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Anisotropic Oscillation Properties in Fractional-Superlattice Quantum Wire Lasers

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The step-edge roughening is suppressed during MOCVD growth for a longer period fractional-layer-superlattice (FLS) by a growth interruption under arsine-free condition. As a result, one-dimensional optical properties are first observed in an $(AlAs)_{1/4}(GaAs)_{3/4}$FLS wire with an FLS period longer than 12 nm. Furthermore, strongly anisotropic oscillation properties are measured in FLS quantum wire lasers.

Introduction

The fabrication of quantum wire (QWR) structure using fractional-layer-superlattice (FLS) is characterized by the densely packed and damage-free QWRs. The lateral period of FLS can be controlled by changing the misorientation angle of the substrate. Fukui and Saito succeeded in the MOCVD growth of FLS for the first time[1]. The straight and clearly contrasted lines observed by the plane view of transmission electron microscopy (TEM)[2] indicate that the FLS has a large degree of lateral compositional modulation and also has an atomically flat lateral heterointerface. To obtain a highly ordered QWRs using FLS, we found that the use of short period superlattice (SPS) as a barrier is effective due to the step-ordering on the SPS surface. The FLS QWR sandwiched by SPS has been applied to current injection QWR lasers[3] and QWR microcavity lasers[4], and lasing characteristics reflecting one-dimensional (1D) carrier confinement have been observed. According to the theoretical analysis using multi-band effective mass theory[5], a FLS period longer than 8 nm is needed to strongly confine electrons and holes in the direction of FLS periodicity. This can be achieved by the use of lower misorientation angle substrates than 2 degrees. The increase in the terrace width, however, affects the step-flow growth and the straightness of step-edges is decreased. In this work, we show that such step-edge roughening can be suppressed during the growth of a longer period FLS than 8 nm by the growth interruption under arsine-free condition. As a result, 1D quantum confinement effects were first observed in the photoluminescence excitation (PLE) spectrum of $(AlAs)_{1/4}(GaAs)_{3/4}$ FLS wire with a period of 12 nm, and strongly anisotropic oscillation properties were also measured in the FLS QWR lasers.

Experimental

GaAs/AlGaAs FLS wires were grown by a low-pressure horizontal MOCVD on GaAs (001) vicinal substrate misoriented toward the $[\bar{1}10]$ direction. Triethylaluminum, triethylgallium and arsine were used as source materials. The growth temperature was fixed at 600°C. The FLS QWRs were obtained by sandwiching 12-nm-thick $(AlAs)_{1/4}(GaAs)_{3/4}$ FLS layers with $(AlAs)_1(GaAs)_2$ SPS. By changing the GaAs substrate misorientation angle θ, we fabricated samples with different FLS periods ranging from 8 nm (θ=2 degree) to 16 nm (θ=1 degree).

Results and discussion

The polarization anisotropy observed by the photoluminescence (PL) measurement for FLS reflects the degree of lateral compositional modulation. Both the two-dimensional nucleation on the terrace and the step-edge roughening that occurred during the FLS growth reduce the degree of compositionl modulation and, as a result, the anisotropy in polarized PL decreases. Figure 1 shows the polarization anisotropy observed in PL for 12-nm-thick $(AlAs)_{1/4}(GaAs)_{3/4}$ FLS QWRs sandwiched by $(AlAs)_1(GaAs)_2$ SPS. The polarization anisotropy is defined as $(I_{//}-I_{\perp})/(I_{//}+I_{\perp})$, where $I_{//}$, $I_{\perp}$ are the PL peak intensities for light electric field vector parallel to and perpendicular to the QWR direction. In Fig.1, the polarization anisotropy is plotted against the nominal terrace width determined by the misorientation angle toward $[\bar{1}10]$. Open circles denote the 3s growth interruptions after each $(AlAs)_{1/4}$and $(GaAs)_{3/4}$ fractional layer growths under the arsine partial pressure of 0.5 Torr. The solid circle is under the 0.04 Torr arsine partial pressure. The triangles are under the arsine-free condition. The dashed line (a polarization anisotropy of 0.6) is the calculated result by assuming the equal carrier confinement in the QWR lateral and vertical directions. When the polarization anisotropy is larger than 0.6, the lateral confinement effect is stronger than vertical one. From Fig.1, when the growth is interrupted under 0.5 Torr arsine partial pressure, the polarization anisotropy decreases with the increase in terrace width over 12 nm, indicating a decrease in the lateral compositional modulation. However, the decrease in the arsine partial pressure during the growth interruption recovers the polarization anisotropy, especially in a wide terrace over 12 nm. The effect of growth interruption was larger after $(GaAs)_{3/4}$ fractional layer growth than $(AlAs)_{1/4}$ growth. This recovery in anisotropy is caused by the step-straightening during the growth interruption. Ga or

