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Artificial control of optical gain polarization by stacking quantum dot layers

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Polarization insensitivity of InAs/GaAs quantum dot (QD) optical amplifier has been demonstrated by controlling the dot shape. The height of the QD has been controlled by stacking closely InAs islands to form a columnar QD. Room-temperature polarized amplified spontaneous emission from the columnar QDs has been investigated by using variable stripe-length method. With increasing the aspect ratio, transverse-magnetic-mode-dominant optical gain has been achieved. We obtained almost polarization insensitive optical gain for QDs with seven stacking layers. © 2006 American Institute of Physics. [DOI: 10.1063/1.2206126]

Semiconductor quantum dot (QD) is a promising material for next generation high-speed optical communication devices.^{1,2} The atomlike density of states improves optical performance of semiconductor lasers such as low-threshold lasing, high- T_0 operation, low chirp, and high-speed modulation. In particular, recent development of well controlled high-quality self-assembled QDs contributes to the development of new optical devices such as QD semiconductor optical amplifiers³ (SOAs). Promising features expected for the QD SOA are high-saturation power, high-speed response based on spectral hole burning, and multiwavelength signal processing enabled by inhomogeneous distribution of QD sizes.

For practical applications of such devices, control of the polarization property is a key issue. There are different kinds of techniques to overcome this issue: (1) hybrid system combining two SOAs in diversity configuration,⁴ (2) control of transverse-mode confinement,⁵ and (3) control of optical gain polarization.⁶⁻⁸ In particular, method (3) is the most reliable and useful approach for practical devices. The requirement is very clear: we have to realize polarization independent band edge. For quantum structures such as quantum well (QW) and QD, composition, strain, and size are important and useful parameters to control the band edge. Tuning the quantized state in a QW by a biaxial tensile strain has been demonstrated to show polarization independent band edge.⁶⁻⁸ In contrast to this, we have proposed a method for QD using a stacking-layer growth.⁹ Layer-by-layer stacking of QD succeeds in making columnar QD.¹⁰ We have shown using photoluminescence (PL) measurements a systematic control of the oscillator strength for transverse-electric (TE) and transverse-magnetic (TM) modes in the shape-controlled QDs.⁹ In this letter, polarization insensitivity of InAs/GaAs QD optical amplifier has been investigated. We have

achieved polarization insensitive optical gain in columnar QDs.

Conventional molecular beam epitaxy was used for columnar-QD growth.¹⁰ InAs islands were grown on a GaAs(100 nm)/AlGaAs(50 nm)/GaAs(400 nm) buffer layer on a GaAs(001) substrate. The substrate temperature for buffer layer growth was 620 °C, and 510 °C for InAs island growth. The arsenic pressure used for buffer layer growth was 1.2×10^{-5} Torr, and 6.0×10^{-6} Torr for InAs island growth. After the first InAs island layer was grown, thin GaAs intermediate layers and InAs island layers were overgrown alternately while the surface was monitored by reflection high-energy electron diffraction. In this experiment, the first island layer was grown with an InAs supply corresponding to a nominal 1.8 ML (monolayer). An InAs island layer (0.7 ML) and GaAs intermediate layer (3 ML) were grown alternately on the first InAs island layer. The stacked upper islands were grown on the lower layer islands aligned vertically on the first layer island. The islands on each layer were observed to be in contact with each other in the perpendicular direction, and the stacked island structures, as a whole, were columnar in shape. The height can be precisely controlled by the stacking-layer number (SLN). Figure 1 shows a typical (110) cross-sectional transmission electron microscopy (TEM) image of columnar QDs (SLN=9) and a schematic image of the stacking layers. The diameter of the columnar QDs is about 17 nm, and the height is about 13 nm.

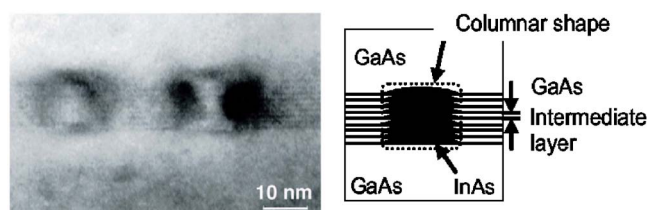


FIG. 1. (110) cross-sectional TEM image of columnar QDs and the schematic image.

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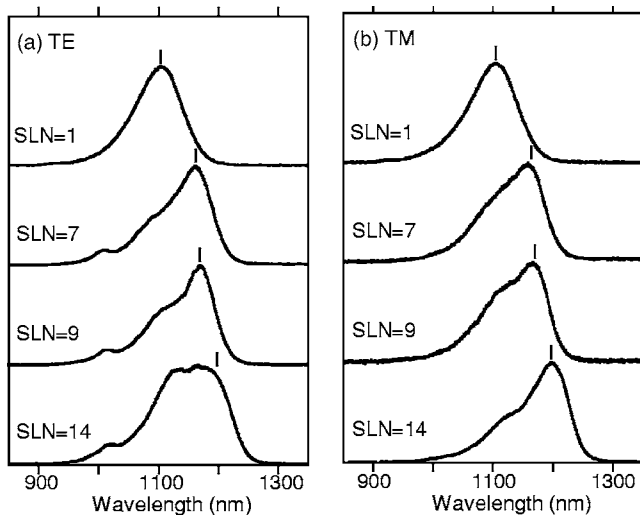


FIG. 2. Polarized edge-emission spectra of columnar QDs with SLN=1, 7, 9, and 14.

