathin [0 – 2 monolayers (ML)] GaAs interlayers underneath the QDs. Submonolayer GaAs coverages result in a shape transition from QDs to quantum dashes for a low V–III flow ratio. It is the combination of reduced growth temperature and V–III flow ratio with the insertion of GaAs interlayers of greater than 1 ML thickness which allows the tuning of the emission wavelength of QDs at room temperature in the 1.55 μm wavelength range. Temperature-dependent photoluminescence (PL) measurements reveal the excellent optical properties of the QDs. Widely stacked QD layers are reproduced with identical PL emission to increase the active volume while closely stacked QD layers reveal a systematic PL redshift and linewidth reduction due to vertical electronic coupling, which is proven by the fact that the linear polarization of the cleaved-side PL changes from in-plane to isotropic. Ridge-waveguide laser diodes with stacked QD layers for their active regions exhibit threshold currents at room temperature in continuous-wave mode that are among the lowest threshold currents achieved for InAs/InP QD lasers operating in the 1.55 μm wavelength range.

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1. Introduction

Quantum dot (QD) lasers and semiconductor optical amplifiers (SOAs) have shown excellent performance.1) Most of these lasers and SOAs are based on self-assembled InAs/GaAs QDs emitting at wavelengths between 1 and 1.3 μm. For longer wavelengths, the QD quality drops markedly. In the 1.55 μm wavelength range, for applications in fiber optical telecommunication systems, the material of choice is InAs/InP. Unfortunately, InAs/InP QDs usually emit at wavelengths beyond 1.6 μm at room temperature (RT). This is due to the small lattice mismatch of 3.2% and the presence of As/P exchange during InAs growth, generating additional InAs on the InP-based material surface and resulting in very large, high QDs. Shorter wavelengths have been realized for QDs by double capping on InP (311)B substrates,2) the reduction of the V/III ratio and InAs supply,3) InGaAs growth,4) and postgrowth annealing,5) or in the case of quantum dashes.6) However, the reproducible continuous wavelength control of InAs/InP QDs in the 1.55 μm wavelength range necessary for device applications is still to be achieved.

We have first solved this problem for InAs/InP QDs grown by chemical beam epitaxy (CBE). Inserting ultrathin [0 – 2 monolayers (ML)] GaAs5) or GaP8) interlayers between the InAs QDs and the underlying lattice-matched InGaAsP layer with a bandgap at 1.25 μm (Q1.25), which is the standard waveguide core material for integrated photonic devices, allows the continuous tuning of the emission wavelength of the InAs QDs from greater than 1.6 to less than 1.5 μm at RT. This is due to the effective suppression of As/P exchange and the consumption of surface-segregated In as a function of the GaAs or GaP interlayer thickness to continuously reduce the QD height and, hence, the QD emission wavelength. The suppression of As/P exchange is based on binary-compound bond strengths: The Ga–P bond strength (54.9 kcal/mol) is larger than the Ga–As bond strength (50.1 kcal/mol), while the smaller In–P bond strength (47.3 kcal/mol) is smaller than the In–As bond strength (48.0 kcal/mol). Hence, both GaAs and GaP surface terminations prevent the substitution of P bound to In by As to create unwanted InAs, inevitably contributing to the QD growth in an uncontrolled way, increasing QD size and size fluctuations.7,8)

In view of applications, the realization of wavelength-tunable InAs/InP QDs grown by metalorganic vapor-phase epitaxy (MOVPE), which is most commonly used for InP-based photonic devices is desired. Here, we review the successful wavelength tuning and applications of MOVPE-grown InAs/InP QDs in Q1.25 InGaAsP based on the insertion of ultrathin GaAs interlayers. As/P exchange is enhanced in MOVPE owing to higher growth temperature, larger group V–III flow ratio, high reactor pressure, long gas-phase diffusion lengths, and complex gas switching and gas exchange processes, making the wavelength control of InAs/InP QDs more critical. When, however, these parameters are optimized, the insertion of an ultrathin GaAs interlayer is as effective for controlling As/P exchange as in CBE. MOVPE-grown InAs QDs with excellent optical quality at RT and an emission wavelength tunable in the 1.55 μm wavelength range are realized.9) Importantly, the QDs can be vertically stacked.10) The wavelength tuning for widely stacked QD layers is reproduced with identical emission to increase the active volume. For closely stacked
QD layers, linear polarization control is achieved by vertical electronic coupling, rendering the emission from the cleaved side isotropic. This is of particular importance for realizing polarization-independent SOAs. Ridge-waveguide laser diodes with stacked QD layers for their active regions exhibit threshold currents at RT in continuous-wave (cw) mode that are among the lowest threshold currents achieved for InAs/InP (100) QD lasers.

