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Interruption time effects on InGaAs/InAlAs superlattices of quantum cascade laser structures grown by MOCVD

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ABSTRACT

We report the growth of high quality InGaAs/InAlAs quantum cascade laser (QCL) structure which composed of superlattices (SLs) and the effects of interruption time between each layer of the SL structure. Inserting an interruption delay during the growth dramatically effects the quality of the SL as indicated by crystallinity, interface sharpness and optical properties. The results show that an increase in interruption time up to a certain value makes sharper interfaces and improves optical and structural properties, but, beyond that value, overall quality starts to degrade. The composition and the growth rate of each single thin layer are determined by using high resolution X-ray diffraction (HRXRD) measurements.

1. Introduction

InGaAs/InAlAs based QCL structures are very popular for mid-infrared wavelength emission range applications [1–6]. They have attractive properties such as high power, continuous wave operation at room temperature and wide tunability [7–9]. Along with the deposition of thin, ternary layers having exactly targeted thicknesses, precise control of alloy composition and sharp interfaces are among the most important issues of QCL structure growths. The typical total thickness of a full QCL structure is around 8–10 μm including hundreds of layers and interfaces [10]. The thinnest layer thickness is about a few monolayers and the laser performance is quite sensitive to background doping and interface roughness [11]. For these reasons, Molecular Beam Epitaxy (MBE) is the preferred technique for growing these structures. However, the thicker cladding layers limits its versatility. On the other hand Metal Organic Chemical Vapor Deposition (MOCVD) could compete with MBE in terms of having a lower background doping level and much higher growth rates of cladding layers (InGaAs or InP) etc [11]. Therefore, only a few groups have the means to use a combination of both techniques; using MBE for thinner layers of active region and MOCVD for thicker layers of cladding region growth [12,13]. It is clear, if possible, that using only MOCVD technique for QCL growths is important for economical and industrial reasons.

Growing high quality InAlAs layers with MOCVD requires Al atoms to have enough time and kinetic energy to bind the right lattice site. Both of these conditions are met by high growth temperature and low V/III ratio [14–17]. Furthermore, obtaining low unintentional doping levels for InGaAs layers also requires higher growth temperatures [18]. However, higher growth temperatures cause the surface degradation and decrease the optical quality remarkably [19]. As a result growing high quality InGaAs layers need relatively lower growth temperatures and higher V/III ratios [20,21]. Using multiple group V

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sources fulfils one of the requirement by making it possible to have different V/III ratios during the growth of each consecutive layer. Unfortunately, changing the growth temperature from one layer to another quickly is very difficult, especially for samples that include hundreds of such thin layers. Therefore, it is important to find an optimized growth temperature that is the same for both of these materials.

There are a few studies in literature about interruption time effect on quantum well and multi layered structures [22,23], but to the best of our knowledge, this is the first report of this type of study for QCL structures.

In this work, we studied interruption time effects between layers on structural, optical and interfacial properties of InGaAs/InAlAs SLs which is the active region for QCL structures grown by MOCVD. The results suggest that the 3.0s interruption time increases overall quality of SLs.

