

# Growth of strain-compensated InGaAs/GaAsP multiple quantum wells by MOVPE

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Received July 17, 2002

InGaAs/GaAsP strain-compensated multiple quantum wells (SCMQWs) and strained InGaAs/GaAs multiple quantum wells (MQWs) were grown on GaAs substrates by metal organic vapor phase epitaxy (MOVPE). The results of double crystal X-ray diffraction (DCXRD) revealed that strain relief had been partly accommodated by the misfit dislocation formation in the strained MQW material. It led to that the full width half maximums (FWHMs) of superlattice satellite peaks are broader than those of SCMQW structures, and there was no detectable room temperature photoluminescence (RT-PL) for the strained MQW structures. With the increasing of the P/As ratio, the separation angle between the substrate peak and the zeroth order peak of SCMQW decreased. The FWHMs of both the zeroth order satellite and RT-PL of SCMQW structures also decreased, whereas the intensity of RT-PL increased. This indicated that the quality of epitaxial layers was improved with the increasing of the strain compensation.

OCIS codes: 160.6000, 160.4760.

Strain-layer quantum well structures have been widely used for optoelectronic devices<sup>[1-4]</sup>. In particular, quantum well laser diodes emitting at wavelength of 0.98 and 1.5  $\mu\text{m}$  have exhibited excellent characteristics when their quantum wells are under lattice strain<sup>[5]</sup>. As the number of strained quantum wells is increased, the total strain-layer thickness approaches a critical layer thickness at which lattice misfit dislocations start to form. For many devices, such as infrared light emitting diodes (LED), short-cavity lasers, distributed Bragg reflector lasers, and optical modulators, a large number of quantum wells are required for optimal performance. Therefore, there has been interest in SCMQW structures where the barrier layers are under tensile strain and quantum wells are under compressive strain<sup>[6-9]</sup>. By doing so, lattice expansion in the barriers can be balanced by lattice contraction in the wells and the combined cycle grows at the GaAs lattice constant. Crystal growth proceeding by this strategy has been coined as *pseudomorphic*<sup>[10]</sup>.

In this letter, we report the growth of SCMQW  $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}_{1-y}\text{P}_y$  by MOVPE. To compare with SCMQW, strained MQW InGaAs/GaAs was also grown. The structural and optical characteristics of SCMQW InGaAs/GaAsP and strained MQW InGaAs/GaAs were investigated by using DCXRD and RT-PL.

The epitaxial layers were grown in a horizontal low-pressure (70 Torr) MOVPE (EMCORE D180) system at temperature 600 °C on Si-doping (001) toward (111) direction 15° GaAs substrates. Precursors were hydrogen phosphide ( $\text{PH}_3$ ), hydrogen arsenide ( $\text{AsH}_3$ ), trimethyl compounds of gallium (TMGa), indium (TMIn) and aluminum (TMAI). The growth rate was near 0.4 nm/s, and the V/III flux ratio of 2 was employed. Figure 1 shows the band diagram of MQW structures consisting of 10 periods in our experiment. Each cycle consisted of a 6-nm well of  $\text{In}_{0.16}\text{Ga}_{0.84}\text{As}$ , and an 8-nm barrier consisted of  $\text{GaAs}_{1-y}\text{P}_y$ . And the cap layer of a 50-nm thick GaAs was grown on the superlattice. Three sam-

ples grown in our experiment (a, b and c) corresponded to  $y = 0.15, 0.09$  and  $0.00$ , respectively. Our estimation for the  $y$  value was based on the pressure during hydride gas flow. For samples a and b, the mole flux ratios of P to As were designed as 5 and 4, respectively. The rocking curve of DCXRD (Philips RD-100) was applied to investigate the characteristics of SCMQW and strained MQW, and the PL spectrum was also measured at room temperature by Philips PLM-100 system.

