GaAs/AlGaAs quantum cascade lasers with different Aluminium content and heterogeneous cascades

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***Abstract*—We have investigated GaAs/Al$_x$Ga$_{1-x}$As quantum cascade lasers (QCLs) with different Al-content and found that this parameter provides an effective way to tune the emission wavelength. By changing the aluminium content of the barriers from 42.0 to 48.5 percent, a shift of the emission wavelengths of 1.5 μm was achieved. Finally, we exploited this tuning parameter to obtain a broad-band emitting QCL with heterogeneous Al-content which covers emission wavelength from 11.9 to 13.5 μm was fabricated. All samples operate up to room temperature.**

QCLs are powerful lasers for the mid- and far-infrared spectral region. In contrast to conventional interband diode lasers the emission wavelength in these intersubband devices relies only on the active region design irrespective of the material bandgaps. This gives a high degree of freedom for designing the emission wavelength, and in fact emission ranges from around 3 μm to 216 μm. On the other hand, a change of the emission wavelength usually requires a complete re-design of the active region with time-intensive calculations. In this work we present another promising approach for tuning the emission wavelength of GaAs/AlGaAs QCLs by varying the barrier height in order to influence the energy levels of the active regions minibands.

GaAs/Al$_x$Ga$_{1-x}$As active regions grown on GaAs substrates are ideal candidates for this approach as Al$_x$Ga$_{1-x}$As is nearly perfectly lattice matched to the GaAs substrate regardless of the aluminium content and we believe that our method can be particularly interesting for THz emitters. Furthermore, we utilized the wavelength tuning with the aluminum content for obtaining a broad band emitting QCLs Therefore we designed an active region with heterogenous Al content resulting in simultaneous emission from 11.9 to 13.5 μm. The presented devices can be operated up to room temperature exceeding the previously reported maximum operation temperature of GaAs/AlGaAs QCLs emitting at about 13 μm [1].

The active region is based on a bound-to-continuum (BTC) design. The calculated bandstructure for x=0.45 and an electrical field of 33.5 kV/cm is shown in fig. 1. Laser transition takes places between states 3 and 2 with an estimated dipole matrix element of 2.2 nm whereas the injector miniband enables a fast extraction of electrons via electron-LO-phonon and electron-electron scattering from the lower laser level 2.

Three samples with a barrier aluminium content x of 0.42 (sample A), 0.455 (B) and 0.485 (C) were grown by solid-

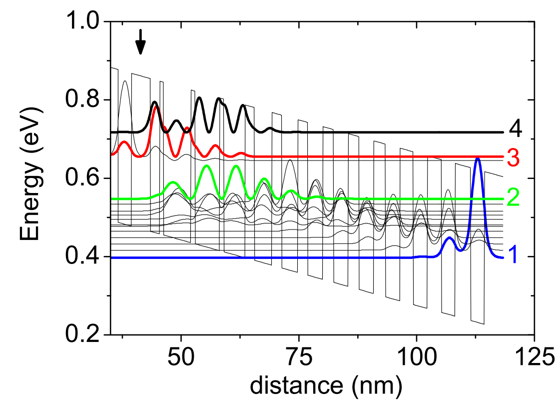

Fig. 1. Bandstructure for one period under an electric field of 33.5 kV/cm. The injection barrier is marked with an arrow. The layer sequence in nm (from left to right, beginning with the injection barrier) is **4.0**/2.0/**0.8**/5.8/**0.9**/5.2/**0.9**/4.5/**2.0**/3.7/**2.1**/3.4/**2.1**/3.2/**2.3**/3.1/**2.3**/3.1/**2.5**/3.1/**2.8**/ 3.0/**3.0**/2.9/**3.25**/2.85 whereas barriers are printed in bold. Underlined layers are doped to a sheet carrier density of $8.3 \cdot 10^{11}$ 1/cm^2.

source molecular beam epitaxy (MBE) in Eiko MBE system. Each structure comprises 50 periods which are embedded in two lightly doped ($4.1 \cdot 10^{16}$ 1/cm^{-3}, 3.2 μm thick) and two heavily doped ($4.7 \cdot 10^{18}$ 1/cm^{-3}, 1.0 μm thick) GaAs layers. The wafers were processed into 21 μm wide ridge wave guide (RWG) structures, 1 mm long resonators were defined by cleaving the ridges whereas the facets were left untreated. The samples were soldered on a copper heat sink, wire bonded and installed in a helium-flow cryostat for characterization. 100 ns long current pulses with a repetition rate of 1 kHz were applied to the devices for the measurement of laser spectra, output power and voltage-current curves. Spectra were recorded using a fourier transform infrared spectrometer.

