Appl. Sci. Converg. Technol. 26(5): 139-142 (2017)
http://dx.doi.org/10.5757/ASCT.2017.26.5.139

Research Paper

InGaAs/InAlAs Quantum Cascade Lasers Grown by using Metal-organic Vapor-phase Epitaxy

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Received August 15, 2017; revised September 12, 2017; accepted September 12, 2017

Abstract In this paper, InP-based InGaAs/InAlAs quantum cascade lasers(QCLs) providing nearly zero emission wavelength mismatch between the measured emission wavelength and the designed transition wavelength of QCLs is presented. The zero emission wavelength mismatch of QCLs influenced by both the accurate compositions and thicknesses of the low-pressure metal-organic vapor-phase epitaxy(MOVPE) grown InGaAs and InAlAs layers throughout the core and the abrupt composition transitions between InGaAs and InAlAs layers. The abrupt interfaces between InGaAs and InAlAs layers have been achieved throughout the core structure by means of controlling individually purged vent/run valves of a closed coupled showerhead reactor. In addition, maintaining substrate temperature constant during InGaAs/InAlAs core growth was a partial factor of uniformity improvement of QCLs. These approaches for reducing the possible discrepancies between the designed and MOVPE grown epitaxial structures could lead to improvement of QCL performance.

Keywords: Quantum cascade lasers, Infrared, III-V materials, MOVPE, MOCVD

I. Introduction

Quantum cascade lasers (QCLs)[1] based on the InGaAs/InAlAs/InP materials system are attractive light sources, because the emission wavelength is wide range from mid- to long-wave infrared (~3-20 um). Unlike typical interband semiconductor lasers, the laser transition of QCL takes place between different two intersubband states in the conduction band of a coupled quantum well structure. Therefore, the QCL wavelength is determined by the energy separation of intersubband states, whose can be design to produce lasers with different wavelengths using the same material system. These QCLs extremely attractive for a variety of applications, such as trace gas sensing [2], infrared countermeasures and free-space optical communications [3]. Most of these applications require high output power and high temperature continuous wave (CW) operation, further in single mode CW operation [4,5]. To realize high-performance QCLs with reliable emission wavelength, it is important that the epitaxial growth of QCLs requires an exact degree of control over alloy composition, layer thickness, and heterointerface quality of the many hundreds of ultra-thin epitaxial layers.

In previous studies, the InGaAs/InAlAs/InP QCLs were grown by metal organic vapor phase epitaxy (MOVPE) showed in a red-shifted emission wavelength about 0.5~1.0 μm to be compared with theoretically designed QCL wavelength [6-9] due to indium surface segregation and graded interfaces [7]. Thus, it is important to precise control the individual layer composition and abrupt interfaces.

In this work, we designed a set of lattice-matched InGaAs/InAlAs/InP multi-quantum-well (MQW) structures of QCLs with the emission wavelength 8.4 μm. Following the designed structure, the QCL were grown by using metal-organic vapor phase epitaxy (MOVPE). We characterized the grown QCLs using high resolution x-ray diffraction (HR-XRD), high resolution transmission electron microscopy (HR-TEM) and atomic force microscopy (AFM). And then, we measured the grown QCLs intensity as function of current density with various temperatures. The emission wavelength of the grown QCLs was compared with the theoretically designed QCLs.

II. Experimental Procedure

The current investigation involves results of quantum cascade laser grown by using MOVPE. The epitaxial structure of the fabricated quantum cascade laser that consists of 35 pairs of injector and active regions, and an injector on the top of the injector and active regions is presented in Fig. 1 and its detailed epitaxial design was reported in the literature [10]. The epitaxial structure is a bound-to-bound two-phonon resonance design. The bound-to-bound two-phonon resonance structure has been

