Quantum-cascade lasers without injector regions

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ABSTRACT

We present the status of quantum-cascade lasers without injector regions, based on a four- and five-level staircase, respectively. First lasers were realized at a wavelength of ~ 10 µm. By applying an optimized design, we achieved high performance injectorless quantum-cascade lasers emitting at ~ 6.7 µm. On the basis of this design, we investigated the influence of doping density and the number of periods of active sections. A sample with a doping sheet density of 2.5×10^{10} cm^{-2} and 60 periods of active sections shows record low threshold current densities of 0.75 kA/cm^{2} at 300 K. Recently, we have further extended the wavelength range even down to ~ 4.2 µm.

Keywords: Quantum-cascade lasers, intersubband lasers, mid-infrared lasers, semiconductor lasers

1. INTRODUCTION

Quantum-cascade (QC) lasers have been investigated for more than a decade by now and are still gaining increasing interest as light sources in the mid- and far-infrared spectral region. A considerable level of performance has been reached, such as emission-wavelengths between 3 and 217 µm^{1, 2}, high output power at high operating temperatures in pulsed mode as well as continuous-wave operation above room-temperature.^{3, 4} As a semiconductor laser, the QC laser has a naturally small and robust cavity design and is particularly useful for spectroscopy, chemical sensing, free-space communications and medical applications.^{5, 6} The classical concept of QC lasers is a periodic repetition of active sections and so-called injector regions. These injector regions have been considered as an essential requirement for laser action in QC lasers. In the active sections the photons are generated, while a bridging miniband in the injector regions enables the transfer of the electrons from the lower states of one active section into the upper state of the next section. Furthermore, due to the doping of these regions, they act as an electron reservoir and provide stable current flow. However, apart from these benefits, the main disadvantage of these structures is the lengthening of the active stage with optically passive and slightly absorbing material and therefore a reduced overlap of the waveguide mode with the active sections. QC lasers without injector regions are expected to yield improved performance, provided that problems like electron transfer can be managed otherwise. Previously, injectorless QC lasers (λ~10 µm) have been realized, but their performances have been low, showing high threshold current densities and a maximum operating temperature of 200 K only.^{8-10} As a first step, we have demonstrated improved injectorless QC lasers (λ ~ 8.4-10 µm), based on a four-level staircase, showing reduced threshold current densities and above room-temperature operation.^{11} It was supposed, that injectorless QC lasers were restricted to this wavelength range, because with the absence of an injector-miniband, shorter wavelength emission (< 8 µm) cannot be achieved without applying very high bias fields. Nevertheless, by applying an optimized design based on a five-level staircase, we achieved high performance injectorless QC lasers emitting at ~ 6.7 µm^{12}. On the basis of this design, we investigated the influence of doping density and the number of periods of active sections. The doping density in the active sections is extremely important, for it affects both, the threshold current density and the maximum operation temperature of the lasers. This is because the free carrier absorption increases with doping leading to high losses, and because the population inversion is reduced by decreasing the doping. A sample with a doping sheet density of 2.5×10^{10} cm^{-2} and 60 periods of active sections shows record low threshold current densities of 0.75 kA/cm^{2} at 300 K.^{13} Recently, we have further extended the wavelength range to smaller values. For short wavelength emission a large conduction band discontinuity is needed. Furthermore, high temperature operation requires an adequate large exit-barrier for the upper laser state, otherwise electrons may escape by thermal activation into the quasicontinuum. We have realized injectorless QC lasers emitting at ~ 4.55 and 4.2 µm by using strained GaInAs/AlInAs with and without AlAs-blocking barriers.

