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Structural properties of multilayer heterostructure for quantum-cascade lasers grown by MBE growth

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Abstract. GaAs/AlGaAs heterostructure with 226 quantum cascades was synthesized by molecular-beam epitaxy. Structural and optical properties studies have shown high level of homogeneity and quality of epitaxial structure.

1. Introduction

Sources of the terahertz (THz) frequency range are in demand for various applications for both commercial and special purposes, including spectroscopy, determination of trace amounts of various substances, development of systems forming images of objects concealed from ordinary optical systems, wide-bandwidth communication systems, etc. One of the main problems is the lack of compact chromatic sources of radiation of sufficiently high-power for this spectral range. The quantum-cascade laser (QCL) is at present believed to be the most promising candidate for the development of THz systems for different purposes [1, 2]. The first QCLs for the THz range were fabricated in the early 2000s [3, 4]. To date THz QCLs of this kind have been developed, which operate up to 200 K [5] and have an emission power of several tens of mW at liquid-nitrogen temperature. Also, roomtemperature laser sources of terahertz radiation have been developed [6] on the basis of the intraband amplification of the differential frequency of two QCLs of the mid-infrared (IR) spectral range [7].

In this study, we have been investigated the possibility of molecular-beam epitaxy (MBE) synthesis of multiple-period multilayer heterostructure for QCLs fabrication in frequency range around 3 THz, and structural properties of grown heterostructure were studied.

Despite the apparent scientific and practical importance of QCLs, this technology started to be developed in Russia only a few years ago. At that time, there were reports about QCLs grown by
molecular beam epitaxy (MBE), with emission at a wavelength of about 5–6 μm [8–10], and those synthesized by epitaxy from metal-organic compounds, intended for a wavelength of ~10 μm [11]. At the same time, no development of THz QCLs in Russia has been reported.

2. Experiments.
The epitaxial structure was synthesized by molecular-beam epitaxy using a Riber Compact 21 MBE machine. Growth was performed on semi-insulating GaAs (100) substrates under arsenic-stabilized conditions. Figure 1 shows the schematic diagram of the grown structure. Particular attention was paid to accurately setting the growth rates and to maintaining their stability during whole the growth run. The growth rates were carefully calibrated on a separate sample directly prior to growth of the multiple-period multilayer heterostructures. The GaAs and AlAs growth rates were set at 0.425 and 0.075 monolayers per second (ML/s). Special high-speed shutters were used to obtain high quality interfaces. In our case, the actuation time of the shutters of the aluminium and gallium sources did not exceed 0.15 seconds. A 200-nm-thick Al$_{0.8}$Ga$_{0.2}$As stop-layer was deposited onto a GaAs buffer layer. The active region contained 226 periods. Each cascade contains a GaAs/AlGaAs double quantum well (QW), between whose levels a QCL transition occurs, and a wider QW serving as the injector/extractor of electrons. The active region was bound from above and below by GaAs:Si contact layers (5 × 10$^{16}$ cm$^{-3}$) with thicknesses of 60 nm. The middle part of the injector/extractor layers also had n-type doping to a concentration of ~2 × 10$^{16}$ cm$^{-3}$. When heterostructures are used for the emission in the THz range are synthesized by the MBE with total thicknesses exceeding 10 μm, the GaAs growth rate may, nevertheless, decrease due to exhaustion of the gallium source in the course of prolonged deposition. Such change in the growth rate was taken into account during the experiment.

![Figure 1. The schematic diagram of the grown heterostructure.](image)

3. Results and Discussion.
The structural properties of the sample were studied by high-resolution X-ray diffraction method (HR-XRD), atomic force microscopy (AFM) and transmission electron microscopy (TEM). For HR-XRD method the D8 DISCOVER Bruker AXS diffractometer (radiation wavelength $\lambda$ =0.15406 nm) with a primary beam half-width of <12 arcsec in the $\Omega$–$\varphi$ scanning mode was used. Figure 2 shows the rocking curve around the symmetric GaAs (004) reflection. The full width at half-maximum (FWHM) of the satellite peaks due to the periodic repetition of QCL cascades is 15–19 arcsec. It is noteworthy that the full width of the superstructure peaks in the model spectrum, found with allowance for
bending of the structure under elastic stresses, is 22.4 arcsec. This means that both the possible effects due to the inaccurately of the cascade thickness within the whole structure and the roughness of the heterointerfaces can be neglected, which confirms that the technological parameters for the case of synthesis of the active region are chosen correctly. The calculated rocking curve for the model structure providing the excellent agreement with the experimental data which is shown in Figure 2.

![Figure 2](image_url)

**Figure 2.** X-ray rocking curve of the QCL structure near the GaAs (004) reflection and the simulated curve.

Figure 3 shows typical AFM (a) and TEM (b) images of grown heterostructure. According to the AFM measurements it seen that average surface roughness is 2 Å, only showing perfect smoothness of the grown structure. In turn, the TEM studies results indicate very abrupt interface between the layers within the whole structure (figure 3b). Both of these facts attest to the high crystallographic and epitaxial quality of the grown structure.
Figure 3. (a) - AFM image of grown sample surface: Terrace length 0.7–0.96 μm, RMS roughness 2 Å.; (b) - TEM image of grown structure.

Thus, the method of molecular-beam epitaxy was used to synthesize multiperiod (226 cascades, ~10 μm) GaAs/AlGaAs epitaxial structures intended for use in the fabrication of quantum-cascade lasers in the terahertz range. Structural properties studies have shown high level of homogeneity and quality of the epitaxial structure. The angular width of the superstructure peaks in the X-ray rocking curve does not exceed 20 arcsec, total surface roughness is as less as 2 Å.

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