2. Experimental details

InGaAs, InAlAs single epilayers and SLs which are used in this study, were grown on 2 inch, (100) oriented, semi-insulating, double side polished (dsp) indium phosphide (SI-InP) substrates by using a horizontal flow reactor (AIXTRON 1 × 2″ or 1 × 3″ 200/4 RF-S) MOCVD system. The system is equipped with Luxtron 880 nm reflectometer and an optical fiber thermometry-light-pipe assembly providing information about growth rate, reflection intensity (thus surface quality) and substrate/surface temperatures at real time. Opto-grade trimethylgallium (TMGa, $Ga(CH_3)_3$), trimethylindium (TMIn, $In(CH_3)_3$) and trimethylaluminum (TMAl, $Al(CH_3)_3$) were used as Ga, In and Al precursors (group-III), respectively. High purity (99,999%) arsine (AsH_3) and phosphine (PH_3) were used as As and P precursors (group-V) and ultra-high purified hydrogen (H_2) and nitrogen (N_2) were used as the carrier gases. Before each QCL structure growth process, an InP wafer is loaded into the reactor, in high purity inert N_2 gas ambient, via glove box then the substrate is thermally deoxidized at 640 °C in PH_3 environment for 5 min and an unintentionally doped ~500 nm InP buffer layer is grown. Several single layer growth studies were done for optimizing the growth temperature, reactor pressure, V/III ratio, source flows and other growth parameters to reach the desired material quality. To grow high quality single InGaAs layer at higher growth temperatures, overpressure of AsH_3 is necessary to obtain high quality epitaxial layers to minimize the surface decomposition. The general considering is the surface degradation comes from the As desorption from the grown surfaces and thus raising V/III ratio with increasing AsH_3 flow rates should help to recover the surface desorption. However, too much As overpressure in InAlAs growth prohibits the Al atoms to move to their sites before the arrival of subsequent Al atoms, degrading the uniformity of alloy composition [19]. As a consequence, unlike InGaAs requiring as high V/III ratio as possible, there exists a range of V/III ratio to obtain high-quality InAlAs epilayers. After optimization studies, growth parameters such as growth temperature, reactor pressure, total carrier gas flow and substrate rotation speed were determined. These values are 640 °C, 50 mbar, 6000 sccm and 60 rpm, respectively. Similarly optimized V/III ratios for InP buffer layer, InGaAs and InAlAs layers are ~120, 600 and 80, respectively. Obtained growth rates for these parameters were ~1 Å/s for InGaAs and InAlAs and 6 Å/s for InP. Single bubbler was used for In, Ga and Al sources but for AsH_3 two separate lines were used to fast switch between the required V/III ratios for InGaAs and InAlAs layers. The structural and optical properties of epitaxial layers were investigated by using high resolution X-ray diffraction (HRXRD) and room temperature photoluminescence (PL).

Optimized InAlAs (Sample A), InGaAs (Sample B) single layers and InGaAs/InAlAs SL calibration structures (cs) (not shown here) which includes of 50 period of 3 nm InGaAs/6 nm InAlAs (cs-1), 50 period 5 nm InGaAs/6 nm InAlAs (cs-2) and 50 period 3 nm InGaAs/4 nm InAlAs (cs-3) were grown to determine composition and crystal quality [24]. Comparing the simulations of XRD measurements for cs-1 and cs-2 (the only difference is from InGaAs layer), we were able to calculate thicknesses and periodicity from SL peaks. The active region of QCL structure composed of 10 stages of the following sequence of nearly-lattice matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ layers: 29/**31**/31/**27**/31/**21**/29/**20**/32/**15**/35/**12**/40/**20**/48/**7**/51/**8**/55/**8**/56/**7**/19/**38** Å where InAlAs layers are given in bold. The same design was used to grow three QCL structures with different interruption times between InGaAs and InAlAs layers as 1.5s (sample C), 3.0s (sample D) and 6.0s (sample E), respectively.

3. Discussion

Fig. 1 shows the 880 nm in situ optical reflectance measurement and temperature measurement during growth of Sample A (InAlAs), Sample B (InGaAs) and Sample C (InGaAs/InAlAs SL). Red curve shows the reactor temperature, the magenta curve, blue curve and the green curve (they are shifted by 0, 580 and 4500 for better visibility, respectively) shows InAlAs, InGaAs and SL in situ reflectances, respectively. In situ optical reflectance and temperature measurement is divided into four parts as follows, corresponding to the three growth stage of films; (1) the increasing of the temperature up to thermal deoxidization temperature which is 640 °C and waiting at this temperature for 5 min under PH_3, (2) the growth of InP buffer layer, (3) preparation of precursor flows (4) growth of InGaAs and InAlAs epilayer or SLs (only stage 4 is shown in Fig. 1). Since the in situ optical reflectance measurement depends on the difference of refractive index between adjacent layers, reflectance curves start from the same point as the growth starts but they can rise or fall depending on the relative refractive index as seen from Fig. 1. The reflectance curve of InGaAs layer has higher amplitude than InAlAs layer and their directions are opposite. Also there is a noticeable damping in the amplitude of oscillations of InGaAs/InAlAs SL due to increasing absorption as the film gets thicker.

HRXRD measurement results of single layer of InAlAs (magenta-sample A) and InGaAs (blue-sample B) are shown in Fig. 2. For these samples we have grown as slightly mismatched to see the thickness fringes and to make a calculation better.