At a heat sink temperature of 80K, comparable threshold current densities of 17.2, 18.1 and 15.8 kA/cm^2 were observed for samples A, B and C, respectively. The three samples showed maximum operating temperatures of 320K (A), 340K (B) and 300K (C). The different maximum operating temperatures can be explained by a lower barrier height (A) which means a

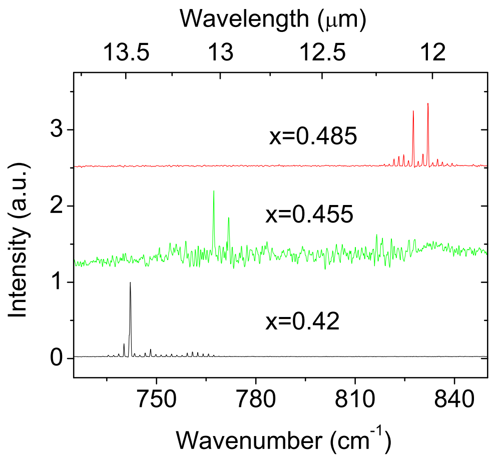

Fig. 2. Laser spectra for x=0.42, x=0.455 and x=0.485 (from bottom to top).

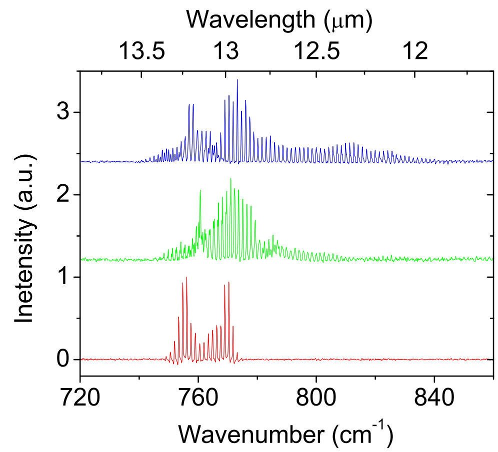

Fig. 3. Emission spectra for current densities of 17.6, 34.8 and 51 kA/cm^2 (from bottom to top) at a heat-sink temperature of 80K. For J=51 kA/cm^2 (top) broad-band emission from 740 to 840 cm^{-1} is observed.

lower electronic confinement and the introduction of indirect states for more than 45 percent aluminium in the barriers (C). The emission wavelength (spectra are shown in fig. 2) of the three samples (13.5 μm (A), 13.0 μm (B) and 12.0 μm (C)) shows a clear dependency on the aluminium content and samples A and B worked up to room temperature and beyond, which is to our knowledge the highest operation temperature of GaAs based QCLs emitting around 13 μm [1].
The presented results represent the first step towards a broad-band QCL design. Such devices provide a wide gain which is required for the realization of widely tunable single mode emitting QCLs [2], [3]. Broad-band emitting QCLs were realized by designing each period of the active region for a slightly different emission wavelength which requires high calculation efforts [4], [5]. Another possibility is the incorporation of only a few different active regions emitting in more widely spectrally separated ranges to obtain continuous broad band emission [2]. With the approach used here, a broad-band emitting QCL can be realized in a very straightforward way: the active region of our broad band QCL consists of 60 period whereas respectively 20 periods have an barrier aluminium content x of 42, 44 and 46 percent. The ratio $\frac{\alpha_i}{\Gamma_i}$ of the absorption losses α_i to the overlap of the optical mode with the periods of a certain aluminium content Γ_i is all about the same. Therefore one can expect similar threshold current densities regardless of the aluminium content. The broad-band active region was grown by MBE and embedded in the same waveguide as the structures presented before. At a heat sink temperature of 80K, the RWG structure showed a threshold current density of 16.2 kA/cm^2 and output powers exceeding 0.8 W. These values are comparable to the values obtained from the samples presented before.

Just above threshold current Fabry-Perot modes around 13.2 μm are observed. With increasing injection current density more and more Fabry-Perot modes appear. Finally at a current density of 43.0 kA/cm^2 multi-mode emission between 13.5 and 11.9 μm can be observed (see fig. 3). The emission stays multi-mode up to a current density of 51 kA/cm^2 which is the maximum current density achievable with our setup. The broad-band emitting sample can be operated up to room temperature.

In conclusion, we have investigated the influence of the Al content in the barrier on the emission wavelength in $Al_xGa_{1-x}As$ QCLs. For three samples with an aluminium content of 42, 45.5 and 48.5 percent emission wavelength of 13.5, 13.0 and 12.0 μm were observed, respectively. The three samples showed a comparable performance and could be operated up to room temperature. A broad-band emitting QCL (11.9 to 13.6 μm) was realized which showed a maximum operating temperature of 300 K.

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