The lattice constant of strained MQWs can be expressed as

$$d = \frac{T_1 d_1 + T_2 d_2}{T_1 + T_2}, \quad (1)$$

where  $T_1$  and  $T_2$  are the widths of the wells and the barriers,  $d_1$  and  $d_2$  are the lattice constants of the well layers and barrier layers, respectively. From the Bragg law,  $2d \sin \theta = n\lambda$ , the formula can be defined as

$$\frac{\Delta d}{d} = -\frac{\Delta \theta}{\tan \theta}, \quad (2)$$

where  $d$  and  $\theta$  are the lattice constant and the diffraction angle of GaAs (004), respectively. The lattice

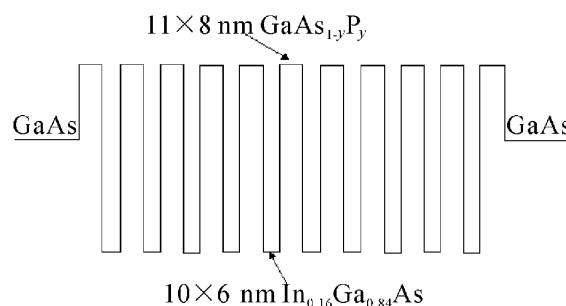


Fig. 1. The band diagram of MQW structures consisting of ten periods of 6-nm thick  $\text{In}_{0.16}\text{Ga}_{0.84}\text{As}$  quantum wells sandwiched between 8-nm thick  $\text{GaAs}_{1-y}\text{P}_y$  barriers.

mismatches between MQW and substrate GaAs in samples a, b and c were calculated to be 0.3%, 0.4% and 1.32%, respectively.

Using DCXRD, we examined the chemical and structural integrity of superlattice formation in these MQW layers. Figure 2 shows the DCXRD results of the three strained MQW structures. The sharp peak in each curve was the (004) Bragg reflection from the GaAs substrate. Each curve showed additional diffraction structures that arose from superlattice formation. The zeroth order and satellite peaks of the superlattice reflection have been marked in each curve. This zeroth-order feature corresponded to the geometric average of the strain in the superlattice. For the nonpseudomorphic structure shown in Fig. 2(c), the zeroth-order superlattice position occurred on the In-rich side of the substrate and displaced by 1200 arc sec. According to Eq. (2), this corresponded to an effective lattice misfit parameter of 1.4% for the well or an In mole fraction of 0.16. From the rocking curve of DCXRD shown in Fig. 2(c), we concluded that strain relief had been partly accommodated by misfit dislocation formation. This information was established by the characteristic of the roll off in FWHM of the satellite line with order and the rapid decay of satellite intensity with order. The FWHM of the superlattice reflections shown in Fig. 2(c) was 350 arc sec, which corresponded to the grains of particle size of 170 nm. It indicated that the heteroepitaxial material itself had been transitioned to a 3-D growth mode and broken up laterally into incoherently diffracting grains. The rapid loss of higher order than the first order superlattice satellite intensity in Fig. 2(c) could indicate the diffusion or surface segregation at the heterointerface.

The diffraction of SCMQR structures showed distinct differences. First, the position of the zeroth order was displaced by only 600 arc sec in Fig. 2(b) and 400 arc sec in Fig. 2(a) from the substrate GaAs peak, respectively. This indicated that partial strain balanced growth had occurred. But it had not reached the zero-net strain. It was also indicated that the strain balance became better with the increasing of the mole flux ratio of P to As. This was also proved by the PL spectra at the room temperature. According to Eqs. (1) and (2),

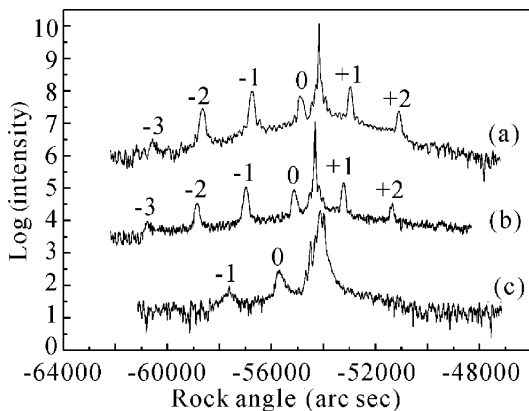


Fig. 2. The rocking curves of SCMQR (a and b) and strained MQW (c) measured by DCXRD. (a) SCMQR  $\text{In}_{0.16}\text{Ga}_{0.84}\text{As}/\text{GaAs}_{0.85}\text{P}_{0.15}$ , (b) SCMQR  $\text{In}_{0.16}\text{Ga}_{0.84}\text{As}/\text{GaAs}_{0.91}\text{P}_{0.09}$ , and (c) strained MQW  $\text{In}_{0.16}\text{Ga}_{0.84}\text{As}/\text{GaAs}$ .

