Substrate Misorientation Effect on Self-Organization of Quantum-Wires in (GaP)m/(InP)m Short Period Binary Superlattices

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GaInP/AlInP multi-quantum-wire lasers with $(GaP)_m/(InP)_m$ short period binary superlattices active layers were grown on misoriented (100)-GaAs substrates toward [011] direction. The substrate misorientation angle (SMA) reflected self-organization. A strong red-shift in photoluminescence peak wavelength and a large difference in lasing wavelength were observed at SMA of 5°. These results indicated an enhancement of self-organization of quantum-wires by substrate misorientation since an anisotropic adatom diffusion was dominantly along $[01\overline{1}]$ directions by the existence of step fronts paralleled to this direction.

I. Introduction

Quantum-wire (QWR) and quantum-dot (QD) lasers are expected to overcome the lasing properties of quantum-film (QF) lasers. In these structures the reduction in state density is induced by multi-dimensional quantum-size effects, leading to narrower optical gain and to higher differential gain. Through these effects, an extremely low threshold current density [1] and characteristics' temperature $(T_0)[2]$ is theoretically predicted. Moreover, it can be expected that strained QWR lasers can provide further improvement in lasing performances[3] due to strain effect.

Recently, in fabrication of QWR and QD laser structures, self-organization schemes during crystal growth have been employed[4][5]. Among them, the strain induced lateral layer ordering process in $(GaP)_m/(InP)_m$ short period binary superlattice (SPBS) active layers [6] are very effective to fabricate GaInP/AIInP compressively strained multi-quantum wire (CS-MQWR) lasers [4] by a gas source molecular beam epitaxy (GS-MBE).

In this study, substrate misorientation effect on selforganization of quantum-wires in (GaP)m/(InP)m SPBS was systematically investigated for understanding of detailed mechanism and controllability of the configuration of quantum-wires. GaInP/AlInP CS-MQWR laser wafers with SPBS active layers were grown on intentionally misoriented (100)-GaAs substrates toward [011] direction. As a result, self-organization was largely depended on substrate misorientation angle (SMA). A strong red-shift in photoluminescence (PL) peak wavelength and a large difference in lasing wavelength was observed at SMA of 5°. These results indicated an enhanced self-organization of QWRs by substrate misorientation, since an anisotropic adatom diffusion was dominantly along $[01\overline{1}]$ directions because of existence of step fronts paralleled to this direction. While, very weak red-shift in PL peak wavelength and no difference in lasing wavelength were observed at large SMA of 15°

suggesting formation of GaInP quantum-film structure.

II. Fabrication & Laser Structure

In the GS-MBE system, molecular beams of the group III materials (i.e., Al, Ga, In) were supplied as conventional solid sources, while the group V phosphorous beam was obtained through the gas cracking cell using the 100 % pure PH₃ gas[7]. The n- and p- type dopants were Si and Be, respectively. The growth temperature was maintained at 490-510 °C and the growth rate for GaInP bulk crystal was 0.86 μ m/h.

To investigate substrate misorientation effect on



Fig.1 A schematic diagram of GaInP/AlInP CS-MQWR lasers with 18 periods (GaP)_m/(InP)_m SPBS active layers

self-organization of QWRs in $(GaP)_m/(InP)_m$ SPBSs, three types of misoriented (100) GaAs substrates with SMA of 0°, 5°, 15° toward [011] direction were used.

Figure 1 shows a schematic diagram for the investigated lasers, in which 6well MQW active layers consisted of the 18 period (GaP)m/(InP)m short period binary superlattice (SPBS) wells and (GaInP)3/(AlInP)2 superlattice barriers (5nm). The m value was changed from 0.5 ML to 2.0ML (thus, the thickness of well regions was changed). Active regions were sandwiched between (GaInP)₃/(AIInP)₂ short period superlattice cladding (SLC) layers. In the growth of lasers, first n-GaAs (70nm) and n-GaInP (10nm) buffer layers were grown on Si-doped substrates, followed by the sequential growth of CS-MQWR laser layers in the following order: n-AlInP cladding layer (0.7µm), undoped SLC layer (80nm), undoped GaInP CS-MQWR active layers, undoped SLC layer (80nm), p-AlInP cladding layer (0.7µm), p+-GaInP cap layer (280nm).

III. Results and Discussions

PL spectra from SPBSs were measured at room temperature. Figure 2 shows a PL spectrum of $(GaP)_{1,2}/(InP)_{1,2}$ SPBS layer at SMA of 5°. Two peaks were observed, emitting at around 717 nm and 666 nm. The longer one corresponded to the electron-heavy hole emission and the other electron-light hole one, respectively. While at SMA of 0° and 15°, only single peak was observed.