2. Wavelength Tuning

2.1 Effect of growth temperature

Figure 1(a) shows the height and base diameter of InAs QDs grown directly on Q1.25 InGaAsP at 480, 500, 520, and 585 °C, determined from the corresponding atomic force microscopy (AFM) images depicted in Figs. 1(b)–1(e). Growth is by low-pressure MOVPE on InP(100) substrates misoriented by 2° toward (110) using trimethylindium (TMI), trimethylgallium (TMG), tertiarybutylarsine (TBA), and tertiarybutylphosphine (TBP) as gas sources and H2 as carrier gas. The reactor pressure and total flow rate are 100 mbar and 15000 sccm, respectively. The QDs are formed by CBE with an average QD height of 3.1 nm, indicated by the much-dimmer QDs, and the PL peak wavelength reveals a blueshift to 1580 nm at 4.8 K. As deduced from Fig. 2(a), the average QD height in the presence of the GaAs interlayer is reduced from 6.0 to 3.1 nm, indicated by the much-dimmer QDs, and the PL peak wavelength reveals a blueshift to 1580 nm at 4.8 K. As for CBE, the role of the GaAs interlayer is to effectively suppress the As/P exchange during InAs QD growth and to consume surface-segregated In on the InGaAsP layer, leading to a marked reduction of the InAs QD height and PL peak wavelength.

The PL spectrum of the InAs QDs with the 2 ML GaAs interlayer [dash-dotted line in Fig. 2(a)] has a shoulder on the short-wavelength side of the peak, which is attributed to inhomogeneous Ga incorporation in the QD layer. This can easily arise owing to delayed gas exchange in the MOVPE reactor. A flushing step of TMG under TBA flow after GaAs interlayer growth for 45 s ensures the presence of pure TMI as a group-III source for QD growth. The resulting InAs QDs are slightly smaller, as shown in the AFM image in
Fig. 2(d). This indicates increased lattice mismatch in the absence of residual Ga in the QD layer due to flushing. The smaller QD size generates an additional blueshift of the PL peak wavelength to 1558 nm at 4.8 K and the shoulder in the PL spectrum shown in Fig. 2(a) is not present in this case. Hence, we proceed with a flushing step of 45 s after the insertion of the GaAs interlayer.

2.3 Effect of group V–III flow ratio

The dependences of the PL spectra at 4.8 K on the TBA flow rate and the corresponding QD surface morphologies are shown in Fig. 3, again for InAs QDs grown on a 2 ML GaAs interlayer at 500 °C, and unchanged TMI flow rate. For the same 6.1 sccm TBA flow rate (partial pressure 0.0059 mbar) used in the previous experiments, the QD PL peak wavelength is 1558 nm at 4.8 K and beyond 1600 nm at RT, despite the small QD sizes. With a reduction of the TBA flow rate from 2.0 sccm (partial pressure 0.0019 mbar) to 1.0 sccm (partial pressure 0.0009 mbar), the QD PL peak wavelength continuously shifts to shorter wavelengths, reaching a peak wavelength of 1355 nm at 4.8 K for the TBA flow rate of 1.0 sccm. This indicates reduced As/P exchange under low TBA flow, i.e., reduced As supply, which simultaneously narrows the PL linewidth owing to an improved bottom interface of the QD layer, reducing QD size fluctuations.7) The increase in the QD diameters in Figs. 3(b)–3(d) is attributed to the larger In adatom migration length for the reduced TBA flow. Even so, the QD PL peak wavelength shortens owing to the reduced As/P exchange for low TBA flow, reducing the height of the QDs penetrating into the InGaAsP layer underneath. Hence, we proceed with a TBA flow rate of 1 sccm for InAs QD formation.