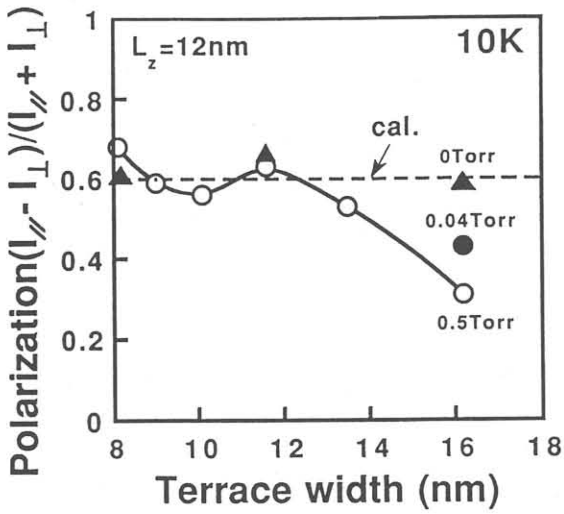

Fig. 1 The polarization anisotropy observed in PL for 12-nm-thick FLS QWRs sandwiched by $(AlAs)_1(GaAs)_2$ SPS at 10 K.

Al atoms adsorbed at rough step-edges detach and incorporate again to smooth the step-edges. This step-straightening is larger for Ga atoms than Al atoms and is also larger under arsine-free condition.

Figure 2 shows a cross-sectional TEM photograph of FLS layer growth on $(AlAs)_1(GaAs)_2$ SPS. The substrate was (001) GaAs misoriented 1 degree toward $[\bar{1}10]$ direction. The clear contrasts between the AlAs (bright region) and GaAs (dark region) were observed to have a 16nm period, which is equal to the mean terrace width on a 1-degree-tilted substrate.

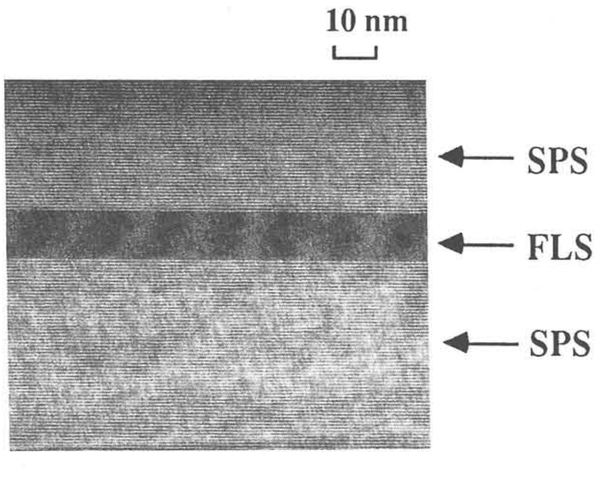

Fig. 2 Cross-sectional TEM photograph of the $(AlAs)_{1/4}(GaAs)_{3/4}$ FLS QWR having 16 nm period (θ=1 degree).
The 12-nm-thick FLS layer is clad by 50-nm thick $(AlAs)_1(GaAs)_2$ SPS.

Figure 3 shows PLE spectra and their polarization dependence measured for (a) a quantum well with $Al_{0.25}Ga_{0.75}As$ well composition, (b) an $(AlAs)_{1/4}(GaAs)_{3/4}$ FLS wire with an FLS period of 8 nm, and (c) an FLS wire with an FLS period of 12 nm. The PLE spectrum for the quantum well is a 2D type, reflecting a staircase-shaped density-of-state, and no polarization dependence is observed. As shown in Fig. 3(b), introducing the FLS compositional modulation in the well results in the appearance of anisotropy in optical absorption near the band edge due to the quantum confinement in the direction to the FLS periodicity.

