InP-based InGaAs/InAlGaAs digital alloy quantum well laser structure at 2 μm*

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The structural and optical characteristics of InP-based compressively strained InGaAs quantum wells have been significantly improved by using gas source molecular beam epitaxy grown InAs/$In_{0.53}Ga_{0.47}As$ digital alloy triangular well layers and tensile $In_{0.53}Ga_{0.47}As$/InAlGaAs digital alloy barrier layers. The x-ray diffraction and transmission electron microscope characterisations indicate that the digital alloy structures present favourable lattice quality. Photoluminescence (PL) and electroluminescence (EL) measurements show that the use of digital alloy barriers offers better optical characteristics than that of conventional random alloy barriers. A significantly improved PL signal of around 2.1 μm at 300 K and an EL signal of around 1.95 μm at 100 K have been obtained.

Keywords: InP-based, digital alloy, lasers, strained materials
PACC: 7340L, 7865K, 6855, 4255P

1. Introduction

Semiconductor lasers with emission wavelength around 2 μm have aroused growing interest mainly due to their applications in spectroscopy and medicine.[1,2] Traditionally such semiconductor lasers are developed in InGaAsSb/AlGaAsSb material system on GaSb substrate.[3−5] $In_xGa_{1-x}As/In_{0.53}Ga_{0.47}As$ ($x > 0.53$) quantum well (QW) structures on InP substrate is an alternative approach in this spectral range. It is promising to achieve superior performances owing to the superior quality of InP substrate as well as the more mature growth and processing technology of InP-based materials as compared to GaSb.[6] The emission wavelength can be tailored by the In composition of InGaAs QWs, whereas it is really a challenge to extend the wavelength to longer than 2.1 μm due to the significant strain.[7−9]

Our former simulations have shown that the emission wavelength can be increased by using triangular QW instead of rectangular one while keeping the same strain content, in the well layer the In concentration varies linearly from 0.53 up to 1 and then down to 0.53 again. It is also beneficial to use tensile InAlGaAs barriers to compensate the extremely compressive strain in the QWs.[10] Furthermore, during experiments the $In_{0.53}Ga_{0.47}As$/InAs digital alloy (DA) was grown by gas source molecular beam epitaxy (GSMBE) to approximate the triangular shape of QWs, and the growth processes have been improved up to better performance.[11,12] DA technology is a novel growth process for multiple compound alloys by growing several short period superlattices, where the growth thicknesses or the growth time of individual layers are digitally controlled and usually MBE is used.[13] DA has been adopted to improve the composition control during the growth,[14] grow alloys in the miscibility gap[15] or improve the interface quality of heterostructures.[16] In this work, InAlGaAs barriers are also performed by adopting DA technology besides the triangular QWs for the further improvement of the structures. The structural and optical characteristics of the QW and laser structures are analysed in detail and compared with those of the structures using InAlGaAs conventional random alloy barriers. The use of DA barrier layers is proved beneficial to the improvement of the optical characteristics of QW laser structures.

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2. Experiments

The samples were grown on InP (100) epi-ready substrates with a VG Semicon V80H GSMBE system. The elemental Ga and Al standard effusion cells as well as In thermo-cell with two heat zones were used as group III sources. Their fluxes were calibrated prior to growth and controlled by changing the cell temperatures during growth. Arsine (AsH_3) and phosphine (PH_3) were cracked to form As_2 and P_2 at 1000 °C and used as the group V sources, and their fluxes were controlled by adjusting the pressure. Standard Be and Si effusion cells were used as p- and n- doping sources, and the doping level was also controlled by changing the cell temperatures.