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2. INJECTORLESS QC LASERS EMITTING AT ~ 8.4-10 µm

2.1 Design and fabrication

The design of our first QC lasers without injector regions consists of only four quantum wells per period and can be regarded as a four-level staircase. It is realized in the material system Ga_{0.4}In_{0.6}As/Al_{0.56}In_{0.44}As with a resulting conduction-band offset of ~ 0.62 eV. The conduction-band profile of two successive active sections and the moduli squared of the relevant wave functions are shown in Fig. 1 for an applied bias field of 80 and 110 kV/cm, respectively. The exact layer sequence is given in the caption. At 80 kV/cm the transition energy is calculated to $E_{32} \approx 123$ meV ($\lambda \approx 10$ µm), while at 110 kV/cm the calculated value is $E_{32} \approx 147$ meV ($\lambda \approx 8.4$ µm). This expected wavelength shift is caused by the Stark-effect, which is very strong in a design with diagonal lasing transition.

The sample was grown by solid-source molecular beam epitaxy (MBE) on a n-type InP substrate. Making use of an integrated Riber phosphorous valved cracker cell (KPC250), the whole structure, including a thick InP-layer was grown...
in one epitaxial run. The active region consists of 60 periods of active sections. The upper cladding is made of a 1.6 µm thick n-Ga0.47In0.53As layer (Si, 6×10¹⁶ cm⁻³), followed by a 2 µm thick n-InP (Si, 1×10¹⁷ cm⁻³) and a 1 µm thick n⁺-Ga0.47In0.53As (Si, 5.5×10¹⁸ cm⁻³) cap layer. The InP substrate and a 1.6 µm thick n-Ga0.47In0.53As layer (Si, 6×10¹⁶ cm⁻³) serve as the lower cladding. After growth, ridge-waveguide lasers with stripe widths ranging from 18 to 30 µm were fabricated by conventional photolithography and nonselective wet chemical etching using a HBr:H₂O₂:H₂O solution. A 250 nm thick SiO₂-layer was deposited for insulation around the laser ridges. On top of the ridge a window was opened for current injection. After evaporation of the top Ti/Pt/Au contacts, the wafer was thinned to 120 µm and a Ge/Au/Ni/Au bottom-contact metallization was made. The facets are left uncoated.

2.2 Results

For characterisation in a large temperature range, all devices were soldered ridge-side up with tin on Au-coated Si-substrates and then mounted on copper heat sinks. The lasers were contacted with wire bonding and placed in a cold finger cryostat with a ZnSe window, typically operated between 77 K and 500 K. The lasers are operated in pulsed mode with 250 ns pulse width and 250 Hz repetition rate. The light is collected with an f/1 Au-coated parabolic mirror and detected with an uncalibrated liquid nitrogen-cooled HgCdTe detector.

![Fig. 2. a) Pulsed light output-current characteristics of a 4 mm long and 30 µm wide device at various heat-sink temperatures (in K) b) Dependence of the threshold current density on heat sink temperature for a 3 mm long and 30 µm wide device.](image)

![Fig. 3. Emission spectra at 77 K and 300 K. The wavelength shift at higher bias fields and therefore, at high temperatures is caused by the Stark-effect, which is very strong in a design with diagonal lasing transition.](image)
Fig. 2 a) shows the pulsed light output -current characteristics of a representative device with 4 mm cavity length and 30 µm width for various heat-sink temperatures. At temperatures up to 300 K the curves are cut, due to the saturation of the detector. The maximum operating temperature is 350 K and the measured values of the threshold current density are 0.9 kA/cm² at 77 K and 3.1 kA/cm² at 300 K. The temperature dependence of the threshold current density of a 3 mm long and 30 µm wide laser is shown in Fig. 2 b). The data can be fitted with an exponential function $J = J_0 \exp \left(\frac{T}{T_0}\right)$, with a characteristic temperature $T_0 = 175$ K. Compared to former injectorless QC lasers the maximum operating temperature has been increased drastically from 200 K to 350 K, along with a significant decrease of the threshold current density. At 77 K it was decreased by a factor of 3. Furthermore, at the time these results were achieved, the values were comparable to those of conventional QC lasers in this wavelength region. Spectral measurements have been performed using a grating spectrometer and an uncalibrated liquid nitrogen-cooled HgCdTe detector. Fig. 3 shows the spectra at 77 K and 300 K. The laser wavelength is close to 10 µm at 77 K. A strong shift in the wavelength is observed at higher bias fields and therefore, at high temperatures (8.4 µm at 300 K). This can be explained by a distinctive voltage-induced Stark-effect, according to model calculations.

