Semiconductor light sources for near- and mid-infrared spectral ranges

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Abstract. 1550 nm band wafer-fused vertical-cavity surface-emitting lasers (VCSELs) and 5-10 µm band multi-stages quantum-cascade lasers (QCL) grown by molecular beam epitaxy (MBE) were fabricated and studied. VCSELs show high output optical power up to 6 mW in single-mode regime (SMSR > 40 dB) and open-eye diagrams at 30 Gbps of standard NRZ at 20ºC. QCL heterostructures show high structural quality (fluctuations of composition and thickness < 1%). 20-µm-stripe width QCLs mounted on copper heatsinks show lasing at ~ 6, 7.5 and 9 µm.

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1. Introduction

Researchers all over the world focus their research on semiconductor lasers of various types due to the wide range of potential applications. For example, semiconductor lasers of the near infrared spectral range are widely used for datacom and telecom applications, optical pumping of solid-state and fiber lasers, material processing etc. Vertical-cavity surface-emitting lasers (VCSELs) have several advantages in comparison with conventional Fabry–Perot lasers - low angular divergence, symmetric far field diagram, low threshold currents, low power consumption, increased temperature stability and radiation hardness, possibility of on-wafer testing of devices.

GaAs-based VCSELs [1] emitting at 850 nm are widely used in optical data communications at continuously shrinking distances and increasing bit data rates and steadily replace copper links [2]. Long-wavelength (LW) vertical-cavity surface-emitting lasers (VCSELs) emitting at 1300 – 1550 nm looks promising for optical interconnects, fiber to the home applications and other Si-photonics related technologies [3]. Compared to GaAs-based short-wavelength VCSELs, LW devices have lower power consumption and optical loss in silica optical fibers [4-6].

There are two main techniques which are used for 1550 nm band VCSEL manufacturing. The first one is based on direct growth of a VCSEL structure on InP substrate followed by a buried tunnel junction (BTJ) formation [47] and a second one that is based on wafer fusion (WF) of InP-based active area with GaAs-based Distributed Bragg Reflectors (DBRs) [8]. At present time commercially available 1550 nm band VCSELs demonstrate data transfer rate of about 3-10 Gbps [9]. The highest data transfer rate of 56 Gbps was reached on 1530 nm band VCSELs with BTJ for 4-5 µm aperture size devices [10].
Quantum cascade lasers (QCL) are lasers which operate based on quantum transitions of one type charge carriers between subbands. Such lasers were proposed theoretically in 1971 [11] but manufactured only in the mid-1990s due to the progress of molecular beam epitaxy (MBE) [12]. QCLs provide the possibility to get lasing over a broad wavelength range from several micrometers to ~100 μm range [12]. Another advantage of QCLs is relatively small dependence of the lasing wavelength shift versus temperature.

Despite alternative approaches to the creation of quantum-cascade lasers based on Si/Ge heterostructures [13], the main research has focused on lasers based on AlIIIBV compounds [12]. To date, lasing of QCL in continuous wavelength (cw) mode based on ternary solid alloys InGaAs/InAlAs, on an InP substrates is demonstrated [14]. In spite of some success obtained in the fabrication of QCL [15] there is an evident needs for further research on increasing of wall-plug efficiency (WPE) of such lasers [16]. One approach to raise the laser efficiency is to use multi-stages QCL [17, 18]. With increase in the number of stages, the threshold power of the QCL weakly changes. (Threshold current density of QCL is inversely proportional to the number of stages N, while its threshold voltage is directly proportional to N) In turn, the use of multi-stage QCL reduces the intersubband light absorption and the heating of the structure (due to decreasing of the threshold current density) and improves the whole laser performance.

This paper is focused on 1550 nm band wafer-fused vertical-cavity surface-emitting lasers (VCSELs) and 5-10 μm band multi-stages quantum-cascade lasers grown by MBE.

2. 1550 nm band wafer-fused VCSELs
Wafer-fused 1550 nm VCSELs comprising active region with seven thin (2.8 nm), compressively strained InAlGaAs multiple quantum wells (MQWs) [19] and AlGaAs/GaAs DBRs that are fully-grown by MBE have been manufactured and studied. Devices with the TJ aperture size of 8 μm demonstrate lasing threshold ~ 1.5 mA and output optical power ~ 6 mW at 20°C (Figure 1). VCSELs show single mode CW operation with a longitudinal side mode suppression ration (SMSR) in the range of 40 - 45 dB with emission close to 1566 nm (see inset in Figure 1).

An open-eye diagram at 30 Gbps of standard NRZ is demonstrated at 20ºC (Figure 2). With the temperature increasing up to 85ºC threshold current increases but is still < 2.5 mA, devices show single mode operation with > 40 dB SMSR and demonstrate open-eye diagram at 20 Gbps of standard NRZ.
Figure 2. Optical eye diagram at bias current of 14 mA, modulation voltage of 0.5 V peak-to-peak, 30 Gbps and 20°C.