At first, two triangular QW structures with different types of barriers were grown after determining the growth parameters by growing lattice matched $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ single layers at the same In flux. The growth rates for $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ were both controlled to around 1 μm/h. During the growth of triangular QW samples, In, Ga, and Al fluxes were all kept unchanged. The growth of samples started with a 200 nm InP buffer layer, followed by two periods of symmetrical InGaAs/InAlGaAs triangular QWs, and finally a 100 nm InP capping layer. The well layers of the two QW structures are the same of 9 nm $In_xGa_{1-x}As$ triangular well layers, which were approximated by using $InAs/In_{0.53}Ga_{0.47}As$ short period chirped superlattices. The thicknesses of $In_{0.53}Ga_{0.47}As$ (d_1) and InAs (d_2) in a short period is obtained from the following equation:

$$\begin{cases} \dfrac{d_1 \times 0.53 + d_2}{d} = x, \\ d_1 + d_2 = d, \end{cases} \tag{1}$$

with x being the expected average of In content within each short period, and d the thickness of the short period, which was set to around 1 nm. The barrier of structure 1 was 9 nm InAlGaAs random alloy obtained by opening the shutters of In, Al and Ga cells simultaneously during the growth. The barrier of structure 2 was 9 nm InAlGaAs DA obtained by nine repeats of $In_{0.53}Ga_{0.47}As$/InAlGaAs short periods. In each short period, the thicknesses of $In_{0.53}Ga_{0.47}As$ and InAlGaAs were 0.6 nm and 0.4 nm, respectively. DA technology is a very convenient method from the MBE growth point of view. The whole growth process of QW structures can be easily controlled by only opening and closing the In shutter during the growth of well layers, while opening and closing the Al shutter during the growth of barrier layers as shown in Fig. 1.

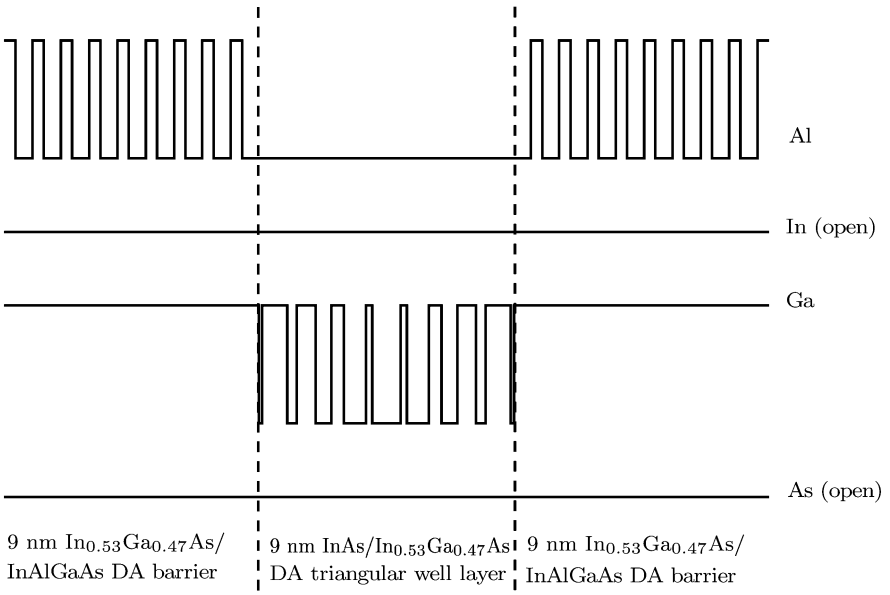


Fig. 1. Schematic of shutter opening sequence during the GSMBE growth of DA QW structures.

The fluxes of sources remain unaltered and no temperature increase or decrease of the sources is needed, hence without any growth interruption during the growth. Two laser structures were then grown using QW Structures 1 and 2 as the active regions, respectively. The layer parameters of the laser structures are listed in Table 1. The growth sequence started with growing Si-doped n-type InP lower cladding and waveguide layers, followed by an active region containing two periods of $In_{0.53}Ga_{0.47}As$/InAlGaAs triangular QWs. The barrier layers of the two laser structures are composed of InAlGaAs random and digital alloy structures, respectively. Then Be-doped p-type InP upper waveguide layer, $In_{0.53}Ga_{0.47}As$ etch stop layer, InP cladding layer were grown in sequence. The growth was finished by a highly Be-doped $In_{0.53}Ga_{0.47}As$ contact layer.