2.4 Effect of GaAs interlayer thickness

For optimized growth temperature (500 °C), gas switching sequence (flushing time after GaAs interlayer growth of 45 s), and group V–III flow ratio (TBA flow rate of 1.0 sccm) for obtaining a QD PL peak wavelength of 1450 nm at RT in the presence of a 2 ML GaAs interlayer, the emission of the QDs is tuned over the 1.55 μm wavelength range by reducing the GaAs interlayer thickness. Figure 4(a) shows the PL spectra taken at RT of the capped QDs for GaAs interlayer thicknesses of 2.0, 1.2, and 0 ML. When the GaAs interlayer thickness is reduced from 2.0 to 1.2 ML, the PL peak wavelength shifts to a larger value from 1460 nm for 2.0 ML GaAs to 1560 nm for 1.2 ML GaAs, covering the 1.55 μm wavelength range by reducing the GaAs interlayer thickness. Figure 4(a) shows the PL spectra taken at RT of the capped QDs for GaAs interlayer thicknesses of 2.0, 1.2, and 0 ML. When the GaAs interlayer thickness is reduced from 2.0 to 1.2 ML, the PL peak wavelength shifts to a larger value from 1460 nm for 2.0 ML GaAs to 1560 nm for 1.2 ML GaAs, covering the 1.55 μm wavelength range by reducing the GaAs interlayer thickness. Figure 4(a) shows the PL spectra taken at RT of the capped QDs for GaAs interlayer thicknesses of 2.0, 1.2, and 0 ML.
GaAs interlayer thickness to reduce the QD height and PL peak wavelength. When the GaAs interlayer coverage is reduced to less than 1 ML, the PL peak wavelength in Fig. 4(a) shortens again. This unexpected observation is due to a shape transition from InAs QDs to quantum dashes elongated along [0001], as shown in Figs. 4(d) and 4(e). Evidently, the shape transition is a reduction of the PL peak intensity which is attributed to the larger lateral size of the quantum dashes, easily causing defects.

The shape transition implies that only the combination of low growth temperature and low V–III flow ratio with the insertion of GaAs interlayers of greater than 1 ML thickness allows the continuous tuning of the emission wavelength of QDs in the 1.55 \( \mu \)m wavelength range at RT. Even in the presence of a GaAs interlayer, the low V–III flow ratio required to shift the QD emission wavelength into the 1.55 \( \mu \)m wavelength range results in the formation of quantum dashes directly on InGaAsP. Notably, the combination of low V–III flow ratio and a thin GaAs interlayer leads to an optimized QD PL efficiency in the 1.55 \( \mu \)m wavelength range when the GaAs interlayer thickness is just greater than 1 ML. Experiments with GaP interlayers\(^8\) were not successful for MOVPE. The RT PL efficiency was very weak, most probably owing to a high sensitivity of MOVPE, compared with CBE, to the high tensile strain in GaP introducing defects in the QDs.

The excellent optical properties of the optimized QDs with GaAs interlayers were confirmed by detailed temperature-dependent PL measurements.\(^9\) The integrated PL intensity of the InAs QDs is almost constant up to 140 K and decreases exponentially at higher temperatures. The activation energy that describes the quenching of the PL intensity is close in value to the difference between the InGaAsP bandgap energy and the InAs QD emission energy. This is consistent with the thermionic emission of carriers from the InAs QD ground states to the InGaAsP barriers, revealing QDs which are free of nonradiative recombination centers.

### 3. Applications

#### 3.1 Stacking

Three or 3.5 ML InAs QDs separated by 40 nm Q1.25
InGaAsP are stacked in up to five layers. As shown in Fig. 5, the linear dependence of PL peak wavelength as a function of the GaAs interlayer thickness of threefold stacked 3 ML InAs QDs (open circles) coincides with that of the single 3 ML InAs QD layers (open squares). The PL peak wavelength of threefold stacked 3.5 ML InAs QDs as a function of GaAs interlayer thickness is consistently shifted by approximately 20 nm to longer wavelengths due to a larger average QD height (solid circles in Fig. 5). The PL peak wavelength of fivefold stacked 3.5 ML InAs QDs with a 1 ML GaAs interlayer is on the line of the threefold stacked 3.5 ML InAs QDs (open diamond in Fig. 5). These results reveal the reproduction and wavelength tuning of widely stacked QDs in identical layers, where vertical strain and electronic coupling can be neglected, to increase the active volume.

The PL peak wavelength of the threefold closely stacked 3.5 ML InAs QDs separated by 4 nm Q1.25 InGaAsP is redshifted by approximately 90 nm relative to that of the widely stacked QDs (solid squares in Fig. 5). The PL linewidth at 4.8 K is reduced by more than 30 meV. Such PL redshift and the linewidth reduction of closely stacked QDs originate from efficient strain coupling and electronic coupling that result in vertically aligned QDs with a strong overlap of electron wave functions. The tuning of PL peak wavelength with GaAs interlayer thickness is unaltered for coupled closely stacked QDs.

