MBE growth and characterization of InAlAs/InGaAs 9 μm range quantum cascade laser

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Abstract. Quantum cascade laser heterosructure consisting of In0.52Al0.48As/In0.53Ga0.47As short-period superlattices have been grown by MBE and investigated by X-ray diffraction, electron microscopy and electroluminescent techniques.

1. Introduction
The idea of quantum cascade lasers (QCL) was proposed in 1971 [1]. The first experimental realization was done in 1994 by F.Capasso’s group [2]. For a now QCLs are the most useful sources of mid-infrared laser radiation [3]. QCLs are used for air pollution detection, gas sensor systems, LIDARs, systems for explosives and chemical warfare agent’s detection, clinical medicine etc. [4] Widespread use of 9 μm wavelength range QCL is provided by several factors. This wavelength matches the atmospheric transparency window of 8-12 μm which allow using 9 μm range QCL for free-space data transfer systems. In addition, this radiation is not harmful to the human body which allow to use these lasers for various medical applications.

It is important to note that for the growth of QCL heterostructures very high precision of composition and thickness of layers is needed. As a result molecular beam epitaxy (MBE) looks like the most suitable approach for the growth of such lasers. The creation of 9 μm range QCLs by MBE is relevant because of the lack of this growth technology in Russia.

2. Experiment
QCL heterostructure under investigation was grown by Connector Optics LLC by using Riber 49 MBE machine. Heterostructure consisted of the following parts: In0.53Ga0.47As: Si (1e18 cm -3) layer with a thickness of 50 nm was deposited on n+ InP substrate, after that In0.53Ga0.47As: Si (5e16 sm -3) layer with a thickness of 4000 nm was grown and 40 cascades of short-period In0.52Al0.48As / In0.53Ga0.47As superlattice were embedded in the middle of this layer. The last layers were 4000 nm thick step-doped In0.52Al0.48As:Si (1e17/1e18 cm -3 ) and 200 nm thick contact layer of In0.52Ga0.47As:Si (5e18 cm -3 ). The active region based on 3-phonon resonant design [5] was calculated to produce...
radiation at 9 µm at 77 K. A theoretical calculation of the energy levels of a single quantum cascade is indicated in Figure 1. The calculated energy of the intersubband transition is 128.6 meV. Each cascade contained the following sequence of layers In$_{0.52}$Al$_{0.48}$As/In$_{0.53}$Ga$_{0.47}$As (in nanometers): 4.0/2.0/0.9/5.8/0.9/5.5/0.9/5.1/1.2/4.4/2.2/4.2/1.8/3.8/1.6/3.3/1.8/3.1/2.3/3.1/2.7/2.9, where bold and underlined layers correspond to In$_{0.53}$Ga$_{0.47}$As and doped with silicon to concentration $5\times10^{16}$ cm$^{-3}$ layers, respectively. Table 1 shows the QCL heterostructure design.

![Figure 1.](image)

**Figure 1.** Conduction band profile and moduli squared wavefunctions of active/injector region of the QCL at 77K under the applied field of 61 kV/cm

| Table 1. QCL heterostructure design. |
|--------------------------------------|
| **Composition** | **Thickness, nm** |
| InP substrate | - |
| GaInAs:Si | 2000 |
| InAlAs/InGaAs | 40 times repeat |
| GaInAs:Si | 2000 |
| InAlAs:Si | 4000 |
| GaInAs:Si | 200 |

Growth was carried out at As$_4$ beam equivalent pressure (BEP) of $5\times10^{-5}$ Torr and substrate temperature of 480°C. InAs growth rate was about 1 Å/s. Prior to the final heterostructure growth the test sample with the superlattice containing 10 cascades of In$_{0.52}$Al$_{0.48}$As/In$_{0.53}$Ga$_{0.47}$As 10 nm thick each was grown to calibrate compositions and thicknesses of the epitaxial layers. Structural properties of the heterostructure were studied using PANalytical X’Pert Pro X-ray diffractometer. For simulation and fitting of structure parameters the software X’Pert Epitaxy and...
Smoothfit of PANalytical company has been used. According to x-ray diffraction measurements the growth rates of the binary compounds InAs, GaAs, AlAs were determined and adjusted.

Figure 2 shows the theoretical and experimental rocking curve of QCL heterostructure, produced by high resolution X-ray diffraction method (HRXRD) near the symmetrical reflection (004) of InP. There are diffraction peaks of InP substrate, cladding layers and periodic cascade structure. Zero peak of satellite structure (sl0) is close to InP substrate peak, which shows the good match of the epitaxial layers and substrate lattice constants. A satellite peak structure is observed in a wide angular range, indicating that there are continuity and planarity of the interfaces forming the periodic structure. Narrow satellite peaks (FWHM less than 20 arcsec) without any splitting indicate that there are no significant variations in composition of cascade layers. The total thickness of one cascade was determined by the difference between the angular positions of the satellites and was equal to 70.0 ± 0.2 nm, which with high precision corresponds to the nominal value of the cascade thickness 69.8 nm. In general, the observed diffraction pattern indicates a high structural quality of QCL heterostructure and good matching of the layer thicknesses for all 40 cascades. This in turn shows a high degree of the growth parameters stability.

![Figure 2. Theoretical and experimental rocking curve of QCL heterostructure, produced by high resolution X-ray diffraction method (HRXRD) near the symmetrical reflection (004) of InP.](image)

Additionally the good quality of QCL heterostructure is confirmed by the results of transmission electron microscopy (TEM) investigation (see Figure 3). It can be seen that within the cascade all layers have planar boundaries and there are no changes in the thicknesses of the cascade layers.

For electroluminescent (EL) measurements QCL heterostructure was processed into 22-μm-stripe-width lasers with ~ 1 mm cavity length. Figure 4 and Figure 5 show scanning electron microscopy (SEM) images of the QCL stripe.
Figure 4 shows the results of the electroluminescence (EL) measurements of QCL. The peak position is in good agreement with the calculated energy of the intersubband transition of 128.6 meV. EL peak at 9.6 μm has FWHM of about 8.1 meV [6], which is comparable with the thermal broadening energy $kT = 7.5$ meV.
3. Conclusions
QCL heterostructure based on In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As short-period superlattices have been grown by MBE technique. The heterostructure shows a high accuracy of compositions and layer thicknesses and high structural quality. EL measurements show emission at ~ 9 μm.

Acknowledgments
This study was supported by the Russian Ministry of Education and Science, project ID: RFMEFI61617X0074.

References
[1] Kazarinov R F and Suris R A 1971 Sov. Phys. Semicond. 5 207
[2] Faist J et al 1994 Science 264 553
[3] Robert F C et al 2010 Chem. Phys. Lett. 487.1 1-18.
[4] Y Yu, A J Hoffman and C F Gmachl. 2012 Nature Photonics 6.7 432-439.
[5] Wang Q J et al 2009 Appl. Phys. Lett. 94 011103.
[6] Sirtori C et al 1996 Appl. Phys. Lett. 68 1745