Table 1. Layer parameters of the QW laser structures.

layer	material	thickness/nm	carrier concentration/cm^{-3}
contact layer	$In_{0.53}Ga_{0.47}As$: Be	300	$p = 1\times10^{19}$
cladding layer	InP: Be	1200	$p = 1\times10^{19}$
cladding layer	InP: Be	500	$p = 5\times10^{18}$
Etch stop layer	$In_{0.53}Ga_{0.47}As$: Be	100	$p = 5\times10^{18}$
waveguide layer	InP: Be	150	$p = 5\times10^{17}$
barrier	InAlGaAs random alloy or $In_{0.53}Ga_{0.47}As$/InAlGaAs DA	9	undoped
triangular well	InAs/$In_{0.53}Ga_{0.47}As$ DA	9	undoped
barrier	InAlGaAs random alloy or $In_{0.53}Ga_{0.47}As$/InAlGaAs DA	18	undoped
triangular well	InAs/$In_{0.53}Ga_{0.47}As$ DA	9	undoped
barrier	$In_{0.53}Ga_{0.47}As$/InAlGaAs DA	9	undoped
waveguide layer	InP: Si	100	$n = 5\times10^{17}$
cladding layer	InP: Si	900	$n = 2\times10^{18}$
substrate	InP: S	350 μm	$n = 2\times10^{17}$

After growth, the structural properties of the QW and laser structures were characterized by using high resolution x-ray diffraction (HRXRD) and transmission electron microscopy (TEM) measurements. A Philips X'pert x-ray diffractometer equipped with a four-crystal Ge (220) monochromator was used for the HRXRD measurements. Cross-sectional samples were prepared for TEM by ion polishing and examined by using a Philips CM200 FEG microscope operating at 160 kV. The optical properties were characterised by photoluminescence (PL) and electroluminescence (EL) measurements, which were both performed on a Nicolet 860 Fourier transform infrared (FTIR) spectrometer with liquid-nitrogen cooled InSb detector and CaF_2 beam splitter. The samples were mounted in a continuous-flow helium cryostat to change temperature. For PL characterisation, a Coherent INNOVA 305 argon-ion laser (514.5 nm) was used as excitation source. Ridge waveguide structures with strip width of 8 μm were fabricated for EL characterisation by standard lithography and deep wet chemical etching processing. A 200 nm-thick SiN layer was deposited by plasma enhanced chemical vapour deposition (PECVD) as insulator. After that, a 4 μm-wide window was patterned on top of the ridge. Ti/Pt/Au was sputtered as a top metallic contact, then the samples were thinned to 100–120 μm and GeAuNiAu was evaporated on the back of the substrate as a back contact. The chips were cleaved in 0.5 mm long bars with the facet uncoated, soldered on copper heat sinks and wire bonded for EL measurements.

3. Results and discussion

The measured HRXRD $\omega/2\theta$ (004) rocking curves of QW structures 1 and 2 are shown in Fig. 2. The signal envelops on the left and right sides of the substrate peaks are related to compressive InAs/InGaAs DA wells and tensile InAlGaAs barriers, respectively. It can be seen that the barrier signal envelope of structure 2 moves closer to the substrate peak as compared with structure 1, which is due to the smaller lattice mismatch between barrier layer and InP substrate in structure 2 than in structure 1. The residual compressive strain in structure 2 is lager than in structure 1. However, the satellite peaks of structure 2 are as dis-

tinct as that of structure 1. This means that the QW structure 1 with DA barrier still has good material quality although there exists a larger residual strain. The result indicates that DA structures are beneficial for the quality improvement of strained QWs. A possible explanation for the benefits of DA technology is