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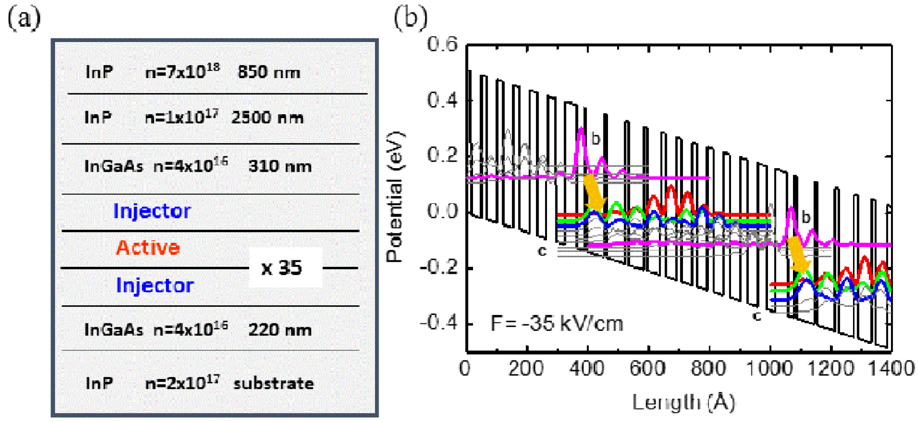

Figure 1. (a) InGaAs/InAlAs/InP MQW QCL structure with the 35 pairs of the injector and the active regions. (b) The QCL structures is bound-to-bound two-phonon resonance design.

often adopted as the baseline quantum cascade laser [11]. All the epitaxial structures here were grown by MOVPE in a Aixtron Crius 31 × 2 inch reactor system equipped with a close-coupled showerhead growth system. Trimethylindium (TMIn, $In(CH_3)_3$), trimethylaluminum (TMAl, $Al(CH_3)_3$), and trimethyl-gallium (TMGa, $Ga(CH_3)_3$) were used as column III precursors and arsine (AsH_3) and phosphine (PH_3) were used as column V precursors. The n-type dopant precursor was 2% silane (SiH_4) balanced in hydrogen (H_2) gas. The substrate used in the study was n-type (1 0 0) InP with different misorientations having tilt angles 0.075 degree. The epitaxial growth was performed at temperatures of 580°C and reactor chamber pressure of 100 mbar. For material characterizations, the Nomarski optical microscopy, atomic-force microscopy (AFM), X-ray diffraction (XRD), transmission electron microscopy (TEM), and photoluminescence (PL) were used to characterize the morphological, structural, and optical properties of the epitaxial layers.

QCL epitaxial structure was fabricated into ridge waveguides using standard optical lithography and dry etching processes. After forming the metal contacts by depositing Ti/Au stacks on the top and bottom of the wafer, the laser diode (LD) bars were cleaved and the cleaved facets were left uncoated. The substrate side was then alloyed onto a Cu heat sink and wire bonded. The devices were tested in pulsed mode at 20 kHz with 1% duty ratio at various temperatures.

III. Results and Discussion

Fig. 2 shows that the surface morphology image of (a) InGaAs, (b) InAlAs, and (c) QCLs were measured by using AFM. As can be seen, the observation of these surface steps exhibit that the growth process of the epitaxial layers undergoes a step-flow mode. The surface root-mean-square (RMS) roughness of the InGaAs and InAlAs layers are ~0.111 nm and ~0.113 nm, respectively. It means that the step-flow growth mode is accomplished with this very high quality epitaxial layers by using MOVPE. However, the RMS roughness of QCLs is slightly higher about ~0.205 nm than that of the other epitaxial layers. The core layers of QCLs are consisted of InGaAs and InAlAs epitaxial layers, on the InP substrates. The each layers have monolayer step heights that can be affected in RMS roughness of MQW structures. So, we can expect that RMS roughness of QCLs is slightly increased with the increasing InGaAs/InAlAs epitaxial layers.

We characterized the long-range uniformity and thickness of the grown QCLs by MOVPE using high-resolution transmission electron microscopy (HR-TEM) as shown in Fig. 3. The HR-TEM image demonstrate the high degree