3. 5-10 μm band multi-stage quantum-cascade lasers

Three different designs of multi-stages quantum-cascade lasers were grown by molecular-beam epitaxy on InP (100) substrates using the Riber MBE49 machine. Grown QCL heterostructures were studied by XRD and TEM. Obtained results indicate high quality of the structures and high precision of the growth technique. Fluctuations of composition and thickness was less than 1% for all 3 structures. To study electroluminescent characteristics of the QCL heterostructures were processed into 20-μm-stripe-width lasers. Cavity length of ~ 1.5 mm was chosen. Lasers were mounted on copper heatsinks and studied in pulsed regime.

The first design with the active region based on bound-to-continuum design [20] was focused on lasing at ~ 6 μm. Before forming the stages of the laser on an InP substrate, an 100 nm InGaAs layer doped by silicon (Si) lattice matched to InP was grown. The heterostructure contains 60 stages formed by the strain-compensated In$_{0.44}$Al$_{0.56}$As/In$_{0.60}$Ga$_{0.40}$As heteropair provided the necessary elastic balance in the QCL stages and a band offset $\Delta E_C$ of no less than 630 meV at the heterointerface [21-23]. The InAlAs cap layer and InGaAs contact layer doped by Si are of thickness 1500 and 50 nm, respectively. The structure demonstrates a lasing at room temperature in pulse mode. LI characteristic is depicted at Figure 3. The threshold current density is about 4.3 kA/cm$^2$. It is observed the multi-mode lasing with emission maximum close to 5.77 μm (see inset in Figure 3). The intermode distance $\Delta \lambda$ between longitudinal modes is ~ 3.7 nm. The effective refractive index for the fundamental mode is $n_{\text{eff}} = \lambda^2/(2L\Delta\lambda) = 3.26$, where $L$ is the cavity length. The calculated reflectance of the mirrors, $R_{\text{eff}} = (n_{\text{eff}} - 1)^2/(n_{\text{eff}} + 1)^2$ is 0.28. The loss factor of the mirrors $\alpha_{\text{in}} = \ln (R_{\text{eff}})/L$ is 9.1 cm$^{-1}$. 
Figure 3. LI characteristic measured at T=300 K. Inset shows a spectrum of QCL with lasing about 5.77 µm at T = 300 K.

The second design with the active region based on two-phonon scheme [24] was focused on lasing at ~ 7.5 µm. Design of the active region is based on In$_{0.53}$Ga$_{0.47}$As/Al$_{0.48}$In$_{0.52}$As and consists of 50 stages. The bottom cladding is formed by consistently grown Si-doped InP (thickness ~ 2000 nm) and InGaAs (thickness ~ 500 nm) layers. After growth of stages Si-doped InGaAs contact layer is grown (thickness ~ 120 nm). Edge-emitting lasers based on the grown heterostructures demonstrate lasing with threshold current density below 1.6 kA/cm$^2$ at a temperature of 78 K.

The third design with the active region based on three-phonon resonance scheme [25] was used for 9 µm range QCL. It contains the 40 stages active region based on In$_{0.53}$Ga$_{0.47}$As/Al$_{0.48}$In$_{0.52}$As. The bottom cladding is formed by Si-doped InGaAs layer (thickness ~ 2000 nm). The top cladding is based on InGaAs and InAlAs with thickness of 1830 and 4000 nm, respectively. n++ InGaAs contact layer is fabricated on heterostructure surface. The spectra of spontaneous emission demonstrate a single emission peak with a width at half maximum (FWHM) of about 50 cm$^{-1}$ with a center at 1030-1040 cm$^{-1}$ with slight blue shift with the increase of current. A typical lasing spectrum demonstrates a single line at the frequency of 1043 cm$^{-1}$ (wavelength 9.6 µm) measured at 78 K.

4. Conclusions

1550 nm band wafer-fused VCSELs and 5-10 µm band multi-stages QCL grown by MBE were fabricated and studied. VCSELs show high output optical power up to 6 mW in single-mode regime (SMSR > 40 dB) and open-eye diagrams at 30 Gbps of standard NRZ at 20ºC. Different scheme of QCL active region was applied to realize lasing at different wavelength. Using X-ray diffraction and transmission electron microscopy analysis, QCL heterostructures high structural quality is demonstrated (fluctuations of composition and thickness < 1%). The heterostructures were used for manufacturing of stripe lasers with 20 µm stripe width. QCLs mounted on copper heatsinks show lasing at ~ 6, 7.5 and 9 µm.
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