In a first attempt, we have demonstrated QC lasers without injector regions, consisting of only four quantum well-barrier pairs, exhibiting threshold current densities as low as 0.9 kA/cm² at 77 K and 3.1 kA/cm² at 300 K. A maximum operating temperature of 350 K was achieved.

3. INJECTORLESS QC LASERS EMITTING AT ~ 6.8 µm

3.1 Design and fabrication

Here, our first design without injector-miniband is combined with the advantages of a vertical transition and a double LO-phonon resonant condition of the three lower states. Fig. 4 shows the conduction-band structure of two successive active sections and the moduli squared of the wave functions for an applied bias field of 96 kV/cm and 127 kV/cm, respectively. At 96 kV/cm, levels 1 and 2 of one active section are resonant with levels 4 and 5 of the following section. Therefore, the electrons are transferred directly from one active section into the next, without the need for a bridging miniband. The transition energy is calculated to $E_{43} = 182$ meV ($\lambda \sim 6.8$ µm). At 127 kV/cm, level 1 is brought into resonance with level 5 and a triple LO-Phonon condition occurs. Using three lower levels instead of two helps to prevent thermal backfilling of the lower laser state, which is especially important in a design without injector-miniband. The exact layer sequence of one active section is given in the caption of Fig. 4. Because of the larger proportion of GaInAs in this injectorless design scheme, the active region is realized in the material system Al0.63In0.36As/Ga0.4In0.6As to achieve strain-compensation. The resulting conduction-band offset is about 0.69 eV. Several samples were grown with varying doping densities and number of periods of active sections. The first sample, referred to as sample A, contains 40 periods of active sections and a doping sheet density of $8.6 \times 10^{10}$ cm⁻². The whole structure was grown by solid-source MBE on a n-type InP substrate. The upper cladding consists of a 0.5 µm thick n-Ga0.4In0.53As layer (Si, $6 \times 10^{16}$ cm⁻³), followed by a 2.5 µm thick n-InP layer (Si, $1 \times 10^{17}$ cm⁻³), a 0.8 µm thick n⁻-Ga0.47In0.53As (Si, $5 \times 10^{18}$ cm⁻³) and a 0.2 µm thick n⁻-Ga0.47In0.53As (Si, $1 \times 10^{19}$ cm⁻³) cap layer. The InP substrate and a 0.5 µm thick n-Ga0.47In0.53As layer (Si, $6 \times 10^{16}$ cm⁻³) serve as the lower cladding. To keep the operating voltages relatively small, the active stack contains only 40 periods. Therefore, the confinement factor of the lasing transverse magnetic (TM) mode is only about $\Gamma \sim 0.47$, but the mode overlap is entirely within active sections. After growth, ridge-waveguide lasers were fabricated and mounted on copper heat-sinks as described previously.

