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Polarization control of gain of stacked InAs/InP (100) quantum dots at 1.55 μm : Interplay between ground and excited state transitions

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The linear polarization of the optical gain of closely stacked InAs/InP (100) quantum dots (QDs) grown by metal-organic vapor-phase epitaxy with emission wavelength tuned into the 1.55 μm region is controlled by the number of stacked QD layers and the injection current. Increasing the number of stacked QD layers to five rotates the linear polarization of the cleaved-side photoluminescence and QD ground state (GS) gain, determined from the amplified spontaneous emission (ASE) of a Fabry-Pérot ridge-waveguide laser, from transverse electric (TE) to transverse magnetic due to vertical electronic coupling. When the QD GS ASE and gain saturate with an increase of the injection current and the excited state ASE and gain become dominant, the linear polarization of ASE and gain changes back to TE. This limits the polarization insensitive operation of QD-based semiconductor optical amplifiers, however, opening routes to novel functionalities.

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Semiconductor quantum dots (QDs) improve the performance of optical devices such as lasers and semiconductor optical amplifiers (SOAs), owing to their discrete density of states.¹ Being compatible with fiber-based optical telecom systems operating in the 1.55 μm wavelength region, InAs QDs on InP substrates are extensively investigated. QD-based SOAs have shown excellent characteristics such as ultrafast response for high-bit-rate signal processing and broadband amplification with high power saturation.^{2,3} However, detrimental for telecommunication applications is the transverse electric (TE) polarized gain of QDs. This is due to the shape anisotropy of the flat, compressively strained QDs with a heavy-hole characteristic of the valence-band ground state (GS).⁴ Aiming at polarization insensitive gain in SOAs, several techniques to increase the QD aspect ratio (height/base) and, hence, the transverse magnetic (TM) polarization have been explored, first for InAs/GaAs QDs^{5–7} and later for InAs/InP QDs.^{8–10} They include (i) close stacking of QDs with thin separation layers to increase the effective QD height due to electronic coupling of the vertically aligned QDs,^{5,8} (ii) introduction of In into the capping layer,⁶ and (iii) increase of the height of columnar QDs,^{7,9,10} with Refs. 7 and 10 addressing gain.

In this letter, we report linear polarization control of gain of closely stacked InAs/InP (100) QDs grown by metal-organic vapor-phase epitaxy (MOVPE). The QD emission wavelength is tuned into the 1.55 μm region through the insertion of a GaAs interlayer underneath the QDs.¹¹ To identify the polarization and saturation behaviors of QD GS and excited state (ES) transitions and their interplay leading to the polarization control of the gain, detailed photoluminescence (PL) and electroluminescence (EL)/amplified spontaneous emission (ASE) measurements are performed. Increasing the number of stacked QD layers to 5 rotates the linear polarization of the cleaved-side PL and QD GS gain, deter-

mined from the ASE of a Fabry-Pérot (FP) ridge-waveguide laser, from TE to TM due to vertical electronic coupling. With an increase of the injection current, the QD GS ASE and gain saturate, and the linear polarization of ASE and gain changes back to TE when the ES ASE and gain become dominant. This offers interesting routes to novel functionalities, limiting, however, the sought for polarization insensitive operation of QD based SOAs.

The closely stacked InAs QDs plus GaAs interlayer (1.5–2 ML) were grown on InP (100) substrates by MOVPE at 500 °C in the center of a 500 nm thick lattice-matched InGaAsP waveguide core with a bandgap at 1.25 μm (Q1.25). The nominal InAs amount and thickness of the Q1.25 separation layers (0.24% tensile strained for strain compensation) were 3 MLs and 5 nm. PL measurements were performed at room temperature (RT) using a Nd:YAG (yttrium aluminium garnet) laser (532 nm) for excitation. The PL was dispersed by a single monochromator and detected by a cooled InGaAs linear photodiode array with a cutoff at 1.6 μm . For the laser structure, the Q1.25 waveguide core was embedded between the 500 nm *n*-InP bottom and the 1.5 μm *p*-InP top claddings, completed by a compositionally graded *p*-InGaAsP contact layer. The FP ridge-waveguide laser cavities were fabricated by deep reactive ion etching 200 nm into the bottom cladding. The cavity length and ridge width were 1 mm and 2.5 μm . Propagation losses measured from similar deeply etched passive waveguides were 2.5 dB/cm both for TE and TM modes, which are suitable for investigation of gain polarization.

Linear polarization-dependent PL measurements were performed by exciting on the cleaved side and collecting the TE- and TM-polarized signals from the cleaved side by setting the polarizer along the in-plane and growth direction, respectively. Calibration of the setup was done by measuring bulk InGaAsP layers. Figure 1 shows the degree of linear polarization of the cleaved-side PL as a function of number of QD stacks together with the polarized PL spectra taken at RT.

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FIG. 1. (Color online) Degree of linear polarization and polarized PL spectra taken at RT from the cleaved side of closely stacked InAs/InP (100) QDs as a function of the number of QD stacks. The inset shows an AFM image of uncapped 3 ML InAs QDs. The scan field is $1 \times 1 \mu\text{m}^2$ and the full height contrast is 10 nm.

For the current excitation conditions, PL probes the QD GS transitions. The atomic force microscopy (AFM) image in the inset shows uncapped QDs with a density of $\sim 3 \times 10^{10} \text{ cm}^{-2}$. The degree of linear polarization is defined as $P = (I_{\text{TE}} - I_{\text{TM}}) / (I_{\text{TE}} + I_{\text{TM}})$, where I_{Tx} denotes the PL peak intensities. P is reduced from 0.7 (TE polarization) for the single layer of QDs to 0.15 for the three closely stacked QDs to -0.05 (TM polarization) for the five closely stacked QDs. Hence, the shape anisotropy of the QDs is effectively controlled due to vertical electronic coupling to render the linear polarization of the cleaved-side PL of the QD GS transition from TE over isotropic to TM with the increasing number of

FIG. 2. (Color online) EL and lasing spectra of the deeply etched ridge-waveguide FP laser with five closely stacked QDs for various cw injection currents at RT. The inset shows the L - I curve.