### 3.2 Polarization control

A direct manifestation of the vertical electronic coupling of threefold closely stacked QDs is provided by the linear-polarization behavior of the cleaved-side PL at RT compared to that for the widely stacked QDs [Figs. 6(a) and 6(b)]. Cross-sectional transmission electron microscopy (TEM) images of the widely and closely stacked QDs are shown in the insets. For the widely stacked QDs [Fig. 6(a)], the PL is strongly transverse electric (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. TE-polarized PL from these compressively strained QDs with the heavy-hole character of the valence band ground state is governed by the shape anisotropy of the QDs having an average height-to-diameter ratio of 0.1–0.2. In contrast, $P$ for the closely stacked QDs at the PL peak position is reduced to 0.1 and it becomes zero at the short-wavelength side of the PL spectrum at around 1.5 µm [Fig. 6(b)]. Hence, vertical electronic coupling eliminates the shape anisotropy of the closely stacked QDs to render the PL emission from the cleaved side unpolarized. This is of particular relevance for polarization-independent SOAs needed in fiber-based optical communication systems. The high structural and optical quality of the threefold closely stacked QDs is confirmed by the PL efficiency at RT, which is one order of magnitude larger than that of the single QD layers.

### 3.3 Lasing

The cw lasing spectrum at RT of the as-cleaved narrow-ridge-waveguide QD laser diode, together with the light output power versus current characteristics in the inset, is shown in Fig. 7. The electroluminescence (EL) spectrum below threshold is included for reference. The active region of the laser diode is composed of fivefold widely stacked InAs QD layers (3.5 ML InAs, 1 ML GaAs, 40 nm Q1.25 InGaAsP separation layers), which are placed in the center of a 500-nm-thick Q1.25 InGaAsP waveguide core. The bottom and top claddings are a 500 nm n-InP buffer on a n-InP substrate and a 1.5 µm p-InP layer completed by a
compositionally graded 75 nm p-InGaAsP contact layer, respectively. The width \( W \) of the ridge waveguide is 3.5 \( \mu \)m and the cavity length \( L \) is 1 mm. Lasing occurs at 1.568 \( \mu \)m with a threshold current of 135 mA. This is QD ground-state lasing. Excited-state lasing is observed at higher currents. The threshold current corresponds to a threshold current density of 4 kA/cm\(^2\), which is reduced to 2 kA/cm\(^2\) in pulsed operation, indicating some heating effects in cw mode. For a 3.6-mm-long cavity, the threshold current density in the pulsed mode is further reduced to 580 A/cm\(^2\). These results are among the best achieved for InAs/InP QD lasers operating in the 1.55 \( \mu \)m wavelength range.

4. Conclusions

In summary, we have realized wavelength-tunable InAs QDs embedded in a lattice-matched InGaAsP matrix on InP(100) by MOVPE. As/P exchange, shifting the emission wavelength of the QDs beyond 1.6 \( \mu \)m at RT, has been suppressed by decreasing the QD growth temperature and the V–III flow ratio. The QD emission wavelength was then reproducibly tuned in the 1.55 \( \mu \)m wavelength range by varying the thickness of an ultrathin (0–2 ML) GaAs interlayer underneath the QDs, controlling the As/P exchange during InAs growth. An extended interruption after the GaAs interlayer growth was essential to obtain well-defined InAs QDs. Submonolayer GaAs coverages resulted in a shape transition from QDs to quantum dashes at low V–III flow ratio. Only the combination of reduced growth temperature and V–III flow ratio with the insertion of GaAs interlayers of greater than 1 ML thickness allowed the wavelength tuning of QDs at RT in the 1.55 \( \mu \)m wavelength range. Temperature-dependent PL measurements revealed defect-free InAs QDs with excellent optical properties up to RT. Widely stacked QD layers were reproduced with identical PL emission to increase the active volume. Closely stacked QD layers revealed a systematic PL redshift and linewidth reduction due to vertical electronic coupling, which was proven by the fact that the linear polarization of the cleaved-side PL changes from in-plane to isotropic. The cw threshold current at RT of ridge-waveguide QD laser diodes with stacked QD layers for their active regions compares well with the lowest threshold currents achieved for InAs/InP (100) QD lasers operating in the 1.55 \( \mu \)m wavelength range.

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