3.2 Results of sample A

Fig. 5 a) shows the pulsed light output-current characteristics of a representative device of sample A with 3.5 mm cavity length and 26 µm width, for various heat-sink temperatures. The maximum operating temperature is 380 K. The temperature dependence of the threshold current density of this laser is shown in Fig. 5 b). The characteristic temperature is $T_0 = 91$ K. Fig. 6 a) shows the voltage- and light output-current density characteristic of another device of sample A with 3.5 mm length and 22 µm width. At 77 K, the measured threshold current density is exceedingly small with 0.2 kA/cm². At 300 K the threshold current density is 2.5 kA/cm² and the threshold voltage is ~ 9.7 V. Fig. 6 b) shows the spectrum at room-temperature. The laser wavelength of sample A is ~ 6.7 µm, which is in good agreement with our calculations.
On the basis of the design shown in Fig. 4 we investigated the influence of the doping density in the active sections of injectorless QC lasers. The doping density in the active sections is extremely important, for it affects both, the threshold current density and the maximum operation temperature of the lasers. This is because the free carrier absorption increases with doping leading to high losses, and because the population inversion is reduced by decreasing the doping. Doping sheet densities were chosen in the range of $2.5 - 8.6 \times 10^{10}$ cm$^{-2}$. Fig. 7 shows the dependence of the threshold current density on the doping sheet density of the active sections. All measurements were done on devices with same cavity length and width of 3.5 mm and 26 µm, respectively, at 300 K heat-sink temperature. The sample with the smallest doping sheet density (sample E, $2.5 \times 10^{10}$ cm$^{-2}$) shows threshold current densities as low as 1.2 kA/cm$^2$. Compared to sample A, the threshold current density was reduced by a factor of 2, only by decreasing the doping level in the active sections. However, this seems to be the lower limit, because the maximum operating temperature, which decreases with the doping level, is only 310 K for sample E, and therefore, a further reduction of the doping density is not useful.
3.4 Increased number of periods of active sections

Besides the doping density, also the number of periods of active sections influences the threshold current density and the maximum operating temperature. Therefore, two more samples (samples F and G) with an increased number of periods (from 40 to 60) have been fabricated. The doping sheet density of sample F is $8.6 \times 10^{10}$ cm$^{-2}$ according to sample A, and the doping sheet density of sample G is $2.5 \times 10^{10}$ cm$^{-2}$, according to sample E. Fig. 8 a) shows the pulsed light output-current characteristics of a representative device of sample F for various heat-sink temperatures. The measured values of the threshold current density are 0.15 kA/cm$^2$ at 77 K and 1.65 kA/cm$^2$ at 300 K. Due to the increased number of periods compared to sample A, the threshold current density was reduced by a factor of 1.5 at 300 K and the maximum operation temperature was increased to 420 K. Fig. 8 b) shows the emission spectrum of sample F at 300 K. The measured wavelength of $\sim 6.8$ $\mu$m is in good agreement with our calculations. Fig. 9 a) shows the pulsed light output-current characteristics of a representative device of sample G with 4 mm cavity length and 25 $\mu$m width for various heat-sink temperatures.
temperatures. The threshold current density is exceedingly small with 0.75 kA/cm² at 300 K and the maximum operating temperature is about 340 K. According to the increase of the number of periods, the threshold voltage was also increased from ~10 V to ~14.5 V. Therefore, a larger number of periods does not further improve the threshold power.

In comparison with our reference sample (sample A) the threshold current density has been reduced by a factor of 2 by decreasing only the doping density in the active sections (sample E). By increasing only the number of periods of active sections (sample F), the threshold current density has been reduced by a factor of 1.5. Finally, we have combined the decreased doping density and the increased number of periods (sample G). Compared to conventional QC lasers in this wavelength region (5-10 µm), we have achieved record low threshold current densities at 300 K.3,4

Fig. 7. Dependence of the threshold current density on the doping sheet density in the active sections. For comparison, the cavity length and width of all devices are 3.5 mm and 26 µm, and the temperature was kept at 300 K.

Fig. 8. a) Pulsed light output-current characteristics of a 4 mm long and 26 µm wide device of sample F at various heat-sink temperatures (in K). b) Emission spectrum of sample F at 300 K.
4. INJECTORLESS QC LASERS EMITTING AT ~ 4.2 - 4.55 µm

Recently, we have further extended the wavelength range of injectorless QC lasers down to 4.2 – 4.55 µm. For short wavelength emission a large conduction band discontinuity is needed. Furthermore, in the injectorless design scheme, very high bias fields are needed for alignment and therefore, high temperature operation requires an adequate large exit-barrier for the upper laser state, otherwise electrons may escape by thermal activation into the quasicontinuum. Here we present the designs of two samples, referred to as sample X and sample Z. For both samples the active region is realized as a five-level staircase in the material system Al0.635In0.365As/Ga0.322In0.678As with a resulting conduction band discontinuity of ~ 0.73 eV. Additionally, sample B contains thin AlAs-blocking barriers, which increase the confinement of electrons in the upper laser state.