Fig. 2 PL spectrum of (GaP)_{1.2}/(InP)_{1.2} SPBS active layers of GaInP/AlInP CS-MQWR lasers grown on misoriented (100) GaAs substrate at substrate misorientation angle (SMA) of 5°

For further discussion about above results, PL peak wavelengths of $(GaP)_{1,2}/(InP)_{1,2}$ SPBSs layers are shown in Fig.3 as a function of SMA. We note that at SMA of 5°, longer one among two peaks was plotted. PL peak

wavelengths were affected by the compositional modulation in the SPBS induced by the self-organization of QWRs[4]. The PL peak wavelengths were strongly dependent on SMA values comparing with those of GaInP bulk case (shown by squares in Fig.3). At SMA of 0° a slight red-shift was observed, indicating that a weak compositional modulation occurred in SPBS layers. However, QWRs' self-organization was confirmed from TEM images. While, at SMA of 5° the strong red-shift was observed, indicating that the compositional modulation was enhanced by substrate misorientation. Thus, self-organization of QWRs might occur.



(GaP)_{1.2}/(InP)_{1.2} SPBS active layers of GaInP/AlInP CS-MQWR lasers

The self-organization of QWRs might relate to two factors. One was that an adatom diffusion was dominantly along $[01\overline{1}]$ direction[8] due to the existence of dimer and missing dimer rows. The other was segregation of first GaP layer due to a large strain energy induced by a large lattice mismatch to the bottom SLC layer. Since there were step fronts paralleled to $[01\overline{1}]$ direction at SMA of 5°, an anisotropic adatom diffusion and segregation of GaP might be enhanced. On the contrary, at SMA of 15°, PL peak wavelength was blue-shifted and came back to the bulk one. This result indicated the compositional modulation was suppressed, probably due to small step widths.

Figure 4 shows the dependence of PL peak wavelength of $(GaP)_m/(InP)_m$ SPBS on monolayer number m, for three SMA cases (0°, 5° and 15°). Here note that the well thickness was changed with m, as the superlattice period was fixed at 18. At SMA of 0° (see closed circles), for m values below 1ML, the PL peak wavelength became shorter than GaInP bulk levels (indicated by solid lines for 0° and 15°) due to the quantum-size effect, and for m values over 1ML, abruptly

lengthened beyond those indicating the produced lateral compositional modulation. On the other hand, at SMA of 5° , a strong red-shift in PL peak wavelength was observed at m values around 1ML, i.e. the compositional modulation was strongly enhanced even for small m values, showing the substrate misorientation effect. While, for a large SMA value of 15°, the strong red-shift like that was not observed. In this case, $(GaP)_m/(InP)_m$ SPBS wells were disordered forming GaInP quantum-film structure.



Monolayer Number m (ML) Fig. 4 Monolayer number dependency of PL peak wavelength of (GaP)_m/(InP)_m SPBS active layers of GaInP/AlInP MQWR lasers



Fig. 5 SMA dependency of lasing wavelength of GaInP/AlInP CS-MQWR lasers with (GaP)_{1,2}/(InP)_{1,2} SPBS active layers

Figure 5 shows SMA dependencies of lasing wavelength for GaInP/AIInP CS-MQWR lasers with $(GaP)_{1,2}/(InP)_{1,2}$ SPBSs. Two types of 50 μ m mesa-

stripe lasers were fabricated, of which stripe axes were formed along [011] and $[01\overline{1}]$ directions. Difference in lasing wavelength between the [011] and $[01\overline{1}]$ stripes lasers, which showed an anisotropic behavior reflecting the compositional modulation [4], was maximized at SMA of 5°. At SMA of 15°, however, no difference was observed, and crystal disordering was produced for such a large substrate misorientation.

IV. Summary

GaInP/AlInP MQWR lasers with $(GaP)_m/(InP)_m$ SPBS active layers were grown on misoriented substrates A strong red-shift in photoluminescence peak wavelength and a large difference in lasing wavelength were observed at SMA of 5°. These results indicated an enhanced selforganization of QWRs by substrate misorientation, since an anisotropic adatom diffusion was dominantly along $[01\overline{1}]$ directions by the existence of step fronts paralleled to this direction. While, very weak red-shift in PL peak wavelength and no difference in lasing wavelength were observed at large SMA of 15°, forming GaInP quantumfilms.

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