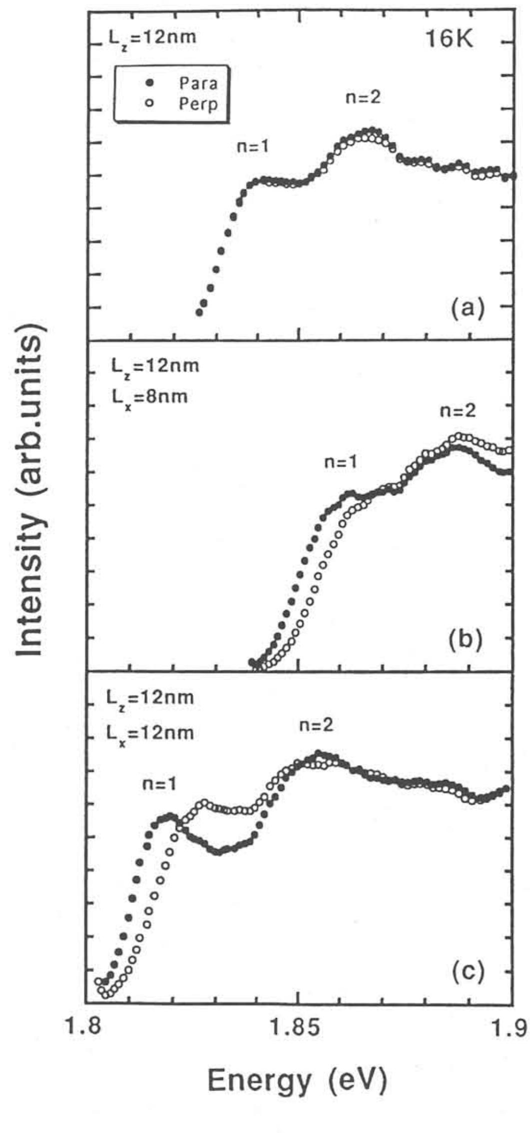

Fig. 3 Photoluminescence excitation spectra measured for (a) a quantum well with $Al_{0.25}Ga_{0.75}As$ well composition, (b) an $(AlAs)_{1/4}(GaAs)_{3/4}$ FLS wire an 8 nm FLS period, and (c) an $(AlAs)_{1/4}(GaAs)_{3/4}$ FLS wire with a 12 nm FLS period. Open and solid circles show the PLE signals for light electric-field-vectors perpendicular to and parallel to the FLS wires, respectively.
(n is index of quantum confinement in the z direction)

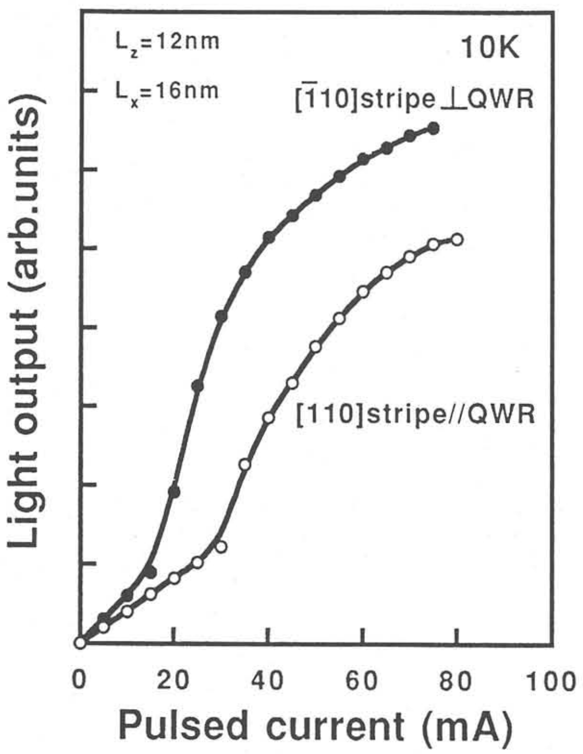

Fig. 4 Oscillation characteristics of current-injection FLS QWR lasers with a16 nm FLS period. Open and solid circles show the results for electrode stripe geometries, parallel to and perpendicular to the FLS wire, respectively.

With increasing FLS period, electrons and holes are more strongly confined in the quantum wires and therefore the optical anisotropy is enhanced. Further, as shown in Fig. 3(c), a peaked PLE spectrum at the band edge (which is a typical feature of 1D quantum confinement) is obtained in the wire with a 12 nm FLS period, reflecting a 1D density-of-state with inverse-square-root shape.

Figure 4 shows oscillation characteristics of current-injection FLS QWR lasers measured at 10 K, for two different stripe geometries: perpendicular ([$\bar{1}$10]) and parallel ([110]) to the direction of quantum-wire array. We found that for the perpendicular geometry, the laser oscillation threshold is lower than that for the parallel geometry, and the oscillation wavelength is longer. The threshold currents were 15 mA (110 A/cm^2) in the [$\bar{1}$10] direction and 30 mA (210 A/cm^2) in the [110] direction.These results are consistent with the results of PLE measurements. In the present wire lasers with a 16 nm FLS period, the anisotropy in the laser oscillation properties is obviously greater than that in the previously reported lasers with an 8 nm FLS period, and the threshold current is lower. This improvement in laser oscillation properties can be attributed to 1D quantum confinement in the wire with the longer FLS period.

Conclusions

The step-edge roughening was suppressed during MOCVD growth for longer period FLS by a growth interruption under arsine-free condition. As a result, 1D quantum confinement effects were first observed in the $(AlAs)_{1/4}(GaAs)_{3/4}$ FLS wire with an FLS period of 12 nm. Furthermore, strongly anisotropic oscillation properties were measured in the FLS QWR lasers.

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