4.1 Sample X

Fig. 10 shows the conduction band profile of two successive active sections and the moduli squared of the relevant wave functions of sample X for an applied bias field of 147 kV/cm and 177 kV/cm, respectively. The detailed layer sequence is given in the caption. Three layers of each active section are Si-doped with 1.1×10^17 cm^-3. According to our previous designs, here at 147 kV/cm, levels 1 and 2 of one active section are resonant with levels 4 and 5 of the following section. The transition energy is calculated to E43 = 284 meV (λ ~ 4.37 µm). At 177 kV/cm, level 1 is brought into resonance with level 5 and a triple LO-Phonon condition occurs. Here, the calculated transition energy is E43 = 290 meV (λ ~ 4.28 µm). More details can be found in reference 18.

The samples have been fabricated into ridge-waveguide lasers with stripe widths ranging from 18 to 30 µm, as described before. All devices were cleaved and mounted on copper heat sinks with the facets left uncoated. Fig. 11 a) shows the pulsed light output-current and voltage-current characteristics of a representative device of sample X with 3.5 mm cavity length and 26 µm width, for various heat-sink temperatures. From the voltage-current characteristics we deduce a threshold voltage of 15 V at 77 K, but stable lasing is not achieved until ~ 17 V. At 220 K, which is the maximum operating temperature, the threshold current density is 4.3 kA/cm^2 and the threshold voltage is also ~ 17 V. At such high bias fields, the upper laser state is located very near to the band edge and therefore electrons can escape into the quasicontinuum, especially at higher temperatures. Because of that, the device operation is limited to low temperatures, and we expect an improvement of the performance by using AlAs-blocking barriers in the active sections, as shown in Fig. 12. Fig. 11 b) shows the spectrum at 77 K. The laser wavelength of sample X is ~ 4.2 µm, which is in good agreement with our calculations.
4.2 Sample Z

In sample X, the upper laser state is located very near to the band edge and therefore, a thermally activated escape of electrons into the quasicontinuum can limit the device performance drastically. To avoid the escape of electrons, AlAs-blocking barriers have been inserted in each active section of sample Z. Fig. 12 shows the conduction band profile of two successive active sections and the moduli squared of the wave functions of sample Z for an applied bias field of 154 kV/cm and 184 kV/cm, respectively. The detailed layer sequence is given in the caption. It was changed slightly compared to sample X, because of the strong influence of the AlAs-layers. The tunneling escape rate of electrons in the upper laser state has to be reduced while it has to stay unchanged for electrons in the lower laser state. Four layers of each active section are Si-doped with $1.4 \times 10^{17}$ cm$^{-3}$. Similar to the design of sample X, here at 154 kV/cm, levels 1 and 2 of one active section are resonant with levels 4 and 5 of the following section. The transition energy is calculated to $E_{43} = 272$ meV ($\lambda \sim 4.55$ µm). At 184 kV/cm, level 1 is brought into resonance with level 5 and the calculated transition energy is $E_{43} = 284$ meV ($\lambda \sim 4.37$ µm). More details can be found in reference 18.