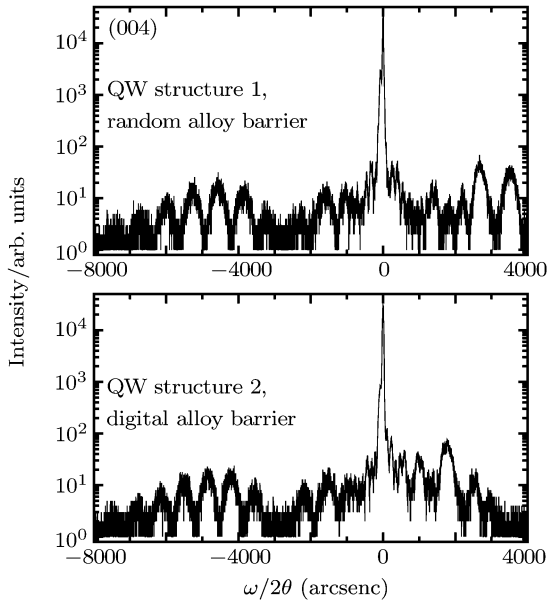


Fig. 2. HRXRD rocking curves of the two QW structures with different barrier layers.

that the multi-interfaces of DA structures help to suppress the lattice relaxation of the lattice-mismatched heterostructures.

The cross-sectional TEM image of the whole laser epitaxy structure is shown in Fig. 3. It can be seen that the laser structure has distinct heterostructure interfaces, and there are no visible threadings or misfit dislocations in the structure, indicating the laser structure has very few dislocations. In the amplified image of the InAs/$In_{0.53}Ga_{0.47}As$ DA QW region as shown in Fig. 3(b), atomic layers can be observed clearly. The thicknesses of the atomic layers lie around 0.29–0.31 nm, which are consistent with the thickness of an InGaAs monolayer. The variations of atomic layer thickness in InGaAs triangular QW for different In contents are not observed clearly owing to the resolution limit of the TEM system. In the figure, the superlattices grown with digital grading thicknesses in each short period are not seen. This means that DA materials have been intermixed as expected, and the DA materials show good pseudomorphic growth. Therefore, the advantages of DA technology include not only the convenience of controlling the composition by adjusting the shuttering times, but also of filtering threading dislocations. The former feature is particularly suitable to perform non-rectangular QW and the latter feature can provide high-quality strained materials.

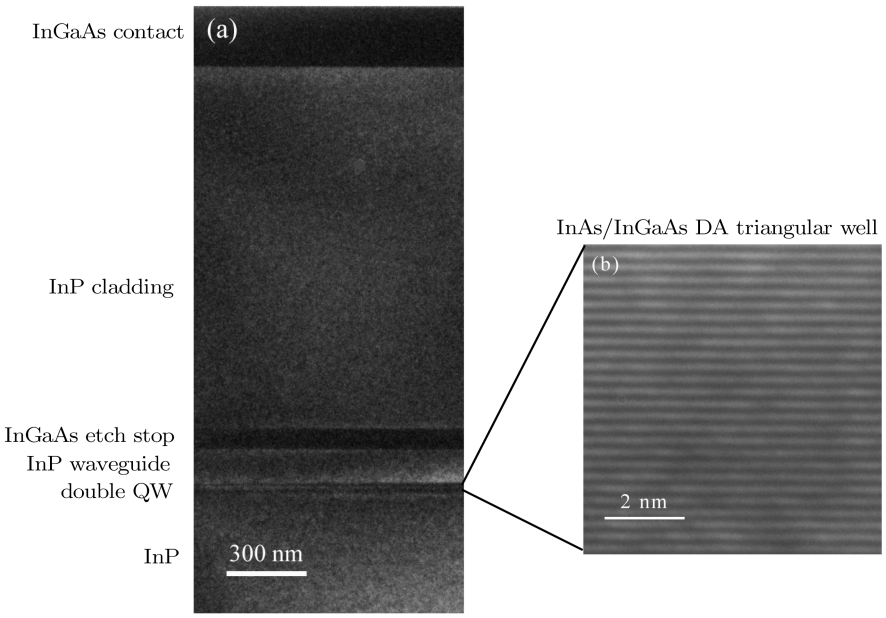


Fig. 3. Cross-sectional TEM images of the whole laser epitaxy structure and the InAs/$In_{0.53}Ga_{0.47}As$ DA triangular well.