The stacked islands were covered with a GaAs(50 nm)/AlGaAs(50 nm)/GaAs(100 nm) cap layer.

The gain and loss measurements were performed for the columnar QDs at room temperature by using the variable stripe-length (VSL) and shifting excitation spot (SES) methods, respectively.^{11,12} The 488 nm line of a cw-Ar-ion laser is used for the excitation. The beam of the excitation laser is focused onto the sample surface by a cylindrical lens. The pump power is 300 W/cm². The stripelike excitation has a width of 10 μ m, and its length is varied continuously up to 500 μ m without changing the excitation power density. After a collective lens, a pinhole is set in order to pick up PL photons traveling inside the stripe. The measured amplified spontaneous emission obeys a relation in the gain region:

$$I \propto \frac{1}{g} [\exp(gl) - 1]. \quad (1)$$

Here g (cm⁻¹) is the net optical gain, and l is the stripe length. On the other hand, the internal loss coefficient α (cm⁻¹) at the peak emission wavelength is measured using the SES method. By moving a slit set close to the sample surface, the relation between edge-emission intensity I and distance l from the edge is given by

$$I \propto \exp(-\alpha l). \quad (2)$$

Polarized PL spectra observed from the cleaved edge are shown in Fig. 2 as a function of the SLN. The peak intensities are normalized. The peak position shifts toward the longer wavelength side with increasing the SLN, because the QD volume is increased with the height. Furthermore, the inhomogeneous broadening tends to decrease with increasing the SLN. As reported in our previous paper,⁹ anisotropy of the PL peak intensity changes dramatically according to the change in the SLN. For the single-island layer sample (SLN=1), the TE-mode PL is dominant. With increasing the SLN, the intensity ratio of the TE-mode PL to the TM-mode PL decreases, and then the TE-/TM-mode PL-intensity ratio is inverted when the SLN is over 9. Finally, the columnar QD with SLN=14 shows obviously TM-dominant PL. Except for the sample with SLN=1, the spectral line shape also shows anisotropy. The ground state s -shell emission wavelengths are indicated by bars for each sample. At high aspect

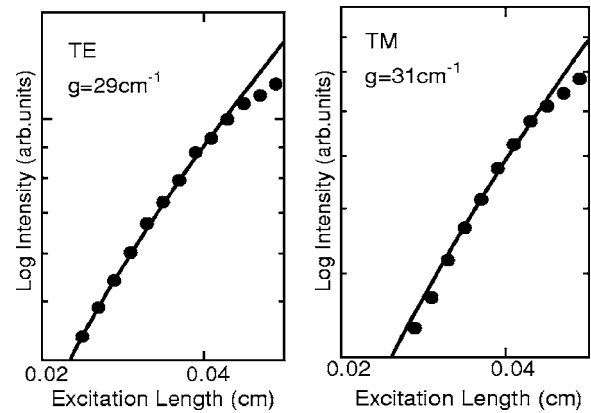


FIG. 3. Amplified spontaneous emission and optical gains for TE and TM modes of columnar QD with SLN=7.

ratios, the TE component of the excited states is found to be enhanced, while the TM component is decreased. That is consistent with polarization properties caused by the mixed valence-band states consisting of heavy-hole (HH) and light-hole (LH) components.¹³ The HH-LH mixing is enhanced with the SLN, because of a reduction in the biaxial strain in the central portion of the columnar QD. Thus, the ground state transition of the columnar QD with a high aspect ratio has a light-hole character, which results in the TM component. In contrast to the ground state, as pointed out theoretically by Saito *et al.*,¹³ the first excited state comes to increase the TE component. Those are characteristic features of the columnar QD.

We performed VSL measurements for these columnar QDs. Figure 3 shows typical results for TE and TM from the SOA structure including columnar QDs with SLN=7, respectively. The ground state peak intensity increases nonlinearly, which indicates amplified spontaneous emission, and then tends to show saturation. The optical gain at the peak wavelength has been analyzed using Eq. (1). The solid lines in Fig. 3 are the best fitted curves over the unsaturated region of the measured intensity. The fitted result gives us a net optical gain. The evaluated gains for the TE and TM modes