Fig. 10. Conduction-band profile and moduli squared of the wave functions of sample X at a bias of 147 kV/cm and 177 kV/cm, respectively. The layer sequence starting from the left-most barrier is: (3.0/2.7) (1.9/3.4) (1.6/4.6) (2.5/1.5) (2.0/1.5) given in nm. The layers in bold face correspond to Al$_{0.635}$In$_{0.365}$As, the ones in thin face to Ga$_{0.322}$In$_{0.678}$As. Underlined layers are Si-doped. The wavy arrows indicate the laser transition.
Fig. 12. Conduction-band profile and moduli squared of the wave functions of sample Z at a bias of 154 kV/cm and 184 kV/cm, respectively. The layer sequence starting from the left-most AlAs-barrier is: (0.5) (0.6/2.7) (2.0/3.4) (1.5/4.6) (2.3/1.7) (2.0/1.4/0.6) given in nm. The layers in bold face correspond to Al$_{0.63}$In$_{0.365}$As, the ones in thin face to Ga$_{0.322}$In$_{0.678}$As. Underlined layers are Si-doped. The first layer in bold italic corresponds to AlAs. The wavy arrows indicate the laser transition.
Fig. 13 a) shows the pulsed light output-current characteristics of a representative device of sample Z with 3.5 mm cavity length and 26 µm width, at various heat-sink temperatures. The threshold current densities are 2.9 kA/cm² at 220 K and 4.8 kA/cm² at 300 K. The maximum operating temperature of sample Z is 370 K. The threshold current density as a function of heat-sink temperature is plotted in Fig. 13 b), with a resulting characteristic temperature $T_0 = 120$ K. Fig. 14 a) shows the spectra with a measured wavelength of ~ 4.55 µm at 77 K and ~ 4.65 µm at 300 K, which is in good agreement with our calculations. In Fig. 14 b) is shown the pulsed light output-current (solid line) and voltage-current (dotted line) characteristic of the same device of sample Z at 300 K. The threshold voltage is ~ 14 V at 300 K, which corresponds to an electric field of 150 kV/cm, which is also in good agreement with our calculations.

We have demonstrated short-wavelength QC lasers without injector regions, with and without AlAs-blocking barriers. Our results show, that a better electron-confinement in the upper laser state due to AlAs-blocking barriers, leads to a drastically improved performance. The maximum operating temperature was increased from 220 K to 370 K and the threshold current density at 220 K was decreased by a factor of ~ 1.5. A threshold current density of 4.8 kA/cm² and a threshold voltage of 14 V were achieved at 300 K. Furthermore, we have realized comparably short emission wavelengths of ~ 4.2 µm and ~ 4.55 µm with an injectorless design concept. Compared to conventional QC lasers in this wavelength region\textsuperscript{20, 21} the threshold current densities of our first short-wavelength injectorless QC lasers are still high, but these structures are not yet optimized, regarding doping concentration in the active sections and number of periods.

![Fig. 13. a) Pulsed light output-current characteristics of a 3.5 mm long and 26 µm wide device of sample Z at various heat-sink temperatures. b) Dependence of the threshold current density on the heat sink temperature.](image)

![Fig. 14. a) Spectrum of sample Z at 77 K and 300 K. b) Pulsed light output-current and voltage-current characteristic of a 3.5 mm long and 26 µm wide device of sample Z at 300 K.](image)
5. CONCLUSIONS

We have presented the status of QC lasers without injector regions, based on a four- and five-level staircase, respectively. Our first lasers, emitting at a wavelength of ~ 10 μm, showed already a drastic improvement of threshold current density and maximum operating temperature compared to earlier attempts of injectorless QC lasers. With an improved design, based on a five-level staircase, we achieved high performance injectorless quantum-cascade lasers emitting at ~ 6.7 μm. On the basis of this design, we investigated the influence of doping density and the number of periods of active sections, and we achieved QC lasers with record low threshold current densities of 0.75 kA/cm² at 300 K. Furthermore, we have extended the wavelength range and demonstrated above room-temperature operation of injectorless QC lasers emitting at ~ 4.65 μm at 300 K. Our results show, that the presence of injector regions is not essential for high-performance QC lasers.

REFERENCES