The PL spectra of the two QW structures at 300 and 100 K are shown in Figs. 4(a) and 4(b). It can be seen that structure 2 shows much better PL characteristics than structure 1. The PL intensity of structure 2 is more than twenty times higher than that of structure 1 at 300 K and about seven times at 100 K in the same measurement conditions, which is due to the benefits of DA barriers. DA structures improve the pseudomorphic growth due to the suppression of the lattice relaxation in lattice-mismatched material systems. Accordingly, the optical characteristics of structure 2 are significantly improved. It can also be observed that the PL peak red-shifts from 2.06 μm for QW structure 1 to 2.13 μm for structure 2 at 300 K, and from 1.93 to 1.95 μm at 100 K. This red-shift is caused by the smaller bandgap of InAlGaAs barrier in QW structure 2.

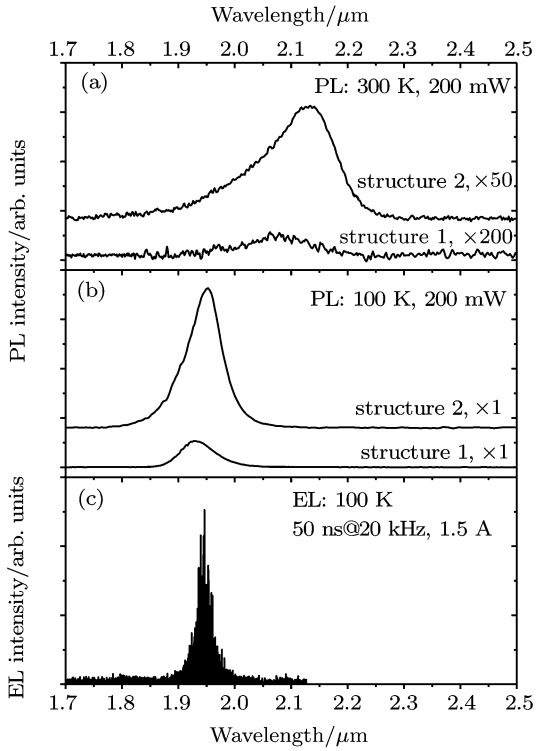


Fig. 4. PL spectra of QW structure 1 with random alloy barrier, and structure 2 with DA barrier at (a) 300 K and (b) 100 K; (c) EL spectrum of the laser structure with active region as QW structure 2 at 100 K.

The EL measurements were performed under pulse driving currents with 50 ns pulse duration and 20 kHz frequency. We did not observe the EL signal of the laser structure using InAlGaAs random alloy barriers even when the temperature was decreased to 10 K, while obvious EL signals can be observed for the laser structure using InAlGaAs DA barriers at temperatures below 100 K. Figure 4(c) shows the measured EL spectrum of the laser structure at 100 K under the driving current of 1.5 A. The EL peak is at around 1.95 μm, which matches well with the PL peak at 100 K. However, the absence of EL signals at temperatures higher than 100 K indicates the relatively low EL efficiency, whereas strong PL signals at room temperature indicate the good PL efficiency and material quality. A possible reason may be the position deviation of the p–n junction from the QW region in the laser structure, therefore further optimisation of the doping control during the growth process may help to obtain lasing at higher temperatures. Nevertheless, this explanation still needs to be proved by other characterisations.

4. Conclusions

InP-based compressively strained InGaAs QWs with InAs/$In_{0.53}Ga_{0.47}As$ DA triangular well layers and different tensile InAlGaAs barrier layers have been grown by using GSMBE. Their structural characteristics have been investigated by HRXRD and TEM measurements, the DA QW structures are grown under good pseudomorphic growth and show favourable lattice quality. The PL and EL measurements indicate that the use of DA barriers offers superior optical characteristics than that of conventional random alloy barriers. The PL signals are significantly improved by using $In_{0.53}Ga_{0.47}As$/InAlGaAs DA barriers instead of InAlGaAs random alloy barriers. An EL signal at around 1.95 μm is achieved at 100 K for the DA barrier structure, whereas no EL is observed for the random alloy barrier structure.

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