FIG. 3. (Color online) (a) TE and TM polarized EL/ASE spectra at low (20 mA) and high (139 mA) cw injection currents at RT of the FP laser with five closely stacked QDs. The inset shows the FP fringes around $1.55 \mu\text{m}$ with 50 pm resolution at 20 mA. (b) TE, TM, and unpolarized integrated EL intensity as a function of injection current.

QD stacks. The PL peak positions are consistent with the TE polarized PL peak at lower energy for the single and three closely stacked QDs and the TM polarized PL peak at lower energy for the five closely stacked QDs.

Figure 2 shows the EL, lasing spectrum, and light-current (L - I) characteristics of the deeply etched FP ridge-waveguide laser with five closely stacked QD layers as gain medium taken in continuous wave (cw) mode at RT. The PL peak wavelength is at $1.575 \mu\text{m}$. The QD GS EL at wavelengths corresponding the PL saturates around 20 mA. The EL peak wavelength blueshifts with increasing current, revealing enhanced carrier filling of smaller, higher energy QDs and increasing contribution from ES transitions, which becomes dominant at shorter wavelengths above 20 mA. ES lasing occurs at $1.45 \mu\text{m}$ at a threshold current of 140 mA.

Figure 3(a) shows the polarization-dependent EL spectra for low cw current (20 mA—chosen because this is the current for unpolarized gain, see below) and close-to-threshold (139 mA) cw current at RT and Fig. 3(b) shows the integrated TE, TM, and unpolarized integrated EL intensities as a function of current. The intensity modulations apparent in Fig. 3(a) at high current are due to mode competition. For currents considerably below 20 mA, both TE and TM polarized intensities purely originating from QD GS transitions are almost identical, in agreement with the PL measure-

FIG. 4. (Color online) TE and TM polarized net modal gain spectra at RT for various cw injection currents of the FP laser with five closely stacked QDs in the QD GS wavelength range and (inset) ES wavelength range.

ments. Above 20 mA, the TM polarized intensity saturates due to the saturation of the QD GS EL. The TE polarization becomes dominant due to EL from ES transitions, which continues to increase up to the threshold current. Accordingly, the ES lasing is TE polarized. Devices with a single layer of three closely stacked QDs behave similarly with, however, the reduced intensity of TM polarized EL, which is not detectable for devices with a single layer of QDs, consistent with the polarized PL results.

The polarized net modal gain, $G = \Gamma g - \alpha_i$, as a function of wavelength and current is determined from the FP fringes of the device with five closely stacked QD layers¹² shown in the inset of Fig. 3(a) with a spectral resolution of the optical spectrum analyzer of 50 pm. Γg and α_i are the modal gain and internal optical loss. Figure 4 summarizes the net modal gain spectra for various cw currents at RT determined from the RG product using facet reflection coefficients R of 0.33 and 0.27, calculated from the field profiles of the TE and TM optical modes, respectively.¹³ In agreement with the PL and EL measurements, the TM polarized gain from the QD GS transitions dominates below currents of 20 mA. The gain peak wavelength continuously blueshifts with increasing current, as that with the EL peak wavelength, which is again due to preferential carrier filling of smaller, higher energy QDs and an increasing contribution from ES transitions, leading to a relative increase of TE polarized gain. The TM polarized gain bandwidth is wider than the TE polarized one. This suggests a larger influence of QD height fluctuations on the inhomogeneous broadening than that of the fluctuations in width. The maximum TM polarized gain is in agreement with the QD GS modal gain of a single layer of QDs of ~ 5 – 6 cm⁻¹, taking into account $\alpha_i \sim 4$ – 5 cm⁻¹.¹⁴ Above 20 mA, the TM polarized gain saturates, even decreases, and the TE polarized gain dominates, originating from ES tran-

sitions at shorter wavelengths, as shown in the inset of Fig. 4. Near the threshold, the maximum gain of 11 cm⁻¹ corresponds well to the mirror loss of the TE polarized optical mode for the 1-mm-long cavity.

In the present structure, polarization insensitive gain from the QD GS transitions is obtained at around 1.57 μ m for an injection current of 20 mA. This operation window can be widened by increasing the tensile strain in the separation layers together with increasing the QD aspect ratio also giving rise to unpolarized gain for ES transitions.^{9,10} For operation on the QD GS transitions, the only route is to increase the active volume. Increasing the QD density easily leads to lateral electronic coupling, causing TE polarization. Therefore, more closely stacked QD layers need to be inserted to increase the GS modal gain without changing the polarization and wavelength.

In summary, we have studied the linear polarization of optical gain of closely stacked InAs/InP (100) QDs grown by MOVPE with emission in the 1.55 μ m wavelength region. Increasing the number of stacked QD layers to five rotates the linear polarization of the cleaved-side PL and QD GS gain, determined from the ASE of a FP ridge-waveguide laser, from TE to TM due to vertical electronic coupling. When the QD GS ASE and gain saturate with increase of the injection current and ES ASE and gain become dominant, the linear polarization of ASE and gain changes back to TE. This limits the polarization insensitive operation of QD based SOAs, opening, however, routes to novel functionalities such as polarization switching at operation wavelengths between QD GS and ES.

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