the lattice mismatches of samples a and b between SCMQR and the GaAs substrate were calculated to be 0.3% and 0.4%, respectively. Second, the FWHMs of the zeroth order peak for samples a and b were 140 and 160 arc sec, respectively. The roll-off characteristics of pseudomorphic satellites did not reveal inhomogeneity and strain relief characteristics. Third, the complete decay of satellite intensity occurred to the fourth order peak for samples a and b. Such rapid decay could be attributed to compositional or strain intermixing in SCMQR structures. The heteroepitaxy on different compounds had found the evidence<sup>[10,11]</sup>. From the rocking curves of SCMQR structures, the separation of the zeroth order from the substrate peak decreased with the increasing of the mole flux ratio of P to As. So the mole flux ratio of P to As should increase further to reach the zero-net strain in the active layer of SCMQR structures.

Figure 3 shows the RT-PL of the MQW structures a and b. The excitation source was a frequency-doubled YAG laser operating at 532 nm and the emission was measured with a Si detector. The In-based MQW structure of sample c with no phosphorus content in the barrier produced no detectable RT-PL with the same excitation intensity as samples a and b. By contrast, good RT-PL characteristics were observed for the two samples of SCMQR structures. The RT-PL peaks of samples a and b were measured to be 928 and 930 nm, respectively. The FWHMs of the emission profiles at room temperature were 25 meV for sample a and 29 meV for sample b, respectively. The shorter-wavelength peak observed in the Fig. 3 at about 860 nm corresponds to that of the GaAs substrate. Under the same excitation conditions, the emission intensity of sample a is higher than that of sample b. It was also indicated that the quality of epitaxial layers for sample a is better than that for sample b.

In summary, two samples of SCMQR InGaAs/GaAsP structures were grown by MOVPE to investigate the strain compensated effect in the active layer. For the comparison, the strained MQW InGaAs/GaAs structure was also grown with the same composition in the wells but no phosphorus content in the barriers. The results of DCXRD revealed that the strain relief had been partly accommodated by the misfit dislocation formation in the strained MQW material. It led to that the FWHMs

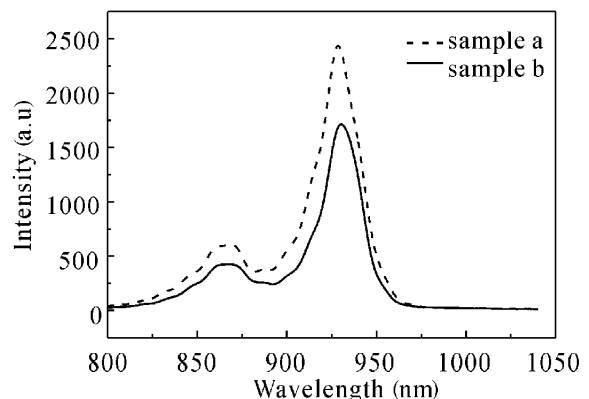


Fig. 3. PL Spectra at room temperature of two SCMQR samples.

of superlattice satellite peaks are broader than those of SCMQW structures and there is no detectable RT-PL for the strained MQW structures. For SCMQW structures, with the increasing of the mole flux ratio of P to As, the separation angle between the substrate peak and the zeroth order peak decreased. The FWHMs of both the zeroth order satellite and RT-PL decreased, whereas the intensity of RT-PL also increased. This indicated that the quality of epitaxial layers was improved with the increasing of the strain compensation.

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