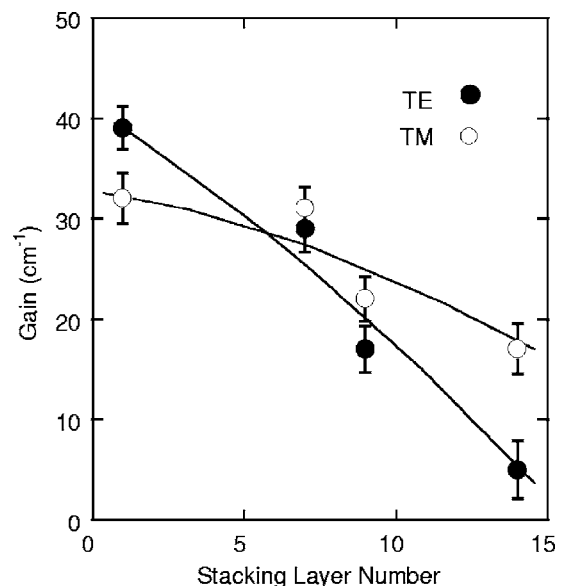


FIG. 4. SLN dependence of polarized optical gain obtained by the VSL method.

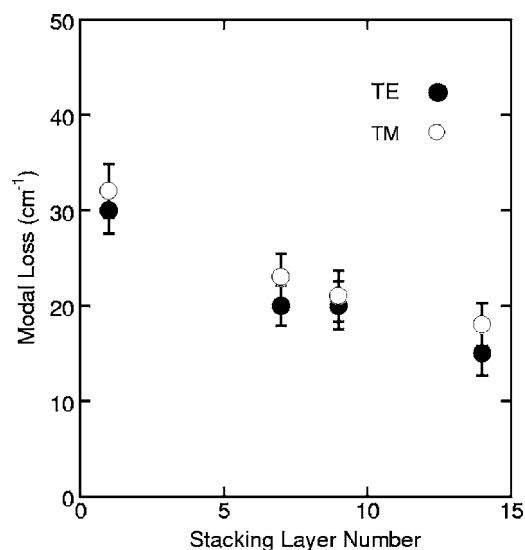


FIG. 5. SLN dependence of polarized optical loss obtained by the SES method.

are 29 and 31 cm^{-1} , respectively. These values are very close and can be regarded to be isotropic. We obtained gains of the other samples using the same method. The SLN dependence of the polarized optical gain is summarized in Fig. 4. The gain curves for the TE and TM modes cross each other near $\text{SLN}=7$. The SLN showing the isotropic gain feature is almost same as the number found for isotropic PL emission.⁹ This correspondence suggests that the relative trend in the SLN dependence of the gain seems to obey the change in the oscillator strength of the columnar QD. On the other hand, both gains monotonically decrease with the SLN. According to the theoretical calculation of the oscillator strength for columnar QDs, the strength is reduced by increasing the SLN, because of special separation of electron and hole wave functions.¹³ The columnar QD with a small SLN strongly confines both electron and hole in a small space, which results in the strong oscillator strength. In the columnar QD with greater SLN, on the other hand, the overlap between the symmetrical *s*-like wave functions of electron and hole wave functions having the *p* character becomes less, and thereby, the oscillator strength becomes weaker.

To confirm the effects of optical absorption on the traveling light, we performed loss measurements using the SES method. This measurement has been done at the same experimental setup as with the VSL method. The results are shown in Fig. 5. The obtained loss is a net modal loss including optical absorption and propagation loss. The modal loss decreases with the SLN in a similar way as the gain in Fig. 4. The loss of the TM component is larger than that of the TE component for all the columnar QDs, which never intersects the TE component curve. The enhanced TM loss can be attributed to the significant loss for the TM light traveling in the active region sandwiched by the cladding layers. Such loss is considered to be independent of the SLN. Therefore, the decreasing characteristics found in the loss result predominantly from the change in the oscillator strength. On the

other hand, the magnitude of loss change is found to be smaller than that for the gain. What does that difference mean? We have to consider contribution of the excited states to the optical gain in columnar QDs with larger SLN. The energy spacing between the ground state and the excited states becomes smaller for larger QDs, which can be confirmed in Fig. 2. The smaller spacing gives rise to populating more carriers efficiently into the excited states under increased excitation. Then, the gain at the ground state is restricted. With increasing the SLN, therefore, the gain is decreased according to both the oscillator strength and the carrier population into the excited states. Since the evaluated optical gain includes effects of optical absorption on the traveling light mentioned above, the isotropic condition ($\text{SLN} \sim 7$) of the net optical gain can be applicable to design polarization insensitive QD-SOA devices.

In summary, polarized optical gain and loss of InAs/GaAs columnar QDs have been investigated as a function of the SLN. The height has been successfully controlled by stacking closely InAs QDs. Polarization insensitivity of the optical amplifier has been demonstrated by controlling the SLN. With increasing the aspect ratio, TM-mode-dominant optical gain has been achieved. We have obtained almost polarization insensitive optical gain for QDs with $\text{SLN}=7$. With increasing the SLN, the oscillator strength is decreased, and contribution of the excited states cannot be ignored for the gain.

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