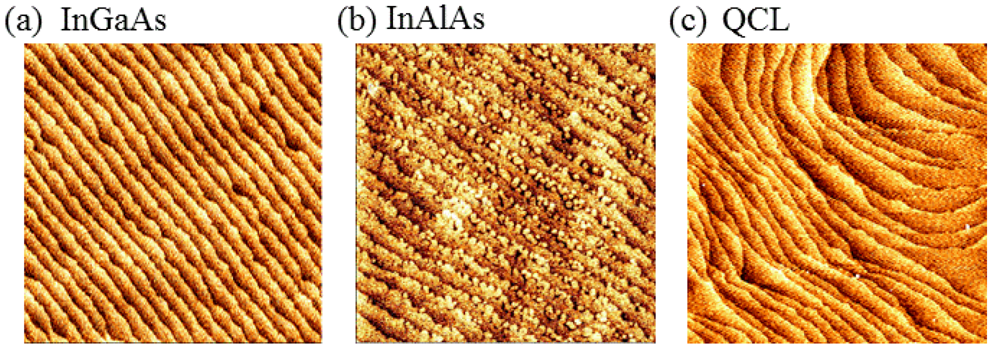

Figure 2. Atomic force microscopy images (5 × 5 μm^2) of the (a) InGaAs, (b) InAlAs, and (c) QCLs.

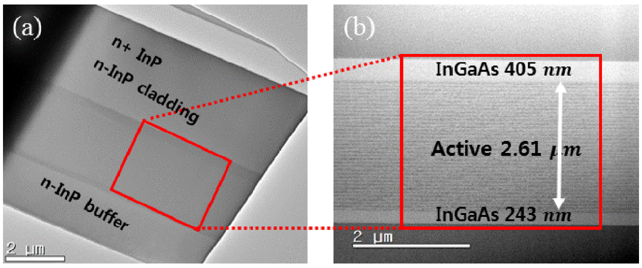

Figure 3. HR-TEM images of (a) total structure of QCL and (b) part of the core region. The InGaAs and InAlAs layer are dark and bright, respectively.

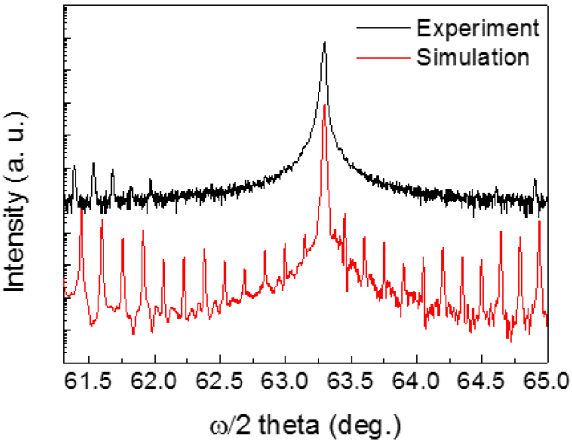

Figure 4. HR-XRD ω/2θ scan measured for the grown QCL (black, top) and simulated result of the designed QCL (red, bottom).

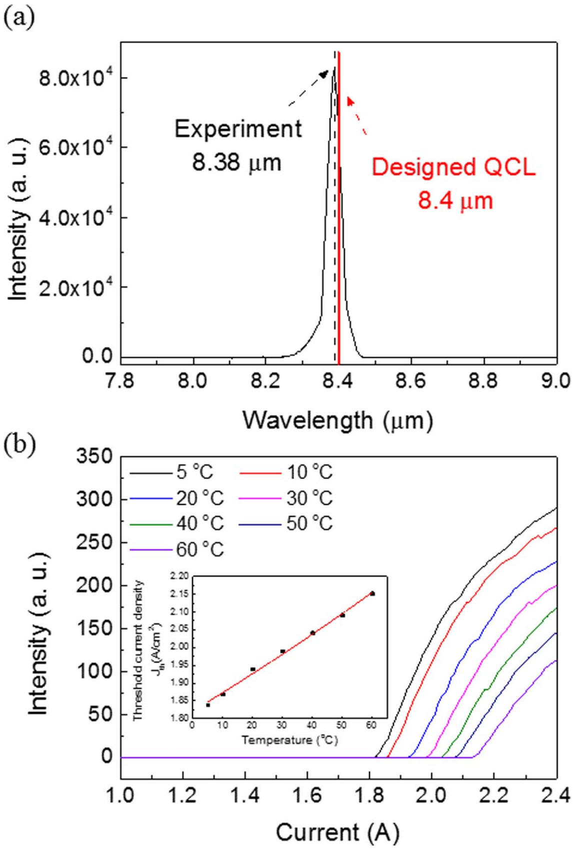

Figure 5. (a) The emission spectra of the grown QCLs by MOVPE in pulse mode. (b) Light intensity vs. current curve obtained from the grown QCL at various temperatures. The inset shows threshold current density vs. temperature.

of contrast available for InGaAs/InAlAs materials system. Fig. 3 (a) and (b) show the total and core region thickness of the grown QCLs, respectively, which are most consistent with the designed QCLs. This structure characterization indicates a high level of accuracy, both for the layer thickness and the compositions within the core region. We could be also shown the MOVPE growth yields a highly uniform and periodic MQW structure. The uniformity of core region MQW is very important for operating device because of determining the width of the QCL gain spectrum with low threshold current [12].

To confirm the MQW structure of QCLs, we performed high-resolution x-ray diffraction (HR-XRD) scans and corresponding simulation as can be shown Fig. 4. HR-XRD result exhibits sharp satellite peaks and highly resolved thickness interference fringes. The satellite peaks position and width of the envelope response alloy composition and individual layer thickness, respectively. The satellites determine the periodicity of the MQW while the position and width of the envelope determine the alloy composition and individual layer thickness, respectively. To compare with the simulations, the satellite peaks of grown QCLs structures are weak and a slightly inconsistent. It is believed that the thickness of barrier/well is not perfectly corresponded with simulated results. The abrupt interfaces were not also perfectly formed between InGaAs and InAlAs during the MOVPE growing process.

We characterized the structure of grown QCLs by using AFM, HR-TEM, and HR-XRD. Furthermore, we measured emission spectra and pulsed L-I characterization of grown QCLs as shown in Fig. 5. The pulse width and repetition rate of the grown QCLs are 200 ns and 20 kHz, respectively. These devices lased when operated in pulse mode at room temperature up to 60°C. Fig. 5(a) shows that high correlation between the emission peak wavelength of grown QCLs and designed wavelength where only 0.02 μm emission wavelength mismatch observed. On the other hand, very large emission wavelength mismatches between the designed and measured emission wavelengths have been reported in the previous literatures [6-9], where the their amount of emission wavelength redshift are in the range from 0.5 to 1.0 μm. Moreover, the origin of the emission wavelength redshift grown by MOVPE is unclear. Since our results demonstrates that the possibility of the suppression of the significant emission wavelength redshift of QCLs grown by MOVPE, we believe that further study would clear the origin of the observed redshift phenomena. Fig. 5 (b) shows the pulsed L-I characteristics of the grown QCLs at various temperatures. The device had a ridge width of 33 μm and cavity length of 3 mm. The threshold current I_{th} is increased from 1.85 A to 2.5 A with increasing temperature from 5°C to 60°C. We can extract threshold current density as a function of temperature from L-I curve as can be seen Fig. 5(b) inset. The solid red line is a fit to the exponential function $J_{th} = J_0\exp(T/T_0)$. The fitting curve is almost consistent with our experimental data. Therefore, we have successfully designed and grown the QCLs by using MOVPE that these lasing temperature is sufficiently high.

IV. Conclusions

In this paper, InP-based InGaAs/InAlAs quantum cascade lasers(QCLs) providing nearly zero emission wavelength mismatch between the measured emission wavelength and the designed transition wavelength of QCLs is presented. The nearly zero emission wavelength mismatch of QCLs influenced by both the accurate compositions and thicknesses of the low-pressure metal-organic vapor-phase epitaxy(MOVPE) grown InGaAs and InAlAs layers throughout the core and the abrupt composition transitions between InGaAs and InAlAs layers. The abrupt interfaces between InGaAs and InAlAs layers have been achieved by means of controlling individually purged vent/run valves of a closed coupled showerhead reactor throughout the core structures. In addition, maintaining substrate temperature constant during InGaAs/InAlAs core growth was a partial factor of uniformity improvement of QCLs. The threshold current and operating temperature was relatively comparable to previous literatures and could be improved by further optimization of epitaxial process, fabrication and packages. This performance of QCLs and the approaches for reducing the possible discrepancies between the designed and MOVPE grown epitaxial structures could lead to improvement of QCL performance.

Acknowledgments

This work was supported by the Technology Innovation Program (10053010) funded By the Ministry of Trade, industry & Energy(MI, Korea).

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